NASA Case Study *MSFC-CS1004-1*
By Thomas Steva and Jennifer Stevens *Rev. 01/21/16*

After Math – Foamology and Flight Rationale

The Space Shuttle was developed by NASA to be a largely reusable launch system which could provide frequent access to low earth orbit. Like all previous launch systems, safe reentry for the crew and payload required the use of a thermal protection system (TPS). Unlike previous spacecraft though, the Shuttle's TPS was exposed from launch, making it sensitive to debris which could be generated by the vehicle on ascent.

The most likely and potentially destructive source of debris was considered to be ice, which could build-up anywhere on the External Tank (ET) where there was exposed metal. Ice could form during ground operations after the cryogenic propellants had been loaded and then be knocked loose on ascent. In order to prevent both ice build-up and boil-off of the propellants, the entire ET and all protuberances (orbiter attach points, pressurization lines, propellant feed lines, etc.) were covered with a spray on foam insulation (SOFI) type TPS. Unfortunately the foam was also susceptible to liberation during ascent, and posed a debris risk of its own. During the early years of the Shuttle Program engineers spent a good deal of effort characterizing the amount of foam that was shed.

All in the Family

While foam loss was always present, over time the Program became accustomed to it, and even accepted a certain amount of loss as normal. If the amount of foam lost was within historical experience it was considered in family, and thus not likely to be a threat to the orbiter

TPS. However, foam debris loss that was higher than typical, or out of family, was scrutinized more closely. In October 2002 a 4”x5”x12” piece of foam of was liberated on STS-112 which struck the External Tank Attach Ring (ETA ring) that joined the left solid rocket booster to the ET. The foam put a 4”x3” dent in the metal attach ring, but did not cause catastrophic damage.

During the Flight Readiness Review (FRR) of the next flight, STS-107, the ET Project presented its flight rationale. It stated that the cause was understood and the risk had been mitigated. The program level Mission Management Team (MMT) concurred, and determined that the vehicle was safe to launch.

In February of 2003, during ascent on STS-107, an ~2 pound piece of foam was liberated from the left ET bipod and impacted the leading edge of Columbia’s left wing. The resulting damage to the Reinforced Carbon-Carbon TPS in that location was severe enough that on reentry a jet of hot gas was able to enter the vehicle. The eventual structural failure of the wing and resultant loss of control led to vehicle break-up, and the loss of the entire crew. Following the Columbia tragedy the Space Shuttle fleet was grounded for two and a half years to determine the root cause of the incident and implement the necessary design changes. The foam application process was also scrutinized and updated.

On July 26, 2005, Space Shuttle Discovery launched on the Return to Flight (RTF) mission, STS-114. On ascent, the ET shed foam from numerous locations, where the largest piece was twenty-five times greater than the certified limit. While the foam missed the orbiter and the mission was ultimately successful, the re-occurrence of foam loss of that magnitude was extremely concerning. The perceived failure to fix the debris issue also caused much criticism from the media and the public. The shuttle fleet was grounded again and two separate in-flight anomaly (IFA) teams were established to determine the root cause of each piece of debris. The teams were also tasked with providing recommendations to the ET project to more thoroughly address the fundamental issues with the production, application, and maintenance of the foam.

On June 26, 2006 the Space Shuttle Program held the STS-121 Flight Readiness Review (FRR). The ET Project provided a status of the design and process changes addressing the IFA teams’ recommendations for ET-119, the external tank on this next scheduled flight. The FRR board’s responsibility was to determine if the vehicle was acceptable to fly. This would be the second Return to Flight mission since the Columbia accident.

- As a member of the Shuttle Program mission management team, given the history of this issue, the changes to the design and foam application processes, and extremely high visibility in the public, what evidence might you be looking for to say it is okay to fly?

Foamed If You Do, Iced If You Don't

The Space Transportation System (STS) External Tank used in the Space Shuttle Program (SSP) was an assembly with two liquid propellant tanks connected by cylindrical piece called the Intertank. A tank holding liquid oxygen (LOx or LO2) was positioned at the top of the tank. Below it, a larger cylindrical tank held liquid hydrogen (LH2). See Figure 1. The tanks were made of aluminum alloy 2219 and/or an aluminum-lithium alloy 2195. They were strong and lightweight, and like all metals, would contract as they got colder and expand as they heated up. Tanks also stiffened and did not flex as much when they were full of liquid. They would also expand circumferentially as they were filled.

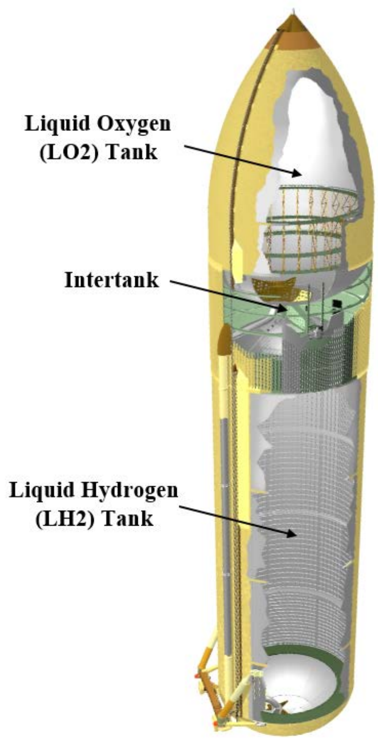


Figure 1 *External Tank Sections (NASA)*

To keep oxygen and hydrogen in a liquid form, the gasses had to be chilled to subzero temperatures. If the temperature rose above their boiling point, they would "boil off", or become gaseous. Oxygen or hydrogen that boils off becomes unusable as a propellant. To prevent boil off during tanking and pre-launch sequences, the tanks were covered with foam for insulation. In addition to preventing boil off, if the tank were uninsulated, water from the air freezing onto the tank would have made it too heavy to lift the planned payload mass to orbit.

Since the ET was not one continuous piece, but was a jointed assembly, there were conditions at certain locations that increased the likelihood of ice buildup during tanking. More pre-flight ice buildup increased the likelihood of ice debris liberation during ascent. Insulating foam helped reduce the generation of ice, but could not eliminate all of it.

Unfortunately, the complex geometries of tank combined with the dynamic environments experienced on ascent made the foam susceptible to liberation as well. While ice was considered a higher risk due to its density, the foam still posed a risk of its own.

Return to Flight 1 (STS-114)

There were several foam (TPS) design changes implemented in key areas on ET-121[1], the tank to be used for the return to flight after the Columbia accident. The bipod ramps were removed altogether and heated plates were installed instead to prevent the build-up of ice. Enhancements were also made to the foam on the Intertank stringers, which took up a large

[1] External Tank numbering differed from the STS, SRB, RSRM, Orbiter, and Engine number systems

portion of the critical debris zone, or area where if foam was shed it was likely to do the most damage. Also included in this region was the Intertank/LH2 tank flange closeout. Closeouts were the manually sprayed areas around complex geometries, and were generally the most susceptible to defects during the application process and thus to foam loss on ascent. Of the prior flights that had usable imagery, 65% of the tanks had foam loss from the Intertank/LH2 tank closeout. As such, several design changes were also incorporated in this location for RTF, which included:

- A change in the flange bolt orientation and nut profile to reduce geometric complexity;
- Sealant to prevent leak paths for liquid nitrogen; and
- An enhanced three-step manual foam application process.

Since Columbia, engineers had also been working with the spray technicians to develop new application techniques for reducing defect size and quantity in all other critical closeout areas.

Protuberance Aerodynamic Load (PAL) Ramps

To implement the design changes for the entire LH2/Intertank flange closeout, another manually sprayed-on portion, the forward section of the LH2 PAL ramp, had to be removed. The purpose of the PAL ramp was to deflect flow over and away from the cable tray and re-pressurization lines (also called presslines) that ran along the length of the ET. This flow was generated by swirl that would come up and around the side of the tank, approximately perpendicular to the lines.

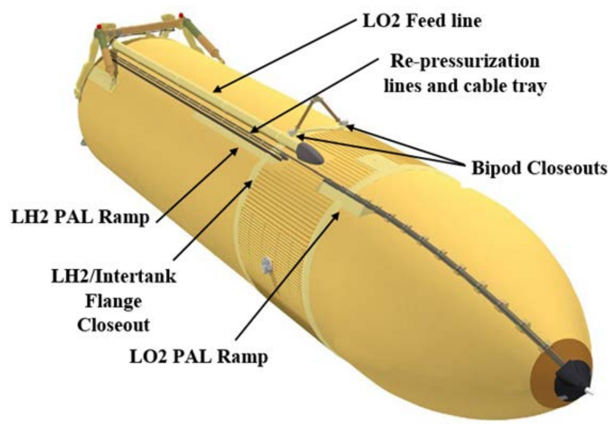


Figure 2 *External Tank Features (NASA)*

There were really two separate ramps: the LH2 PAL ramp which ran from above the LH2/Intertank flange down the H2 tank and along the cable tray for almost 40 feet, and the LO2 PAL ramp which ran from roughly the mid-section of the Intertank up along a portion of the LO2 tank for approximately 14 feet.

Figure 3 LO2 PAL Ramp (NASA)

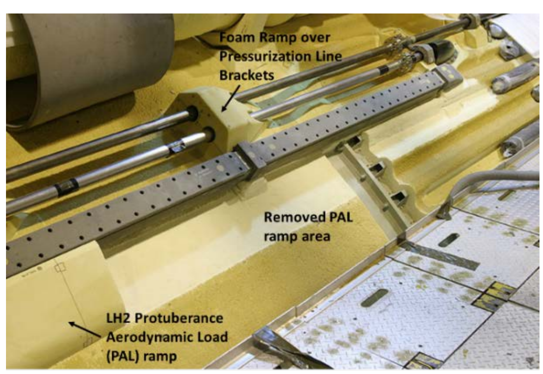


Figure 4 LH2 PAL Ramp with Part Removed (NASA)

In order to properly blend in the removed portion of the LH2 ramp with remaining original structure, it was well agreed that first 10 feet would need be removed and replaced. However, whether or not the entire ramp (both LH2 and LO2 segments) should be removed and re-sprayed as well was a matter of considerable discussion.

