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Position Paper External Tank Thermal Protection System (TPS) Manually Sprayed "fly-as-is" Foam Certification

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Position Paper
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Introduction

The External Tank (ET) has several different types of closed cell foam, various ablator materials, and ice/frost that form potential contributors to the debris environment around the Space Shuttle Orbiter on ascent. Following the STS-107 accident, the ET Project was levied additional debris requirements including stringent limitations for Thermal Protection System (TPS) foam debris shedding.

The root cause of TPS foam debris shedding has been attributed to internal defects (voids) within the foam structure. Entrapped gas or liquid nitrogen/liquid air within the defect (void) expands during ascent due to the reduced ambient pressure and aerodynamic heating. Depending on the size, depth and geometry of the defect, the resultant pressure differential may cause failure of the surrounding foam. This type of failure mode has been identified as "cohesive" failure and results in chunks of foam being shed from the tank. Previously, nearly all debris control efforts focused on debonding/adhesion failure modes that could result in large areas of foam loss due to loss of adhesion to either the substrate or tie coat adhesive (Conathane). It should be noted that this failure mode applies to both sprayed and poured foams, but manually sprayed foams are the focus of this paper.

For the Return to Flight Shuttle mission, the ET Project plans on using tank (ET120) that was manufactured prior to the enhanced foam application procedures. Based on Columbia Accident Investigation Board recommendations, previous flight history, and dissections, decisions were made early in the return to flight process to remove manually sprayed foam in the area of the bipod fitting and the intertank to liquid hydrogen tank flange (Figure 1). Since that time, other areas were added to "remove and replace" category based on data acquired in the return to flight process. These include the forward 10 feet of the protuberance airload (PAL) ramp on the liquid hydrogen tank and the longeron areas at the liquid hydrogen aft end. These "remove and replace" areas are having foam reapplied using the enhanced processes. Approximately 95% of the foam is being left on the tanks as it was originally sprayed with no rework or repair. These areas consist mainly of "acreage foam" applied with an automated process, but a number of manually sprayed and poured areas will be left as "fly-as-is."

For the return to flight effort, the ET Project has aggressively pursued a TPS certification program including:

1. Destructive analysis (dissection) of portions of existing tanks (mainly ET94)
2. Statistical and engineering analysis of dissection results to determine likely sizes and locations of foam defects
3. Thermal vacuum testing to determine the relationship between foam defect (void) size, depth, and geometry to foam debris mass

4. Development, verification, and validation of new manual spray processes and manufacturing procedures for re-work of selected areas of existing tanks.
5. Enhancement of process controls on manually sprayed foams.

Manually sprayed foams include BX250 and BX265. BX265 replaced BX250 due to environmental issues with the blowing agent in BX250. Generally speaking, BX250 is installed on tanks through ET120 and BX265 is installed on tanks subsequently processed (ET121 on). All redesign/rework areas use BX265.

The subject of this position paper is the ET Project's plans to certify/develop flight rationale for the existing manually sprayed "fly-as-is" TPS foam. The NESC has conducted this assessment based on alternate viewpoints presented at the ET Certification Technical Interchange Meeting held Oct 20-21, 2004.

