Volume IV
Appendix F.5

Space Shuttle STS-107 *Columbia* Accident Investigation, External Tank Working Group Final Report – Volume 1

This report summarizes the results of the analysis, design, production, and performance of External Tank (ET-93), performed by the External Tank (ET) Working Group (ETWG), as part of the STS-107 *Columbia* Accident Investigation.

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Space Shuttle STS-107
Columbia Accident Investigation
External Tank Working Group
Final Report—Volume I

ETWG Final Report

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Section 1 Purpose

This report summarizes the results of the analysis, design, production, and performance of External Tank (ET-93), performed by the External Tank (ET) Working Group (ETWG), as part of STS-107 *Columbia* Accident Investigation.

Section 2 Signature Page

We certify that the information contained herein is true to the best of our knowledge and represents the completion of the investigation and reporting process for the External Tank Working Group supporting the STS-107 *Columbia* Accident Investigation.

External Tank Working Group Final Report

Approved by

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Section 4 Executive Summary

The principal External Tank contributor to the loss of STS-107 is potentially detrimental debris, in the form of foam loss in the bipod area. The mechanism for bipod debris is the interaction (linking) of manufacturing defects, brought about by the complex launch environment, ultimately resulting in liberation of foam. Critical defects include: linear internal voids, attributable to foam curing mechanisms over complex contours ("rollovers"); weak knit lines between layers of foam; voids; and/or delaminations.

The ETWG process involved five complementary elements:

- A Fault Tree was developed to assure a systematic review of the entire ET.
  - 3470 Fault Tree blocks were dispositioned, assessing debris and interface issues on the entire vehicle.
  - Of the 3470 blocks, 142 were determined to be "possible events."
  - After thorough review of all critical portions of the tank, and in consideration of the findings documented by the other Shuttle Element Working Groups, the only significant anomaly was the event observed at approximately 82 sec after launch: foam loss in or near the left hand forward bipod ramp.
  - Six Fault Tree blocks were identified as likely contributors to release of major debris from the left hand forward bipod ramp area. The categories of contributing elements follow:

    Design verification and process validation did not account for all TPS material and processing variability or adequately address all failure modes.

    Quality Control (QC) verification of the manual spray application process did not preclude the existence of TPS defects that could cause release of debris.

    Available acceptance testing/inspection techniques were not capable of detecting adverse "as-built" features, which could compromise TPS integrity.

    Independent of the preceding elements, an undetected/unknown anomaly may have been present in the fabricated components.
- Consultation with outside experts was utilized to provide an independent assessment of postulated failure mechanisms and associated evaluation methods and to generate additional theories regarding possible failure modes and associated contributors.
- Coupon through full-scale component testing was performed to better understand foam systems and material interactions in the complex bipod region. This testing confirmed the defect interaction mechanism described above, and it demonstrated that other postulated foam release mechanisms, such as cryopumping, were unlikely to have led to major loss of TPS debris on STS-107.

- 13 major test programs and hundreds of tests were completed. Testing confirmed temperature distributions assumed in thermostructural analyses and revealed that significant foam loss could only occur as a result of the interaction of multiple, grossly out-of family manufacturing defects.
- Dissection of six bipods revealed manufacturing defects in all six ramps, in numbers sufficient to statistically support the preceding test observation.
- Testing of specimens containing simulated defects showed substantial loss of strength, confirming that defects could join and form debris surfaces.
- High-energy foam loss mechanisms (cryopumping, cryoingestion, *etc*.) could not be demonstrated in the laboratory, even when natural barriers to those mechanisms were artificially removed.
- Variability within the fleet was attributed to natural variations.

  Major variation: number and distribution (pattern) of defects

  Minor variations: loads, environments, *etc*.

- Analysis of critical areas was updated using state-of-the art analysis tools.
  - A detailed solid finite element model (FEM) was developed to replicate the geometry, materials, and environments at the bipod region.
  - All analyses confirmed assumed interactions of environments and supported definition of critical areas of the structure.
- Independent S&MA assessments were performed for systems in-place on the External Tank program (Non-Conformances, Failure Modes and Effects Analysis (FMEA), and Critical Items and Hazards).

Section 5 Method of Investigation, Board Organization, and/or Special Circumstances

5.1 Method of Investigation

5.1.1 General

The origin of the External Tank Working Group was the activation of the MSFC Space Shuttle Contingency Plan, MSFC-SSCP-5-77, specifically, para. 6.1.1, Contingency Working Groups: "…Working groups are activated by the SSPO Manager upon declaration of a contingency. The SSPO Manager works with the appropriate element project manager to coordinate working group activities..."

The primary focus of the ETWG was causes or issues that might have contributed to the *Columbia* accident and those associated with damage to the left wing of the Orbiter. The secondary focus was causes or issues that are generically similar to those that might have contributed to the *Columbia* accident or which otherwise merit consideration by the Space Shuttle Program (SSP).

A Fault Tree was the primary process driver. Two approaches were used:

- A top-down approach, which was used to develop logical fault paths in the classic FT format. The FT analyses and results are developed in great detail within this report.
- A "cross-cutting" approach, which involved the development of "scenarios," or possible chains of events that may or may not be "straight paths" on the FT. In the latter case, they were called "cut sets." Scenario development is a deductive or reverse logic tool where the consequence (top undesirable event) is developed into a number of root or base events. Partial scenarios/questions/observations/comments were identified during brain-storming sessions, interim FT reviews, and manufacturing process document examinations. These statements were collected in a variety of formats and transitioned into an archived database with linage to the originator, creation date, and FT. The identification of the Orbiter left wing debris zone limited the comments to those involving material release forward of the hydrogen to intertank flange. Review of these comments showed a combination of unique circumstances, linked events, and redundant ideas that were subsequently distilled into 54 separate or associated possible scenarios. Each of these possible scenarios had reference to specific FT blocks. These linkages are shown in Volume II, an interactive compact disk of the ETWG FT, and the scenarios also appear therein as a separate, linked database. The scenario analysis resulted in the systematic formulation of the causes of TPS debris loss in STS-107, shown in Section 7.2.1.11, "Conclusions."

Testing and analysis were used as required to augment the existing database. Ascent performance data, available through the ET, Orbiter, and Solid Rocket Booster (SRB), were available to support analyses of the interface branches. With the exception of the 82-sec foam loss event observed during ascent and Orbiter Vehicle Engineering (OVE) analyses, very little physical evidence existed

to support the Debris FT "branches." This necessitated a "probabilistic' treatment, using testing and analysis as required to evaluate the various possibilities for debris.

FT blocks were categorized as either "Possible" (Probable, Remote, Improbable) or "Impossible" contributors to damage to the Orbiter left wing. The FT process methodology is shown in Figure 5.1.1-1. Areas reviewed during the investigation area are shown in Figure 5.1.1-2.

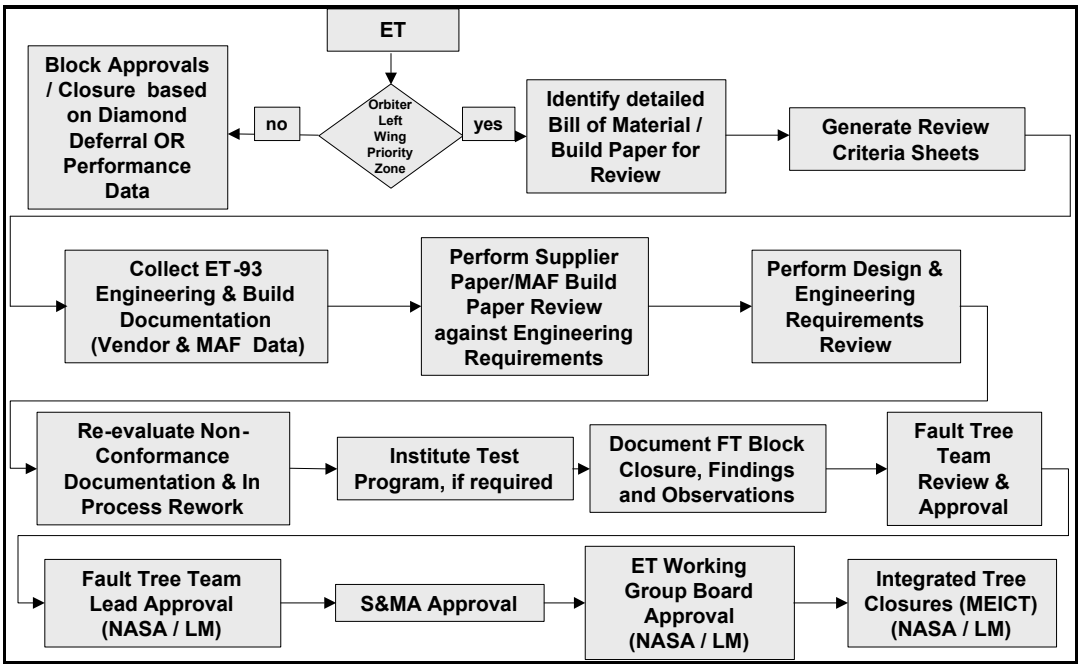

Figure 5.1.1-1. Fault Tree Process Methodology

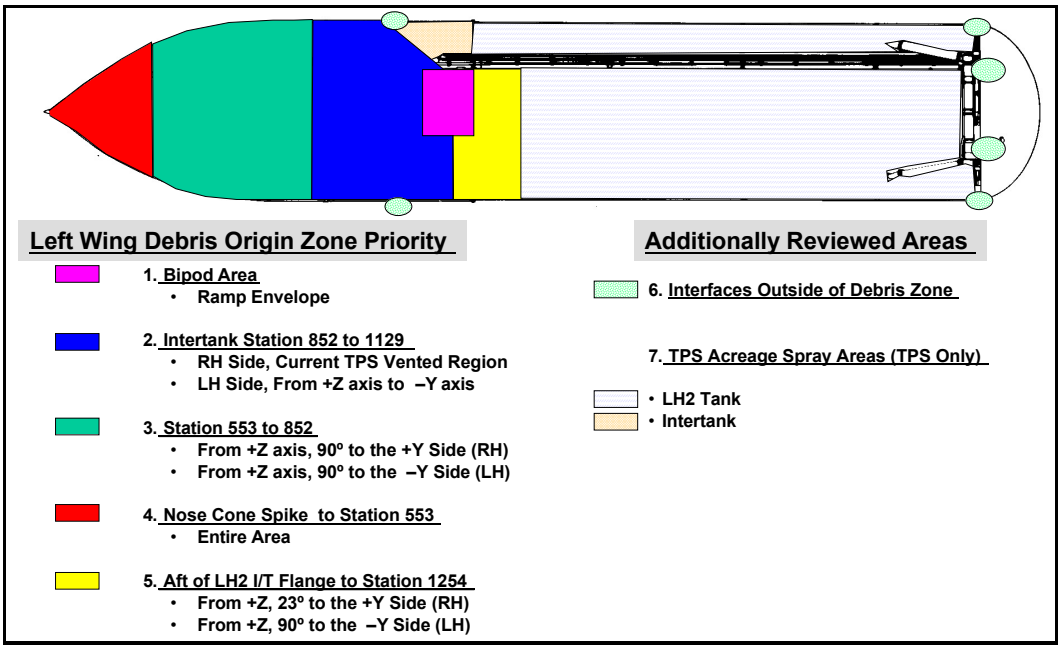

Figure 5.1.1-2. ET-93 Structure Reviewed during Fault Tree Investigation

5.1.2 Scope of Assessments

In general, data evaluated consisted of the following categories: (Note: Specific areas were adjusted to be consistent with appropriate data review for the FT branch assessed.)

- System requirements
- Design assessments
  - Structural materials
  - Analyses and verification
- STS-107 loads and environments
  - Best estimated trajectory (BET) loads
  - Flexible body loads
- ET-93 build records (supplier, MAF, and KSC processing records)
  - Standard Material Specifications (STMs)
  - Standard Process Specifications (STPs)
  - Manufacturing Process Plans (MPPs)
  - Acceptance testing records
  - Nonconformance Documents (NCDs)
  - In-Process Repair Authorizations (IPRAs)
  - KSC Problem Report and Corrective Action (PRACA)/Action Requests (ARs)

  - Practitioner Interviews
  - Previous ET Build histories
- Flight Performance Data
  - Film and Post Flight Inspections
  - All available electrical and propulsion measurements
  - Evidence of nominal performance or anomalies
  - Interface and structure functional performance
  - Any direct or indirect effects on TPS and Orbiter reentry system
  - Previous ET Flight histories
- STS flight experience, pre-flight predictions/expectations, and post-flight performance reconstructions
- Propulsion performance
- Electrical performance
- Additional Assessments
  - Personnel Training Records
  - Inspections and dissections of “sister” External Tanks

5.1.3 Fault Tree Closure Database

An electronic database was developed to manage the FT block closure process. A secure web site was established to allow access from local and remote locations. Electronic routing and approval provided an opportunity to reduce time significantly and provide an opportunity to share and correlate investigation results. The electronic investigation database is included as Volume II of this report.

Branch closures were performed at the lowest level and the system prompted approval through electronic notification. Each closed block required each of NASA, S&MA, and Lockheed Martin Corporation (LMC) approvals, both at the development level and at the FT management levels. A permanent record of approvals is recorded in the FT database.

5.2 Board Organization

The investigation effort was organized with multiple teams to allow effective simultaneous investigation efforts. Team structure is shown in Figure 5.2-1.

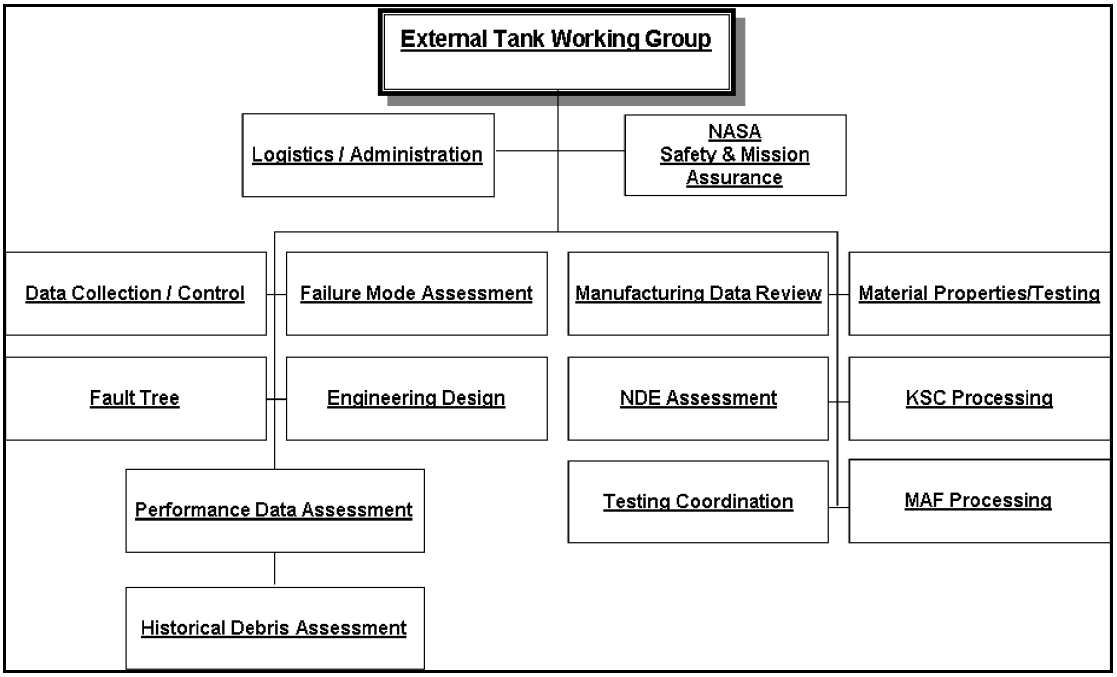

Figure 5.2-1. ETWG Organization

5.3 Special Circumstances

A Space Shuttle contingency was declared by Mission Control, Houston, as a result of the loss of communications with the Space Shuttle *Columbia* as it descended toward a landing at KSC, Florida, on February 1, 2003. Communication and tracking of the Shuttle were lost at 9:00 a.m. EST at an altitude of about 203,000 ft above north central Texas. It was later determined that the Space Shuttle *Columbia* and its crew of seven were lost.

At 9:29 a.m. EST, the NASA Headquarters Contingency Action Plan for Space Operations was activated. Data at all NASA sites and contractors was impounded at 10:00 a.m. EST, and the Headquarters Action Team was activated. Contingency plans were executed at ET contractors and suppliers.

5.3.1 ET-93 Performance until Notification of Mishap

Propellant loading was started at 2:07 a.m. CST on January 16, 2003. Launch occurred at 9:39 a.m. CST of the same day. All component and compartment pre-launch temperatures were maintained within acceptable limits. Loading and flight performance was satisfactory with the exception of TPS debris. Purges and the ET intertank heater operated properly. There were no ET-related Integration Control Document (ICD), Launch Commit Criteria (LCC), or Operations and Maintenance Requirements and Specifications Document (OMRSD) violations during loading. Liquid hydrogen (LH2) and liquid oxygen (LO2) tank ullage pressures were at predicted levels throughout loading and flight. All ET

measurement instruments performed satisfactorily. Main Engine Cut Off (MECO) occurred at approximately 502.6 sec after SRB ignition (T-0), with ET separation occurring at approximately T+523.8 sec. There was no unacceptable ice/frost formation reported by the Ice/Frost Team. In-flight video revealed that, at approximately T+81.7 sec, a piece of TPS debris from the left bipod ramp was shed and struck the left wing area of the Orbiter.

5.3.1.1 ET-93 History

The original launch of ET-93, STS-116, was delayed because of the discovery of cracks in Orbiter feedline flowliners. As a result, ET-93 was demated from the SRBs, and the mission was postponed until after *International Space Station* missions STS-112 and STS-113 were completed. The following dates provide the history of major milestones for ET-93:

DD-250	November 20, 2000
SRB Mate	May 8, 2002
SRB Demate	August 29, 2002
SRB Mate	November 4, 2002
Orbiter Mate	November 20, 2002
Rollout	December 9, 2002
Launch	January 16, 2003

5.3.1.2 ET-93 Loading Summary

Propellant loading was started at 2:07 a.m. CST on January 16, 2003. Two ground equipment problems delayed start of loading. All loading requirements were met. There were no ET-related ICD, LCC, or OMRSD violations.

5.3.1.2.1 LH2 Loading Summary

Loading of the LH2 tank was normal. All loading cycle durations were within previous experience. LH2 chilldown duration was 414.8 sec, near the maximum of 416 sec for the Light Weight Tank (LWT) since STS-40. Replenish duration was less than average because of a delay in the start of loading. The delay was related to two ground equipment problems. Table 5.3.1.2.1-1 summarizes the loading cycle durations as compared to LWT history since STS-40.

Table 5.3.1.2.1-1. LH2 Loading Cycle Durations

Cycle*	ET-93	Minimum	Average	Maximum
Chilldown	414.8	382	397	416
Slow Fill	2386	1437	2509	3524
Fast Fill	2926	2604	2779	3128
Fast Fill Reduced	1444	1127	1569	3412
Topping/Replenish	19,512	17,254	23,500	30,255
Total	**26,683**	**24,462**	**30,755**	**37,679**

* All cycle durations shown in seconds

The End of Replenish (EOR) absolute ullage pressure was 15.02 psia (versus 14.85 psia nominal). The EOR ET LH2 propellant load was 230,926 lbm (109 lbm

less than nominal), which is –0.05% and well within the requirement of +/-0.40%. This includes the effect of ET-93 specific LH2 tank volume.

5.3.1.2.2 LO2 Loading Summary

The LO2 replenish flow rate indication (MSID GLOQ2009A) was observed to be unusually high (approximately 200 gpm versus 130 gpm typical). IPR 107V-113 was taken as a result. If this measurement were inaccurate, it would have resulted in erroneously terminating Slow Fill up to 15 sec early (OMRSD S00FD0.073). The replenish flow rate was within historical limits throughout loading (in particular during Replenish) showing that such indications have occurred in the past. Slow Fill duration was 28 sec shorter than average for LWT since STS-40 but was 32 sec longer than the minimum LWT Slow Fill (STS-94). The concern is that initiating Fast Fill early may cause thermal shock to the LO2 tank vortex baffle. Examination of the original derivation of the 11-min timer for Slow Fill (MMC-3527-83-0018) showed that there is 54 sec of margin. It was concluded, therefore, that the Slow Fill duration was satisfactory and loading proceeded.

The LO2 tank vent valve actuation pressure (MSIDs GLOP4015A, GLOP4515A) exceeded the 800-psig maximum OMRSD limit (S00GEN.760) during replenish. The exceedence was related to a creeping of the 750-psig gaseous helium (GHe) regulator (S72-0697-01 facility GHe supply panel) that supplies the LO2 tank and LH2 tank vent valve actuation systems and the Ground Umbilical Carrier Plate (GUCP) cavity purge system. IPR 107V-115 was taken as a result. The regulator setting drifted because of ambient temperature changes and is not an uncommon occurrence. The maximum pressure observed was 816 psig. The concern is to maintain operation within the certified OMRSD valve timing limits. The ET Project approved a maximum pressure of 850 psig via waiver EK10320 based on the valve proof pressure of 1300 psig and minimal impact to leakage and valve timing during replenish. Both vent valves remain open throughout replenish, so valve timing issues are not an issue. Timing is also not an issue when the valves are closed before prepressurization.

Replenish duration was less than average because of a delay in the start of loading. The delay was related to two ground equipment problems.

Loading of the LO2 tank was otherwise normal. Geyser prevention procedures provided significant temperature margins throughout the vehicle LO2 feed system. The performance of the anti-geyser system is shown in Figures 5.3.1.2.2-1 and 5.3.1.2.2-2, which show the helium inject supply pressure and delta pressure data. Table 5.3.1.2.2-1 summarizes the loading cycle durations as compared to LWT history since STS-40.

Table 5.3.1.2.2-1. LO2 Loading Cycle Durations

Cycle*	ET-93	Minimum	Average	Maximum
Chilldown	1467	1439	1578	1706

Slow Fill	676	644	704	815
Fast Fill	7229	6928	7225	7805
Topping/Replenish	16,782	14,617	20,714	27,977
Total	26,154	23,972	30,272	37,225

* All cycle durations shown in seconds

The EOR absolute ullage pressure was 15.49 psia (versus 15.26 psia nominal). The EOR ET LO2 propellant load was 1,382,980 lbm (990 lbm less than nominal), which is –0.07% and well within the requirement of +/-0.29%. This includes the effect of ET-93 specific LO2 tank volume.

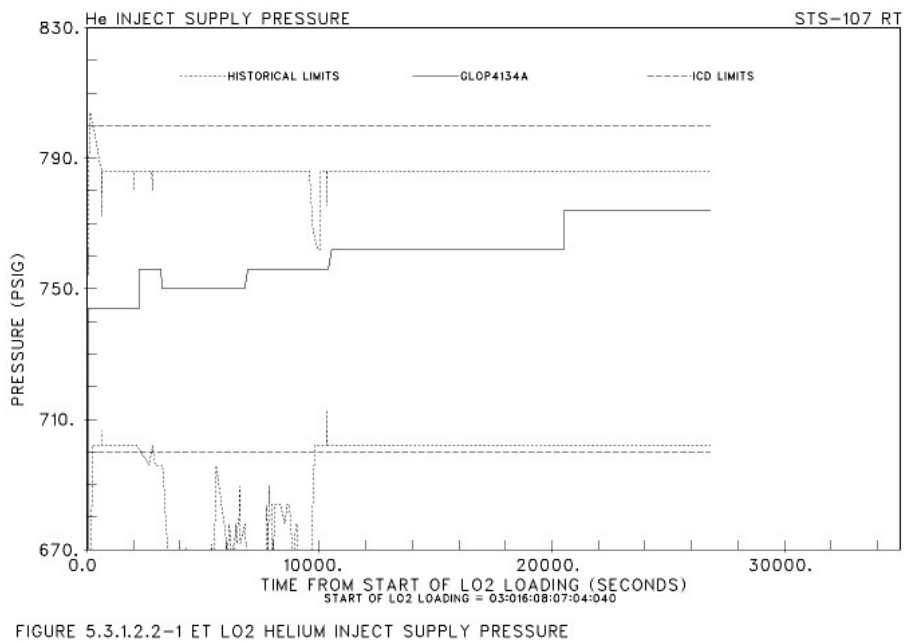

Figure 5.3.1.2.2-1. ET LO2 Helium Inject Supply Pressure

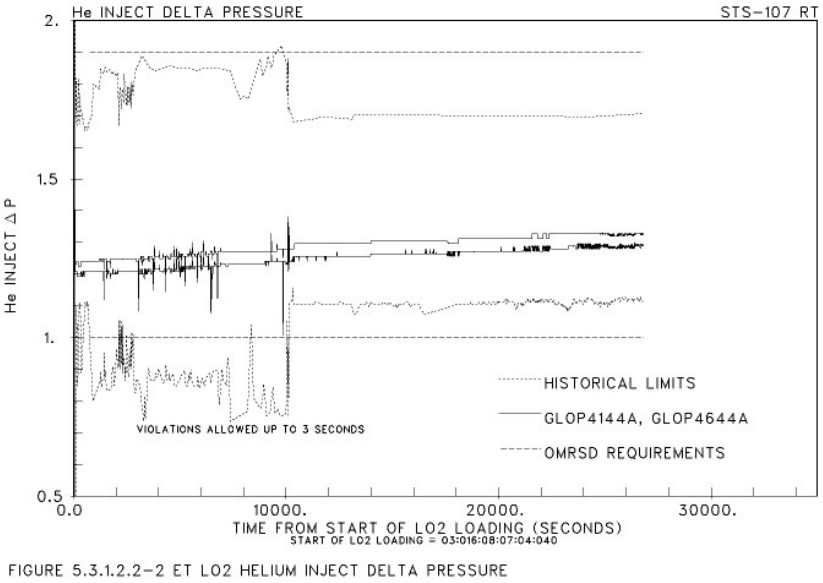

Figure 5.3.1.2.2-2. ET LO2 Helium Inject Delta Pressure

5.3.1.2.3 Thermal Assessment

There were no LCC violations on any of the ET thermal systems. Pre-launch compartment purge flow rate for the nose cone was within the ICD requirements. All electrical heater on/off timelines were met, as were power requirements for the forward bipod and facility purge heaters. All component and compartment pre-launch temperatures were satisfactorily maintained.

In discussions concerning compartment temperatures (Sections 5.3.1.2.3.1 and 5.3.1.2.3.2 below), there is a distinction made between basic redline limits in the text and measurement limits as denoted in the figures. Measurement limits allow for instrumentation and systems errors to protect against exceedance of the basic redline limits.

5.3.1.2.3.1 Nose Cone Compartment Purge

A heated gaseous nitrogen (GN2) purge is used to maintain a dry, thermally controlled environment inside the ET nose cone during pre-launch operations. This purge is initiated 30 minutes before chilldown and is terminated within the time period of T-3 min and T-70 sec. Temperatures inside the nose cone are controlled, using feedback from the primary or secondary temperature probe (MSID T41T1820H or T41T1821H) mounted inside the nose cone, by a controller that regulates power to the facility heater. Set point for the nose cone temperature control is 60°F throughout the entire operation.

Maximum and minimum basic redline limits for the nose cone gas temperatures are 140 °F and 0 °F. There is an allowance, per the LCC, for a minimum basic redline limit temperature down to 0 °F for low relative humidity conditions (protected by a 5-°F LCC redline limit). This allowance is in consideration of the low probability of ice/frost forming at the nose cone vent exit during low humidity conditions. There is also an OMRSD maximum temperature limit of 350 °F identified for the purge gas exiting the heater: MSID GLOT4104A (primary) or GLOT4604A (secondary).

Pre-launch measured nose cone gas temperatures are shown in Figure 5.3.1.2.3.1-1. Corresponding temperatures for the nose cone purge heater outlet are presented in Figure 5.3.1.2.3.1-2. Data in both figures are typical in that an increased demand on the nose cone purge heater is shown as the LO2 loading progressed. There were no LCC or OMRSD temperature violations for either the heater outlet or the nose cone compartment.

Figure 5.3.1.2.3.1-3 shows that the measured nose cone purge flow rate was within the ICD requirement of 9 to16 lbm/min, as it has been since KSC installed critical flow nozzles to limit flow rate (STS-55 on Pad A and STS-51 on Pad B).

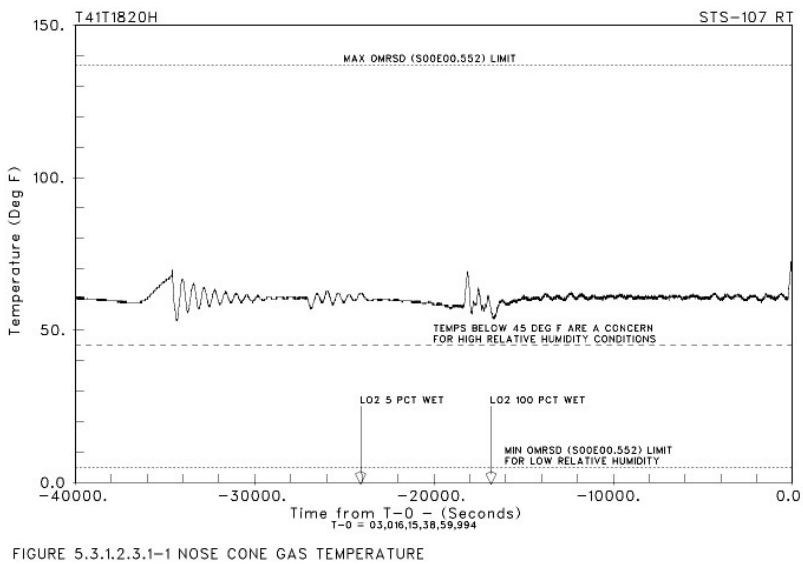

Figure 5.3.1.2.3.1-1. Nose Cone Gas Temperature

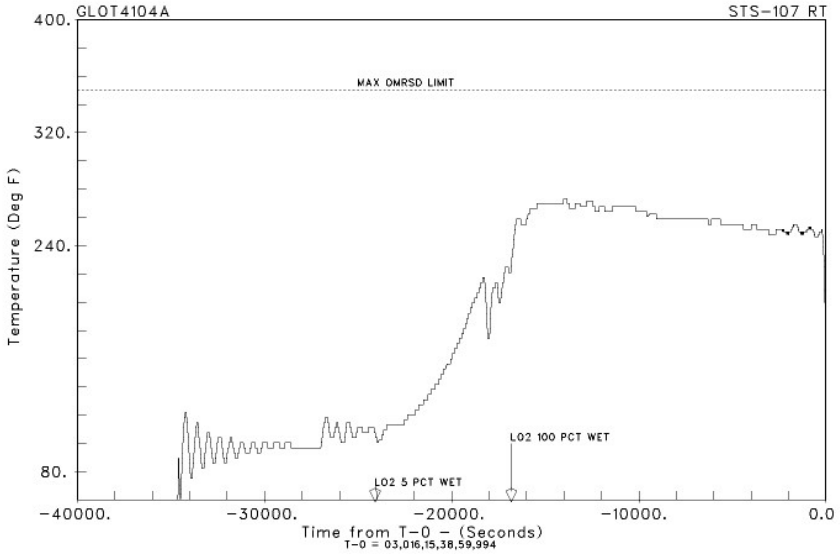

Figure 5.3.1.2.3.1-2. Nose Cone Purge Heater Outlet Temperature

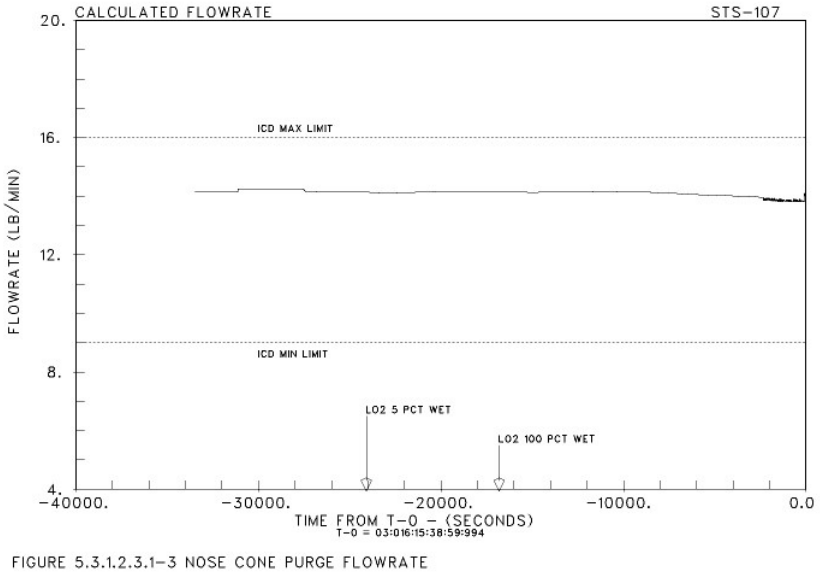

Figure 5.3.1.2.3.1-3. Nose Cone Flowrate

5.3.1.2.3.2 Intertank Compartment Purge

A heated GN2 purge is used to maintain a dry, thermally controlled environment inside the ET intertank during pre-launch operations. This purge is initiated 30 min before chilldown and is terminated within the time period of T-3 min and T-70 sec. Temperatures inside the intertank are controlled by either using the feedback from the primary or secondary temperature probe (MSID T41T1810H or T41T1811H) or the feedback from the primary or secondary heater outlet temperature probe (MSID GLHT5736A or GLHT5737A), which regulates power to the facility heater. The first set of probes is mounted in the intertank, whereas the sec set of probes is located downstream of the heater. Normally, the intertank temperature is controlled based on the output from the intertank sensors with a set point of about 65 °F throughout the propellant loading operation. The set point is subsequently changed to about 56 °F before T-1 hr and is maintained there. During the chilldown and loading phase, the maximum and minimum OMRSD limits for the intertank gas temperatures are 103 °F and 37 °F, respectively. Between T-1 hr and T-3 min, the LCC defines the basic redline limits for the intertank gas temperature as 87 °F maximum and 32 °F minimum with an allowance for maximum and minimum redline exceedances of up to 5 min and 15 min, respectively. The ICD limit for the intertank purge is 350 °F. Measured temperatures of the purge gas exiting the heater, MSID GLHT5736A (primary) or GLHT5737A (secondary), and an analytically derived temperature drop of 6 to 8 °F between the heater outlet and the interface are used for ICD limit verification.

Typically, the gas in the intertank is cooled when either of the tanks is being loaded. The presence of LO2 in the aft dome of the LO2 tank and/or the presence of LH2 in the LH2 tank causes the thermostatically controlled heaters on the launch stand to increase the heater output. In practice, the heater set point is usually lowered when both tanks are in stable replenish, which is much earlier than the 1 hr before launch as required by the LCC.

Pre-launch measured intertank gas temperatures are shown in Figure 5.3.1.2.3.2-1. Corresponding temperatures for the intertank purge heater outlet are presented in Figure 5.3.1.2.3.2-2. The heater outlet temperatures were slightly lower than normal because of the lower demand on the heater that resulted from increased foam coverage on the aft dome of the LO2 tank. The intertank compartment temperatures were in the normal range. Both data traces are typical, showing increased demand on the purge heater as the loading progressed. These data show no LCC, OMRSD, or ICD temperature violations for either the intertank compartment or the heater outlet.

Figure 5.3.1.2.3.2-3 shows the GN2 mass flow rate versus time calculated from the intertank venturi pressure data, which indicated fluctuations in flow rate from approximately 133 lbm/min early in the countdown to an average of 119 lbm/min at the completion of loading. The minimum ICD purge flow limit of 103 lbm/min

was established to prevent air intrusion through the intertank vent areas for a worst-case wind scenario: 47 kts peak wind from 345 deg. Actual peak wind gust velocity during loading and launch was 10 kts from approximately 330 deg as indicated by looking at data from both camera sites 3 and 6. An ICD revision (Interface Revision Notice 0702), which was approved by Level II on September 17, 1992, changed the acceptable flow limits on the purge flow rate to 103 and 158 lbm/min based on an updated analysis. Additionally, effective on STS-73 the facility side of the intertank purge system was modified to provide a trickle purge to reduce the likelihood of intertank air intrusion problems in the event of a hold at T-31 sec.

All objectives of the intertank purge were met; temperatures inside the intertank compartment were maintained within accepted limits; all the components within the intertank performed satisfactorily; and pressure decay and separation pressures were as expected.

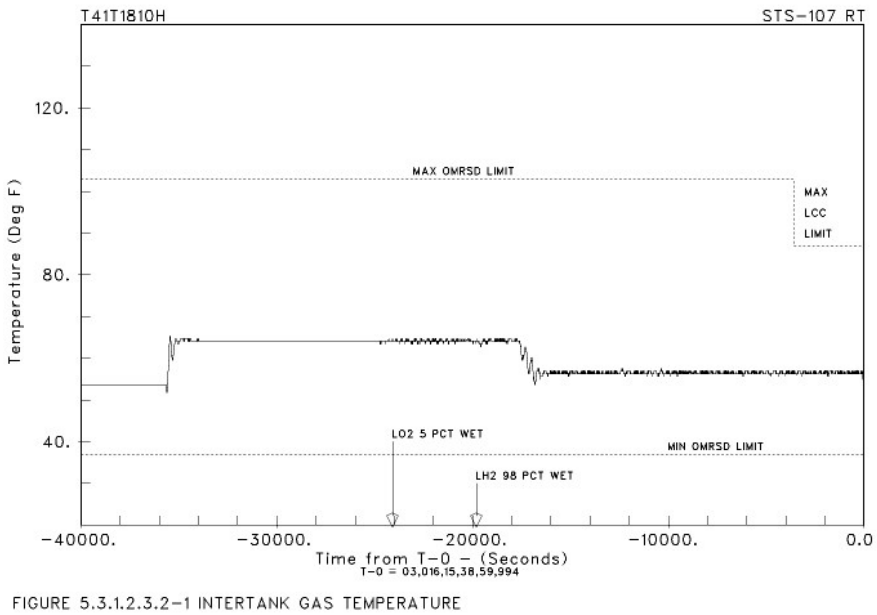

Figure 5.3.1.2.3.2-1. Intertank Gas Temperature

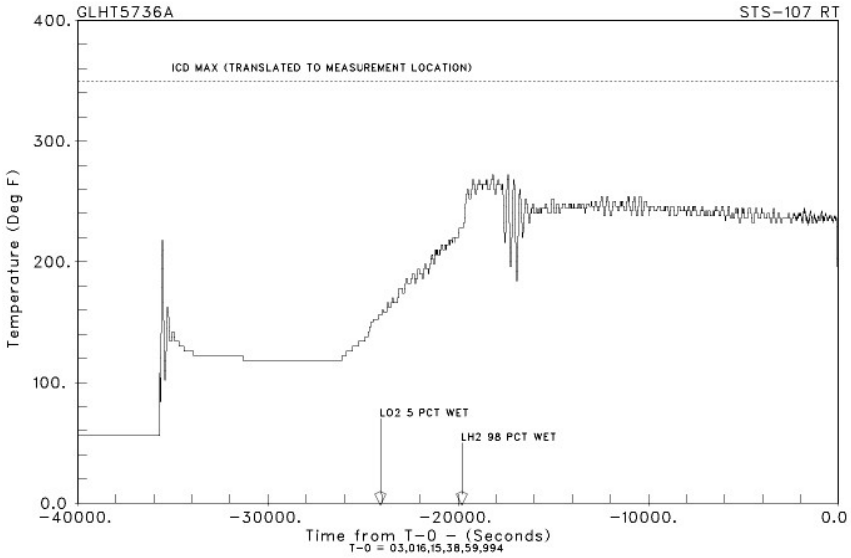

Figure 5.3.1.2.3.2-2. Intertank Purge Heater Outlet Temperature

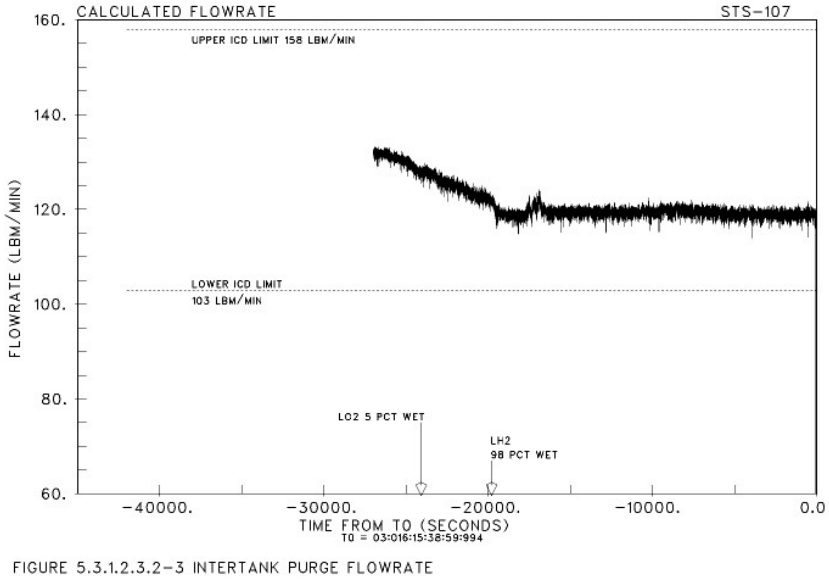

Figure 5.3.1.2.3.2-3. Intertank Purge Flowrate

5.3.1.2.3.3. Anti-Icing Pressline Purge

Heated helium is used to purge the gaseous hydrogen (GH2) and gaseous oxygen (GO2) pressurization lines until just before prepressurization. This requirement was implemented to eliminate the potential for ice/frost forming on the pressurization line at the slide mount bracket locations. Interface temperature of the helium supply is controlled within the acceptable OMRSD range of 245 ±15 °F; interface temperature data are monitored throughout the pre-launch operations (MSID GLHT4577A). Helium anti-icing purge flow rates through the GH2 and GO2 pressurization lines are controlled by the facility to comply with the ICD values of 0.30 ±0.06 lbm/min and 0.45 ±0.09 lbm/min, respectively.