Use-As-Built or Remove-and-Replace?

On July 9, 2004 a briefing was held for the Space Shuttle Program managers to make a final decision on whether or not to remove and replace the entire PAL ramp for the RTF mission. Historically the PAL ramp had a very good track record, with no observable debris generation for flights with available imagery. Only approximately 60% of all flights had usable imagery though, so it was unknown if there was debris generated from the PAL ramps during the other 40% of flights. Since the STS-121 tank (ET-119) still contained the manually sprayed portion which had been installed prior to Columbia without the updated process enhancements, the remainder of the PAL ramp was thought by many to still pose a considerable risk.

Those in favor of the use-as-built option noted that replacing the ramp was risky in its own right. Removal of a portion of foam would almost inevitably result in the damage of the underlying acreage foam. To re-spray the ramp it would require sanding and blending of the chopped up area. As one NASA materials engineer noted: “The sanding/blending effort basically made the foam look like a golf course, and so you were replacing one complicated geometry with another.” In addition, the PAL ramp was a tricky place to work on and required the use of platforms, which would lay over the foam to gain access. Collateral damage to the foam in the surrounding area posed additional risk as well.

Justification Evidence

Of central importance to the argument for the use-as-built option was the available data on the effectiveness of the spray process enhancements that had been developed. In July 2004, one year before the eventual flight of STS-114, the process enhancement effort was still in the early phases. The data at that point was based on dissections of the removed 10 feet of the original ramp on the STS-121 ET and test sprays of a new ramp with the enhanced techniques.

Comparison of the two showed a reduction in the frequency of small defects from the improved foam application, but not on defect size. Nor did it show a reduction in the number of larger defects that posed the most risk. Given this data, and the perceived historical reliability of the PAL ramp, the technical authority and program managers considered other items, namely the bipod ramp and flange closeout, of higher priority for near term improvement. The existing certification rationale for the PAL ramps was considered sufficient and it was deemed that the risk of debris would not be reduced for this location by replacing the existing foam.

On the other hand, those in favor of the remove-and-replace option had more confidence that the enhanced processes would provide an improvement. They felt that the risk of collateral damage could be effectively controlled, and that replacement of the entire ramp would considerably reduce the void content. Some of those in favor were the materials engineers working in the trenches day in and day out with the ET technicians. They had a hands-on understanding of the continual improvement the enhancements were beginning to show.

- What evidence or considerations inform the decision of whether or not to remove the whole PAL ramp?
- How complete is the dataset you have been presented?
- You make the call: Use-As-Built or Remove-and-Replace?

Flying As Built

At the ET pre-FRR, prior to the program FRR, the majority of the board members voted in favor of the use-as-built option. Both the contractor and NASA ET project managers then recommended this option to SSP management at the July 9, 2005 program FRR. Ultimately the SSP Manager concurred.

On July 26, 2005, a little over a year after the ET Project decision to use-as-built, STS-114 was launched. At 127 seconds into the flight a 1 pound piece of foam 36”x11”x7” was liberated from the LH2 PAL ramp. The foam was from the older portion of the ramp which had not been replaced. This was within the 135 second mark, the time up until which calculations conducted on hypothetical debris scenarios had indicated that debris from the ET could achieve a great enough velocity, with respect to the vehicle, to do critical damage to the Orbiter tiles. After 135 seconds into flight there is not sufficient atmosphere to cause debris transport to the wings.

It is important to consider that some foam loss was expected and flight rationale for the TPS was based on certification limits for debris size. These limits were derived from testing and analysis, which incorporated experimental data from ground tests and a simplified fracture mechanics. They also incorporated safety factors to compensate for the considerably large unknowns in the material behavior of the foam. Probabilistic risk assessment (PRA) was then used to determine the maximum expected debris mass. The pre-flight assessment for STS-114 showed all expected debris sources to be lower than the certified limit.

Ultimately though, the flight performance of the foam on STS-114 turned out to be significantly different than the prediction. The PAL ramp mass, based on post separation imagery of the divots left in the tank, was almost _80_ times greater than the PRA maximum and _25_ times greater than the certified limit.

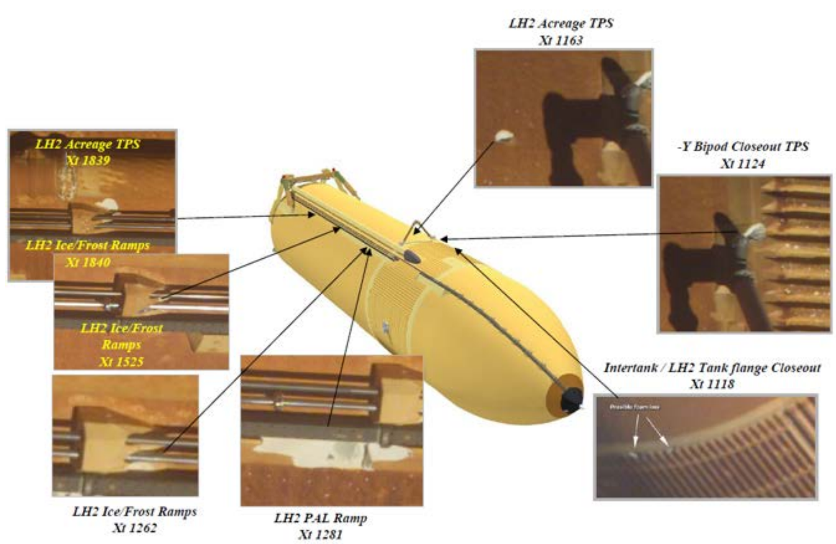


Figure 5 Major areas of foam loss on STS-114 Imagery obtained from orbiter after tank separation.
(NESC/NASA, STS-114 External Tank In-Flight Anomaly Final Report)

In addition to the PAL ramp there were 15 other instances of significant foam loss. While all were within the certification limit, 13 still exceeded the upper bound of the PRA. Even though the majority of these events occurred after the 135 second mark, the shocking size of the PAL ramp combined the high number of unexpectedly large occurrences was a major concern. For the media and for the public it was a frenzy. After two and a half years of working the issue the orbiter was nearly hit again by a dangerously large piece of debris.

Those inside NASA were surprised and concerned, but they were far more educated now on the risk. They knew that the enhanced ascent and on-orbit imagery utilized for RTF helped to shed light on the true extent of foam loss, allowing for scrutiny beyond that which was available before. They also knew that the process controls and design changes were still in the early phases of implementation. Improvements were expected to reduce the risks further. In the ET presentation for STS-114 FRR debris was ranked as a 3x3 on a 4x3 risk matrix of likelihood versus consequence (severity)[2]. The rating means the likelihood of occurrence was deemed infrequent with an expectation that the consequence would be catastrophic if it did occur. This was the highest risk level still deemed acceptable for flight.

Though public perception leading up to the flight may have been that NASA had fixed the issue, internally the truth was recognized as anything but. The considerable amount of work that had gone into understanding and modifying the foam after Columbia, with the resultant attempt at defining an acceptable risk posture, represented the first efforts for the Program in coping with an issue they were realizing had no easy design solution.

Enter The Foamologists

The robotically sprayed North Carolina Foam Industries (NCFI) and manually sprayed BX-265 SOFI used for the thermal protection system on the External Tank were both essentially the same type of foam. At 2.27 pounds per cubic foot (lb/ft^3) it was, by comparison, much lighter and more fragile than nearly all other materials on the vehicle. The seemingly innocuous nature of foam was a big contributor to the miscalculation of its true risk, and ultimately the loss of Columbia. Outside of the Materials and Process engineering community, foam was thought of as a familiar and uncomplicated. It was just foam.

Even after the conclusions of the accident investigation board the perception of the simplicity of the foam persisted. While the potential for a catastrophic hazard was now recognized, the solution everyone thought was simple: just don’t let it come off. As Scotty Sparks, an engineer at NASA’s Materials and Processes lab recalled, “Everyone was a foamologist - the public, the media, even those not directly involved at NASA, thought they knew how to fix it, that it was just foam.”

[2] Risk matrix guidelines for scoring is explained in NSTS 22254 Rev. B, Methodology for Conduct of Space Shuttle Program Hazard Analyses, Section 4.6.2. Per 4.6.2.5b Infrequent: Could happen in the life of the program. Controls have significant limitations or uncertainties. Per 4.6.2.4a Catastrophic: Hazard could result in a mishap causing fatal injury to personnel and/or loss of one or more major elements of the flight vehicle or ground facility.

Proposed design solutions poured in. These ranged from concepts involving the installation of some form of netting or a wire mesh to retain the foam, to structural modifications such as large shrouds, a new double-walled tank with the insulation in-between, or even attaching the Shuttle on top of the stack. While some seemed almost reasonable at first, in reality they were all impractical. Beyond decreasing performance of the vehicle, any significant design change would also face major obstacles in terms of analyses and re-certification. Recertification efforts would be on par with that of designing and building an entirely new launch system. Ultimately, the most affordable and most reasonable solution was to address problem of the foam quality itself. This mostly meant focusing on void content, which turned out to be a very challenging problem in its own right.

Cryopumping and Cryoingestion

Divoting, which was the primary means of foam liberation, was caused by the vaporization of liquids trapped below the foam surface. Imperfections during application of the foam would result in voids, or air pockets. As the cryogenic propellant was loaded, the trapped air, in a process called *cryopumping*, would condense into a liquid. On ascent the propellant draining from the tank would drop below the location of the void. With no cryogenic propellant keeping the void area cold, the liquefied air would change back into a gas. As the vehicle ascended to higher altitudes the ambient pressure also decreased. This effect, combined with aerodynamic heating, or the warming of the TPS surface because of the vehicle passing through the air, further contributed to the expansion of the trapped air. The resulting difference in pressure across the foam surface would cause it to shear and pop off the tank. The telltale divots left behind were then observable by post-separation imagery acquired from the Orbiter.