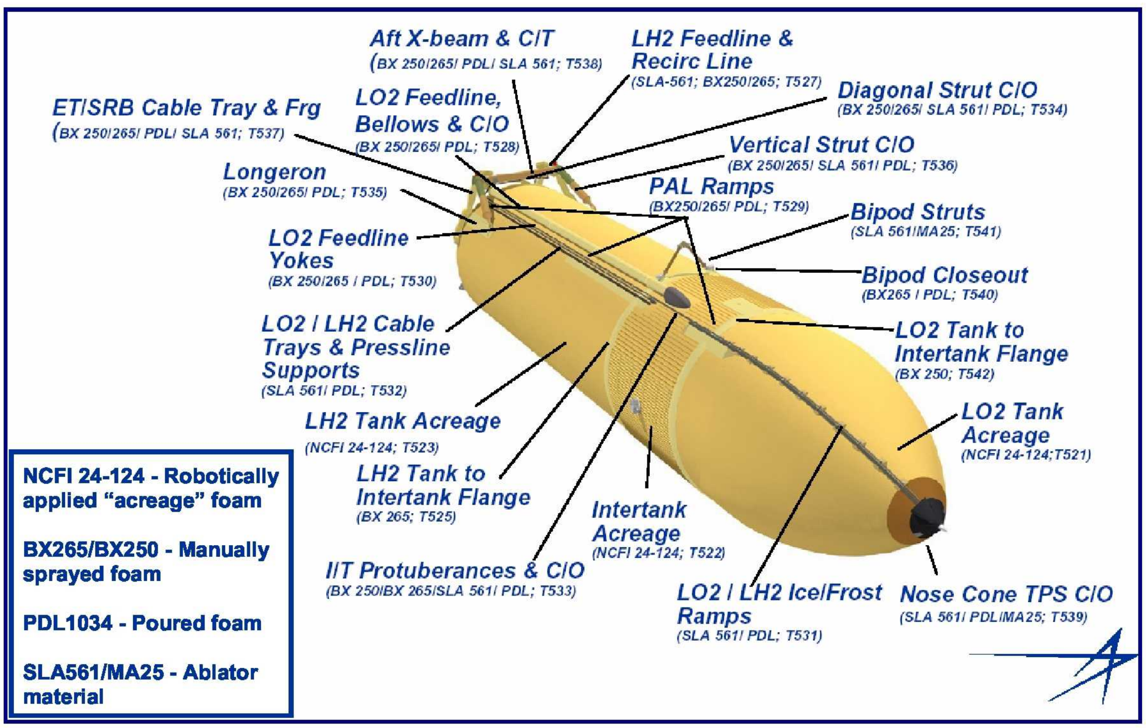

Figure -1. External Tank Overview

Certification Overview

Requirement Certification is the formal documentation of the requirement verification and validation. To certify the manually sprayed "fly-as-is" foam, one must either:

a) verify the "fly-as-is" foam application process will only introduce voids smaller than the critical void size to ensure the TPS foam debris shedding requirements are not violated, or
b) verify directly that the flight ET meets its TPS foam debris requirements by testing, inspection and/or analysis.

During manufacture of the previous ETs, including ET120, the TPS foam application *process* did not have the proper controls or procedures to prevent the formation of defects (voids) that would cause foam shedding. Therefore, the ET120 foam *hardware* "as sprayed" must be verified to comply with the new debris requirements. Figure 2 below provides an example logic diagram to achieve tank verification and subsequent certification.