Heater outlet temperature data for the anti-icing purge flow are presented in Figure 5.3.1.2.3.3-1. These data are shown in comparison with the OMRSD limits with select loading events identified on the time scale and indicate that, except for the shutdown transient, the anti-icing purge supply temperature was within specified OMRSD requirements throughout the pre-launch operations.

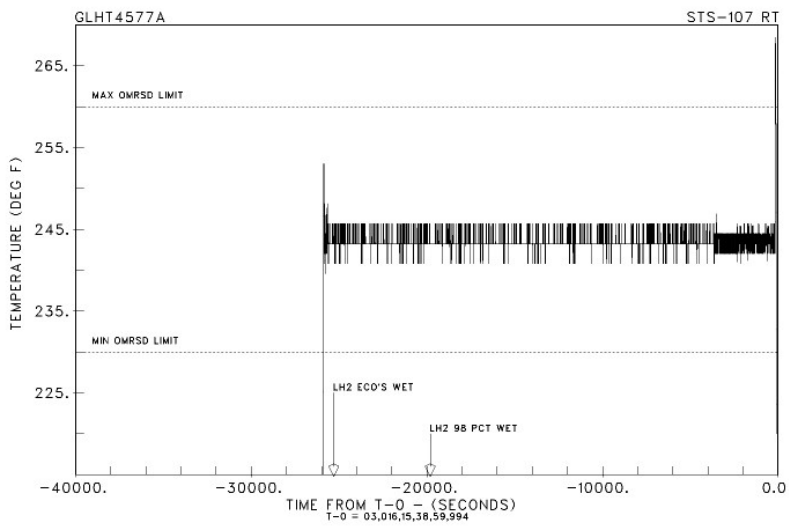

Figure 5.3.1.2.3.3-1. Anti-Icing Pressline Purge

5.3.1.2.3.4 Bipod Heaters

Calrod heaters are used in each of the bipod fittings to limit ice/frost formation on the bipod spindle to less than 6 sq. in. each. Control must be exercised to not turn the heaters on before the cryogen reaches the bipod location (to prevent overheating of the fitting and the surrounding TPS) and to turn them on in a timely manner after the cryogen has reached the bipod location (to prevent the formation of unacceptable ice). For this reason, the bipod heaters are to be turned on from 4 to 5 min after the 98% liquid level sensors are wet. This timeline

was developed from a series of bench tests at MAF and from the bipod spindle temperature data during LH2 loadings on ETs 14 through17; effective on ET-18 (flown on STS-51D), the bipod spindle temperature sensors were deleted.

The health of the bipod heater system is monitored during pre-launch operations using displays that record source voltage and current. Special programs are used to correct heater voltages based on cable/heater simulated tests and to display the wattage of each heater. Limits for each recorded and calculated data stream are unique to each launch pad. Details of the instrumentation and limits for the launch pad are presented in Table 5.3.1.2.3.4-1. All values were within the required limits and no anomalous conditions were reported. The bipod heaters were turned on within the time limits prescribed in the OMRSD, and they remained on until the umbilicals were dead-faced at T-31 sec.

Table 5.3.1.2.3.4-1. Bipod Heater Standard Configuration HOSC Display

PAD A -Left Bipod -3.5 Vac Right Bipod -3.5 Vac			
PAD A	LOW REDLINE	LOW WARNING	HIGH WARNIN
VOLTAGE			
G56V1115A (LFT)	86.0	87.0	90.00
M40Z1000S	82.5	83.5	86.50
M40Z1000S	86.0	87.0	90.00
M40Z1001S	82.5	83.5	86.50
CURRENT			
G56CO155A(LFT#1)	0.80	0.85	1.15
G56CO165A(LFT#2)	0.80	0.85	1.15
G56CO175A(RHT#1)	0.80	0.85	1.15
G56CO185A(RHT#2)	0.80	0.85	1.15
WATTAGE			
M40Z1002S(LFT#1)	66.0	70.98	99.48
M40Z1004S(LFT#2)	66.0	70.98	99.48
M40Z1003S(RHT#1)	66.0	70.98	99.48
M40Z1005S(RHT#2)	66.0	70.98	99.48

Voltage requirements for the bipod heaters are 85 ±0.85 Vac at the umbilical (GUCP). Voltage is established by tests using a cable/heater simulator with fixed resistors equivalent to the heater, ET cable, and pad cable resistance. When the correct current is measured through the heater simulator (1 ±0.2 amp), the voltage at the source is recorded.

Source voltages (MSIDs G56V1115A and G56V1125A) and currents (MSIDs G56CO155A, G56CO165A, G56CO175A, and G56CO185A) are monitored on all heaters during pre-launch. Huntsville Operations Support Center (HOSC) displays also provide corrected heater voltages (M40Z1000S and M40Z1001S) via a special computations program "Elect 1." These corrected voltages are based on the cable/heater-simulated test. Displays for the heater voltages are based on the worst-case drop from the source voltage (G56V1115A). Warning and redline limits for the heater voltages are 3.5 V lower than the source voltage limits. The HOSC also displays calculated wattages (M40Z1002S, M40Z1004S, M40Z1003S, and M40Z1005S

5.3.1.2.3.5 Thermal Environment

Ice/frost formation on an exposed surface is a function of surface temperature and the ambient conditions to which it is exposed. For the ET, a special thermal analyzer subroutine (SURFICE F) was developed to compute surface temperatures. The ambient conditions are recorded at a 60-ft high tower at camera site 3 and camera site 6. It is assumed that ambient data from camera site 3 or 6, which are approximately 1280 ft southeast and northwest of the launch pad, respectively, are valid for use as input for ambient conditions in the ET ice/frost calculations. The ambient data from camera site 6 was used in all the ice/frost and surface temperature calculations. Table 5.3.1.2.3.5-1 summarizes the ambient conditions encountered during pre-launch after the earliest Fast Fill time and the estimated TPS surface temperatures at lift-off, assuming nominal TPS thickness. Ambient conditions of temperature, relative humidity, wind velocity, and wind direction are plotted in Figures 5.3.1.2.3.5-1 to 5.3.1.2.3.5-4, respectively. Also shown on these figures are the significant loading timelines. These parameters are then used in the computer subroutine SURFICE F, which in addition to calculating the sprayed-on foam insulation (SOFI) surface temperature also calculates condensation rate and ice/frost rate in four regions of the ET.

The minimum surface temperatures for the LO2 tank and the LH2 tank were 21 °F and 17 °F, respectively. With these surface temperatures, ice/frost was predicted for the ET acreage during loading; only light frost was predicted for the upper region of the LH2 tank just before launch. Condensation was predicted for the four regions, given the humidity range of 67 to 97%. These predictions are consistent with the visual observations during pre-launch operations.

Table 5.3.1.2.3.5-1. Ambient Thermal Conditions after Earliest Fast Fill Time

	Range of Pre-launch Ambient Conditions		**Acreage Temperature* Predictions at Lift-off (°F) Winds from 135°** at 3.2 kts**
	Min	**Max**	
Temperature	48.8	64.8	LO2 Ogive 43.8
Humidity (%)	67.2	97.2	LO2 Barrel 33.6
Dew Point (°F)	47.4	58.0	LH2 Barrel (Fwd) 32.0
Wind Speed (kts)	0.0	9.6	LH2 Barrel (Aft) 42.0
Wind Direction (deg)** Surface Temp (°F)	62.6 16.8	393 44.7	(Predictions based on ET ambient conditions of 65°F and 68% relative humidity)

* Based on 5-minute average, ambient conditions
** Based on 360 deg north

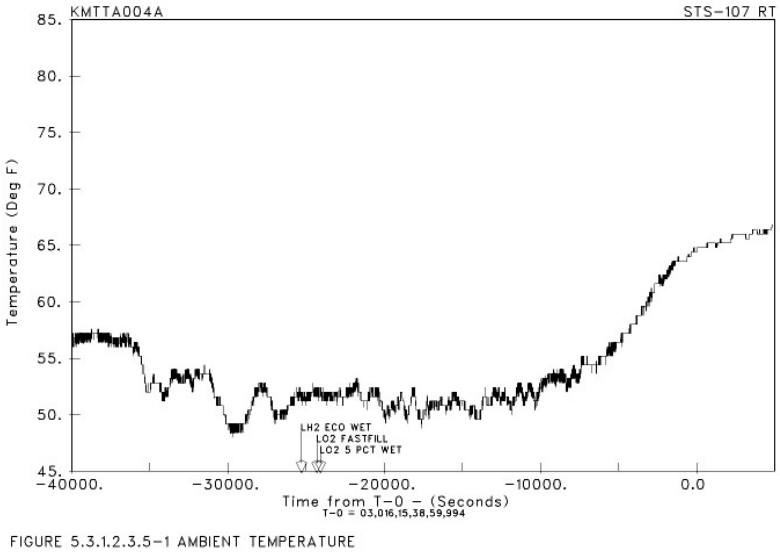

Figure 5.3.1.2.3.5-1. Ambient Temperature

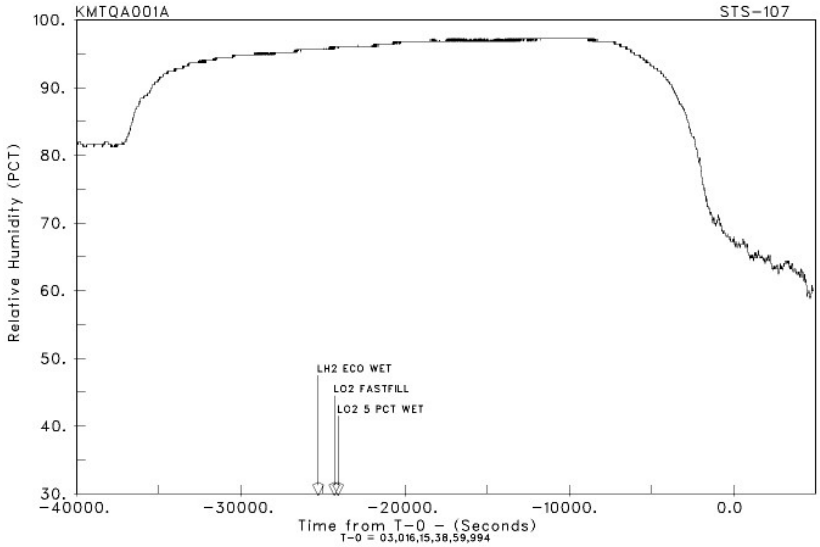

FIGURE 5.3.1.2.3.5-2 RELATIVE HUMIDITY

Figure 5.3.1.2.3.5-2. Relative Humidity

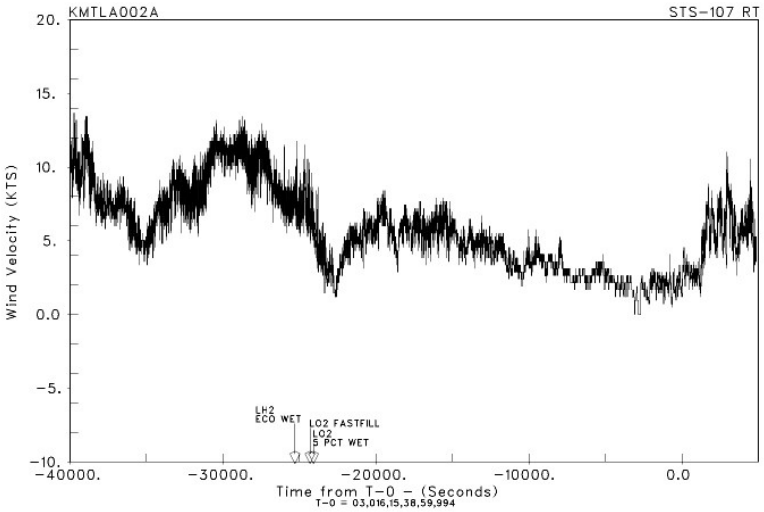

FIGURE 5.3.1.2.3.5-3 WIND VELOCITY

Figure 5.3.1.2.3.5-3. Wind Velocity

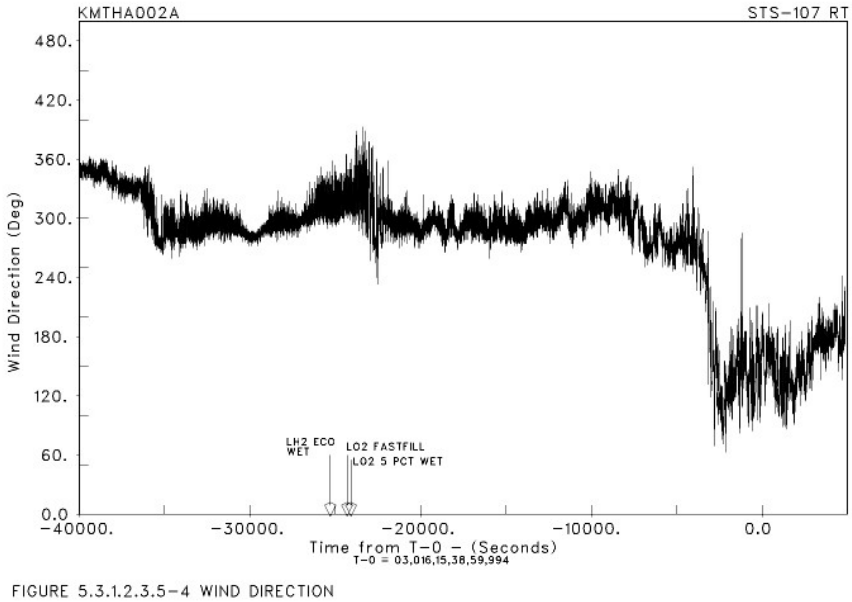

Figure 5.3.1.2.3.5-4. Wind Direction

5.3.1.2.3.6 TPS Assessment

Table 5.3.1.2.3.6-1 shows results of camera scans. Tables 5.3.1.2.3.6-2 through 5.3.1.2.3.6-5 show TPS surface conditions at selected times, with wind data based on 360 deg north.

Table 5.3.1.2.3.6-1. Camera Scan Results

Approx. CST Time	Scan/Results
2:30 a.m.	Initial scans completed/no anomalies
3:15 a.m.	LO2 feedline camera scan completed/no anomalies
4:15 a.m.	LO2 feedline camera scan completed/no anomalies
5:00 a.m.	Camera scan completed/no anomalies
6:00 a.m.	Camera scan completed/no anomalies
9:00 a.m.	Camera scan complete/no anomalies

Table 5.3.1.2.3.6-2. Pre-Loading TPS Surface Temperatures

TPS Conditions before Loading (~12:40 a.m.):		
Temperature: 49 °F Humidity: 94%	Wind Direction: 289 deg Wind Speed: 6 kts	
ET Section	Infrared (IR) Temperatures	
	RSS	CS2
LO2 Ogive	52 °F	52 °F
LO2 Barrel	47 °F	48 °F
Upper LH2	48 °F	49 °F
Lower LH2	50 °F	49 °F

Table 5.3.1.2.3.6-3. Fast Fill Surface Temperatures

Fast Fill TPS Conditions (~3:30 a.m.):			
Temperature: 51 °F Humidity: 96%	Wind Direction: 296 deg Wind Speed: 5 kts		
ET Section	Surface Temperatures	IR Temperatures	
		RSS	CS2
LO2 Ogive	40 °F	49 °F	47 °F
LO2 Barrel	30 °F	34 °F	44 °F
Upper LH2	25 °F	33 °F	45 °F
Lower LH2	37 °F	43 °F	39 °F

Table 5.3.1.2.3.6-4. Replenish TPS Surface Temperatures

Replenish TPS Conditions (~7:00 a.m.)		
Temperature: 50 °F Humidity: 97%	Wind Direction: 282 deg Wind Speed: 3 kts	
ET Section	Surface Temperatures	IR Temperatures RSS
LO2 Ogive	32 °F	36 °F
LO2 Barrel	20 °F	37 °F
Upper LH2	19 °F	38 °F
Lower LH2	30 °F	36 °F

Table 5.3.1.2.3.6-5. Pre-Launch TPS Surface Temperatures

Pre-Launch TPS Conditions (~8:48 a.m.):		
Temperature: 61 °F Humidity: 77%	Wind Direction: 166 deg Wind Speed: 0.5 kts	
ET Section	Surface Temperatures	IR Temperatures RSS
LO2 Ogive	39 °F	53-75 °F
LO2 Barrel	30 °F	43-60 °F
Upper LH2	39 °F	38-58 °F
Lower LH2	30 °F	44-60 °F

Final TPS inspections were conducted from approximately 5:15 to 6:45 a.m. Results from those inspections are listed below.

- Nose Cone: No condensation was noted. The seals were in good shape. No anomalies were observed.
- LO2 Tank: Handheld IR temperatures ranged from 30 to 34 °F. Firing room IR readings indicated temperatures of 35 to 40 °F (RSS). No condensation was noted. No anomalies were observed.
- Intertank: No cracks were observed in the stringer valleys. GH2 vent ice/frost was typical. No leaks or unusual vapors were observed.
- LH2 Tank: Handheld IR temperatures ranged from 20 to 36 °F. Firing room IR readings indicated temperatures of 35 to 41 °F (RSS). Light to moderate condensation was noted. No acreage anomalies were observed. Typical TPS crack on the –Y vertical strut cable tray forward face (12 in. x 0.375 in. with no off-set) was observed. Red tape was noted in the L-1 walk down and documented on IPR-107V-0105 and was observed to still be in place.

No facility or vehicle issues were noted. All observations were acceptable per 8303 criteria. There were no Interim Problem Report/Problem Report (IPR/PR) or LCC violations noted.

5.3.1.3 LH2 Tank Prepressurization

STS-107 was the fifth flight to use a cluster of three Block II Space Shuttle Main Engines (SSMEs). To accommodate the higher start pressure requirement of these engines, the LH2 tank prepressurization band was raised by 5.2 psi. Overall, LH2 tank prepressurization for ET-93 was satisfactory. Prepressurization was initiated at T–104.4 sec and the time to reach the control band was 16.3 sec. Three pairs of rapid GHe bursts were observed. The occurrence of rapid bursts has been observed before and is expected to continue to occur in the future. Rapid bursts are caused by a combination of variables: the set of pressure transducer biases, the short helium prepress burst duration (0.5 sec), signal conditioner and other electrical dispersions in the prepress control circuit, helium temperature, and slight variations in individual transducer construction (winding details, wiper hysteresis).

Ullage pressure transducer No. 1 was biased lower than the No. 2 and 3 transducers, as reported in the Pre-Flight Mission Report, and its indicated response is consistent with that of a low bias transducer. The bias was about 0.10 to 0.15 psi more than predicted, which is not too unusual.

The initial prepressurization of the LH2 tank into the control band indicated a slower rise rate for STS-107 than on the last LWT flight (STS-99, ET-92) but similar to the LWT ET-91 (STS-90). This suggests that the helium mass flow rate and/or helium temperature for STS-107 was not out of family but may have been on the low side. This is supported by the longer time to reach the prepressurization control band. Lower helium flow or colder helium can lead to a larger number of prepressurization cycles. LCC ET-04 limits the number of cycles

to a maximum of 13. This was not a problem as there was still a 30-sec margin to exceeding the maximum prepressurization cycle count. There were 10 prepressurization cycles during the LCC counting period. There were expected margins to LCC ET-05 pressure limits of 46.1 to 48.0 psia.

5.3.1.4 LO2 Tank Prepressurization

LO2 tank prepressurization was normal. Prepressurization was initiated at T–153.8 sec, and the time to reach the control band was 11.5 sec. There were expected margins to LCC ET-06 pressure limits of 19.3 to 22.5 psid. There were 21 prepressurization cycles before Engine Start Command, which is very common.

5.3.1.5 ET-93 Flight Summary

Launch occurred at 9:39 a.m. CST on January 16, 2003. Flight performance was satisfactory with the exception of TPS debris. LH2 and LO2 tank ullage pressures were at predicted levels throughout flight. All ET measurement instruments performed satisfactorily. MECO occurred approximately 502.6 sec after SRB ignition, with ET separation occurring at approximately T+523.8 sec. In-flight video revealed that at approximately T+81 sec, a piece of TPS debris from the left bipod ramp was shed and struck the left wing area of the Orbiter.

5.3.1.5.1 Propulsion Analysis

There were no propulsion system performance observations or anomalies noted.

5.3.1.5.1.1 LH2 Tank

In-flight pressurization of the LH2 tank was normal. The pressure decayed from the prepressurization control band (46.1 to 48.0 psia) to the in-flight control band of 32 to 34 psia in 7.2 sec and was maintained there through the end of powered flight. Approximately 959 lbm of GH2 were used to pressurize the tank from Engine Start Command. There were 13 GH2 Flow Control Valve cycles. These results constitute very nominal performance. Pressurant supply pressures and temperatures delivered by the SSMEs were within previous experience and very near predicted values. LH2 ET/Orbiter interface pressures and temperatures were within ICD limits. Uncover times for the 98% and 5% liquid level sensors were well within previous experience. The LH2 residual at MECO was 3320 lbm, very near predicted.

5.3.1.5.1.2 LO2 Tank

In-flight pressurization of the LO2 tank was normal. The maximum ullage pressure was 26.2 psid and occurred at T+149.5 sec. The minimum ullage pressure was 13.5 psid and occurred at T+12.5 sec. Approximately 2825 lbm of GO2 were used to pressurize the tank from Engine Start Command. These results constitute very nominal performance. Pressurant supply pressures and temperatures delivered by the SSMEs were within previous experience and comparable to predicted values. LO2 ET/Orbiter interface pressures and

temperatures were within ICD limits. Uncover times for the 98% and 5% liquid level sensors were within previous experience. The LO2 residual at MECO was 7354 lbm, very near predicted.

5.3.1.5.2 Structural Analysis

5.3.1.5.2.1 Loads Assessment

The LWT interface loads FTO1 through FTO9, FTB1 through FTB10, P1 through P13, and Zero Margin (α/β) constraints were predicted during the STS–107/ET–93 United Space Alliance (USA)/MOD reviews of the L–3.5 hr and L–2.0 hr Jimsphere balloon data on January 16, 2003. The interface loads provide a rapid validation of the ET interface predictions associated with the measured Day-of-Launch (DOL) conditions. For the data reported, using the L+15 min wind and L-30 min atmosphere, the FTB 5 and 6 interface loads were the highest at 92 and 93 %, respectively (at 76.9 sec into the flight). There were no issues with the ET protuberances. Data from the same balloon predicted the ET's Protuberance Zero Margin Q dispersed was 97% of limit at Mach 0.79. In accordance with Block Update 2002.01 (CR 052550MD), α - β are now reported as vector length margin. The minimum α - β margin was 1.88 at Mach 1.0.

Since the DOLILU II I-LOAD is now the only I-Load available, the ET interface loads provide a method to determine if the assessment made by Level II, and identified in BOEING letter 98MA0717 dated March 31, 1998, remains a valid selection criterion for the ET's DOL Active Indicator List. The interface loads protect the ET against exceedances of contractual design limits, and the Zero Margin squatcheloid provides the airload constraint for the protuberances during the USA/MOD operations for the as- measured pre-launch winds for each flight.

5.3.1.5.2.2 Compartment Venting Performance

Vent areas of the intertank and nosecap compartments that affect loads were:

COMPARTMENT	TOTAL VENT AREA (sq. in.)
Nosecap	19.9 ±2.7
Intertank (Generic)	60.1 ±4.4
Intertank (ET-93)	60.2 ±2.2

Intertank vent area for ET-93 is based on a measured area of 39.4 sq. in. at the base of the LO2 feedline fairing plus an additional 1.6 sq. in. related to LO2 feedline shrinkage from cryogenic temperatures. Planned pre-flight venting walkdowns and inspections verified the remaining intertank vent area of approximately 19.2 sq. in.. Similar planned venting walkdowns and inspections revealed no evidence of open issues associated with the nose cone vent area or with any of the other ET vented compartments, *e.g.,* cable trays, fairings, as defined in the ET leak/vent drawings.

Two normal mission trajectories are used for the pre-flight predictions: a ‘minimum’ throttle profile trajectory and a performance enhancement (PE) high

dynamic pressure trajectory. Minimal deviations in predicted pre-flight and post-flight pressure differentials were observed for the intertank compartment. For the nose cone compartment, there are some noticeable changes in the pressure differential for the initial 2 min of the flight. The differences in dynamic pressure and the angle of attack between the pre-flight predicted trajectories and the post-flight trajectory are the reason for the deviation. The dynamic pressure and attitude directly influence the pressure coefficient characteristics, which are much more sensitive to changes for the nose cone compartment vents than they are for the intertank vents. The deviations between the pre-flight and post-flight nose cone compartment pressures are not a flight concern.

Pre-flight predictions are based on two sets of criteria:

- LWT PE, Block 2A SSMEs, July, High Q, Low Energy, 104.5% Nominal Power Level, Narrow Throttle Bucket
- LWT PE, Block-2A SSMEs, February, Low Q, High Energy, 104.5% Nominal Power Level, Widest Throttle bucket.

Post-flight reconstructions are based on actual reconstructed BET induced environments.

5.3.1.5.3 ET Film Coverage

5.3.1.5.3.1 Ascent Video

Multiple pieces of ice debris were observed falling from the ET/Orbiter umbilicals during SSME ignition through lift-off. This is a typical observation. Ice debris was also observed falling near the LH2 recirculation line. No damage to the launch vehicle was noted.

At approximately 81 sec, a piece of debris was shed from an area near the ET/Orbiter forward attachment and is assumed to be a piece of the left bipod ramp TPS foam. Three separate cameras show the debris striking the left wing area of the Orbiter. The debris appeared to disintegrate upon contact with the wing. Comparison views of the strike area immediately before and after impact with the Orbiter were inspected for indications of surface damage. Although no damage was discernable from the videos, the resolution was insufficient to draw any conclusions.

5.2.1.5.3.2 On-Orbit Video and Film

Video taken by the crew of the ET after separation was downlinked and reviewed. The only view obtained was from the far side of the ET and provided no information on the source of the debris. All other video and photos were lost with *Columbia* on reentry.

5.3.1.6 ET-93 Entry and Disposal

STS-107/ET-93 entry data from a BET are presented in Table 5.3.1.6-1. Information relevant to the ET entry ground track and debris impact is depicted in Figure 5.3.1.6-1. The prediction for the ET impact point is based on state separation vectors and assumes the ET remains intact. As indicated in the figure, the post-flight predicted intact impact point is approximately 47 n.mi. uprange from the pre-flight prediction.

Table 5.3.1.6-1. ET Post-Flight Data

ET Telemetry Separation Time (from T-0)	507.2 sec
2ET Altitude @ ET/Orbiter Telemetry Separation	60.81 n.mi. 369,492 ft
Impact Point Latitude	2.283 deg N
Impact Point Longitude	139.420 deg W

For previous flights, NORAD provided observed ET entry data for assessment by Aerospace Corporation. These data supported the ground track prediction and allowed for assessment of the ET rupture altitude. Rupture altitude estimates for 63 extracted flights from STS-1 through STS-73 were statistically combined to produce ±3 sigma limits. This assessment of rupture altitudes was discontinued after STS-73 when the contract with Aerospace Corporation was canceled. The contract was reinstated to obtain additional rupture altitudes to encompass the Super Light Weight Tank (SLWT) design. The preliminary SLWT design database shown below consists of the current revised empirical rupture altitudes obtained from the Aerospace Corporation:

Flight	ET	Rupture Altitude (kft)
STS-91	96	238.8
STS-95	98	245.5
STS-88	97	235.8
STS-96	100	235.8
STS-93	99	221.8
STS-103	101	221.2
STS-99	92	236.4
STS-106	103	230.9
STS-92	104	233.9
STS-97	105	234.5

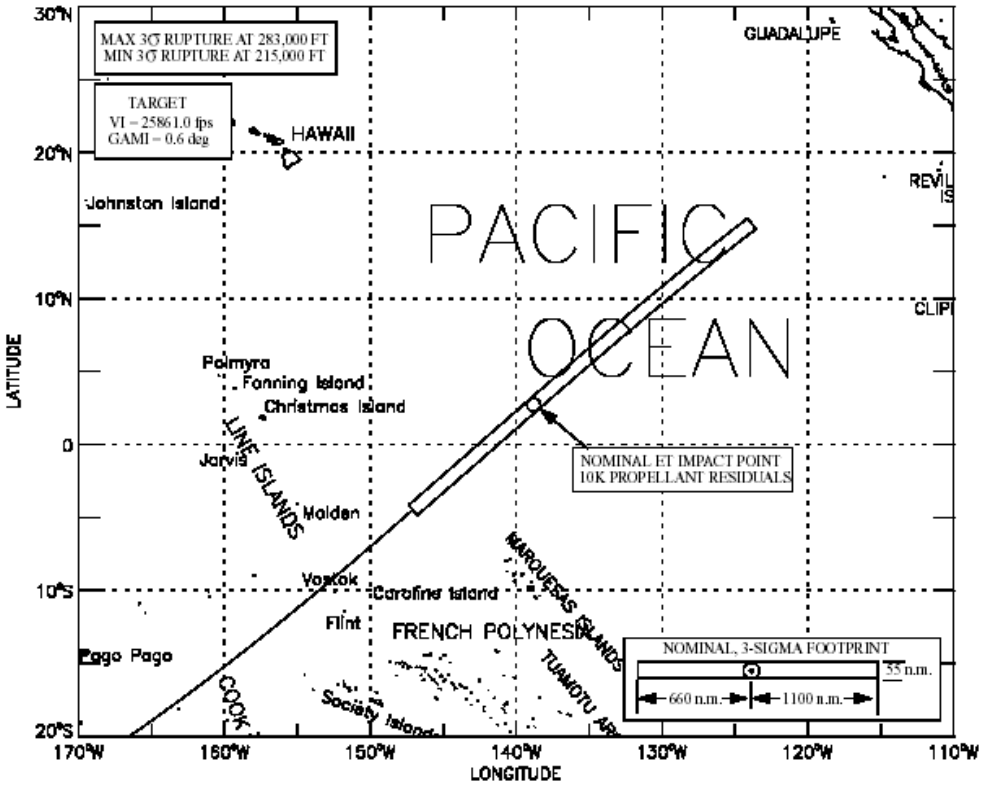

Figure 5.3.1.6-1. ET-93 Nominal Impact Area

5.3.1.7 ET-93 Mass Properties

The mass properties data provided are intended as a reference to compare flight-to-flight data and to assist with subsequent post-flight analyses. Figure 5.3.1.7-1 depicts ET post-MECO reconstructed weight history for missions since STS-40. Table 5.3.1.7-1 defines ET mass properties at lift-off (T-0) and post-MECO (after SSME shutdown transients). This information is based on the ET actual weight report (SE40) and Boeing reconstructed propellant data and is used to assist USA in generating entry trajectories for ET heating analyses.

Note: STS 79-84, 99, and 103 reconstructed data are generated using predicted dry weight. STS 85-98, 100-102, and 104-112 reconstructed data are generated using actual dry weight.

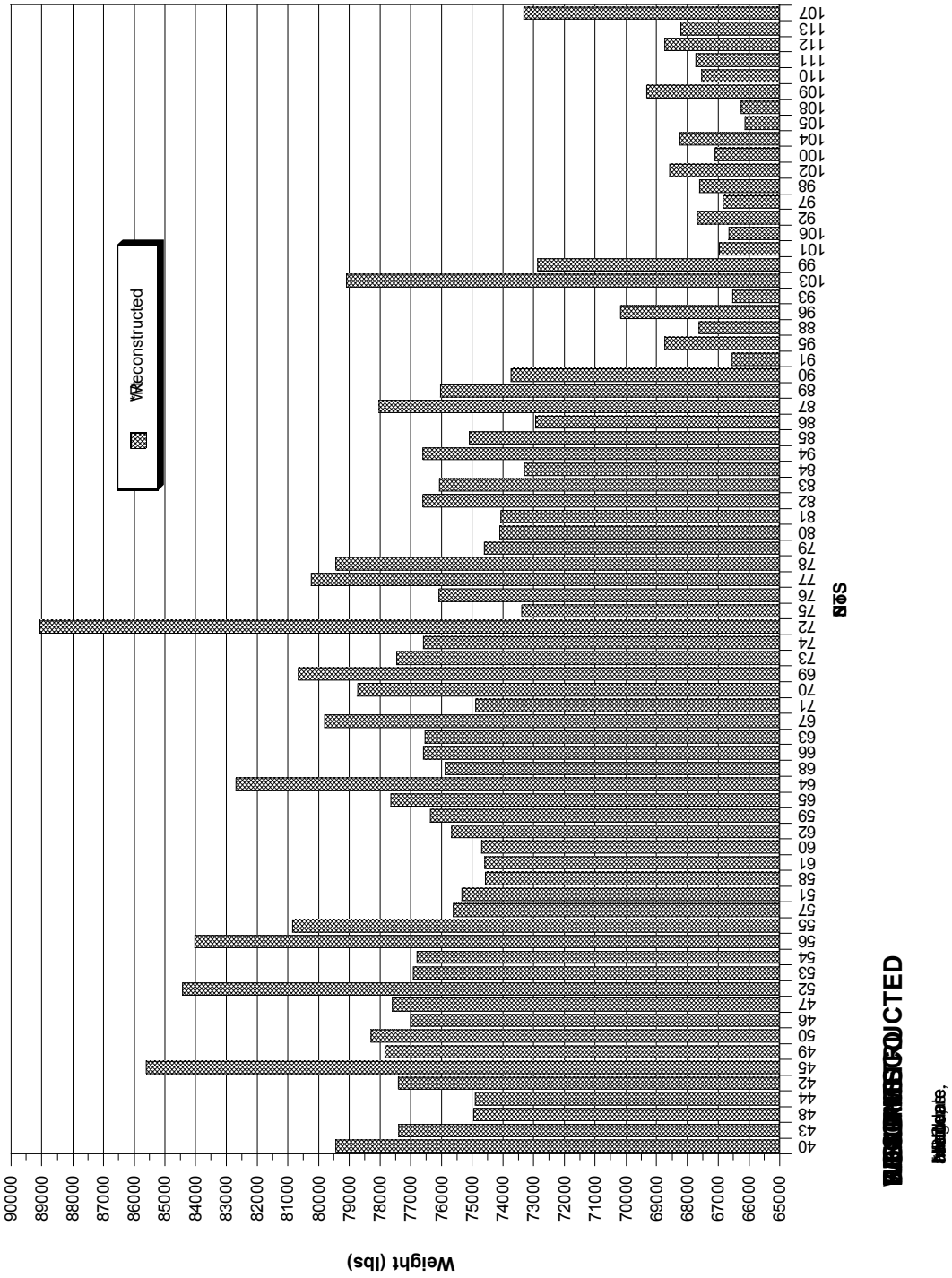

Figure 5.3.1.7-1. ET Post-MECO Reconstructed Weights

DESCRIPTION	WEIGHT	CG			GYRATION			MOMENTS			PRODUCTS		
		X	Y	Z	KX	KY	KZ	IX	IY	IZ	PXY	PXZ	PYZ
	LBS	INCHES			INCHES			SLUG-FT2/1000			SLUG-FT2/1000		
Ignition													
ET-93	65,115.0	1,355.18	2.70	424.70	158.33	519.63	519.86	352.32	3,794.91	3,798.27	2.73	154.65	6.45
LO2 Propellant*	1,366,913.0	732.40	0.56	401.35	15.74	165.31	164.79	73.09	8,062.53	8,011.89			
LO2 Ullage*	96.0	422.34	-0.30	399.20									
LH2 Propellant*	228,971.0	1,608.90	-0.02	400.06	3.23	313.69	313.67	0.52	4,863.11	4,862.49			
LH2 Ullage*	63.0	1,059.78	0.00	400.00									
NPC's	457.0	1,286.30	0.00	402.20	82.77	419.38	424.67	0.68	17.35	17.79			
Sep. Hdwr.	893.0	1,954.00	0.00	429.60	178.61	317.68	351.62	6.15	19.45	23.83			
TOTAL	1,662,508.0	878.31	0.56	402.10	35.06	383.84	383.65	441.14	52,867.67	52,816.36	116.98	557.93	31.98
Post-MECO													
ET-93	64,970.0	1,354.60	2.71	424.71	158.50	518.89	519.13	352.30	3,775.73	3,779.11	2.73	154.65	6.45
LO2 Residuals*	1,179.0	2,035.40	70.00	570.59	12.67	35.88	34.09	0.04	0.33	0.30			
LO2 Ullage*	2,911.0	724.09	0.48	401.16									
LH2 Residuals*	2,270.0	2,149.60	-1.99	406.25	29.20	59.22	53.39	0.42	1.72	1.40			
LH2 Ullage*	1,063.0	1,589.16	0.00	400.00									
NPC's	47.0	1,360.62	-0.01	408.43	42.72	465.03	479.61	0.02	2.19	2.33			
Sep. Hdwr.	888.0	1,954.00	0.00	429.60	178.61	317.68	351.62	6.15	19.45	23.83			
TOTAL	73,328.0	1,375.92	3.48	425.27	152.06	536.50	536.66	365.95	4,555.49	4,558.34	12.80	180.81	9.04

Table 5.3.1.7-1. Mass Properties Data

5.3.2 Foam Loss History

5.3.2.1 Methodology

Evaluation of ET TPS performance is accomplished through an evaluation of the ground (ascent) and on-orbit imagery (most comprehensive). The +Z side of the ET (critical debris zone) is typically observed from the 16-mm or 35-mm cameras installed in the Orbiter umbilical wells. The -Z TPS performance is typically observed from crew handheld cameras; therefore, assessment of the -Z TPS performance is difficult because of the distance of the ET to the camera.

5.3.2.2 TPS Loss from All Sources Excluding Bipod Ramps

Of the 113 Space Shuttle flights, 79 flights had useable imagery of the +Z axis from these cameras. The data collected during the STS-107 accident investigation were aggregated into major areas of TPS loss (Volume III). TPS loss has been observed on 82% of the missions with useable imagery. Areas of observed loss are shown in Figure 5.3.2.2-1. Recent material changes and configuration changes were also reviewed in an attempt to further assess TPS loss. Foam loss over time is shown in Figure 5.3.2.2-2. The loss of acreage TPS is primarily related to an increase in intertank acreage TPS loss attributed to a recent material change (the blowing agent, HCFC 141b) in the intertank acreage TPS. The TPS loss phenomenon observed since this material change was subsequently mitigated through venting of the TPS to allow entrapped pressure to outgas. Although intertank TPS loss, through 'popcorn-type' divots, still occurs, the size and quantity of the divots has been greatly reduced.