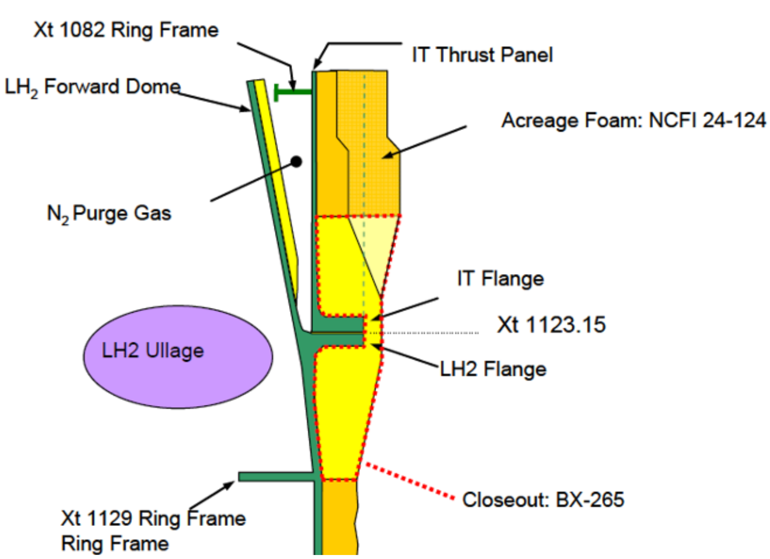


Figure 6 Illustration of the Thrust Panel Y-joint Area (NASA)

In a similar process, called *cryoingestion*, the nitrogen gas used to purge the internal compartments of the tank prior to launch, such as the Intertank, would come into contact with the exposed metal surfaces cooled by the cryogenic propellants. This would cause the nitrogen gas in the immediate vicinity to condense into a liquid, pool, and then seep between mechanical interfaces to fill voids or areas where the foam had peeled away from the tank surface (called debonds).

One area in particular that had ideal conditions for cryoingestion was the LH2/Intertank flange (Figure 6). After assembling the tank, access was extremely limited to the Y-joint created between the Intertank barrel and the LH2 tank dome and it was not feasible to apply insulation in that location on all surfaces. The resultant areas of exposed metal allowed for the liquefaction and pooling of a significant amount of nitrogen in that region. This condition was the cause of much of the foam liberation see from the flange closeout on previous flights.

Tough Math

The material properties of the foam did not lend themselves easily to the use of conventional structural analyses either. Simplified models had to be used, and only when combined with extensive testing could a rough method for correlating defect size to likelihood of debris generation be developed. This method was the divot/not-divot curve (Figure 7). It provided a relationship between defect dimension and defect depth which could be used to predict whether or not divoting would occur.

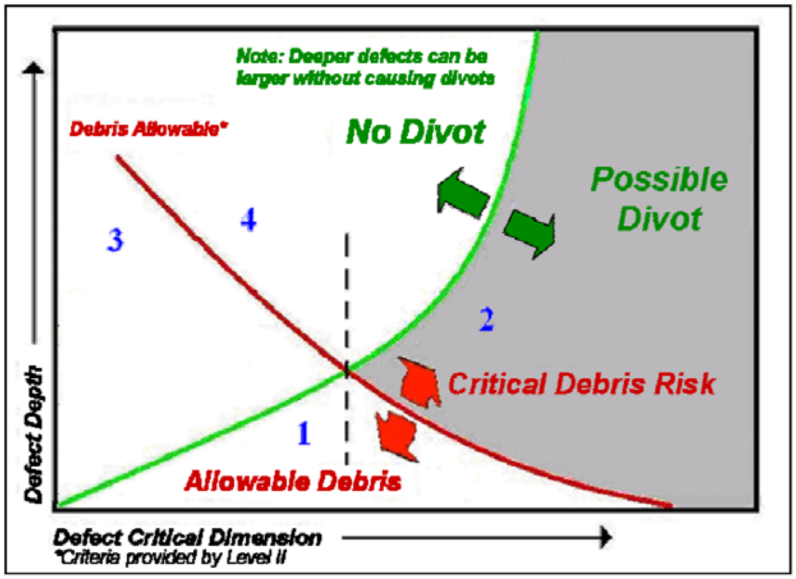


Figure 7 Generalized Divot/No-Divot Curve (NASA)

With the addition of the allowable debris estimates (based on transport analysis and energy of impact), the curve produced a means for identifying critical flaw size. As effective as the concept of the tool was though, there was considerable uncertainty inherent in where the divot/no-divot line actually was due to the complexities of the foam properties. Reliably predicting and avoiding debris hazards remained challenging.

Adding further to this complexity was the potential for crushing or fragmentation, a result of localized loading to the foam surface. Unknown localized foam damage would render the predictions made using the physics-based models irrelevant. Collateral damage could occur from working around the foam, excising portions of foam, or using tooling around foam. Crushing or fragmentation could also occur

Figure 8 Lockheed Martin technicians at NASA's Michoud Assembly Facility apply ice frost ramps to ET-128 (NASA) during manufacturing when the manual spray portions were added, or during handling and stack procedures.

On the pad, tanking and de-tanking of the cryogenic propellants caused the tank to expand and contract. Cycles of loading and unloading (tanking and de-tanking) propellants into the ET could occur if there was a launch scrub and subsequent stand down or some pre-flight check out. Expansion and contraction cycles put stress on the foam and could lead to cracks at the surface. Launch scrubs happened frequently enough require certification justification for that particular condition as well. In flight, crushing and fragmentation could occur from other debris strikes.

Ultimately, damage to the foam could lead directly to new voids or could weaken the cohesive strength around pre-existing voids. Voids due to damage could also divot when they might otherwise not have. All of these factors made assessing the root cause of any particular debris event very difficult, and sometimes impossible. It also limited the applicability of analysis using physics-based predictive models in approving each Certificate of Conformance for each ET prior to flight[3]. In the absence of predictive math models, the ET project and SSP had to develop a process for justifying certification to fly.

- If you can't predict the behavior of the material using math models to justify why you think it is safe to fly, what do you base your decision on?

[3] A Certificate of Conformance is a document signed by all board members at the conclusion of each pre-FRR and FRR certifying that, in their judgment, the element or vehicle is safe to fly.

Return to Return to Flight, Again (STS-121)

Following the events of STS-114, the Shuttle Program stood down again and went back into Return to Flight mode, with anomaly investigations, dedicated risk mitigation activities, and slow down of flight hardware production.

Two in-flight anomaly (IFA) investigation teams were formed. One, referred to as the IFA team, was tasked with doing a detailed fault tree analysis to determine the root cause of each major piece of debris. The other, known as the Tiger Team, performed a peer review of the IFA team's process and results, as well as an independent engineering assessment of the Shuttle Program's efforts to solve the debris loss issue.

In October of 2005 the Tiger Team presented an interim report that had key near- and long-term recommendations for the ET Project. In April 2006 the IFA team presented its conclusions and recommendations to the ET Project. Of note is that a definitive cause for the PAL ramp was never fully determined. Appendix B provides a more detailed summary of the results from the IFA team final report.

In short, collateral damage, which was originally suspected due to a noticeably visible rework site at the same location of the foam loss, and cryopumping were both ruled out. The final hypothesis was that "since there is nothing unique about Xt 1270 [the location of the foam loss event], it is likely that thermal cracks coupled with other BX-265 [manually sprayed foam] defects produced the unique conditions necessary to liberate foam."

Not only does this serve to highlight the complexity involved in determining the cause of a single event, but it also demonstrates how challenging it was to use data from past failures to develop certification criteria for void content that would ensure that divoting would not occur in the future.

In total the two teams produced 109 recommendations. To combat the inability to provide definitive design solutions, many of these recommendations were about process enhancements and inspection capabilities.

Continuing to Move in the Direction of Goodness

On June 16, 2006 the ET Project held its FRR for STS-121. Responses for the Tiger Team and IFA team recommendations had been presented to the ET Configuration Control Board in March and May of 2006, respectively. While closure for the majority of the recommendations would not ultimately be granted until October of 2006, and for the remainder not until January of

2009, by the time of STS-121 FRR many of the enhancements had begun to be implemented. The most significant change to the ET was the removal of the PAL ramp altogether.

No Longer PALs

The genesis of the PAL ramp occurred early on in the development of the Shuttle Program. A preliminary assessment had led the aerodynamicists of the day to believe it necessary to prevent high loading on the pressurization lines and cable tray. And so it was, and there it remained for many years. Approximately one year before Columbia the need for it had actually begun to be re-assessed, however it was not until the liberation event on STS-114 that the issue was brought back into focus and worked aggressively.

Through Computational Fluid Dynamics (CFD) analysis, wind tunnel testing, and examination of available flight data, it was determined that the support brackets for the pressurization lines and cable tray were sufficiently strong to withstand the aero-environment without the ramps. In this case, removal of the debris source turned out to be an effective solution for preventing foam loss.

There remained, though, the other areas from which foam had been shed on the RTF mission. Most notably were the Ice/Frost ramps (which covered the pressline brackets), two locations on the acreage foam, the bipod closeout, and LH2/Intertank Flange.

Evidence You Can Trust

Along with the foam application processes enhancements, the Tiger Team and IFA recommendations keyed in on additional documentation and inspection efforts. Prior to Columbia there was no inspection of closeouts. After Columbia, but prior to STS-114, void content was extrapolated based on dissections of previously sprayed closeouts or test sprays. While an inference could be made, this was not direct evidence of the quality of the application.

To provide direct evidence, a non-destructive evaluation (NDE) technique was needed. Such technology was in fact in existence and was being evaluated prior to STS-114, but had not yet had sufficient time or testing to be well understood or calibrated for use with the foam. There were several techniques: Backscatter X-Ray, Terahertz imaging, and shearography. The first two were most useful for the closeouts, while the last allowed for inspection of the entire acreage.

