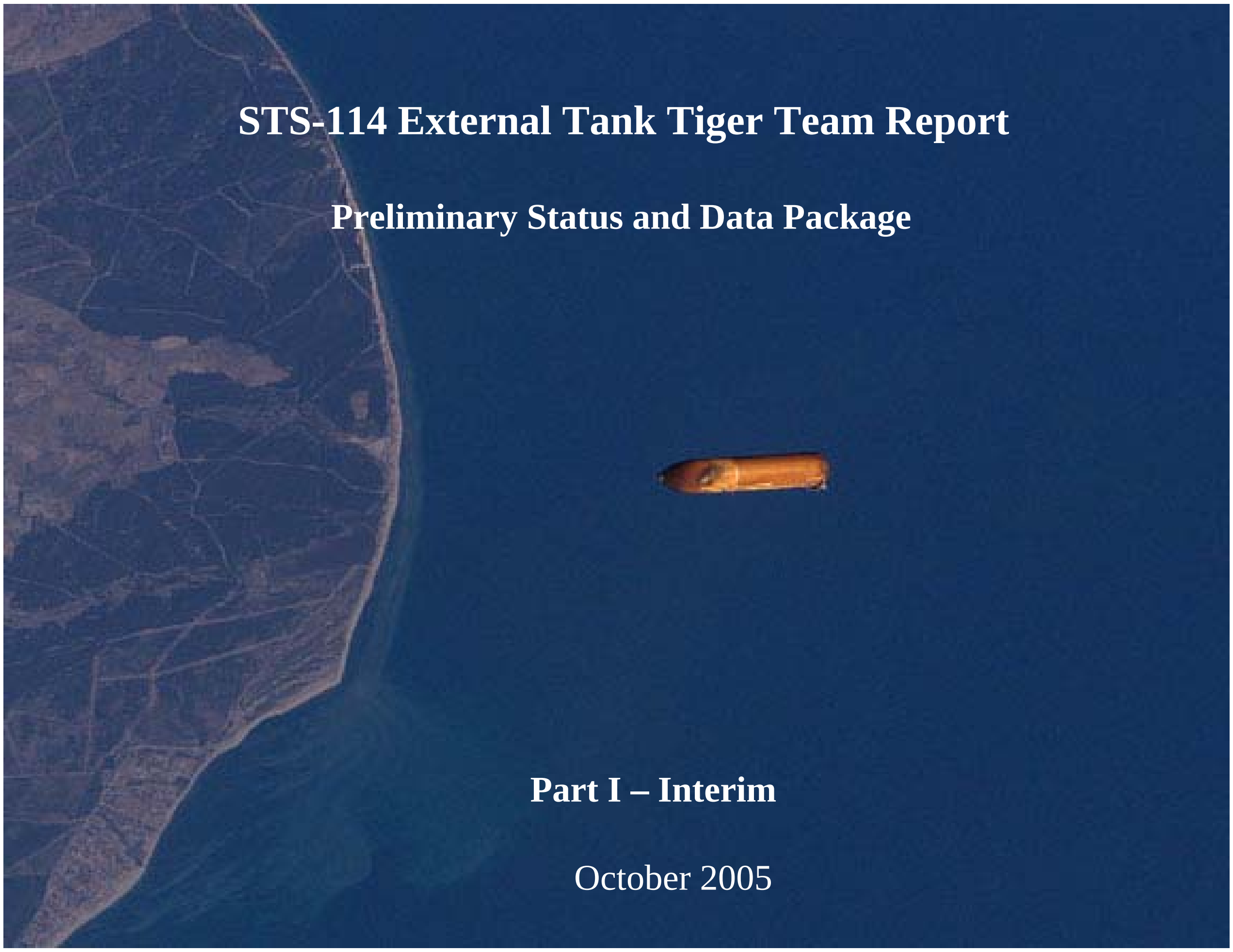

STS-114 External Tank Tiger Team Report

Preliminary Status and Data Package

Part I – Interim

October 2005

Concurrence

External Tank Tiger Team

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Rev A	Incorporates Associate Administrator for Space Operations comments per 09-13-05 telecon.	09-15-05
Rev B	Incorporated Rick Gilbrech's comments and changes	09-27-05
Rev C	Incorporated Peer Review comments. Removed ITAR-restricted data.	10-07-05

Table of Contents

Appendices

List of Figures

List of Tables

1.0 Executive Summary

As a result of foam loss on STS-114, an ET Tiger Team was chartered by the Headquarters Mission Director for Space Operations (MDSO) and NASA's Chief Officer for Safety and Mission Assurance (COSMA), to review unexpected External Tank (ET) Thermal Protection System (TPS) foam loss. Foam losses of significance occurred in five areas of ET foam, including the Protuberance Air Load (PAL) ramp, the left bi-pod fitting closeout, several locations on the ice/frost ramps covering the re-pressurization line attachment brackets, two locations on the liquid hydrogen (LH_2) tank-to-intertank flange, and two locations in the LH_2 tank acreage. The largest piece, approximately one pound, was from the PAL ramp. The ET Tiger Team reviewed foam performance to determine most likely root causes, to determine whether these were unique to STS-114/ET-121, and to make both near- and long-term recommendations to minimize likelihood of recurrence.

The ET Tiger Team addressed overarching environmental, processing, and materials issues that might have contributed to the foam loss. No off-nominal ascent flight environment effects were identified. However, Inflight Anomaly (IFA) Resolution Teams should ensure ascent environmental loading and associated stress on TPS foam is fully understood. A high correlation between areas of the tank with the highest levels of processing traffic (those adjacent to work platforms, mats, etc.) and the locations from which foam was lost on STS-114 and previous missions was observed. The ET Tiger Team also noted that ET-121 was subjected to an unusual level of rework due to modifications incorporated for return to flight (RTF). With respect to materials, this was the first flight of BX-265 liquid oxygen (LO_2) and LH_2 PAL ramps; all tanks prior used BX-250 ramps.

The ET Tiger Team provided a number of recommendations for near-term and long-term actions to minimize the possibility of foam loss from future external tanks. These recommendations are predicated on the assumption that on-going efforts by the Space Shuttle Program's (SSP) IFA Resolution Teams to identify root cause, including ongoing test and analysis, will be taken to fruition.

Key near-term recommendations include:

- Remove and replace the entire length of the LO_2 and LH_2 PAL ramps using improved application processes.
- Implement modifications required to prevent cryopumping through bi-pod heater wiring.
- Investigate the possibility of venting ice/frost ramp "fingers".
- Improve hardware protection provisions to minimize the potential for collateral hardware damage during processing.

Key long-term recommendations include:

- Elimination of the PAL ramp at the earliest possible opportunity coincident with rigorous aerodynamic test and analysis.
- Develop hard covers for ice/frost ramps and implement in conjunction with PAL ramp elimination.
- Eliminate tank traffic to the extent possible in the long-term and implement a no-touch processing policy.
- Develop and certify nondestructive evaluation (NDE) techniques for all ET TPS applications.

2.0 Team Charter

The ET Tiger Team was chartered by the NASA HQ Mission Director for Space Operations (MDSO) and the COSMA to independently assess unexpected TPS foam loss which occurred during the STS-114 mission, and to make recommendations for near- and long-term improvements to preclude recurrence of the problem. The ET Tiger Team operated independently of a SSP IFA Resolution Team that was established for the same purpose, but reports to the SSP Manager.

The initial portion of the effort was a three-week assessment during which the ET Tiger Team was asked to determine whether or not the failures were unique to the STS-114 tank (ET-121), to identify probable causes, and to make near-term and long-term recommendations.

The ET Tiger Team was led by Dr. Richard Gilbrech, Deputy Director, NASA Engineering and Safety Center (NESC), Langley Research Center. Team members included David A. Hamilton, NESC Chief Engineer, JSC; Dr. Michael P. Nemeth, Senior Research Engineer, LaRC; Dr. Donald R. Pettit, Astronaut, JSC; Dr. Charles F. Schafer, Deputy Manager, Propulsion Research Center, MSFC; Timmy R. Wilson, NESC Chief Engineer, KSC (executive secretary); and Harry Dean, MSFC (close call investigation ex-officio member).

3.0 Scope

This document summarizes the three-week initial portion of the ET Tiger Team's work. Follow-on efforts will be documented in the Part II: Final Report.

4.0 Background

STS-114 post-launch photo and video analysis highlighted the loss of a significant piece of foam from the PAL ramp and fifteen other instances of significant ET foam loss (refer to Table 4.0-1 and Figure 4.0-1). Nine of the 16 were referred for immediate assessment to one of five of the SSP's independent IFA Resolution Teams. Four of the remaining seven foam losses appeared to have been caused by debris strikes from sources external to the tank. One of the seven represented foam lost from an area of the LH_2 intertank flange outside the critical debris zone and not subjected to RTF modifications. The remaining two, one from a LO_2 feedline bracket and one from the aft thrust structure, are still under assessment by the SSP video analysis teams.

Table 4.0-1. Foam Loss Incidents

Location	Release Time (sec/MET)	Size			Coordinates			Mass (lbm)	EIS Cert Limit Location Specific (lbm)	Max Expected Mass (lbm)	NSTS 60559 Table C-1 Mass for Risk Assessment (lbm)
		Length (in.)	Width (in.)	Depth (in.)	X_T	Y_T	Z_T				
LH2-Intertank Flange	271 *	7.5	7.5	2.0	1121	-166	422	0.066	0.075	0.010	3σ : 0.0018
LH2-Intertank Flange	271 *	4.5	4.5	1.0	1120	-167	401	0.011	0.075	0.010	3σ : 0.0018
-Y Bipod	148.1	8.4	7.3	1.5	1124	-56	558	0.023	0.030	0.020	3σ : 0.00438
LH2 Barrel (PDL Repair)	135.8	4.8	3.3	1.0	1163	-46	560	0.003	0.030	0.003	0.002
LH2 Barrel	150 *	10.3	7.8	0.7	1839	82	544	0.039	0.070	0.003	0.002
LH2 Ice/Frost Ramp	154.8	5.6	3.5	2.9	1262	93	540	0.024	0.037	0.014	3σ : 0.00257
LH2 Ice/Frost Ramp	N/A	7.3	1.9	2.5	1525	94	544	0.022	0.052	0.014	3σ : 0.00257
LH2 Ice/Frost Ramp	N/A	4.0	2.6	0.3	1841	89	543	0.002	0.070	0.014	3σ : 0.00257
LH2 PAL Ramp	127.1	36.3	11.0	6.7	1281	102	535	1.001	0.039	0.017	0.013
+Y Thrust Strut Flange	N/A	10.3	4.2	1.2	1918	122	543	0.069	0.074		0.024
LH2 Barrel	N/A	8.0	1.0	1.0	1291	-32	563	0.005	0.039	N/A	0.002
LH2 Barrel	N/A	8.0	1.5	1.0	1646	-32	563	0.008	0.059	N/A	0.002
LH2 Barrel	N/A	6.0	0.8	0.5	1728	0	566	0.002	0.064	N/A	0.002
LH2 Barrel	N/A	4.0	1.0	0.5	1803	26	564	0.001	0.068	N/A	0.002
LO2 F-L Sprt Brkt	N/A	3.5	1.0	1.0	1377	80	560	0.005	0.044		0.004
LH2-Intertank Flange	> SRB Sep	3.0	3.0	0.8	1123	-25	236	0.003	N/A		N/A

Foam loss incidents assigned to SSP IFA Resolution Teams are highlighted in yellow. "Mass" is the calculated mass based on imagery of the foam and estimated density. The "EIS Cert Limit" represents the Program requirement levied on the ET Project. "Max Expected Mass" is the maximum mass loss expected based on pre-flight dissection data. The "NSTS 60559 Mass" is the 3σ mass loss projection used in the DVR probabilistic risk assessment. Release times indicated with an (*) are under assessment as these debris were not directly observed leaving these foam loss locations, but observed debris movements were consistent with these locations and release times.

It is important to note that with exception of the PAL ramp, all the foam lost from STS-114 met the ET Project End-Item Specification (EIS) limit for the tank. These limits were established by test and analysis of existing ET foam. However, in 14 instances, the foam lost exceeded the maximum expected value based on pre-flight estimates built upon dissection data, and significantly exceeded the National Space Transportation System (NSTS) 60559 3σ projection used in the Delta Verification Review (DVR) probabilistic risk assessment (Table 4.0-2). The apparent disparity between specified limits and pre-flight projections was the subject of considerable discussion among ET Tiger Team members and is discussed in Additional Findings, Section 11.0.

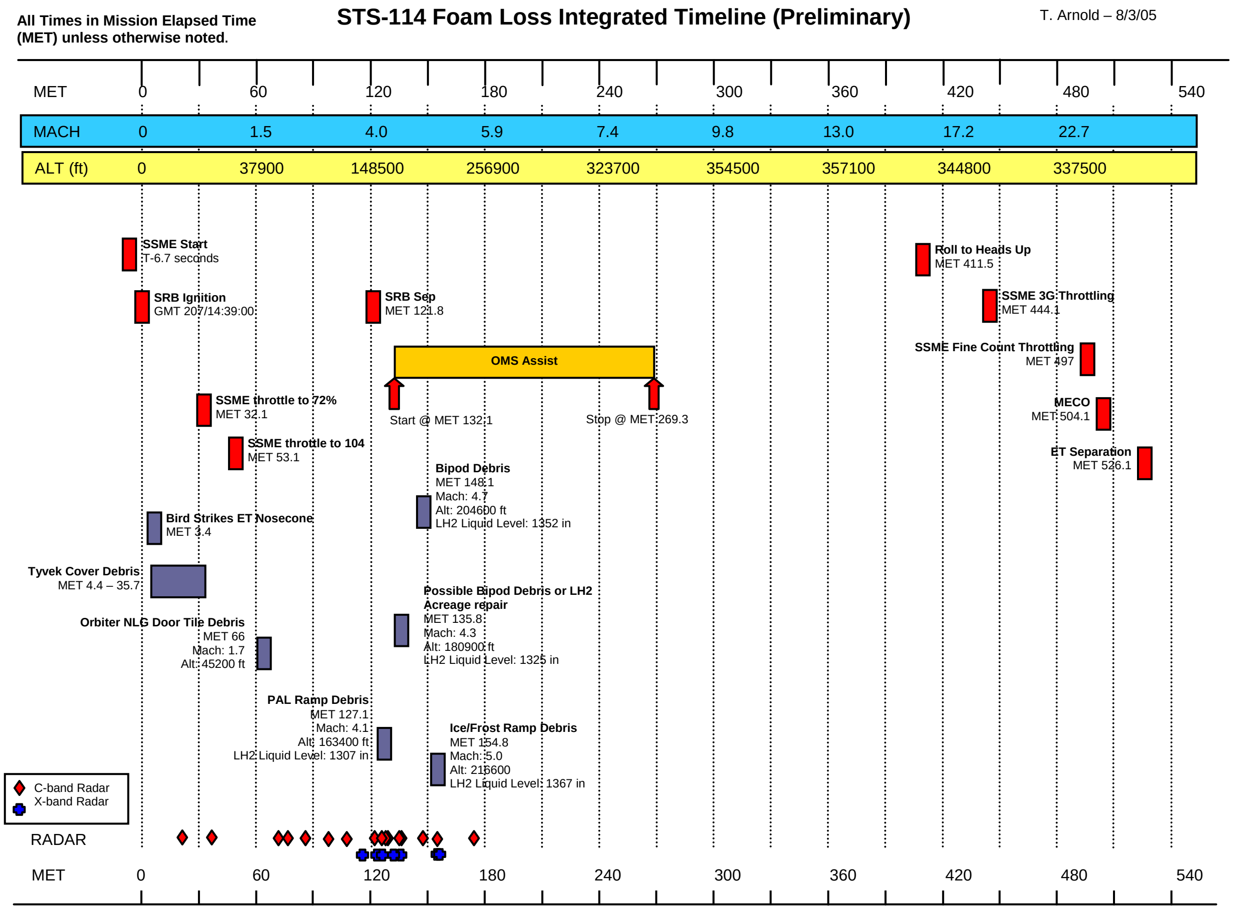

Figure 4.0-1. STS-114 ET Foam Loss Timeline

It is also important to note that the ET TPS was certified with a number of limitations documented in NSTS-60555 (ref. 14). These limitations led to a high reliance on probabilistic risk assessments for development of flight rationale. These pre-flight probabilistic assessments considered only a single large-scale cohesive failure mode (divoting due to pressurized differences between ambient air in a trapped void and external pressure inflight also called “delta pressure”). Supporting experimental data was obtained from idealized flat aluminum substrates with a simple shingle-type foam spray application and no complex geometric features. A simplified fracture mechanics approach was used to develop insight into the shape of the divot/no-divot curves built from the experimental data and to develop an analytic representation that could be adjusted by “knockdown” factors and factors of safety (FoS) to account for simplifications and unknown effects. Data was developed for only the first 135 seconds of flight. Foam lost after 135 seconds was not considered a critical threat due to the low aerodynamic loads and minimal potential for debris transfer beyond that point. At least three of the STS-114 failures occurred after 135 seconds and one, the loss from the PAL ramp, occurred at 127.1 seconds. Imagery from ET film cameras is currently under assessment, but initial indications are that as many as five or six of the other 16 pieces may have been lost late in ascent with one loss possibly occurring after ET separation. Note the time estimates are subject to limitations imposed by camera angles, resolution, and frame speed (1/30 sec), which can result in some events not being recorded. Whether the late-occurring losses should have been expected based on the limited pre-flight data or whether the probabilistic modeling should be expanded to include additional failure modes and ascent timelines was also a subject of much discussion.

While the pre-flight probability predictions addressed only divoting, a number of other ET TPS foam failure modes have been observed experimentally and in historical post-separation imagery of the tank. These include substrate debond, popcorning (small divots), delamination, transverse cracking, fragmentation/crushing, strength failure, aero-shear failure, and fatigue (ref. 47). STS-114 IFA Resolution Team efforts guided through fault tree analysis have focused primarily on two key failure modes: divoting and fragmentation or crushing.

Divoting is a large-scale cohesive failure mode resulting from the expansion of gas trapped in voids within the foam cellular structure, cryoingestion of condensed liquid nitrogen (LN_2) into trapped voids, or cryopumping of air into trapped voids. Voids may be trapped as the foam is sprayed, or form due to debonds at the substrate or knitlines[1]. During ascent, the TPS experiences aerodynamic heating, heating of the tank structural surface from the drop in propellant level and influx of hot ullage gas, and a reduction in external pressure. Subsequent expansion of the trapped gas or cryogenic liquid causes a build-up of pressure that may overstress and shear the foam with resultant foam shedding in the form of divots.

Crushing or fragmentation can result from surface loading during processing or from external local impact due to debris or ice striking the TPS during ascent. This failure mode is dependent on the incident angle and geometric shape of the impacting debris or the area of incidental contact as well as the magnitude and duration of the loads. Crushing damages the foam cellular structure and either creates relatively large internal voids that subsequently divot or effectively changes the material properties of the cells and weakens the foam. For example, if the cohesive strength of the foam near one or more voids is compromised, a divot could be produced by a sealed void that otherwise would not produce a divot. Fragmentation or crushing prior to flight may also crack the foam, leading to cryopumping and subsequent divoting on ascent.

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[1] A relatively thin layer of densified foam that forms at the interface of foam layers made by separate spray passes

5.0 Overarching Concerns

The ET Tiger Team examined overarching environmental, processing, and materials concerns that might have contributed to foam loss.

5.1 Ascent Environment

Compared to previous missions, the STS-114 ascent environment was relatively benign. Program System Engineering and Integration (SE&I) reconstruction of the ascent environment surfaced no unusual events that might have been expected to contribute to foam loss. Mach number, dynamic pressure, angle-of-attack (alpha) and angle of sideslip (beta) are the primary trajectory parameters affecting air loads. With the exception of minor excursions in alpha and beta, STS-114 Best Estimated Trajectory (BET) parameters were within the STS flight experience envelope, and the alpha and beta excursions were within the design envelope. The Q-Alpha and Q-Beta comparisons (i.e., squatcheloids) show that STS-114 BET derived parameters are within design limits (ref. 1). A single cross-wind event was noted at 55,000 feet (ref. 2), and second-stage yaw rate and lateral accelerations, soon after staging, were at the high end of the SSP experience base, but bounded by first stage accelerations (ref. 3). Neither event would have contributed to ET foam loss. Aerodynamic heating was below certification levels at all debris liberation locations and at least 10 percent below certification levels at all ET body points (ref. 4).

Accelerometer data collected in the intertank area during the STS-114 mission was reviewed. Data was collected at six locations in the general vicinity of the bi-pod. The first 25 seconds of this data are saturated as expected due to characteristics of the instrumentation and, since signal loss occurred after the solid rocket booster (SRB) separation, data beyond that point is meaningless. All valid accelerations that were recorded were found to be within NASA RP-1074 design limits (ref. 5).

While no unusual ascent environmental effects were noted that would have caused foam loss from ET-121, the potential for localized effects remains and is still under investigation by the IFA Resolution Teams (Appendix C). The teams should attempt to gain a complete understanding of ascent environmental loading at all foam loss locations.

Recommendation R07: Complete on-going PAL ramp and ice/frost ramp localized environmental analyses to understand whether local environmental effects might contribute to foam loss.

5.2 Processing

ET TPS application is a lengthy and complex effort which includes a substantial number of manual operations. The risk of collateral damage during ground processing appears significant.

Fabrication and normal pre-shipment processing of ET-121 were completed in September 2002. ET-121 was constructed with an LH_2 tank initially intended for ET-117, but re-worked when a post-proof test inspection found cracks in the structural barrel 3 ortho-grids that required replacement of that barrel and the adjacent 1624 T-ring (ref. 6). A LO_2 tank barrel also required panel removal and replacement during assembly.

Initial TPS installation for ET-121 was identical to that of past tanks except that this was the first tank sprayed with BX-265 PAL ramps. The BX-265 foam replaced the Freon-based BX-250. RTF modifications performed from November 2003 through March 2005 included a significant number of non-standard activities including rework of the LH_2 intertank flange foam, installation of redesigned bi-pod fittings and closeout foam, and installation of the LO_2 feedline bellows drip lip (ref. 7 and 8). The forward portions of the LO_2 and LH_2 re-pressurization lines were removed for access to the LH_2 intertank flange. This work drove removal and replacement of the upper portion of the three forward LH_2 ice/frost ramps (stations 1151, 1205, and 1270). The forward ten feet of the LH_2 PAL ramp was also removed to facilitate flange rework and subsequently replaced with an enhanced BX-265 manual spray process.

ET-121 was shipped to KSC on March 5, 2005 and mated in preparation for the STS-121 mission (ref. 7). The tank was re-manifested for STS-114 due to problems with the original STS-114 tank (ET-120). ET-121 LO_2 and LH_2 diffusers were replaced at KSC and bellows heaters installed. This work required removal of the nose cap and non-routine access to the intertank area. The tank was exposed to two cryogenic fill and drain cycles prior to launch, the first due to tanking and a subsequent launch scrub and the second due to tanking for launch. TPS performance in the vicinity of the foam loss areas was normal during both launch attempts with no cracking, frost formation, or off-nominal performance observed.

ET-120 processing activities were reviewed and found to be similar to ET-121, except the PAL ramps were initially sprayed with BX-250. The forward ten feet of the LH_2 PAL ramp was removed and replaced with an enhanced BX-265 manual spray process. ET-120 was initially completed in July 2002 and RTF rework was completed in December 2004 (ref. 8). The tank was shipped to KSC for STS-114 and exposed to two cryogenic fill and drain cycles for tanking tests before being re-manifested. TPS behavior was normal during both tanking tests with no significant cracking, frost formation, or off-nominal performance noted.

ET-119 processing differed slightly from ET-121 and ET-120 in that the tank was completed and shipped to KSC, then returned to Michoud Assembly Facility (MAF) for RTF modifications including bellows heater installation (ref. 9). The PAL ramps were initially sprayed with BX-250, then the forward ten-foot section of the LH_2 PAL ramp was removed and replaced with an enhanced BX-265 manual spray process. The tank was returned to KSC in June 2005 where the LH_2 diffuser replacement was performed. ET-119 has not been exposed to cryogenic conditions.

Ground-handling loads (transport, lifting, etc.) appear to be well-encompassed by flight environments. Loading effects during tank transfer to the vertical position were assessed for their impact on the TPS and found to be negligible. The tank is lifted using a 4-point sling that attaches to the forward ET/SRB fittings and at the aft Orbiter/ET interface ball fittings. The tank is at ambient temperature and the internal pressure is approximately 6 psig. As the tank is lifted to the vertical position, the entire weight is reacted at the forward SRB fitting locations and distributed through the intertank structure. The aft attach locations are used to stabilize the tank and prevent “swinging” during the lift. Once the tank is vertical, the weight of the ET structure below the lift points induces a very small net tension load through the LH_2 tank shell. The internal pressure induces additional net tension loading and helps stabilize the shell structure. For an ambient temperature condition with 6 psig tank pressure, the mechanical in-plane shell stresses are much lower than the flight limit values (~18 percent of flight limit at 34 psig) and thermal stresses due to coefficient of thermal expansion (CTE) mismatches do not exist. The additional tensile stress induced by the weight of the tank as the lift operation occurs is only a small fraction (~12 percent) of the loading induced by the 6 psig internal pressure and is negligible for TPS bondline delamination. The resulting TPS bondline FoS for an ambient tank at 6 psig is greater than 2.0. For outer fiber cracking during lift, the forces that drive the large changes in shell curvature are not present and the resulting TPS outer fiber cracking FoS is also greater than 2.0 (ref. 10).

