NESC Peer-Review of the Flight Rationale for Expected Debris Report

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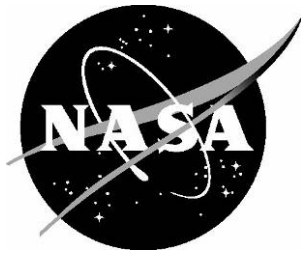
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Signature Sheet

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List of Acronyms

atm	atmosphere
BLT	Boundary Layer Transition
bp	Body Point
BSM	Booster Separation Motor
C/E	Capability/Environment
C/E	Capability Margin
CATIA	Computer-Aided Three-Dimensional Interactive Application
CFD	Computational Fluid Dynamics
CHFT	Catalytic Heating Tool
CHT	Cavity Heating Tool
DTA	Debris Transport Analysis
DVR	Design Verification Review
E	Environment
EC	Elevon Cove
EOM	End of Mission
ET	External Tank
ETD	External Tank Door
FEM	Finite Element Model
FOS	Factor of Safety
fps	feet per second
FRCS	Forward Reaction Control System
FRIC	Fibrous Refractory Composite Insulation
GN&C	Guidance Navigation and Control
HS	Half Span
HRSI	High-temperature Reusable Surface Insulation
HWISS	Heavy Weight International Space Station
lbm	Pounds per meter
I/F	Ice/Frost
IPSS	Impact Penetration Sensor System
IT	Intertank
KE	Kinetic Energy
LAP	Lower Access Panel
LCC	Launch Commit Criteria
LH_2	Liquid Hydrogen
LN_2	Liquid Nitrogen
LO_2	Liquid Oxygen
LRSI	Low-temperature Reusable Surface Insulation
Me	Mach (edge) number
MET	Mission Elapsed Time
MLGD	Main Landing Gear Door

MPM	Maximum Predicted Mass
NASA	National Aeronautics and Space Administration
NCFI	North Carolina Foam Industries
NDE	Non Destructive Evaluation
NESC	NASA Engineering and Safety Center
NLGD	Nose Landing Gear Door
NSTS	National Space Transportation System
OEX	Orbiter Experiment Support System
OML	Outer Mold Line
OPO	Orbiter Project Office
PAL	Protuberance Air Load
PDL	Process Data Logging (FoamMix®)
RCC	Reinforced Carbon-Carbon
RCG	Reaction-Cured Glass
RCS	Reaction Control System
RSRM	Redesigned Solid Rocket Motor
RTF	Return-To-Flight
RTV	Room Temperature Vulcanizing
SCMMT	Special Configuration Math Model Tool
SE&I	Space Shuttle Systems Engineering and Integration
SIP	Strain Isolation Pad
SLD	Subject Load Device
SOASD	Smooth OML Aerothermal CFD Solution Database
SRB	Solid Rocket Booster
SSP	Space Shuttle Program
SSS	Space Shuttle System
STS	Space Transportation System
SwRI	Southwest Research Institute
TBR	To Be Recorded
TM	Transport Mechanism
TMM	Thermal Math Model
TPS	Thermal Protection System
V&V	Verification and Validation
VTLE	Vertical Tail Leading Edge
WLE	Wing Leading Edge
WOW	Worst-on-Worst

Executive Summary

Since the loss of *Columbia* on February 1, 2003, the Space Shuttle Program (SSP) has significantly improved the understanding of launch and ascent debris, implemented hardware modifications to reduce debris, and conducted tests and analyses to understand the risks associated with expected debris. The STS-114 flight rationale for expected debris relies on a combination of all three of these factors.

A number of design improvements have been implemented to reduce debris at the source. The External Tank (ET) thermal protection system (TPS) foam has been redesigned and/or process improvements have been implemented in the following locations: the bipod closeout, the first ten feet of the liquid hydrogen (LH_2) tank protuberance air load (PAL) ramp, and the LH_2 tank-to-intertank flange closeout. In addition, the forward bipod ramp has been eliminated and heaters have been installed on the bipod fittings and the liquid oxygen (LO_2) feedline forward bellows to prevent ice formation. The Solid Rocket Booster (SRB) bolt catcher has been redesigned. The Orbiter reaction control system (RCS) thruster cover "butcher paper" has been replaced with a material that sheds at a low velocity. Finally, the pad area has been cleaned to reduce debris during lift-off.