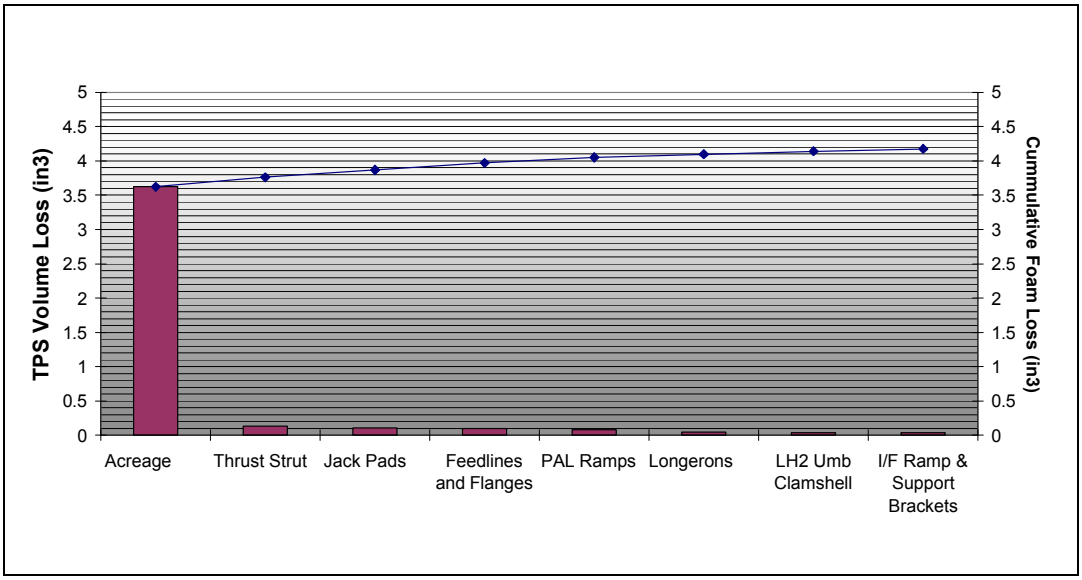

Figure 5.3.2.2-1. Areas of Observed Loss

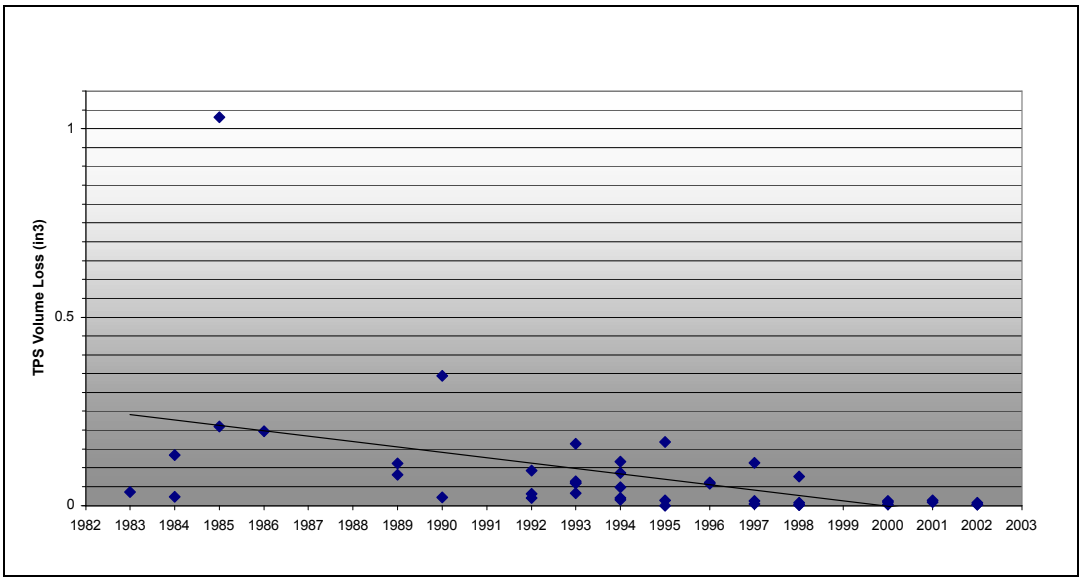

Figure 5.3.2.2-2. Foam Loss Trend

While on-orbit imagery is the only valid method for determining ET TPS performance, post-landing inspection of the Orbiter TPS is sometimes used as a measure of TPS performance. Figure 5.3.2.2-3 shows the number of Orbiter lower surface infects correlated to TPS damage. As shown below, there have been cases when Orbiter tile damage could not be correlated to significant ET TPS loss. Statistical analyses of data indicate that ET foam loss has a weak correlation to Orbiter damage. There are other significant sources of damage to the Orbiter tiles.

Foam loss data from the bipod ramp, flange, LO2 tank, Intertank, and LH2 tank were used in the analysis. Using all observed foam loss and Orbiter data correlated to this set of missions, there were no significant pair-wise correlations between foam loss and Orbiter hits. The regression chart of TPS loss weight versus tile damage is shown in Figure 5.3.2.2-4. Analyses of those missions that only assess missions with observable loss, however, indicate a slight correlation. None are statistically significant at the standard $p = 0.05$ level. Significance is approached at the $p = 0.10$ level for volume versus hits >1 in. ($p = 0.102$), volume versus lower surface hits ($p = 0.095$), weight versus hits >1 in. ($p = 0.098$), weight versus lower surface hits ($p = 0.096$), and weight versus lower surface hits >1 in. ($p = 0.106$). The associated regression chart for this case is shown in Figure 5.3.2.2-5.

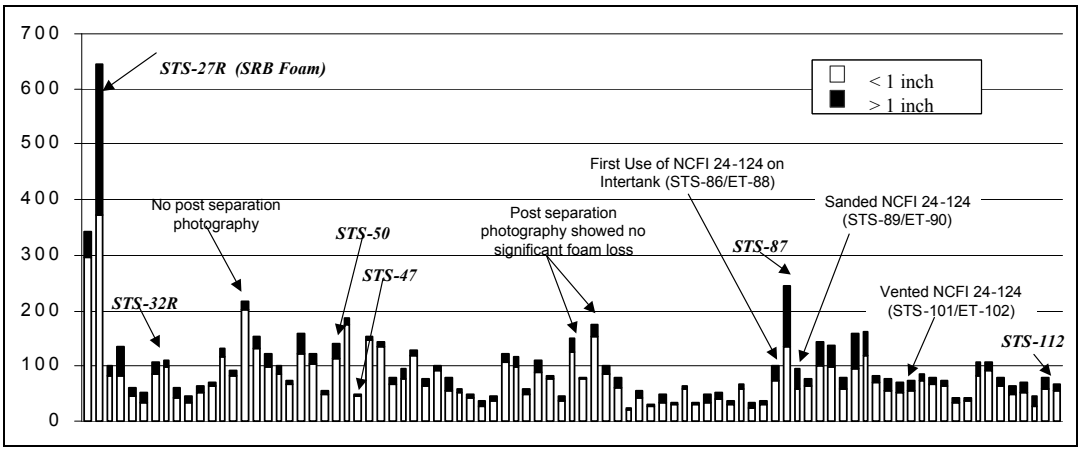

Figure 5.3.2.2-3.a. Orbiter Tile Damage

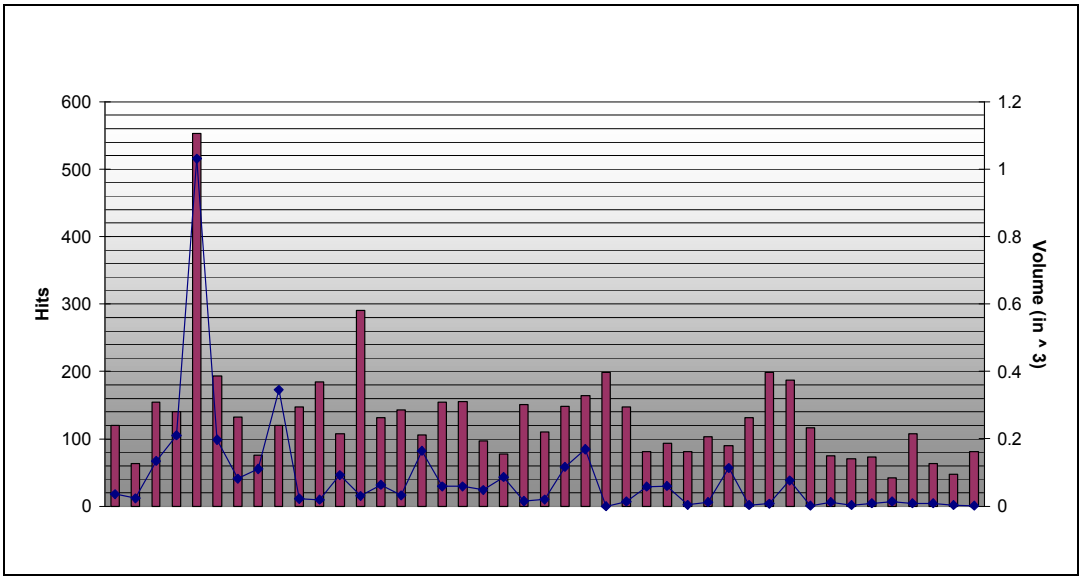

Figure 5.3.2.2-3.b. Total Orbiter Damage and TPS Volume Loss

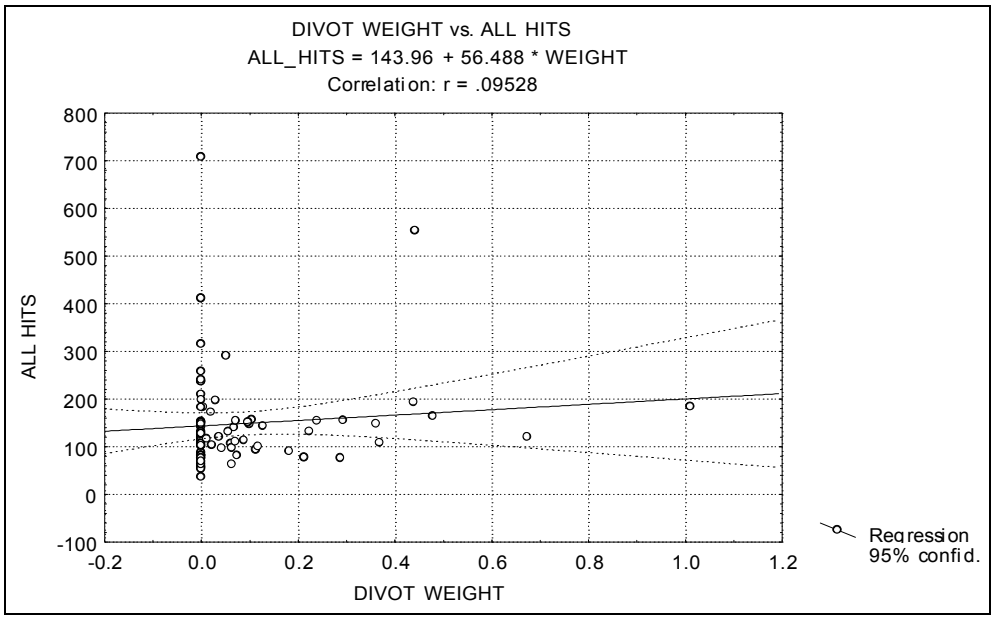

Figure 5.3.2.2-4. Correlation of Divot Weights to Orbiter Hits for All Missions

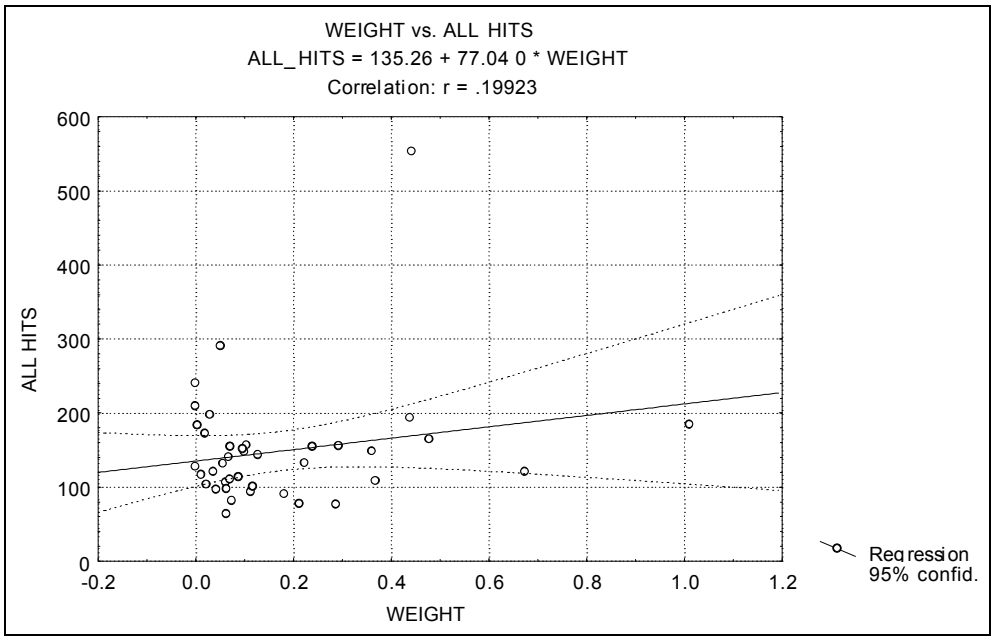

Figure 5.3.2.2-5. Correlation of Visible Foam Loss to Orbiter Damage

ET TPS loss is visible on each flight and can be categorized as either “typical” or “significant.” Typical” TPS loss is characterized as divots that are frequently observed with a mass of <0.1 lb. Divots of this mass are small shallow divots usually seen on the intertank-to-LH2-tank flange or tank acreage TPS. Smaller

divots (also known as "popcorning") are commonly observed on the intertank thrust panels and LH2 aft dome. "Significant" TPS loss, as categorized by the SSP, is usually related to the size (>0.2 lb), location, or pattern of TPS loss that has occasionally correlated to an increased level of Orbiter TPS damage quantity or TPS damage size. Significant events through the program history are shown in Figure 5.3.2.2-6. Programmatic action was required for those events that were characterized by the Space Shuttle Program as 'significant' events, *i.e.,* determination of cause and identification of corrective action. As these TPS loss events were observed, flight rationale for the subsequent vehicles was presented to the SSP, and to the extent possible, probable causes were assessed, eliminated, or mitigated.

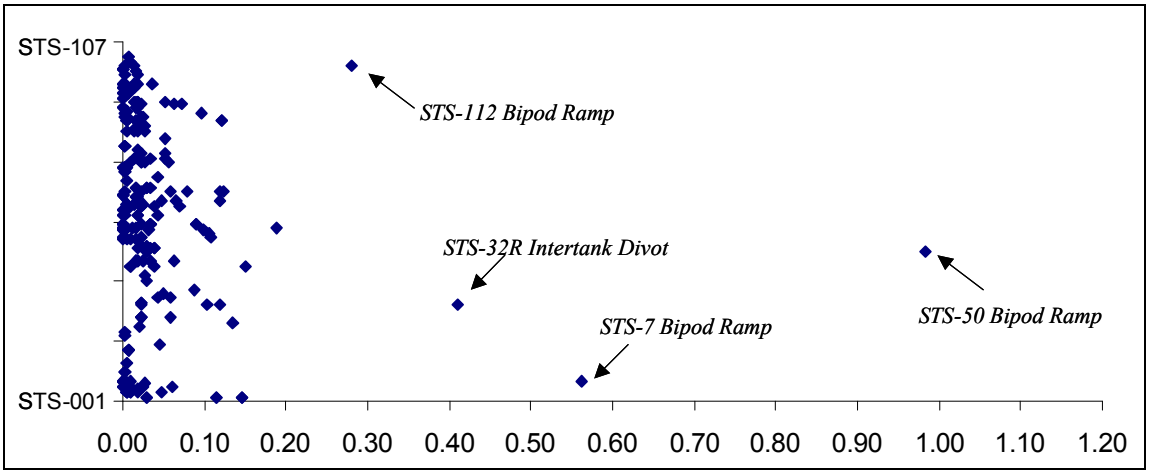

Figure 5.3.2.2-6. TPS Mass Loss (lb)

Historically, initiatives on the ET have gradually resulted in reduced foam loss over time. A progression of the aggregate of foam loss, as categorized by major TPS changes, is shown in Figure 5.3.2.2-7.

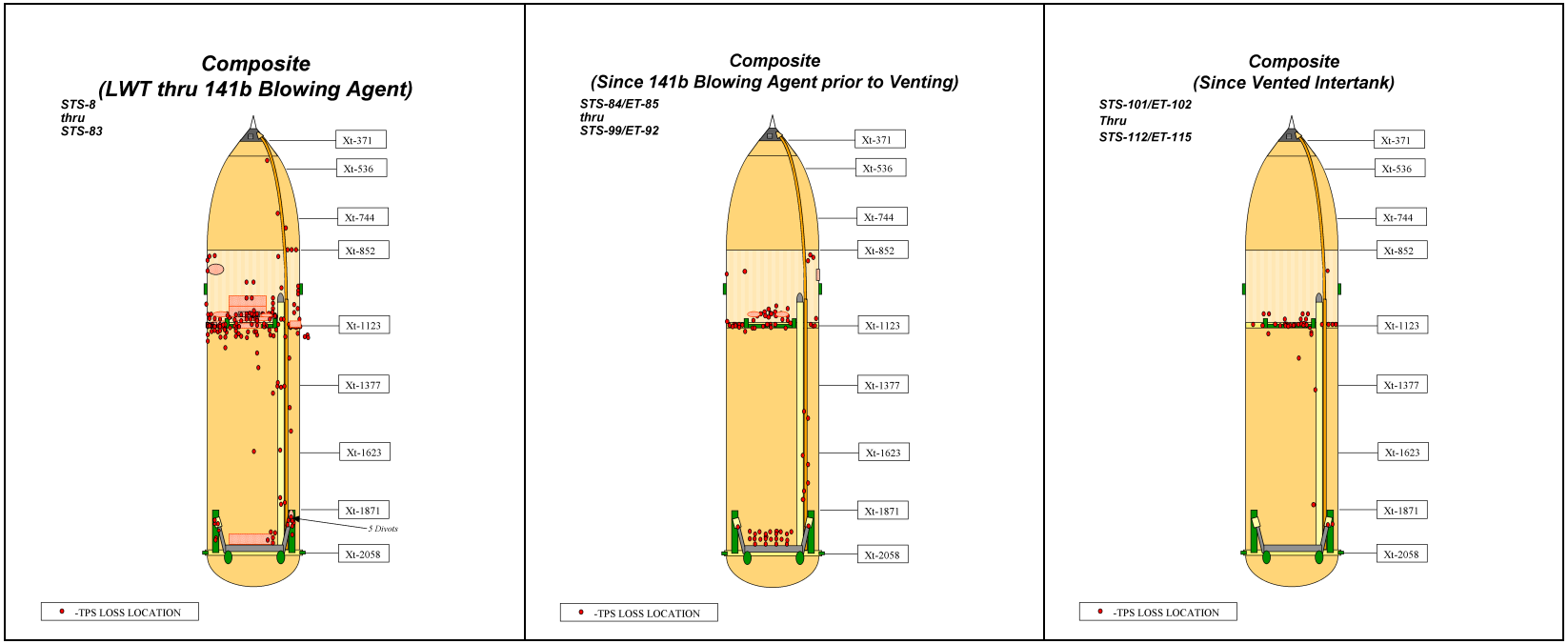

Figure 5.3.2-7. Schematic of Aggregate Foam Loss

5.3.3 Bipod Ramp TPS Loss

5.3.3.1 Bipod Area Description

The forward Orbiter attachment is a bipod. Interfaces between the ET and the Orbiter are shown in Figure 5.3.3.3-1. The bipod, weighing approximately 190 lb, has rotational freedom at its attachment to the forward LH2 tank ring frame and rotates about a Y-axis reference line so that changes in overall tank length resulting from thermal effects will not introduce loads into the Orbiter.

The forward bipod TPS configuration includes a complex combination of foams, ablator [Super-Light Ablator (SLA)] and underlying bipod structural substrate elements (Figure 5.3.3.1-2.) SLA is applied to the substrate, both using spray and manual hand-packed operations. Foam (BX-250 SOFI), is manually applied over the substrate and machined to final configuration. A schematic of the entire configuration and underlying details is shown in Figure 5.3.3.1-3.

The bipod ramp design has been stable since early in the ET program. There have been no changes in material and minimal changes to configuration, processing, and personnel certification/training. The BX-250 ramp angle, as described below, has been constant since ET-14:

- 30° maximum with a 5.0- ±1.0-in. radius at the forward edge (from 45° ±5.0, no radius). This was changed as a result of suspected foam debris (STS–7/ET-6).
- A 5.0- ±1.0 in. radius at the forward edge was eliminated at ET-76.

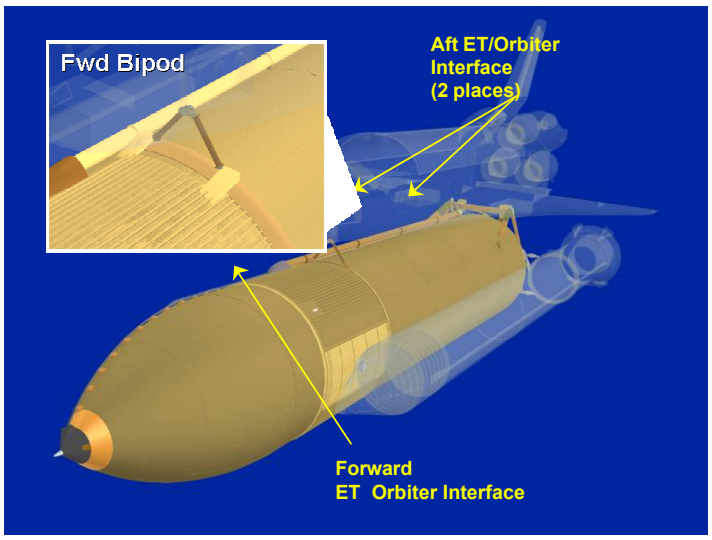

Figure 5.3.3.3-1. ET/Orbiter Interfaces

Bipod Housing
(Prior to Foam Application)

Bipod Ramp
(After Final Foam Trim)

Figure 5.3.3.1-2. Bipod TPS Configuration

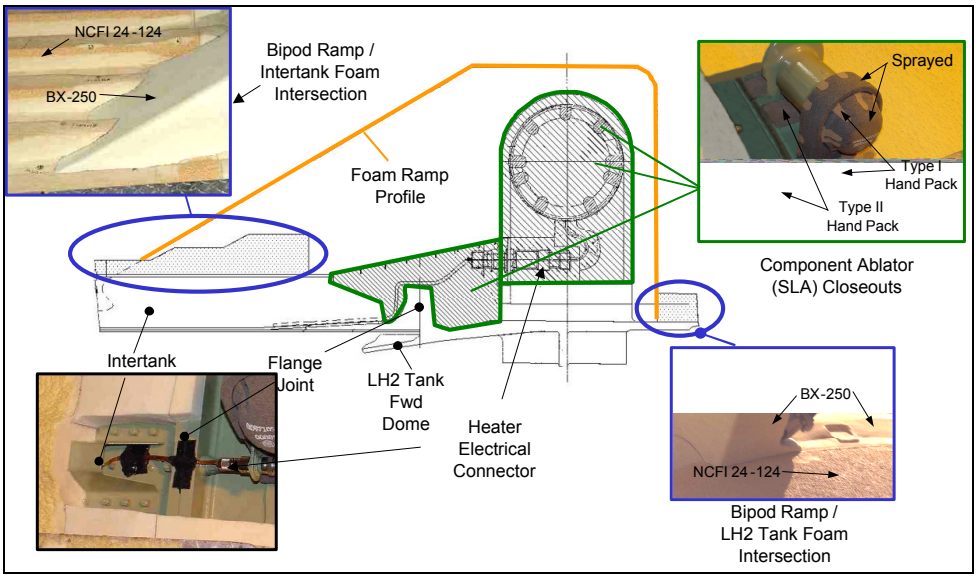

Figure 5.3.3.1-3. Bipod Closeout Schematic

5.3.3.2 Results

Assessment of post-flight imagery has shown five prior occurrences of bipod ramp TPS loss. All instances of ramp loss were isolated to the -Y (left hand) ramp. The first occurrence, STS-7/ET-6 (Figure 5.3.3.2-1), showed a large portion (18 in. x 12 in.) of the bipod ramp missing. The TPS area had an estimated weight of 0.6 lb. This TPS loss event was attributed to a repair in the forward edge of the ramp. Following this occurrence of TPS loss, the ramp repair criterion was limited to a maximum of 3 sq. in. on the forward face of the bipod ramp.

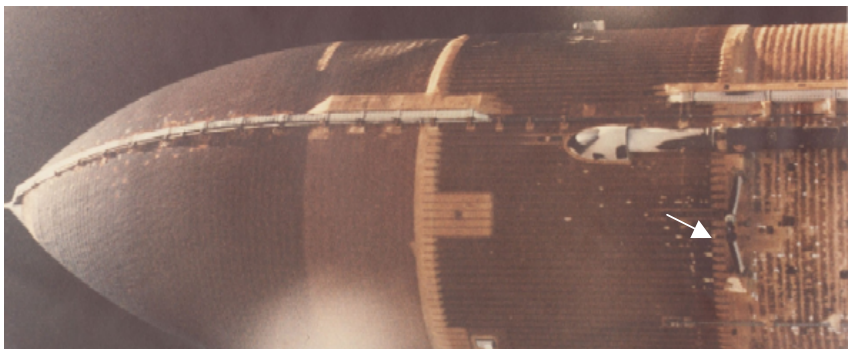

Figure 5.3.3.2-1. STS-7/ET-6

The TPS loss event on STS-50/ET-50 encompassed the majority of the bipod ramp, measuring 26 in. x 10 in. and weighing 0.98 lb (Figure 5.3.3.2-2). This loss was attributed to voids/debonds in the Isochem bond layer of the non-vented two-tone TPS area. ET-50 was the last ET built with this intertank TPS configuration.

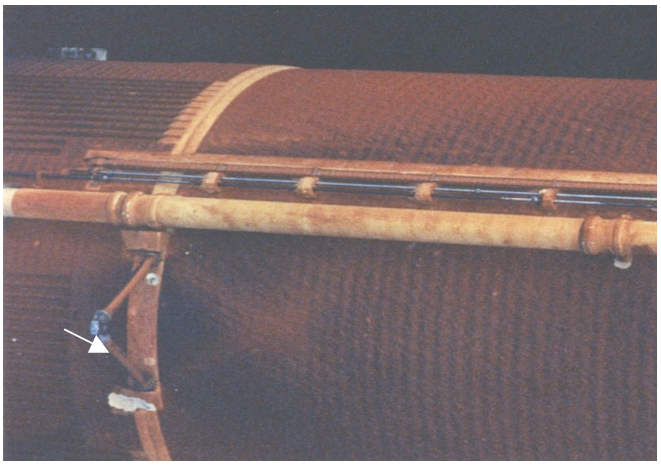

Figure 5.3.3.2-2. STS-50/ET-50

On STS-52/ET-55, the TPS loss was estimated to be 8 in. x 4 in., weighing 0.02 lb. (Figure 5.3.3.2-3)

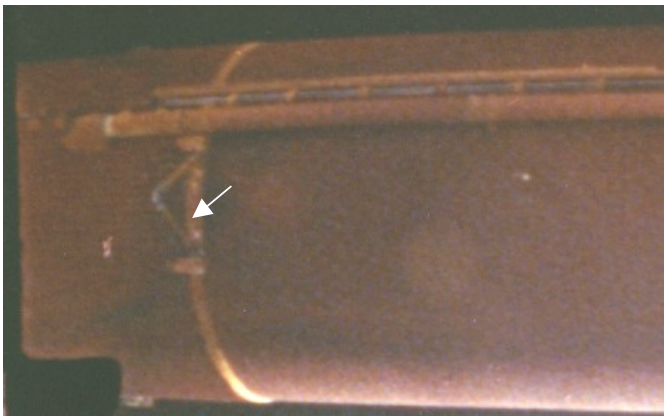

Figure 5.3.3.2-3. STS-52/ET-55

On STS-62/ET-62, there was a small divot in the aft face of the ramp measuring approximately 3 in. x 1 in. and weighing 0.001 lb. (Figure 5.3.3.2-4)

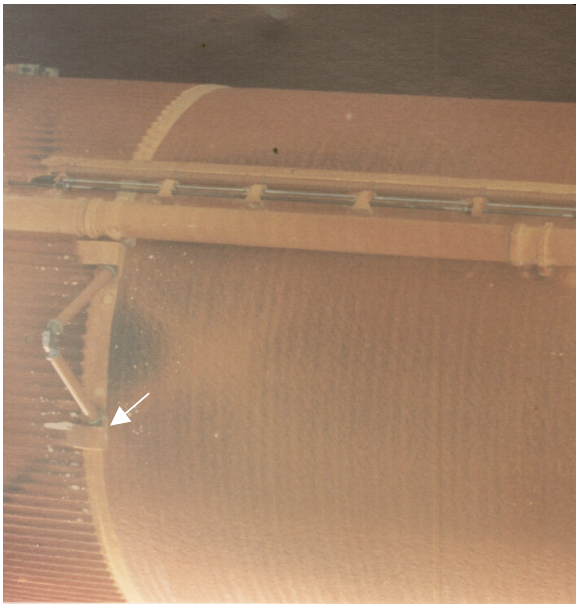

Figure 5.3.3.2-4. STS-62/ET-62

On STS-112/ET-11, the TPS loss location and shape was similar to that observed on STS-52 (Figure 5.3.3.2-5). The TPS loss on STS-112 was estimated to be 7 in. x 12 in. with a mass of 0.3 lb.

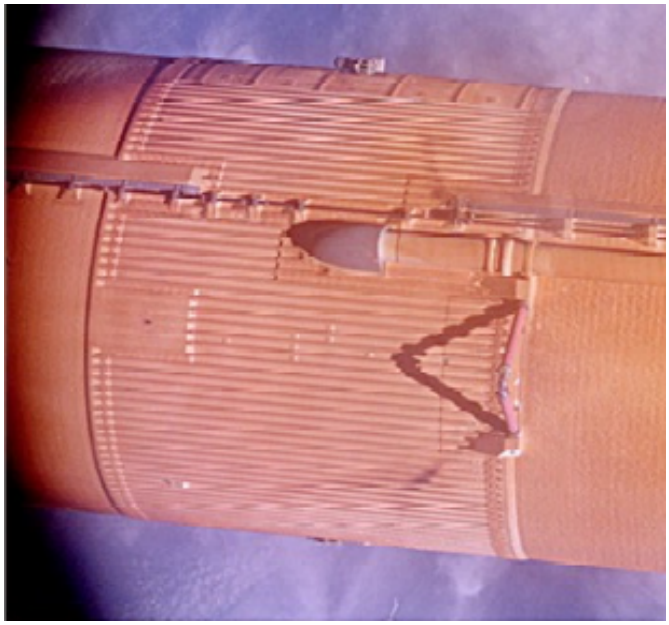

Figure 5.3.3.2-5. STS-112/ET-115

Following this occurrence of ramp loss, the ET Project initiated plans to evaluate the materials, design, and processes used for the ramps.

On STS-32R/ET-32, there was loss of foam very near the bipod ramps. The data for this event have been included in the following statistical analysis. The details of the event are described in Section 5.3.3.5.

5.3.3.3 Analysis

Statistical analyses of production, on-pad, and flight parameters were performed to characterize similarities in foam loss, both on the structure and with respect to direct loads to bipod foam. Assessed variables included:

- Production at MAF
  - Dates
  - Days in storage
  - Process variables
- Processing at KSC
  - Age at launch
  - Exposure
  - Tanking time
  - Thread count and offset at bipod area
  - On-pad environment
    - Rainfall
    - Temperature
    - Dew point

Relative humidity
Wind
Pressure

- Performance Data
  - Dynamic pressure (Q)
  - Angle of attack (α, alpha)
  - Sideslip angle (β, beta)
  - Q-alpha
  - Q-beta
  - In-plane wind velocity (V_{IP})
  - Out-of-plane wind velocity (V_{OP})
  - Vehicle weight and center of gravity
  - Flight regimes (Mach 0.6 – 2.2)
  - Bipod struts (P1, P2), load indicators ET4-1 through ET4-7
  - Tile damage
  - Foam loss

5.3.3.4 Results

No differences were found between any MAF production data or KSC processing data with the exception of on-pad rainfall. Comparison of distributions suggests most foam loss missions were wetter in total, as a maximum on a single day and on average. ET-112 data appear to be an outlier, however, even compared to all missions.

Sideslip angle, Q-beta and out-of-plane wind velocity showed a statistical correlation with regard to STS foam loss flights. Results are shown in Figures 5.3.3.4-1 through 5.3.3.4-4.

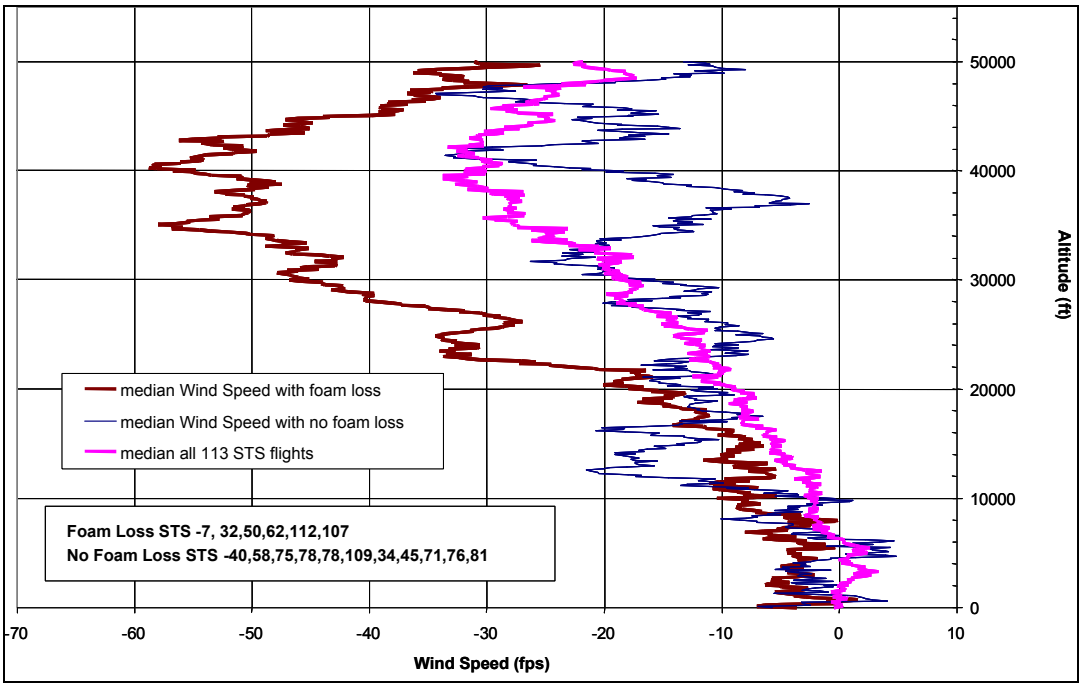

Figure 5.3.3.4-1. Altitude vs. Out-of-Plane Median Wind Speed for Bipod Foam Loss and No Bipod Foam Loss Flights

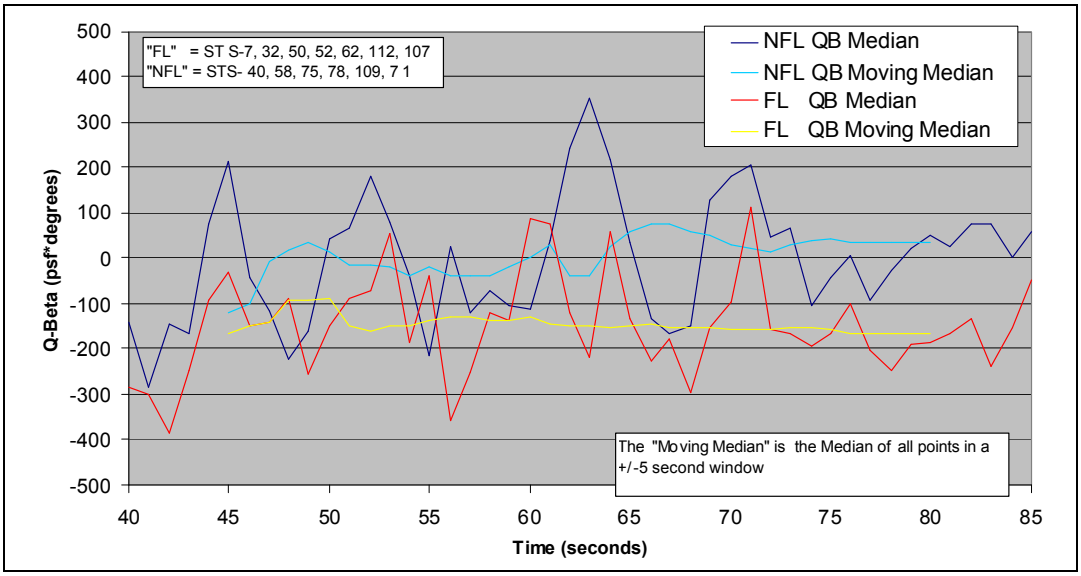

Figure 5.3.3.4-2. Q-Beta over Time for STS Flights with and without Bipod Foam Loss

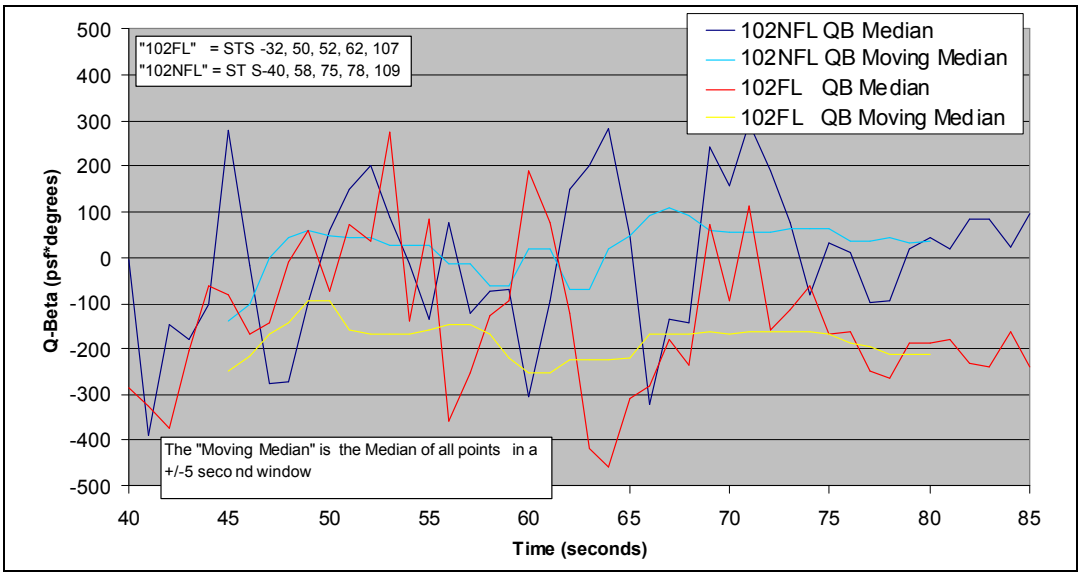

Figure 5.3.3.4-3. Q-Beta over Time for OV-102 Flights with and without Bipod Foam Loss

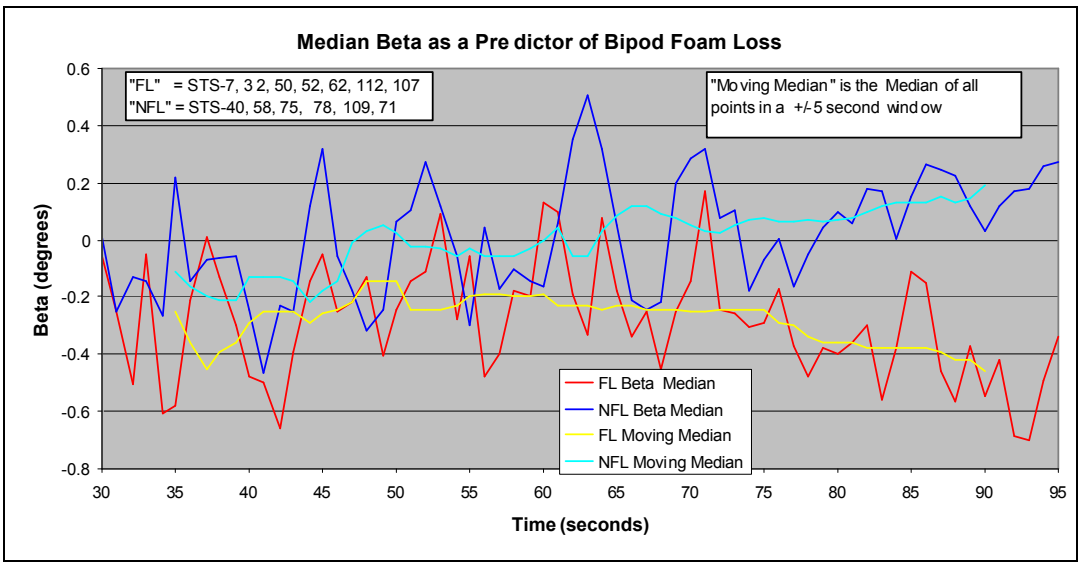

Figure 5.3.3.4-4. Beta over Time for Flights with and without Bipod Foam Loss

Bipod structural loads that were reviewed (P1, P2, FT01, FT02, *etc.*,) do not show a statistical difference with respect to STS flights with and without foam loss. These loads are more influenced by inertia and thrust effects. The analytical geometrical location of the integrated vehicle center-of-gravity and weight does not show a statistical difference with respect to STS flights with and without foam loss.