While ground-handling loads were judged inconsequential, the occurrence of collateral damage during ground processing appears significant with numerous cuts, scratches, crushed foam and other damage documented during ET-121 processing. The rework of ET-121 and subsequent tanks, and the performance of that work after installation of the LH_2 PAL ramp, represents a significant departure from the normal processing flow. A high correlation was noted between areas of the tank with the highest levels of processing traffic (those adjacent to work platforms, mats, etc.), the locations of documented repairs known as nonconformance documents, or NCDs, and the locations from which foam was lost on STS-114 (Figure 5.2-1). Comparison to the –Z side of the tank, which sees relatively little processing activity, illustrates the point (Figures 5.2-2 and 5.2-3). Data collected for ET-119 and ET-115 shows a similar pattern: foam loss typically occurs in locations that have seen the highest levels of processing traffic (Appendix A). This suggests the possibility that undetected collateral damage may be a direct or contributing cause of some foam loss.

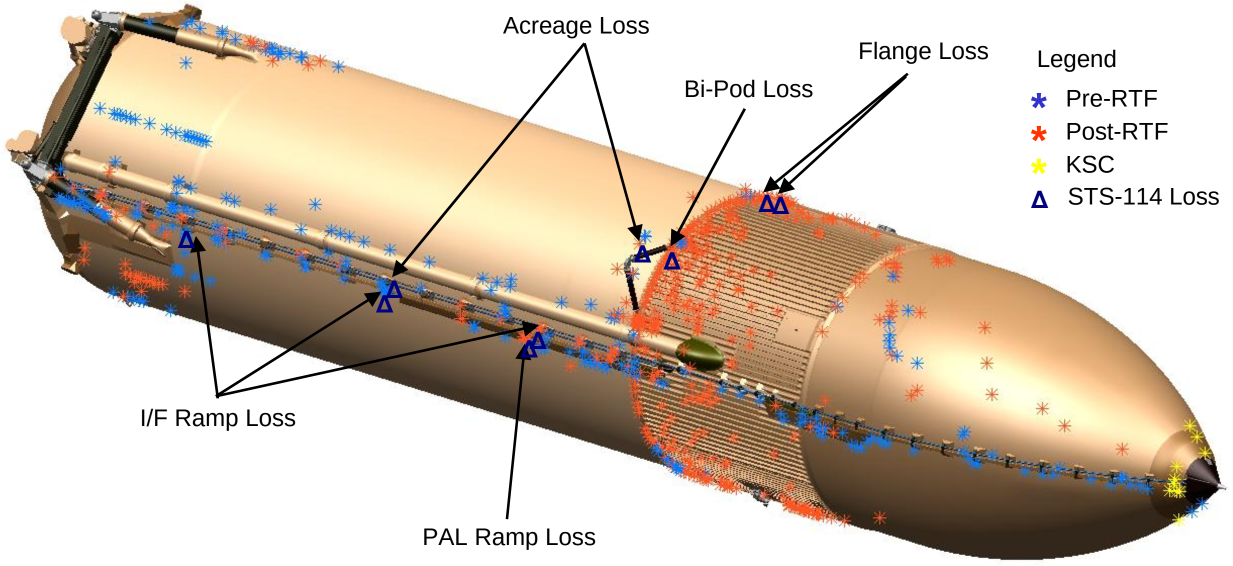


Figure 5.2-1. ET-121 Nonconformance Document (NCD) Map with STS-114 Foam Loss Overlay

NCD locations shown here and in Figure 5.2-2 are approximate. Since all NCDs do not carry detailed x-y-z coordinate data, not all discrepancy locations are plotted.

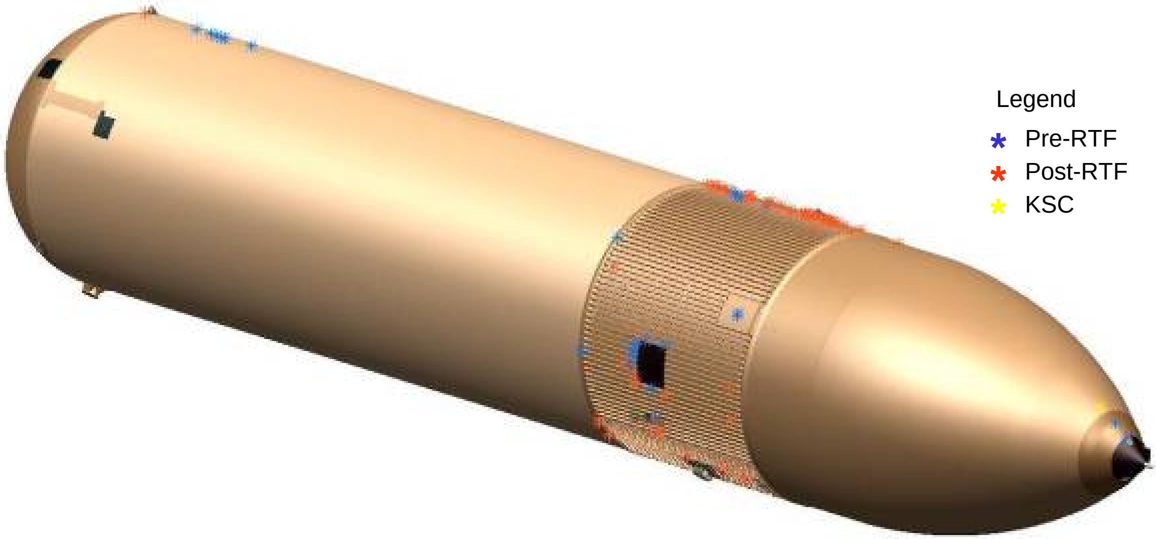


Figure 5.2-2. ET-121 Nonconformances Documented on the –Z Side of the Tank

Figure 5.2-3. ET-121 On-Orbit +Z / -Z Comparison

On-orbit photographs of ET-121 clearly show a higher level of foam loss in the acreage on the +Z (near) side of the tank as compared to the –Z (back) side (refer to Figure 5.2-3 and Appendix B). This is the side of the tank that sees the highest level of traffic during processing, again raising the possibility that undetected collateral damage to the acreage TPS may be a contributor to foam loss.

MAF personnel take steps to protect the tank TPS from collateral damage, but the protective mats and "bridges" used to cover the hardware and provide access to work locations are not under configuration control. Foam loading from these mats and bridges has not been fully assessed, although TPS foam has very little damage tolerance. The SSP's IFA Resolution Teams have testing planned to better characterize the effects such loads have on manually-sprayed BX-265 and the robotically-sprayed North Carolina Foam Institute (NCFI) acreage foam (Appendix C).

Recommendation R08: Complete BX-265 and NCFI material characterization tests including crush tests.

Foam repair processes were originally validated by simulating specific repairs in the MAF TPS engineering lab and measuring the bond adhesion values. Minimum values recorded were then compared to stress allowables for acceptance (ref. 11). Given the high correlation between repaired areas and in-flight foam loss, the ET Tiger Team recommends all TPS repair processes be revalidated and recertified. The potential for void entrapment should be assessed during revalidation and the sensitivity of repairs to process variations defined (depth, size, cutout geometry, etc.). The potential for damaging adjacent foam during repairs should also be evaluated, including the impact of installing and removing tape, masks, etc.

Recommendation R10: Revalidate and recertify foam repair processes to demonstrate structural strength of the repairs and ensure integrity of surrounding TPS is not compromised.

MAF personnel have done a commendable job implementing Foreign Object/Debris (FOD) control measures. However, a more formal, rigorous damage protection program should be implemented to enhance the protection of flight hardware and minimize the potential for collateral damage during processing. The following specific actions should be taken in conjunction with this recommendation:

1. Formally control access to flight hardware through use of access logs and implementation of a "buddy system" to help mitigate the potential for undetected damage.

2. Validate the design of mats and other access aids with respect to load diffusion, contact stress, and material chemistry compatibility.

3. Initiate formal tool design and configuration controls for access aids, pads, and covers, and determine, certify, and enforce weight limits and usage configurations. Periodically audit these items to determine that adequate protection is provided.

4. Establish written rules and procedures for working on a tank, with or without mats and other access aids.

5. Mark the edges of platforms and protective covers for personnel visual reference, especially when work areas are masked with "kraft" paper for spraying, to prevent inadvertent walk-off of mats and minimize the potential for kick loads.

6. Ensure KSC handling and repair processes are consistent with enhanced procedures recommended for implementation at MAF.

7. Implement changes to minimize and eventually eliminate "on-tank" technician work by maximizing use of fixed platforms and modifying worker access (i.e., tank in a vertical or overhead orientation). This effort should be done incrementally, with complete implementation occurring on the first pristine tank.

Recommendation R11: Improve hardware protection provisions to minimize the potential for collateral hardware damage during processing.

Recommendation R17 (Long-Term): Eliminate tank traffic to the extent possible and implement a no-touch processing policy.

The following specific actions should be taken to improve in-process as well as damage and repair record-keeping:

1. Acquire high-resolution digital photos and/or videos of all damage before and after re-work, and cross-reference to applicable processing paper. Provide sufficient scale and detail, and provide links to an electronic catalog of reworks and repairs.

2. For each tank, develop and maintain detailed damage and repair maps that can be used to help identify deficiencies in handling protection measures.

3. Upgrade processing documentation for all tanks, i.e., NCDs and In-Process Repair Authorization Sheets (IPRAS), to include specific high accuracy x-y coordinates of all damaged and repaired areas, and maintain data in an electronic system.

4. Obtain high-resolution closeout photographs after each incremental TPS closeout application step (i.e., primer/surface preparation, bi-pod wedge spray, fitting/wire installation, and upper closeout spray) and at completion of each manual closeout or pour operation.

5. Conduct a 100 percent coverage high-resolution photographic survey of each tank with focus on known high traffic areas at tank shipment and prior to transfer to the launch pad at KSC. Catalog photographs for ready reference.

Recommendation R12: Improve in-process data collection and documentation to include digital photos of all damaged TPS pre-and post-repair and collection of specific x-y coordinates for all repairs.

No hazard controls exist related to potential loss of ET TPS except limited tactile and visual inspections and those processing controls in place when the foam is sprayed. The ET-121 PAL ramp was subjected to terahertz and backscatter NDE after installation. Since those techniques are not certified, the data collected was used only for engineering analysis. These NDE techniques do hold promise as does shearography. The ET Tiger Team recommends the SSP continue to aggressively pursue these tools with the goal of developing verification methods for all ET TPS. The team recommends every effort be made to improve NDE techniques and field-certified hardware and software suitable for validating TPS integrity as soon as possible. NDE should be performed on all foam loss areas of the next flight tank using the best-available techniques and, where possible, the results substantiated by dissection data.

Recommendation R13: Develop and implement improved damage detection processes, including NDE and tactile inspections in all foam loss areas.

Recommendation R18 (Long-Term): Develop and certify NDE for all ET TPS applications.

5.3 Materials

As noted previously, ET-121 marked the first use of BX-265 for flight tank PAL ramps, the LH_2 intertank flange, and bi-pod closeouts. BX-265 was certified as a BX-250 replacement with limitations noted in NSTS 60555 and NSTS 60559 specifically relating to the statistical significance of the BX-250 properties database (ref. 12 and 13). The major difference between the two foams is the blowing agent. BX-250 uses CFC-11, banned by the EPA as an ozone depleting agent, and BX-265 uses HCFC-141B. Material properties of these foams are application-sensitive and no more BX-250 is available for additional tests, so a side-by-side comparison of the materials is difficult. Nonetheless, BX-265 does appear to be at least as suitable for use on a tank as BX-250, providing it is properly applied. The IFA Resolution teams have outlined a program of additional testing to better characterize BX-265 mechanical properties (Appendix C).

Contamination control at MAF consists of FOD control and minimizing the introduction of items that could cause the degradation of a process (ref. 14). With the introduction of FOD control, unnecessary chemicals, materials, and maintenance items were removed from work areas to minimize the potential for cross-contamination. In addition, all historical and new chemicals and materials used on site at MAF were evaluated to establish their contamination potential. This is an ongoing effort led by the Michoud Materials Evaluation Team (MMET).

6.0 PAL Ramp

Damage Description

A section of foam approximately 36 x 11 inches (1 lbm) was lost from the LH_2 PAL ramp at 127.1 seconds mission elapsed time (MET) (Figure 6.0-1).

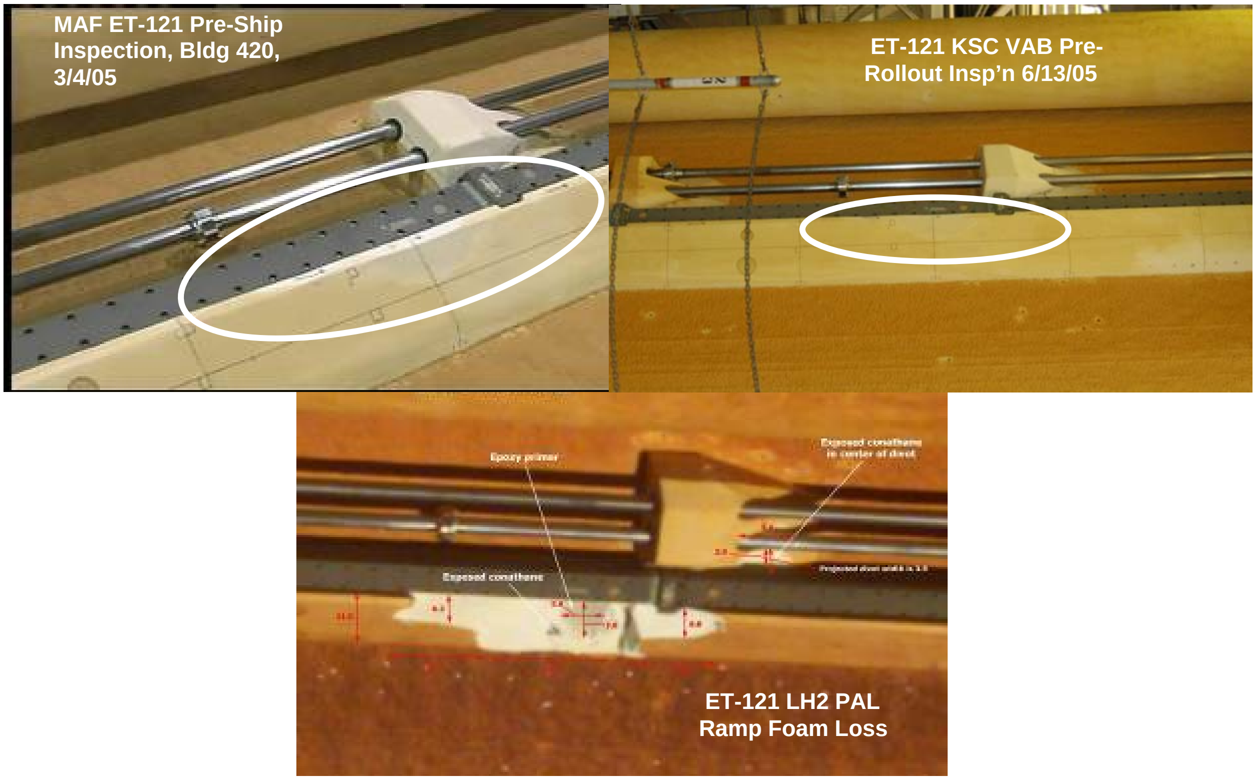


Figure 6.0-1. STS-114 PAL Ramp Foam Loss

Flight Environments

The PAL ramp foam loss occurred 5.3 seconds after SRB separation, a time when aerodynamic loads are relatively benign. The separation event caused the bow shock wave from the SRB to traverse the Orbiter/ET stack and thus the LH_2 PAL ramp (Figure 6.0-2). As the shock wave passes by the PAL ramp foam loss region, a surface pressure transient, and thus a load transient, will occur. This transient is low due to the low dynamic pressure (q-bar < 35 psf) at SRB separation and deemed insufficient by itself to cause the foam loss observed (ref. 1).

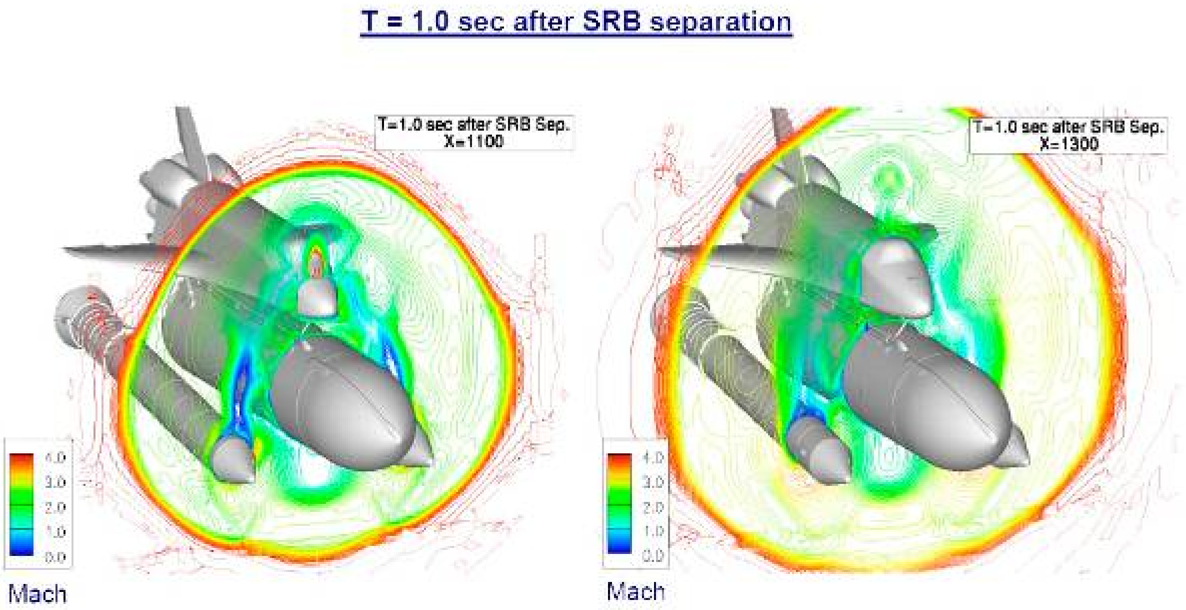


Figure 6.0-2. Shock Impingement at SRB Separation

The loads transfer associated with SRB separation was also assessed (ref. 10). At the time of separation, SRB thrust is significantly reduced and the Space Shuttle Main Engine (SSME) thrust load is the largest amplitude forcing function through the LH_2 tank barrel structure. To assess the transient loads at the LH_2 PAL ramp during SRB separation, an analysis was performed to generate a comparison of the maximum design shell compression loads for both the pre-staging and post-staging load conditions. The results of the analysis show that SSME-induced compression loading does increase from pre- to post-staging, but the overall tank shell loading remains in tension (i.e., there is insufficient loading to overcome internal pressure-induced shell loading). The absence of net compression eliminates the potential for localized shell buckling as a contributor to the PAL ramp foam loss event. Because the LH_2 tank shell is a stiff, pressure-stabilized structure and the loads transfer is somewhat gradual as the SRB thrust drops off, the effect of the loads transfer on the PAL ramp is negligible.

Thermal effects were also assessed. The primary load drivers for bondline delamination of the PAL ramp foam are CTE mismatch-induced TPS stresses at cryogenic conditions and the mechanical in-plane shell stresses caused primarily by tank pressurization (ref. 10). The loads that drive this failure mode occur during tanking and during ascent when the tank is at cryogenic temperature and the internal pressure is ~34 psig. While wide-panel and cryoflex verification testing have successfully verified the TPS for the critical thermal and mechanical strain conditions to a FoS of 1.25, the ET Tiger Team noted that the PAL ramp foam loss occurred just after the LH_2 tank liquid level dropped below the foam loss area and an associated temperature gradient existed. While perhaps not sufficient to cause the loss of foam in and of itself, this thermal change does have implications as a possible contributor and requires further assessment.

A discrete Finite Element Model (FEM) analysis is in-work to further substantiate the structural response of the aluminum substrate in the region of the LH_2 PAL ramp for the load environments experienced during SRB separation. Localized flow-field effects are also being assessed (Appendix C).

Processing

The forward 10 feet of the LH_2 PAL ramp was removed and re-sprayed in February 2005 with an enhanced BX-265 manual spray process. The aft 28 feet of the LH_2 PAL ramp and the entire 14 feet of the LO_2 PAL ramp were manually-sprayed with BX-265 in June 2002 before process improvements were implemented. The foam loss occurred in the older aft section of the LH_2 PAL ramp. Removal of the forward 10-foot section was the topic of discussion prior to STS-114, and the PAL ramp aft section use-as-is decision was the subject of significant pre-flight discussion, which resulted in written minority opinions recommending the removal and replacement to take advantage of process enhancements (ref. 15). When the decision was made to fly the aft portion of the LH_2 PAL ramp as-is, limited data existed to quantify the improvements provided by the enhanced PAL ramp sprays. Additional data subsequently collected shows the enhanced process offers substantial improvement (Table 6.0-1).

Table 6.0-1. Effect of Process Improvements on Defect Number and Size

ET / Ramp	Number of Defects	Number of Defects / Linear Foot	Largest Void Volume (in3)	Largest Characteristic Dimension (in)
As-built LO2 ramp (15 feet)				
ET-94	8	0.53 / linear ft	0.144	1.10
ET-123	10	0.67 / linear ft	0.28	1.10
As-built LH2 Ramp				
ET-94 (38 feet)	34	0.89 / linear ft	0.151	1.00
ET-120 fwd 10 feet	9	0.90 / linear ft	0.17	1.05
ET-121 fwd 10 feet	3	0.30 / linear ft	0.019	0.63
Enhanced LO2 Ramp				
1st Spray	16	1.06 / linear ft	0.179	1.0
2nd Spray	2	0.13 / linear ft	0.05	0.4
3rd Spray	2	0.13 / linear ft	0.056	1.9
Enhanced LH2 Ramp				
1st Spray (full)	13	0.89 / linear ft	0.081	0.9
2nd Spray (partial)	4	0.40 / linear ft	0.063	1.0
6 LH2 V&V runs	9	0.15 / linear ft		0.9

Four nonconformances associated with processing were documented in the PAL ramp foam loss areas and reviewed in detail by the PAL Ramp IFA Resolution Team. The most significant is an NCD for an area of crushed foam 0.2" deep by 0.6" long on the ramp directly over the area where PAL ramp foam was lost. The crushed foam was removed by sanding and blending and the rework area was clearly visible in pre-flight photographs. The sand-and-blend area visible in closeout photographs is much larger (18"L x 9"W). This larger size is due to a requirement to blend until surface waviness requirements are met (Figure 6.0-3). Two NCDs (apparent duplicates) were also documented for rollovers at the base of the PAL ramp along the entire edge adjacent to the cable tray and a fourth for out-of-spec LH_2 barrel primer thickness. The ultimate disposition of these three NCDs was to use as-is. None of these discrepancies would have caused the PAL ramp foam loss, although the first is significant as an indicator of collateral damage which occurred during rework in the PAL ramp area.

NDE of the PAL ramp was performed before flight to gather data useful for long-term development of NDE tools. Post-flight evaluations of terahertz and backscatter data techniques highlighted a low density region along the leading edge of the PAL ramp most prominent in the area of foam loss, a concentration of knitlines in the region, and a low density indication (Figures 6.0-3 and 6.0-4). These NDE observations were generally consistent with other parts of the ET-121 LH_2 and LO_2 PAL ramps and were thought insignificant at the time the data was collected (ref. 16). The NDE results in the ET-119 LO_2 PAL ramp are very similar to those in the ET-121 LH_2 PAL ramp divot region. Eight of the 10 indication types identified in the divot region were observed in the LO_2 PAL ramp. The sharp low density indication (Type 9 in Figure 6.0-3) and the broad low density indication (Type 10 in Figure 6.0-3) were not observed in the ET-119 LO_2 PAL ramp.