With the certification of these NDE techniques, the location, size, and depth of voids could be determined without dissection. These techniques also provided a much more comprehensive set of data by which the enhanced application techniques could be assessed. It is interesting to note that partly due to this capability it was ultimately recognized that the data set used to make the decision on whether or not to remove and replace the PAL ramp for STS-114 was incomplete. In the end, the extra data provided more definitive proof that the processes enhancements championed by the material engineers were in fact effective, and significantly reduced the number of critical voids.

The NDE data, when combined with enhanced divot/no divot curves obtained from additional testing and refined fracture mechanics analyses, could also be used to predict the mass of debris which might be generated as the result of any given defect. This was still not a certification in the traditional sense; that is it did not involve structural testing of as built hardware, but it did provide significantly more information to make a more accurate assessment of risk.

The predicted masses were then compared against maximum allowable requirements, which had also undergone refinement due to the development of debris transport analysis (DTA). DTA could take a given mass of foam from any location, determine the path it would take, and then provide the impact energy if it was predicted that it would re-contact the vehicle. From this a maximum allowable mass from any location could be derived, and then levied as a requirement.

At this point, as Mike Prince, MSFC Materials and Process (M&P) Engineer, stated, “For STS-114 we knew there was still a lot of work to be done and considerable risk. For STS-121, however, we thought things were getting to be about as good as they could get.”

Key Decision Point:

- At STS-121 FRR, as an SSP manager, you are presented with NDE data from several critical closeout locations on the ET. The foam is not void free, but the predicted mass is below the requirement level, though it is still 85% in one location. Keep in mind that prior to STS-114 you were told that the expected mass for every location was below the requirement. Given the enhanced application processes, inspection techniques, and analytical tools:
    - Do you think the risk posture being presented is accurate?
    - Is it acceptable to fly?

After Word

STS-121 flew without major incident. Though never fully eradicated, the amount shed did improve dramatically from STS-121 and on. This was due to the incredible efforts of NASA engineers and the ET contractor in the years following Colombia.

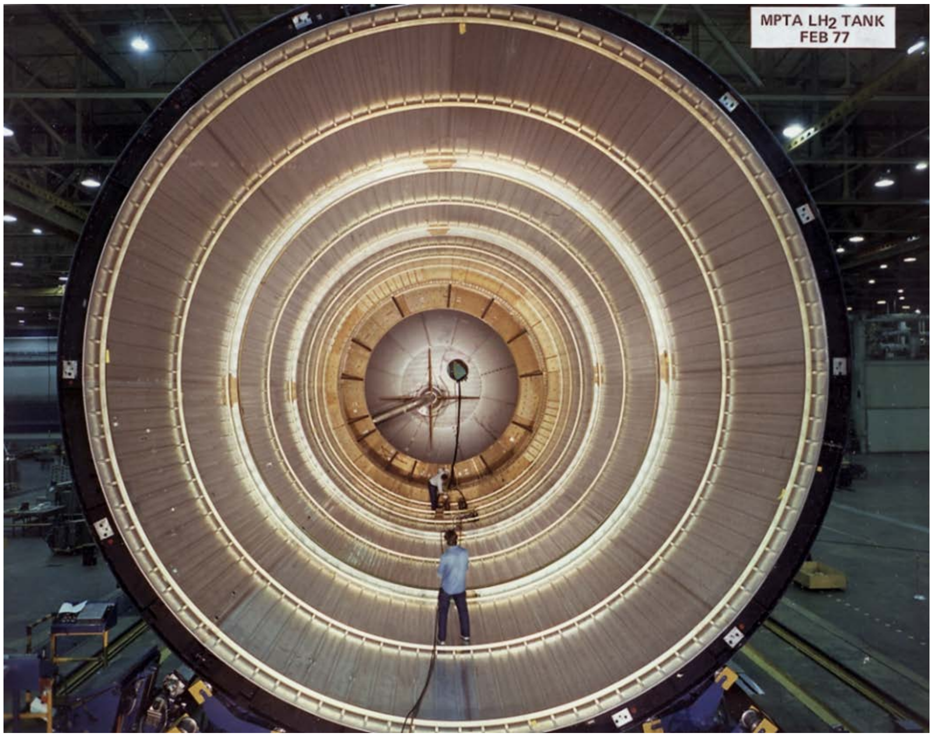


Figure 7 ET Hydrogen Tank (NASA)

NASA website Space Shuttle : Shuttle Basics; http://www.nasa.gov/returntoflight/system/system_STS.html

Acknowledgement

The authors would like to thank Matt Lansing, Mike Prince, and Scotty Sparks for sharing their first-hand knowledge and observations about this period of the Space Shuttle Program. Without their interviews the case study would not have been possible. An extra thanks also go to Mr. Lansing for providing the original idea to do this case, and for helping to get it off the ground.

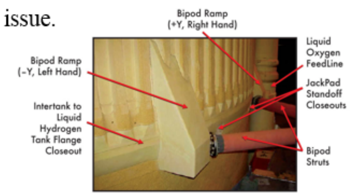
Appendices

Appendix A: Timeline

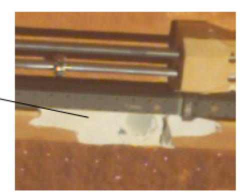
Appendix B: Executive Summary of PAL ramp conclusions from IFA Team Final Report

APPENDIX A: Timeline

January 2003, Columbia (STS-107). The left bipod foam ramp comes loose from the ET during ascent and strikes the leading edge of Columbia's wing. Damage to the reinforced carbon-carbon thermal protection panels results in excessive heating to the internal structure of the wing on re-entry, ultimately leading to the destruction of the orbiter. Shuttle fleet is grounded to fix debris issue.



July 2005, Return to Flight (STS-114). Foam liberated from multiple locations, including the bipod ramp. Largest piece is from the LH2 PAL ramp, the mass of which is 20 times greater than the certified requirement for debris. Fleet is grounded again to fix debris issue.



August 2005. Two independent in-flight anomaly (IFA) teams (IFA team and Tiger Team) established by NASA to determine root cause of all foam loss and provide recommendations to the External Tank Project for corrective action.

June 2006, Flight Readiness Review for RTF 2 (STS-121). Major findings of IFA investigation team identified and re-designs implemented. STS-121 launched on July 4.

October 2006. Closure rationale for 69 of 87 IFA team and 12 of 22 Tiger Team recommendations are presented to the Propulsion Management Council (PMC). The remaining recommendations are tracked as Technical Items in the ET Risk Management Database.

September 2006 – November 2008. 9 Shuttle missions

December 2008. Lockheed Martin presents closure rationale for remaining open recommendations to TPS Process Control Board and ET Project Chief Engineers Review Board. In January of 2009 closure accepted by PMC.

Appendix B
Executive Summary of PAL ramp conclusions from IFA Team Final Report
NASA Document

The independent External Tank (ET)-121 In-Flight Anomaly (IFA) Investigation was chartered by Mr. Michael Rudolphi, Space Shuttle Program (SSP) Deputy Manager Propulsion, to investigate unexpected Space Transportation (STS)-114 ET Thermal Protection System (TPS) foam loss. Foam losses of significance occurred in five areas on the ET TPS (Figure 4.0-1), including the liquid hydrogen (LH_2) Protuberance Air Load (PAL) Ramp, -Y Bipod fitting closeout, several locations on the LH_2 Ice/Frost Ramps (IFRs) covering the gaseous hydrogen (GH_2) and gaseous oxygen (GO_2) repressurization line attachment brackets, two locations on the LH_2 tank-to-Intertank (IT) Flange, and two locations on the LH_2 tank acreage. The largest piece, approximately one pound, was lost from the LH_2 PAL Ramp. The IFA Investigation Team was tasked to review the TPS performance to: determine most likely root cause(s), determine whether these foam losses were unique to STS-114/ET-121 or a systemic issue to the ET, and make recommendations to minimize likelihood of foam loss recurrence.

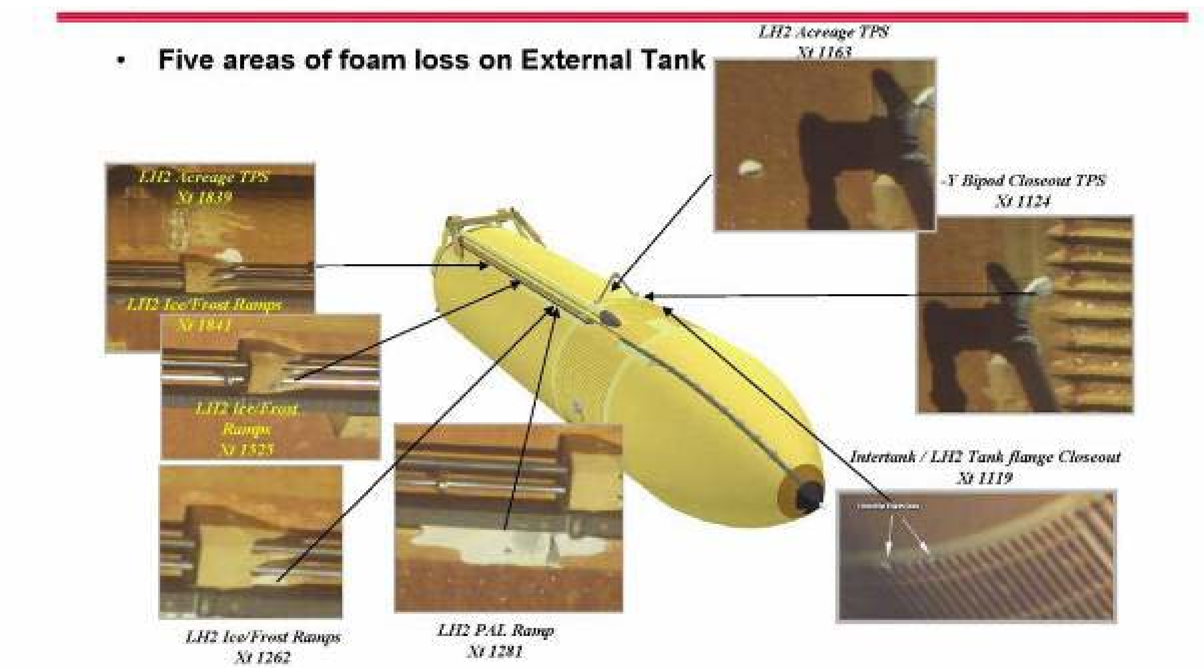


Figure 4.0-1. Five Areas of Foam Loss on STS-114 ET

The foundation of the IFA Investigation Team structure and membership was that the leadership of the individual teams and overall investigation would be independent from the ET Project, providing a “fresh set of eyes” directing the investigation, including evaluation of Return To Flight (RTF) I activities with respect to foam loss areas. The structure and reporting of the IFA Investigation Team is outlined in Figure 3.0-1.