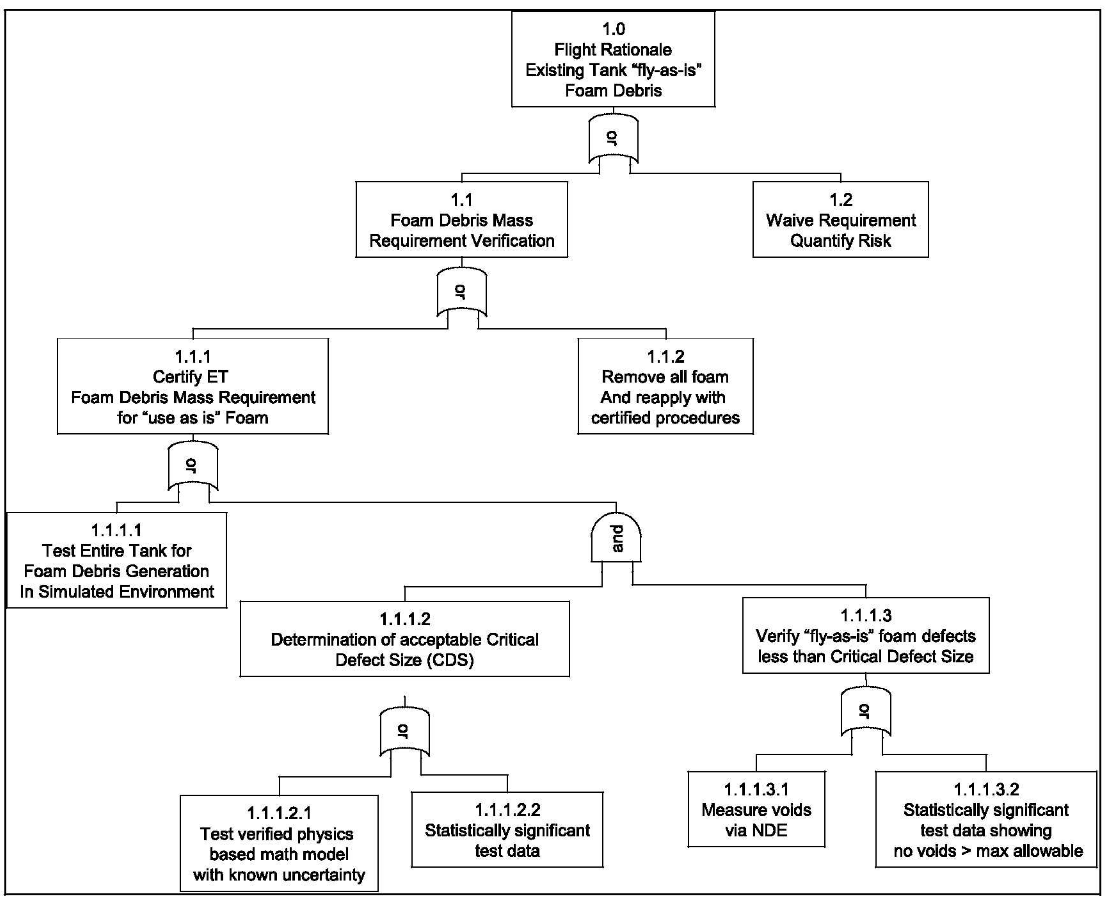

Figure – 2. Top Level Logic Diagram for "fly-as-is" foam debris requirement verification.

To verify that the ET will not shed foam larger than the debris requirements, the "test as you fly" option could include testing the entire ET in the simulated environment (Figure 2; block 1.1.1.1). Unfortunately, no facility exists that is large enough has the required capabilities to test the entire tank.

Therefore, to verify the existing manually sprayed foam on the ET120 meets the foam debris requirements, one must do both of the following:

1) Determination of acceptable Critical Defect Size (CDS) (Figure 2; block 1.1.1.2) and,
2) Verify "fly-as-is" foam defects are less than Critical Defect Size determined in (1) above (Figure 2; block 1.1.1.3).

This is the basic ET Project approach for the debris requirement (cohesive failure mode) verification.

First to determine the acceptable void size, the ET Project has collected test data correlating defect size, depth, and geometry to debris generation. This test program is referred to as "critical defect testing." Defects of 'slot' and 'cylindrical' shape are tested, based on principles of fracture mechanics. Data are gathered for both voids filled with gas alone and with liquid nitrogen (to simulate conditions that could exist due to cryopumping). These data are then subjected to theoretical treatments based on fracture mechanics to yield a 'divot /no divot' curve. This testing is being done for all the major types of foam existing on the tank, but the preponderance of the data points are being run for manually sprayed BX 265 foam.

Next it is required to determine if any defects within ET120 are greater than the largest allowable defect determine by the above test. Despite 18 months of concentrated effort, no reliable Non-Destructive Evaluation (NDE) techniques exist at this time. Several promising techniques were identified and the ET Project is continuing to pursue these techniques. Only one area of ET120 has been inspected by NDE (the liquid hydrogen protuberance airload ramp). That inspection is for 'engineering information', not for hardware acceptance.

Since the defects cannot be detected with NDE techniques, the ET Project is attempting to develop a statistical approach based on destructive examination of test panels and existing hardware, primarily dissection of ET94. Originally, the defects were classified based on part-by-part location, but due to the limited sample size, the data set has been re-partitioned into defects due to chemistry, process, and geometry.

Findings

Several unanswered questions/concerns have been identified with the critical defect testing and analysis program. Many of these relate to the level of conservatism (or non-conservatism) in the testing or to the usage of the data/application of "factors" to account for environments. Testing concerns include:

1) Voids are not representative of those found in flight hardware (perfect cylinders/slots with knife cuts at expected failure points, machined foam).
2) Test panels are flat with no substrate geometry effects accounted for with spray pattern. This may be non-conservative.

Analysis of divot/no divot curve and determination of margin concerns include:

1) Material variability (strength, fracture toughness, density) may not be accounted for in a comprehensive manner. Adjustments and knockdowns applied to the curve may not have adequate basis in data/analysis to determine the degree of conservatism applied
    a. Lack of data on fracture properties for foam
    b. How to apply a factor of safety and value of factor of safety
2) No allowance for 'frequency of occurrence' exists in the current process

Several concerns remain regarding the use of statistical analysis of defect size from dissection data. These include:

1. Tank-to-tank differences: Process control was applied to very few variables, and internal defects were not considered a process failure when the as-built tanks were produced. Among the variables controlled (and documented) are spray area temperature and humidity, substrate temperature at the beginning of a part spray, and component temperatures and proportions. Rise-time between layers and overlap time between layers of foam was qualitatively understood by practitioners and Quality Inspectors, though a method for timing was not provided and records were not collected. Measurements made on witness panels and from plug-pulls include tensile strength, density, and failure type/location. The relationship between these controls variables and measurements to defect production has not been determined. The assumption that ET94 will have the same type and distribution of effects as any as-built tanks is unfounded.