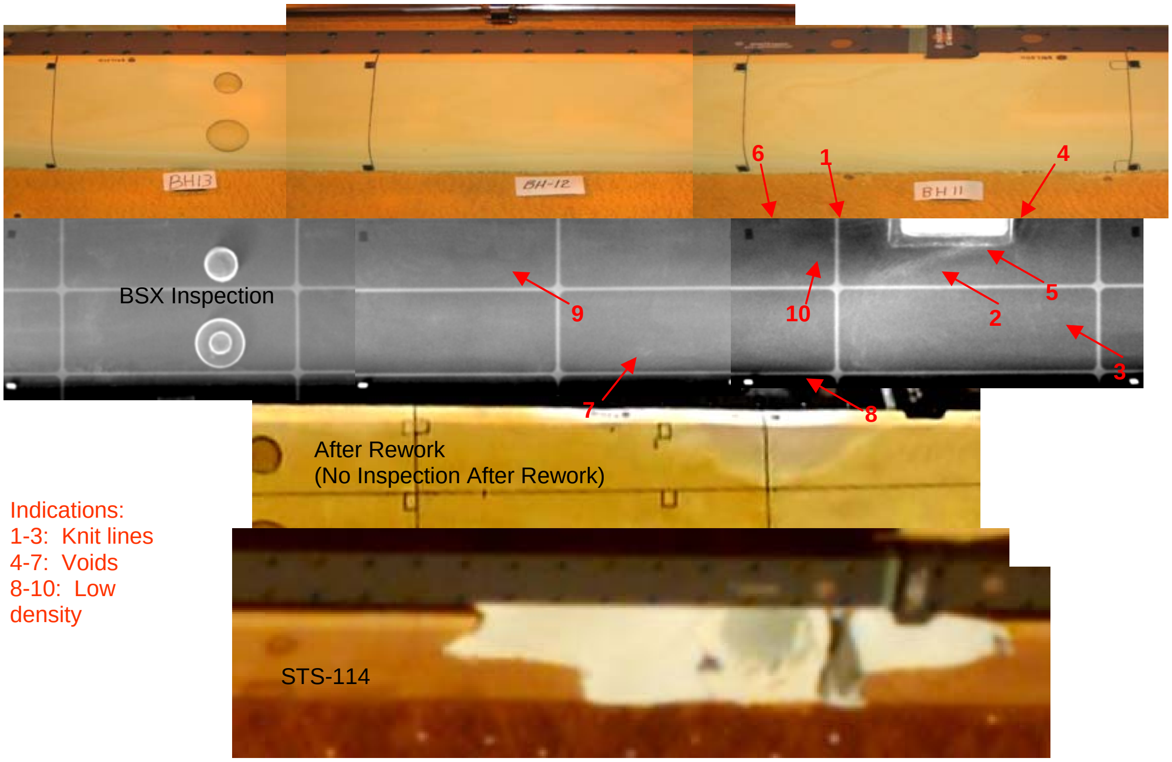
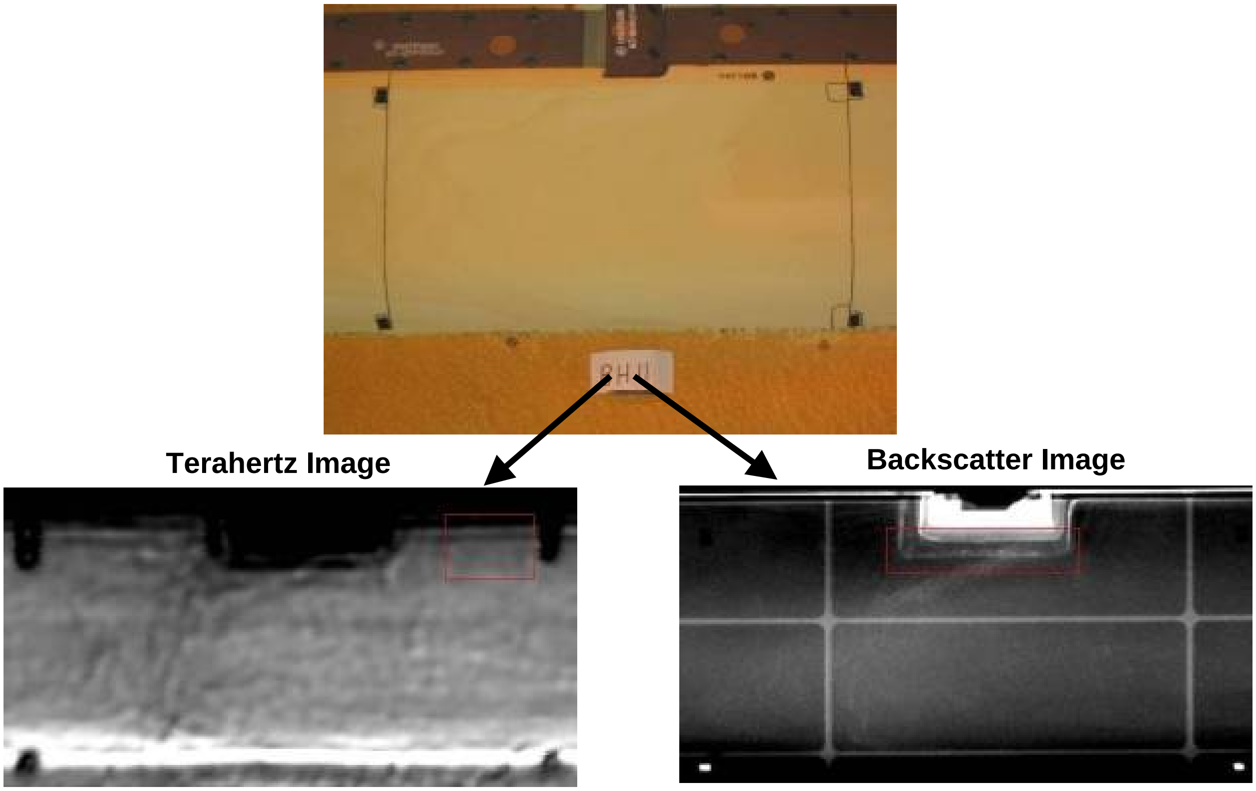


Figure 6.0-3. Backscatter Image of ET-121 PAL Ramp Foam Loss Area



(Light Color = lower density)

(Dark Color = lower density)

Figure 6.0-4. Terahertz and Backscatter Indications in the ET-121 Foam Loss Area

Note NDE was performed before the PAL ramp crushed foam was documented and the sand-and-blend rework performed. No post-RTF rework NDE exists.

The PAL ramps ordinarily are the last major TPS component installed, yet RTF modifications drove extensive work in the immediate vicinity of the lost foam. At least one instance of collateral damage occurred per the NCD noted earlier. Protective mats and bridges were used for access over the LH_2 PAL ramp when the work was done, imparting unknown loads into the BX-265 material (Figure 6.0-5). The ET Tiger Team noted that these protective covers are not configuration-controlled and have not been subjected to rigorous engineering analysis. The PAL Ramp IFA Resolution Team has additional testing planned to better characterize the response of BX-265 and NCFI to loads imparted during processing (Appendix C).

Figure 6.0-5. Re-enacted Image Demonstrating Tank Re-Work over the PAL Ramp

Mats were used to provide hardware protection during ET-121 RTF rework. Bridge shown in the upper right is a shop-aid used to provide access across the PAL ramp and re-pressurization lines for work on the LO_2 *feedline.*

Materials

The ET-121 PAL ramp was composed of BX-265, sprayed over a sanded, Conathane-coated NCFI substrate that has approximately ½ of the average tensile strength of BX-265. Review of processing data found no evidence that materials used in fabrication of the STS-114 PAL ramps were substandard. Plug pull and lead-in and lead-out spray environmental data was nominal (ref. 17). BX-265 has a 50 degrees F higher application temperature than BX-250, and the PAL Ramp IFA Resolution Team is planning tests to verify that no unexpected interaction occurs between BX-265 and Conathane due to the higher application temperature (Appendix C).

Most Probable Causes

None of the material reviewed by the ET Tiger Team has established a distinct root cause for the ET-121 PAL ramp foam loss, although the on-going fault tree analysis has surfaced several possibilities. The lack of a cryogenic source in the PAL ramp foam loss area rules out cryoingestion as a possible cause. Shape and size of the defect suggest a void may have been trapped near the substrate when the PAL ramp was sprayed, although such a void would have been much larger than expected voids. Cryopumping through an accompanying leak path could have then initiated the sequence of events that led to foam loss. The ET Tiger Team noted the defect occurred in the immediate vicinity of the cable tray bracket, and the ice/frost ramp foam closeout in this area extends into the PAL ramp spray region, offering a sharp corner likely to trap voids during foam application (Figure 6.0-6). The bracket is thermally coupled to the LH_2 barrel structure, increasing the likelihood that temperatures in the region would have been conducive to cryopumping. Fracture due to a combination of foam defects or undetected collateral damage, coupled with an external force is a possible cause. The external force most likely is a thermal stress imposed on the PAL ramp as liquid level dropped due to the differing CTEs of aluminum, NCFI, PDL, and BX-265.

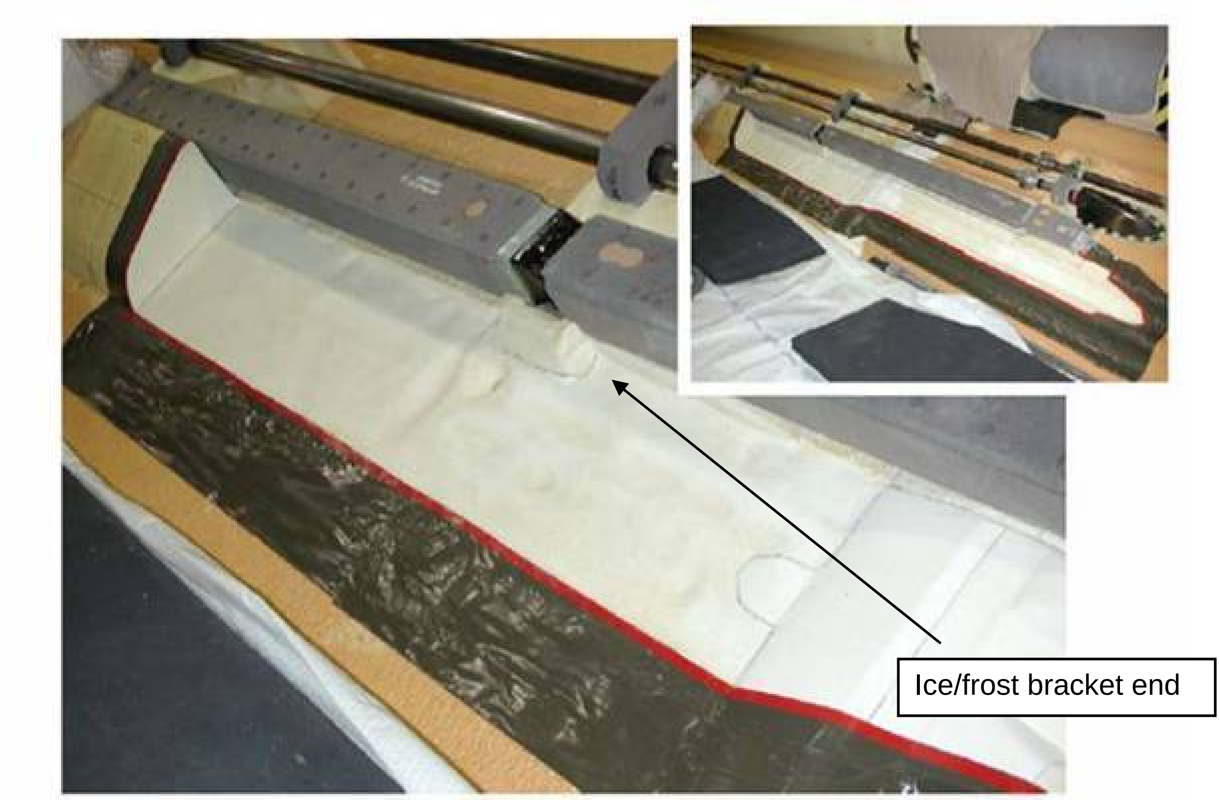


Figure 6.0-6. ET-120 PAL Ramp prior to Re-spray Showing Location of the Ice/Frost Bracket

Complex geometry in this area may contribute to void formation during PAL ramp spray.

ET Tiger Team Recommendations

In the absence of overwhelming evidence pointing to a distinct root cause, the ET Tiger Team recommends action be taken prior to STS-121 to eliminate the likely contributing causes noted above. Since all existing tanks were sprayed before new processing enhancements were implemented, voids or other defects may exist that could be eliminated if the PAL ramps were re-sprayed. Consequently, the ET Tiger Team recommends the existing PAL ramps be removed and replaced with best-available controls and in such a manner as to minimize the potential for void formation and entrapment.

Recommendation R01: Remove and replace the entire length of the LO_2 and LH_2 PAL ramps using the best available quality controls. Verify the underlying acreage foam integrity prior to re-spray.

Recommendation R02: Minimize or eliminate the portion of the ice/frost ramp that projects beneath the PAL ramp area to reduce the potential for void formation during PAL ramp spray.

NDE is not mature enough to effectively screen potential defects and validate integrity of the tank TPS. However, the techniques available do hold promise and the ET Tiger Team recommends the SSP aggressively pursue development and certification of NDE suitable for validating all ET TPS. Dissection and study of the existing ramps – especially that on ET-120 which has seen two cryogenic fill and drain cycles – offers an opportunity to gain additional data to further that goal, and to better understand the root cause of the STS-114 PAL ramp foam loss. The ET Tiger Team strongly recommends the SSP take maximum advantage of that opportunity and dissect all the existing PAL ramps, including ET-120. NDE should be performed before the existing PAL ramps are removed, on the NCFI substrate after removal of the PAL ramps, and on the new PAL ramps after they are installed. NDE observations should be compared against actual dissection data and a detailed comparison (predictions vs. actuals) generated for each of the dissected PAL ramps.

Recommendation R06: Complete NDE and dissection of existing PAL ramps, including the area beneath the PAL ramp in the vicinity of the ice/frost ramps, to better understand the ET-121 failure and identify areas needing improved manual spray processes.

In the future, the only way to ensure no foam will be lost from the PAL ramps is to eliminate ramps altogether. A wind tunnel test program has been completed for both the LO_2 and LH_2 cable trays without the PAL ramps, and initial results indicate the PAL ramps are not required to protect the cable trays from aeroelastic instabilities (ref. 18). STS-114 LO_2 tank cable tray data collected to validate test program results is under analysis, but initial results appear to confirm the test program conclusion that the PAL ramp can be eliminated. Wind tunnel limitations did not permit testing to continue beyond the flight envelope required to establish a 32 percent margin for the LH_2 tank cable tray as required by NSTS-07700 Vol. X. Additional testing is required before the LH_2 PAL ramp can be removed. The ET Tiger Team recommends the SSP undertake whatever additional testing is required to substantiate wind tunnel results, including instrumentation of flight cable trays if necessary, and that the PAL ramps be eliminated at the earliest opportunity.

Recommendation R14 (Long-Term): Eliminate the PAL ramps at the earliest possible opportunity, coincident with rigorous aerodynamic test and analysis.

While tight processing controls have improved the quality of manual sprays, automated sprays offer the potential for further improvements. The ET Tiger Team recommends automated sprays be aggressively pursued as an interim measure until the ramps can be eliminated.

Recommendation R15 (Long-Term): Aggressively pursue implementation of robotic PAL ramp sprays in parallel with the ramp removal effort.

7.0 Bi-Pod

Damage Description

A 7 x 8 inch divot (0.023 lbm) was observed on the forward outboard portion of the –Y bi-pod closeout at approximately 148 seconds MET (Figure 7.0-1). Exposed substrate is visible in the post-ET separation photographs. Loss occurred in proximity to the bi-pod fitting heater wires, as indicated by Computer Aided Three-Dimensional Interactive Application (CATIA) modeling (Figure 7.0-2).

Figure 7.0-1. STS-114 Bi-pod Foam Loss

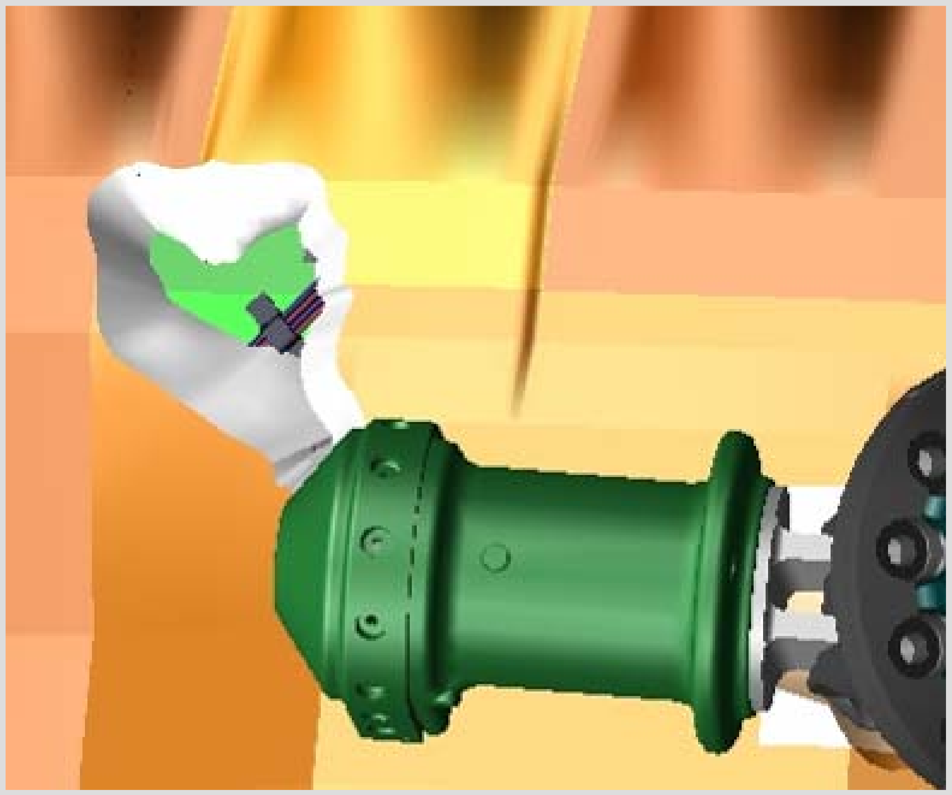


Figure 7.0-2. CATIA Model of the STS-114 Bi-Pod Foam Loss Area
Wiring location is approximate.

Flight Environments

Reconstruction of the ET-121 ascent environment surfaced no unusual conditions that would have contributed to loss of the bi-pod foam. Accelerometers installed in the intertank area for STS-114 recorded no values outside certified limits (ref. 5). STS-114 reconstructed BET aeroheating was found to be within STS-114 mission specific (MS) certification at 44 locations. The heat load at body point BP 21087 slightly inboard of the –Y bi-pod fitting is depicted in Figure 7.0-3 (ref. 30).

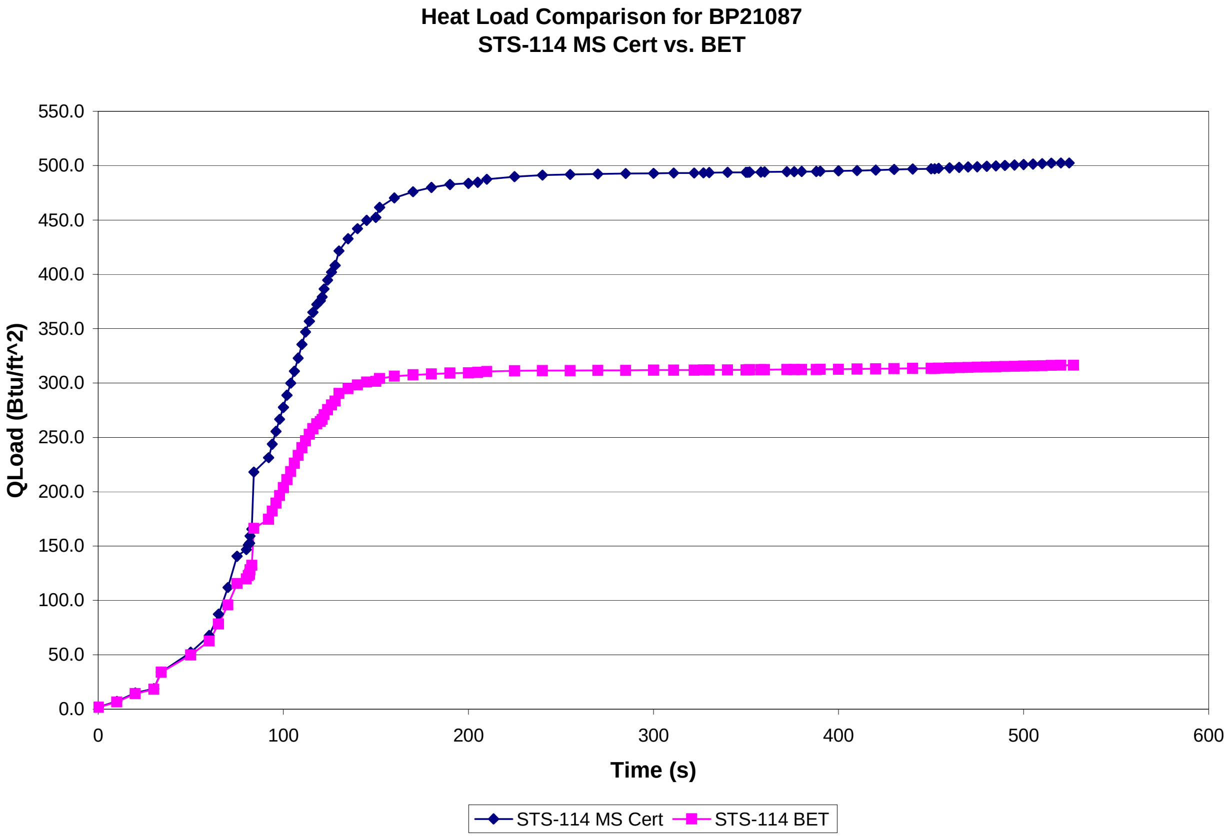


Figure 7.0-3. STS-114 Bi-Pod Heat Load Comparison to Certification Limits

Processing

A newly-designed ET bi-pod area closeout was implemented on ET-121 and flown for the first time on STS-114. The bi-pod aerodynamic ramps were removed in conjunction with the new design and heaters installed to prevent ice formation during tanking. Wiring for the heaters was routed from each bi-pod spindle along the tank skin, into a stringer, and into the intertank above the flange (Figure 7.0-4). The wiring was secured with an epoxy overcoat and sprayed with BX-265 closeout foam. During thermal/vacuum testing of high-fidelity 3’ x 5’ bipod test panels required for certification of the redesigned closeout, one to two cracks were noted in the BX-265 during each of 14 cryogenic cycles (ref. 24). The cracks varied from 1/4 inch to 2 inches in length and formed during simulated de-tanking (warm-up) periods. Despite the cracking, no divots were formed during either of two simulated ascent cycles. The cracks were thought to be caused by high thermally-induced TPS stress levels generated as a result of CTE differences between the aluminum substrate, TPS, and other dissimilar materials including primer, adhesives, and wiring. No cracking was observed on ET-121 during either the scrubbed or actual launch attempts. It is worth noting that during the warm-up period of the first tanking test of STS-114 with ET-120, cracks similar to those seen on the test panels were observed.

Figure 7.0-4. Bi-Pod Heater Wire Routing

Two NCDs were recorded. One NCD associated with the final closeout addressed two relatively small surface voids (0.1 in x 0.05 in x 0.05 in deep and 0.5 in x 0.2 in x 0.2 in deep) in the forward cavity, one of which required a repair with a Polymer Development Laboratories (PDL) foam material. The second NCD was associated with the PDL spindle pour trim done prior to final closeout and addressed an area on the forward top surface of the spindle pour that was trimmed 0.1 inch – 0.2 inch too thin. The ET Project's disposition was to use as-is.

During the first ET-120 tanking test, the +Y bi-pod spindle heater required about 30 watts more power than the –Y spindle. During LH_2 replenish, the –Y heater "caught up" and passed the +Y heater by about 80 watts. A similar current shift did not occur during the second ET-120 tanking test, but a shift of about 150 watts was recorded during both ET-121 tankings (ref. 25). This power shift phenomenon was investigated to determine whether it held clues to the bi-pod foam loss, but no connection between the two has been established. Heater and bi-pod testing were performed to determine if cryogenic effects on wiring could cause the heater power shift, but heater power was able to maintain bi-pod temperature even as the wire was chilled down to -423 degrees F. Elimination of all cable resistance would only account for a seven-watt increase in power (ref. 25).

Operation of the heaters during STS-114 Engine Cut-Off (ECO) sensor testing was assessed to ensure off-nominal heater operation had not caused damage to the bi-pod closeout. Parameters were monitored during all testing to ensure heater power-on did not drive temperatures above established limits.

Materials

The bi-pod area was sprayed with BX-265 over aluminum primer. Review of processing data found no evidence that the ET-121 bi-pod foam was substandard. Plug pull and environmental data was nominal (ref. 26).

Most Probable Causes

Although the new bi-pod closeout was specifically designed to minimize the potential for entrapment of a sealed void, the possibility remains one may have existed in the closeout and divoted on ascent. Also, the possibility of cryopumping through the combination of a void and a crack in the closeout cannot be eliminated. CTE-induced cracking could enable a cryopumping path, allowing a normally non-debris producing sealed void to produce debris with a relatively large amount of mass. However the location of the failure, adjacent to the -Y bi-pod spindle heater wiring, suggests another possibility the ET Tiger Team considers more likely. The unsealed Kapton insulation jacket covering the bi-pod heater wiring provides a path for transfer of LN_2 from the intertank to the bi-pod closeout area. As a result, the potential for cryoingestion exists, an issue not noted in pre-flight certification and testing. Tests performed by the Bi-Pod IFA Resolution Team have confirmed that a leak path exists and have verified the ability of the heater cabling to hold gas pressure in a cryogenic environment. Formation of a frozen nitrogen block within the cabling has also been verified. While the Bi-Pod IFA Resolution Team plans more testing to confirm this theory, the most probable cause of the STS-114 bi-pod foam loss is believed to be cryoingestion through the heater wiring cable.

ET Tiger Team Recommendations

Efforts to redesign the bi-pod closeout to minimize foam loss after STS-107 were extensive and it is unlikely much more can be done to minimize the potential for void formation. The presence of a cryogenic path through the heater cabling must be addressed before flight whether or not it was the cause of the STS-114 failure. The ET Tiger Team recommends the SSP pursue appropriate modifications to eliminate this potential cause.

Recommendation R03: Implement modifications required to prevent cryopumping through bi-pod heater wiring.