The understanding of the sources and mechanisms that produce foam debris was established by a rigorous root cause investigation and the dissection of significant sections of foam removed from flight-ready ETs. Quantifying the risk associated with debris has been a major challenge. Activities included tests and analyses to predict expected/possible debris, transport tests and analyses to define debris trajectories and the velocity at impact, and tests and analyses to determine the impact capability of the Orbiter TPS components. These tests and analyses have addressed all types of ET foam and tank locations, ice from several locations on the ET, and butcher paper from the RCS thruster cover.

The SSP requested that the NASA Engineering and Safety Center (NESC) conduct a peer-review of the flight rationale for expected debris. The NESC assembled a multi-disciplinary team of subject matter experts to address each component of the proposed flight rationale. The team reviewed the debris sources data, transport test and analysis data, Orbiter impact capability test and analysis data, and the overall methodology to establish flight rationale and associated risks. The NESC peer-review began with the element level certification activities in 2004 and continued through the development of the end-to-end Space Shuttle System (SSS) level flight rationale in 2005. The NESC team has been working closely with the SSP team and has provided numerous recommendations throughout the review process on possible areas of improvement to the foam spray process, hardware redesign, and in quantifying the risks associated with expected debris. Virtually, all of the NESC recommendations have been implemented by the SSP team. This report documents the findings of the NESC peer-review of the flight rationale logic and conclusions. (Previously issued NESC position papers documented

the findings and recommendations regarding element level certification for expected debris). Provided below is a summary of the NESC findings for the principle elements of the flight rationale. The conclusions and recommendations are highlighted.

Physics of Foam Debris Generation: Each foam location on the ET has been assessed for susceptibility to large foam loss based on physical arguments about the type of foam, and the void temperature and pressure conditions during ascent. The large acreage locations, where the automated spray method is used, were eliminated from concern since no voids were found in these areas during dissection of foam on tank ET-94. Other locations can contain voids which have leak paths and may be susceptible to cryoingestion or cryopumping, depending on their location on the tank and the thickness of the foam. Divoting from sealed voids due to thermal/vacuum conditions is the most likely source of foam debris and can occur in every location on the tank with manually applied foam. **The NESC concluded that an analysis of each specific location on the tank that takes into account the local temperature, pressure, and location of voids is a valid method for determining the most likely divoting mechanism for each ET foam debris case.**

"Worst-on-Worst (WOW) Estimate" of the Impact Capability Margin (C/E): The WOW estimate of the C/E is actually the certification rigor methodology for structural design. C is the capability of TPS to survive the impact and E is the debris environment, both quantified in kinetic energy (KE) for impacts to the RCC and velocity for impacts to tile. The WOW estimate includes a 1.4 factor of safety (FOS) on C and a 1.25 FOS on E. The methodology compounds conservatisms that are included in each of the three analyses (debris liberation, debris transport, and impact capability) that must be combined to estimate the C/E. The minimum predicted impact C/E is well less than 1.0 for many WLE RCC panels, the RCC nose cap and chin panel, and many tile locations. **Therefore, the locations of the Orbiter with a C/E less than 1.0 are not certified for expected debris using the standard WOW approach.** To further address these locations, a "best estimate" approach was used to compute a less conservative estimate of the C/E. In addition, a Monte Carlo-based probabilistic analysis was used to quantify the risk for the most difficult cases.

"Best Estimate" of the Impact Capability Margin (C/E): The "best estimate" is a quasi-deterministic method. The capability and expected debris mass are point-values; and the debris transport analysis is the result of a Monte Carlo simulation. All FOSs used in the certification methodology are removed from the estimates of C and E. In addition, the expected debris mass has been reduced to the smaller mass debris due to the sealed voids divoting mechanism. The NESC concurs that the "best estimate" method is less conservative than the "WOW estimate" and is useful in understanding the level of risk due to expected foam debris. The system level FOS should be at least 1.4, if all other FOSs are removed from the C and E estimates. **A number of debris cases for RCC and tile do not have an impact C/E greater than 1.4 based on the "best estimate" method and several locations are below 1.0.**

Recommendation #1: The NESC concurs with the Delta System Design Verification Review (DVR) (April 26-27, 2005) finding that an end-to-end Monte Carlo-based probabilistic analysis will be conducted for the foam debris cases that do not have a "best estimate" impact C/E of at least 1.4.