2. Foam-to-foam differences: Manually sprayed foam on ET94 and ET120 is predominately BX 250. The manually sprayed foam on approximately half of the remaining as-built tanks is BX265. It has not been conclusively proven that the defects that appear in BX250 and BX265 are similar in frequency and size. The formulas vary in not only blowing agent, but the formula was modified in hopes that the application of the foam, in terms of rise-time and overlap time would remain unchanged. However, BX265 is sprayed at a much higher temperature (BX250 was sprayed at about 110 degrees F, while BX265 is sprayed at about 155 degrees F). Whether the higher temperature effects defect frequency or maximum defect size is unknown. The sprayers were forced to change their arm/hand position to avoid hot component feedlines resting on their hands. Whether this awkward body position changed defect production is not known. Assuming that defect frequency and size from a BX250 tank is representative of a BX265 tank is unjustified.

3. Data partitioning: Partitioning the data into meaningful sets for analysis after the data has been collected and examined raises the concern of statistical bias. Keeping the data separate by part can be easily justified, but yielded very small samples of defects. The present new partitioning of the defects into chemistry, process, and geometry may be useful. However, setting the criterion for this division in an unbiased manner is difficult.

4. Distribution Selection: Choosing a distribution to represent the observed data is a critical step in the statistical analysis. There is currently no engineering rationale to choose one distribution over another. Several distributions may fit the data equally well, and provide very different estimates of the expected maximum.

5. Incorrect statistical parameter:
   To explain, consider these two random variables:
   a) The measurement of a single foam defect, selected at random (ET Project approach).
   b) The measurement of N foam defects, and the selection of the maximum of the N values.

   For N>1, these variables are not the same. In particular, the equivalent 3-sigma point in the distribution of (a) can be much less than that of (b). If one is trying to ensure that none of the foam defects exceed a critical size, probability statements about variable (b) are needed to characterize the risk. This is not an academic argument in the case of foam defects as the estimated risk of the two approaches differs by at least two orders of magnitude.

Conclusion

During manufacture of the existing ETs, the TPS foam manual spray application processes lacked defined requirements to ensure that defects produced were less than the critical size. Therefore the only remaining option to certify the “fly-as-is” foam is to verify ET120 tank hardware meets the new foam debris requirements.

The ET Project has undertaken a significant effort studying the existing “fly-as-is” TPS foam. Overall the ET Project has been methodical and thorough, however:

1) Analytical modeling to determine critical defect size has large uncertainties
    a. Difficult phenomenon to model - foam structural characteristics not well understood
    b. Test correlation uncertainties
2) No direct verification methods available
    a. NDE technique(s), though potentially promising, are still under development
3) Statistical methodology inadequacies
    a. Insufficient dissection data available for statistical significance
    b. Tank-to-tank variability not addressed
    c. BX250 foam versus BX265 differences not addressed
    d. No engineering rationale for selection of one distribution over another
    e. Potential for bias in partitioning logic
    f. Incorrect statistical parameter

Verification certification of “fly-as-is” foam is not achievable with the available data. In the absence of certification, an alternate flight rationale based on acceptable risks must be developed. The ET Project has pursued an aggressive activity and although this data is insufficient to directly verify “fly-as-is” foam meets the debris requirements, it may provide risk quantification to develop an alternate flight rationale.

Recommendations

Certification of manually sprayed “fly-as-is” foam is not achievable with the available data. The ET Project should quantify the risks associated with “fly-as-is” foam and build flight rationale based on mitigation of those risks through inspection, tests and analysis.

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14. ABSTRACT
During manufacture of the existing External Tanks (ETs), the Thermal Protection System (TPS) foam manual spray application processes lacked the enhanced controls/procedures to ensure that defects produced were less than the critical size. Therefore the only remaining option to certify the "fly-as-is" foam is to verify ET120 tank hardware meets the new foam debris requirements. The ET project has undertaken a significant effort studying the existing "fly-as-is" TPS foam. This paper contains the findings of the study.

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