The ET-120 bi-pod closeout has seen at least two cryogenic cycles and may hold additional clues to the cause of the STS-114 foam loss. Since cracking was observed in verification and validation (V&V) closeouts during warm-up from cryogenic cycles and the potential for cryopumping through a crack in the bi-pod closeout has not been eliminated as a possible root cause of the ET-114 foam loss, the ET Tiger Team strongly recommends the SSP dissect the ET-120 bi-pod closeout.

Recommendation R04: Dissect the ET-120 bi-pod closeout.

8.0 Ice/Frost Ramps

Damage Description

Foam was lost from ET-121 ice/frost ramps at three locations: station 1262 (5.6 x 3.5 inches/0.024 lbm) at 154.8 seconds MET, station 1525 (7.3 x 1.9 inches/0.022 lbm along the outer edge of the ramp coincident with the re-pressurization line) and 1841 (4 x 2.6 inches/0.002 lbm extending beneath the re-pressurization lines). Refer to Figures 8.0-1 through 8.0-4. Note the station locations refer to the Xt coordinates of the damage and differ slightly from the Xt locations of the ramps themselves, which are depicted in Figure 8.0-1.

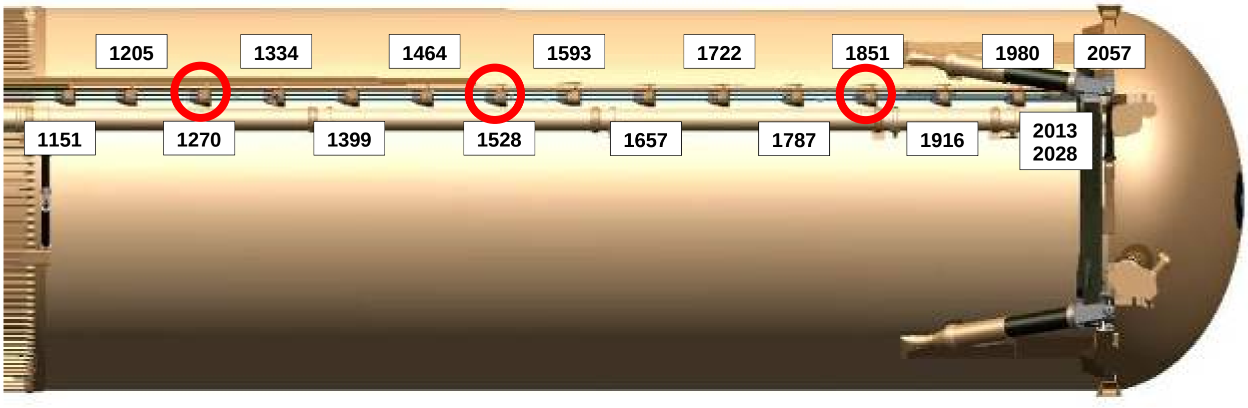


Figure 8.0-1. LH$_2$ Ice/Frost Ramp Location Map Showing Location of the Three Ramps that Shed Foam

Figure 8.0-2. Station 1262 Ice/Frost Ramp Foam Loss

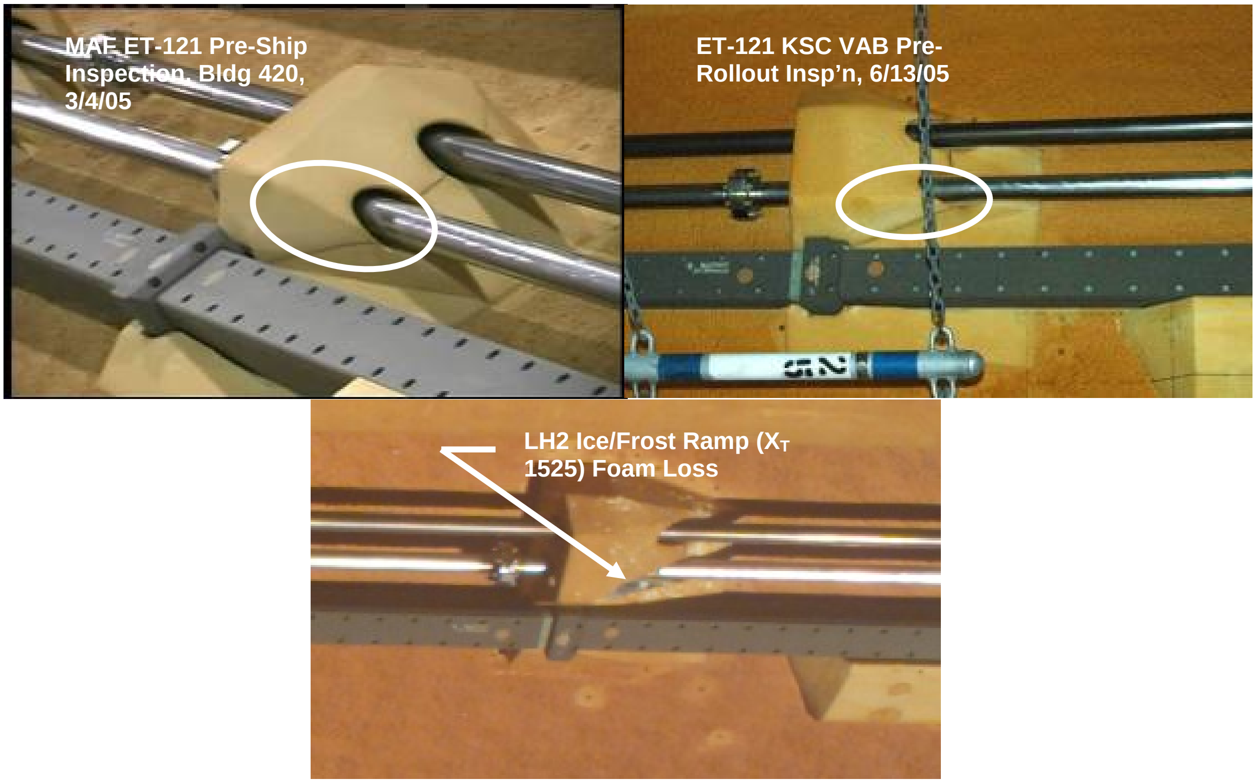


Figure 8.0-3. Station 1525 Ice/Frost Ramp Foam Loss

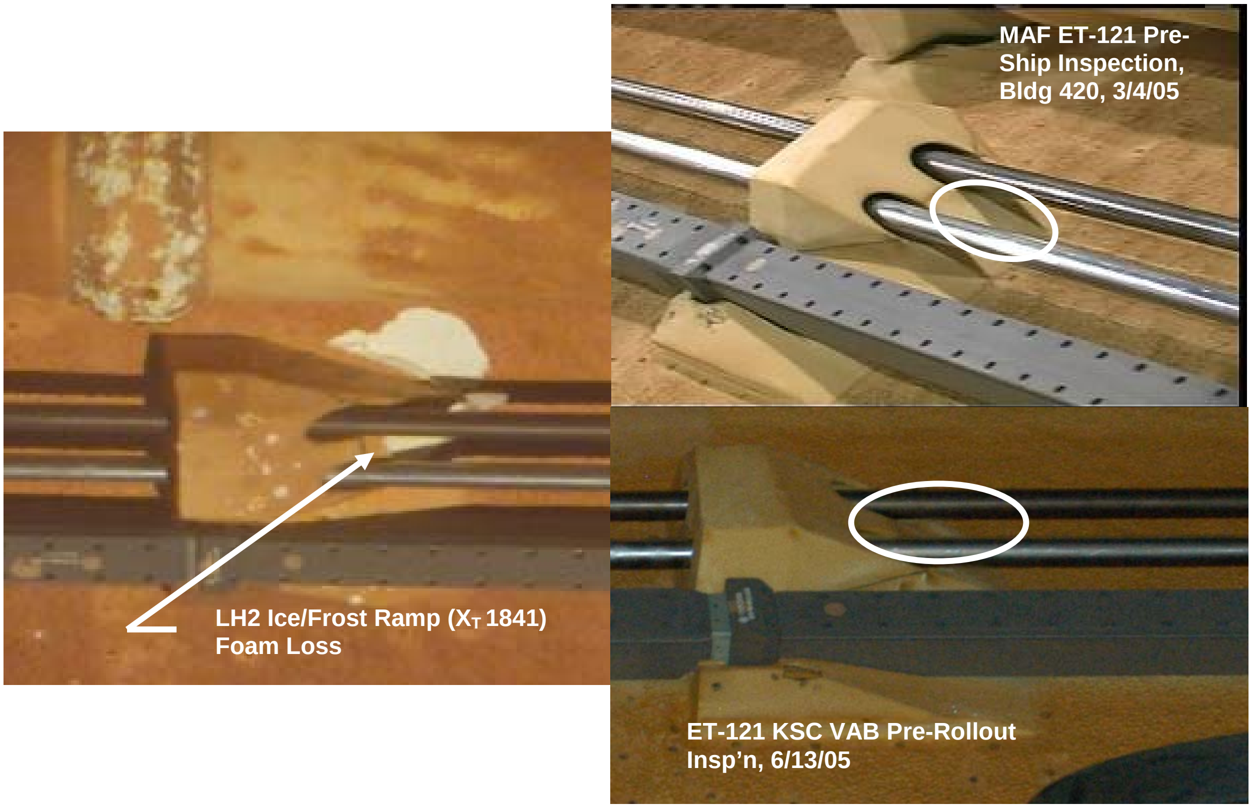


Figure 8.0-4. Station 1841 Ice/Frost Ramp Foam Loss

Flight Environments

Aerodynamic loads on the ice/frost ramps derived from the STS-114 BET parameters were well below the maximum design loads (Table 8.0-1) (ref. 1).

Table 8.0-1. Maximum Aerodynamic Loads on ET-121 Ice/Frost Ramps vs. Maximum Design Loads

Ramp Location	Maximum Design Side Force (lbs)	STS-114 BET Side Force (lbs)	Maximum Design Axial Force (lbs)	STS-114 BET Axial Force (lbs)
1270	276.3	52.8	1018.6	857.0
1528	293.0	56.0	1093.9	951.2
1851	262.5	50.2	955.5	829.8

Maximum design side forces for all ramps are at Mach 1.55. Maximum design axial forces for the station 1270 ramp are at Mach 1.25 and for stations 1528 and 1851 at Mach 1.55.

Foam loss from the 1270 ramp occurred at 154.8 seconds when ambient pressure was at 0.002 psia and maximum dynamic pressure on the ramp was 3.6 psf. This equates to an axial force of 4.26 lbs and a side force of 0.17 lbs. Again, these loads are considerably less than the maximum design loads of 1018.6 lbs and 276.3 lbs, respectively (ref. 1).

The potential that vibration from the re-pressurization lines might have contributed to the loss of ice/frost ramp foam was assessed, but appears to be unlikely (ref. 19). Loads from substrate and pressurization line vibration effects are included in TPS assessments and were factored into design of the PAL ramps. The re-pressurization lines are subject to the base drive random vibration environment specified in the EIS and NASA RP1074. These vibration environments are defined for lift-off and maximum dynamic pressure events. The loads analysis using this environment assumes a fully developed response at each frequency (i.e., resonances are assumed). For the TPS assessments, a load factor of 325 g equivalent static load is specified for the forward LH_2 tank, due to vibration of LH_2 substrate. Stress levels at this g load are low compared to other foam loading.

Materials

The LH_2 ice/frost ramps are fabricated from PDL-1034 poured foam. The lower portion of each ramp is applied directly to the acreage NCFI without any bonding agent, while the upper portion is applied to the lower over a layer of Conathane adhesive.

A commercially-available carnuba/naptha blend paste wax, MMCO5732800, is used as a mold release agent during fabrication of molded ramps. This release agent, applied to the inside by hand, has been in use since 1997, and has not been changed since the first molded ramps were fabricated (ref. 21).

Processing

With exception of the 1593 ramp, the LH_2 ice/frost ramps are fabricated using a poured mold process first introduced with ET-112 and flown five times prior to ET-121. Three of the six missions flown have had adequate imagery to permit observation of the ramps, and of these only the three STS-114 failures have been documented. Prior to ET-112 a bag-mold process was used. Imagery was returned from 13 of the 30 missions flown using the PDL pour bag molds, and four instances of foam loss were noted on three of the 13 missions.

The upper portion of the 1270 PAL ramp was removed for RTF rework and then replaced, increasing the potential for collateral damage in the area (shown in Figure 6.0-4). The ET Tiger Team noted that ice/frost ramps in general seem to have a number of associated multiple NCD repairs (Figure 8.0-5). While none were definitely shown to relate to the STS-114 foam loss as noted below, their presence does point to the relatively high level of processing traffic and rework required during ramp fabrication. The repairs are of more significance to the surrounding acreage than to the ramps themselves (refer to Section 9.0, Acreage).

Three NCDs were documented during processing, one pertaining to an initial material viscosity test failure attributed to shipment-related settling of the PDL material, one to voids noted during removal dissection of the original 1270 upper ramp, and one to increase the PDL charge size required for fabrication of the 1270 replacement ramp (ref. 28, 29, and 30). None of the NCDs reviewed was considered a probable contributor to the loss, although the presence of a void noted during 1270 upper ramp dissection clearly demonstrates the potential for void entrapment during the fabrication process. Two IPRAS were reviewed, one for a void in the 1270 ramp and one for a knife cut in the 1851 ramp (ref. 30 and 31). The void repair was in an area of the ramp where foam was lost, but the knife cut repair is not a likely contributor to foam lost from the 1851 ramp.

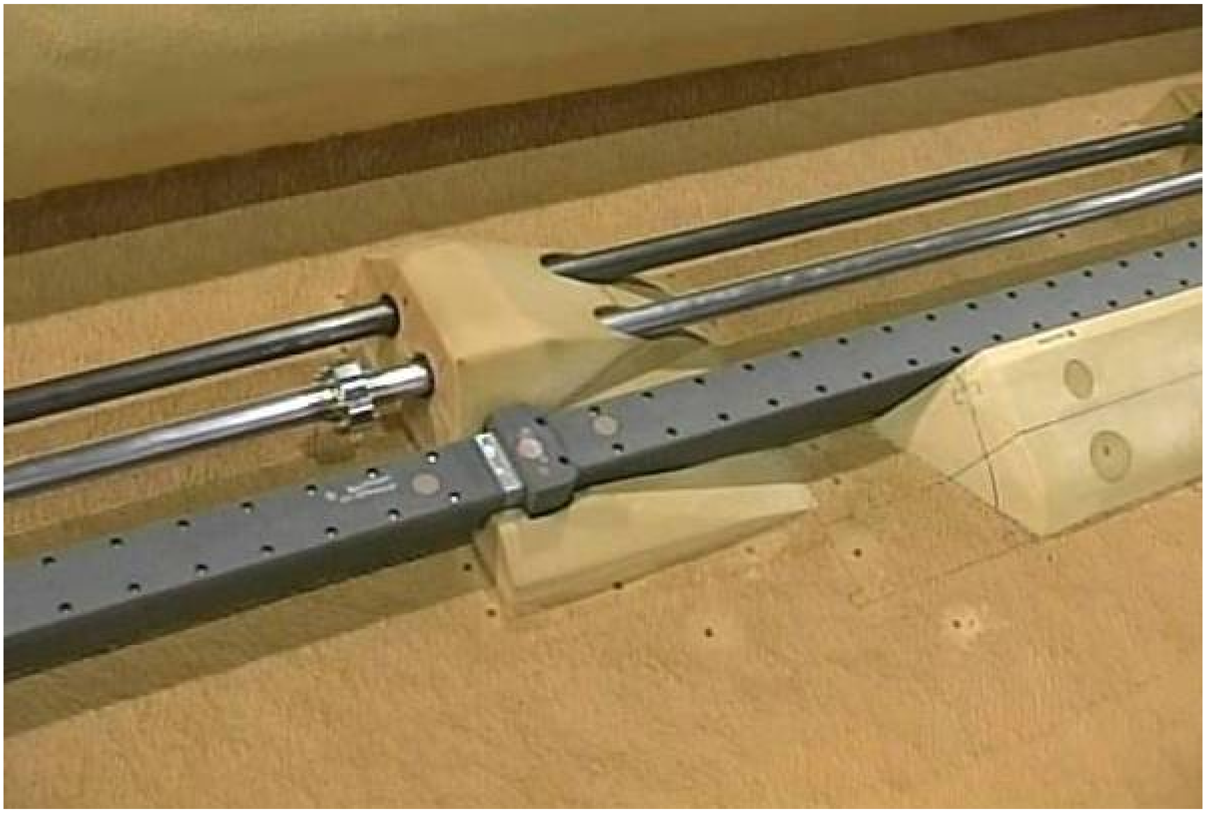


Figure 8.0-5. Repairs in the Vicinity of the ET-121 Station 1528 Ice/Frost Ramp

Note the black quality control inspection markings in the photo above.

Most Probable Causes

Location 1262

Since the station 1262 ramp foam was observed to separate from the tank in two pieces, erosion can be ruled out as a possible cause of the loss from this location and thermal analysis indicates temperatures in the area are not cold enough for cryopumping. The low ambient pressure at the time (0.002 psia) is consistent with foam loss through divoting due to an entrapped void, and this is the most probable cause for the 1262 ramp failure.

Location 1525

The Conathane layer between the upper and lower ramp halves is visible in foam loss location 1525 imagery (Figure A.3-2) suggesting the possibility of an adhesive debond in the area. An entrapped void with subsequent divoting is also a possibility.

Location 1841

The 1841 foam loss was probably caused by an entrapped void with subsequent divoting. Secondary debris impact is also a possibility, due to the location of the damage.

ET Tiger Team Recommendations

While ice/frost ramps appear to be more easily fabricated using the compressive mold process, the technique leaves the foam susceptible to trapped voids. Dissection tests and a pour using clear molds are planned by the Ice/Frost Ramp IFA Resolution Team to better understand the potential for void formation during ramp fabrication (Appendix C). It may be possible to reduce the number or size of voids trapped by increasing the number of vents, or otherwise modifying the molds. However, it is unlikely the voids can be completely eliminated. The potential for divoting could be reduced by venting the ramp fingers similar to the way intertank acreage is vented. The relatively thick foam of the ice/frost ramps makes venting feasible without cryopumping, and the ET Tiger Team recommends the SSP aggressively pursue this option in the near-term. Other configuration changes that might improve structural integrity of the ramps should also be assessed, including trimming the fingers and rounding sharp edges that are likely to produce stress concentrations.

Recommendation R05 (Near-Term): Investigate the potential for venting ice/frost ramp fingers to minimize the potential for divoting through trapped voids, and assess configuration changes to improve structural integrity.

There is some potential the ice/frost ramps could be completely eliminated, though with increased potential for ice formation on exposed surfaces. Hard covers could be developed for the ramps that would eliminate the possibility of foam loss with minimal collateral effect and the ET Tiger Team recommends this option be pursued in the long-term.

Recommendation R16 (Long-Term): Develop hard covers for ice/frost ramps and implement in conjunction with PAL ramp elimination.

9.0 Acreage

Damage Description

Divots were noted in acreage foam aft of the -Y bi-pod attachment point at station 1163 (4.8 x 3.3 inches/0.003 lbm) and adjacent to the ice/frost ramp at station 1839 (10.3 x 7.8 inches/0.03 lbm). Refer to Figures 9.0-1 and 9.0-2.

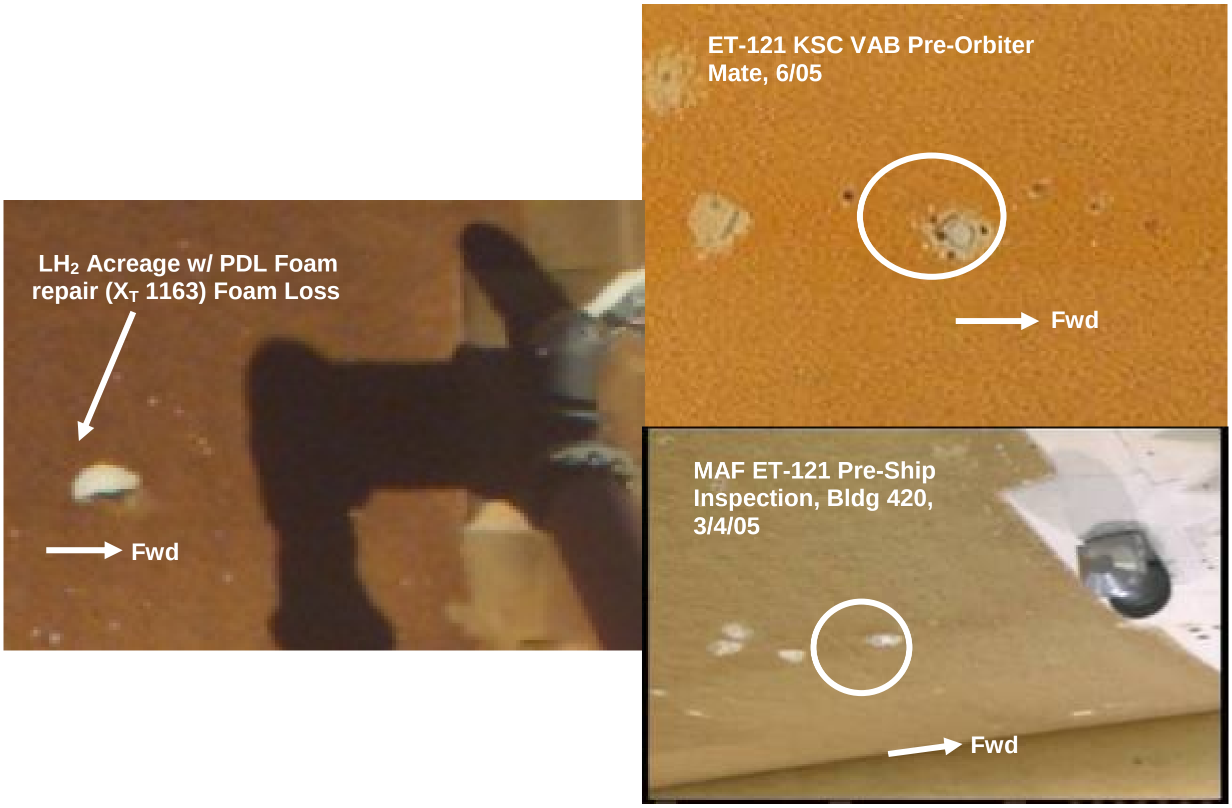


Figure 9.0-1. Station 1163 Acreage Foam Loss

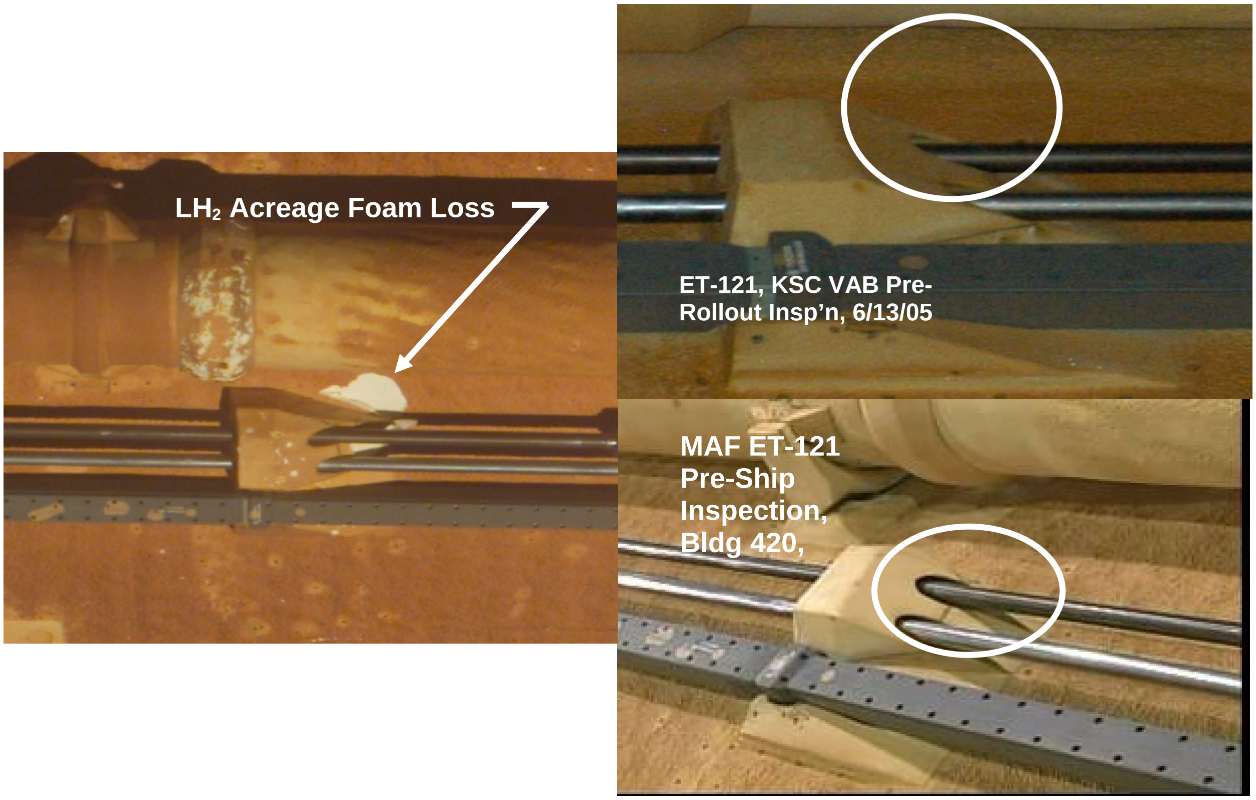


Figure 9.0-2. Station 1839 Acreage Foam Loss

Flight Environments

Reconstruction of the ET-121 ascent environment surfaced no unusual conditions that would have contributed to loss of acreage foam. Accelerometers installed in the intertank area for STS-114 recorded no values outside certified limits (ref. 5).