ET Foam Debris Environment (E): The cryopumping and cryoingestion divoting mechanisms are included in the "WOW estimate", but <u>not</u> included in the "best estimate" of the debris mass. Divoting from cryopumping requires a "smart" leak path that is large enough to allow a void to fill with condensed air during the pre-launch hold, but is small enough to preclude venting as the air is vaporized during ascent. The results of component level tests simulating the flight environment support the supposition that divoting from cryoingestion and cryopumping are highly unlikely to occur. Therefore, the "best estimate" values of E are based on the smaller mass, but more likely debris caused by the sealed void divoting mechanism. The NESC concurs with the logic of not including cryoingestion and cryopumping in the "best estimate" of E used in the impact C/E because this is a quasi-deterministic method. However, all divoting mechanisms and all void data must be included in the Monte Carlo-based probabilistic analysis.

Recommendation #2: Cryoingestion should be included in the Monte Carlo-based probabilistic analysis of the debris cases that do not satisfy the system level "best estimate" impact C/E of at least 1.4.

Impact Capability (C) for RCC: The value of impact capability that corresponds to the onset of damage in RCC (or the Non Destructive Evaluation (NDE) threshold for detectable damage) is a requirement, and should not be thought of as a knockdown factor to account for an uncertainty. The damage onset requirement was established by the arcjet burn-through tests and the analysis of the WLE and nose cap. The SSP based the "best estimate" value of C on only the as-fabricated properties of the RCC test panels. The NESC reviewed the engineering data and concluded that the value of C used in the "best estimate" must account for both expected material variability and end-of-life aged RCC. **Therefore, the NESC computed values of the "best estimate" impact C/E are approximately 20 percent lower than the SSP values.** In addition, the nose cap geometry and material are significantly different from the WLE RCC panels. No impact tests or arcjet burn-through tests have been conducted on the nose cap geometry or material. **The impact capability margins (estimated to be less than 1.0) for the nose cap and chin panel are based only on analytical results from math models that have not been verified to be accurate for the nose cap geometry and material.**

Recommendation #3: The "best estimate" value of C should be computed using material properties that accounts for material variability inherent in RCC and the end-of-life aged RCC properties.

Recommendation #4: Impact tests and arcjet tests should be conducted on the nose cap geometry and material to verify the analysis methodology and results used to develop the flight rationale.

RCC Burn-Through and Hole Growth Damage Requirements: After reviewing the engineering data supporting the RCC burn-through requirements and the RCC Damage Growth Tool used to develop the nose cap and WLE damage maps, the NESC concurs that the arcjet data is adequate to establish the RCC impact damage requirement for re-entry of STS-114 (0.020" coating loss for time to breach, and 0.020" coating loss plus a mid-plane delamination for hole growth). However, the experimental data from the stagnation flow arcjet tests are not sufficient to validate the tool for all impact damage cases and for vehicle locations subjected to crossflow flight conditions. Stagnation flow arcjet tests are a reasonable simulation of the nose cap flow conditions whereas properly designed wedge flow arcjet tests are a better simulation of the crossflow flight conditions of the WLE. Therefore, the level of conservatism, uncertainty in results, and limitations on the use of the tool cannot be established for all vehicle locations and damage cases. Because of this shortcoming, the current tool should only be used by experienced subject matter experts such as the tool developers. Specifically, caution must be exercised in using this tool to predict hole growth.

Recommendation #5: Additional arcjet tests with specimens containing actual impact damage rather than simulated impact damage, particularly wedge flow tests, are required to establish the level of conservatism in using the RCC Damage Growth Tool for all vehicle locations and impact damage cases.