For altitudes of 25,000 to 45,000 ft (~Mach 1 to Mach 2), the STS flights with bipod foam loss had a statistically higher out-of-plane wind speed (20 to 40 fps) than those flights without bipod foam loss. During the high Q region of STS Flight (Mach 1 – 2), foam loss flights had a statistically higher negative Q-Beta as compared to flights with no foam loss. This statement is also true for *Columbia* flights with and without foam loss. The higher negative Q-Beta orients the vehicle's left hand (LH) side into the wind and, therefore, results in more wind exposure to the –Y bipod ramp.

Computational Fluid Dynamics (CFD) analysis of the LH bipod ramp shows that as Beta gets more negative (+2, 0, -1.56 deg), the axial, radial, and side forces on the Bipod Foam decrease for a constant alpha (-3.88 deg) and 1.4 Mach number. Shock loadings (impingements and movements) are extremely complex and very dependent on Mach Number, angle of attack (α), and angle of sideslip (β). Also, the LOX feedline produces asymmetric flow (Figure 5.3.3.4-5). A recent updated CFD geometry/grid system to include intertank stringers, detailed +Y bipod ramp and feedline geometries was developed. Results confirmed that there are a number of differences between air loads at the two ramp locations. The +Y ramp side force is much less sensitive to sideslip/β:

- At Mach 1.40, the –Y radial load is more than double +Y load.
- At Mach 2.46, the –Y radial load is smaller than the +Y load.

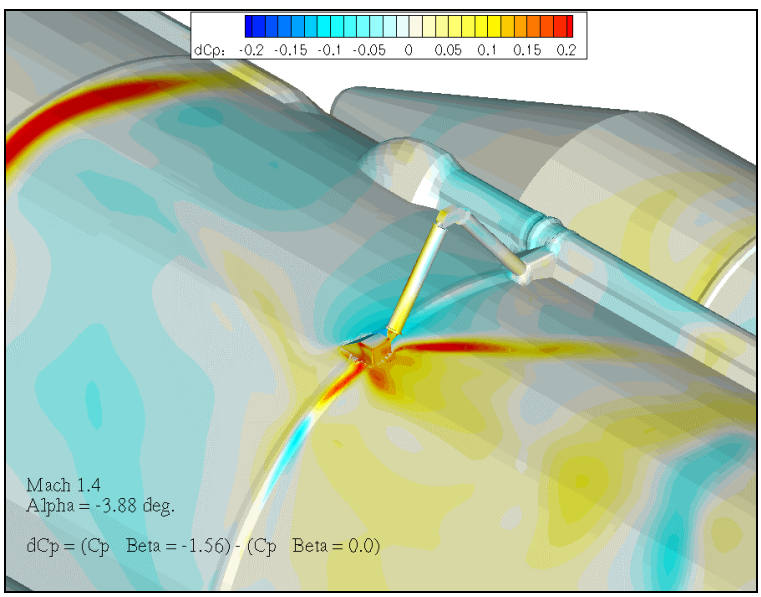

Figure 3.5.3.4-5. CFD Model of Bipod Region

5.3.3.5 History of Significant Foam Loss

A summary of the significant foam loss events experienced during the history of the ET program is presented below.

- STS-32R/ET-32 (launched January 9, 1990)

  Post-separation umbilical camera films showed several large divots in the area of the bipods. Two of the divots, measuring 12 to 14 in. in diameter, were located between the bipods just forward of the intertank-to-LH2-tank flange. A third divot, approximately 14 in. in diameter, was located between the bipod ramps and extended into the intertank-to-LH2-tank flange. The largest divot, measuring 28 in. wide, surrounded the forward part of the -Y (LH) bipod (Figure 5.3.3.5-1).

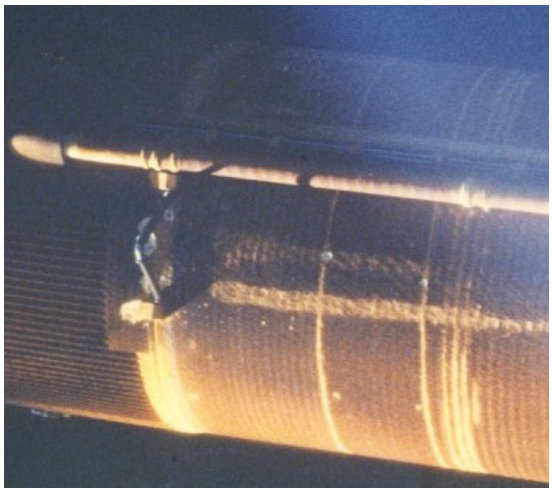

Figure 5.3.3.5-1. STS-32R/ET-32 Post-Separation Photograph

The most probable cause of this TPS loss was related to inadequate depth of drilled holes (venting) in this two-tone TPS location in conjunction with localized voids at the TPS CPR-488/Isochem bond layer. Following this occurrence of TPS loss, an inspection was added to the manufacturing process to verify vent hole depth. The most probable cause and corrective actions to preclude recurrence were presented/approved at the Level II Program Requirements Control Board (PRCB(PRCBD S044812A) on February 6, 1990.

Background on Isochem bond layer issues:

The two-tone TPS configuration on +Z side of Intertank was characterized by TPS (BX-250) applied in stringer valleys with a layer of Isochem adhesive over the top before final application of TPS (CPR-488).
Random divots had been experienced in the past for this configuration. The divots were caused by reaction between the Isochem resin and CPR-488 producing debonds/voids The Isochem problem surfaced because the supplier of the material switched sub-tier suppliers of the resin which later analysis showed was not as stable when heated (copper versus Silmar

resin). The supplier was subsequently required to use the original material. An interim corrective action was implemented earlier in the program (STS-27/ET-21) to reduce the potential for large size divots. The corrective action applied the use of holes drilled through the outer TPS layer to the Isochem interface to provide a vent path for the gasses in localized voids. The use of vent holes was only allowed in a non-cryogenic region so as to preclude the formation of ice/frost in the holes. The final corrective action was to implement an improved spray process, which eliminated the BX-250 and Isochem.

- STS-35/ET-35 (launched January 2, 1990)

  Post separation umbilical camera films showed five divots on the left side (-Y axis) of the intertank-to-LH2-tank flange closeout and five divots on the right side of the closeout (+Y axis). The largest divots ranged from 8 to 10 in. in diameter (Figure 5.3.3.5-2). Divots from this area (previously observed on other ETs) did not show a correlation with an increased level of Orbiter tile damage.

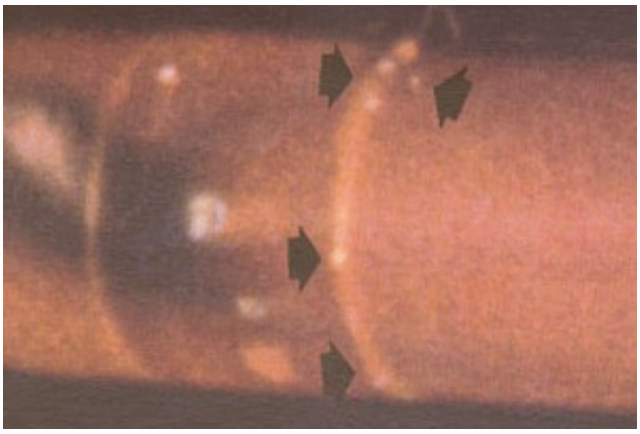

Figure 5.3.3.5-2. STS-35/ET-35 Post-Separation Photograph

The most probable cause of this TPS loss was localized voids behind the intertank-to-LH2-tank flange bolts. The closeout is a very complex manual two-step operation with TPS sprayed into a narrow/deep cavity and around the attach bolts. A review of the manual spray TPS technique showed that voids were a consequence of operator technique. Following this occurrence of TPS loss, an improved application technique was developed to reduce the potential for voids around the flange bolts. This process was validated and the operators were required to demonstrate their ability to perform the closeout successfully. Through the process enhancement, the number of divots was reduced but not completely eliminated.

The most probable cause and corrective actions to preclude recurrence were presented/approved at the Level II PRCB (PRCBD S044824C) on June 14, 1991.

- STS-42/ET-52 (launched January 22, 1992)

  Post-separation crew handheld camera films showed two divots on the intertank acreage. The divots were estimated to be approximately 8 to 14 in. in diameter (Figure 5.3.3.5-3).

Figure 5.3.3.5-3. STS-42/ET-52 Post-Separation Photograph

FT analysis was used to identify the possible causes of the divots. Major areas included excessive flight environments, mechanical damage, processing or assembly anomalies, and other causes, *i.e.,* material age, BSM impingement, fluid spill.

The most probable cause of this TPS loss could not be determined. ET–52 was the second tank to fly with the revised TPS configuration and application method (replaced two-tone configuration with two-gun spray application). No corrective actions were implemented.
Closure of this TPS loss occurrence was presented/approved at the Level II PRCB (PRCBD S044848H) on 09/01/92.

- STS-50/ET-50 (launched June 25, 1992)

  Post-separation umbilical camera films showed two areas of TPS damage near the forward bipod area. The first showed approximately 60% of the –

variations in the spray process, such as spray angle, within the existing production operation.

The most probable cause and corrective action to preclude recurrence was presented/approved at the Level II PRCB (PRCBD S044895N) on July 29, 1993.

- STS-58/ET-57 (launched October 18, 1993)

  Post-separation umbilical camera films showed three areas of TPS loss on the intertank +Z side. One divot (approximately 28 in. L x 3 in. W) was in the acreage TPS, and the other two divots were identified as the TPS from the jack pad closeouts. Exposed primer was observed in both jack pad cavities (Figure 5.3.3.5-9), Divots of this magnitude and the Orbiter tile damage were within the STS experience base.

  The most probable cause of the intertank acreage divot on STS-58 is the same as suspected for the TPS loss on STS-56 – Anomalies in the TPS caused by rollover/crevicing phenomenon.

  The most probable cause of the jack pad closeout was cryopumping of a subsurface void under the PDL pour TPS closeout. Following this jack pad closeout TPS loss occurrence, a tool was developed to allow spray around the holes masking the jack pad tooling holes, leaving four 1-in. diameter holes on each side of the closeout to eliminate the large closeout/repair area (6 in. x 6 in. square). The jack pad itself is now closed out in conjunction with the flange closeout.
  The most probable cause and corrective actions to preclude recurrence were presented/approved at the Level II PRCB (PRCBD S044897L) on May 23, 1994.

Figure 5.3.3.5-9. STS-58/ET-57 Post-Separation Photograph

- STS-87/ET-89 (launched November 19, 1997)

  Post-separation crew handheld camera films showed areas of missing TPS on the +Y and -Y thrust panels (Figure 5.3.3.5-10). Post-landing inspection also showed a significant increase in Orbiter tile damage: 308 damage sites on the Orbiter lower surface, with 132 sites greater than 1 in. The total number of lower surface damage site and the number of damage sites greater than 1 in. were out of family when compared to previous missions.

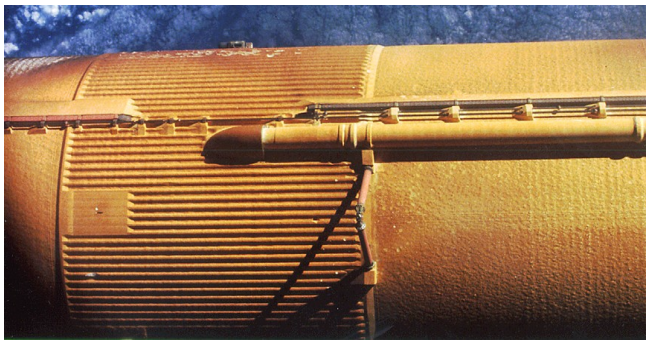

Figure 5.3.3.5-10. STS-87/ET-89 Post-Separation Photograph

The most probable cause of this TPS loss was a combination of the following factors:

- Reduced mechanical properties of the TPS and its trapped gases
- Environmentally induced cell gas pressure from heating, vacuum, and moisture in the cells
- Stress concentrating geometry, especially evident on the intertank thrust panels and to a lesser extent on the skin/stringer panels.

For the subsequent flights, incremental corrective actions were implemented to reduce TPS loss. An incremental approach was used to ensure that the corrective actions would 'do no harm'. The corrective actions included reduction in TPS thickness (STS-89/ET-90), reducing the amount of TPS that could be shed, and the placement of closely spaced, small diameter vent holes in the intertank TPS beginning with ET-101 (STS-103). SRB-mounted cameras showed the vent holes significantly reduced both the number and size of the "popcorning" debris from the intertank thrust panels. The vented area was expanded on each mission until the desired product was achieved.

The long-term corrective action plan was presented at the Level II PRCB (PRCBD S062127) on January 13, 2000. The plan incorporated the use of vent holes on the intertank thrust panels and the +Z stringer panel to

reduce the number and size of the TPS debris. The final corrective action was implemented for ET-102 (STS-101) and subsequent missions.

Background on intertank thrust panel TPS loss

Significant amounts of TPS loss and related Orbiter tile damage began occurring when CPR-488 was replaced with NCFI 24-124 TPS on the ET intertank. The change in TPS insulation materials was necessitated by the requirement to use environmentally compliant blowing agents (HCFC-141b) and the termination of production of one of the major constituents of CPR-488 by the supplier.

A study to gain an understanding of the TPS loss event ensued; the first data gathering exercise included the installation of a camera on one SRB of STS–95/ET-98. This camera imaged the ET intertank thrust panel during flight and provided the first opportunity to view TPS loss up close and in real time (Figure 5.3.3.5-11). The camera showed TPS loss initiating approximately 92 sec into the flight and continuing until SRB separation, at which time the view was lost.

Figure 5.3.3.5-11. STS-95/ET-98 Post-SRB-Separation Photography

TPS loss was seen to be most severe on the tops and sides of the thrust panel ribs but was not limited to these areas. Some material loss was also observed on the skin-stringer areas of the intertank. From a visual standpoint, the TPS loss closely resembled the phenomenon known as ‘popcorning’, which has been observed in thermal-vacuum testing at MSFC and MAF test facilities.

- STS-112/ET-115 (launched October 2, 2002)

  Post-separation crew handheld camera films showed an area of missing TPS (approximately 4 in. x 5 in. x 12 in.) on –Y bipod ramp exposing the bipod housing SLA closeout (Figure 5.3.3.5-12).

The ET Project was assigned an action at the SSP PRCB (S062151) on October 24, 2002 to analyze the ET bipod loss of TPS experience for root cause and corrective action.

The most probable cause of this TPS loss occurrence was suspect subsurface void(s) during bipod ramp closeout coupled with launch environments. The most probable cause was presented at the SSP PRCB (S062151, Action # MSFC-ET/1-1) on December 19, 2002 and at that time, the Project identified the corrective action that was under evaluation. The proposed corrective action was to enhance the closeout configuration by eliminating the SLA under the TPS, thereby eliminating the potential for air entrapment (subsurface voids). The final corrective action was to have been presented at the SSP PRCB on February 6, 2003.

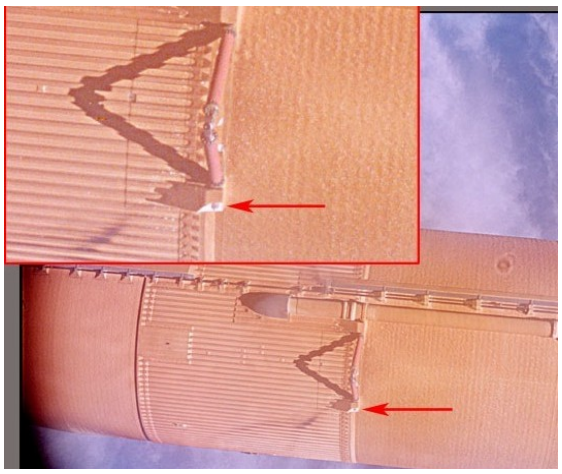

Figure 5.3.3.5-12. STS-112/ET-115 Post-Separation Photography

5.3.4 Summary

The ET has approximately 16,750 sq. ft. of external TPS. The overall ET TPS performance over the history of the program has consistently improved. Some areas have been problematic. As problems arose, evaluations were performed, and improvements were implemented.

The observed anomalies for the acreage TPS applications on the LH2 barrel and aft dome and LO2 tank have been few and minor in nature. These areas are applied to "smooth" structure by tightly controlled automated equipment and processes. In these areas, the very low-density TPS material is subjected to highly strained -423 °F substrate conditions, while the surface is subjected to ascent heating conditions that can raise the surface temperature to over 600 °F in approximately 1 in. of material thickness.

The TPS application to the intertank area has presented two major observed problems over the history of the program related to difficulties inherent to the

spray application of TPS over the external intertank stringers and thrust panel stiffeners. In both occurrences, extensive successful efforts to resolve the material loss observations resulted in venting of the intertank TPS (for two very different causes and for two very different venting configuration implementations) to eliminate or minimize the forces that caused the material loss. Resolution of the problems also included significant efforts to refine the processes and controls of applying the TPS to this complex structure.

Problems that have been observed on the myriad of small manual applications or parts over the history of the program (including LO2 feedline flange closeouts and pressurization line support TPS ramps) have been minimized or eliminated through significant efforts to improve mold tooling and processes as they were observed.
Some complex manual applications, especially the LH2-to-intertank splice application and to a much lesser extent the bipod ramp application, have presented a history of observed material loss which has been addressed with less than complete success in the past and should be the subject of an extensive re-evaluation in return to flight efforts.

Section 6 ET-93 Unique Elements and Acceptance

6.1 ET-93 Unique Elements

6.1.1 As-Designed Configuration

ET-93 was the second External Tank in the LWT Deferred Build Block. It was the first in-line production (MAF-processed) implementation of In-Flight Anomaly (IFA)/intertank TPS venting at the thrust panels and +Z stringer panels. It was the first LWT with machined foam on the intertank +Z stringers. ET-93 also represented the first use of BX-265 on the aft upper ET/SRB fairings.

This tank was also part of the continuing waterfall of improved extrusions on the External Tank. Grain sizes on Al 2219 extrusions were effectively screened for implementation to assure smaller grains and higher properties in welded hardware (Class II designation).

6.1.2 As-Built Configuration

ET-93 had no "out-of-family" nonconformances (NCs). All ET-93 processing anomalies were considered to be 'in-family' and the tank was generally low in overall NCs.

Typical repair work scope in critical areas included the following:

- Bipod Fitting Area: Two voids were observed in the SLA on the outboard side of the LH (-Y) bipod fitting. An area of crushed PDL foam was also identified on the aft side of the LH (-Y) Spindle Face. Two voids and two gouges were observed on the right hand (RH) (+Y) aft side.
- Flange Area: A small number of small voids were found on the upper flange.
- Closeout Processing Anomalies: SLA on the +Y bipod did not meet tensile strength requirements. The material was retested and passed minimum requirements. The area at the 10 o'clock position (facing the bipod looking outboard) approximately 0.4 in. L x 0.15in. W at the widest point did not meet the engineering drawing requirement. The area was assessed for risk of ice formation and established to be above minimum.
- Damage to Intertank –Z Stringer Foam: The foam on 37 consecutive stringers on intertank panels 6, 7, and 8 (-Z side of tank) was damaged by foam cutter head interference. The damage location was about 66 in. forward of the intertank-to-LH2-tank flange closeout. Twelve of the 37 damage locations were accepted 'use as is.' Loose foam was removed and red dye was also used to direct removal of cracks, cuts, crushed foam, and debonds/delaminations. The remaining foam exceeded that required for ascent and reentry. The remaining 25 damage locations were repaired in accordance with the approved repair procedures.
- Repair of LH2 recirculation burst disc

6.1.3 Processing

ET-93, a lightweight tank (LWT), was built as one of the "deferred LWT" builds, *i.e.,* it was built during the SLWT process flow. Weld schedules/parameters were adjusted for LWT materials to accommodate the materials change (Al 2219 for the LWT tanks versus Al 2195 for the SLWT vehicles), material thicknesses, and weld land thicknesses. One out-of-position event occurred during ET-93 processing. Weld repairs for the LO2 tank forward ogive weld, typically performed in a horizontal position, were performed in a vertical weld position to accommodate the existing production flow. (All repair processes were appropriately certified, performed, and validated.)

ET-93 was the first LWT to have the intertank access door closed out at MAF. ET-93 was mated and demated on STS-112 before mate with STS-107. During the course of processing, the ET/SRB attach fairing TPS was damaged and repaired.

No new tools were used on ET-93. The only tooling change identified for this effectivity was associated with modification of the air supply used for the TPS port bond tension tester. No new equipment or process or planning changes were associated with ET 93. There were neither new production vendors nor validations on hardware.

The following is a summary of new materials lots:
Hand Pack Type I Batch Number – 208080-101 Hand Pack Type II Batch Number – 208120-101DC-1200 Lot Number – 360747 (For Type I H/P)C-1200 Lot Number – 00G173 (For Type II H/P)GX-6300 Lot Number – 208080-102 (For Type I H/P); 208070-101Gx-6300 Lot Number – 208120-101 (For Type II H/P); 208100-101Conathane Lot Number – 00G114.

No new personnel were assigned to hardware fabrication. All sprayers and hardware mechanics had previous production experience.

6.1.4 Operational

ET-93 was the first tank to fly with three Block II engines. The LWT configuration was previously certified at ET-92 for the associated increased LH2 prepress pressures. ET-93 was the first LWT to use an Inconel 718 bellows probe on the Ground Umbilical Control Assembly (GUCA) quick disconnect (ground half of interface hardware). It also represented the first implementation of the nose cone heater outlet maximum temperature increase and the nose cone purge outlet maximum pressure increase. STS-107 was the first LWT to fly using the Haz Gas 2000 system. It was also the first tank incorporating the 2.0-sec delay in the ET separation sequence. (No impact was predicted for LWT.)

Paper/processing changes included:

- ET Sensor Requirements: Added/revised tables to clarify the functional requirements of the point level sensors.
- ET/Orbiter Visual Leak Monitoring: Relocated requirements from the OMRSD to LCC. There was no change in the requirement for visual monitoring.

6.2 ET-93 Acceptance

6.2.1 Overview

The SSP Flight Preparation Process (FPP) is defined in National Space Transportation System (NSTS) 08117, Requirements and Procedures for Certification of Flight Readiness. It defines the procedures for the Project Milestone Reviews, the Program Milestone Reviews, and the Flight Readiness Review (FRR). It also defines the endorsement documentation required at the completion of the FRR, which provides the Certification of Flight Readiness (CoFR) for a specific flight.

The FPP is incrementally implemented through milestone reviews, which ensure the readiness of all organizations for the operational phase following each review. Figure 6.2.1-1 illustrates the milestone review process for the Shuttle Projects. For the ET Project, the FPP requires a hardware element acceptance review and participation in the ET/SRB Mate Milestone Review and the FRR.

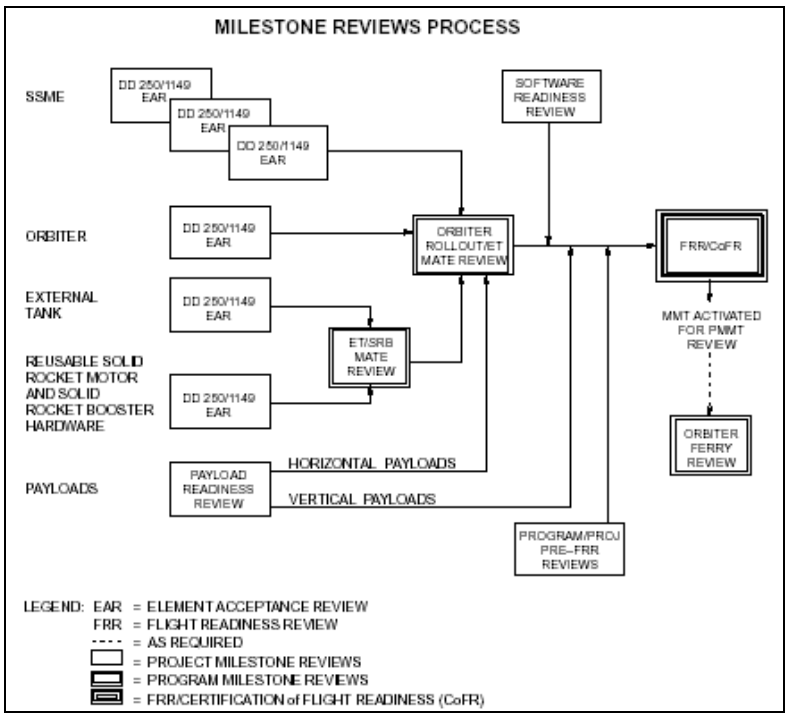

Figure 6.2.1-1. Milestone Review Process

6.2.2 Assessment of Flight Hardware

The External Tank Project builds and flies ETs under the provisions of contract NAS8–36200 for LWT articles and SLWT articles through ET-121. Subsequent articles are produced under the provisions of NAS8-00016. These contracts define the requirements for manufacturing, assembly, test, checkout, and delivery of operational flight articles.

In preparation of milestone reviews identified by the FPP, an assessment of the ET readiness for flight is conducted by the contractor and coordinated with the Project Office. Based on the results of the assessments, the ET Project Office and the contractor coordinate a list of candidate topics for the milestone reviews. At a minimum, the assessment of each ET includes:

- Baseline End Item Configuration: A comparison of the as–designed to the as–built end item configuration
- Acceptance Checkout: Completion of Acceptance Checkout Requirements, (MMC–ET–TM04k), including resolution of checkout discrepancies and any required associated retesting, will be documented and resolved by the appropriate NCD
- Ship–Loose Hardware: In preparation for shipment of the subject ET to the launch site, statusing of all shipping support hardware and uninstalled flight hardware.
- Planned Work/Mod Kits: Identification of all mission specific installations and/or assemblies and authorized modification kits scheduled for initiation/completion at the launch site
- Deferred Work: Identification of specific processing/manufacturing procedures normally performed/completed at MAF for which rationale is provided to justify performance and/or completion at the launch site for the subject effectivity
- Changes: All changes to the previous vehicle as–built/as–flown configuration or operating requirements for which the current mission is the first effectivity
- Processing Anomalies: Any out–of–family occurrence unique to or peculiar to the baselined methods of processing hardware
- Verification/Certification Status: As applied to this mission effectivity, a certification baseline status of program requirements revisions authorized since the previous mission.
- Exceptions/Waivers: Identification of any departures from specification and drawings and appropriate disposition of waivers, deviations or exceptions to program requirements, including project or program signature
- Prior Mission Performance: Review of available data from the previous mission in the following disciplines to assure current processes/procedures are adequate to support the current mission:
  - OMRSD/LCC
  - Instrumentation

  - Main Propulsion System (MPS)
  - Hazardous gas
  - Thermal Protection System
  - ET disposal
  - Orbiter tile damage
  - Post-separation photos
- KSC Processing: A status of launch site vehicle processing activity with application to the subject mission
- Discrepancy Report (DR)/PR/OMRSD Status: A status of discrepancy reports, problem reports, and OMRSD changes associated with this mission effectivity
- Mission Unique Assessment: Identification and assessment of mission profile unique integrated vehicle loads (flight and pre-flight), thermal environments, and other mission-specific data provided through analysis and/or instrumentation
- S&MA Assessment: Audit/monitor by the Office of Safety and Mission Assurance of applicable disciplines of ET Project/contractor operations and status findings to include the following:
  - ALERTs
  - DC&Rs
  - Material Review Boards (MRBs)
  - Hazards/Critical Items Lists (CILs)
  - Latent Defects/CAPs
  - Trending

6.2.3 ET Incremental Readiness Reviews

Incremental reviews are held to assess the readiness of the ET for continuing operations in support of specific mission objectives.

6.2.3.1 Hardware Element Acceptance Review (HEAR)

The delivery of each ET End Item to NASA (DD 250) is marked by this review. The NASA RMO holds this review for the ET Project Manager, and a NASA S&MA representative accepts the ET. At this time, the configuration and requirements for the article have been established. The current status of the ET as related to limited life, certification, planned work, and hardware acceptance testing and inspections is reviewed. The review also includes Deviation Approval Requests, non-compliance reports, Hazards, CAPS, DC&R, and MRB actions. A hardware readiness statement is signed at the conclusion of this review. This review is chaired by the ET Project Manager and is supported by the prime contractor, Shuttle Processing, Program Integration, and S&MA. At the conclusion of this review, a certification statement is signed to attest to readiness of the ET to be delivered to the launch site for flight processing.

6.2.3.2 Contractor Pre-Flight Review (PFR)

The emphasis of the Contractor PFR is on first–time, first effectivity (out–of–family) changes baselined since the last review. At a minimum, the following topics are presented at the review. Supporting information is included as an appendix to the presentation material.

- Modification Kits/Field Engineering Changes
- Significant Changes – Class I changes, Class II changes affecting
- Significant Processing Anomalies
- Verification/Certification Status
- Exceptions/Waivers
- Prior Mission Performance
- KSC Processing
- DR/PR/OMRSD Status
- Mission-Unique Assessment
- S&MA Assessment
- CAPS Status.

In addition, the review may include special topics related to the configuration or processing of the hardware or other events with possible impacts on ET readiness for flight.

Topics presented at this review are carried forward to the ET Project Pre-Flight Review.

6.2.3.3 S&MA Pre-Flight Assessment (PFA)

This review assesses all changes for readiness and acceptability before further presentation to the ET Project. Subjects include the following topics:

- Modification Kits/Field Engineering Changes
- Significant Changes – Class I changes, Class II changes affecting.
- Significant Processing Anomalies
- Verification/Certification Status
- Exceptions/Waivers
- Prior Mission Performance
- KSC Processing
- DR/PR/OMRSD Status
- Mission-Unique Assessment
- S&MA Assessment
- CAPS Status.

6.2.3.4 ET Project Pre-Flight Review

The ET Project Pre-Flight Review is conducted by the ET Project and is chaired by the ET Project Manager or designee. Review participants include: Contractor (LMSSC-Michoud), ET Project Office, Shuttle Processing, Space Shuttle Systems Integration, and S&MA. The review is typically held at MAF with MSFC/KSC/JSC participation by video or teleconference.

The emphasis of the ET Project Pre-Flight Review is on first–time, first effectivity (out–of–family) changes baselined since last review. At a minimum, the topics below are presented at the review. Supporting information is included as an appendix to the presentation material.

- Modification Kits/Field Engineering Changes
- Significant Changes – Class I changes, Class II changes affecting.
- Significant Processing Anomalies
- Verification/Certification Status
- Exceptions/Waivers
- Prior Mission Performance
- KSC Processing
- DR/PR/OMRSD Status
- Mission Unique Assessment
- S&MA Assessment
- CAPS Status

At the conclusion of the review, a board chaired by the ET Project Manager (or designee) decides if follow-up review is required before the FRR. At this time, topics to be carried forward to the FRR are identified.

6.2.3.5 Shuttle Program ET/SRB Mate Milestone Review

The ET Project presents significant changes, NCs, or issues as applicable to the milestone review and any out–of–family events occurring during processing following the delivery of the vehicle to the launch site.

6.2.3.6 Orbiter Rollout/ET Mate Readiness Review

The ET Project participates in this review if any out–of–family events occur during launch processing after the ET/SRB Mate Review and are considered to be a constraint to vehicle processing at the launch site.

6.2.3.7 SSP Flight Readiness Review

The ET Project presents significant changes, NCs, or issues as identified in the previous milestone reviews and any out–of–family events occurring during launch processing following the Orbiter Rollout/ET Mate Readiness Review. The CoFR is signed by the contractor and element Project Managers at the conclusion of this review.

6.2.3.8 Pre-Launch Mission Management Team Review

The ET Project participates in this review if any fleet issues are identified or out–of–family events occur during launch processing post SSP FRR.

Section 7 Data Analysis

7.1 Requirements

This section summarizes the top-level contractual environment requirements applicable to ET-93 verification. Only requirements imposed on the ET Project are included. Sub-tier requirements generated by in-house analysis are included in the assessment of the sub-tier hardware.

Requirements relevant to the following are included:

- Acoustics and random vibration
- Airloads
- Entry and breakup
- Gas temperatures, flow rates, and pressures
- Thermal
- Vehicle loads

There is a brief discussion on how the environments are implemented by stress analysis and verification testing.

The LWT was certified for generic environments, including the Performance Enhancement environments (NSTS 08209 Volume VII, Section 8.0). Additionally, mission-specific analyses were also performed for STS-107/ET-93.

7.1.1 Generic Requirements

7.1.1.1 End Item Specification

Top-level requirements for the LWT are defined in CPT01M09A, “External Tank Contract End Item (CEI) Specification – Part 1” End Item Specification (EIS).

7.1.1.2 Performance Requirements

Performance requirements for the LWT are specified in paragraph 3.2.1.5.2 of the EIS. These requirements include:

- 3.2.1.5.2.1 Fatigue
- 3.2.1.5.2.2 Design Factors of Safety
- 3.2.1.5.2.4 External Tank Entry Heating
- 3.2.1.5.2.5 ET/Orbiter Safe Separation Distance and ET Rupture Altitude

No source documents are referenced by these paragraphs.

7.1.1.3 Induced Environments

Requirements for induced environments are called out in paragraphs 3.2.7.2 (1) through (23) of the EIS.

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- 3.2.7.2(1) Vibration, Shock, and Acoustics
- 3.2.7.2(17) ET/ORB Umbilical Interfaces and LO2 Feedline Loads
- 3.2.7.2(21) Vehicle Interface and Distributed Loads
- 3.2.7.2(22) Protuberance Airloads
- 3.2.7.2(23) Thermal Environments (including requirements for entry analysis)

Documents referenced by these paragraphs are identified in the paragraphs 3.3.1 through 3.3.6.

7.1.1.3.1 Induced Environments: Vibroacoustics

LWT components are designed and verified to the vibration, shock, and acoustics requirements specified in the EIS, paragraph 3.2.7.2(1). General environments are specified in NASA Reference Publication 1074, "Preliminary Vibration, Acoustic, and Shock Design and Test Criteria for Components on the Lightweight External Tank," February 1981

- Section VII: Vibration and Shock Specifications
- Section VIII: Acoustic Test Specifications

Specific exceptions are also called out:

- Vibration criteria for intertank Zone 3-3, forward of XT 980 are defined in SD74-SH-0082, "Revised Shuttle Acoustic and Shock Data Book," June 1987
- Vibration criteria for ET/Orbiter attach structure are defined in TMX-64868, November 1976, modified by letter ED-23-77-151, 5 July 1977
- Environments (random vibration and acoustic) for specific components are directly identified in the EIS, paragraph 3.2.7.2(1).

7.1.1.3.2 Induced Environments: Vehicle Loads

Paragraph 3.2.7.2(21) of the EIS specifies requirements for ET/Orbiter and ET/SRB interface loads and loads distributed over the ET structure. Loads shall be determined from the requirements of STS85-0169-3, "Structural Design Loads Data Book," Volume 3, "External Tank Structural Loads."

The LWT is certified to vehicle interface and distributed loads from load cases generated by Boeing and approved by Level II Integration and defined in the following sections of the Loads Data Book.

- Pre-launch Section 1.3
- Lift-off Section 1.4
- Maximum Dynamic Pressure Section 1.5
- Post High-Q Section 1.6
- Roll Maneuver Section 1.7

7.1.1.3.3 Induced Environments: Protuberance Airloads

LWT protuberances are designed and certified to the requirements of the following document, as required by the EIS, paragraph 3.2.7.2(22)

- "Structural Design Loads Data Book," STS85-0169 Volume 3, Book 1, September 2001

Airloads for major interface hardware are determined from an envelope of several databases called out in paragraph 3.2.7.2(22)(b), and airloads for SLWT Intertank Thrust Panel TPS (applicable to LWT) are in paragraph 3.2.7.2(22)(c). Other relevant contractual documents:

- "Operational Aerodynamic Design Data Book," STS85-0118, August 1996
- "Shuttle Vehicle Mold Lines and Protuberances," ICD-2-00001

7.1.1.3.4 Induced Environments: Venting

Venting of all critical void areas where pressure is not required is specified in paragraph 3.2.6.3.1(b) of the EIS. Venting Certification Cycle trajectories are called out in EIS paragraph 3.2.7.2(23)(I). Compartment venting requirements are covered by the following document:

- "External Tank/Solid Rocket Booster," ICD-2-24001

7.1.1.3.5 Induced Environments: Thermal

Thermal environment requirements for the LWT are detailed in paragraph 3.2.7.2(23) of the EIS, as follows.

- Para 23(A). Thermal interface requirements:
  - SSD97D0459, "Space Shuttle Program Thermal Interfaces Design Data Book Performance Enhancement Light Weight Tank," October 1997, replaces obsolete document SD74-SH-0144, "Space Shuttle Program Thermal Interface Design Data Book IVBC-3," July 1995 referenced in EIS. EIS update is pending.
- Para 23 (B). Ascent thermal environments:
  - Johnson Space Center (JSC) letter MS4-96-045, "Performance Enhancement (PE) Certification Thermal Environments for Lightweight Tank (LWT)," June 10, 1996
  - JSC letter MS4-97-092, "Performance Enhancements (PEs) for 109 Percent Intact Abort Certification External Tank Thermal Environments for Super Lightweight Tank (SLWT) and Lightweight Tank (LWT) Configurations," October 17, 1997
- Para 23(D). Ascent plume thermal environments:
  - SSD-90-D0016, "Space Shuttle Generic ETR Plume Heating Data Book External Tank," per PRCBD S052638", March 27, 1991

- Para 23(K).
  - JSC letter MS2-01-004, "Heating factors for ET intertank Hi-Lock Fastener TPS amps," January 24, 2001

7.1.1.3.6 Induced Environments: Entry

Entry thermal environment and trajectory requirements for the LWT are detailed in paragraph 3.2.7.2(23) of the EIS.

- Para 23(E). Entry breakup thermal environments (Note, although SLWT, all documents were directed to be applicable to ET91 through 95):
  - JSC letter MS4-94-144, "Nominal No-Fail Heating for SLWT Breakup Analysis," December 21, 1994
  - JSC letter MS4-96-046, "Transmittal of Mean SLWT Entry Trajectory," June 5, 1996
  - JSC letter DM7-96-05, "Mean SLWT Entry Trajectory Delivery for -Z Side Heating Analysis," June 19, 1996
- Para 23(F). Entry heating trajectories:
  - JSC 26025, "External Tank (ET) Entry Trajectory Data Book," September 14, 1992
  - JSC letter MS4-97-003, "Trans-Atlantic Abort Landing (TAL) External Tank (ET) Entry Trajectories for Rupture Time Analysis," January 9, 1997
- Para 23(G). Entry thermal environments:
  - MMC-ET-SE05-580, "Aero/Thermal Entry Heating Data Book for the External Tank – SLWT," April 1997

7.1.1.3.7 Main Propulsion System Certification Trajectories

MPS certification trajectories for the LWT are specified in paragraph 3.2.7.2(23)(H) of the EIS.

7.1.1.4 Interfaces

Interface requirement documents controlling ET propulsion analysis are specified in the following paragraphs of the EIS:

- 3.6.2.2 Orbiter/ET Interfaces
- 3.6.2.3 ET/SRB Interfaces
- 3.6.2.4 ET/SS Launch Pad and MLP

Documents referenced by these paragraphs are identified below.

7.1.1.4.1 Design Requirements

LWT pressure and temperature design requirements are controlled by the following paragraphs of the EIS:

- Para 3.6.2.2. Orbiter/ET Interfaces
  - ICD-2-12001, "Orbiter Vehicle/External Tank,"

- Para 3.6.2.3. ET/SRB Interfaces
  - ICD-2-24001, "External Tank/Solid Rocket Booster,"
- Para 3.6.2.4. ET/SS Launch Pad and MLP
  - ICD-2-0A001, "Shuttle System Launch Platform Stacking & VAB Servicing."

7.1.1.4.2 Operational Requirements

Operational and procedural requirements are imposed by the following documents:

- Operations & Maintenance Requirements & Specifications Document (OMRSD), Files II and IV
- Launch Commit Criteria (LCC), ET 01-10, MPS 01-47(Partial), HazGas 01-12 (Partial)

7.1.1.5 ET-Derived Requirements

All ET internal loads resulting from the environments defined above are documented in the Loads Data Book (LDB), LM Drawing 80900200101. Models to produce these loads were derived using standard finite element techniques. The analysis to produce loads (from the models and prescribed environments) uses computer codes developed in-house, and maintained under configuration control; these programs are based on standard and accepted principles of mechanics. All the analysis models and results are stored on the AS4000 Jazz computer at Huntsville.