Processing

ET-121 LH_2 tank acreage foam was machine-sprayed using a mature process unchanged since ET-85 and thought to create few, if any, voids.

A review of nonconformance documentation found a repair was made at the 1163 location with eight sand and blend repairs in the immediate vicinity (ref. 22). An NCD was also identified for a foam repair at station 1170, outboard of the foam loss area. In addition, IPRAS were identified for two in-board voids at the bottom of the station 1851 ice/frost ramp, an outboard knife cut in the ice/frost ramp at station 1851, and for crushed acreage foam 18 inches outboard of the station 1851 ice/frost ramp. Correlation of these discrepancies to the acreage foam loss is not immediately clear, but they are consistent with the observation that the bi-pod and ice/frost ramp areas of the tank are subjected to a relatively high level of processing traffic; thus, there is high potential for collateral damage. Foam loss at the 1839 location is of special interest in this regard. The ET Tiger Team noted that acreage foam has been lost adjacent to ice/frost ramps a number of times in the past, including at least four times in the immediate vicinity of the 1839 ramp (Figure 9.0-3). Acreage foam in this area decreases from 1.5 to 1.01 inches in thickness, a change which may exacerbate the potential for collateral damage during ice/frost ramp fabrication.

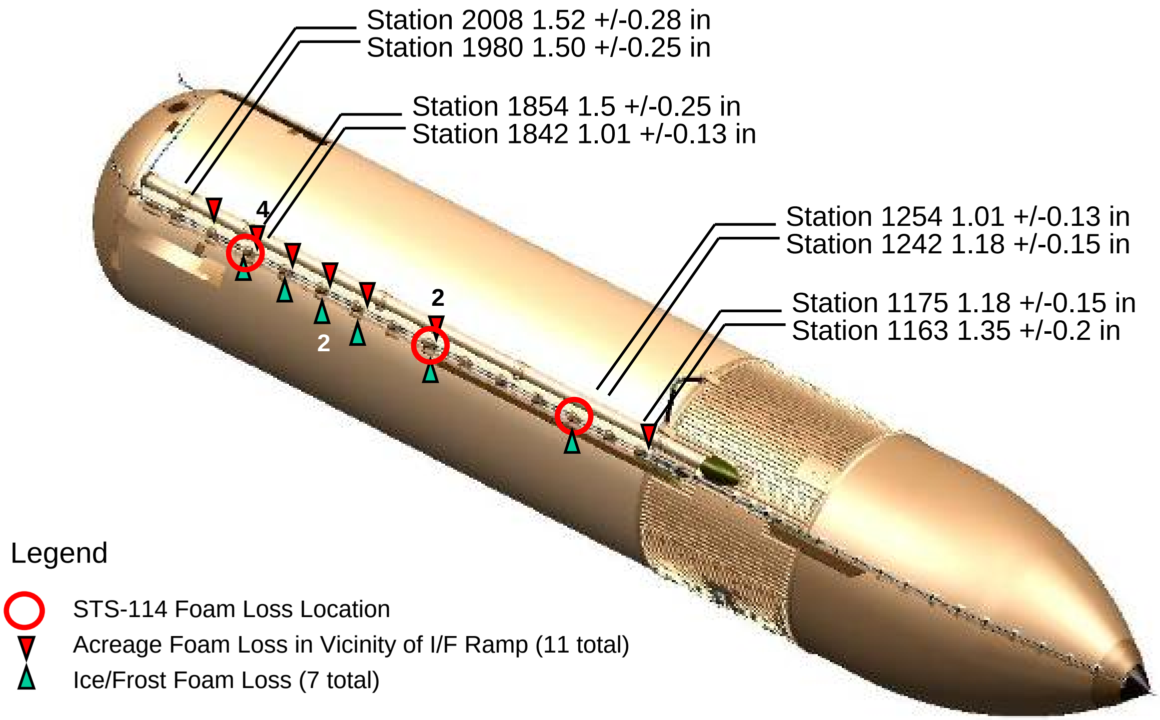


Figure 9.0-3. Acreage and Ice/Frost Ramp Foam Loss History

Acreage foam thickness variations up to ½-inch occur in vicinity of the 1851 and 1270 ice/frost ramps.

The molds typically leave a visible line where the seal contacts the acreage (Figure 9.0-4). The ET Tiger Team also noted that the STS-114 location 1839 acreage failure has a sharp line coincident with the 1851 ramp (Figure 9.0-5). Variabilities in the molds were also noted, including contact area thicknesses, curvature radius, etc. Molds are not tracked by serial number but by part number, making it difficult – if not impossible – to determine which mold was used to fabricate any specific ramp. The IFA Resolution Teams have testing planned to better characterize the material properties of NCFI and to ascertain what role, if any, damage induced by ice/frost ramp fabrication may play in acreage foam loss (refer to Appendix C).

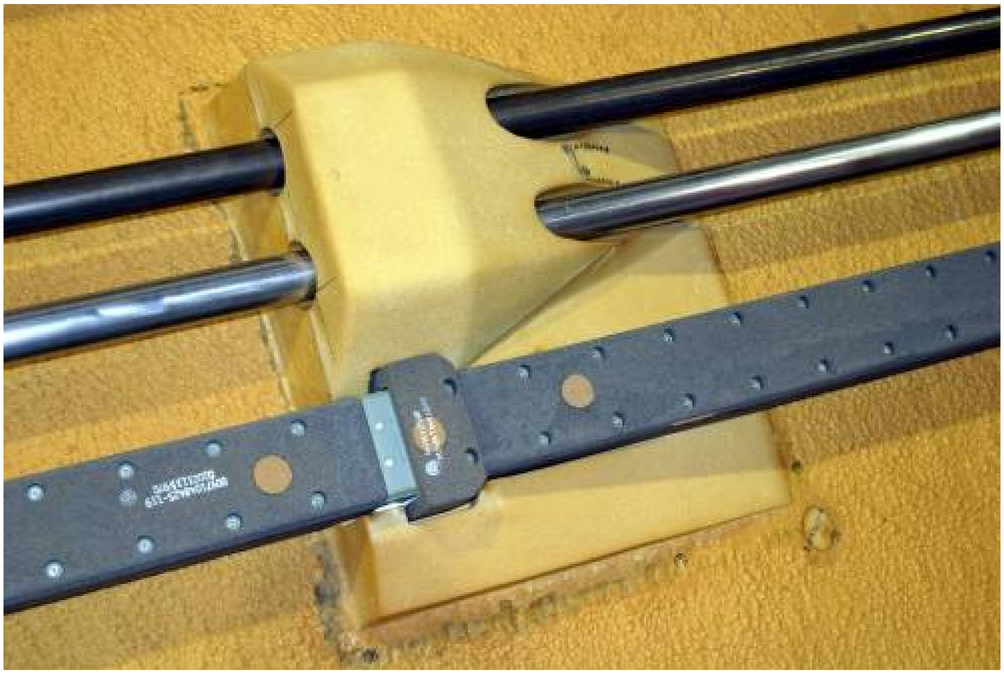


Figure 9.0-4. ET-118 Ice/Frost Ramp

Discolored area of acreage adjacent to the ramp is caused by the lower compression mold bladder seal.

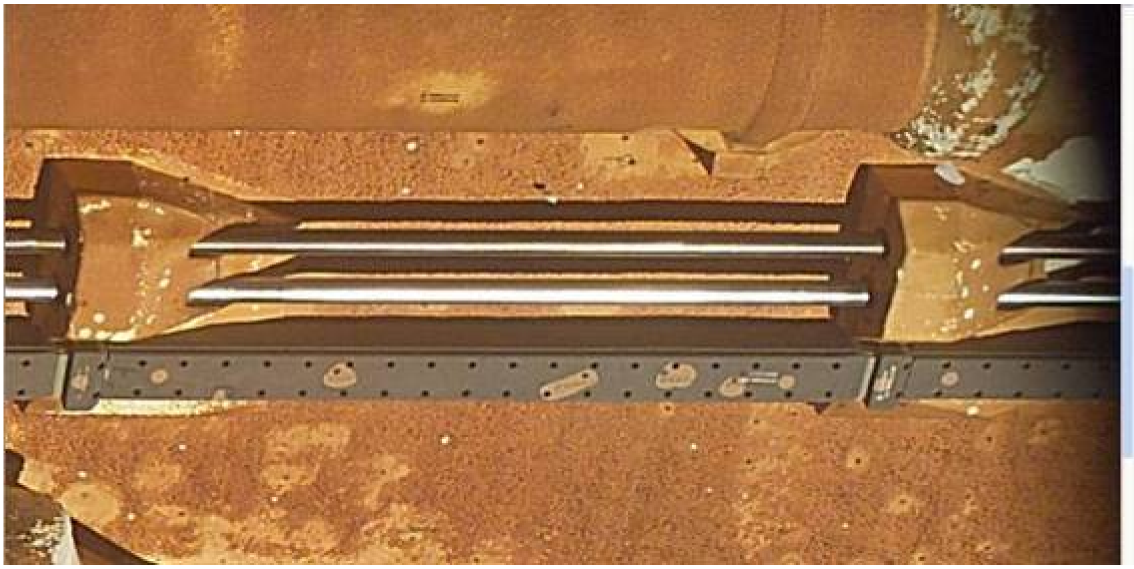


Figure 9.0-5. STS-114 Acreage Foam Loss in Vicinity of 1851 Ice/Frost Ramp (upper right-hand corner of photo)

Sharp separation line appears to be consistent with ice/frost ramp mold line. Note mold line visible on acreage adjacent to the next aft (1916) ramp.

Materials

The LH_2 tank acreage was sprayed with NCFI over the aluminum primer. Review of processing data found no evidence that the ET-121 acreage foam was substandard. Plug pull and environmental data were nominal (ref. 23).

Probable Causes

Cryoingestion can be ruled out as a possible cause due to the lack of a cryogenic source in the vicinity of either acreage failure. The most probable causes of the acreage foam loss at station 1163 are believed to be undetected damage adjacent to the PDL repair in that area, or a void – possibly trapped when the repair was performed – which divoted on ascent. Collateral damage could have been caused by application or removal of the repair kit hardware or could be related to small areas of crushed foam. Incidental collateral damage from ice/frost ramp installation is believed to be the cause of the 1839 area acreage foam loss.

ET Tiger Team Recommendations

There is presently no definitive root cause underlying the loss of acreage foam. The most probable causes point to incidental damage which affected the material properties or strength of the acreage foam. The ET Tiger Team has made several recommendations to improve handling processes and minimize the possibility of undetected collateral damage (refer to Section 5.2, Overarching Concerns, Processing, and recommendations R11 and R12). The ET Tiger Team also recommends the potential for damage during ice/frost ramp fabrication be fully investigated and corrective action implemented if necessary.

Recommendation R09: Perform sufficient test and dissection to determine whether ice/frost ramp fabrication compromises the integrity of adjacent acreage TPS.

10.0 LH_2 Intertank Flange

Damage Description

Two areas of foam (7.5 x 7.5 inches/0.066 lbm and 4.5 x 4.5 inches/0.011 lbm) were lost from the upper LH_2 intertank flange closeout on the –Y axis in the SRB thrust panel structure (Figure 10.0-1). Time of loss is unknown, but is believed to have occurred after SRB separation. The damage was difficult to discern in flight photography and did not appear to have significant depth. The flange closeout is a 3-step process where the first step is a point fill of the stringers with BX-265 followed by upper and then the lower section manual sprays of BX-265. These last two closeouts are divided into ten 22° "windows" labeled A through J. The smaller of the two foam loss regions was at the spray window G and H juncture, two individually hand-sprayed circumferential sections separated by a Conathane bond. The larger was at the flange and intertank acreage spray juncture, also separated by a Conathane layer.

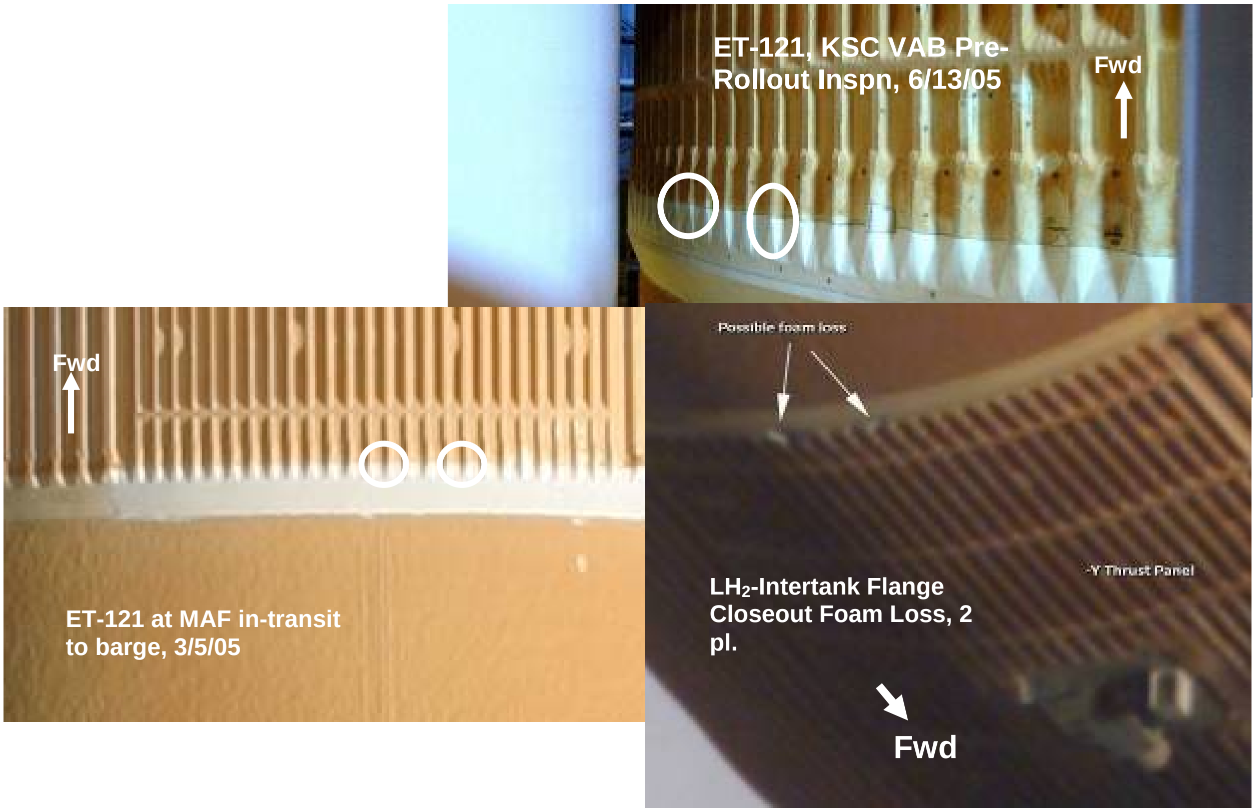


Figure 10.0-1. STS-114 PAL Ramp Foam Loss

Flight Environments

No unusual ascent environmental factors were noted that would have contributed to foam loss from the LH_2 intertank flange.

Processing

A newly-designed LH_2 intertank flange closeout intended to minimize the potential for cryoingestion from the “crotch” region at the intersection of the LH_2 tank dome and the intertank was implemented on ET-121 and flown for the first time on STS-114. Foam was removed from the LH_2 intertank flange for this RTF modification. The flange bolts were reversed (oriented with bolt heads below the flange and nuts on top) and Loctite applied to seal the threads. The flange was stripped to bare metal and machine-sprayed foam in the LH_2 tank acreage and intertank was trimmed. The aluminum substrate was primed, and then the LH_2 intertank flange TPS closeout was applied in a multi-step process involving injection of BX-265 in the thrust panel “pockets”, and manual spray of BX-265 in circumferential “windows.” Conathane adhesive was applied to foam surfaces that were to have further foam application.

Two NCDs were processed for the LH_2 intertank flange. The first involved thin NCFI intertank foam adjacent to the flange closeout area. The second involved foam residue at bolt locations which was removed. Neither is believed to have contributed to the STS-114 foam loss and no foam repairs, including sand and blend, were indicated in the foam loss region.

Materials

The LH_2 intertank flange was sprayed with BX-265 over aluminum primer and injected BX-265 in the thrust panel “pockets”. Review of processing data found no evidence that the ET-121 LH_2 intertank flange foam was substandard. BX-265 foam properties and ambient environmental data were within specified limits (ref. 27).

Most Probable Causes

Foam loss occurred in the SRB thrust structure area of the flange (shown in Figure 10.-1). Since this is a single machined part with few leak paths for LN_2 from the intertank, cryoingestion is the least likely candidate for the foam loss. Cryopumping or divoting due to an entrapped void are the most probable causes. Since analysis indicates that substrate temperatures at the foam loss location are probably too high to support cryopumping, the entrapped void/divoting scenario is the most likely of these. Occurrence of the foam loss at the intersection of spray segments suggests the possibility that some problem at these interfaces may exist, a concern still under investigation by the LH_2 Intertank Flange IFA Resolution Team. It is also possible that damage occurred during trimming of intertank acreage foam which resulted in a void in the machine-sprayed NCFI.

ET Tiger Team Recommendations

Changes to reduce the potential for void entrapment and cryoingestion in order to minimize foam loss in the LH_2 intertank flange were implemented after STS-107 and additional changes have not been identified. The ET Tiger Team does not recommend additional hardware modifications, but development of NDE techniques should be pursued and a certified NDE technique for the LH_2 intertank flange developed and fielded as soon as possible (refer to Section 5.2, Overarching Concerns, Processing, and recommendations R13 and R18).

11.0 Additional Findings

While the primary focus of this assessment was on nine specific STS-114 foam loss events, the ET Tiger Team noted that debris was also shed from other areas of the tank. Even those that did not shed debris on this mission remain a concern. Of the sixteen foam loss events noted, only nine were referred to IFA Resolution Teams for assessment. The seven remaining events should be rigorously evaluated to determine whether they contain any clues that might explain loss from the nine areas under evaluation and to ensure foam is not shed from other locations in the future. In addition, widespread minor divoting ("popcorning") is visible in on-orbit photographs, especially in the +Z LH_2 acreage and intertank areas (refer to Appendix B). While popcorning is generally considered an acceptable condition due to the small size and correspondingly small mass of the liberated debris, the ET Tiger Team noted the Orbiter received 152 lower-surface debris hits during STS-114, 21 of which were greater than one-inch in diameter (ref. 32). The source of this damage is not readily apparent, but further analysis of the popcorning phenomenon is warranted to determine whether a connection exists and whether additional corrective action should be taken. This issue is especially important given the correlations noted among tank traffic, collateral damage, and foam loss (refer to Section 5.2, Overarching Concerns, Processing) and the fact that upcoming tanks have seen a higher-than-normal level of processing traffic for RTF rework.

Observation O02: LO_2 bracket and thrust strut foam loss incidents should be referred to appropriate IFA Resolution Teams for review, and SSP should rigorously address popcorning and the secondary impacts to ET acreage foam.

Long-term changes to eliminate foam where it is not required for thermal protection should also be pursued. Removal of non-mandatory foam eliminates potential debris sources.

Recommendation R21 (Long-Term): Minimize or eliminate use of foam in all non-thermal applications.

The potential for ice formation on exposed metallic surfaces has not been eliminated. In fact, the four acreage "scratches" could have been caused by LO_2 feedline bracket ice. The SSP should continue to aggressively pursue design changes or pre-launch abatement techniques that may eliminate ice as a debris source.

Recommendation R20 (Long-Term): Aggressively pursue techniques to eliminate ice formation on exposed ET surfaces and minimize the potential for ice debris impact.

Substantial improvements to the ET TPS spray processes have been made since their inception at the July 2003 Program Requirements Control Board (PRCB). However, since the ET Project was unable to certify the ET TPS as a structural system without substantial limitations (ref. 12), it is imperative the SSP continue to assess the efficacy of the ET TPS process controls in ensuring consistent performance of the end product. The ET Tiger Team recommends a continuous improvement process be implemented with the following specific elements (ref. 29).

1. Implement a characterization or test program to determine the sensitivity of as-sprayed foam to critical processing parameters (i.e., gun types, component temperatures, environmental temperature and humidity, overlap-time requirements, spray techniques, etc.).
2. Incorporate controls to prevent long-term process creep, including configuration control of manufacturing and non-conformance review and approval processes.
3. Ensure all future reworks, repairs, new configurations, and verification test articles are performed per the revised, enhanced work instructions.
4. Review the adequacy of High-Fidelity Production Test Articles (HFPTA), document deficiencies, and develop a means to improve existing HFPTAs.
5. Incorporate any "best practices" (material and/or equipment changes) into the training and recertification program on an ongoing basis as part of a continuous improvement process.
6. Develop bondline contamination-sensitivity data to support existing and updated contamination control requirements.
7. Subject TPS processes to periodic independent review to assess spray process improvements.

Recommendation R19 (Long-Term): Continue and strengthen TPS spray process improvement efforts.

While cryoingestion was not likely the cause of the STS-114 flange foam loss, some improvement in the overall design could be realized by eliminating the formation of LN_2 in the region through design improvements to the internal insulation.

Observation O01: The SSP should continue to pursue design change options for preventing LN_2 accumulation in the LH_2 intertank flange area.

The ET Tiger Team discussed the apparent “disconnect” between the ET EIS and Orbiter debris allowable limits (Table 4.0-1). The attempt to close this gap through a probabilistic risk assessment had obvious shortcomings as the STS-114 foam loss incidents demonstrate. The SSP should continue to aggressively pursue a better solution to this problem and, if possible, set a single specified requirement for ET foam loss. In addition, the issue of foam loss after 135 seconds MET needs to be better understood so the significance of specific foam loss observations can be evaluated. The combination of thermal effects and high delta-pressure which occurs late in ascent may be expected to create larger divots in the foam with greater frequency. Predictive models should be expanded to include failure modes other than divoting and ascent times beyond 135 seconds.

Recommendation R22: The SSP should address the inconsistencies between the ET EIS and Orbiter debris allowable limits.

The ET Tiger Team noted that rigorous certification of the TPS foam as a structural element of the tank was compromised by the lack of validated structural analysis methods that could be used to guide and supplement verification testing. This deficiency led to a high reliance on probabilistic risk assessments. To better understand foam failures, the SSP should continue efforts to characterize material strength, fracture toughness, and other parameters for all materials and applications as required to develop a more robust failure prediction capability. Additionally, testing should be conducted to address the application of the divot/no-divot curves to regions of the tank with complex geometric features. Sensitivity studies to correlate substrate geometry and process variability with the maximum expected defect size should be continued. Similarly, a rigorous damage tolerance test program should be implemented to fully understand the debris threat associated with handling damage.

Observation O03: Structural analysis technologies used for ET TPS foam certification should be enhanced.

12.0 Lessons Learned

L1. Adherence to Systems Engineering Principles. There is some evidence that schedule considerations played a role in the decision to replace only the forward 10-feet of the ET-121 PAL ramp. While an enhanced re-spray process had been developed, the level of improvement it offered was not quantified. Consequently, there was no quantitative data available upon which to base the PAL ramp removal decision and no specific requirement for PAL ramp "quality" was established. Thus, the SSP chose a path that minimized impact to schedule and unintentionally accepted additional risk. Programs can avoid this problem by adhering to rigorous systems engineering principles, setting specific requirements, and pressing forward only when those requirements have been met. In the case of ET-121, this would have meant setting specific requirements for foam properties and performance and collecting quantitative data to demonstrate these requirements had been met.

L2. Rigorous Configuration Control. Lack of configuration control over ET access aids, pads, covers, and tooling appears to have contributed to collateral damage to the tank TPS. Programs should establish rigorous configuration control over all tooling and production processes to ensure risks to hardware are minimized. Continuous improvement programs should be implemented early-on to identify best practices, incorporate them incrementally after rigorous assessment, and monitor to ensure process creep does not occur.

13.0 Recommendation Summary

Recommendations are summarized and cross-referenced to the text in Table 13.0-1.