Five major teams were established to address the five areas of foam loss:

1. Team 1: LH_2 IT Flange (refer to Section 7.1 and Section 8.1)
2. Team 2: -Y Bipod Closeout (refer to Section 7.2 and Section 8.2)
3. Team 3: LH_2 PAL Ramp (refer to Section 7.3 and Section 8.3)
4. Team 4: LH_2 IFR (refer to Section 7.4 and Section 8.4)
5. Team 5: LH_2 Acreage (refer to Section 7.5 and Section 8.5)

Independent Core Team membership consisted of the NASA Independent Lead (IL) (technical expert not directly involved with ET RTF I), who was supported by ET Project Leads from NASA and Lockheed Martin Space Systems Company (LMSSC) and a Safety and Mission Assurance (S&MA) Lead from NASA and a Safety and Product Assurance (S&PA) Lead from LMSSC. ET Project Leads served as advisors to the IL, providing technical expertise and ET flight hardware knowledge and experience. S&MA and S&PA Leads assured investigative rigor in addition to providing technical expertise and familiarity with ET flight hardware. Specific assignments of ET Project and S&MA Leads were made to achieve independence (i.e., these representatives were assigned to a different team than what they had worked in the RTF I redesign effort). The Core Team was responsible for organizing and planning the investigation, directing the efforts of the Technical Support Team, reviewing and dispositioning fault tree blocks, and recommending closure rationale to the Fault Tree Closure Board (FTCB).

Technical Support Teams comprised of NASA and LMSSC personnel and external experts were established to assist each of the five FLE Core Teams. Technical Support Team members had, in most cases, worked the RTF I redesigns and had hardware, materials, processing, or analytical expertise with extensive knowledge of the ET TPS. However, a number of additional subject matter experts were selected for their specific discipline expertise as required for the particular investigation area. The discipline experts served as knowledge sharers and educators for the independent team members and were charged with the responsibilities of gathering and reviewing technical documentation and data, planning and performing tests and analyses approved by the Core Team, and preparing rationale for fault tree block closure.

The IFA Independent Teams were also supported by the Integration Team and the Scenarios Team. The Integration Team served as the primary interface to the SSP Systems Engineering and Integration (SE&I) and Propulsion SE&I organizations. Responsibilities included ensuring consistency of input data used by all teams (e.g. processing and mission timelines, imagery analyses, loads and environments; providing test integration and scheduling support; and scheduling of fault tree block review and closure processes).

Failure scenarios were utilized to verify fault tree completeness and to ensure that a systems approach was considered for fault tree closures. The Scenario Team provided a focal point for scenario development, the results of which were coordinated and iterated with each Core Team. Scenario Team input provided an integration mechanism across the fault tree blocks and various failure mechanisms and was initiated with the objective to facilitate early identification of potential corrective actions.

The Investigation Management Team was structured similarly to the independent IFA Investigation Core Teams, with independent NASA and LMSSC leadership for the overall investigation, technical and ET hardware expertise provided by the NASA and LMSSC ET Chief Engineers, and NASA S&MA and LMSSC S&PA leads providing expertise in TPS systems. Technical Advisors provided invaluable guidance based on their in-depth knowledge and familiarity with ET TPS, and were frequently called upon to support and interface with the Core Teams.

The investigation followed a rigorous fault tree approach utilizing the ET Hazard Analysis Logic/Fault Tree T.02 “Loss of TPS” as the baseline for all teams. The T.02 had been reviewed and approved by the Shuttle Safety Review Panel and the Space Shuttle Program Review Control Board (SSPRCB). Approach ground rules placed strong emphasis on thorough documentation of closure rationale through: data and documentation review; analyses and tests; did not allow “eurekas”; and established the position that everything was suspect until proven safe.

The fault tree block disposition process was consistent across all teams. Technical Support Team members compiled/developed all relevant technical data and generated the preliminary block closure rationale. These team members were assigned responsibility for the block to generate the proposed closure rationale for presentation to the entire independent team. The independent team debated the rationale, approved the disposition, and recommended closure to the FTCB. The FTCB was chaired by the NASA Investigation Manager and co-Chaired by the LMSSC Investigation Manager. FTCB members were the NASA and LM ET Chief Engineers and the NASA S&MA, LMSSC S&PA, and NASA and LMSSC Engineering leads. The FTCB had final authority for fault tree block closure rationale and dispositions with formal presentation of the top three fault tree levels by the responsible independent team member.

Peer Review of the IFA Investigation Team process and results was performed by the ET Tiger Team. This team was established by the Associate Administrator for the Space Operations Mission Directorate and the Chief Officer for Safety and Mission Assurance (COSMA) to perform an independent engineering assessment of the SSP’s efforts to resolve the STS-114 foam loss anomalies. Although the duration of the ET Tiger Team’s formal investigation was limited, with direction to provide a final report by September 30, 2005, the team remained involved throughout the IFA Investigation Team’s efforts. The ET Tiger Team served as the Peer Review team for the IFA Investigation Team interim status report including recommendations to the ET Project in October 2005. The ET Tiger Team was briefed by the IFA Investigation Team on investigation status and results on a periodic basis, and members contributed valuable feedback and recommendations to the IFA Investigation Team. The ET

Tiger Team completed its Peer Review responsibilities at the IFA Investigation Team's final outbrief to the ET Project in April 2006.

LH_2 IT Flange

Two foam losses were experienced by the LH_2 Intertank Flange from the –Y Thrust Panel. The approximate dimensions of the losses provided by the Imagery Analysis Team (IAT) were 7.5 inches x 7.5 inches and 4.5 inches x 4.5 inches with no substrate visible. The LH_2 IT Flange Independent Team performed an analytical assessment explained in Section 7.1.5 and estimated the depth at approximately 0.8 inches for both locations. The time of release was estimated by the IAT to be 271 seconds based on circumstantial evidence.

Three credible failure scenarios were identified as potential explanations of the LH_2 IT Flange foam loss event (FLE). The first and most probable scenario was foam loss caused by voids in the LH_2 IT Flange closeout manual spray foam (BX-265) subjected to ascent thermal and pressure environments. This type of failure is generally termed a "void/delta-P (pressure)" failure in which pressure from the blowing agent gas entrapped in a subsurface void at atmospheric pressure acts against the foam during ascent as the external pressure is reduced and aeroheating of the external surface reduces the strength capability of the foam until failure occurs. A second credible scenario, assessed as unlikely by the LH_2 IT Flange Independent Team, was foam loss from RTF I activities at the interface of the LH_2 IT Flange foam subjected to ascent thermal and pressure environment. This failure scenario is also termed a void/delta-P failure, but in this case, the voids were caused by undetected damage to the foam incurred during the removal and reapplication of the LH_2 IT Flange foam during the RTF I flange redesign effort. The LH_2 IT Flange Independent Team identified two possible sources of damage/voids: undetected damage in NCFI 24-124 IT acreage foam interface resulting from removal of the original closeout foam; and undetected knife cuts in NCFI 24-124 during pocket trim in reapplication of the closeout foam. The third failure scenario, also assessed as unlikely by the LH_2 IT Flange Independent Team, was foam loss caused by cryopumping of a void in the pocket spray communicating with the atmosphere from a path between the void and the foam external surface. Cryopumping requires the confluence of several necessary conditions: (1) the presence of a void or cavity to entrap gas, (2) a communication (leak) path to atmosphere enabling additional gas to be drawn into the cavity, (3) the cavity is subjected to temperatures that are cold enough to condense or freeze atmospheric gases (typically water vapor, nitrogen (N_2), and/or oxygen (O_2)), (4) the communication path is of a character that gas can be drawn in, but it cannot escape rapidly, allowing pressure to rise as phase changes in the frozen or liquefied gases occur with increasing temperatures, and (5) temperature increases sufficient to enable the phase change(s) to occur.

In assessing the first failure scenarios, reportable voids (criteria for reportable being > 0.5 inch in one direction or > 0.3 inch in two directions) may have been contained in the pocket spray portion of the LH_2 IT Thrust Panel Flange closeout that resulted in the observed FLEs. Although the presence of reportable voids was mitigated through extensive RTF I design and application improvements, the manual spray process may not preclude such voids in the pocket spray of the LH_2 IT Thrust Panel Flange. No visual evidence of void formation in the BX-265 foam applications was found in thorough reviews of the production spray videos. Divoting analysis of extensive data for flat panels indicated that a small reportable void (0.42 inches) located 0.8 inch deep into the foam is capable of expelling divots of the characteristics observed in during STS-114. Thermal vacuum testing[4] representative IT Thrust Panels containing four pockets each was conducted to support the investigation. Results from tests of engineered voids introduced in the limited number of tested panels indicated the likelihood of shedding foam from small reportable voids is remote, notwithstanding the LH_2 IT Flange Independent Team's conclusion that this was the most probable scenario.

For the second scenario, thermal vacuum test results indicated that large gouges are required in the acreage NCFI 24-124 to yield the magnitude of FLEs observed. The acreage interface of ET-121 was thoroughly inspected by multiple LMSSC and Government Quality personnel during the LH_2 IT Flange processing and the Flange Team considers the presence of any residual large gouges in this area to be highly unlikely. Quality inspection of similar areas of the ET-122 LH_2 IT Flange by an independent team as part of this IFA investigation provided additional verification regarding the adequacy of the inspection process. The likelihood of this failure scenario was considered improbable.