External Tank structural temperatures are documented in the Thermal Data Book (TDB), LM Drawing 80900200102, and reflect thermal analyses for design certification environments. The TDB thermal models use the requirements as documented in the End Item Spec as boundary conditions. The thermal math models are lumped parameter representations of the flight hardware based on the structural drawings. Materials data used in the models are test derived and referenced in the TDB. Systems Integrated Numerical Differencing Analyzer and Fluid Integrator (SINDA/FLUINT), which is widely used and accepted as an industry standard, is used in combination with in-house written subroutines, maintained under configuration control, to solve diffusion-type equations to generate temperatures. All models and results are archived on the AS4000 Blues computer in Huntsville.

The venting analysis data are documented in "Compartment Venting (Lightweight Model)," MMC-ET-SE05-95. The venting environments defined by Level II are referenced in MMC-ET-SE05-95. Venting analysis is carried out by computer codes [FD275 (One Compartment Venting,) MULTICOMP (Multiple Compartment Venting), and HAZGAS (Intertank Hazardous Gas Program)] maintained under configuration control. These programs use coefficients derived

from wind tunnel testing or flight measurements, or a combination of both. All models and results are archived on the AS4000 Blues computer in Huntsville.

MPS performance, including pressurization of the ET and propellant feed from the ET, is reviewed by Level II Propulsion Systems Integration Group (PSIG). The ET Project predicted ET performance is documented in Pre-Flight Prediction report; post-flight performance assessments are documented in the Quick Look, Flight Evaluation, and Engineering Evaluation reports. Design Criteria and Requirements are governed by the ICD, LCC, OMRSD, and the EIS. LWT LH2 pressure requirements were updated for PE trajectories by IRN IC-1432, which was approved by PRCBD S060604P signed 08-26-98. There were two subsequent updates:

- IRN IC-1657 approved by PRCBD S060604T signed December18, 2000
- IRN IC-1675 approved by PRCBD S06060V signed February 20, 2001

LWT LO2 requirements were updated by IRNs IC-1248, IC-1288, and again for PE trajectories by IC-1432. Approval of the IRN signifies acceptance by ET of the proposed revisions. In each instance, the ICD was updated by the specified IRN.

The two primary models used to assess ET performance are the Single Node Pressurization Program and the Propellant Loading Program. These models and results, maintained under configuration control, are archived on the AS4000 Blues computer in Huntsville.

7.1.1.6 ET Implementation of Requirements

To ensure ET hardware structural integrity and compliance with the EIS structural Factor of Safety requirements, a formal stress analysis is performed and documented in the ET Stress Report (826-2188). The stress report integrates all critical system- and element-level induced environments to produce a margin of safety for the as-designed ET hardware. The stress analysis is a key element in the overall design certification and verification of ET hardware. In addition to the stress analysis, a significant amount of ET hardware is verified by structural testing. Traceability to the appropriate certification/verification testing and analysis for a particular hardware element is documented and maintained by Systems Engineering.

In addition, LWT critical load indicators, documented in report 826-2363 “LWT Structural Load Indicators and Capabilities” are used for all flight assessments. Any violations of an indicator are flagged. Subsequent analysis then either clears the ET for the particular condition, or imposes a flight constraint.

Certification of the LWT design and hardware requirement compliance is documented in the Design Certification Sheets (DCSs), Certificates of Qualification (COQs), and Hardware Certification Sheets (HCSs) maintained by Systems Engineering. Table 4.2.2-1 of the EIS cross-references each design requirement to a DCS. EIS tables 4.3-1 and 4.3-3 list hardware and their

associated COQs and HCSs. The MMC-ET-TM09 document generated for each flight tracks the NSTS 07700, Vol. X, Book 1 requirements to EIS paragraph numbers, DCS, and ICD. Final certification of the ET is at Flight Readiness Review, where any deviation from baseline requirements is addressed. The specification flowdown and verification process is shown in Figure 7.1.1.6–1.

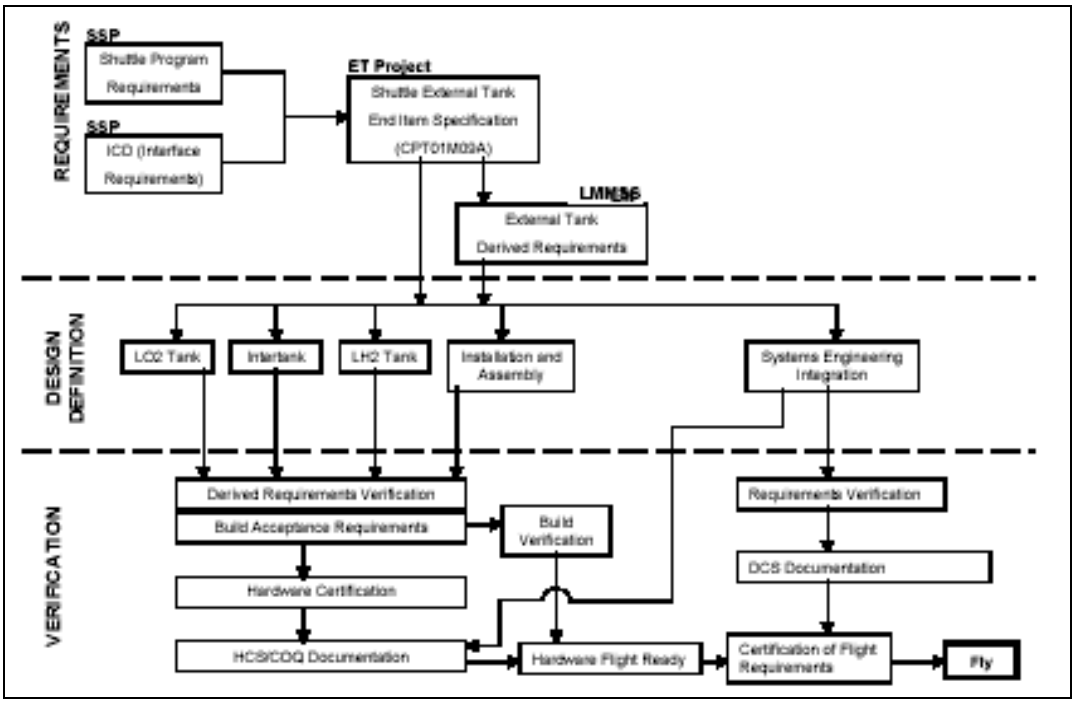


Figure 7.1.1.6-1. Requirements Flowdown

7.1.2 Flight-Specific Assessments

The following paragraphs address flight-specific assessments that were made for STS-107/ET-93. These assessments were performed using the same methods and tools described for the assessment of generic requirements.

7.1.2.1 Flight-Specific Assessments – Loads

7.1.2.1.1 Lift-off Loads Flight Margins Assessment (FMA) – Boeing

This study assessed lift-off loads using PE criteria, Block II SSME thrust and mass properties. The assessment was made against 826-2363, "LWT Structural Load Indicators and Capabilities," Rev R, January 2001.

One exceedance was identified and provided to the ET Project for evaluation (ref: Boeing letter 02MA0264, June 13, 2002). Lockheed Martin subsequently cleared this exceedance, reference contract letter 02MO-0540, July 23, 2002.

7.1.2.1.2 High-Q loads Launch Probability FMA – Boeing

This assessment was performed to certify operational high-Q design targets with LWT. Evaluation was made against 826-2363, "LWT Structural Load Indicators and Capabilities," Rev R, January 2001.

No exceedances were identified, as documented in the Boeing presentation to the Level II Loads Panel, "STS 107 SI IVA Flight Readiness," S. del Basso, November 18, 2002.

7.1.2.2 Flight Specific Assessments – Pressurization

7.1.2.2.1 Pressurization Performance Assessment – Boeing

This assessment evaluated GO2 and GH2 pressurization performance with Block II SSMEs. ICD violations were identified and provided to the ET project for assessment (Boeing letter 02MA0584, December 4, 2002)

ICD violations were cleared by Lockheed Martin. (Reference contract letter 03MO0025)

7.1.2.3 Flight-Specific Assessments – Thermal

7.1.2.3.1 Flight Margins Assessment for Late TAL Heating Analysis

This assessment included a 2-sec mated coast extension and Block II SSMEs. Exceedances were provided to the ET project for assessment (Boeing letter 02MA0161).

These exceedances were cleared by Lockheed Martin. (Reference Thermal Panel presentations on February 28, 2002, and a SSEIG presentation on December 9, 2002)

7.1.2.4 Flight-Specific Assessments – ET Separation

7.1.2.4.1 RTLS ET Separation and TAL Hit Evaluation

This evaluation included a 2-sec mated coast extension and Block II SSMEs. No issues were identified (reference Boeing presentation to Ascent GN&C Panel, "STS-107 RTLS ET-Sep and TAL Hit Evaluation," G. Manich and S. Bingham, 11/13/01).

7.2 Fault Tree Analysis

There were four possible dispositions for each event in the FT:

- Not Possible
- Possible-Probable
- Possible-Remote
- Possible-Improbable.

Each basic event in the FT was assumed to be a cause or contributor to the shedding of debris or a contributing interface event if the event occurred. Details of the assessment of each FT branch are presented in the following sections. Each event was assessed for possibility of occurrence. If deemed possible, the event was assessed for the likelihood of occurrence. The assessment criteria were:

- Possible-Probable: The supporting data identified a high likelihood that the event occurred.
- Possible-Remote: The supporting data did not indicate a high likelihood of occurrence but did provide rationale that supported the potential for occurrence.
- Possible-Improbable: The supporting data did not indicate the event having a remote likelihood of occurrence but did not completely rule it out.
- Not Possible: The supporting data was sufficient to rule out the occurrence of the event.

The disposition of event blocks using these criteria was a subjective process. No probabilistic risk assessments or other numerical tools were used to reach conclusions. The ETWG established an arbitration board for cases in which the branch lead disagreed with the disposition selected by the initiator. NASA S&MA personnel were in the review/approval loop for every event disposition and rationale. The disposition of intermediate event blocks was selected to be the same as the most likely possible contributing event since, with the exception of cut sets (see Section 5.1.1), “or” gates were used to relate all events.

Early in the accident investigation, the scope of the investigation was prioritized to focus on debris that could strike the left wing of *Columbia*. With the support of the Shuttle Integration Group, the ETWG established a map of geographic zones (Figure 7.2-1) on the ET from which debris could originate and have credible aerodynamic transport to the left wing during lift-off and ascent. Only the hardware items within these zones were studied for debris potential. Investigation of items outside these zones was indefinitely deferred, and these items were identified in the FT as undeveloped events. (Deferred locations were to be reprioritized in the event of additional investigation results implicating the region in the accident, and additional locations were analyzed at the discretion of the major FT branch leads.)

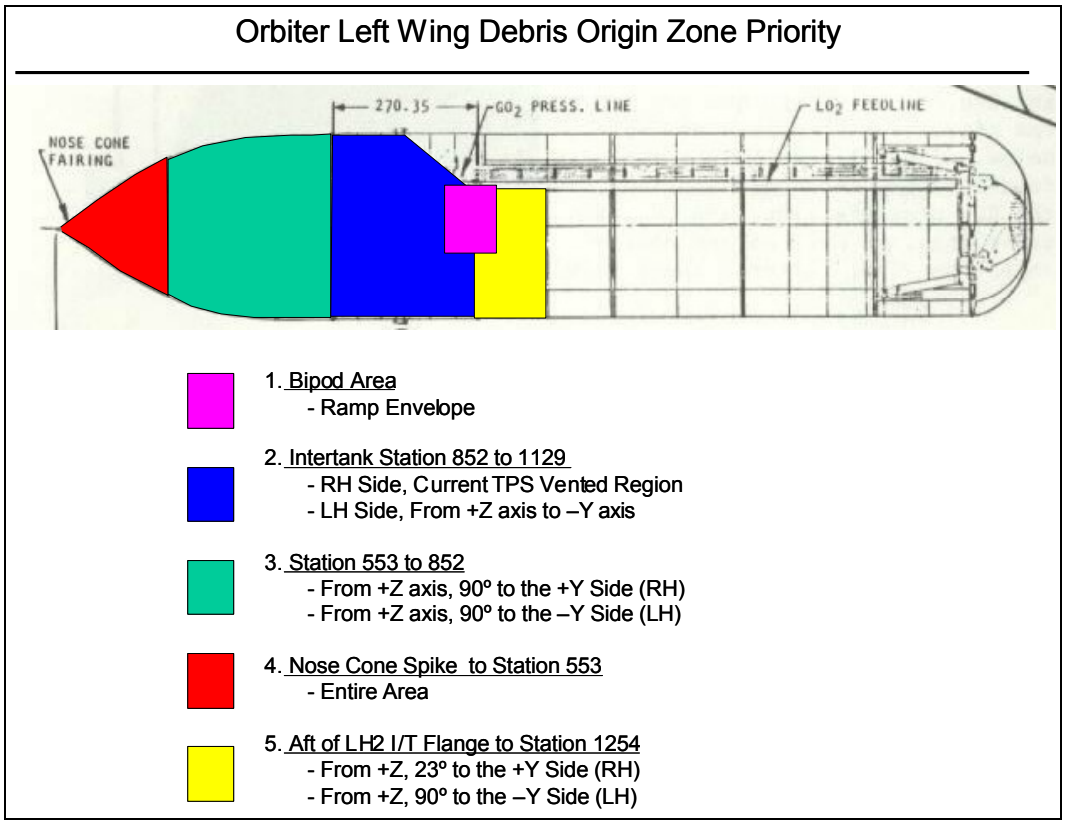


Figure 7.2-1. Prioritized Hardware for the Fault Tree Investigation

The top levels of the ETWG FT are shown in Figure 7.2-2. FT branches were developed to focus on the two possible causes associated with the External Tank following a successful ascent: debris damage to the Orbiter or contributions by the ET to an interfacial event. A demarcation of responsibility has been defined on the FT. The responsibility of the ETWG was established to be one of defining possible, likely credible debris or interface events. Disposition of those events with respect to the STS-107 accident was allocated to the OVE Working Group, as shown in Figure 7.2-2.

Results of the investigation of the 3470 blocks are included in Volume II, an electronic, interactive Fault Tree (CD) with attachments and query capability.

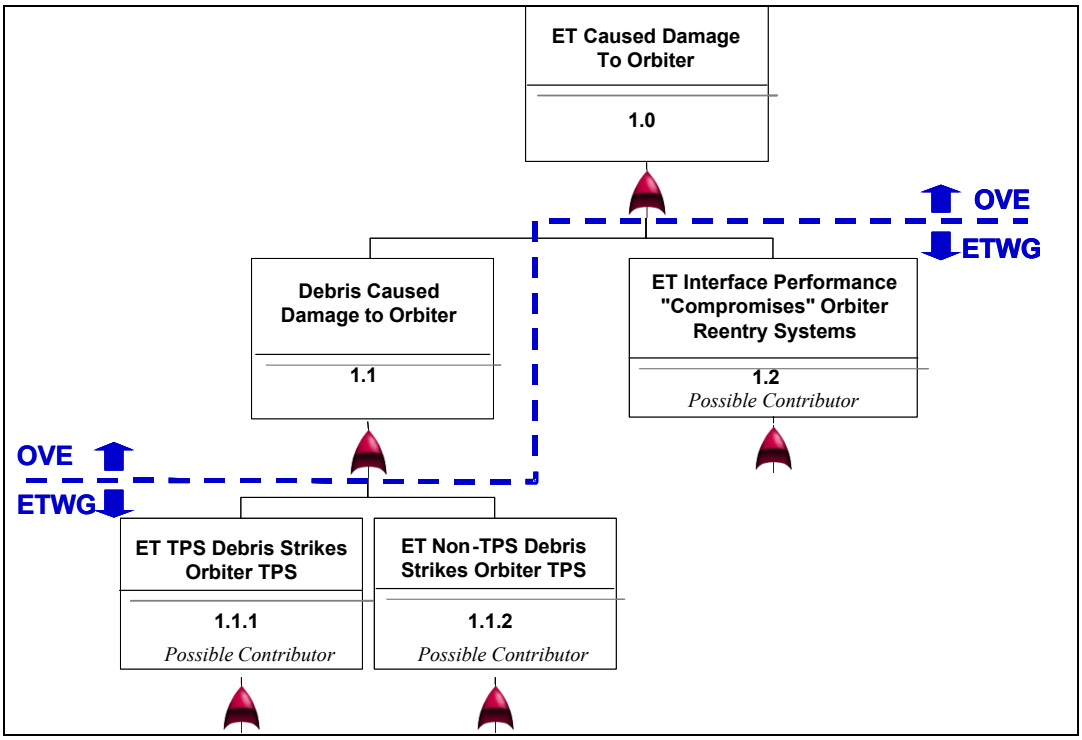


Figure 7.2-2. ETWG Top Fault Tree Levels

7.2.1 TPS Branch

7.2.1.1 Summary

The TPS Debris branch of the ETWG FT was one of two main branches investigating scenarios of debris originating from the External Tank and striking the Orbiter *Columbia* during lift-off and ascent on mission STS-107. In addition to assessing specific causes for the STS-107 accident, the TPS Debris Team was chartered with identification and assessment of additional debris-oriented issues. The Team mission and direction were two fold:

- First, identify any and all items that could have led to, or resulted in, the *Columbia* mishap.
- Second, and equally important, identify all items that must be addressed to enhance and improve the robustness of the ET TPS systems.

The assessment of TPS contributions to the STS-107 accident was systematically organized to assure complete coverage of all critical TPS systems, processes, practices, and implementation. The TPS tree branch was partitioned in tiers:

- The first level was organized by TPS materials (NCFI 24-124, NCFI 24-57, PDL 1034, BX-250, SLA-561, SS-1171, BX-265, and MA 25).
- The next level was organized by all components of the ET that use that material.

- The next level identified all lower level subcomponents.
- The next level identified the main thrust areas of the investigation:
  - Debris Due to Design
  - Debris Due to KSC Processing
  - Debris Due to Vendor
  - Debris Due to MAF Processing.

On conclusion of the assessment of the ET-93 TPS materials, processes, design, verification, validation, and operational performance, the following debris generation categories were identified:

- PDL Repairs
- Operator Input to Process
- External Impacts to ET TPS Produce Debris
- Inadequate Design and Verification Methodology
- Debris Due to Manufacturing Process Plan - (Manual spray overlap times not verified by QC)
- Improper Storage – shelf life discrepancies in STP
- Improper Application – additional operator verification steps needed
- Inadequately Defined Acceptance Testing
- Undetected Anomaly due to Processing at a Vendor, MAF or KSC

The following FT blocks were classified as "red," or likely contributors to large foam loss on ET-93:

- BX-250 – "BX 250" (WBS 1.1.1.4)
- "Bipod" - (WBS 1.1.1.4.1)

The following FT blocks were classified as "yellow," or possible contributors to TPS loss, either separately or in conjunction with other evets.

- BX-250 – "Bipod - Inadequate Design Methodology" - (WBS 1.1.1.4.1.1.1.1)
- BX-250 – "Bipod - Debris Due to Anomalous MAF Processing - Debris Due to Inadequate MPP" (WBS 1.1.1.4.1.1.3.2.1)
- BX-250 – "Bipod - Debris Due to Anomalous MAF Processing - Inadequately Defined Acceptance Testing" (WBS 1.1.1.4.1.1.3.3.6)
- SLA-561 – "Bipod Fitting - Inadequate Design Methodology" - (WBS 1.1.1.5.1.1.1.1)
- SLA-561 – "Bipod Plate Connector - Inadequate Design Methodology" - (WBS 1.1.1.5.1.2.1.1)

7.2.1.2 Team Charter

The ETWG directed the development and completion of a Fault Tree as the primary method or tool by which the ET potentially could have caused or

contributed to the loss of STS-107. One of the branches identified on the tree was "ET TPS Debris Strikes Orbiter TPS." The TPS Team charter was to review the engineering and build processing paper, beginning with the basic material vendors and ending with the launch at KSC. The first priority was to identify any abnormalities or concerns that could have resulted in the liberation of TPS within the Critical Debris Zone defined above. The secondary objective was to identify observations for assessments as possible enhancements following the Investigation.

7.2.1.3 Team Overview

The Team was composed of both NASA/MSFC and LMSSC personnel. The Team core members represented the senior TPS experts in the MSFC community.

The basic responsibility of the TPS Debris Team revolved around determining what happened, establishing corrective action, finding related issues, and determining additional appropriate corrective actions if required.

Scotty Sparks, NASA, and Mike Quiggle, Lockheed Martin, led the TPS Debris Investigation Team. The dedicated NASA S&MA Team Lead was Chris Reinecke.

7.2.1.4 Scope of Review

The scope of the TPS Debris Team review included all TPS materials and processes, from design and development through production and flight performance; all facets of the TPS process for configurations in the Critical Debris Zone; and, determination of probable cause for the liberation of TPS debris.

7.2.1.4.1 TPS Systems Overview

There are basically two types of TPS materials used on the ET: low density closed-cell foams, used for high insulation efficiency, and denser composite materials, used for high heat capability. Each type has variations that provide for application ease (spray, pour, pre-mold/bond installations) and specific mission requirements. Foams are used at low heating rates, and the composites are used where the foams are inadequate. The initial TPS thickness is determined by pre-launch requirements, and additional material (foam or ablator) is added as dictated by ascent and re-entry requirements.

The majority of the ET TPS is North Carolina Foam Insulation (NCFI) 24-124 SOFI and SLA-561 bonded ablator. NCFI 24-57 SOFI, a more dense and more heat-resistant foam, protects the aft LH2 tank dome. The SRB booster plume thermal environments require a more robust foam system than that applied to the acreage. The SOFI is applied over the SLA when both highly efficient insulation and high heating capability are required. In areas not exposed to ascent heating (LO2 tank aft dome and LH2 tank forward dome) and in various benign closeout

areas, urethane foams (BX-250, BX-265, SS-1171, and PDL-1034) are used because of their more liberal application constraints.

The pre-launch requirements basically define the foam installation thickness. Maintaining good quality/stable propellants and minimizing ice are the primary considerations. Protuberances and interface hardware utilize thermal isolators, heaters, and foam cover as required to provide an equivalent ice deterrent.

In summary, the TPS before launch serves the following functions:

- Maintains LO2 and LH2 boil-off rates below the vent valves capabilities
- Insures LO2 and LH2 specified temperatures at the Orbiter interface
- Controls air liquefaction on the LH2 tank
- Controls ice formation on the ET surface.

The ascent mission phase defines the requirement for an ablator. Maintaining the primary structure and subsystem components within the design temperature limits is the primary consideration. Heat input is derived from aero convective flow, the SSME and SRB plumes, the SRB separation motors, and autogenous tank pressurization gas.

Another function of the TPS occurs during ET re-entry when structural temperatures and tank pressures contribute to the ET fragmentation process and consequential debris size and impact area (footprint). The residual material must be adequate to provide the entry function and assure low altitude fragmentation to meet the 100- x 600-n. mi. footprint limits.

Figure 7.2.1.4.1-1 shows those TPS areas that were a part of the assessment for STS-107. Table 7.2.1.4.1-1 shows the various TPS systems and pertinent information about each.

7.2.1.4.2 TPS Materials and Application Analysis

The classical analytical methods used to analyze TPS consist of calculating stresses/strains using consistent equations/analytical methods. The analysis is used to correlate test conditions to flight conditions based on the most critical environments and failure modes. Since the flight stresses/strains and the test-demonstrated stresses/strains are calculated using the same methodology, the Test Demonstrated Factor of Safety (TDFS) adequately represents the relationship between the test conditions and flight conditions.

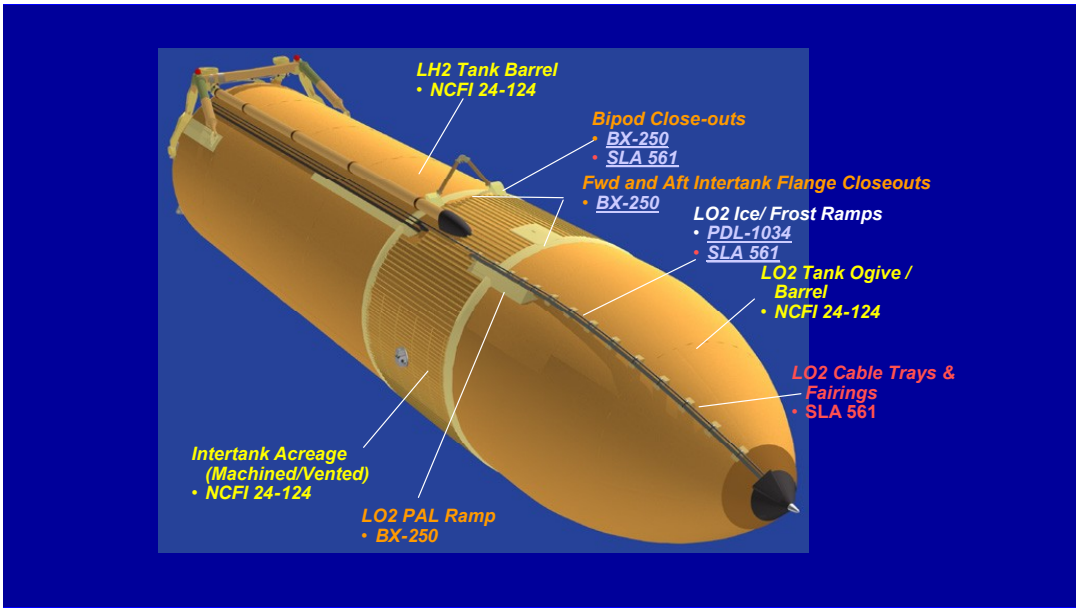


Figure 7.2.1.4.1-1. Reviewed External Tank TPS Systems

Table 7.2.1.4.1-1. TPS Materials Systems Properties Overview

Foam/Property	**NCFI 24-124**			**NCFI 24-57**			**PDL-1034**			**BX-250, BX-265 and SS-1171**		
• Application	LO2, LH2, Intertank sidewall			LH2 aft dome			Closeouts, repairs			LO2 aft dome, LH2 forward dome, closeouts		
• % of Total Foam	77%			7%			2%			14%		
• Process	Spray			Spray			Pour/Mold			Spray		
• Description	Isocyanurate			Isocyanurate			Urethane			Urethane		
Requirements	**Spec Reqmt**	**Typ Prop**	**Flt Reqmt**	**Spec Reqmt**	**Typ Prop**	**Flt Reqmt**	**Spec Reqmt**	**Typ Prop**	**Flt Reqmt**	**Spec Reqmt**	**Typ Prop**	**Flt Reqmt**
• Density (pcf)	2.0-2.5	2.2	N/A	2.6-3.1	2.97	N/A	2.3-3.1	2.6	N/A	1.8-2.6[3]	2.4	N/A
• Tensile, RT (psi)	30 min.	44	19	40 min.	66	19	60	113	19	35 min.	53	19
• Tensile, -423°F (psi)	N/A	34	19	N/A	49	19	N/A	50	19	N/A	62	19
• Tensile, +300°F (psi)	N/A	32	19	N/A	36	19	N/A	71 [1]	10	N/A	35 [1]	19
• Compression (psi)	25 min.	33	20	35 min.	49	20	30	61	20	24 min.	30	20
• Recession Rate @ 7 Btu/ft sq. sec.) (in./sec.)	N/A	.0094	N/A	N/A	.0099	N/A	N/A	.0303	N/A	N/A	.017 [2]	N/A
• Thermal Conductivity @ RT (Btu/hr ft°F)	.025	.017	N/A	.0225	.0180	N/A	.016	.015	N/A	.015	.013	N/A
• Cryostrain (ksi)	61 @ -423°F	65 @ -423°F	pass	58 @ -423°F	65 @ -423°F	pass	N/A	60 @ -423°F	pass	N/A	65 @ -423°F	pass

The critical failure modes for TPS on the ET are bond line delamination, outer fiber cracking, and bond adhesion. Detailed discussion of analysis methodology, inputs, and results are contained in section E of the SLWT External Tank Stress Report, EAS No. 3521-826-2188, Rev AA-S. A brief discussion of the critical TPS failure modes, along with the critical inputs to the analysis, is provided below.

Analysis of the bond line delamination failure mode requires substrate strain, substrate bending/flexure, material thickness, thermal gradient, thermal expansion/contraction, and modulus. Cryogenic thermal gradient, CTE mismatch between TPS and substrate, and the resulting differential thermal strain of the TPS and the aluminum substrate are primary drivers for bond line delamination. In essence, the TPS shrinks more than the aluminum, which produces a thermal stress distribution tangential to the tank surface. A free body diagram, in Figure E.1.6.2.2-2 pg. 3 Section E of the SLWT Stress Report (EAS No. 3521-826-2188 Rev. AA-S), shows the tangential thermal stress distribution, which is counteracted by a bond line stress distribution or “peel” stress. The aluminum substrate is considered infinitely rigid, and the “peel” stress is conservatively reacted on the TPS. This failure mode is most critical during pre-launch when the substrate is cryogenic. For non-cryogenic hardware, substrate strain is the primary driver for bond line delamination. Previous testing of TPS shows that bond line delamination failures are accompanied by a crack of the TPS, which progresses through the thickness of the TPS resulting in a ‘peeling’ of the TPS from the metallic substrate.

Analysis of the cracking caused by outer fiber strain failure mode requires substrate strain, substrate bending/flexure, material thickness, and the outer fiber strain capability. Substrate bending/flexure is the primary driver for outer fiber strain. This failure mode is critical for pre-launch and flight when the ET experiences thermal contraction caused by cryogenic temperatures and maximum tank internal pressure.

Analysis of the failure mode of bond adhesion requires cell burst pressure, substrate temperatures, local acceleration forces, and the TPS bond tension capability. The effect of cell pressure is the primary driver for bond adhesion of ET foam and vibroacoustic loading for ablator. As the Shuttle ascends, ambient pressure decreases, internal cell pressure increases because of increased substrate and TPS temperature, and acceleration loads produce forces on the TPS perpendicular to the tank surface. These forces are reacted through the TPS, producing stress in the TPS and on the TPS/substrate bond line. Bond adhesion stresses are critical at the end of ascent, when the TPS experiences maximum acceleration and thermal environments. The cell burst pressure adjacent to the cryogenic substrate will be significantly below the maximum possible of 14.7 psid as a result of reduced cell pressures due to cryogenic cooling. The analysis conservatively neglects relief related to cryogenic temperatures, however, and assumes pure vacuum so that the maximum

possible differential pressure is analyzed. For regions through the thickness of the TPS exposed to flow heating effects, testing has shown that the BX-250 material will recede before developing sufficient cell pressure to cause foam divots.

Protuberances are subjected to air loads during ascent. Direct tangential air loads are reacted as shear loads on the TPS material. The protuberance footprints provide adequate area and strength to accommodate the applied air loads. Crush pressure is an additional derived requirement because of aerodynamic load inputs normal to the ET tank membrane, which are analyzed and considered negligible. Other negligible environments are documented within pgs. 43-46, section E.2.5.6, of the SLWT Stress Report EAS No. 3521-826-2188 Rev. AA-S.

Cryogenic thermal gradient produces a moment or "peel" stress at the ET TPS/substrate bond line. Subsequent aerodynamic and substrate warming during ascent relieves thermal loading at the TPS to substrate bond line. During ascent, thermal analysis results predict significant outer surface temperature increases during ascent.

The ET NASTRAN model is used to derive the design (in-plane) substrate strain requirement. The ET NASTRAN model is the latest version of the model previously verified by correlation to STA test results (MMC-ET-TM03-0, Vol. I and III). The NASTRAN model loads are formatted and read into a FORTRAN program, which computes margins of safety for multiple load case assessments. Aerodynamic loads can be considered to be acting in normal and tangential directions to the ET membrane. Stress analysis uses 'zero margin' maximum air loads as provided in the Super Lightweight and Lightweight External Tanks Loads Data Book 80900200101 Rev. H, Table 12.31.3-1, to calculate shear stresses on TPS protuberances. The reconstructed loads for STS-107/ET-93 are lower in magnitude than the loads provided for the 'zero margin' analysis and result in increased factors of safety.

The basic ground rule used for the TPS analysis is to combine the most critical contributors for a given failure mode and to compare the resulting parameter, *e.g.,* maximum moment, stress, strain, cell pressure, radius, to test data using consistent analytical methods. The primary failure mode is bond line delamination. For this failure mode, the analysis considers thermal gradient, substrate strains (thermal and mechanical) and flexure. The LWT Delta Critical Design Review (CDR) established the methodology for determining factors of safety based on the internal moment, and RID T-1 initiated a minimum factor of safety requirement of 1.10 relative to strain compatibility.

7.2.1.5 TPS Debris Branch Fault Tree Structure (Lower Branches and Sub-Branches)

The TPS Debris Fault Tree section consisted of 2788 blocks, of which 2134 were "basic event" blocks. ("Basic event" blocks are those FT blocks that reflect the lowest level of analyzed event.) The tree was organized by the 8 different TPS material types (Figure 7.2.1.5-1.) and the tree was developed to a 9-digit level. TPS configurations that were not located in the Critical Debris Zone were "Diamond Deferred." There were 35 blocks that fit that definition (Example: TPS applied to the internal LO2 dome.) (The Diamond Blocks were not developed to the 9-digit level; had they been, the total number of blocks would have encompassed several thousand more.) Two FT branches, 1.1.1.2 "NCFI 24-57" (exclusively used for the LH2 aft dome acreage, outside the STS-107 debris zone) and 1.1.1.8 "BX-265" (exclusively used for the ET/SRB aft fairings, outside the STS-107 debris zone), were entirely "Diamond Deferred."

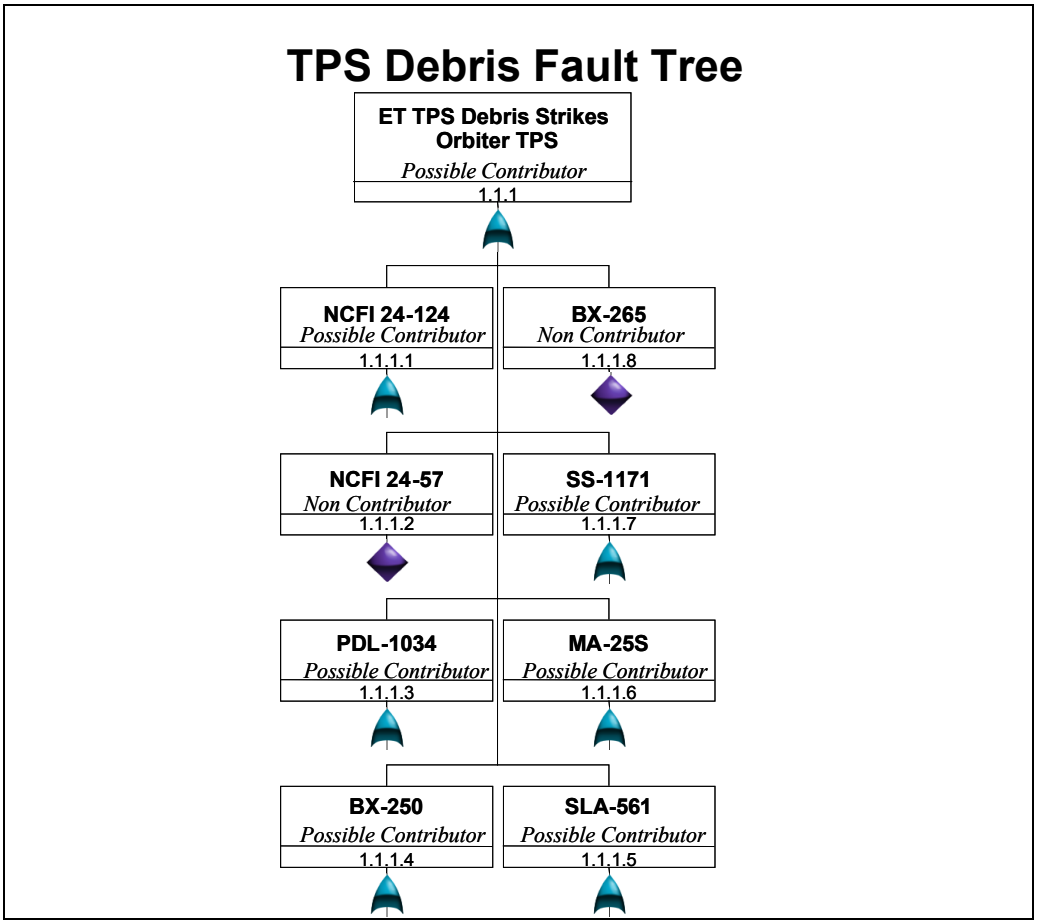


Figure 7.2.1.5-1. TPS Debris Branch Top-Level Subheadings

Each material was then populated with groupings of similar TPS configurations utilizing that material. Within each grouping, every different TPS configuration was identified by the applicable 8097XXXXXXX drawing number and its

corresponding FMEA code number and was transformed to a 1.1.1.X.X.X or a 6-digit code. Each TPS configuration 6-digit number was then expanded to include 7 digits to establish the four major areas that would be reviewed for each TPS component for each TPS material. For example, examination of the block number 1.1.1.4.1.1.1.1.1 reveals:

- The 1 in the 3rd column indicates that this is TPS
- The 4 in the 4th column indicates that this is BX-250
- The 1 in the 5th column indicates that this is a BX-250 Bipod TPS component
- The 1 in the 6th column indicates that this is the TPS Closeout Assembly, Forward Bipod Fittings Drawing 80971008434 and FMEA Code 5.8.35.1

A total of four possible numbers can be used in the 7th column. These represent the four primary areas of the TPS configurations that were potentially reviewed for inadequacies. Not every configuration required all areas to be assessed, as some areas were not applicable. The four major areas were:

- Debris Due to Design Resulting in a Cohesive, Shear, Delamination, or Crack Failure of TPS
- Debris Due to Vendor Manufacturing/Processing Resulting in a Cohesive, Shear Delamination, or Crack Failure of TPS
- Debris Due to MAF Processing Resulting in a Cohesive, Shear, Delamination, or Crack Failure of TPS
- Debris Due to KSC Processing Resulting in a Cohesive, Shear, Delamination, or Crack Failure of TPS

There are possibly 7 numbers that can be used in the 8th column, depending upon the major area identified in the 7th column:

- If the 7th column is Debris Due to Design Resulting in a Cohesive, Shear, Delamination, or Crack Failure of TPS, the following were underlying causes:
  - Inadequate Design Methodology
  - Inadequate Design Implementation
- If the 7th column is Debris Due to Vendor Manufacturing/Processing resulting in a Cohesive, Shear, Delamination, or Crack Failure of TPS, the following were underlying causes:
  - TPS Raw Material
  - Cleaning Raw Material (Acreage (NCFI) – Other parts provided cleaned/ready for TPS)
  - Primer Raw Material (Acreage (NCFI) – Other parts provided primed/ready for TPS)
  - Ducommun/MAF Material (Acreage (NCFI) – Other parts provided ready for TPS)
  - Adhesive Raw Material
  - Undetected Anomaly

- If the 7th column is Debris Due to MAF Processing Resulting in a Cohesive, Shear, Delamination, or Crack Failure of TPS, the following were underlying causes.
  - Debris Due to MAF Training
  - Debris Due to Manufacturing Process Plan
  - Debris Due to MAF TPS Material Processing
  - Debris Due to MAF Cleaning Material Processing (Acreage (NCFI))
  - Debris Due to MAF Priming Material Processing (Acreage (NCFI))
  - Debris Due to MAF Welding Processing (Pressure Vessels Acreage (NCFI))
  - Debris Due to MAF Adhesive Material Processing
  - Debris Due to External Events During MAF Processing
  - Debris Due to Mechanical Assembly Anomaly
  - Undetected Anomaly
- If the 7th column is Debris Due to KSC Processing Resulting in a Cohesive, Shear, Delamination, or Crack Failure of TPS, the following were underlying causes.
  - Debris Due to Nominal KSC Processing
  - Debris Due to Anomalous KSC Processing
  - Undetected Anomaly

There were possibly 8 numbers that could be used in the 9th column, depending upon the focus identified in the 8th column. Only three of the major areas were carried out to a 9th column. (KSC Processing was not expanded further.)

- The Debris Due to Design can expand to a 9th digit to capture the following basic events:
  - Inadequate Material Testing
  - Inadequate/Incorrect Analysis Methods
  - Inadequate Verification
  - Incorrect Materials Identified
  - Incorrect Processes Identified
  - Incorrect Configuration/Dimensions Identified
  - Incorrect ET Effectivity Identified
- The Debris Due to Vendor Manufacturing/Processing Raw Material blocks can expand to a 9th digit to capture the following basic events:
  - Incorrect Materials
  - Shelf Life Issue
  - Improper Storage
  - Contamination During Testing

  - Improper Shipping
  - Inadequate Resolution of Identified Anomaly
- The Debris Due to MAF Processing Training blocks can expand to a 9th digit to capture the following basic events:
  - Inadequately Trained Operator
  - Uncertified Operator
- The Debris Due to MAF Processing Manufacturing Process Plan blocks can expand to a 9th digit to capture the following basic events:
  - Debris Due to Inadequate Manufacturing Process Plan
  - Debris Due to Operator Not Following Manufacturing Process Plan
- The Debris Due to MAF Processing Material Process blocks can expand to a 9th digit to capture the following basic events:
  - Shelf Life Issue
  - Improper Storage
  - Contamination During Processing
  - Improper Surface Preparation
  - Improper Application Process
  - Inadequately Defined Acceptance Testing
  - Inadequately Performed Acceptance Testing
  - Inadequate Resolution of Identified Anomaly

7.2.1.6 Evaluation Criteria

A DCMA and/or NASA representative and a Lockheed Martin representative reviewed design, processing, acceptance, and build paper for each material system of each TPS configuration identified in the Critical Debris Zone.