Table 13.0-1. Recommendation Summary Table

Number	Page	Description	PAL Ramp	Bi-Pod	Ice/frost	Acreage	LH_2 Flange	Processing	Collateral	Near-Term	Long-Term
R01	25	Remove and replace the entire length of the LO_2 and LH_2 PAL ramps using the best available quality controls. Verify the underlying acreage foam integrity prior to re-spray.	X							X	
R02	25	Minimize or eliminate the portion of the ice/frost ramp that projects beneath the PAL ramp area to reduce the potential for void formation during PAL ramp spray.	X							X	
R03	31	Implement modifications required to prevent cryopumping through bi-pod heater wiring.		X						X	
R04	31	Dissect the ET-120 bi-pod closeout.		X						X	
R05	39	Investigate the potential for venting ice/frost ramp fingers to minimize the potential for divoting through trapped voids, and assess configuration changes to improve structural integrity.			X					X	
R06	25	Complete NDE and dissection of existing PAL ramps, including the area beneath the PAL ramp in the vicinity of the ice/frost ramps, to better understand the ET-121 failure and identify areas needing improved manual spray processes.	X							X	
R07	11	Complete on-going PAL ramp and ice/frost ramp localized environmental analyses to understand whether local environmental effects might contribute to foam loss.	X		X					X	
R08	15	Complete BX-265 and NCFI material characterization tests including crush tests.	X			X				X	
R09	47	Perform sufficient test and dissection to determine whether ice/frost ramp fabrication compromises the integrity of adjacent acreage TPS.			X	X				X	
R10	15	Revalidate and recertify foam repair processes to demonstrate structural strength of the repairs and ensure integrity of surrounding TPS is not compromised.						X		X	

Number	Page	Description	PAL Ramp	Bi-Pod	Ice/frost	Acreage	LH$_2$ Flange	Processing	Collateral	Near-Term	Long-Term
R11	16	Improve hardware protection provisions to minimize the potential for collateral hardware damage during processing.						X		X	
R12	16	Improve in-process data collection and documentation to include digital photos of all damaged TPS pre-and post-repair and collection of specific x-y coordinates for all repairs.								X	
R13	17	Develop and implement improved damage detection processes, including NDE and tactile inspections in all foam loss areas.						X		X	
R14	25	Eliminate the PAL ramp at the earliest possible opportunity, coincident with rigorous aerodynamic test and analysis.	X								X
R15	26	Aggressively pursue implementation of robotic PAL ramp sprays in parallel with the ramp removal effort.	X								X
R16	40	Develop hard covers for ice/frost ramps and implement in conjunction with PAL ramp elimination.			X						X
R17	16	Eliminate tank traffic to the extent possible and implement a no-touch processing policy.						X			X
R18	17	Develop and certify NDE for all ET TPS applications.						X			X
R19	52	Continue and strengthen TPS spray process improvement efforts.						X			X
R20	51	Aggressively pursue techniques to eliminate ice formation on exposed ET surfaces and minimize the potential for ice debris impact.							X	X	
R21	51	Minimize or eliminate use of foam in all non-thermal applications.							X		X
R22	52	The SSP should address inconsistencies between the ET EIS and Orbiter debris allowable limits.							X	X	

Number	Page	Description	PAL Ramp	Bi-Pod	Ice/frost	Acreage	LH_2 Flange	Processing	Collateral	Near-Term	Long-Term
O01	52	The SSP should continue to pursue design change options for preventing LN_2 accumulation in the LH_2 intertank flange area.					X				X
O02	51	LO_2 bracket and thrust strut foam loss incidents should be referred to appropriate IFA Resolution Teams for review, and SSP should rigorously address popcorning and the secondary impacts to ET acreage foam.							X	X	
O03	53	Structural analysis technologies used for ET TPS foam certification should be enhanced.							X		X

14.0 Acronym List

BET	Best Estimated Trajectory
CATIA	Computer Aided Three-dimensional Interactive Application
CFD	Computational Fluid Dynamics
COSMA	NASA HQ Chief Officer for Safety and Mission Assurance
CTE	Coefficient of Thermal Expansion
DEG F	Degrees Fahrenheit
DVR	Delta Verification Review
ECO	Engine Cut-Off
EIS	End-Item Specification
ET	External Tank
FEM	Finite Element Model
FOD	Foreign Object/Debris
FoS	Factor of Safety
HFPTA	High-Fidelity Production Test Articles
IFA	Inflight Anomalies
IPRAS	In-Process Repair Authorization Sheets
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LBM	Pounds Mass
LH_2	Liquid Hydrogen
LMMSS	Lockheed Martin Missile and Space Systems
LN_2	Liquid Nitrogen
LO_2	Liquid Oxygen
MAF	Michoud Assembly Facility
MDSO	NASA HQ Mission Director for Space Operations
MET	Mission Elapsed Time
MMET	Michoud Materials Evaluation Team
MS	Mission Specific
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NCD	Nonconformance Document
NCFI	North Carolina Foam Institute
NDE	Nondestructive Evaluation
NESC	NASA Engineering and Safety Center
NSTS	National Space Transportation System
PAL	Protuberance Air Load
PDL	Polymer Development Labs
PRCB	Program Requirements Control Board
psf	pounds per square foot
psi	pounds per square inch
psia	pounds per square inch, absolute
psig	pounds per square inch, gauge

RTF	Return to Flight
SE&I	Systems Engineering and Integration
SSME	Space Shuttle Main Engine
SSP	Space Shuttle Program
TPS	Thermal Protection System
V&V	Validation and Verification

Appendix A. Nonconformance Maps

A.1 ET-121 Nonconformance Maps

The following drawings depict the locations where NCDs were documented during ET-121 processing. Positions are approximate and, since x-y-z coordinate data was not available for all NCDs, does not include all nonconformances.

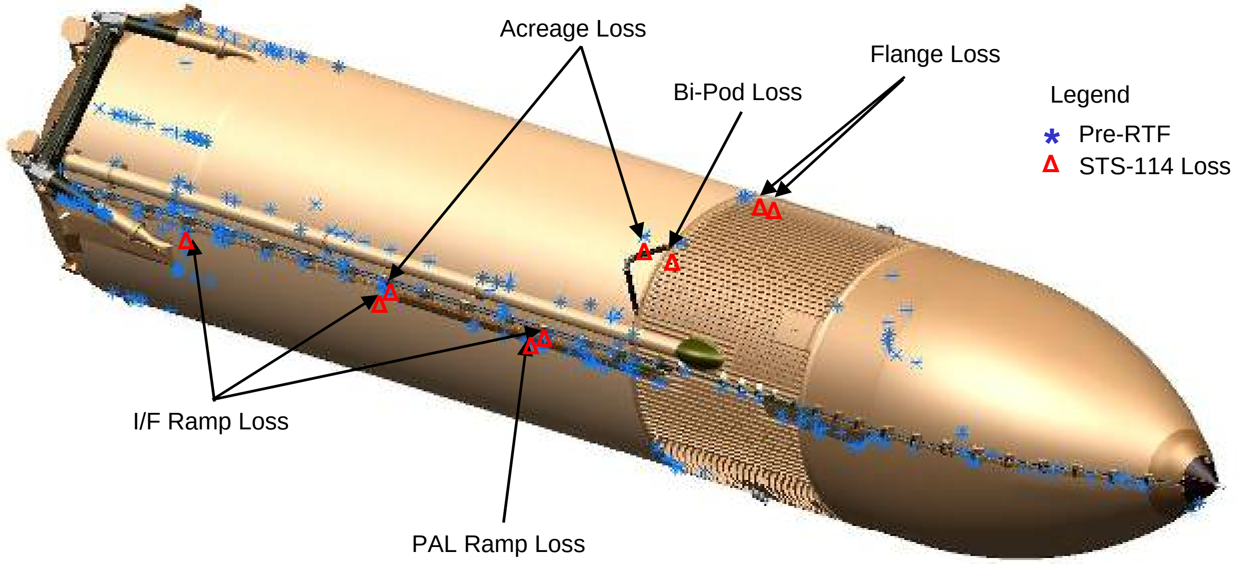


Figure A-1. ET-121 Nonconformances Documented Before Implementation of RTF Mods

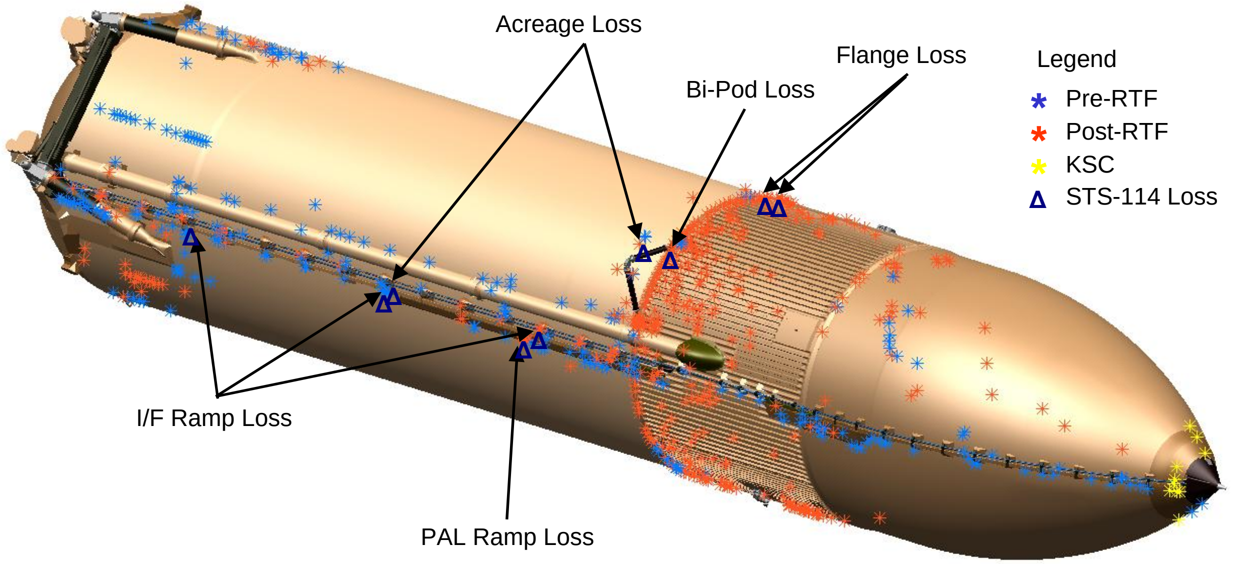


Figure A-2. ET-121 Nonconformances Documented Before and After Implementation of RTF Mods, Including Post-KSC Processing

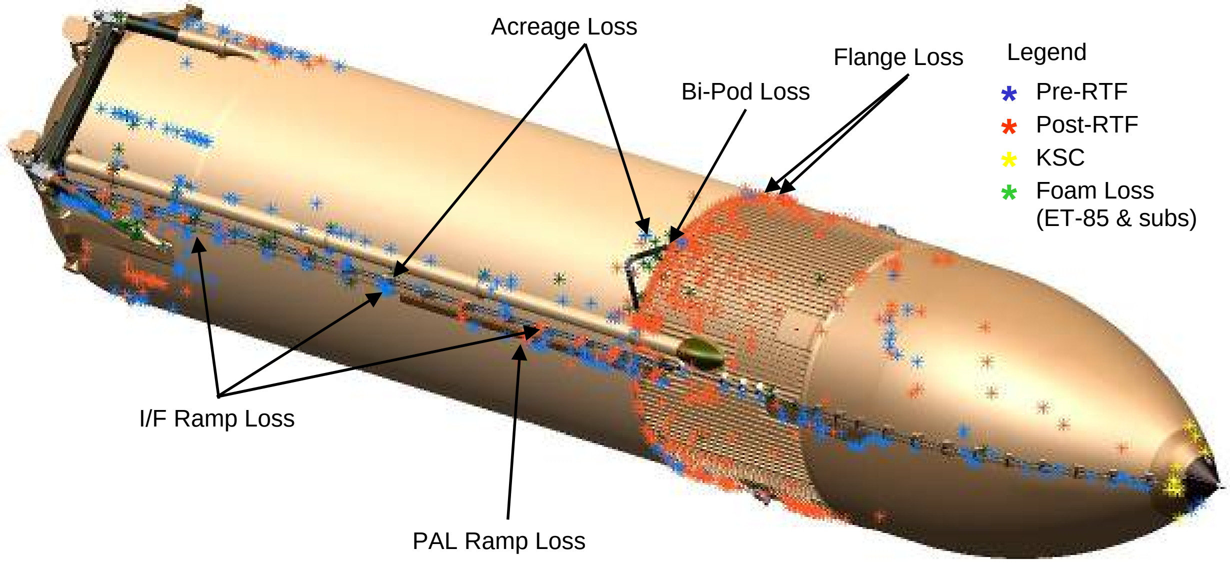


Figure A-3. ET-121 Nonconformances with STS-85 and Subs in-Flight Foam Loss Overlaid

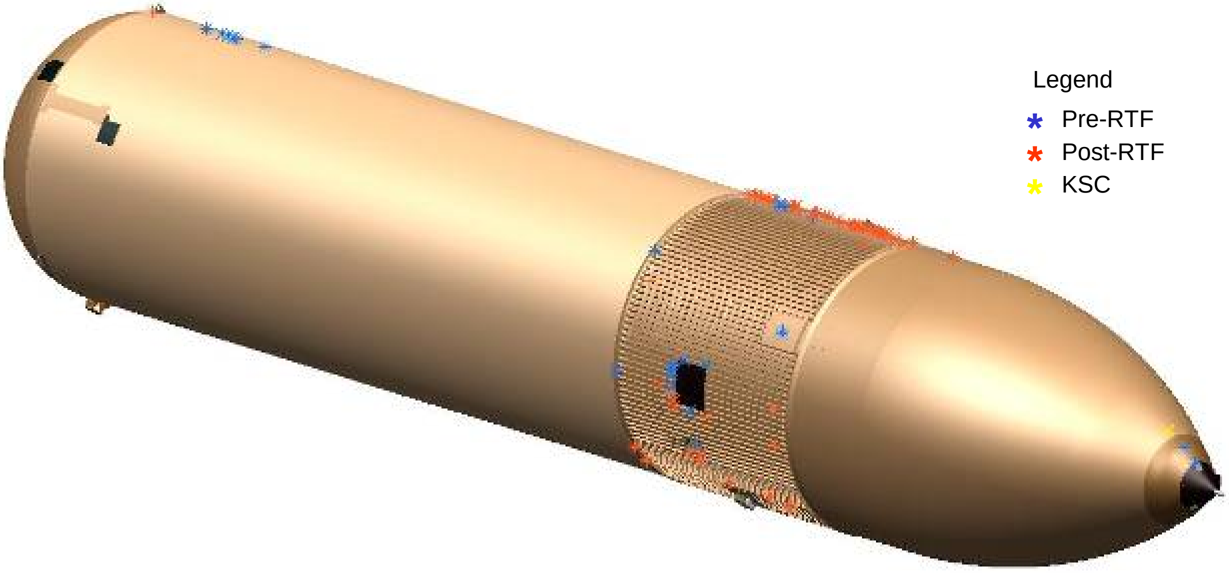


Figure A-4. ET-121 Nonconformances Documented on –Z Side of Tank

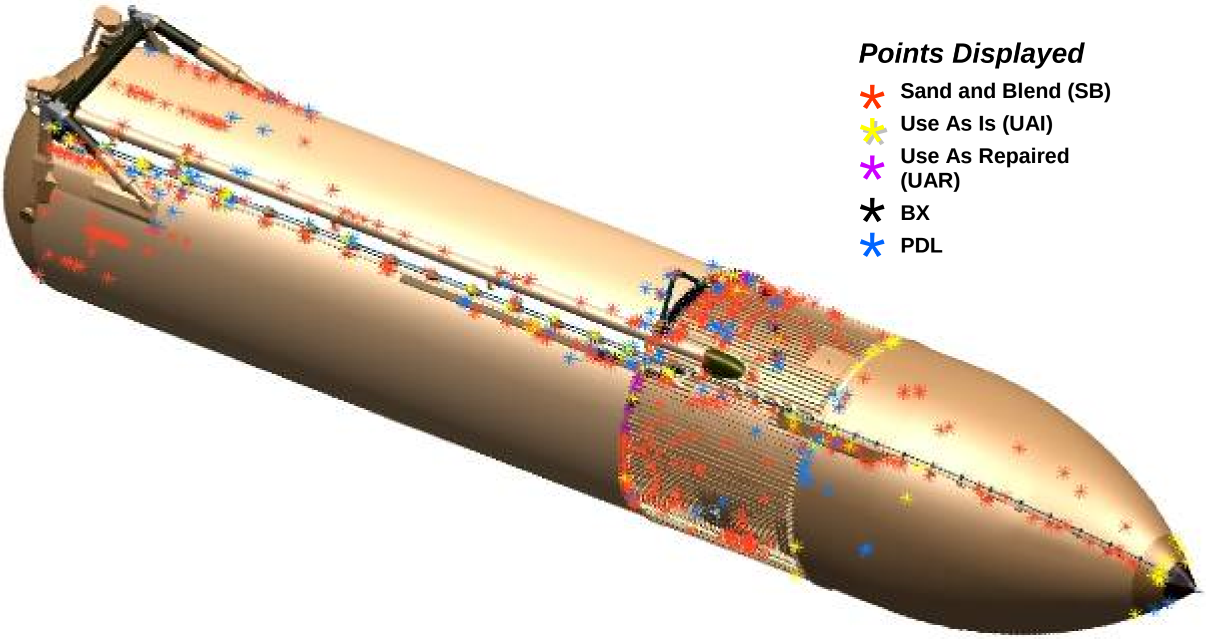


Figure A-5. ET-121 Nonconformances by Type

A.2 ET-115 Nonconformance Maps

The following drawings depict the locations where NCDs were documented during ET-115 processing. Positions are approximate and, since x-y-z coordinate data was not available for all NCDs, does not include all nonconformances.

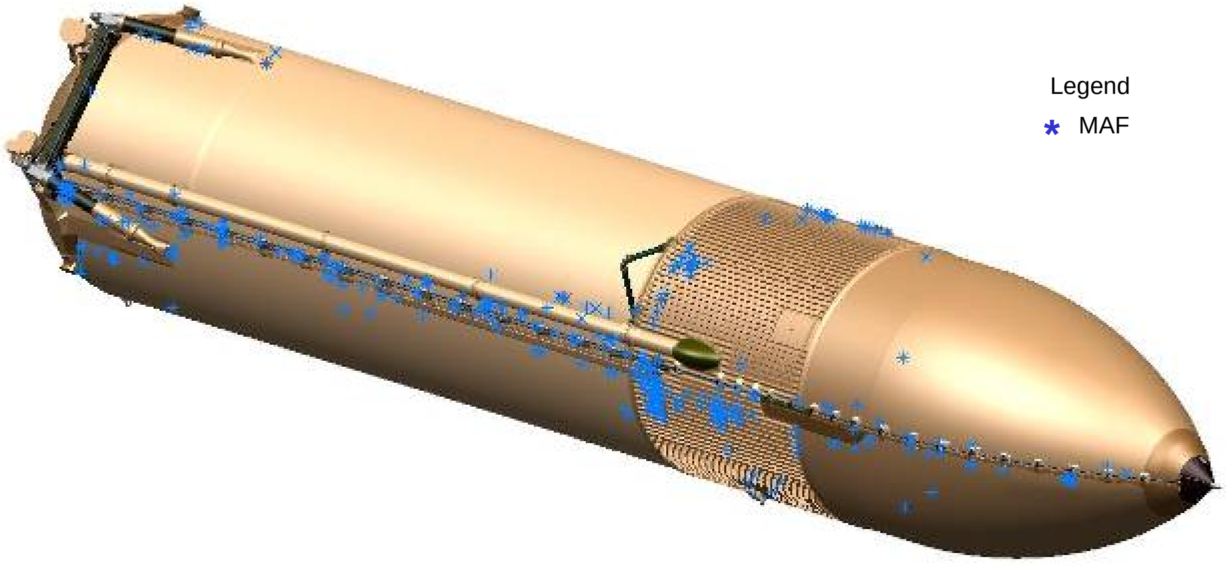


Figure A.2-1. ET-115 Documented Nonconformances

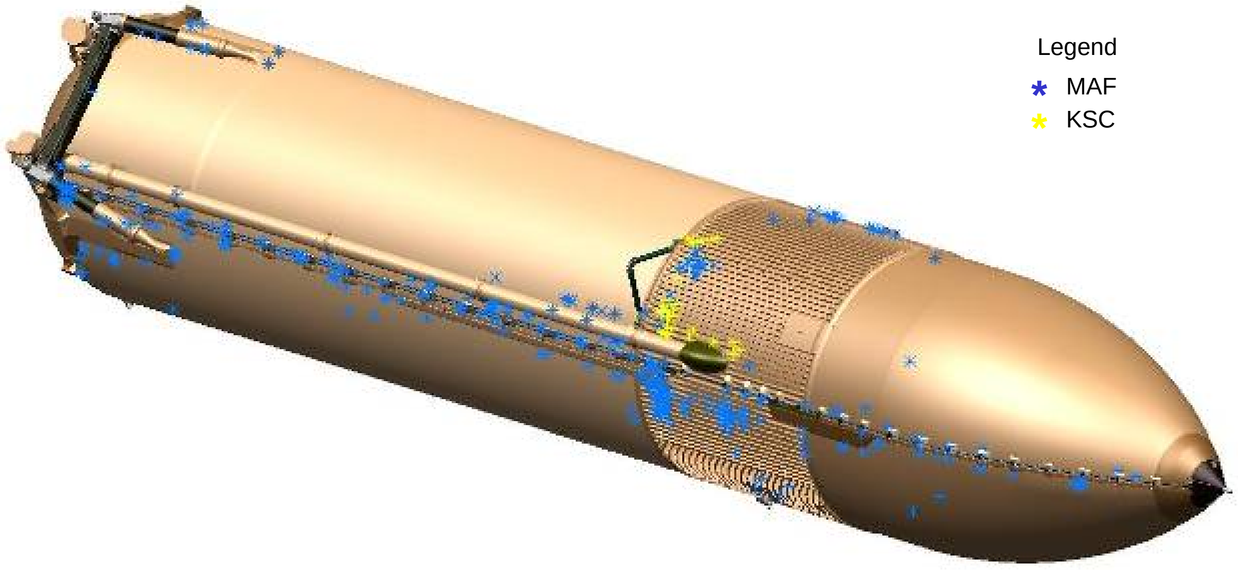


Figure A.2-2. ET-115 Nonconformances Documented at MAF and KSC

A.3 ET-119 Nonconformance Maps

The following drawings depict the locations where NCDs were documented during ET-119 processing. Positions are approximate and, since x-y-z coordinate data was not available for all NCDs, does not include all nonconformances.