Past Flight History: The data on debris generation and impact damage recorded from previous flights provides a compelling basis for a flight rationale for Orbiter acreage tile. However, it has less relevance for impacts on the Orbiter RCC. The recorded incidents of foam debris generation are documented from a limited number of cameras. So this information lacks the fidelity required to precisely define the debris mass. Also, a large database (about 14,000 cases) of actual damage to tile has been recorded over the life of the Orbiters. A subset of about 300 damage cases, referred to as the platinum dataset, are adequately documented to provide a benchmark for the computational methodology developed to predict tile damage. **The NESC concluded that the platinum dataset is also a valid basis for supporting the flight rationale.**

Tile and Structural Capability Models: A suite of Math Model Tools (Damage, Aerothermal, Thermal and Structural Analysis Tools) are utilized to describe the capability of the acreage Orbiter tile and structure. This description of capability is documented as a "damage map" and is utilized in various forms and versions throughout the flight rationale. The tools have been subjected to peer-review to understand the basic workings of all tools, assumptions, limitations and key parameters passed between the tools. The methodology, used in the production of the "certification rigor" or "1st generation" damage map, incorporates all the standard certification

rigor methodologies and factors. Therefore, the conservatism of the capability established is believed to be quite high.

Recommendation #6: Certification of tools for both in- flight and as a part of the flight rationale should include a thorough end-to-end validation. This validation should emphasize interfaces between tools, demonstrating understanding of modeling accuracy and uncertainty, as well as end-to-end correlation to both test and historical damage.

Recommendation #7: The generation of a less conservative, predictive damage map should be produced for quantification of pre-flight risk of tile acreage catastrophic damage and compared to flight history for the purposes of model validation.

Flight Rationale for Tile: Both the "WOW" and "best estimates" of the impact C/E for many tile locations are considerably less than 1.0. However, the Math Model Tools used to estimate these impact C/Es also conservatively overestimates the severity of some damage cases previously recorded in the flight history database. Flight history clearly illustrates the damage tolerance capability of acreage tile. Therefore, a flight rationale has been constructed which gives increased confidence in our understanding of the debris environment and indicates that for typical debris there is not a catastrophic hazard for foam impacts on tile (excluding seals and penetrations). However, the use of flight history is not sufficient to characterize the accepted risk if several cases of severe impact damage occurring in a noncritical tile location had occurred to a more critical close-by tile location.

Recommendation #8: A Monte Carlo-based probabilistic analysis that includes the distribution of foam defects as well as the Monte Carlo debris transport analysis should be conducted to determine the likelihood of an impact which exceeds the tile damage tolerance capability.

Risk Assessment for Foam Debris: The Aerospace Corporation has conducted Monte Carlo-based probabilistic analyses of the most severe foam debris sources (LO_2 ice/frost ramp, LO_2 intertank flange, LH_2 intertank flange, LO_2 PAL Ramp, and Bipod Closeout). The Aerospace Monte Carlo-based probabilistic model used methodologies that have been peer-reviewed and validated by comparison to other analysis results and ground test data. In addition, the input distributions used in the analyses have also been peer-reviewed. **While the end-to-end predictive capability (numerical results) has not been verified, the results of sensitivity studies and comparison to flight data suggest that the results are conservative.** Based on the results of these analyses and an assessment of the controls for each foam source, the NESC concurs with the SSP that the likelihood of debris from each foam source exceeding the critical impact capability for RCC is Improbable. The NESC concurs with the SSP that the likelihood of foam debris exceeding the critical impact capability of Tile is either Remote or Infrequent, depending on the foam source. The highest computed risk is for tile seals and penetrations,

which is not overly conservative relative to flight history, and furthermore, has not been fully characterized. **The NESC has concluded that the probabilistic results, supplemented by additional engineering data, physics considerations, and the level of control over debris liberation, provide a reasonable engineering foundation for a flight rationale for STS-114 based on accepted risk due to expected foam debris.**

Recommendation #9: The risk assessment for seals and penetration should be completed, including the threat from popcorning foam debris and ice debris.