In assessing the necessary conditions for cryopumping, the presence of internal voids from manual spray process or damage cannot be excluded. While cracks are allowed in this area of the flange[5], inspection of ET-121 by the Final Inspection Team reported no observable cracks in the area of interest on the LH_2 IT Thrust Panel Flange closeout. Also, close examination of ET-120, which had been processed similarly to ET-121 and subjected to two cryogenic cycles, did not reveal any cracks in the LH_2 IT Thrust Panel Flange. A 3-D thermal analysis of the LH_2 IT Flange pocket region did indicate that in the area where the failure occurred, thin regions of foam near the substrate and ribs were cold enough to condense air. During flight, foam heating from internal and external sources would cause any liquefied air in the voids to change phase, generating significant pressure rises capable of liberating foam. The likelihood of this failure scenario was judged to be improbable by the LH_2 IT Flange Independent Team.

Y Bipod Closeout

A single foam loss occurred at the –Y Bipod closeout. Approximate dimensions of the FLE were 8.4 inches x 7.3 inches x 1.5 inches in depth. The loss occurred at 148.1 seconds Mission elapsed time (MET)) with exposed tank substrate visible in the imagery. The Bipod TPS application process was redesigned after STS-107, which allows the fittings to be partially exposed. Heaters are mounted in a copper plate which is sandwiched between the bottom of the

[4] Thermal vacuum testing is terminology "short hand" for testing that exposes the materials to simulated thermal and pressure environments representative of ET ascent conditions.
[5] Criteria specified in NSTS 08303

Bipod fitting and a phenolic isolator that interfaces with the LH_2 tank aluminum surface. Bipod heater and sensor cables are routed in two four-cable runs from the fitting into the IT stringer. Approximately two feet from the stringer entrance, each cable has its Kapton[6]™ tape wrap removed to expose the braided shield. The cables are then taken two at a time and encased by the braided Overall Shield (OVS) in such a way that four harnesses are created. These harnesses run approximately another 18 inches in the stringer and penetrate the IT wall, where there is a gaseous nitrogen (GN_2) purge during pre-launch processing. These cables and their processing are integral to the failure scenarios identified by the Bipod Independent Team.

Three credible scenarios were identified by the Bipod Independent Team: (1) Cryoingestion[7] within/through the Bipod heater electrical cables, (2) Cryoingestion under the Bipod heater cables between the LH_2 IT Flange and Bipod mount, and (3) Cryopumping of a foam void in close contact with the Bipod heater cables. Early in the investigation, subscale testing was performed, demonstrating both a leak path and void volume within the heater/RTD cables such that the cables can ingest a significant amount of gas, which, if not vented, can cause cracking in the foam above the cables. Testing also demonstrated that the LH_2 IT Flange could act as a thermal valve, freezing the nitrogen in the cables thus restricting the venting of the vapor created during ascent. A detailed thermal analysis of the flight environments predicted that the thermodynamic processes (freezing and thawing) would have occurred in the observed locations and consistent with the timeframe to produce a pressure load that could create the divot. Further, testing of Hydrogen Test Panel 2.2 used during the initial RTF I effort to certify the new Bipod design confirmed that the cables within that panel did cryoingest air and vent to crack overlying foam. Both analysis and test data indicated that cryoingestion within the heater/Resistance Temperature Device (RTD) cables is the most plausible scenario.

The second scenario was based on dissection of the Hydrogen Test Panel 2.2, noted to have cracked and vented in the RTF I testing. Dissection of the test panel revealed that no adhesive had been applied to the bottom of the cables, which resulted in a leak path to the LH_2 IT Flange and volume along the bonded cable runs. This volume could have been supplied with GN_2 through the LH_2 IT Flange from the IT purge and the joint gap. The thermal environment would follow the same trend as predicted for Scenario #1. The LH_2 IT Flange joint gap would also act as a thermal valve, restricting the venting of the vapor created during ascent. Although there is no physical proof the ET-121 Bipod cables had these gaps beneath them, since assembly drawings indicate removal of gaps beneath the cables during the bonding process, the Bipod Independent Team inferred the possible existence of those gaps in flight hardware from those present on the test panel built using flight certified processes.
Assessment of the necessary conditions for cryopumping indicated that this scenario was also credible. Manual foam application processes can create random, unidentified voids in the Bipod TPS. Results from divoting analysis calculations indicated that voids having dimensions greater

[6] A registered trademark of the Du Pont De Nemours and Company Corporation

[7] Cryoingestion involves the same physics as cryopumping, but is used to indicate ingestion of nitrogen gas or liquid from the Intertank.

than or equal to 0.34-inch (cylinder) or 0.18-inch (slot), which are statistically credible, would be sufficient to generate the debris observed on ET-121 via cryoingestion/cryopumping. Cracks in the TPS, which could provide a leak path from any such void to atmosphere, are allowed in the Bipod area[8] based on the results of redesign certification tests during RTF I. Cracks were observed extending from the surface to the substrate during the dissection of the ET-120[9] Bipod closeouts. Thermal analysis supports the potential for condensation and freezing of both N_2 and O_2 during pre-launch operations and the possible vaporization of N_2 and O_2 during ascent if a void were in contact with the cable runs adjacent to the IT LH_2 Flange. Because cryopumping requires a confluence of specific events to create the observed failure, this scenario was considered less likely than the prior two scenarios.

LH_2 PAL Ramp

A piece of foam, having approximate dimensions of 36.3 inches in length x 11 inches in width and 6.7 inches in depth, was liberated from the LH_2 PAL ramp at 127.1 seconds MET. Early in the investigative process, the LH_2 PAL Ramp Independent Team identified two scenarios as potential explanations for the FLE. These were: (1) cryopumping and (2) fracture by a combination of foam damage/defects and external forces during ascent.

Among the necessary conditions for cryopumping, the presence of a cavity or void and leak paths to atmosphere were postulated, with strong supporting evidence provided by dissection results from ET-120. The driver for the cryopumping failure scenario became the existence of appropriate thermal conditions. The thermal environment was thoroughly assessed using 3-D thermal analyses including detailed local structural features and uncertainties associated with LH_2 liquid level passage time and LH_2 tank ullage gas temperatures. Results of the analyses indicated that any air which may have been cryopumped at the FLE location probably would have remained liquefied at the substrate at the time the foam loss occurrence. The predicted temperatures were warm enough to only support a phase change from solid to liquid air, corresponding to a maximum cavity pressure ranging from 2.7 to 6.1 psia, respectively, for the center and the forward perimeter of the FLE. The LH_2 PAL Ramp Independent Team concluded that at these relatively low pressures, voids in the NCFI 24-124 along the substrate would have to be too large to be a credible, single root cause failure mode resulting in the foam loss exhibited by ET-121.

Factors considered in investigating the fracture failure scenario included foam defects, collateral damage, and the effects of the normal environments, on-pad and ascent. Application process deficiencies evaluated as potential proximate causes included debonds at substrate (both acreage,

---

[8] Criteria specified in NSTS 08303

[9] ET-120 was extensively examined as part of this investigation including dissection of the Bipods, PAL Ramps, and IFRs. This tank is being processed for flight use and additional dissection information will be obtained from the regions adjacent to the LH_2 IFRs. The reader should consult the latest version of the dissection reports for ET-120 to obtain the most comprehensive understanding of the defects associated with this tank.

NCFI 24-124, and LH_2 IFR, PDL 1034); voids in LH_2 acreage, IFR, and PAL Ramp, BX-265; and knitline delaminations. While there is no direct evidence that these conditions existed on ET-121, they cannot be excluded. All of these factors were dispositioned by the LH_2 PAL Ramp Independent Team as potential contributors with various likelihoods, with the exception of voids in the acreage NCFI 24-124. In addition, nondestructive evaluation (NDE) records of ET-121 revealed two features directly related to the BX-265 loss debris site: a confluence of knitlines that aligned with the forward end of the debris location, and a region of low density foam approximately 2 inches wide and running almost the entire length of the debris site at the toe of the ramp. Test results from LH_2 PAL Ramp sections removed from ET-123 containing similar features indicated by NDE were not degraded below design values.

Collateral damage drew much attention and speculation immediately after the LH_2 PAL Ramp loss was observed due to the presence of a sizeable and clearly visible (lighter in color due to sanding) “sand and blend” repair that had been performed on the LH_2 PAL Ramp at the location of the FLE. The nonconformance document description of this damaged region stated “*area of crushed BX-265 foam at top edge of (LH*$_2$*) PAL Ramp at Xt 1270 measurement is 0.6-inch long x 0.2-inch deep*.” The sand and blend repair was subject to strict aerodynamic profile requirements resulting in the final blended area being substantially larger than the original defect size. To assess the potential for collateral damage to the underlying NCFI 24-124 acreage foam underneath the damage site, a series of tests was conducted to measure the potential loads on the LH_2 PAL Ramp due to working/walking loads. A follow-on series of tests was then conducted to assess damage to underlying NCFI 24-124 due to worst case static and dynamic loads acting on the LH_2 PAL Ramp. In all load cases, damage was restricted to the BX-265 foam and there was no damage to the underlying acreage NCFI 24-124. The LH_2 PAL Ramp Independent Team concluded collateral damage to the acreage NCFI 24-124 due to statically applied walking/working loads and impact loads applied to the LH_2 PAL Ramp was an improbable contributing event of the ET-121 FLE.