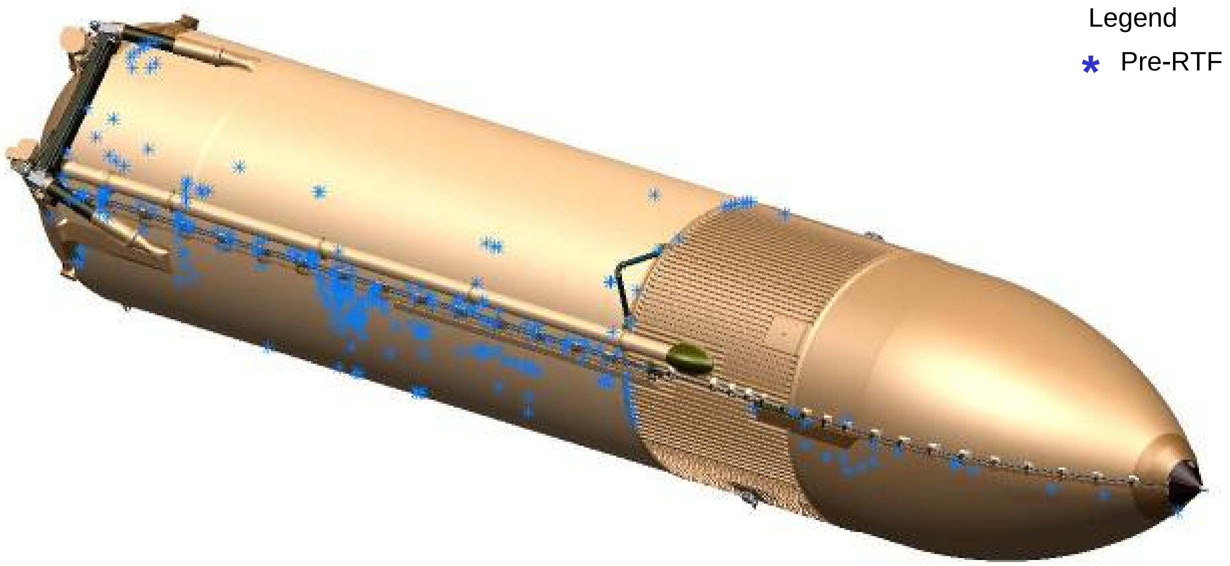


Figure A.3-1. ET-119 Nonconformances Documented Before Implementation of RTF Mods

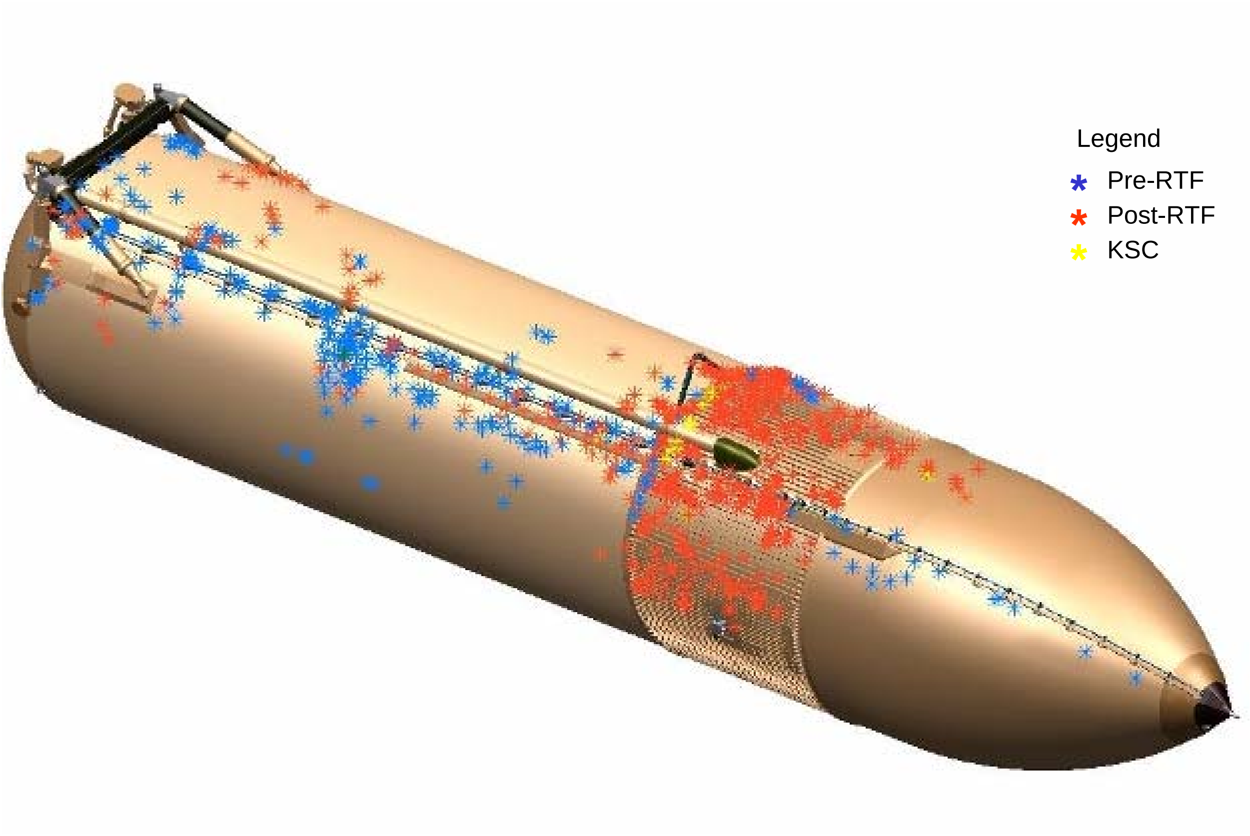


Figure A-3.2. ET-119 Nonconformances Documented Before and After Implementation of RTF Mods, Including Post-KSC Processing