Risk Assessment for Ice Debris: The Boeing Company has conducted Monte Carlo-based probabilistic analyses of ice debris from the ET feedline bellows at the forward, mid and aft locations and the ET feedline brackets at locations 1129 and 1377. (Ice and baggie debris from ET umbilicals has not been rigorously analyzed). While ice liberation tests of a feedline bracket have been conducted, the limited results do not provide an adequate test basis for building distributions of the debris mass. Furthermore, limitations in simulating the actual flight environment cast a doubt over the suitability of the test results to establish the time of release of the ice debris. Therefore, several different distributions of mass debris and several scenarios of time of release were used to estimate the probability of ice debris exceeding the Orbiter critical impact capability. A less conservative tile damage capability allowable (50 percent damage depth) was used in the ice analysis than the foam analysis. (This is unacceptable for deterministic analyses). The results indicate that the estimated likelihood of exceeding the critical damage capability for the RCC is Improbable. The estimated likelihood of exceeding the critical damage capability for tile is very high (Probable or Infrequent). (Seals and penetrations were not explicitly addressed in the probabilistic analyses). However, the Monte Carlo analysis results vary by **three orders of magnitude,** depending on the input mass distribution assumption and the scenario for time of release, which could result in the risk being classified anywhere from Probable to Remote. In addition, a relative comparison between the bellows ice liberation test and the bracket ice liberation test suggests that significantly more ice is liberated from the bellows than from the bracket. Therefore, a reasonable qualitative argument can be advanced that eliminating the bellows ice has significantly lowered the overall risk to tile from ice debris. **Based on the available test data and analysis results, the NESC has concluded that the feedline brackets, bellows, and ET umbilical ice debris environment is not sufficiently characterized or understood to assign the level of risk. To establish the flight rationale for STS-114, additional work is required to develop adequate controls for ice.**

Recommendation #10: A physics-based engineering analysis of the risk to tile from ET umbilical ice and baggie debris should be conducted to ensure that adequate impact capability exists for impact scenarios consistent with past flight environment.

Recommendation #11: An evaluation of effective controls of ice debris from the ET umbilical ice should be completed prior to STS-114 and implemented via Launch Commit Criteria (LCC).

Recommendation #12: An evaluation of effective controls of ice debris from the feedline brackets should be completed prior to STS-114 and implemented via Launch Commit Criteria (LCC). In addition, risk mitigation methods that can be implemented for subsequent missions to reduce overall program risks should be pursued as a high priority.

Recommendation #13: Focus the flight test objectives to obtain engineering data during STS-114 to characterize the ice debris environment for the ET feedline brackets at locations 1129 and 1377, mid bellows, and ET umbilical. Additional ground tests should be conducted to supplement the flight test data.

Recommendation #14: The end-to-end predictive capability of the Boeing and Aerospace probabilistic analysis codes, which were independently-developed, should be verified. One approach to achieving this verification is to compare the analysis results from the two codes for at least one debris case.

1.0   Introduction and Background

1.1   Introduction

Recent work completed by the Orbiter Project Office (OPO) engineering team and the External Tank (ET) Project engineering team indicates that the SSS cannot be fully certified for flight through expected foam or ice debris liberation from the ET. The certification strategy included conservative assumptions for uncertainties in loads, material properties, and analysis methods that are incumbent in the engineering standard practice for designing human space flight vehicle systems. This approach, referred to as the "WOW" estimate of system capability, compounds conservatisms, and therefore, represents a potentially unrealistic estimate of the actual system capability. The WOW estimates indicated that the system impact capability for expected debris, measured by the ratio of Orbiter impact tolerance "capability" (C) divided by the expected debris (foam or ice) "environment" (E), resulted in C/E ratios less than one for some Orbiter locations. In response to these results, the SSS has revised the end-to-end certification strategy from *Certification* to *Accepted Risk*. The Accepted Risk strategy will be based on "best estimates" of C and E in areas where the WOW estimate does not provide C/E greater than one. In addition, Monte Carlo-based probabilistic analyses will be conducted to estimate the risks for the most severe cases of foam and ice debris. Space Shuttle Systems Engineering and Integration (SE&I) will be developing the flight rationale for the Accepted Risk strategy. Mr. John Muratore requested that the NESC conduct an independent peer-review of the flight rationale.

The NESC assembled a team of subject matter experts with knowledge of ET foam debris generation, debris transport analysis, Orbiter TPS tile and WLE RCC impact damage capability, and system level risk assessment tools. This team reviewed the following elements:

- Flight rationale logic.
- Available engineering data to support the flight rationale.
- Methods to determine the likelihood and "best estimate" of the debris impact mass.
- KE, impact tolerance of the Orbiter TPS tile, and RCC.
- Characterization of risks.

The Findings, Conclusions, and Recommendations of the peer-review are documented herein.