The four possible dispositions for each event in the FT were used to categorize observations.

7.2.1.7 Approach

As a ground rule, all blocks were classified as a possible cause or contributor, until sufficient data were provided to reclassify them. The data included interviews, vendor and build paper review, testing, ascent photography, performance data, analysis, and engineering judgment.

The review scope for TPS is shown in Table 7.2.1.7-1. The Team reviewed each process step to verify compliance with the engineering requirements, *e.g.,* mix constituents, application time, certified operator, and acceptance test results, etc. Discrepancies were documented as issues or were resolved as either incorrectly entered data or that the anomaly was not a critical step and could not have been a cause or contributor to TPS debris.

Table 7.2.1.7-1. TPS Team Review Scope

Scope Item
Materials Specifications (STM) (26 ea)
Process Specifications (STPs) (22 ea)
Manufacturing Process Plans (159 ea)
Vendor data packages for the LO2 tank, LH2 tank, intertank structure
Vendor TPS materials data
TPS drawings (49)
NCDs (69) and IPRAs
Receiving acceptance data packages
Lab results
Interviews with practitioners associated with critical processes
Bipod TPS fabrication
Intertank to LH2 and LO2 tank interface closeout fabrications
Trend data for ET 93 TPS as compared to the 25 previous tanks were developed and compared

7.2.1.8 Results

Specific findings will be discussed in the categories of major TPS materials systems, consistent with the structure of this FT branch.

7.2.1.8.1 NCFI Fault Tree Blocks Summary (Fault Tree Branch 1.1.1.1)

7.2.1.8.1.1 Background

The primary foam material used on the ET is NCFI 24-124 spray-on foam insulation (Figure 7.2.1.8.1.1-1). It is a blown, closed cell rigid foam system with higher temperature stability than conventional urethane foams. (The NCFI 24-57 material is similar to NCFI 24-124 and provides improved temperature stability for the aft dome engine plume heat environment.) Locations are shown in Figure 7.2.1.8.1.1-1.

Table 7.2.1.8.1.1-1 provides a brief history of the evolution of the acreage spray foam.

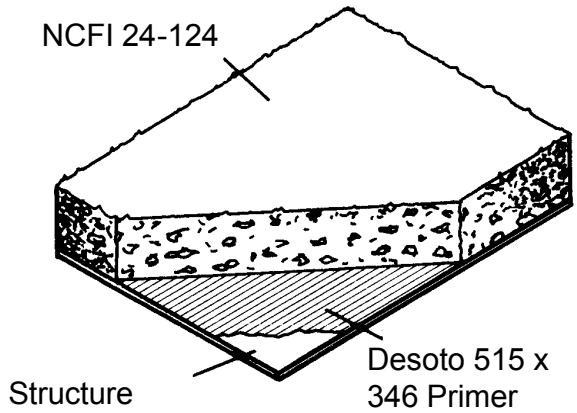


Figure 7.2.1.8.1.1-1. NCFI Material Application

Table 7.2.1.8.1.1-1. Spray Foam Acreage Development History

•	**1974**	**CPR 421 Selected for ET application**
•	**1975**	**Hooker Chemical (now Oxychem) polyol special arrangement for ET usage**
•	**1975**	**Toxicity issue identified with use of CPR 421 (Polyol with Flame Retardant)**
•	**1976**	**CPR 488 qualified to replace CPR 421 (Flame Retardant removed)**
•	**1982**	**NCFI 22-65 replaces CPR-488/SLA on LH2 Aft Dome**
•	**1984**	**UpJohn changes Isocyanate formulation used in CPR 488 (Iso 0414D)**
•	**1985**	**Dow acquisition of UpJohn and production location changed from Torrance to LaPorte**
•	**1986**	**1st production at LaPorte, Qualification of facility required**
•	**1988**	**UpJohn Isocyanate change #2 (PAPI Lite)**
•	**1993**	**CFC 11 blowing agent manufacture discontinued (accelerated EPA date of 1995)**
•	**1994**	**Oxychem phases out production of Polyol used in CPR 488, supplier refuses to continue making polyol due to expensive plant upgrades (CPR 488 lost)**
•	**1995**	**Qualified NCFI 24-124 to replace CPR 488, NCFI 24-57 to replace NCFI 22-65**
•	**1995**	**FR 1138 Flame Retardant discontinued used in both NCFI 24-124 and NCFI 24-57**
•	**1997**	**IFA issue identified with use of NCFI 24-124 on Intertank**
•	**1998**	**Bayer upgrades Texas plant to manufacture isocyanate vs. Spanish Iso used in NCFI foams**

Receiving and acceptance tests that are performed at MAF and at the vendor's are shown in Table 7.2.1.8.1.1-2.

Table 7.2.1.8.1.1-2. Acceptance Tests

Receiving Acceptance Required Test	Vendor Required Test
* Cream Time	Cream Time
* Rise Time	Rise Time
* Tack-Free Time	Tack-Free Time
* Density, Sprayed foam	Density, Free Foam
* Compressive Strength	HCFC 141b Content (percentage) added to material formulation
* Tensile Strength	
* Viscosity (Components A and B)	
* Specific Gravity (Components A and B)	
* Amine Equivalent (Component A)	
* Water Content (Component B)	
* Hydroxyl Number (Component B)	
* Acid Number (Component B)	
* HCFC 141b Content (Components A and B)	
Workmanship (Components A and B)	
Finger Printing (Component B)	
* Test performed on Shelf -life lots	

The internal cell structure of the NCFI material is a closed-cell foam, as shown in Figure 7.2.1.8.1.1-2.

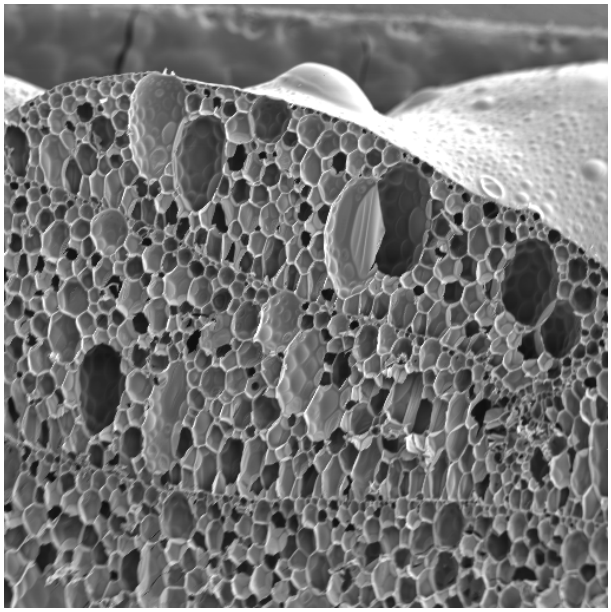


Figure 7.2.1.8.1.1-2. NCFI Scanning Electron Microscopy Photomicrograph (30X)

The foam acreage materials are low viscosity, two-component liquid systems, which are applied to the acreage structure by automated spray equipment. The

application is controlled to provide an "as-sprayed" finish within the required ET thickness, roughness, and waviness constraints without machining. During the SLWT design process, however, a decision was made, which is being revisited as the acreage foam transitions to NCFI 27-68, to machine the intertank TPS surface in acreage regions outside of the LO2 and LH2 ice/frost regions for weight savings. Figure 7.2.1.8.1.1-3 shows a section through the intertank thrust panel foam.

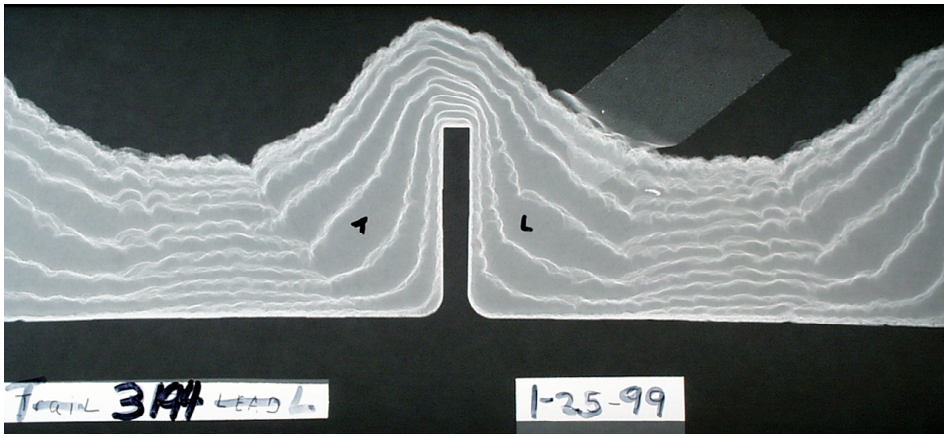


Figure 7.2.1.8.1.1-3. Foam Structure

7.2.1.8.1.2 Analysis Methodology

7.2.1.8.1.2.1 Stress

The stress analysis performed for the NCFI 24-124 TPS applied to the acreage External Tank membrane (LMMSS Drawings 80971118408-529 LO2 Tank Foam Application, LMMSS 80971118413-509 Intertank Foam Application, and 80974018411-510 LH2 Tank Foam Application) utilized classical stress analysis methods that take into account the substrate strain, substrate bending/flexure, cell burst pressure, local acceleration forces, aerodynamic loads, and thermal effects as individual environments. The primary failure modes for TPS include bond line delamination, bond adhesion, and outer fiber cracking. Detailed discussion of analysis methodology, inputs, and results are contained in section E of the SLWT External Tank Stress Report EAS No. 3521-826-2188, Rev AA-S.

As summarized above, the classical analytical methods used to analyze TPS consist of calculating stresses/strains using established equations/relations. These equations/relations are used to correlate test data to flight data, based on the most critical environments and failure modes. Since the flight and the test demonstrated stresses/strains are calculated using the same methodology, the TPS Factor of Safety adequately represents the relationship between the test data and flight data.

Based upon the above rationale, the analysis for individual environments was correctly validated and adequately represented the relationship between flight and test. Methodology, analyses, and conclusions were reviewed for the acreage foam. Outer fiber cracking and bond line delaminaton failure modes were assessed against stresses and material strengths.

For the failure mode of bond adhesion, stresses are critical at the end of ascent, when the TPS experiences maximum acceleration and thermal environments. To ensure a more robust design for NCFI 24-124 acreage TPS, the minimum bond tension allowable (35 psi per process specification LMMSS Drawing STP-1535) exceeds the bond adhesion requirement, which is provided in the cell pressure section.

The acreage TPS material specification, geometry, and thickness LWT TPS and substrate configurations are similar to SLWT; however, LWT substrate thickness is more robust and results in reduced substrate strain levels.

7.2.1.8.1.2.2 Thermal Gradient

The stress analysis uses the critical thermal gradient experienced during pre-launch, which is –297 °F (LO2)/-423 °F (LH2) at substrate and ambient at the outer surface. Thermal gradient produces a moment or “peel” stress at the ET TPS/substrate bond line. Subsequent aerodynamic and substrate warming during ascent relieves the thermal moment at the TPS to substrate bond line.

Substrate temperature effects are considered for bond line integrity. Aerodynamic heating and back face heating contribute to bond line temperatures, which increase the TPS cell pressures. The critical bond line temperatures are provided in the External Tank TDB 80900200102, Rev G. Upon assessment of the data, the design temperature requirements are adequate and correct.

7.2.1.8.1.3.3 Acceleration Forces

Stress analysis uses “G” loads as provided in the Super Lightweight and Lightweight External Tanks LDB 80900200101, Table 12.30.2-1 for the bond adhesion requirement. Table 12.30.2-1 is provided as Table 7.2.1.8.1.2.3-1.

Table 7.2.1.8.1.2.3-1. Acceleration Forces (Table 12.30.2-1)

Zone	Location	Station (Xt)	LWT (G's) (1)	SLWT (G's) (3)
1	Nose Cap	322 to 371	550	550
	(2) Nose Cone/Ogive I/F	371	157	157
2	Fwd Ogive	371 to 536	425	425
3	Aft Ogive	536 to 744	150	150
	LOX Barrel	744 to 852	150	150
4	Intertank - Includes LOX Dome LH2 Fwd Dome	852 to 1130	275	275
5	LH2 Fwd Cylinder	1130 to 1624	250	325
6	LH2 Aft Cylinder	1624 to 2058	225	230
7	Aft LH2 Bulkhead	2058 to cap	350	350

Based upon the above information, the design acceleration requirement was adequate and correct.

7.2.1.8.1.2.4. Cell Pressure

The TPS cell pressure is the primary driver for the limit bond adhesion requirement for acreage TPS. The bond adhesion requirement is derived from an adjusted cell pressure for a maximum substrate temperature of 300 °F under pure vacuum. The maximum temperature and pure vacuum inputs account for 21.1 psi of the requirement, whereas the dynamic load and mass inputs account for 2.5 psi. The maximum bond adhesion design requirement for LO2 acreage NCFI 24-124 TPS is 23.6. At 80 sec, the temperature is conservatively assumed to be 70 °F, which results in a 17.2-psi bond adhesion requirement. To ensure a more robust TPS bond, the minimum allowable bond adhesion requirement for NCFI 24-124 is 35 psi in accordance with STP-1535.

Based on the above information, the cell pressure and derived bond adhesion requirements are adequate and correct.

7.2.1.8.1.2.5. Substrate Strain

The TPS critical case for substrate strain (in plane) is driven by the lift-off flight regime in the LO2 tank barrel. As mentioned previously, the delamination failure mode is critical at pre-launch in the presence of the maximum thermal gradient and internal ullage pressure. The lift-off regime introduces an additional environment as the Shuttle system accelerates and produces mechanical strain on the substrate, in addition to the ullage pressure and cryogenic effects. The ET NASTRAN model is used to derive the design (in plane) substrate strain requirement. The ET NASTRAN model is the latest version of the model previously verified by correlation to STA (MMC-ET-TM03-0, Vol. I and III). The NASTRAN model loads are formatted and read into a FORTRAN program, which

computes margins of safety for multiple load case assessments. The maximum design (in plane) substrate strain requirement for all flight regimes is 0.0036 in./in. for the LWT LO2 tank barrel and 0.0048 in./in. for SLWT LO2 barrel. LWT is a more robust design and is enveloped by SLWT LO2 tank barrel strain.

Based upon the above information, the design (in-plane) substrate strain actual and derived requirements are adequate and correct.

7.2.1.8.1.2.6. Substrate Bending/Flexure

Substrate bending of the acreage TPS is caused by the combined effects of internal pressure and cryogenic shrinkage of the LO2 tank. The relative stiffness of the ring frame to the surrounding tank membrane creates a transition in radial deflection. Additionally, the LO2 Protuberance Air Load (PAL) ramp flanks the outboard side of the cable tray system at 31° 31' from the +Z and spans across the LO2-to-intertank flange. The LO2 PAL ramp is 7 in. in height, is sprayed over existing NCFI 24-124, and acts as additional insulation for the NCFI; therefore, more of the underlying NCFI is cryogenic through the thickness, which results in increased thermal moments on the NCFI. The ramp also induces mechanical moment on the underlying NCFI because of the significant height of the ramp relative to acreage NCFI. The LO2 PAL ramp test verifies the NCFI 24-124 configuration as well as the BX-250 ramp configuration for substrate bending and thermal effects.

BOSOR analysis is utilized to determine radii of curvature as a function of tank station for acreage TPS and PAL ramp requirements. The I/T-to-LO2-tank splice joint is divided into regions. This methodology was verified by correlation to the "Intertank Formed Skin/Stringer Panel Compression Test" for the SLWT program. The BOSOR analysis has also been correlated to the LH2 STA and ISTA verification tests (MMC-ET-TM03-0, Vol. I and III).

Based on the BOSOR analysis results, the LO2 acreage TPS radius of curvature requirement is 200 in. and 160 in. for limit and ultimate design loads, respectively. The most critical requirement on the LWT LO2 tank occurs on the barrel membrane where the substrate strain is 0.0036 in./in. Radius cryoflex testing combines substrate strain with maximum cryogenic thermal gradient.

Based upon the above information, the design substrate bending actual requirements and derived requirements are adequate and correct. Critical analysis results are summarized in Table 7.2.1.8.1.2.6-1.

Table 7.2.1.8.1.2.6-1. Summary of Acreage Stress Analysis Parameters

Primary Failure Modes			Delamination				O/F Cracking		Bond Adhesion				Factor of Safety is based on:	Minimum Test Demonstrated / Analytical Factor of Safety	Test Report Reference, Stress Report Reference, or Test Data
Analysis Inputs		TPS t	Gradient ΔT	Shrinkage αΔT	Modulus E	Strain ε	Substrate Bending	O/F ε	Substrate Temp.	Press. ΔP	Vac.	Accel. "G"s			
Derived Requirements		(Thick/Thin) (in.)	Total Moment (in.-lbs.)			Strain (in./in.)	Radius (in.)	Strain (in./in.)	Cell Pressure (psi)				1		
LO2 Fwd Ogive	Flight Requirement	3.50		49.0		<0.0036	Infinite	N/A		23.6 (17.2 @ 80 secs)					826-2188
	Wide Panel Test	3.50		54.8		3 N/A	Infinite						Mom	1.12	826-3000-07
	Radius Cryoflex Test	3.50		100.2		0.0054	500						Sub ε	1.50	TPS-0466-96
	Bond Tension Test									30.0			ΔP	1.27	STP-1535
LO2 Aft Ogive	Flight Requirement	2.40/1.05		29.2 / 5.9		0.0036	>200	0.0125		19.2 (15.2 @ 80 secs)					826-2188
	C/E "1a"	1.80		3 N/A		0.0064	Infinite						Sub ε	1.77	826-3000-10
	Wide Panel Test	3.50		54.8		3 N/A	Infinite						Mom	1.88	826-3000-07
	Radius Cryoflex Test	1.82		40.8		0.0066	100						Mom	1.40	TPS-2112-96
	Flexstrain Test	1.87						0.0240					O/F ε	1.92	TPS-0001-98
	Bond Tension Test									30.0			ΔP	1.56	STP-1535
LO2 Barrel	Flight Requirement	1.15/1.05		7.6 / 5.9		0.0036	200	0.0067		15.9					826-2188
	C/E "1a"	1.80		23.6		0.0064	Infinite						Sub ε	1.77	826-3000-10
	Radius Cryoflex Test	1.90		40.8		0.0066	100						Sub ε	1.84	TPS-2112-96
	Radius Cryoflex Test	1.32		26.1		0.0066	50						Sub ε	1.84	TPS-2112-96
	Flexstrain Test	1.87						0.0240					O/F ε	3.57	TPS-0001-98
	Bond Tension Test									30.0			ΔP	1.89	STP-1535
Intertank	Flight Requirement	1.80		12.0		0.0022	1976	0.0010		19.7 (15.4 (@ 80 secs)					826-2188
	C/E "1a"	1.80		23.6		0.0064	Infinite						Mom	1.97	826-3000-10
	Flexstrain Test	1.87						0.0240					O/F ε	2 24.96	TPS-0001-98
	Bond Tension Test									30.0			ΔP	1.52	STP-1535
LH2 Tank Barrel	Flight Requirement	1.77/1.01		20.9 / 6.0		0.0033	600	0.0030		16.3 (15.5 (@ 80 secs)					826-2188
	C/E "1a"	1.80		23.6		0.0064	Infinite						Mom	1.13	826-3000-10
	Radius Cryoflex Test	1.90		40.8		0.0066	100						Mom	1.95	TPS-2112-96
	Radius Cryoflex Test	1.32		26.1		0.0066	50						Mom	1.24	TPS-2112-96
	Flexstrain Test	1.87						0.0240					O/F ε	7.99	TPS-0001-98
	Bond Tension Test									30.0			ΔP	1.84	STP-1535
LO2 Splice Joint	Flight Requirement	1.15					200								826-2188
	LO2 PAL Ramp Test	1.25					160						Rad	1.25	MMC-ET-SE05-549
LH2 Splice Joint	Flight Requirement	1.35					600								826-2188
	LH2 PAL Ramp Test	1.25					480						Rad	1.25	MMC-ET-SE05-549

Notes:
1 **The minimum factor of safety is based on the allowable divided by the flight requirement for the following derived requirement:**
Total Moment = Mom
Substrate Strain = Sub e
Radius of Curvature = Rad
O/F strain = O/F e
Cell pressure = DP
2 **The FS is based on longitudinal bending. Hoop bending produces O/F cracking, is covered in 1.1.1.1.2.1.1.1.2, and is acceptable per "8303" picture book (MMC-ET-SE05-404 Appendix A)**
3 **N/A = Not Applicable. The test was not meant to cover all derived requirements for the TPS for the hardware.**

7.2.1.8.1.2.7 Adequacy of Stress Analysis Methodology

The basic ground rule used for the TPS analysis was to combine the most critical contributors for a given failure mode and to compare the resulting maximum stress, strain, or cell pressure to test data using consistent analytical methods. The primary failure mode for the acreage TPS is bond line delamination. For this failure mode, the analysis does consider the critical environments consisting of thermal gradient, substrate strains (thermal and mechanical), and flexure.

Based on the rationale above, the NCFI 24-124 acreage TPS analysis methodology is adequate for the combination of critical ‘design’ environments.

7.2.1.8.1.2.8 Findings

The conclusion reached through analysis of the NCFI branch of the FT was that this TPS material, and specifically the acreage ET structures, could not have been a cause or contributor to the TPS Debris associated with STS-107. The design, vendor, MAF, and KSC blocks were all “green”.

7.2.1.8.2 PDL-1034 Fault Tree Blocks Summary (Fault Tree Branch 1.1.1.3)

7.2.1.8.2.1 Background

Urethane closed cell rigid foams are used for applications that do not require high temperature materials. As with NCFI, these are two-part liquid systems. BX-250, BX-265, and SS-1171 are materials that have a short work time and are suitable for spray-pour operations with automatic mix equipment. PDL-1034 is a material that has a longer work time (40 sec.) and is suitable for hand pour operations or for filling complex shaped cavities. Both have overall properties similar to NCFI, except that they have limited thermal substrate conditions and have limited ablation capability. The closed-cell foams resist moisture absorption and the elements without significant performance degradation. Basic material properties are shown in Table 7.2.1.4-1, above.

PDL-4034 was the original pour foam selected for the ET. PDL is useful for mold-in-place applications for closeouts, for TPS repairs, and for filling areas that are difficult to which to apply spray foam. The integrity of all ET PDL-4034 pour foam insulation (POFI) applications was questioned upon finding debonds during LO2 feedline flange closeout repair on LWT-27 during May 1986 (CAPS T-055C). A preliminary assessment of all PDL-4034 POFI applications was made by the resulting debris Team, which used flight separation photographs to conclude that the LO2 feedline flange and thrust strut flange closeouts were the only problem applications. A new mold process was developed and during retrofit of ETs, NASA again raised the question of acceptability of all other PDL applications. A Tiger Team was created to perform that assessment.

The Tiger Team was composed of members of Materials Engineering, Design Engineering, Manufacturing Engineering, Quality Engineering, and Advanced Manufacturing Technology (AMT). Their task was to assess the quality of every PDL-4034 closeout in terms of adequacy of process control, process instructions, MPP validation results, and bond adhesion to the appropriate substrates; the objective was to assure that the process was sufficient to meet the void criteria and bond adhesion requirements of the design. Report No. 826-2060-02 details the methodology used to make this assessment, the findings, resulting conclusions, and recommendations. In addition, it will serve as documentation of the validation of all PDL-4034 scheduled closeouts. PDL-1034 was subsequently chosen to replace PDL-4034. The following is a brief chronicle of PDL history:

- Original ET material, PDL 4034, manufactured by PDL
- 1994-Urethane Technologies purchased Polymer Development Laboratories.
- 1995-First lot of UTI PDL-1034 (HCFC 141b) intended for production.
- 1996-Re-certification plan for UTI PDL-1034 created involving NASA and LMMSS
- 1997-Atlanta Facility and PDL-1034 formulation rights awarded to Hess

- 2000-BASF Procures Hess Polyurethane's, Inc.
- 2001-BASF moves production of PDL 1034 to Carrolton, Texas
- 2002-BASF Carrolton Facility conditionally certified pending evaluation of 3 lots.

7.2.1.8.2.1 Receiving Inspection / Shelf Life Storage

Upon receiving shipments from the vendor, the following receiving inspection testing is done per STP-1532:

- Viscosity (A&B)
- Specific Gravity (A&B)
- Amine Equivalent (A)
- Tack-Free Time
- Workmanship (A&B)
- Cream Time
- Water Content (B)
- Hydroxyl Number (B)
- Density
- Hydrochlorofluorocarbon (HCFC) Content (B)
- Tensile Strength
- Compressive Strength
- Rise Time
- Thermal Conductivity
- Flammability
- Hydrolytic Stability
- Coefficient of Expansion.

A review of each item was performed. Results were documented in FT block closures. Table 7.2.1.8.2.1-1 provides a matrix of the specimens tested in the qualification of PDL-1034. Table 7.2.1.8.2.1-2 summarizes the PDL-1034 analysis inputs, derived requirements, and verification results.

Table 7.2.1.8.2.1-1. PDL-1034 Qualification Specimens

Test Description:	-423°F	-320°F	RT	+200°F	Total
Bond Tension	60	60	60	60	240
Flatwise Tension	24	29	49	24	126
Density/Compression			4		4
Plug Pull			17		17
Cryoflex @ 1.5"	4	48			52
Monostrain	12		12	20	44
Torsion Shear	6		6	6	18
Poisson's Ratio	6		6	6	18
Wide Panels	1 repair				1 repair
Combined Environments	1 repair				1 repair
Hot Gas	25				25
Wind Tunnel	9				9

Table 7.2.1.8.2.1-2. PDL-1034 Analysis Inputs, Derived Requirements, and Verification

Primary Failure Modes		All	Delamination	Bond Adhesion				Factor of	Minimum Test	Test Report
Analysis Inputs		TPS t	Strain e	Substrate Temperature	Pressure ΔP	Vacuum	Acceleration "G"s	Safety is	Demonstrated Factor	Number / LMMSS
Derived Requirements		in.	Strain in./in.	min/max	psi		psi	based on: 1	of Safety	Dwg. Number
Bipod Fitting	Flight Requirement	0.50	0.0043		19.1					826-2188
Spindle INC718	Monostrain Test	0.38	0.0069					Sub ε	1.60	826-2188
	Bond Tension Test	2.00						ΔP	1.42	826-2188
LH2 & LO2	Flight Requirement	2.50	0.0006		23.1					826-2188
Intertank Flanges	Monostrain Test	0.38	0.0069					Sub ε	11.50	826-2188
Closeout	Radius Cryoflex Test	2.00	0.00542					Sub ε	9.03	TPS-3038-95
	Bond Tension Test	2.00			27.2			ΔP	1.18	826-2188
Bipod Fitting	Flight Requirement	0.54	0.00135		18.7					826-2188
Base Plate	C/E "1a"	1.80	0.0059					Sub ε	4.37	826-3000-10
	Monostrain Test	0.38	0.0069					Sub ε	5.11	826-2188
	Bond Tension Test	2.00			27.2			ΔP	1.45	826-2188
LO2 Tank /	Flight Requirement	7.00			23.2					826-2188
I/T Pal Ramp	Bond Tension Test	2.00			27.2			ΔP	1.17	826-2188
Closeout										
LO2 Ogive &	Flight Requirement	1.90	0.0048		19.7					826-2188
Barrel	C/E "1a"	1.80	0.00587					Sub ε	1.22	826-3000-10
Closeout	Monostrain Test	0.38	0.0069					Sub ε	1.44	826-2188
	Bond Tension Test	2.00			27.2			ΔP	1.38	826-2188
	Radius Cryoflex Test	1.54	0.0075					Sub ε	1.56	TPS-3260-95
P/L & C/T	Flight Requirement	0.50	0.00496		18.7					826-2188
Support Bracket	Monostrain Test	0.38	0.0069					Sub ε	1.39	826-2188
	Bond Tension Test	2.00			27.2			ΔP	1.45	826-2188
Ice Frost Ramps	Flight Requirement	5.50			30.97					826-2188
	Bond Tension Test	2.00			35			ΔP	1.13	STP 1532

Notes:

1 **The minimum factor of safety is based on the following derived requirement:**
Substrate Strain = Sub ε
Cell pressure = ΔP
Shear stress= τ

7.2.1.8.2.2 Findings

The current TPS material testing, analysis methodology, and verification adequately addresses the combination of critical design environments for PDL–1034.

7.2.1.8.3 BX-250 Fault Tree Blocks Summary (Fault Tree Branch 1.1.1.4)

7.2.1.8.3.1 Background

BX-250 was the primary SOFI material identified for the ET during the proposal activities. It was essentially supplied by MSFC as a flight-verified material, with proven processing capability from the Saturn program. Early in the ET program, some testing was conducted to expand the database supplied by MSFC for ablation/erosion characteristics in aero-thermal ascent environments, so that analysis techniques could be developed to predict thickness requirements in the relatively severe (compared to Saturn) Shuttle environments. Tests revealed that BX-250 was not appropriate for the majority of the acreage areas of the ET, and alternate, more erosion resistant materials were identified and developed (CPR-421, CPR-488, and NCFI 24-124).

During the development/verification activities for the CPR material, BX-250 was included on most major test articles for closeouts and repairs. These test articles included the mini-tank test series (LH2), a heated 10-ft diameter tank (LH2), and the combined environments panel test series (liquid helium). In most cases, these test configurations for the BX-250 closeouts were not designed to simulate the ET configurations but were representative of the BX-250 applications on the ET. In addition, a wind tunnel test series was conducted in Arnold Engineering Development Center (AEDC) Tunnel A at maximum dynamic pressure to verify that the PDL in the ramp configuration used around cable trays and pressurization line attachments and BX in a ramp configuration representative of the aft SRB cable tray (and by similarity to the bipod ramp) could withstand the aero-loading environments. Combined environments test panels included a panel that represented the BX over SLA closeout on the LH2 tank aft dome apex. Additionally, a combined environments facility calibration panel completely coated with BX was tested to assess the stress distributions on the panels at cryogenic temperatures and loads above yield. Another test developed and implemented for verification of BX applications was the PAL ramp test. This test employs a “plank” coated with the acreage SOFI material (CPR or NCFI) with a full-scale section of a PAL ramp applied (LO2, LH2, and SRB cable tray). The test article is chilled to the appropriate temperature and then “bent” to the appropriate radius in a test fixture to simulate the vehicle design cases.

7.2.1.8.3.2 Receiving Inspection

Upon receiving shipments from the vendor, the following receiving inspection testing is performed per STP-1536:

- Viscosity (A&B)
- Specific Gravity (A&B)
- Amine Equivalent (A)

- Water Content (B)
- Hydroxyl Number (B)
- Acid Number (B)
- Density (Free Foam)
- HCFC Content (B)
- Tensile Strength
- Density (Sprayed Foam) Compressive Strength
- Tack-Free Time
- Workmanship (A&B)
- Cream Time
- Rise Time
- Thermal Conductivity
- Flammability
- Hydrolytic Stability.

7.2.1.8.3.3 Acceptance Testing

Each BX-250 spray application must meet acceptance criteria per STP-1536, which provides processing parameters for BX-250, density criteria, and a minimum room temperature acceptance value of 35 psi for tensile strength. For each application, plug pulls, core holes where applicable, and densities are evaluated against the acceptance criteria. These physical and mechanical properties link the spray application for each tank back to the material property database.

Table 7.2.1.8.3.3-1 summarizes the BX-250 analysis inputs, derived requirements and verification results. The detailed review of the bipod area is included in Volume III.

Table 7.2.1.8.3.3-1. BX-250 Analysis Inputs, Derived Requirements, and Verification

LMMSS Drawing Number (* = 809)	W.B.S Fault Tree Block	Primary Failure Modes / Analysis Inputs / Derived Requirements		TPS t (in.)	Delamination: Gradient ΔT, Shrinkage αΔT, Modulus E → Total Moment (in.-lbs.)	Delamination: Strain ε → Strain (in./in.)	O/F Cracking: Substrate Bending → Radius (in.)	Shear: Airload σ → Stress (psi)	Bond Adhesion: Substrate Temp., Press. ΔP, Vac. "G"s, Accel. → Cell Pressure (psi)	Factor of Safety is based on: (2)	Minimum Test Demonstrated / Analytical Factor of Safety	Test Report Reference, Stress Report Reference, or Test Data
*71008434-090	1.1.1.4.1	Bipod Ramp (1)	Flight Requirement LO2 PAL Ramp Shear Test Bond Tension Test	11.70 8.25	461.6 1269.0	Negligible N/A	Negligible 160	13.2 17.5	< 23.1 (21.3 @ 80 seconds) 35	Mom τ ΔP	2.75 1.32 1.52	826-2188 MMC-ET-SE05-549 826-2188 826-2188
*71008422-509	1.1.1.4.6	LO2 PAL Ramp	Flight Requirement LO2 PAL Ramp Test Shear Test Bond Tension Test	8.25 8.25			200 160	7.2 17.5	< 23.1 (21.3 @ 80 seconds) 35	Rad τ ΔP	1.25 2.43 1.52	826-2188 MMC-ET-SE05-549 826-2188 826-2188
*71118414-509	1.1.1.4.3	LO2 Flange C/O	Flight Requirement Cryoflex Test Bond Tension Test	4.00 2.70	37.5 202.5	<0.0006 0.0074	Negligible 50		< 23.1 (21.3 @ 80 seconds) 35	Mom ΔP	5.40 1.52	826-2188 TPS-0260-97 826-2188
*71018424-519	1.1.1.4.2	LH2 Flange C/O	Flight Requirement Cryoflex Test Bond Tension Test	3.25 2.70	39.7 202.5	0.0006 0.0074	Negligible 50		< 23.1 (21.3 @ 80 seconds) 35	Mom ΔP	5.10 1.52	826-2188 TPS-0260-97 826-2188
*71008428-019	1.1.1.4.5	LO2 Feedline Supports	Flight Requirement Widepanel "2" Bond Tension Test	1.25 2.10		0.0048 0.0064			< 23.1 (21.3 @ 80 seconds) 35	Sub ε ΔP	1.33 1.52	826-2188 826-3000-07 826-2188
*73018416-509	1.1.1.4.4	I/T TPS Wedges	Flight Requirement Widepanel "2" Bond Tension Test	1.88 2.10		0.0022 0.0064			< 23.1 (21.3 @ 80 seconds) 35	Sub ε ΔP	2.90 1.52	826-2188 826-3000-07 826-2188

Notes: (1) **Addressed in detail in Appendix 1**

(2) **The minimum factor of safety is based on the allowable divided by the flight requirement for the following derived requirement:**
Total Moment = Mom
Substrate Strain = Sub e
Radius of Curvature = Rad
O/F strain = O/F e
Cell pressure = DP
Shear stress= t

7.2.1.8.4 SLA-561 Fault Tree Blocks Summary (Fault Tree Branch 1.1.1.5)

7.2.1.8.4.1 Background

The primary ablator material is molded or sprayed SLA-561 (Figure 7.2.1.8.4.1–1). It is a composite mixture of silicone resins highly filled with cork particles, silica glass eccospheres, silica fibers, and phenolic microballoons that, after fabrication, is bonded onto the prepared structure. Ambient and heat cures, during fabrication, are required to achieve strength. Similar formulations are used to accomplish sprayed parts and to accomplish "hand pack" ambient cure applications. The materials are compatible with cryogenic stressed structure (within design constraints).

The SLA strength requirements were established during ablator qualification on ET-1. The strength and density requirements are documented in STPs 1506, 1508, 1509, 1510 and 1522, which control SLA processing. All SLA raw materials must meet receiving inspection material property test requirements to ensure that SLA finished product strength and density are achieved. Each and every completed SLA batch is tested to verify strength and density via testing on the production part and/or its associated process witness panel.

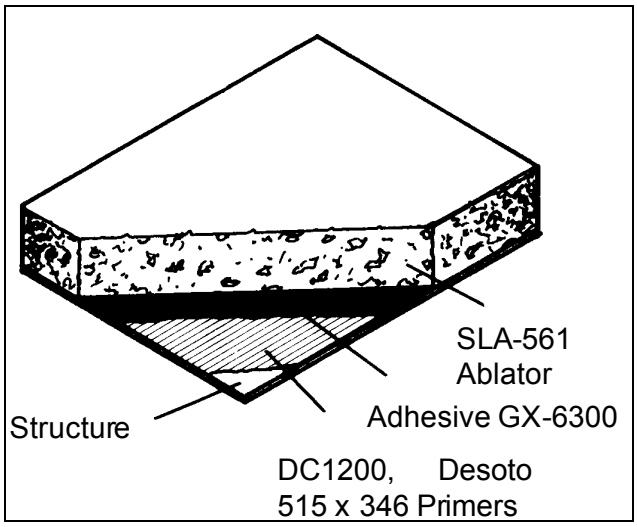


Figure 7.2.1.8.4.1–1. SLA-561

The rest of the SLA material properties, which were established during ablator qualification and/or requalification for the resin change in 1995, are linked to SLA finished product requirements via the SLA qualification material properties database. All SLA is formulated per the process established during the qualification of SLA. This SLA application process, which was established during the qualification programs, is documented in each STP for lot-to-lot and acceptance testing. This process indirectly verifies the established properties. The process is documented in STP specifications, which controls all SLA processing parameters. The requirements that must be met on each production part and/or its associated process witness panel are summarized below for receiving inspection and ablator testing to verify required homogeneity, tensile strength, and density. [Note: (A) refers to the SLA base mix and (B) refers to the curing agent.]

- Receiving Inspection and Shelf Life Requirements
- Processed Ablator Testing (3 lots of material)
- Color (A & B)
- Bond Tension
- Tensile Strength
- Flatwise Tension
- Elongation
- Monostrain
- Viscosity (A)
- Cryoflex
- Index of Refraction
- Cryogenic Lap Shear
- Gel Time or Mixed

- Torsion Shear
- Viscosity
- Plug Pull
- Haze (A & B)
- Density
- Specific Gravity
- Specific Heat
- Density
- Pot Life
- Shelf Life
- Minimum Cure Temp
- Minimum Cure Time
- Flammability
- SOFI Adhesion
- Poisson's Ratio
- Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA).

7.2.1.8.4.2 Analysis

The TPS critical cases for substrate strain (in plane) for the subsequent parts are listed in Table 7.2.1.8.4.2-1.

The maximum strain exhibited by this group of parts is 0.00496 at 120 °F on the LO2 P/L and C/T brackets. Substrate bending/flexure is minimal and its effects are included in the substrate strain requirement. As previously stated, direct aerodynamic loads are analyzed and considered negligible. Air loads, however, can act in normal and tangential directions, and they are incorporated into the component hardware derived substrate strain requirement.

TDFSs for the most critical SLA-561 parts met the EIS Factor of Safety and are provided in Table 7.2.1.8.4.2-2. The LO2 Pressline/Cable Tray Support experiences the highest substrate strain of all SLA-561 parts.