Appendix B. ET-121 On-Orbit Photographs

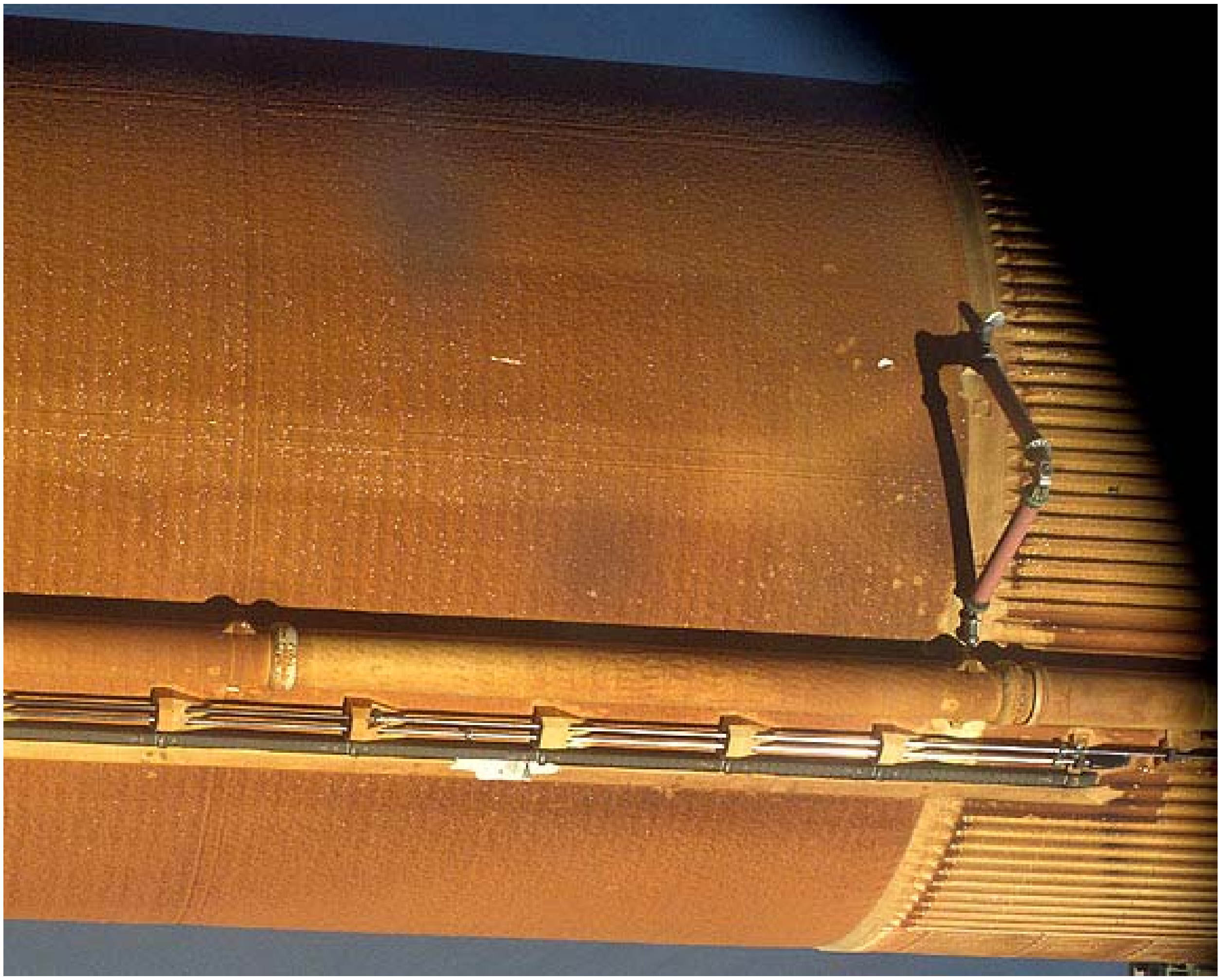


Figure B.1. ET-121 +Z View On-Orbit

Figure B.2. ET-121 –Z View On-Orbit

Figure B.3. ET-121 Bi-Pod Area On-Orbit

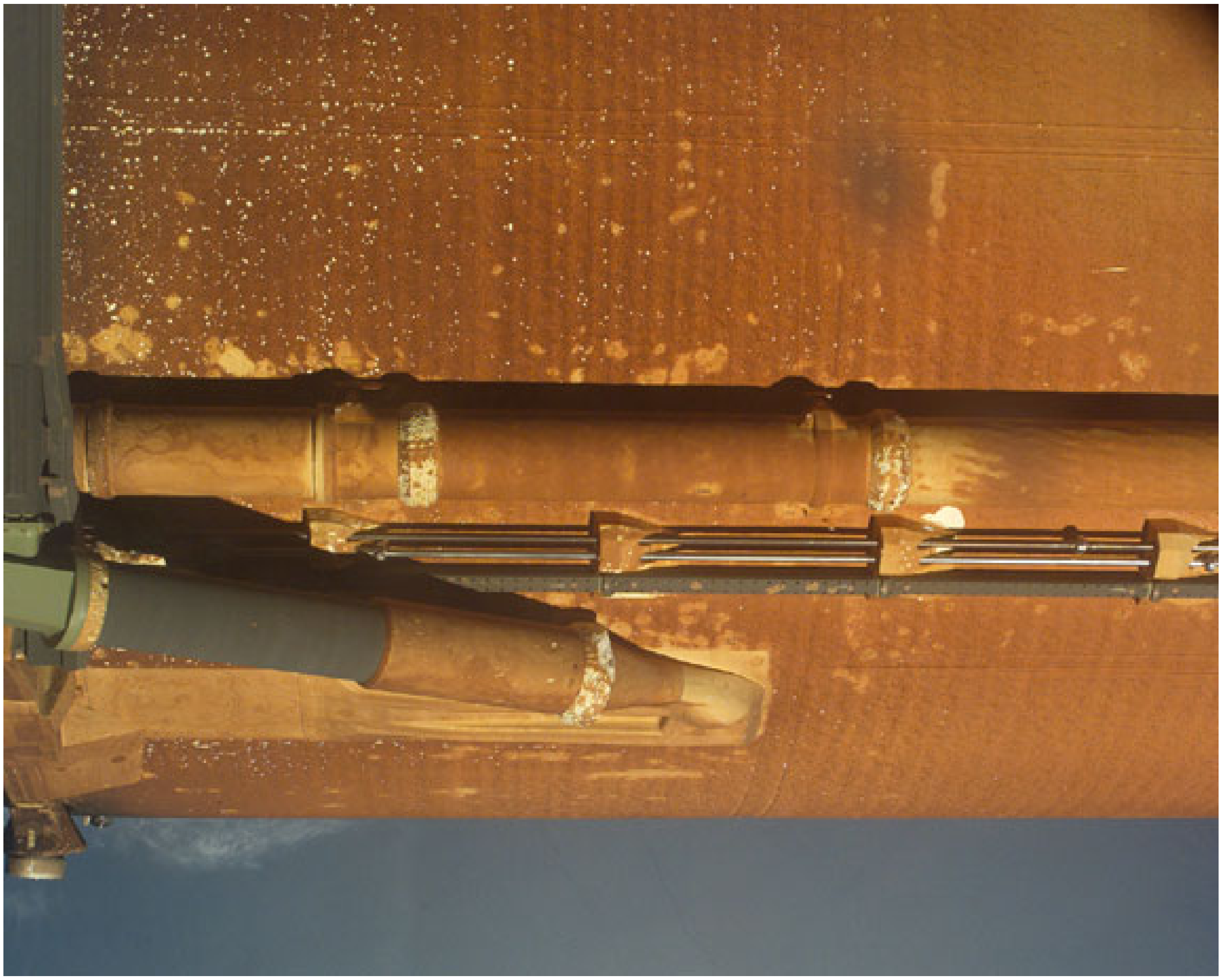


Figure B.4. ET-121 Aft On-Orbit

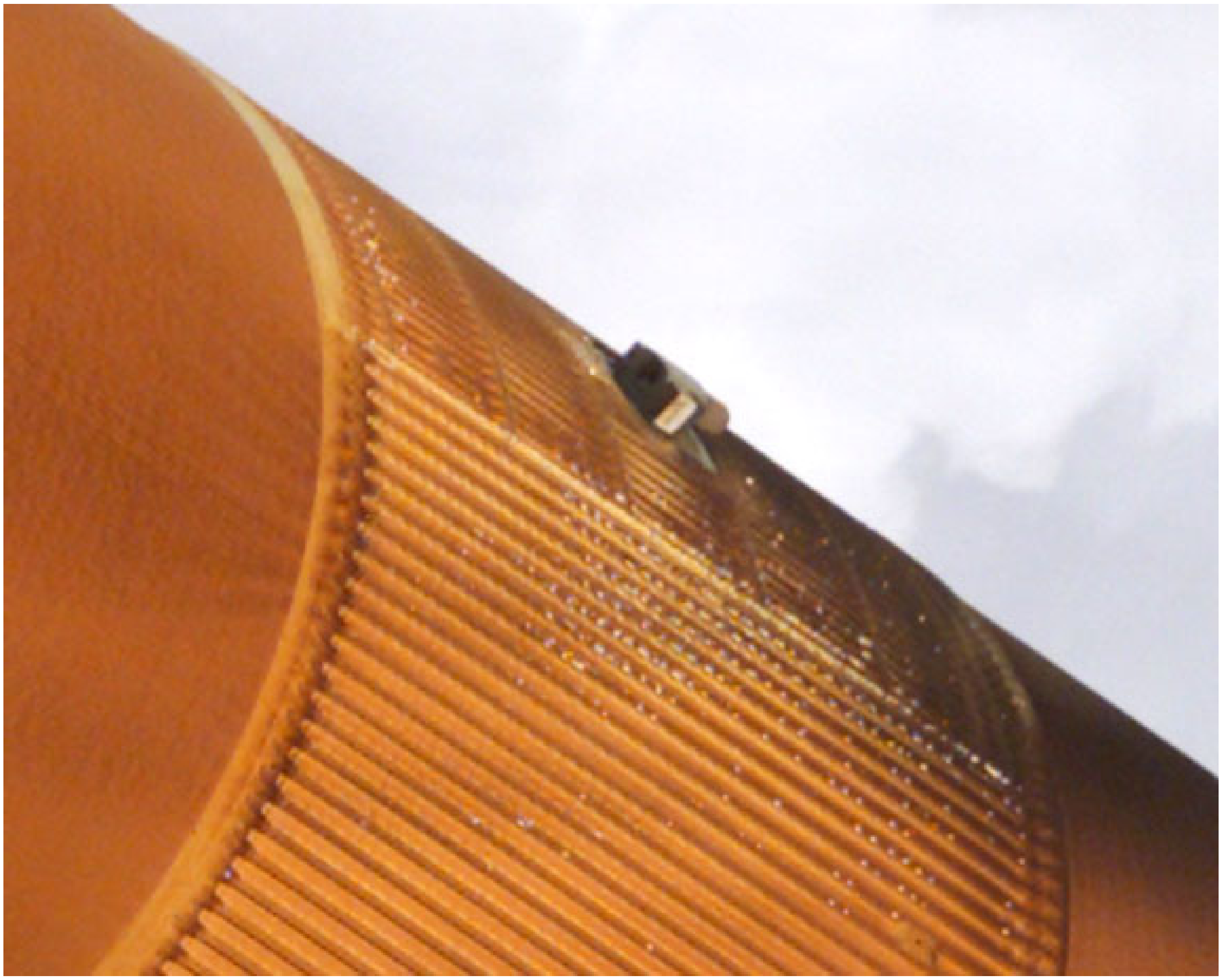


Figure B.5. ET-121 Intertank Popcorning

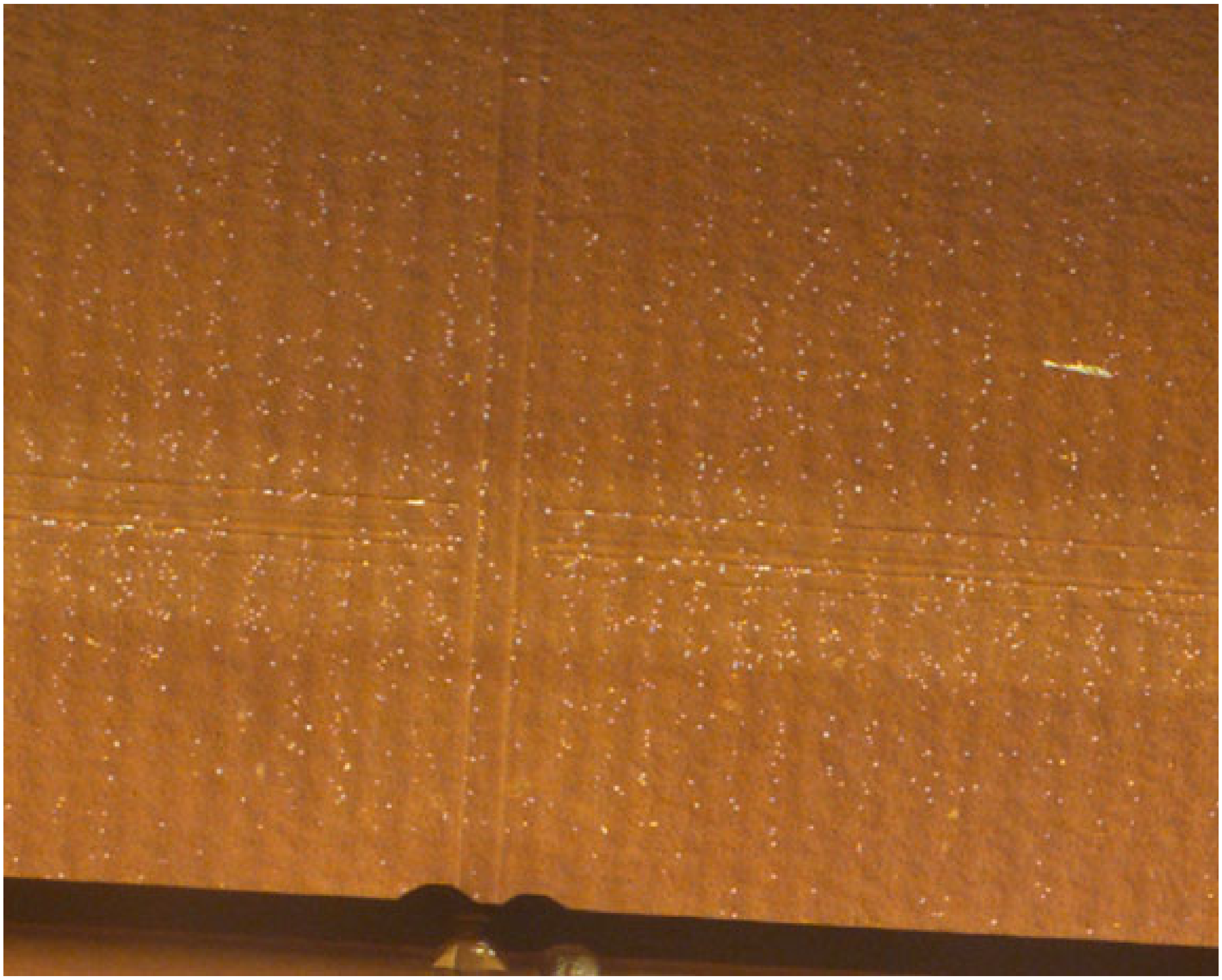


Figure B.6. LH_2 Acreage Popcorning Near LO_2 Line

Figure B.7. PAL Ramp and Acreage Foam

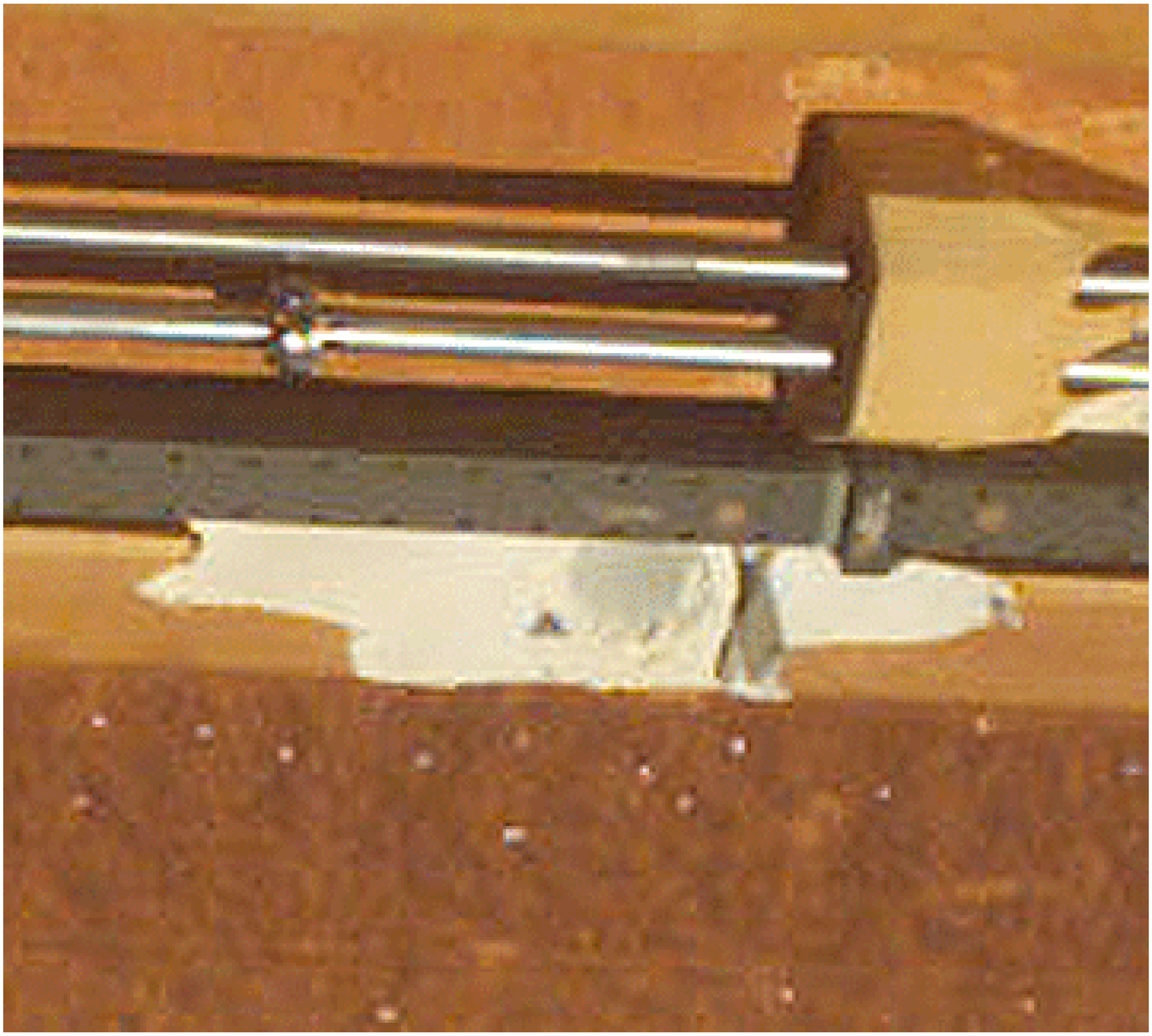


Figure B.8. Close-up of PAL Ramp Foam Loss Area

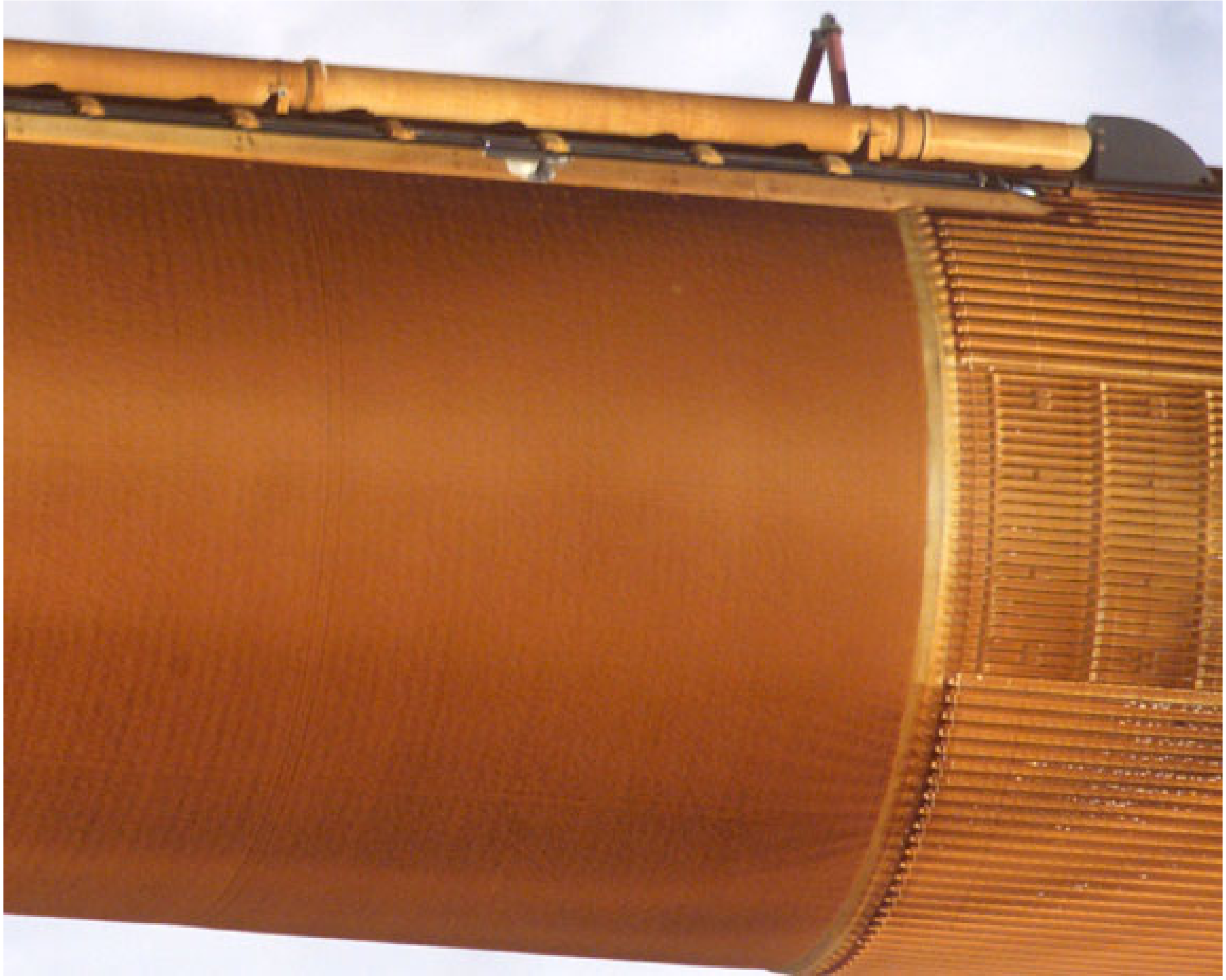


Figure B.9. Tank +Y View

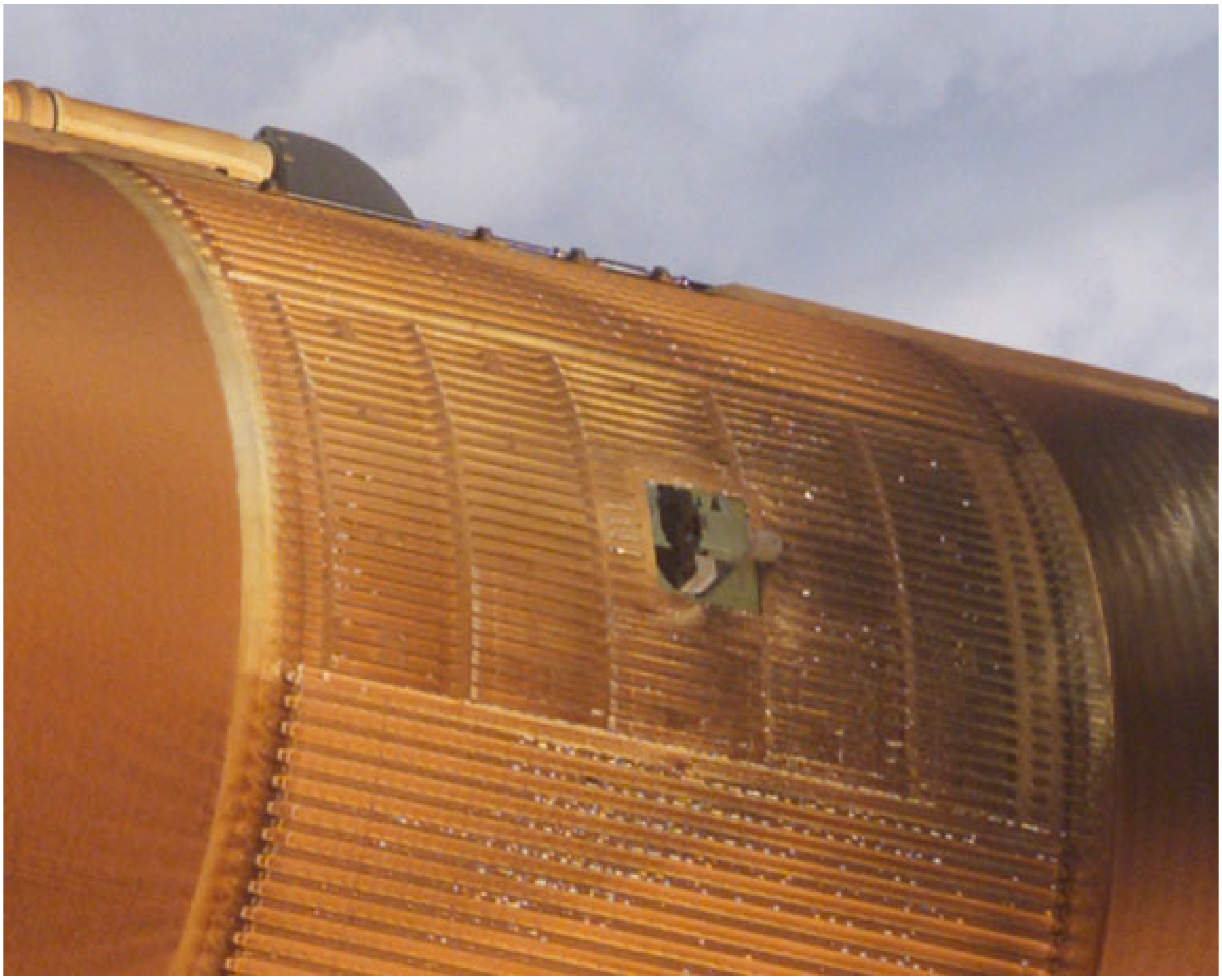


Figure B.10. Thrust Panel and +Y SRB Attachment

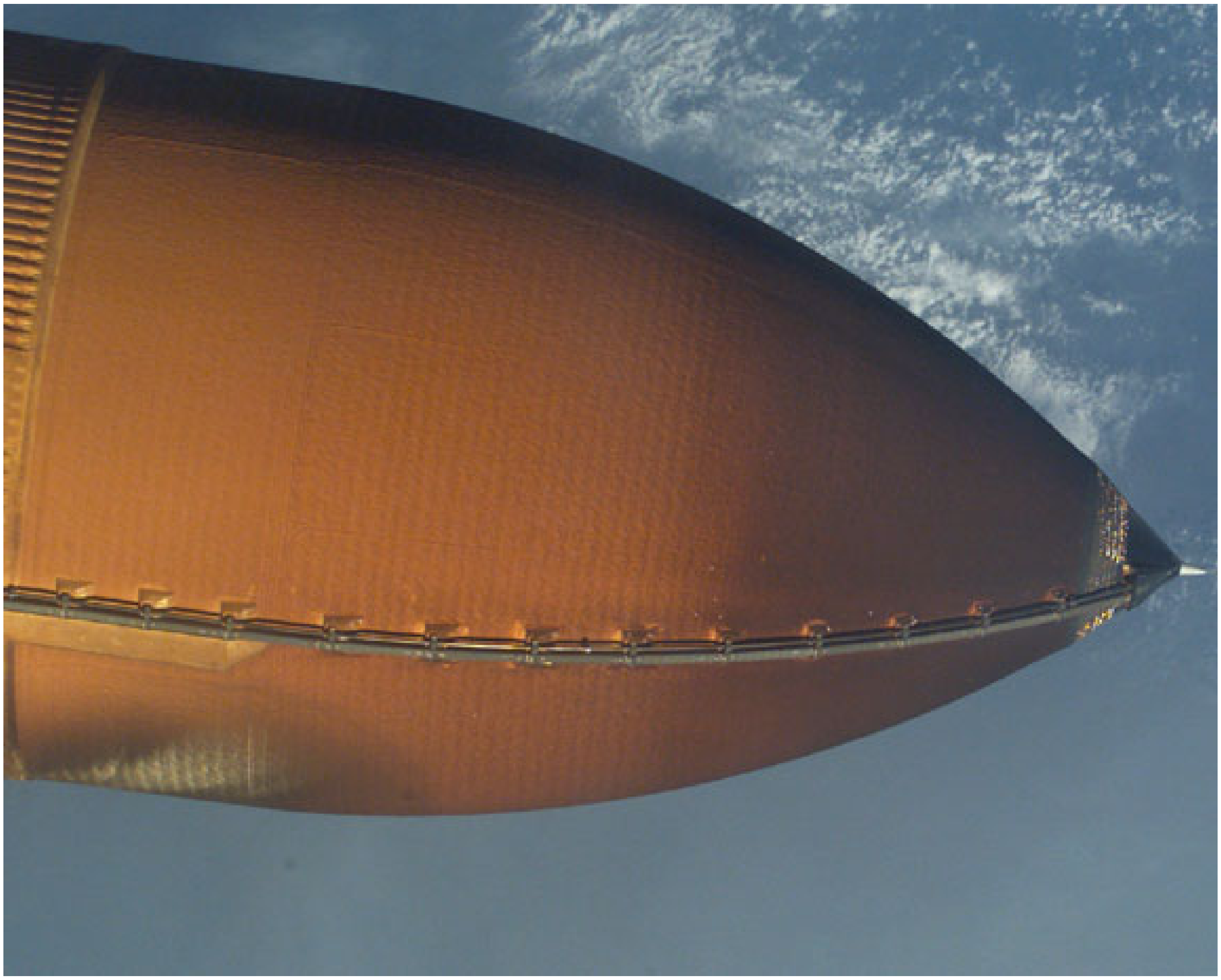


Figure B.11. LO_2 Tank Acreage

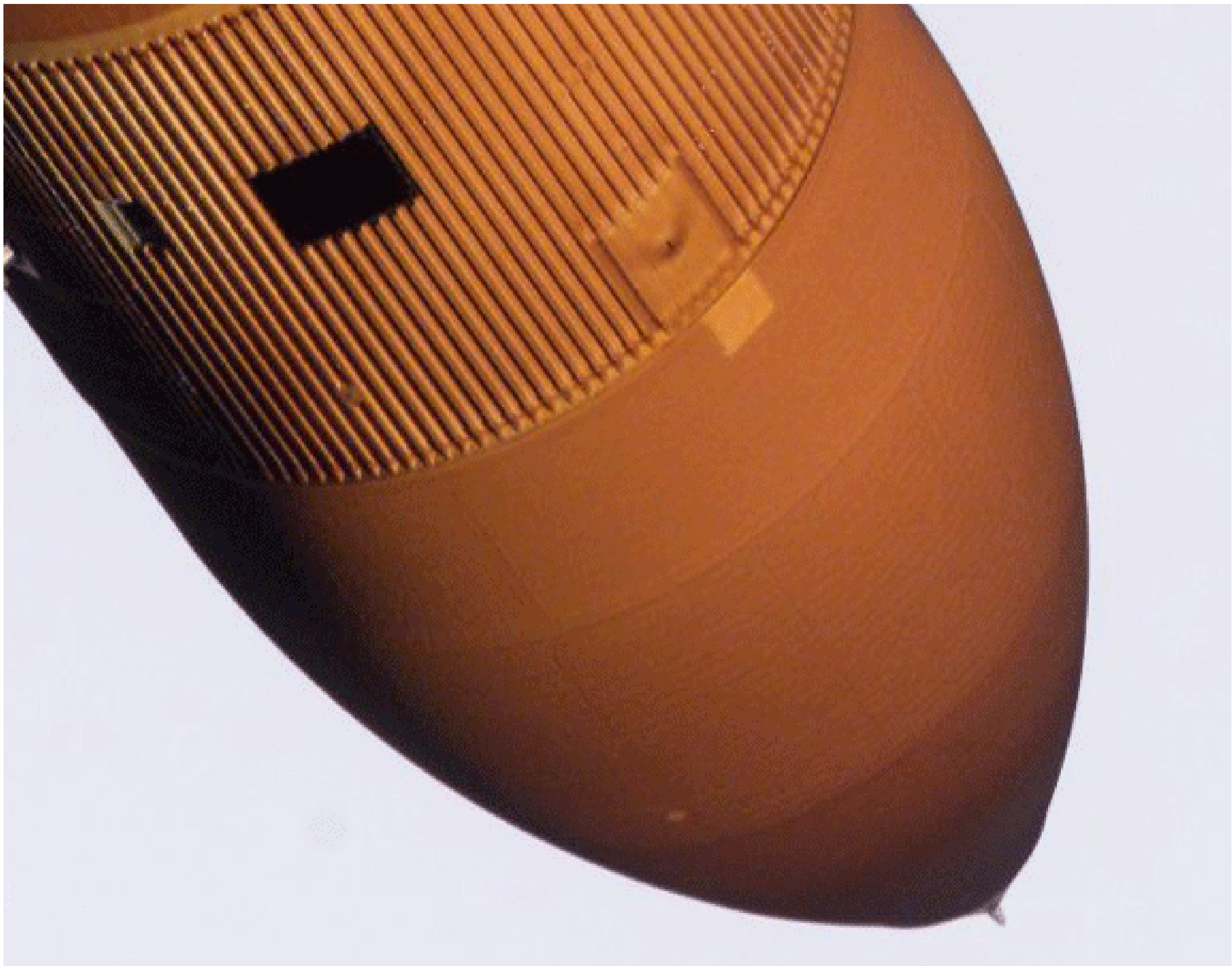


Figure B.12. LO_2 Acreage, -Z View

Appendix C. Test and Analysis Summary

Table C.0-1 summarizes on-going tests and analyses required to close fault tree blocks associated with the STS-114 ET foam loss events, and cross references that work to ET Tiger Team recommendations.

Table C-1. Test and Analysis Summary Table

	Reference		Description	Constraint				
	IFA Resolution Team	ET Tiger Team Near/Long Term Recommendation		PAL Ramp Removal	PAL Ramp Re-Spray	Bi-Pod Wiring Mod	Tank Ship to KSC	Third Flight
PAL Ramps	PAL-001	6	Perform NDE of existing PAL ramps before removal [1] [4]	X				
	PAL-002	6	Dissect existing PAL ramps [1] [4]	X				
	PAL-003		Characterize material properties of crushed / damaged BX-265 [4]		X			
		1	Demonstrate NCFI integrity [1]		X			
	PAL-004		Determine effect of BX-265 on chemistry of NCFI at Conathane I/F [4]		X			
	PAL-005		Assess overspray (mist) affect on adjacent spray BX-265 Conathane bond [4]		X			
	PAL-006		Perform combined environment PAL ramp test [4]		X			
	PAL-007		Characterize properties of NCFI rind [4]		X			
	PAL-008		Determine residual stress between BX-265 and NCFI [4]		X			
	PAL-009	2	Assess PDL bracket closeout as source of PAL ramp void [4]		X			
	PAL-010		Determine BX-265 / NCFI thermal residual stresses [4]		X			
	PAL-011		Establish PAL ramp working limit loads [4]		X			
	PAL-012		Establish effect of knitline cracking on potential fracture propagation [4]		X			
		7	Complete CFD of aero loads on PAL ramp		X			
		6	Perform NDE of new PAL ramps [2]				X	
		18	Implement certified technique for NDE of ET PAL ramps					X
Bi-Pod	BP-001		Heater cable cryopumping leak path test [5]			X		
	BP-002		Heater cable cryoingestion leak path test [5]			X		
	BP-006		Perform LN_2 leak check testing [5]			X		
	BP-007		Perform pressurization bench test [5]			X		
	BP-008		Perform thermal pressurization bench test [5]			X		
		13	Pursue best effort on NDE to detect defects in this area			X		
		4	Dissect existing bi-pod closeout on all reworked tanks to look for voids [3]			X		
		18	Implement certified technique for NDE of bi-pod closeout					X
Ice/frost Ramps	IFR-001A		Perform ice/frost ramp pour and dissection [4]				X	
	IFR-004		Perform ice/frost ramp thermal vac testing [4]				X	
	IFR-005		Perform transparent mold PDL pour				X	
	IFR-006	9	Dissect existing ice/frost ramps [3] [4]				X	
	IFR-006B	13	Pursue shearography of ET-122 around I/F ramps [4]				X	

	Reference		Description	Constraint				
		7	Complete CFD of aero loads in vicinity of ice/frost ramps				X	
		9	Determine loads placed on substrate during ice/frost ramp fabrication				X	
		5	Investigate potential for venting ice/frost ramp fingers to minimize divoting [4]				X	
		18	Implement certified technique for NDE of ice/frost ramps					X
Acreage	AC-001	9	Characterize material properties of crushed / damaged NCFI [4]				X	
	AC-002A	9	Perform microscopic examination of Conathane after cryocycling [4]				X	
	AC-002B		Dissect PDL repairs to look for voids [4]				X	
	AC-002C		Perform thermal-vac test with engineered voids [4]				X	
	AC-003		Perform thermal vac test of station 1160 configuration				X	
	AC-006		Perform thermal vac test with cryo of various states of compression [4]				X	
	AC-007A		Characterize potential for undetected NCFI damage				X	
	AC-007B		Dissect ET-94 and ET-120 PDL acreage repairs				X	
	AC-008		Examine Conathane for evidence of cracking				X	
	AC-009	9	Determine shear load imparted on NCFI from impact [4]				X	
	AC-010	13	Perform shearography of ET-120 around ice/frost ramps [4]				X	
	AC-012		Determine working / walking loads quantifying load distribution through mats [4]				X	
	AC-013		Perform static indent characterizing effect of working / walking loads [4]				X	
	AC-014		Quick-look thermal-vac and dissection bounding potential mat loads [4]				X	
		18	Implement certified technique for NDE of acreage TPS					X
Flange	F-001	9	Perform thermal-vac test on thrust panel flange configuration [4]				X	
	TBD		Perform 3D analysis to further evaluate cryo-ingesion/pumping conditions				X	
		13	Pursue best effort on NDE to detect defects in this area				X	
		18	Implement certified technique for NDE of flange					X

Notes:

[1] Perform on all tanks with existing PAL ramps
[2] Perform on all PAL ramp re-sprays
[3] May be performed on ET-120 only
🟨 [4] Tests referenced in 3 Oct 05 IFA Team Status Overview
🟩 [5] Testing complete

Appendix D. Community Suggestions

A number of ideas have been received by the ET Tiger Team and the NASA Engineering and Safety Center (NESC) from people inside and outside of the Agency. These ideas have been, and are being, reviewed. Fixes proposed by the community at large generally fall into several categories including use of exterior netting covering the tank, use of netting embedded into the foam, the use of covers for the tank that form partial or complete external shrouds or shields, the use of foam reinforcement fibers, the use of alternate tank wall configurations (for example, double wall vacuum bottle type configurations), the use of plastic wrap, and others. These ideas aim at preventing release of foam by mechanical means, catching pieces of lost foam, deflecting lost foam away from the vehicle, the avoidance of foam use, or a major reconfiguration of the launch vehicle.

There are several engineering issues that were considered in screening these suggestions. Any idea for reducing foam loss from the ET, or any idea for mitigation of the potential deleterious effects of foam loss, will have a set of engineering requirements and constraints that would affect its implementation. In some cases, such as the suggestion to build a double-walled tank or the suggestion to put the Space Shuttle on top, a major system redesign would be required. These would likely involve development times comparable to development of a new launch system. Other suggested fixes, such as large shells or shields, involve significant increases in mass and major issues related to the dynamics of the system and the interaction of the system with ascent environments. Ideas that involve foam reinforcement have the potential for increasing size of foam debris that may be liberated and, therefore, increasing debris mass. For some ideas, such as use of nets or shields, attachment methods may have inherent thermal shorts to the tank, significantly increasing heat transfer and potentially providing new places for ice to form. In addition, these approaches may be negatively affected by multiple tanking cycles and by aerodynamic heating. Implementation of some of the ideas would raise compatibility issues such as potential mismatches in thermal expansion or contraction, mismatches in mechanical properties such as stiffness, and chemical compatibility. Some of the ideas may have considerable impact to other parts of the launch system. The addition of foam to the inside of the hydrogen tank, for example, would present high risk to the main engines. Any new implementation of an engineering fix to the problem of foam loss will involve a V&V program to determine efficacy of the fix and its potential for deleterious impact on the system. Some of these V&V activities could be very extensive and lengthy.

A few of the ideas such as the addition of vent holes in the foam have been implemented in other areas of the tank including the intertank region. Others such as analysis of the effects of moisture on foam are currently being considered.

The ET Tiger Team is recommending the following suggestions for further consideration by the SSP or by NESC. These suggestions typically include an approach with some novelty or some preliminary analysis and/or testing to support their feasibility.

1. Reinforce the ET foam with a 3-D fiber mesh. This suggestion for fiber-reinforced foam goes beyond the typical, with an optimized 3-D mesh, building of test samples, and initial strength tests performed. This proposed solution could be applied to specific regions involving poured,

molded, or sprayed foam. Clearly more work must be performed including aerodynamic testing of foam in which cracking and surface configuration changes have been induced by the processes that normally produce divots and the ability of the reinforcing fibers to prevent debris liberation demonstrated.

2. Use a mesh skin for the ET made from glass or ceramic fiber materials and silicate binders. This proposal has considered the high ascent heating rates. This solution could be applied to specific regions involving poured, molded, or sprayed foam.

3. Use an elastomer spray overcoat. The idea is to seal any leak paths and provide a minimal amount of encasement. A few quick tests are necessary to see if this is feasible or if it would actually make things worse (might prevent an air entrapped void from cracking and venting). This solution could also be applied to specific regions instead of the entire tank.

4. Use a specifically suggested ET primer for foam application. This is applicable only if root cause is identified as adhesion failure at foam/aluminum tank interface. The suggester has over 27 years of experience in commercial foam applications and has found one primer, Con-Bond, to be superior to others for ensuring a good foam-to-aluminum bond.

5. Use debris net of titanium wire mesh for the ET. This suggestion included some preliminary calculations. This is another solution that could apply to specific tank regions.

6. Specific individuals were recommended or volunteered to provide their expertise. Areas of expertise of these specialists include insulating foam and aerothermal environments.

7. Use alternate blowing agent 245f.

8. Apply pre-molded, bonded foam to the tank. A similar design has been incorporated in the common propellant tank bulkhead of the Space-X Falcon launch vehicle and could be used in specific applications such as the PAL ramps. This design is relatively mature and has seen application on other launch vehicles. Atlas uses a similar bonded-foam design. The Falcon foam is a dense, high-strength material that must be scored prior to installation to give it enough flexibility to conform to the curved tank bulkhead. A similar installation technique would probably be required both for conformance to the ET substrate and to give the material enough flexibility to move during chill-down without cracking. Natural voids would be created at the substrate due to the scoring, raising the potential for cryopumping and divoting. An adhesive bond at the NCFI interface would probably be required and mismatches in CTE could either crush or open cracks in the weaker acreage material, providing leak paths for cryopumping and increasing the potential that large areas of foam could be liberated on ascent. External environments for ET differ significantly from the Falcon tank environments, with higher heating and pressure differentials to impact foam strength and performance. The SSP would have to address these issues and trade the inherent risks against those associated with the current design before deciding on a change to the existing TPS.

Appendix E. References

1. *Flow Field Effects*, Roy Steinbock, LMMSS, Action Item Response ET-35, undated.

2. *Quicklook Report of STS-114 Downlist,* Mark West, Mary Beth Guion, Mike Cagle, Phil Reid, Boeing, undated.

3. *Quicklook Report of STS-114 Downlist Part 2, Trending Plots,* Mark West, Mary Beth Guion, Mike Cagle, Phil Reid, Boeing, undated.

4. *STS-114 Element BET Heating Environments,* Robin Taylor, Integrated Vehicle Analysis Team, Thermal Panel, 04 Aug 05.

5. *Confirm Environment Data Collected with Intertank Instrumentation,* LMMSS, Action Item Response ET-19, undated.

6. *Significant Structural Issues Encountered During ET-121 Construction,* LMMSS, Action Item Response ET-13, undated.

7. *ET-121 Scheduling Overview*, LMMSS, undated.

8. *ET-120 Scheduling Overview*, LMMSS, undated.

9. *ET-119 Scheduling Overview*, LMMSS, undated.

10. LMSS, Action Item Response ET-5c-1, ET-30a, ET-31a, undated.

11. *How Were Repairs Certified at MAF and KSC?,* Action Item Response ET-45, undated.

12. NSTS 60555, *Verification Limitations for the External Tank Thermal Protection System*, 05 Jun 05.

13. NSTS 60559, *Expected Debris Generation and Impact Tolerance Requirements, Groundrules, and Assumptions*, 08 Jul 05.

14. *What specific engineering evaluation was done during the selection process for waxed cups and tape adhesives?,* Action Item Response ET-43a, LMMSS, 19 Aug 05.

15. *ET-120 PAL Ramp Rationale for Partial Removal,* SSP PRCB S2153, 12 Feb 04.

16. *LOX Ramp NDE Summary,* LMMSS, Action Item Response ET-27, 15 Aug 05.

17. *Data Summaries: PAL Ramp Lead-In and Lead-Out Component Temps, PAL Ramp Lead-In Pressures, PAL Ramp Lead-Out Pressures, LH PAL Ramp Core Tensiles, LH2 PAL Ramp Plug Pulls, PAL Ramp Plug Pull Data*, LMMSS, Action Item Responses ET-3a-3 and ET-3b-3, undated.

18. *PAL Ramp Deletion,* LMMSS, Action Item Response ET-37.

19. *Potential for Re-Pressurization Line Vibration to Affect Ice/frost Ramp Foam,* LMMSS, Action Item Response ET-24, 12 Aug 05.

20. *ET-114 Camera TIR011 Debris Size Analysis,* Jeremy Myers, NASA MSFC EV-12, 1 Sep 05

21. *Ice/frost ramp release agents,* LMMSS, Action Item Response ET-22, 11 Aug 05.

22. NCD 067005, Item 2, 24 Feb 05.

23. *Data Summaries: LH Barrel Density, LH2 Barrel Process Data, LH Barrel Plug-Pulls*, LMMSS, Action Item Response ET-3a-5, undated.

24. *Bi-Pod Closeout Cracks,* LMMSS, Action Item Response ET-58, undated.

25. *Why Does –Y (LH) Current Draw Differ for +Y (RH)*, LMMSS, Action Item Response ET-28, 12 Aug 05.

26. *Data Summaries: Bi-Pod Lead-In and Lead-Out Component Temps, Bi-Pod Lead-In Pressures, Bi-Pod Lead-Out Pressures, Bi-Pod Ramp Density, Bi-Pod Wedge Closeout Plug-Pulls, Bi-Pod Wedge Closeout Ratio,* Action Item Response ET-3, LMMSS, undated.

27. *Data Summaries: 1540 Environment, Lead-In and Lead-Out Component Temps, Density, Lead-Out Pressures, Substrate Temperatures,* Action Item Response ET-3a-1, LMMSS, undated.

28. Knight, N. F., Jr.; Nemeth, M.P.; and Hilburger, M. W., T. L, *Assessment of Technologies for the Space Shuttle External Tank Thermal Protection System and Recommendations for Technology Improvement-Part 2: Structural analysis Technologies and Modeling Practices*, NASA/TM-2004-213256, Aug 04.

29. *Continued Improvement of ET TPS Processes*, MSFC Materials and Processes Lab, 21 Aug 05.

30. *Heat Rate and Heat Load Plots for BP21087 STS-114 MS Cert vs. STS-114 BET,* Pedro Lopez, Integrated Vehicle Analysis Team, Boeing, 13 Sep 05.

31. *Provide cutaway of Ice Frost Ramp Construction & Specific Sequence of Build-up Operations,* LMMSS, Action Item Response ET-25, 13 Aug 05.

32. *STS-114 Orbiter Post-Landing Inspection Debris Assessment,* 11 Aug 05.