Early in the investigation, the LH_2 PAL Ramp Independent Team postulated a logic path for existence of thermally induced cracks in the acreage NCFI 24-124 beneath the LH_2 PAL Ramp which was subsequently demonstrated to be remarkably accurate. Key factors included the tensile strength of the acreage NCFI 24-124; coefficient of thermal expansion (CTE) mismatch between the acreage foam and the tank aluminum substrate; thermal expansion mismatch between the acreage foam and the LH_2 IFR PDL 1034; stress concentrations at corners of the LH_2 IFR footprint; and the insulation effect of the LH_2 PAL Ramp BX-265. This last aspect could extend high thermal stresses further from tank substrate promoting larger cracks in the NCFI 24-124 under the LH_2 PAL Ramp than in the acreage (subsequently known as the “thick foam over foam” issue). This failure scenario was thoroughly investigated using 3-D stress analyses, fracture mechanics, laboratory testing, and dissection of ET-120, which proved invaluable in understanding foam failure and potential foam liberation mechanisms (the reader is encouraged to review the summary of the ET-120 dissections results, Section 7.3.2, and the comparison between ET-120 cracks and features of the ET-121 debris site, Section 8.3.1.2). The 3-D stress analysis of the LH_2 PAL Ramp predicted the stresses in both the NCFI 24-124 and

BX-265 exceeded the minimum measured tensile strength of these foams in locations consistent with the observed cracks on ET-120 and the features of the debris site of ET-121.

In addition, the “thick foam over foam” issue exists at the LH_2 IFR locations. Comparison of analytical predictions with the LH_2 PAL Ramp geometry indicates the highest stresses exist locally at the LH_2 IFR, which suggests this is the most likely initiation site for thermally-induced cracks. Finally, there is a debond/delamination at the intersection of the thermal crack and the tank substrate at several locations. Presence of such delaminations is consistent with analytical predictions, since a peel stress and shear stress result from the intersection of the free surface created by the thermal crack and the tank substrate, noted in the ET Stress Analysis Report. This was also confirmed by results of laboratory testing. Although the investigation was not able to determine the “crack driving force” necessary to grow the crack along the substrate and liberate foam debris, the analysis and test results demonstrate that the necessary and sufficient conditions exist in LH_2 PAL Ramp configurations for delamination along the substrate and the potential for debris liberation.

The LH_2 PAL Ramp Independent Team concluded that the most like failure scenario was a combination of the two scenarios described as follows:

1. Cracks most likely formed in the acreage NCFI 24-124 underneath the LH_2 PAL Ramp due to the CTE mismatch between the aluminum LH_2 tank and foam and the stress concentration at the LH_2 IFR.

2. The discontinuity stresses at the intersection of the thermal crack and the tank substrate led to the formation of a delamination.

3. The delamination along the substrate extended until the surrounding NCFI 24-124 became overstressed due to the peak tensile stress in the foam resulting from the external near-vacuum pressure during ascent after about 100 seconds.

4. It is possible that the NCFI 24-124 failure could be assisted by cryopumping due to the phase change from frozen to liquid air which began to boil as the LH_2 tank ullage gas warmed up the interior surface of the aluminum substrate.

5. Since there is nothing unique about Xt 1270, it is likely that thermal cracks coupled with other BX-265 defects produced the unique conditions necessary to liberate foam.

LH_2 IFR

Foam losses occurred at three LH_2 IFRs. Approximate dimensions for the FLEs were the following: Xt 1262 two losses: one loss is 7.7 inches x 2.8 inches and the other loss is 3 inches in diameter; Xt 1525: 7.3 inches x 1.9 inches x 2.5 inches in depth; and Xt 1841: 4.0 inches in diameter. A notable feature of the Xt 1525 loss is that a small section of the Conathane® bondline between the upper and lower ramps was visible. The losses at Xt 1262 occurred at 154.8 MET. No time of loss estimates are available for the other losses.

Xts 1262 and 1841

Three failure scenarios were identified by the LH_2 IFR Independent Team for both Xt 1262 and Xt 1841(in order of likelihood): (1) void/delta-P due to process voids within the PDL 1034, (2) impact, and (3) cryopumping. A divoting analysis was performed to assess the void/delta-P scenario involving: analysis of "divot/no divot"[10] curves; generation of a statistically significant dissection database for sizes and distribution of voids in the LH_2 IFR; and imagery analysis. A geometric analysis was performed to estimate the size and depth of void required to produce the FLE observed in STS-114 flight imagery. Credibility of such void sizes was assessed by comparison to dissection data. The LH_2 IFR Independent Team generated a statistically significant database of sizes and distribution of voids in the LH_2 IFR regions through dissections of 15 full-scale, flight manufacturing process mock-up LH_2 IFRs and 7 LH_2 IFRs from ET-120. Dissection results demonstrated a substantial increase in the maximum observed void size and frequency relative to the distribution utilized for STS-114[11]:

1. Large numbers of voids in the LH_2 IFR lower sections support high potential for lower ramp divoting during ascent, as observed in STS-114 for Xts 1262 and 1841.

2. Maximum observed[12] void sizes are consistent with divoting analysis for void/delta-P where the size void required to produce the LH_2 IFR foam losses observed in STS-114 imagery can be expected to exist.

Based on the results of the LH_2 IFR mockup and ET-120 dissection data, the revised divoting analysis, and flight imagery, the LH_2 IFR Independent Team concluded that void/delta-P was the most probable failure scenario for Xts 1262 and 1841.

The approach to assess the possibility of debris impact damage to the three LH_2 IFRs began with the list of known debris sources for STS-114[13]. Dynamic flow field Debris Transport Analysis (DTA) was utilized to determine which of the known debris sources was credible for each LH_2 IFR. STS-114 specific DTA was requested for the Xt 1377 LO_2 feedline BX-265. Results of the DTA were then assessed and combined with information obtained from flight imagery and geometric accessibility. Debris events that were determined to be capable of impacting the LH_2 IFRs were sorted according to the component of the impact kinetic energy (KE) along the angle

[10] Divot/no divot curves were generated during RTF I to understand PDL 1034 divot characteristics by placing engineered voids of various sizes at various depths in PDL 1034 flat panels and exposing these to simulated ascent thermal and pressure environments to test whether they would produce a divot.
[11] Prior to STS-114, dissection data for LH_2 IFRs fabricated using the current bladder mold seal process only existed for upper ramp sections, which are much smaller and lack the significant geometric complexity of the lower ramps.
[12] The largest credible void size expected to exist and used in prior divoting analyses was always larger than the maximum observed void size. Use of a revised largest expected void size rather than the maximum observed void size would clearly further strengthen the conclusion.
[13] Missing gap fillers were documented for STS-114, but no DTA exists at the time of this report to correlate the specific debris sources to LH_2 IFR foam loss areas.

that would produce the largest amount of PDL 1034 removal. Estimates of the PDL 1034 that would be liberated due to different levels of KE were based on documented impact test results.

BX-265 from the Xt 1377 LO_2 feedline bracket had the highest KE of the debris sources capable of impacting Xt 1841. The LH_2 IFR Independent Team concluded that impact damage at Xt 1841 was not likely based on the limited accessibility of the damage site and the imagery appearance. For Xt 1262, impact was ranked as non-contributor for foam and Orbiter tile repair putty and improbable for ice debris, due to low KE of credible debris sources forward of Xt 1262. For Xt 1841, impact was ranked as improbable for foam and ice debris and Orbiter tile repair putty.

Cryopumping was initially considered a non-contributor due to thermal analysis results indicating that the foam loss areas lacked thermal conditions to liquefy air. The potential for cryopumping was reassessed on the basis of ET-120 dissection results, since thermal cracks beneath the LH_2 IFRs[14] could provide a leak path to atmosphere and delaminations provide a volume for liquefied air near the substrate. The LH_2 IFR Independent Team concluded that the cracks/delaminations would have to communicate with voids in the LH_2 IFR, based on the appearance of the observed FLEs from flight imagery. Communication between a reservoir of liquefied air near the substrate and a void farther from the substrate is unlikely, due to the complexity of the interaction. However, the possibility of cryopumping for Xts 1262 and 1841 could not be excluded.

Xt 1525

Failure scenarios for Xt 1525, in order of likelihood, were: (1) impact, (2) debond or weak bond and (3) void/delta-P due to process voids within the PDL 1034. Circumstantial evidence from imagery, DTA, and KE assessments (approach described above) provided evidence of potential impact. The Xt 1377 LO_2 feedline bracket BX-265 had the highest KE of the debris sources capable of impacting Xt 1525. Detailed LS-DYNA™[15] impact analyses were conducted for potential LO_2 feedline BX-265 and ice impact. Damage prediction for BX-265 impact was similar to, but not as extensive as, observed foam loss in flight imagery. The simulation predicted a crack penetrating to the GH_2 and GO_2 repressurization line cavity and, in conjunction with the disturbed LH_2 IFR outer mold line (OML), this degradation would likely lead to further foam damage due to aerodynamic loads. The LH_2 IFR Independent Team concluded that Xt 1525 PDL 1034 loss due to TPS debris impact was remote and the likelihood of the loss being due to ice or Orbiter tile repair putty was improbable.

The second credible scenario identified for Xt 1525 was a weak Conathane® bond or debond, based primarily on the appearance of the PDL 1034 loss region in flight imagery[16]. A finite element analysis was performed to evaluate the stresses induced in the Xt 1525 LH_2 IFR due to

[14] Thermal cracks extended under the PAL Ramp at Xt 1334, not under inboard or forward IFR.
[15] Registered trademark of the Livermore Software Technology Corporation, California
[16] The black Conathane® layer was clearly visible.

the aerodynamic environment compared to those caused by thermal and vacuum environments. Results suggest that aerodynamic loads are too low based on the predicted Xt 1525 LH_2 IFR ascent pressure environments to cause a FLE, unless other factors weaken, or alter the OML. Therefore, it was judged by the LH_2 IFR Independent Team that a TPS debond could lead to a failure in conjunction with aerodynamic loads if a debond sufficiently weakened the ramp, or if it caused a significant change in the ramp OML. RTF II Arnold Engineering Development Center (AEDC) wind tunnel test data, which was not available until late into the investigation, suggested that a PDL 1034 defect or damage in the upper LH_2 IFR could combine with aerodynamic loads to produce a PDL 1034 FLE above the Conathane® layer, independent of a compromised bondline or impact event. Due to limitations of the fault tree, this potential failure mode (though not ranked by the LH_2 IFR Independent Team) is categorized as an extension of the TPS debond scenario.