Table 7.2.1.8.4.2-1. Critical Analysis Cases

Part	Stress Report Section	TPS Thickness	Temperature @max load	Flight Strain
Bipod Fitting	C.4.2.6	0.35	-272	0.0015
Connector Plate	C.4.2.6	0.35	-272	0.0015
Bipod Strut	E.2.5.6	0.52	100	0.0036
GO2 P/L Barry Mounts on LO2 Tank	D.7.15 / E.2.5.7.2	0.64	35	0.00231
CO-cell M, LO2 P/L Brackets Sta 464.34	D.7.1 / E.2.5.7.2	0.34	120	0.00496
LO2 Cable Tray Segment	D.2.1 / E.2.5.7.2	0.6	130	0.00371
LO2 Tank P/L & C/T Support, Sta 371	D.7.1 / E.2.5.7.2	0.5	120	0.00496
Cover Cable Tray	D.2.1 / E.2.5.7.2	0.35	130	0.00367
LO2 Tank C/T Covers & LO2 C/T Tray Fairing	D.2.1 / D.8.2 / E.2.5.7.2	0.63	130	0.00367
Gap Closures - LO2 Tank C/T	D.2.1 / E.2.5.7.2	0.63	130	0.00371
LO2 Tank P/L & C/T Support Bracket	D.7.1 / E.2.5.7.2	0.5	120	0.00496
Composite Nose Cone Foam Seal & Blend	D.8.1	2	100	0.00201
GO2 & GH2 P/L Barry Mount Slide Cap	D.7.15 / E.2.5.7.2	0.57	35	0.00231
Fairing - LH2 C/T Fairing - LO2 Feedline	D.8.5 / E.2.5.7.2	0.62	120	0.00396
Fairing - LO2 Tank Cable Tray	D.8.2 / E.2.5.7.2	0.6	120	0.00396
Yoke LO2 Feedline	C.4.2.6.7	0.4	100	0.00228

Table 7.2.1.8.4.2-2. SLA-561 Analysis Inputs, Derived Requirements, and Verification

Primary Failure Modes		All	Delamination			Bond Adhesion			Factor of Safety is based on: 2	Minimum Test Demonstrated Factor of Safety	Test Report Number / LMMSS Dwg. Number
Analysis Inputs		TPS t	Gradient ΔT	Shrinkage αΔT	Modulus E	Strain ε	Substrate Temperature min/max	Pressure ΔP psi	Vacuum Acceleration "G"s psi			
Derived Requirements		in.	Total Moment in lbs			Strain in./in.						
1 Bipod Fitting & Connector Plate	Flight Requirement	0.35	3	2742.0		0.0015	-423 / 188		1.95			826-2188
	Monostrain Test	0.38				0.0068	-320			Sub ε	4.54	826-2188
	Cryoflex Test	0.60		89.6		0.0047	-320			Sub ε	3.14	3077-B
	Bond Tension Test	2.00					200		46	ΔP	23.59	826-2188
	Plug Pull Test	0.52					70		15	ΔP	7.69	STP 1522
	C E "1a"	0.20		48.9		0.0051	-423			Sub ε	3.41	826-2188
Bipod Strut	Flight Requirement	0.52				0.00357	70 / 380		2.78			826-2188
	Monostrain Test	0.38				0.0264	70			Sub ε	7.39	826-2188
	Cryoflex Test	0.60				0.0047	-320			Sub ε	1.32	3077-B
	Bond Tension Test	2.00					300		34	ΔP	12.23	826-2188
	Plug Pull Test	0.52					70		15	ΔP	5.40	STP 1509
LO2 Pressline & Cable Tray Support	Flight Requirement	0.50				0.0050	120		1.95			826-2188
	Monostrain Test	0.38				0.0264	70			Sub ε	5.32	826-2188
	Bond Tension Test	2.00					200		46	ΔP	23.59	826-2188
	Plug Pull Test	0.52					70		15	ΔP	7.69	STP 1506
GO2 Pressline Barry Mounts	Flight Requirement	0.50	3	25.3		0.0023	35		1.95			826-2188
	Monostrain Test	0.38				0.0264	70			Sub ε	11.43	826-2188
	Bond Tension Test	2.00					200		46	ΔP	23.59	826-2188
	Cryoflex Test	0.60		89.6		0.0047	-320			Sub ε	2.03	3077-B
	Plug Pull Test	0.52					70		15	ΔP	7.69	STP 1506

Notes:

1 **Addressed in detail in Appendix 1**

2 **The minimum factor of safety is based on the following derived requirement:**
Total Moment = Mom
Substrate Strain = Sub e
Radius of Curvature = Rad
O/F strain = O/F e
Cell pressure = DP
Shear stress= t

3 **Not Applicable. This is for engineering information only. The bond line delamination analysis methodology is used for acreage TPS applications. The handpack SLA 561 application on the bipod fitting heater wire and barry mounts is assessed for substrate strain and bond adhesion. The bond line delamination failure mode is not applicable for this local application. In addition, this SLA application is serrated and encapsulated in BX-250 foam.**

7.2.1.8.4.3 Findings

SLA-561 TPS testing, analysis, and verification adequately address the combination of critical design environments with exception to the bipod fitting application.

7.2.1.8.5 SS-1171 Fault Tree Blocks Summary (Fault Tree Branch 1.1.1.7)

7.2.1.8.5.1 Background

SS-1171 was initially tested and selected for potential replacement of BX-250. The chemical, physical, and mechanical properties are similar between SS and BX, and the materials are considered interchangeable on the ET. SS-1171/141b Phase III requalification was accelerated in March 1994. This acceleration was related to the fact that BX-250 with 141b in the formulation yielded inconsistent data and could not perform per the engineering requirements. Data obtained in Phase II formulation optimization supported the preliminary conclusion that SS-1171 / 141b was a viable foam replacement for BX-250. Phase III requalification initiated in mid Fiscal Year (FY) 1994 and FY 1995 continued to yield promising data. Five lots of material were sprayed in the TPS Engineering Spray Booth at various room temperatures, substrate temperatures, and percent relative humidity. Results were analyzed, and it was concluded that SS–1171/141b chemical, physical, and mechanical properties are comparable to that of BX–250/CFC-11. In 1995, various flight qualification tests, such as thermal acoustic panels, combined environment panels, plasma arc, wind tunnel test, LO2, LH2, and SRB PAL ramp test, were performed. All flight simulation testing and analysis were acceptable and comparable to BX-250.

7.2.1.8.5.2 Receiving Inspection/Shelf Life Storage

Upon receiving shipments from the vendor, the following receiving inspection testing is performed per STP-1536.

- Viscosity (A&B)
- Specific Gravity (A&B)
- Amine Equivalent (A)
- Water Content (B)
- Hydroxyl Number (B)
- Acid Number (B)
- Density (Free Foam)
- HCFC Content (B)
- Tensile Strength
- Density (Sprayed Foam)
- Compressive Strength
- Tack-Free Time

- Workmanship (A&B)
- Cream Time
- Rise Time
- Thermal Conductivity
- Flammability
- Hydrolytic Stability

7.2.1.8.5.3 Acceptance Testing

Each SS-1171 spray application must meet acceptance criteria per STP-1536 (shown in Table 7.2.1.8.5.3-1), which provides processing parameters for SS-1171, density criteria, and a minimum room temperature acceptance value of 35 psi for tensile strength. For each application, plug pulls, core holes where applicable, and densities are evaluated against the acceptance criteria. These physical and mechanical properties link the spray application for each tank back to the material property database.

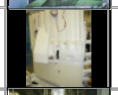
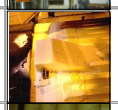
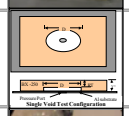
Table 7.2.1.8.5.3-1. SS-1171 Qualification Specimens (Ref. MMC-ET-SE05-549)

Test Description:	-423°F	-320°F	RT	+200°F	TOTAL (Each Lot1to2) (All Nominal Spray Conditions)	TOTAL (EachLot 3to5) (All Nominal Spray Conditions)	TOTAL (EachLot 6to7) (All Nominal Spray Conditions)	TOTAL (All Lots) (All Nominal Spray Conditions)
Bond Tension	1000	1000	1000	1000	4,000	1,536	1,920	16,448
Flatwise Tension	1000	1000	1000	1000	4,000	1,056	1,920	15,008
Density/Compression			300		300	264	288	1,968
Plug Pull			124					124
Cryoflex @ 1.5"	150				150	150	150	1,050
Monostrain	64	14	36	32	146	146	146	1,022
Torsion Shear								50
Wide Panels	1							1
Combined Environments	2							2
PAL Ramp	3							3
Hot Gas	25							25
Plasma Arc	19							19
Wind Tunnel	36							36

7.2.1.9 Summary of Tests

Tests that were performed in support of this investigation are summarized in Table 7.2.1.9-1. Test reports are included in Volume III.

Table 7.2.1.9-1. Test Summary

		Test Objectives	Conclusions
Tile Damage Test Support (including BX 250 Impact Characterization)		Provide ongoing ET interface and credible ET debris size inputs to Orbiter tile impact testing. Determine crush characteristics of BX 250 under cryo and vacuum.	Preferred BX 250 Failure Mode is internal cell crushing over spalling or divoting. Vacuum does not change impact failure modes. Colder specimens fail in more brittle manner.
Bipod Thermal/ Vacuum/ Cryogenic Test		Simulated bipod configuration with cryogenic backface, simulated ascent skin temperatures, and ascent pressure profile to characterize TPS debris generation.	Simulated environments on nominal configuration hardware produced no effects.
Foam Loss Secondary Effects Assessment		Static and dynamic coupon tests of BX 250/SLA lay-ups in tension and shear	Tests showed BX-250 failures <= -100 deg F. No failures in SLA for dynamic tests.
Bipod Foam Dissection Test		Perform dissection of ET 120 and ET 94 bipod areas to characterize the subsurface configuration of the as-processed hardware.	Substrate complexity produces characteristic roll-over. Analysis of roll-over voids and at weak knitlines indicate potential for foam loss near machined surfaces.
I/T to LH2 Tank Splice Dissection Test		Perform dissection of ET 120 and ET 94 Intertank to LH2 splice to characterize the subsurface configuration of the as-processed hardware.	Substrate complexity produces characteristic roll-over. Analysis of roll-over voids and at weak knitlines indicate potential for foam loss near machined surfaces.
SLA Data Augmentation Test		Augment existing SLA basic materials database to expand knowledge of cryogenic behavior (LN2 absorption, etc.) to support fault tree closure and engineering analysis.	Additional data consistent with historic database and analytical projections
SLA Data Base		Designed experiments of type I and II SLA to characterize effects of mixing, packing, lay-up, moisture and conditioning and interaction with BX250	SLA processing is sensitive. Multiple complex contributors to cracking exist.
Cryopumping / Cryoingestion Fundamental Data Test		Perform test series for collection of fundamental cryopumping and cryoingestion data to support fault tree closure and engineering analysis	Cryoingestion not accomplishable due to SLA back-pressure. Forced LN2 in SLA produced cracking (not divots) in 100% of tests (consistent with hardware observations).
Thermal/ Mechanical/ Vacuum Bipod Configuration Test		Perform test of simulated bipod configuration to include structural loads, cryogenic conditioning, and ascent skin temperatures	Data will be used to confirm scenario hypothesis and provide data and test bed for return-to-flight.
Thermal/Bending/ Vacuum Bipod & Flange Tests (incl. Simulated Defects)		Perform thermal and mechanical tests of bipod configuration using bending to simulate structural loads. Cryogenic conditioning and ascent temperature profiles.	Data will be used to confirm scenario hypothesis and provide data and test bed for return-to-flight.
Defect/Pressurization Tests		Evaluate BX-250 SOFI sensitivity to the presence of subsurface voids under internal pressure loading and cryogenic environments	Interval void/delamination depth is inversely proportional to likelihood of divot formation.
Moisture Tests		Determine water absorption characteristics of BX 250	Foam does not absorb moisture. Optimized freezing conditions for water may produce a layer of ice 0.004 in thick at exactly 32 def F at the liquid/solid interface.
Crush Test		Determine depth of crushed BX 250 below visible damage due to compression loading.	Foam crushes to 30-40% max below visible deformation.

7.2.1.10 Recommendations

Observations have been organized into three general categories: Manufacturing, Design, and Material. Within each category, several issues or concerns have been identified and should be assessed as a follow-on activity to the investigation.

First and foremost of the observations noted was the need for a thorough review of procedures for training and certification. In particular, the manual spray applications appear to be without the formalized attention inherently required for these processes, and they are in need of training requirements that extend beyond normal TPS processing.

1. Special certifications need to be assessed for those manual spray configurations that are in the ET Critical Debris Zone or for which the size/location is such that liberation of TPS debris could lead to a potentially catastrophic event. The configurations for which special certifications need to be closely assessed are, as a minimum, the LO2 and LH2 PAL ramps, the intertank/LH2 tank flange closeout, the intertank/LO2 tank flange closeout, the longerons, and the aft dome apex closeout.
2. Enhancements to training are required, *i.e.,* mock-up sprays and dissections, length of certification before renewal, and on-the-job training. The use of mock-ups and dissections should be assessed for all TPS applications and instituted as appropriate. No sprays on flight hardware should be allowed without acceptable passing results on mock-ups. The logic for length of time that a certification is valid needs to be re-evaluated; for example, a renewal for a plug pull certification occurs on a 1-year basis, while the TPS spray certification is good for 2 years. Certification retention needs to be tied to performing a TPS spray on flight hardware on a regulated time interval and said spray passing inspection. An individual's service in an OJT capacity needs to be monitored and potentially revoked if certification is not achieved within a specified period of time. A mechanism for transferring best practices from production back to the classroom must be initiated. Finally, TPS material or equipment changes must be introduced into the classroom and an assessment must be performed to determine whether the changes are significant enough to necessitate the recertification of affected individuals.
3. The project should assess implementation of a more active system to document training status for those people requiring certification. Notification of lapsed certifications should be more proactive and visible, *i.e.,* Compliance Training, with notification to the employee, employee's supervisor, the Director of ET Production, and the Director of Safety and Quality Assurance. This visibility must exist as a minimum for TPS and, incidentally, welding, and other areas should be assessed for applicability.

Attention must also be focused on MPP steps requiring documentation, stamps, stamp warranty, and acceptance testing. Specific issues with these topics need to be assessed, reviewed, and addressed. The manual spray applications appear to be without the formalized attention inherently required for these processes. The manual applications are certainly more process related and complicated and in need of training requirements that extend beyond normal TPS activities.

1. Engineering should reassess those steps in an STP (PPD) that must be stamped by Engineering and/or Quality as critical steps within a MPP. Such

steps include, but are not limited to, spray overlap times and not initiating the spray on the part.

2. Engineering should also review the STPs and add those steps that need to be recorded within the MPPs, *i.e.,* separate lines for the stamp of the individual(s) actually performing the spray operation and the individual operating the equipment, the identification number of the formulator used for a spray operation, and the ratio of the A and B components before and after the spray.
3. Quality should reassess the proper use of stamps to buy off MPP steps. In particular, the practice must be reassessed by which a supervisor, who has not undergone the same level of training as a subordinate, stamps off the associated work. Stamps represent the acceptance of flight-quality workmanship, and their use must reflect the importance that they carry.
4. Quality should consider the revocation of stamps for those individuals with lapsed certifications or other options that guarantee that only currently certified individuals perform tasks requiring certification.
5. Production and Quality have responded in a very positive manner with respect to contamination control. This topic should be monitored on a continuing basis and significant issues reported to the Program Manager.
6. Engineering should reassess all aspects of acceptance tests. This review should include as a minimum the procedures for curing and testing TPS and witness panels. TPS that is part of the acceptance testing must not only be from the same material lot as the flight article but must be sprayed and cured under the same conditions as the flight article and have configuration characteristics, *i.e.,* thickness, similar to that of the flight part. The rationale and continued applicability of performing early testing, *i.e.,* 24 hr versus 48 hr for SLA, needs to be re-evaluated. Engineering should also continue assessment of NDE systems to locate internal voids and defects based on the recommendations of the TPS Verification Team.
7. The practice of IPRAs should be reviewed. There should be consistency across the production flow with respect to the use of Standard Repair Instructions. Engineering should review those repairs that can be performed as an IPRA, the logic flow that defines if they remain appropriate, and the sequence for transitioning to an NCD. Finally, a mechanism must be established that requires Engineering to participate in the solution for recurring IPRAs.
8. Production should develop a mechanism to enhance the data recorded within the MPPs and adherence to the statements within the MPPs. Several issues were documented, *i.e.,* incorrect times recorded, incorrect material lot codes. Several instances were also identified, particularly for SLA, where one or more constituents were outside the allowance tolerances. There also appeared to be instances where batch sizes not approved by STP were

prepared. Although this might prevent waste for small applications, it is a violation and must be avoided.

TPS design should also be reassessed. Issues identified within the FT with respect to design included inadequate verification. This was related, in large part, to the fact that verification/validation sprays did not identify the potential issues associated with the bipod ramp. These issues included the voids, rollovers, and thermal cracks that could exist and that were identified during the dissections of this area that were part of the Investigation. Another inadequacy that was identified was the insufficient testing to address possible failure mechanisms, such as the defects identified during the dissections. Finally, the fact that the design did not preclude the possibility of cryopumping is another issue.

1. Engineering should reassess the TPS verification. Initial focus should be directed toward those higher risk items, specifically manual spray operations located within the Critical Debris Zone. This task will verify that every failure mode is addressed by sufficient rationale for each TPS configuration.
2. One specific and important deliverable that should be produced by the TPS Verification Team is a matrix of additional testing that is required to preclude the failure modes identified for each TPS configuration. This will include any basic material property, subcomponent, or full-scale verification/validation testing required. Acceptance testing should also be reassessed for potential improvements. Any tasks required to provide “Added Confidence” for existing configurations, such as PAL ramps, should also be recommended. Finally, Engineering should continue assessment of NDE systems to locate internal voids and defects.
3. The intertank/LH2 flange closeout should be assessed for Return to Flight, including a longer term redesign to a ”smooth intertank,” which would encompass the flange closeout and a smooth LO2 tank. The smooth LO2 tank should be the first area of focus.

Finally, attention must also focus on the TPS material. Specific issues should be addressed. The manual spray applications appear to lack the special attention inherently required for these processes. The manual applications are certainly more process related and complicated and, as stated above, are in need of training requirements that extend beyond normal TPS activities.

1. Engineering should reassess several issues. First, there is the definition and criteria for shelf life. Current requirements allow for the vendor to manufacture the TPS products 90 days before shipment. Once received at LM, the vendor guarantees the product for 6 months and typically two extensions of 3 months each are allowed with the completion of designated testing. A reassessment is needed to consider changes, such as the vendor’s simply guaranteeing the products for 9 months from the date of manufacture and eliminating allowance of extensions.

2. Receiving and acceptance testing needs to be reviewed from several perspectives. With respect to the laboratory equipment, the equipment should be calibrated against standards, and the tolerances for each measurement should be documented. An understanding of each component in a given material should be developed, including the upper and lower compositional limits. Material Data Analysis Team (MDAT) review times should be assessed so that trending data can be assessed and actions can be initiated in a timely manner. An assessment should be performed with respect to the leadership of the MDAT; it appears that Material Sciences should guide the task, and the membership should include the cognizant engineers associated with the systems. One objective of this group should be to make the "technicians" aware of the material trends and to gain their participation in the trending analysis.
3. The end users of material property test data, such as recession and thermal conductivity, should have access to the raw data. The Material Sciences group should verify the test setup and the subsequent testing procedures, but the cognizant engineers for the material system and the properties that are being evaluated should have access to the raw data and the data reduction process.
4. Engineering should continue to work closely with the vendors to understand all changes that could potentially alter the performance of TPS materials, with the objective of keeping current the receiving and acceptance testing protocols. Although the date of manufacture is known, blending at the vendor's should be assessed, including the time of manufacture for the base constituents. Since the TPS materials are not a large part of any vendor's business base, NASA must explore all avenues that could result in any enhancements to the material capabilities.
5. Engineering should resolve discrepancies that exist within the shop paperwork. While the STM calls for controlling the temperature of the TPS materials to 50 °F to 70 °F, the STP allows production to store the material at high as 85 °F upon release to the floor. The documentation should be made consistent and should incorporate reasonable and realistic exposure times and temperatures. This situation appears to exist for all foam systems, although the potential exposure times vary greatly for each.
6. Engineering should also complete an assessment of the additional testing or verification that is required to support a change in the Safety Factor requirement for TPS. The EIS currently calls out a requirement of 1.10. The testing that is currently performed has substantiated the use of higher safety factors. An assessment assuming a required Safety Factor of 1.40 should be performed and the issues identified. The use of a Safety Factor of 1.25 may be acceptable for acreage foam, since it is a more controlled process, but the goal for all TPS should be a Safety Factor of 1.40.

7.2.1.11 Conclusions

An unconservative TPS design and a process that did not account for BX-250 and SLA-561 processing variations in the bipod most probably caused the liberation of major TPS debris from STS-107/ET-93. These findings were limited to the bipod region, based upon ascent photographic coverage of STS-107, which indicated an anomalous condition in the bipod region, coupled with historical foam loss records. With respect to STS-107/ET-93, all other TPS materials were without significant findings. In particular, PDL-1034 used in the bipod region was found to be a non-credible initiator or source of debris, based on volume used and its proven performance in combined environment and aerodynamics testing.

As-built data for each of the TPS materials indicated that the final product was built in accordance with engineering specifications. All nonconformances were either returned to engineering configuration or otherwise properly dispositioned by the Engineering organization. Extensive analysis and testing, including full-scale testing of flight configuration bipod hardware, revealed that nominally built hardware should perform nominally, even in the case of out-of-family induced environments. That testing and analysis also provided, however, sufficient insight to conclude that the release of debris from STS-107/ET-93 was caused by a combination of worst-case effects, attributable to the following root causes.

7.2.1.11.1 BX-250

- Design Methodology: The potential for cryopumping and/or cryoingestion, the presence of subsurface defects, and the fact that these phenomena are not addressed by verification and validation testing resulted in identifying “Inadequate Design Methodology” as a possible/remote cause or contributor to the release of debris from STS-107/ET-93.
- MAF Processing Plan: The manufacturing paperwork and the associated checks and controls on the material and processing parameters were not sufficient to provide assurance that the as-built configuration would satisfy nominal engineering requirements. This included Quality Control buy-off stamps of critical operations, which were not required, and possibly not practical, which made it impossible to confirm the absence of subsurface defects, as revealed by dissection of flight assets. An optimized manual spray technique with enhanced operator training might have controlled the number and size of these features, but the Processing Plan required neither. These factors led to identifying “Inadequate MAF Processing Plan” as a possible/remote contributor.
- Acceptance Testing: The acceptance testing was not sufficient to determine whether the as-built material properties and/or the internal configuration were sufficient to satisfy flight requirements. Verification of material properties is performed on a “witness” specimen, utilizing material that will subsequently be machined away and discarded; the flight ramp material is not tested. Dissection and subsequent testing of ET-94 bipod ramp material revealed

the possibility of out-of-family mechanical properties, as well as internal features such as voids and "rollovers." Although the actual number, size, or location of such features on ET–93/STS-107 can not be determined, testing of specimens containing defects showed clearly that identifying and properly dispositioning them, utilizing a suitable NDE technique, would have improved the performance of the foam closeout. These factors led to identifying "Inadequate Acceptance Testing" as a possible/remote contributor.

- Undetected Anomaly: Notwithstanding the preceding findings, material properties and non-destructive testing are inherently probabilistic in nature. For that reason, the possibility of an "Undetected Anomaly" had to be identified as a possible/remote contributor.

7.2.1.11.2 SLA-561

- Design Methodology: There existed a potential for a high-energy release of debris related to cryopumping and cryoingestion, with SLA-561 serving as a reservoir or a path, respectively. There was also a possibility of SLA-561 being entrained with foam debris if the temperature at the interface exceeded –100 °F. These factors led to the identification of "Design Methodology" as a possible/remote contributor.
- Undetected Anomaly: In the absence of the high-energy release mechanisms or the temperature-related entrainment of SLA-561 within foam debris, there still existed the possibility of a (secondary) loss of debris because of undetected cracks or low-strength material within the SLA-561. For that reason, the possibility of an "Undetected Anomaly" had to be identified as a possible/remote contributor.

7.2.2 Non-TPS Debris Branch

7.2.2.1 Summary

The Non-TPS Debris branch generally investigated all possible debris sources other than those directly attributable to the TPS. In executing this investigation, there was some overlap with the activities of the team managing the other FT debris branch, TPS Debris, and with the team managing the Interfaces branch. This overlap will be described as appropriate in the following sections.

Upon conclusion of a detailed review, the Non-TPS Debris Team identified two items as possible debris sources:

- Ice: which has been historically observed during launch. (Acceptable ice conditions were noted on STS-107, however.) (WBS 1.1.2.13.2)
- Non-TPS debris from interface hardware (WBS 1.1.2.13.5)

Each item was dispositioned by the ETWG and identified as a non-contributor to the *Columbia* accident.

7.2.2.2 Team Charter

The charter of the Non-TPS Debris Team was to support the *Columbia* accident investigation by assessing the likelihood that the External Tank shed any debris other than TPS on STS-107. The team was responsible for ensuring that the Non-TPS Debris branch of the FT was sufficiently developed to adequately investigate all potential debris within this charter.

7.2.2.3 Team Overview

A joint NASA and Lockheed Martin team was assembled to investigate the events of the Non-TPS Debris FT branch. The backgrounds of the members provided the team with necessary expertise in appropriate engineering disciplines, as well as in production, quality assurance, and safety.

Pat Rogers, NASA, and Ashok Prabhakar, Lockheed Martin, led the Non-TPS Debris Investigation Team. Deputy Team Leads were Rob Wingate (NASA) and Camille McConnell (LM). The dedicated NASA S&MA Team lead was Darol Moore.

7.2.2.4 Scope of Review

The Non-TPS Debris branch of the FT investigated all possible sources of debris to the Space Shuttle *Columbia* (OV-102) from the ET (ET-93) other than those directly attributable to the TPS during lift-off and ascent of STS-107. This section of the FT was developed primarily as a component-by-component audit, rather than as a logic-based study of failure events. Components were identified for review based on the CIL Aerodynamically Sensitive Items (ASI)[1], augmented by a separate review of potential non-TPS debris items conducted by the ET Contingency Team during the first week of February 2003. (ASI are those hardware items exposed to the air stream that could be a debris source to the Orbiter should they fail structurally.) Each component or assembly was investigated for debris potential related to design deficiencies, inadequate manufacturing and processing, or mission problems. Other non-TPS debris concerns, such as ice and foreign object debris (FOD), were also included in this FT branch for completeness.

Consistent with the methodology used on all teams, the scope of the investigation into non-TPS ET debris was limited to focus only on debris that could strike the left wing of *Columbia*. The major hardware assemblies that were reviewed are illustrated in Figure 7.2.2.4-1.

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[1] MMC-ET-RA04b-K, Volume IV, Space Shuttle External Tank Critical Items List (CIL) Aerodynamically Sensitive Items (ASI), June 29, 2001 including Change Notice DCN-003, October 18, 2002.

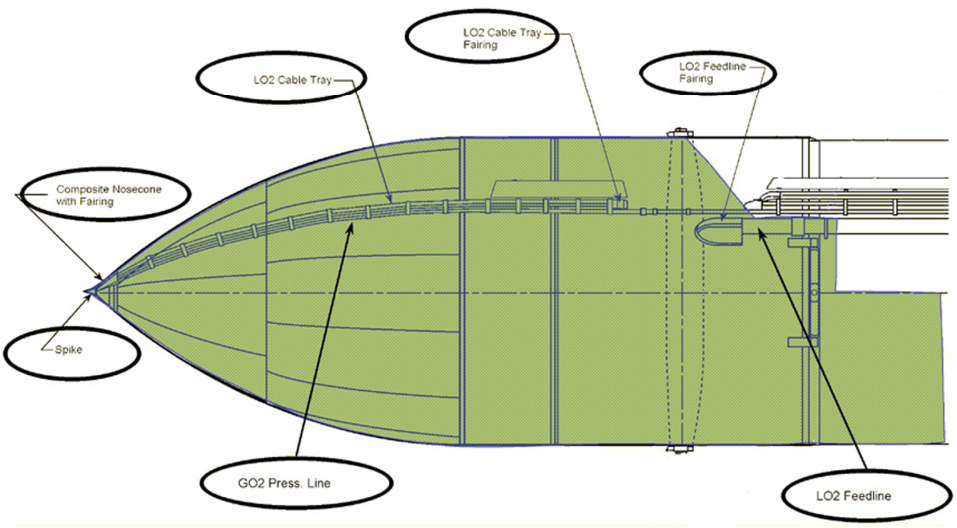

Figure 7.2.2.4-1. Overview of General ET Hardware Investigated in the Non-TPS Debris Fault Tree Branch

The scope of the Non-TPS Debris investigation into substrate structure was limited to address substrate structure not identified on other branches of the ETWG FT.

For hardware within the scope of the Non-TPS Debris branch and which also was covered by TPS, *e.g.,* the feedline fairing, all aspects were considered for the structural design and fabrication, up to and including primer application, but excluding TPS selection, application, or performance. Debris issues directly attributable to the TPS remained under the scope of the TPS Debris branch.

The interface hardware, *e.g.,* the bipod fittings and struts, was included within the scope of the Non-TPS branch; however, the investigation into this hardware for debris potential was conducted by the team working the FT branch dealing with the performance of the ET interfaces. The Interfaces Team documented all findings with respect to debris from interface hardware as part of their disposition of all events in the interfaces branch of the FT. These findings were then cross-referenced to the appropriate event in the Non-TPS Debris branch of the FT.

The possibility of debris caused by the installation of counterfeit or substandard fasteners was investigated as part of a separate review of quality records for all fasteners on ET-93 that, should they have failed, would have created debris to the Orbiter left wing. Information regarding the fastener review, as related to the various ET assemblies, is presented in section 7.2.2.8.1.

7.2.2.5 Non-TPS Debris Branch Fault Tree Structure

Main branches of the Non-TPS Debris section of the FT are shown in Figure 7.2.2.5-1. The fully indentured breakout of the Non-TPS Debris Branch is included in Volume II. The Non-TPS Debris FT section had 498 blocks, of which 343 were "basic event" blocks. This section was developed primarily as a component-by-component audit rather than as a logic-based study of failure events. As such, main branches within this FT section appear more typical of a drawing tree than a traditional FT. Organization of the main branches was heavily influenced by the layout of the ET stress report and a drawing tree 'mind set.'

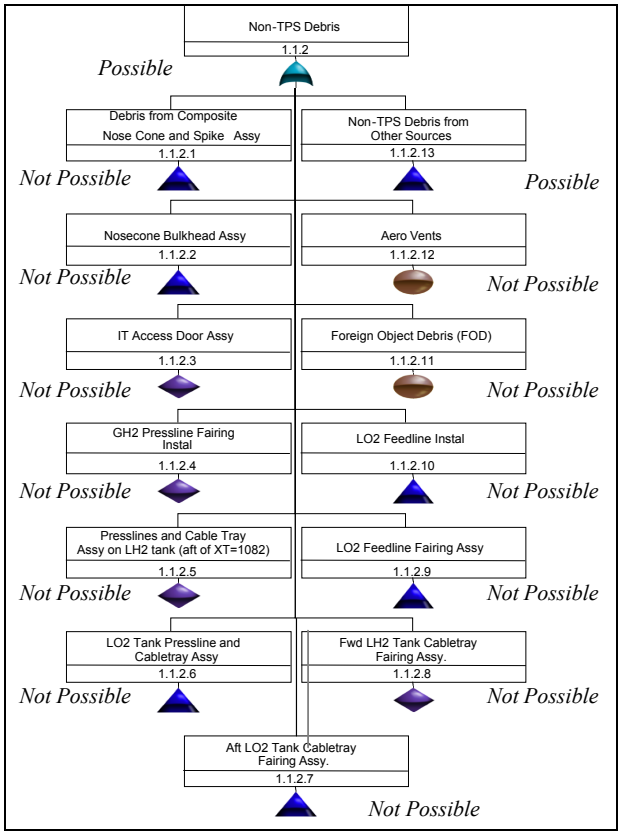

Figure 7.2.2.5-1. Main Branches of the Non-TPS Debris Section of the ETWG STS-107 Fault Tree

7.2.2.6 Evaluation Criteria

As with each other FT branches, there were four possible dispositions for each event in the FT: Possible-Probable, Possible-Remote, Possible-Improbable, or Not Possible. Each basic event in the Non-TPS Debris branch of the FT was assumed to be a cause or contributor to the shedding of debris if the event occurred. Each event was assessed to see if it could have happened, and if so, the event was assessed for the likelihood that it did happen.

The disposition of event blocks was a subjective process. No probabilistic risk assessments or other numerical tools were used to arrive at conclusions. The ETWG established an arbitration board for cases where the branch lead disagreed with the disposition selected by the initiator. The Non-TPS Debris team never had a need to use the arbitration board. It is also important to note that NASA S&MA personnel were in the review/approval cycle for every event disposition and rationale.

The disposition of intermediate event blocks was selected to be the same as the most likely possible contributing event since "or" gates were used to relate all events.

7.2.2.7 Approach

The general process for auditing components for debris potential is illustrated in Figure 7.2.2.7-1. The components identified for investigation in the Non-TPS Debris FT branch are actually hardware assemblies composed of several individual parts. All MAF and vendor build paper, *i.e.,* fabrication records, was reviewed for each part under investigation. For non-serialized parts, multiple data packages for each part from relevant manufacturing dates and production uses were reviewed to assess the hardware installed on ET-93. The build paper review verified that parts were manufactured per drawing requirements using the correct materials, processes, and procedures. Review of all build paper was conducted in accordance with the ground rule that each record be reviewed by both a Lockheed Martin representative and a U.S. Government representative (DCMA and/or NASA S&MA). A review of some fabrication records was not performed if it was the engineering judgment of both Lockheed Martin and NASA that debris potential was not possible because of containment of the parts. Approximately 253 drawings and 228 packages of build paper (MAF and vendor) were reviewed.

Criteria checklists were used to assess the fabrication of each part or assembly. Sufficient evidence of proper manufacture was typically considered to consist of:

- Certification that the correct materials were used (type, grade, and heat treatment), *e.g.,* material certification
- Certificates of Conformance
- Document Accountability Sheets (DASs)
- Acceptance Test Data
- Reference in the build paperwork that the correct steps/instructions were used, including STPs or supplier PIs for forming, heat treat, cleaning, NDE, necessary to meet all drawing requirements.

All NCDs pertinent to ET-93 hardware under investigation were audited for proper disposition. For those hardware items where assessment of primer was required, a separate criteria checklist was used to audit such things as primer type, lot code, shelf life, pot life, cure time, etc.; however, evidence of a

successful wet tape test was considered to be the only necessary criterion. All primer checklists were delivered to the TPS Debris Team for review.

The possibility of debris caused by the installation of counterfeit or substandard fasteners was investigated as part of a separate review of quality records for all fasteners on ET-93 that, should they have failed, would have created debris to the orbiter left wing. Information regarding the fastener review is presented in section 5.4.2.2.8.1. Fasteners are an example of non-serialized parts that required the review of multiple fabrication/receiving records to assess the quality of hardware that could have been installed on ET-93. In four cases, the Non-TPS Debris Team had to expand on the initial fastener review and examine purchasing records to determine if fasteners installed on ET-93 were drawn from purchase lots that the fastener review had identified as having questionable quality.

The SLWT Stress Report was reviewed as necessary to audit the stress analysis. In reviewing the applicable requirements, data and requirements from Level II were considered outside the scope of this investigation. Review of the Lockheed Martin ET Loads Data Book and Thermal Data Book was also considered to be out of the scope of the investigation; however, correct use of this data in the stress report was verified.

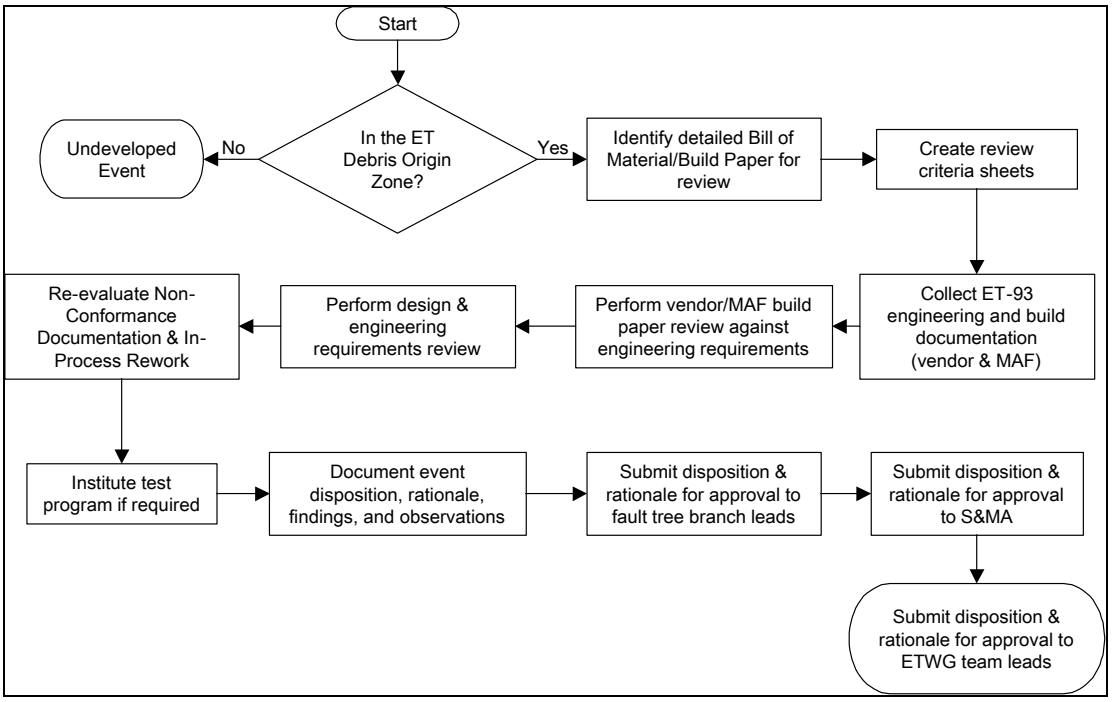

Figure 7.2.2.7-1. Process for Auditing Hardware for Debris Potential

7.2.2.8 Results

7.2.2.8.1 Summary of Findings

It is possible, but improbable, that ET-93 shed non-TPS debris capable of striking the left wing of the Space Shuttle *Columbia* during the lift-off and ascent of STS-107. It is possible, but improbable, that ice or interface hardware was the source of this debris.

No findings pertinent to the *Columbia* accident investigation were found for any other Non-TPS Debris basic events. There were no findings of debris potential for any of the other Non-TPS hardware items audited, including the composite nose cone and spike assembly, the nose cone bulkhead assembly, the LO2 cable tray and pressurization line assembly, the aft LO2 tank cable tray fairing assembly, the LO2 feedline fairing assembly, the LO2 feedline installation, or the aerovents. The disposition and rationale for every event in the FT are documented in the ETWG STS-107 Fault Tree Block Closure database. There were some observations, *i.e.,* audit items, that should be corrected but that were not considered either a debris issue or pertinent to the *Columbia* accident investigation. The audit items are discussed below.

The initial fastener review conducted outside of the Non-TPS Debris Team found two lots of 25L3-6-6 bolts and one lot of 33L1-3 nuts of questionable quality and of potential concern to the Non-TPS Debris Team. Further review of manufacturing lot traceability to purchase orders ruled out the use of both of the suspect bolt lots in any of the Non-TPS Debris hardware on ET-93 in the debris origin priority zone (see the rationale for event blocks 1.1.2.9.2, 1.1.2.6.1, and 1.1.2.10.3.) Use of under-strength nuts from the suspect lot was found to only be a potential investigation concern for the intertank cable tray and pressurization line supports; however, revised stress analysis with reduced nut strength allowables was used to conclude this discrepancy was not a debris concern. (See the rationale for event block 1.1.2.6.3.)

7.2.2.8.2 Pertinent Findings and Rationale

The following findings with regard to Non-TPS ET debris on STS-107 were provided to the NASA Accident Investigation Team (NAIT) and the *Columbia* Accident Investigation Board (CAIB).

7.2.2.8.2.1 Ice

Sequence of events:
Ice→Non-TPS Debris From Other Sources→Non-TPS Debris

Basic event block 1.1.2.13.2 “Ice” documents the investigation of external ice as a possible debris hazard to the Orbiter. There is also reference to external ice in basic event block 1.1.2.11 “FOD.” Ice debris could not be completely ruled out

because historically external ice has been observed, and acceptable ice conditions were noted on STS-107 as described below.

All observations noted by the KSC STS-107 Ice/Frost Team were deemed acceptable in accordance with the Ice/Debris Inspection Criteria, NSTS-08303, and no anomalies were noted in the as-run OMI 6444-J04-R01, "Space Shuttle Vehicle Ice and Debris Assessment." The observations (ice formation on the aft ET/Orbiter umbilicals and the LO2 feedline bellows, a crack in the vertical strut forward surface TPS, light frost on the ET TPS acreage) were consistent and "in-family" to previously documented occurrences and dispositioned with regard to the STS-107 mission. There were no Interim Problem Report (IPR)/PR or LCC violations nor facilities or vehicle issues. The limited ice/frost conditions noted were judged to be typical. In addition, the KSC Integrated Film Review Team completed an extensive post-launch review of all pad-based and long-range tracking launch films. (Long-range tracking films provide a view of the ET up to SRB separation, at which time the view of the ET is greatly diminished and no discernable details can be obtained.) Typical ice/frost was noted falling aft from the ET/Orbiter umbilicals at SSME startup and T-0. Ice/frost from the LH2 umbilical was noted contacting the LH2 Orbiter umbilical doorsill during SSME start-up, with no damage observed. Ice from the ET umbilicals or LO2 feedline was not observed contacting any other portion of the ET.
Since the presence of any ice whatsoever could not be completely ruled out, the possibility of ice sufficient to be a threat to the Orbiter was considered improbable based on the following:

- No anomalous icing conditions were noted in the STS-107 Final (Pre-Launch) Inspection results. This inspection, conducted on January 16, 2003 (day of launch) between 0615 and 0745 hours, documents the ambient conditions and analytical "SURFICE" predictions.
- Just minutes before launch, certain areas of the tank, including the bipod, were scanned using infrared (IR) spectroscopy to assess the surface temperature. The bipod was recorded to be 64-68 deg F and the LH2 acreage was recorded at 48 deg F. These temperatures are not sufficient to form ice.
- The ambient temperature at the time of launch was 65 °F.