The divoting assessment for the void/delta-P scenario was inconclusive for Xt 1525 due to the geometry of the PDL 1034 loss region and the divot/no-divot test database being limited to flat panels. The Xt 1525 FLE did not have the appearance of a void/delta-P divot loss as observed in previous RTF I testing, and dissection data from LH_2 IFR mockups and ET-120 showed that the upper ramps have few recordable voids.

In summary, for the Xt 1525 LH_2 IFR, impact, TPS debond, and foam defects/damage combined with aerodynamic loads, are the most credible scenarios. However, divoting due to void/delta-P cannot be excluded.

Acreage

Two losses occurred in the acreage NCFI 24-124. One was aft of the –Y Bipod at Xt 1160 with approximate dimensions of 4.8 inches x 3.3 inches x 0.6 inches in depth. This FLE occurred at 135.8 seconds MET and was adjacent to an area of foam damage of unknown origin that had been repaired using standard repair procedures for removing damaged acreage foam and injecting PDL 1034 into the resulting cavity. Image analysis indicated the PDL 1034 repair was not lost. The second loss was adjacent to the inboard forward edge if the LH_2 IFR at Xt 1851[17]. The approximate dimensions of this FLE were 10.3 inches x 7.8 inches x 0.7 inches in depth. No time of loss estimate was available from flight imagery.

Two failure scenarios were identified by the Acreage Independent Team for the Xt 1160 FLE: (1) in-process damage resulted in an internal defect or area of crushed NCFI 24-124 that acted as a sealed void and divoted due to a differential pressure during ascent, and (2) a void was assumed to exist in the PDL 1034 repair which created a divot preferentially through the acreage NCFI 24-124 due to differential pressure during ascent. Two sources of collateral damage were

[17] The official location for foam loss was Xt 1839 but, initially in the investigation, the foam loss location was identified as Xt 1851. It retained this designation throughout this investigation and has gained notoriety within the SSP community because of its failure characteristics as the “1851 scenario”.

postulated for the first scenario. First, failure to remove the entire damage area may have occurred in the repair process due to ineffective use of the dye penetrant. Application instructions for the dye penetrant are inadequate and interviews with personnel using this method confirmed variability in technique. The second possibility is that damage was incurred after the repair was made and not detected. However, testing of the measured stresses in acreage NCFI 24-124 from normal and accidental or atypical activities through the protective mats did not produce load levels that damaged the NCFI 24-124. Thermal vacuum tests of acreage foam that had been damaged with an indenter did liberate foam divots, indicating that cohesive failure mechanism from crushed damage was possible.

The second failure scenario for Xt 1160 assumed a void in the PDL 1034 repair and subsequent compromise of the Conathane® for a failure initiating in the repair which preferentially created a divot in the adjacent acreage NCFI 24-124. Although limited tests involving cryocycling of laboratory repairs did not reveal any cracks in the Conathane® or voids in the repairs, the Acreage Independent Team concluded that this scenario was credible.

Acreage adjacent to the forward and inboard sides of the LH_2 IFR at Xt 1851 and other LH_2 IFRs has had recurring historical foam loss with similar morphology[18]. The acreage failure at Xt 1851 received significant attention and has been the catalyst for substantial debate regarding redesign of the LH_2 IFR. Four scenarios identified by the Acreage Independent Team were, in order of likelihood: (1) cryopumping beneath the LH_2 IFR, (2) undetected in-process collateral damage (crushed foam) acted as a sealed void and was liberated due to delta-P, (3) cryopumping under the LH_2 IFR coupled with undetected in-process collateral damage (combination of first two scenarios), and (4) propagation of the acreage NCFI 24-124 delaminations from underneath the LH_2 IFR due to delta-P loads.

Cryopumping failure scenario was the result of the same “thick foam over foam” design deficiency discussed previously for the LH_2 PAL Ramp foam loss. The same factors and mechanisms existed, with the exception that in this case, the thermal insulation was provided by the LH_2 IFR, not the LH_2 PAL Ramp. Thermal cracks formed in the acreage NCFI 24-124 beneath the LH_2 IFR as predicted by 3-D thermal and stress analyses for pre-launch thermal loads in the LH_2 IFR/acreage system. Delaminations, created by the peel stress and shear stress resulting from the intersection of the free surface created by the thermal crack and the tank substrate, were also predicted by the Acreage Team, which led to their request that dissection techniques utilized for the LH_2 IFR and underlying acreage on ET-120 be optimized for the detection of delaminations. Results of the ET-120 dissections confirmed the presence of thermal cracks and delaminations in the acreage NCFI 24-124 beneath the LH_2 IFR (see Figure 4.5-1). These results indicate that requisite conditions for cryopumping are rather systemic, with the must uncertain supporting condition being leak path.

[18] The Flight History Photo Assessment reported 26 of 506 visible ramps had foam losses in the acreage on the inboard side of the LH_2 IFRs.

Delaminations provide the void or cavity volume. The cavity is adjacent to the substrate, so the necessary thermal conditions exist to: (a) liquefy or solidify air in the pre-launch environment, and (b) subsequently support phase change when substrate warming occurs after the passage of the LH_2 liquid level in the tank late in flight. Several possibilities for leak paths to atmosphere were postulated by the team including the network of cracks in PDL 1034 around the pressline bracket, (found on ET-120 and LH_2 IFR pathfinder tests), which could provide a connection between the atmosphere and the delamination, or thermal cracks in the acreage NCFI 24-124 extending to the surface. Load generated by the phase change was sufficient to propagate the delaminations from under the LH_2 IFR to the inboard free surface of the acreage NCFI 24-124. When the delamination reached the free surface, the unsupported acreage NCFI 24-124 was liberated in a dynamic event of the pressure release.

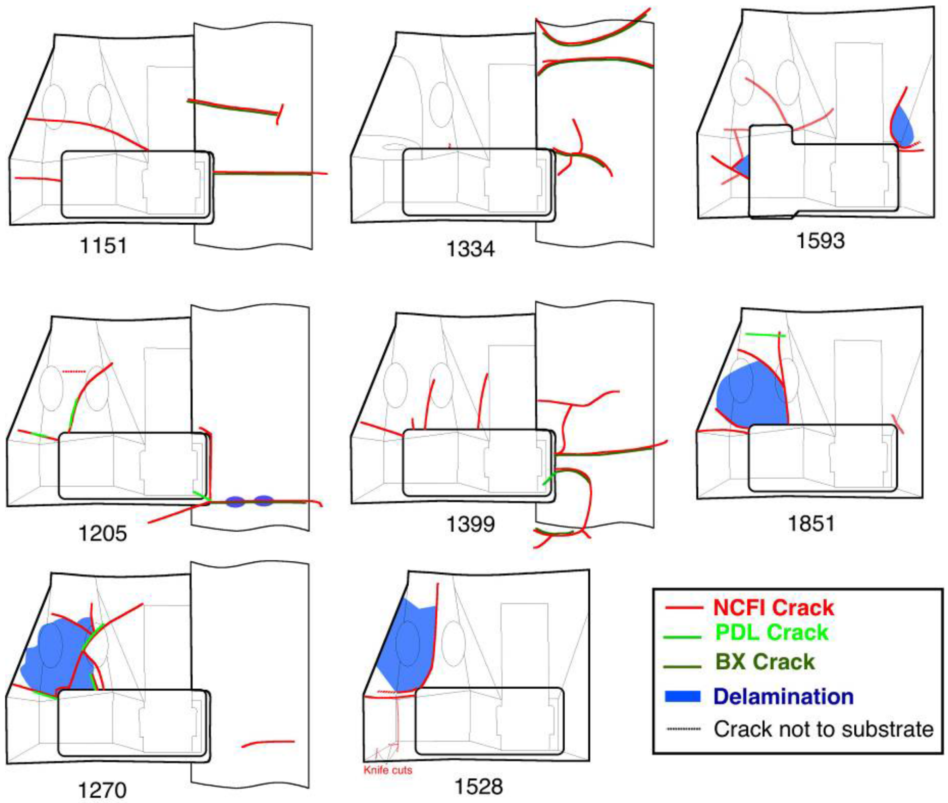


Figure 4.5-1. Thermal Cracks and Delaminations in the Acreage NCFI 24-124 (NASA)

The undetected collateral damage scenario involved the same mechanisms described for the Xt 1160 FLE. The LH_2 acreage area inboard of the ramp at Xt 1851 experienced significant traffic associated with multiple installation and repair processes that could have led to undetected in-process damage (crushed foam) in the acreage NCFI 24-124. Tests results from assessments of potential collateral damage mechanisms and performance tests of damaged NCFI 24-124 in simulated ascent thermal and pressure environments were directly applicable to both Xt 1160 and Xt 1851 collateral damage scenarios. Divot analysis predicted that the defect would have to be large or caused by multiple small defects that would appear as a single loss event.

Coupling of the first two scenarios was also considered credible. The likelihood of this scenario was dependent upon the delamination in the acreage NCFI 24-124 under the LH_2 IFR being adjacent to crushed foam in the acreage free surface. From a probabilistic standpoint this was deemed less likely than either of the contributing scenarios.

An analysis to evaluate the propensity for a delamination in the acreage near the substrate beneath the Xt 1851 LH_2 IFR to propagate at any time during flight due to delta-P loading was conducted to assess the feasibility of the fourth scenario. The analysis, using thermodynamics principles and an idealized fracture mechanics case, yielded a positive margin of 1.3, indicating that it is improbable that such a delamination would propagate at any time during flight due to delta-P loading.

Failure scenarios and root causes were identified for each of the five FLE areas and the associated recommendations for corrective actions were developed. IFA Team recommendations of corrective actions that are relevant to STS-121/ET-119 have been previously transmitted to the ET Project (and accepted via Corrective Actions Requests (CARs) a, b, c, d, and e), the SSP, the ET Tiger Team, and NESC through numerous reviews. The complete list of recommendations is provided in Section 9. Lessons learned from the IFA investigation which may affect other foam application areas of the ET were also identified and provided to the ET Project.

The IFA Investigation Teams provided numerous recommendations to minimize the possibility of foam loss from future ETs.