It should be noted that the possibility of ice recontacting the External Tank and causing the generation of TPS debris was also investigated in the TPS Debris event block 1.1.1.1.4 "External Impacts to ET TPS Produce Debris."

7.2.2.8.2.2 Non-TPS Debris From Interface Hardware

Sequence of events:
Non-TPS Debris From Interface Hardware→Non-TPS Debris From Other Sources→Non-TPS Debris

The basic event block 1.1.2.13.5 "Non-TPS Debris From Interface Hardware" highlights findings related to potential sources of debris. These findings are

traceable to basic event findings from the ET Interface Performance branch of the FT. The ET team responsible for FT branch 1.2, "ET Interface Performance 'Compromises' Orbiter Reentry Systems," conducted the investigation of the debris potential of the interface hardware while they investigated interface performance. Details of the debris potential findings are documented in this report and the basic event FT blocks as shown in Volume II. Each finding is categorized as a possible, but improbable, contributor to the *Columbia* accident.

7.2.2.8.3 Interaction of Findings

The FT logic in the Non-TPS Debris branch assumes "or" gates between all events. No interaction of any findings is necessary to progress from a basic event to the top event of the branch. Of the two findings in the Non-TPS Debris branch, the events of ice and debris related to interface hardware was judged to be unrelated, and interaction of these findings to create a more likely or worst-case event was judged to be not possible.

7.2.2.8.4 Observations

During the audit of hardware for debris potential on STS-107, several observations were noted that were not considered a debris issue, but that should be corrected. The observations, *i.e.,* audit items, were logged by Lockheed Martin Product Assurance into the ET-93 Non Fault Tree Database and will require NASA S&MA concurrence with the resolution. Fifty-eight observations resulting from the investigation by the Non-TPS Debris team were input to the database. One example of an observation is shown in Figure 7.2.2.8.4-1.

7.2.2.9 Summary

It is possible, but improbable, that ET-93 shed non-TPS debris capable of striking the left wing of the Space Shuttle *Columbia* during lift-off and ascent of STS-107. Specifically, it is possible, but improbable, that ice or interface hardware was the source of this debris.

A Fault Tree branch was developed as part of the overall ETWG STS-107 Fault Tree to conduct the investigation into any debris originating from the External Tank other than that directly attributable to the TPS. This FT branch was developed primarily as a component-by-component audit rather than as a logic-based sequence of failure events. Debris potential related to design deficiencies, inadequate processing, or mission problems was investigated. The investigation included review of supporting analyses and manufacturing and launch processing paperwork, as required. All appropriate ET-93 fabrication records and manufacturing NCDs were reviewed in detail in accordance with the ground rule that each record be reviewed by both a Lockheed Martin representative and a U.S. Government representative (DCMA and/or NASA S&MA).

The FT basic event blocks 1.1.2.13.2 "Ice" and 1.1.2.13.5 "Non-TPS Debris From Interface Hardware" highlight findings related to potential, but improbable, sources of debris. These were the only discrepancies noted during the

investigation into ET-93 non-TPS debris that were considered findings pertinent to the *Columbia* accident investigation.

7.2.2.10 Summary of Tests

No tests were conducted to support the disposition of events in the Non-TPS Debris branch of the ETWG Fault Tree.

7.2.2.11 Results of Tests

No tests were conducted to support the disposition of events in the Non-TPS Debris branch of the ETWG Fault Tree.

7.2.2.12 Recommendations

It is recommended that corrective action be taken as necessary to address the observations (or the root cause of the observations).

7.2.3.5 Interfaces Branch Fault Tree Structure

The ET Interface Team FT consisted of four major branches:

- Structural Interfaces (1.2.1)
- Propulsion Interfaces (1.2.2)
- Electrical Interfaces (1.2.3)
- Transportation & Handling (T&H) Interfaces (1.2.4)

There were a total of 184 FT blocks; of these blocks, 143 were basic events.

The top level of the FT is shown in Figure 7.2.3.5-1. Decomposition of the tree was consistent with methods used by the other teams. Supplier contributions, materials, processes, verification, assembly, and processing were each considered. The fully indentured breakout of the Interfaces Branch is included in Volume II.

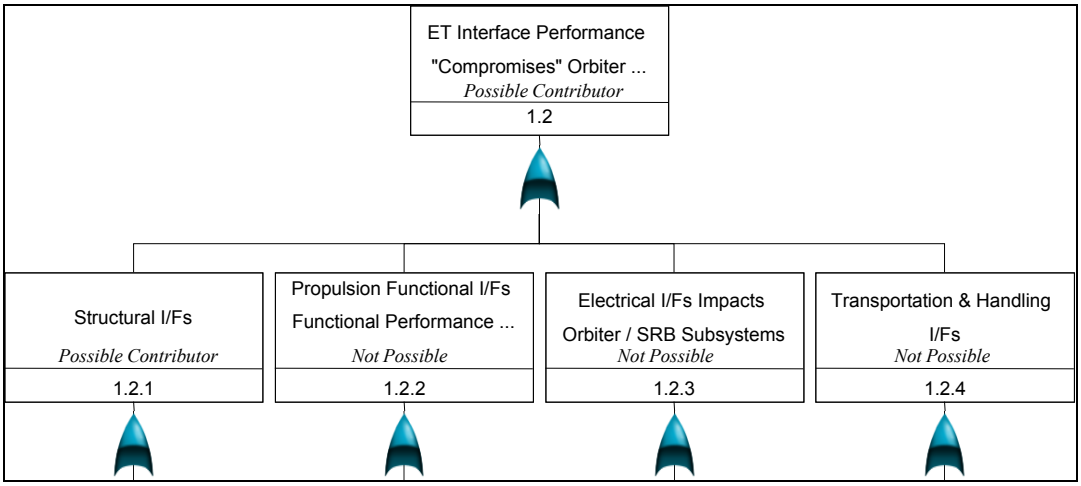

Figure 7.2.3.5-1. Top-Level Interfaces Fault Tree

7.2.3.6 Evaluation Criteria

The interface investigation Team used the same ground rules as the ETWG ground rules identified in Section 7.2 with the following exceptions:

- No ET interfaces were “Diamond Deferred” based on the ETWG “out of left wing debris zone” ground rule.
- Performance analysis was used to support closure of structural, electrical, and propulsion I/Fs outside of the ETWG debris zone.

7.2.3.7 Approach

Because each area of interface investigation required differing evaluation methods, both approaches and findings will be summarized by section.

7.2.3.8 Results

7.2.3.8.1 Structural Interfaces Fault Tree Blocks Summary (Fault Tree Branch 1.2.1)

7.2.3.8.1.1 Approach

The objective of the ET structural I/F investigation was to re-evaluate ET structural I/F requirements and to verify whether ET structural performance could have contributed to the *Columbia* incident. This included both performance anomalies that could have impacted other ET or vehicle systems or the potential for any of the interfaces to be a source of debris.

Two basic approaches were used in the investigation of the ET structural interfaces: a performance-based approach to interfaces outside the ETWG Debris Zone, including post-flight reconstructions of structural or mechanical performance and film review; and detailed analysis and build/processing paper reviews combined with performance analysis and film reviews for the interfaces within the ETWG Debris Zone. The forward bipod and forward ET/SRB interfaces used the later approach (reference Figure 7.2.3.4-1, EO-1, EB-1 and EB-2), and all other interfaces used the former approach.

The performance-based assessment of STS-107 structural I/Fs included either load reconstructions, propulsion-based performance analysis, or post-flight operational reconstructions. Ascent and post-separation film was used wherever possible. The following is a list of the affected interfaces:

1.2.1.2 EO-2 Aft Attach, -Y (Loads based)
1.2.1.3 EO-3 Aft Attach, +Y (Loads based)
1.2.1.4 EO-4 LH2 Umbilical Plate (Mechanical) (propulsion performance)
1.2.1.5 EO-5 LO2 Umbilical Plate (Mechanical) (propulsion performance)
1.2.1.8 Canceled (EB-2 Fwd SRB Attach +Y is addressed in 1.2.1.7)
1.2.1.9 Aft SRB Attach -Y (EB-3, EB-5, EB-7) (Loads)
1.2.1.10 Aft SRB Attach +Y (EB-4, EB-6, EB-8) (Loads)
1.2.1.11 GUCA (Mechanical) (propulsion performance, film review, post- flight inspections)
1.2.1.6 EO-6 LO2 Cross Beam/Orbiter (Aerodynamic) (acceptance inspections, film review)
1.2.1.12 LO2 Vent Hood (film review)
1.2.1.13 Post-Separation ET/Orbiter Contact or at ET Breakup (post-flight analysis, post-separation film)

The second structural interface investigation approach included performance-based loads reconstructions, similar to the first approach, but also included detailed review of the interface requirements; design, supplier and MAF fabrication paper; KSC processing paper; and special investigations of

operational anomalies. These interfaces were within the ETWG left-wing debris zone. This approach was used on the following interfaces:
1.2.1.1 EO-1 Fwd Bipod Attach Interface
1.2.1.7 EB-1 Fwd SRB Attach -Y & EB-2 Fwd SRB Attach +Y

The following discussion will address the detailed approach, data, and investigation results of each of these groups of structural interfaces.

7.2.3.8.1.2 Performance-Based Approach: Loads Evaluation

For structural I/Fs outside of the ETWG left-wing debris zone, two approaches to structural performance were applied to determine if these interfaces had any indirect relationship to the *Columbia* incident: structural loads reconstruction of primary interfaces and an evaluation of STS-107 propulsion system performance data, for mechanical interfaces.

The evaluation of load reconstructions of STS-107 was performed by comparing flight specific load indicators from STS-107 load reconstructions against design limits. Three different sets of load indicators were reviewed, including pre-launch, lift-off, and ascent load (BET) indicators. The interfaces affected included the following branches of the Fault Tree:
1.2.1.2 EO-2 Aft Attach, -Y (Loads based)
1.2.1.3 EO-3 Aft Attach, +Y (Loads based)
1.2.1.9 Aft SRB Attach -Y (EB-3, EB-5, EB-7) (Loads)
1.2.1.10 Aft SRB Attach +Y (EB-4, EB-6, EB-8) (Loads)

As noted previously, three I/Fs within the ETWG left-wing debris zone were also included in this performance-based evaluation and will be discussed at this time.
1.2.1.1 EO-1 Fwd Bipod Attach Interface
1.2.1.7 EB-1 Fwd SRB Attach -Y & EB-2 Fwd SRB Attach +Y

Figures 7.2.3.8.1.2-1 and 7.2.3.8.1.2-2 show the location of the load indicators evaluated with respect to the ET interfaces: truss members and interface load indicators. The Boeing analysis group, through the SSP loads board, provided the reconstructions to the Interface Team. The BET loads reconstruction was based on a rigid body analysis. In addition to the BET loads indicator sets, an additional flexible body reconstruction was provided.

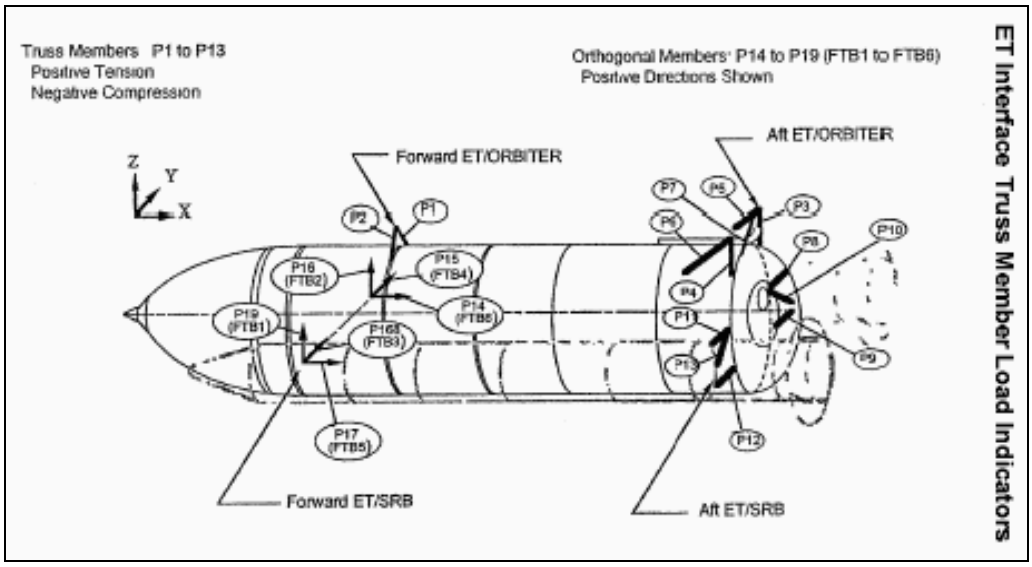

Figure 7.2.3.8.1.2-1. ET Strut Load Indicators

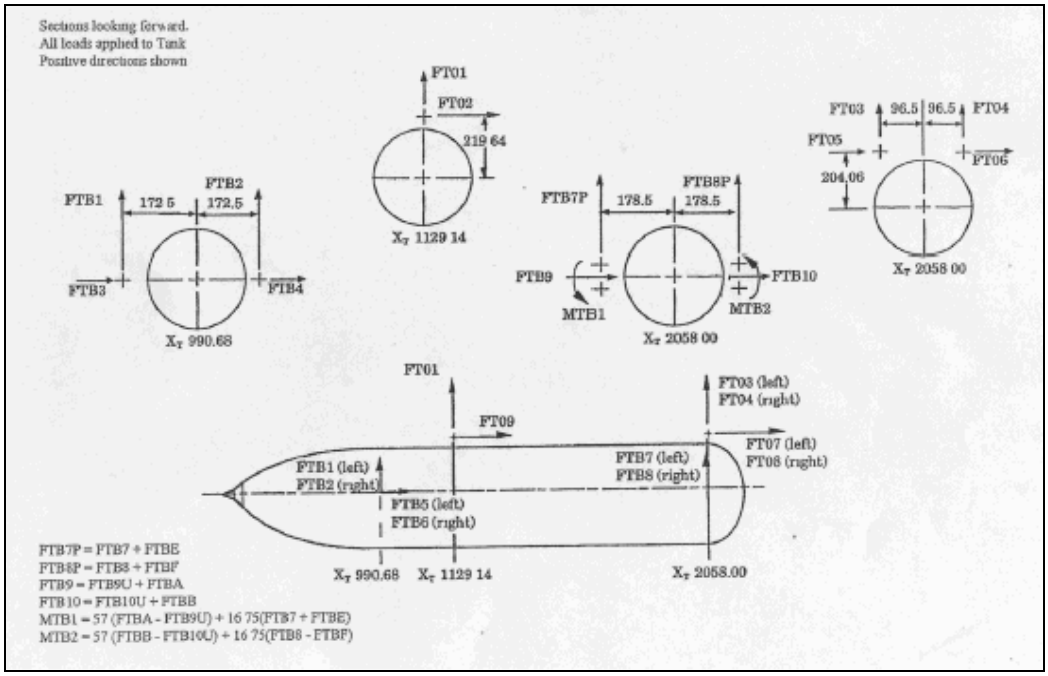

Figure 7.2.3.8.1.2-2. ET Interface Load Indicators

No loads issues were found with any phase of operations. All indicators were well within design limits. The flex body loads reconstruction was actually less than the BET reconstruction, so they did not affect the evaluation. All of the analysis to date shows no evidence of excessive or anomalous loading.

Table 7.2.3.8.1.2-1 is an example of the loads comparisons done for each of these interfaces. The ETWG Fault Tree database contains a complete set of all load indicators that were reviewed.

Table 7.2.3.8.1.2-1. Example of ET BET Load Indicators

- **Loads Shown: Forward Bipod**

Load Indicator	Max Positive (% of limit load)	Max Negative (% of limit load)
FTO1	15	31
FTO2	26	20
FTO9	24	11
P1	19	34
P2	15	27

Structural loads reconstructions were not available for propulsion related, mechanical interfaces, which included the following:
1.2.1.4 EO-4 LH2 Umbilical Plate (Mechanical)
1.2.1.5 EO-5 LO2 Umbilical Plate (Mechanical)
1.2.1.11 GUCA (Mechanical)

The performance of these I/Fs was evaluated, based on the propulsion and electrical functional performance of the interfaces, which provided a strong indicator of nominal performance. No anomalous performance or unusual conditions were evident during STS-107 operations. In addition, film review and post flight inspection reports of the GUCA provided high confidence that there were no issues related to the mechanical performance of this interface. No off-nominal conditions or anomalous conditions were evident.

The investigation found no evidence of anomalous operations of these structural I/Fs, and it was concluded that these I/Fs performed nominally and in no way contributed to the *Columbia* incident.

7.2.3.8.1.3 Findings

There were four findings identified as a result of the structural interfaces investigation effort. The findings were limited to the forward bipod and the forward SRB interfaces within the ETWG debris zone, and all were judged

"possible but improbable." A summary of the findings and the probability rationale/corrective actions are listed in Table 7.2.3.8.1.3-1.

Table 7.2.3.8.1.3-1. Structural Interface Investigation Findings

Finding	Fault Tree Block	Probability Rationale/ Corrective Action
Use of proper torque sequence was not called out in MPP for bipod strut flange fasteners. This could lead to debris.	1.2.1.1.3.5 Incorrect Parts Assembly *Parents* 1.2.1.1 EO-1 Fwd Bipod Attach Interfaces 1.2.1.1.3 Incorrect/Inadequate MAF Processing	Probability Rationale: Potential debris source determined improbable due to final torque verification and separation analysis showing high margin of Safety. Corrective Action: Modify MPP to include proper torque sequence requirements and verification
The Loctite® fastener locking compound for the intertank-to-SRB fitting fasteners (2 per each SRB fitting) did not have lot traceability recorded on the MPPs. This could potentially be a source of debris.	1.2.1.7.3.1 Incorrect Parts Material Usage *Parents* 1.2.1.7 EB-1 Fwd SRB Attach -Y & EB-2 Fwd SRB Attach +Y 1.2.1.7.3 Incorrect/Inadequate MAF Processing	Probability Rationale: Potential debris source determined improbable due to final Torque verification and separation analysis showing high margin of Safety. Corrective Action: Modify affected MPPs to verify shelf life
Use of proper torque sequence was not called out in MPP for bipod fitting installation on tank. This could lead to debris.	1.2.1.1.3.5 Incorrect Parts Installation *Parents* 1.2.1.1 EO-1 Fwd Bipod Attach Interfaces 1.2.1.1.3 Incorrect/Inadequate MAF Processing	Probability Rationale: Potential debris source determined improbable due to final torque verification and separation analysis showing high margin of safety. Corrective Action: Modify MPP to include proper torque sequence requirements and verification
Omission of breakaway torque verification in OMI that installs RSS fairing.	.2.1.7.4.1.1.4 Incorrect Parts Installation *Parents* 1.2.1.7 EB-1 Fwd SRB Attach -Y & EB-2 Fwd SRB Attach +Y 1.2.1.7.4.1.1 Incorrect/ Anomalous ET/SRB Mate	Probability Rationale: Potential debris source determined improbable due to final torque verification and separation analysis showing high margin of safety. Corrective Action: Update OMI to include verification of break-away torque

Finding	Fault Tree Block	Probability Rationale/ Corrective Action
Operational anomaly related to Bipod foam loss exposing underlying bipod interface hardware leading to connector/connector plate becoming debris	1.2.1.1.5.4 Bipod hardware/ components under foam are exposed during ascent and become debris *Parents* 1.2.1.1 EO-1 Fwd Bipod Attach Interfaces 1.2.1.1.5 Operational Anomalies (Pre-launch, Ascent, Separation)	Probability Rationale: Analysis and test demonstrated loss of underlying hardware highly unlikely. Corrective Action: Redesign effort will eliminate bipod heater connector/connector plate

7.2.3.8.2 Propulsion Interfaces Fault Tree Blocks Summary (Fault Tree Branch 1.2.2)

7.2.3.8.2.1 Approach

The objectives of the ET propulsion interface investigation was to re-evaluate ET propulsion interface requirements, to reverify the ET propulsion analysis process, and to determine whether there were any STS-107/ET-93 propulsion system performance anomalies that could have contributed to the *Columbia* incident. These objectives were met by performing a thorough evaluation of STS-107/ET-93 fluid interface data versus pre-flight predications and against historical experience. The historical evaluation included the development of historical limits for measurements near the fluid interfaces for different survey groups of past flights including LWTs (67), SLWTs (21), and Block II cluster flights (5).

The propulsion interfaces FT branch was broken down into five functional performance groups, as shown in Volume II.

For each of these functional performance groups, extensive STS-107 performance data comparisons were made against the I/F requirements as well as the historical performance groups identified above and documented as part of the FT closure rationale. Review of recorded STS-107/ET-93 ET loading and flight propulsion data, including post-flight performance reconstruction and interface data, indicated no data outside of requirements, STS program experience, or pre-flight predictions and expectations. The data examined encompassed the loading, prepressurization, and ascent (through ET separation) operations.

7.2.3.8.2.2 Findings

No indications of any unusual propulsion conditions were found in the functional or interface data. There were no findings related to the STS-107 ET propulsion interface performance. ET propulsion system performance was determined not to be a contributor to the *Columbia* incident.

7.2.3.8.3 ET Electrical Interfaces Fault Tree Blocks Summary (Fault Tree Branch 1.2.3)

7.2.3.8.3.1 Approach

The objective of the ET electrical interface investigation was to re-evaluate ET electrical I/F requirements, to reverify the ET electrical acceptance testing and inspections, and to determine whether there were any STS-107/ET-93 electrical system performance anomalies that could have contributed to the *Columbia* incident. These objectives were met by performing a thorough evaluation of STS-107/ET-93 electrical acceptance testing at MAF and at KSC and by verifying all available pre-launch and ascent electrical measurements and film and available post-flight inspections of the GUCP and SRB interfaces.

The electrical interfaces FT branch was broken down into seven functional performance groups, as shown in Volume II. For each these major branches, electrical design, MAF and KSC acceptance data, and operational electrical performance data were evaluated for adequacy and/or anomalies.

7.2.3.8.3.2 Findings

All ET-93 acceptance and inspection test paper and electrical related NCs/PRs were evaluated against the requirements, and no issues were identified. No indications of any unusual conditions were recognized in the functional or I/F data. There were no findings related to the STS-107/ET-93 electrical I/F performance. ET electrical system performance was determined not to be a contributor to the *Columbia* incident.

7.2.3.8.4 ET Transportation & Handling Interfaces Summary (Fault Tree Branch 1.2.4)

7.2.3.8.4.1 Approach

The objective of the ET T&H interfaces investigation was to re-evaluate ET T&H interface requirements, plans, and ET-93 specific events for any anomalies or incidents that could be related to the *Columbia* incident. This branch captured all T&H-related activities beginning with initial transport to the barge at MAF and including transport to the barge, barge transport, KSC stand-alone processing, and Mobile Launch Platform (MLP) and pad integration before pre-launch. Orbiter and SRB mating operations were evaluated as part of FT branches 1.2.1.1 (Bipod Structural Interface) and 1.2.1.7 (-Y and +Y SRB Structural Interfaces). These objectives were met by performing a thorough evaluation of STS-107/ET-93 related to T&H and mating, including MPPs and Manufacturing Handling Plans (MHPs) at MAF and T&H-related OMIs at KSC. Special attention was given to verification of planned inspection steps and results of these inspections that may have been documented during T&H operations.

7.2.3.8.4.2 Findings

All ET-93 T&H-related requirements, MPPs, and MHPs were reviewed and no anomalies or incidents were found. In addition, the NC system was searched, and no ET-93 T&H NCs were found. No issues were found in the review of ET-93 KSC interface-related processing paper. A review of the KSC PRACA systems identified no ET-93 T&H-related problem reports. There were no findings related to the STS-107/ ET-93 T&H interface processing. ET-93 T&H-related processing was determined not to be a contributor to the *Columbia* incident.

7.2.3.9 Summary of Tests

No tests were conducted to support the disposition of events in the Interfaces branch of the ETWG Fault Tree.

7.2.3.10 Recommendations

The Interfaces Team recommends corrective action to address the low-risk items uncovered during the investigation:

- Implement corrective action to modify affected MPPs to verify shelf life of Loctite® material
- Update all appropriate MPPs to include torque sequence requirements and verification.

Section 8 Contributing Root Causes, Significant Observations, and Recommendations

Root causes and associated observations and recommendations are summarized in Table 8-1.

Table 8-1. Root Causes and Associated Observations and Recommendations

No.	Root Cause	Observation	Recommendations
E-1	Debris	• TPS debris loss observed at 81.7 sec during STS-107 ascent most probably originated from left-hand bipod ramp • Other areas on ET have histories of debris shedding	• Review verification and validation of complex closeout configurations for performance risks • Redesign (and reverify/revalidate) high risk configurations • Incorporate inspectability of as-built configuration in assessment of acceptable hardware design
E-2	Defect formation in TPS	Dissections have shown various types of defects in the as-applied TPS.	• Develop a characterization/test program to determine gun types, fan pattern settings, overlap time requirements, spray techniques, etc., that will enable TPS applications without defects for both current and any "improved" systems. • Incorporate periodic dissections of production parts in QC plans
E-3	Material Properties and Validation	Compression tests of BX 250 SOFI identified significant difference in properties in rise direction vs. perpendicular to rise direction.	• Develop a characterization/test program to determine material strength/debris potential vs. thickness, vs. density, vs. spray pattern, vs. rise direction, vs. etc., for all TPS systems and application methods.
E-4	Stress Models	The stress model for modeling TPS materials is not adequate to predict failure.	Consult with other and outside entities to develop 2-D or 3-D models that can accurately predict failure.
E-5	General TPS Environment	Changes in precursors, materials, requirements, and vendors create a turbulent environment, making control of TPS materials, systems and processes difficult	• Form a TPS Materials Working Group (Civil Service and contractor team) to address the following topics. Consider implementation of rigor associated with structural materials • Training and Certification • Raw Material Acceptance • MPP Process Control • MPP Acceptance Testing

			• Traceability • Contamination Effects and Control • Production Parts Dissection Recommendations
E-6	MPP Process Control and Acceptance Testing	Difficult application techniques and operations are left to the discretion of the operator during hardware processing	• Develop more detailed technique sheets for difficult manual SOFI sprays and ablator hand pack operations. Include Engineering (Material Sciences) oversight and approval
E-7	Acceptance Testing / Inspection Technique Limitations	Available acceptance testing/inspection techniques are not capable of rejecting ramps with diverse "as-built" features that would threaten the TPS integrity	• Assess nondestructive evaluation methods for evaluation of critical defects
E-8	MPP Process Control and Acceptance Testing	Due to ease of logistics, witness specimens are maintained in a separate area from the hardware during the cure cycle	• Review the adequacy (number, location and size of specimens) of witness coupon process. For example when spraying multiple parts, make coupons from an extra part rather than a separate witness panel. • Maintain witness specimens in the same area and environment in which the parts are cured
E-9	Spray Process Control & Equipment Traceability	• The engineering requirement for verification of ratio and other processing parameters is not adequate. Ratio could be checked as infrequently as 2 years. • No traceability of actual foam spray equipment used (including proportioner) to the ET component being insulated.	• Implement a 100% recording of spray equipment operational data. • Check ratios from SOFI spray proportioner on a more frequent basis (two cup method or extended spray to check output.) • Record serial number of proportioner in the event an error is found in the unit.
E-10	Spray Overlap Time Verification	Determination that overlap time requirements have been met are subjective at best.	• Develop and implement QC methods for overlap time verification on difficult configurations
E-11	Training and Certification of Manual Spray Practitioners	• Current foam spray certification of operators is permanent, providing certain "on-the-job training" is performed and a person performs one successful spray close-out every two years. • Tooling and mockups for training need to be improved and kept current with changes in	• Review time period for recertification • Reduce Manual Spray certifications from 2 years to 1 year • Assess reducing the time to revoke certifications for non-use • Include spray operations on test panels during training prior to

		production materials and application methods.	spraying on hardware by OJT. • Implement test panels more representative of actual part geometries and techniques (24"x 24" instead of 6" panels when required, specific guns, total thickness, knitline thickness, orientation, and part complexity) • Increase number of specific certifications, if required • Evaluate continuous improvement of the process. Any best practices (material and/or equipment changes) should be certified and incorporated into the training and recertification program. • Establish pass/fail criteria based on design-critical attributes, e.g., mechanical properties, critical void locations • Improve the process of involving Training personnel in process and tooling changes that affect training courses.
E-12	Stamp Warranty Implementation	• One person observed as stamping for multiple operations • Stamps not fully legible • Shop supervisors do not hold individual certifications; however, some are authorized to stamp off build process operations, and do in fact stamp operations off.	• Review stamp warranty practices and training • Review practices for stamp replacement • Review training and cert requirements for Supervisors • Review the description of supervisors approval of processes
E-13	Raw Material Acceptance and Control	• Specification for a particular material stated that material shall meet requirements when stored in original sealed containers at one temperature range for 6 months. Implementing documentation (process specification) allowed relocation in the preparation/using area at a larger temperature range with no reduction in shelf life. • Trending data is based on original acceptance test data only	• Reassess storage requirements and update documentation for consistency • Fingerprinting and Acceptance data trends need increased tracking when trends are observed within statistical or STP acceptance limits. • Incorporate NCD test results in trend databases
E-14	Traceability Issues	Improperly recorded numbers identified	• Improperly recorded numbers should be emphasized in training. • Correct lost logs • Consider more clocks with military time and date to minimize

			errors. • Review paperless manufacturing system requirements to verify minimized potential for errors • Proper recording practices and correction of current faults should be implemented (Munafo verbal interpretation)
E-15	General Traceability and Data Retrieval	Reduced staffing levels have resulted in increased reliance on supplier quality and related documentation, sometimes making access difficult	• Assess overall levels vendor quality control and recommend additional controls, as needed
E-16	Contamination Effects and Control	Potential SOFI contaminants identified in walk-down of factory	• Establish a Contamination Control Team • Incorporate contamination control requirements and selected verification methods into STPs. • Conduct contamination walk-downs on a regular basis
E-17	Torque Sequence Call-out in Build Paper	A specified torquing sequence was not identified in the bipod strut MPP. (However, training methods mandate the star-pattern sequence and the final torque of the fasteners was verified in the MPP.)	• Modify build paper to reflect star-pattern torque sequence • Review running torque and break-away torque verification requirements
E-18	Loctite® Shelf Life Traceability Call-out Requirement	• Loctite® fastener locking compound used at the Forward ET/SRB fittings did not have any lot traceability recorded on the MPP. Loctite® is used to retain fasteners as a secondary locking feature when other locking features are not applicable. • There is a shelf life associated with Loctite®. The material is verified in Receiving/Labs prior to being issued to Production. The MPP only requires recording the grade and not the shelf life	• Modify build paper to reflect shelf-life recording requirement
E-19	ICD Responsibilities	ICD Responsibilities for bolt catcher were unclear between elements	• Reassess all interfaces to assure clear responsibility delineation between elements and updated ICDs • Implement a full requirements/verification

			traceability tool on critical implementations
E-20	Post-Flight Performance Assessment	Post-flight assessment of TPS performance was difficult at best.	• Implement downlinked digital video coverage of the external tank. • Improve the Orbiter umbilical well imaging and launch imaging capability.
E-21	Debris	100% guarantee of no foam debris is impossible	• Develop a viable and quantitative definition of debris • Develop a better understanding of the effect of ET foam debris particle impacts on Orbiter TPS.
E-22	TPS	Changes in precursors, materials, requirements and vendors create a turbulent environment, making control of TPS materials, systems and processes difficult for all elements of the Shuttle Program.	• Form a TPS senior expert advisory board to be made available to all Shuttle Program elements as a resource for assessment of future changes, and to provide continuity and assess credibility of verification.
E-23	Staffing Levels	External Tank Civil Service & Contractor workforce levels have declined for the past several years	• Assess technical and other critical staffing levels to assure adequate capability for Return-to-Flight activities and for follow-on sustaining engineering. • Sponsor the TPS Materials Working Group
E-24	Chief Engineer function	The current Shuttle Project Management scheme at MSFC has the Chief Engineer reporting to the Project Manager; this tends to inhibit proper checks and balances on technical issues.	• Work to re-institute at MSFC an organizational separation of the Project Manager and Chief Engineer functions.
E-25	Contract Award Fee Criteria	Incentivization to reduce NCDs greatly reduced the number of NCDs but did not result in a corresponding improvement in TPS performance.	• Contract incentive methodology should be changed to base performance onuses on more representative technical performance metrics.
E-26	Influence of Technical Operations	Product Assurance and Production Operation organizations control the fabrication, repair methods, and training requirements for ET manufacturing.	• The team for implementing the preceding functions should consist of Product assurance, Production Operations, AND Technical Operations personnel.
E-27	Contingency Teams	The MSFC Contingency Plan document should be updated to reflect lessons learned regarding the team make up, technical expertise required (depending on the problem), and chain of	• The MSFC SSPO should work with the STS-107 Working Groups to update the Contingency Plan.

		command.	
E-28	Contingency Teams	While initial completion schedules for the investigation were aggressive and did ensure no less than "full throttle" effort by the Working Groups, these schedules caused compromises to be made in testing and analysis options.	• Initial schedules should be reassessed and revised at the earliest opportunity during an investigation based on assessments of the magnitude of technical efforts that will be required during the investigation. This will ensure that severe "short cuts" will not be required to meet schedule that could possibly adversely affect the quality of the investigation.
E-29	Contingency Teams	The urgencies of flight schedule and budget too often force the Agency into a reactive mode when dealing with contingencies. There seems to be neither time nor resources available to proactively seek out and solve problems before they occur.	• Create and fund a function, either within the Shuttle Program or accountable to it, that would proactively seek out, define preemptive actions against, and advocate resources to correct the so-called "Unknown Unknowns" that threaten mission success.
E-30	Contingency Teams	There was a certain amount of confusion over the focus of the Fault Tree. Strictly speaking, it should have been directed specifically toward events that could have led to the loss of STS-107; however, good engineering judgment dictated that the scope should be broader, and that the Shuttle Program could gain a large benefit with a small additional expenditure of resources by expanding the Fault Tree investigation to identify other events that could cause a similar result in the future.	• As a minimum, state in the documentation guiding incident investigations that the working groups should determine factors that could have been causal to the incident, and also any other events that might be generically similar but for one reason or another did not cause this particular incident.
E-31	S&MA	S&MA is expected to take a leadership role in incident investigations; however, S&MA investigative procedures and required forms are not in place. Furthermore, S&MA does not have its own funding for investigations, having to rely on the Project Manager, for example, to provide travel funding.	• S&MA should develop an Operational Instruction (OI) for incident investigations. Early in the process, discretionary funding should be provided to S&MA.

Section 9 Definition of Terms

α, alpha	Angle of Attack
AEDC	Arnold Engineering Development Center
ALERTS	Acute Launch Emergency Reliability Tips
AR	Action Report
ASI	Aerodynamically Sensitive Items
β, Beta	Sideslip Angle
BET	Best Estimated Trajectory
CAIB	*Columbia* Accident Investigation Board
CDR	Critical Design Review
CEI	Contract End Item
CFD	Computational Fluid Dynamics
CIL	Critical Items List
CM	Configuration Management
CoFR	Certificate of Flight Readiness
COQ	Certification of Qualification
CTP	Controlled Test Plan
D&V	Development and Verification
DAS	Document Accountability Sheet
DC&R	Design Criteria and Requirements
DCMA	Defense Contract Management Agency
DCS	Design Certification Sheet
DFI	Development Flight Instrumentation
DoD	Department of Defense
DOL	Day of Launch
DR	Discrepancy Report
DTA	Differential Thermal Analysis
EIS	End Item Specification
EOR	End of Replenish
ET	External Tank
ETA	External Tank Attach
ETM	Engineering Test Motor
ETP	Engineering Test Plan
ETWG	External Tank Working Group
FEM	Finite Element Model
FMEA	Failure Modes and Effects Analysis
FMA	Flight Margin Assessment
FOD	Foreign Object Debris
FPP	Flight Preparation Process
FRR	Flight Readiness Review

FSS	Fixed Service Structure
FT	Fault Tree
FTA	Fault Tree Analysis
FY	Fiscal Year
GHe	Gaseous Helium
GN&C	Guidance, Navigation, and Control
GN2	Gaseous Nitrogen
GO2	Gaseous Oxygen
GUCP	Ground Umbilical Cable Panel
GUCA	Ground Umbilical Cable Assembly
HCFC	Hydrochlorofluorocarbon
HCS	Hardware Certification Sheet
HEAR	Hardware Element Acceptance Review
HOSC	Huntsville Operations Support Center
HPM	High Performance Motor
HR	Hazards Report
ICD	Integration Control Document
I/F	Interface
IFA	In-Flight Anomaly
IOP	Ignition Over Pressure
IPR	Interim Problem Report
IPRA	In-Process Repair Authorization
IR	Infrared
JSC	Johnson Space Center
KSC	Kennedy Space Center
LCC	Launch Commit Criteria
LDB	Loads Data Base
LH	Left Hand
LH2	Liquid Hydrogen
LM	Lockheed Martin
LMC	Lockheed Martin Company
LMSSC	Lockheed Martin Space Systems Company
LOCV	Loss of Crew and Vehicle
LO2	Liquid Oxygen
LOX	Liquid Oxygen
LWT	Lightweight Tank
MAF	Michoud Assembly Facility
MDAT	Material Data Analysis Team
MECO	Main Engine Cut Off

MEICT	Multi-Element Integrated Closure Team
MET	Mission Elapsed Time
MHP	Manufacturing Handling Plan
MLP	Mobile Launch Platform
MPP	Manufacturing Process Plan
MPS	Main Propulsion System
MRB	Material Review Board
MRT	Mishap Response Team
MSFC	Marshall Space Flight Center
NAIT	NASA Accident Investigation Team
NASA	National Aeronautics and Space Administration
NC	Nonconformance
NCD	Nonconformance Document
NCFI	North Carolina Foam Insulation
NEQA	NASA Engineering and Quality Audit
NPC	Nonpropulsive Consumables
NSTS	National Space Transportation System
OFI	Operational Flight Instrumentation
OI	Operational Instruction
OIS	Operational Intercommunication System
OMI	Operations and Maintenance Instruction
OMRSD	Operations and Maintenance Requirements and Specifications Document
OPT	Operational Pressure Transducer
OVE	Orbiter Vehicle Engineering
PAL	Protuberance Air Load
PAS	Problem Assessment System
PASR	Problem Assessment System Report
PCA	Process Control Alert
PD	Process Departure
PDL	Polymer Development Laboratories
PE	Performance Enhancement
PFA	Pre-Flight Assessment
PFOR	Post-Flight Observation Record
PFR	Pre-Flight Review
POFI	Pour on Foam Insulation
PR	Problem Report
PRACA	Problem Report and Corrective Action
PRCB	Program Requirements Control Board
PRD	Program Requirements Documents
PRR	Program Requirements Review
PSIG	Propulsion Systems Integration Group

Q	Dynamic Pressure
QAR	Quality Assurance Representative
QC	Quality Control
QTP	Qualification Test Plan
RH	Right Hand
RMS	Root-Mean-Square
RSRM	Reusable Solid Rocket Motor
RSS	Rotating Support Structure
S&A	Safe and Arm Device
S&MA	Safety and Mission Assurance
SCN	Specification Change Notice
SINDA/FLUINT	Systems Integrated Numerical Differencing Analyzer and Fluid Integrator
SLA	Super Light Ablator
SLWT	Super Light Weight Tank
SOFI	Spray-On Foam Insulation
SPC	Statistical Process Control
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SSEIG	80? 82?
SSME	Space Shuttle Main Engine
SSP	Space Shuttle Program
SSV	Space Shuttle Vehicle
STM	Standard Material Specification
STP	Standard Process Specification
STS	Space Transportation System
T&H	Transportation and Handling
TAL	Trans-Atlantic Abort
TD	Technical Directive
TDB	Thermal Data Book
TDFS	Test Demonstrated Factor of Safety
TGA	Thermogravimetric Analysis
T_o	Lift-Off
TPS	Thermal Protection System
TR	Technical Report
USA	United Space Alliance
UUEC	Unexpected, Unexplained Event or Condition
VAB	Vehicle Assembly Building
V_{IP}	In-Plane Wind Velocity
V_{OP}	Out-of-Plane Wind Velocity
VV&A	Verification, Validation & Accreditation

WBS	Work Breakdown Structure