1.2   Background

An end-to-end strategy has been developed for certifying the SSS for expected debris. Using the definitions developed by the SE&I, expected debris is defined as debris generated by the vehicle that is inherent in the system design. Shuttle System certification verifies and validates that the SSS can fly through the expected debris environment without any change to configuration or capability. The end-to-end strategy consists of three interrelated parts and is discussed in the following paragraphs.

1. Capability/Environment (C/E) ratio to define the system capability margin for certification.

2. Hierarchical approach to system certification and/or developing a flight rationale.

3. Verification and Validation (V&V).

Impact tolerance C is defined as the ability of a specific element (Orbiter WLE, tiles, windows, etc.) of the SSS to withstand an impact without change to capability or configuration. The expected debris E is defined as the debris generated from any system element and transported to impact into a specific element with capability C. Both C and E are currently defined in terms of KE for RCC. Depth of damage is used for acreage tile. For certification purposes, capability is the allowable impact KE for the element and environment is the actual (predicted) impact KE of the debris. Therefore, the C/E ratio, determined for each element in the system, has the potential to define the actual or true capability margin possessed by the SSS. The C/E ratio must also include all uncertainties and dispersions. An uncertainty is accounted for by using bounding values of a parameter without the knowledge of its distribution. Dispersions are defined as the known distribution of values about a mean value of a parameter. The SSP has adopted a value of 1.5 for "best estimate", chosen at the SSS level, and 1.0 for WOW as required values of C/E.

A hierarchical approach to developing an acceptable flight rationale includes three levels for system certification and two additional levels for a flight rationale if the system cannot be certified as possessing adequate impact tolerance capability. These five levels are as follows:

1. Prove that there is no expected debris. (Certified)

2. The C/E ratio is acceptable for the "WOW" case analysis. (Certified)

3. The impact tolerance capability (C) is not exceeded by the debris environment (E) using a Monte Carlo analysis of the dispersions; and, C/E is greater than 1.5, chosen at the SSS level. (Certification is not demonstrated. The flight rationale is based on accepted risk).

4. The flight rationale is Accepted Risks based on realistic estimates of impact capability, including an engineering assessment of the physics of each debris source. Relevant flight history data and engineering data such as the reduced void (defect) count for the new redesigned foam will also be used to develop the flight rationale. (Certification is not demonstrated. The flight rationale is based on accepted risk).

5. Use other risk acceptance approaches such as damage tolerance and Monte Carlo-based probabilistic analyses of debris cases that do not satisfy any of the four previous levels. (Certification for impact damage capability is not demonstrated and risks are quantified. The flight rationale is based on adequate damage tolerance to complete the mission).

The SSP is implementing a plan to verify and validate the end-to-end certification process. The SE&I defined verification as the determination that an element meets requirements. Validation

is defined as the determination that the system meets top level requirements in the operational environment, models reflect the real world, and that software requirements are correct. Three primary technical elements comprise the determination of the C/E ratio ― debris generation, debris transport, and impact tolerance capability. A comprehensive test program is being implemented to verify and validate each of the three technical elements. However, computational tools must be used to link together analytically the three elements because a system level test is not possible. Therefore, V&V must also include the computational tools and models.

2.0 The 0.0002 lbm Debris Threshold

2.1 Assessment of Engineering Data

1. There are 60 debris sources which have been cleared on the basis of being less than a 0.0002 lbm threshold. This family of debris sources was segregated based on being an order of magnitude less than "best estimates" for other debris sources.

2. The analysis of this type of debris was limited to assuming the maximum drag rapidly drives the velocity of the debris to zero while the vehicle is assumed to be traveling at the maximum free stream velocity of approximately 4000 fps. This results in a KE at impact of less then 30 ft-lb, which is significantly below any known damage tolerance to the vehicle.

3. These debris sources were considered a much lower priority than larger debris, and the ability to test these mass velocity combinations was characterized as "impossible".

4. This family of 60 debris cases is classified as remote/catastrophic on the risk matrix.

2.2 Limitations and Gaps

1. There is limited analysis and no test to support this rationale. The velocity of 4000 fps may bridge low velocity impact and hyper velocity impact and, therefore, KE comparison may no longer be valid.

2. There is a wide diversity of debris types and sources under the 0.0002 lbm threshold. Including all of these in one block of the risk matrix, makes it difficult to establish the true risk, or to identify the one or two critical debris source/target pairs.

2.3 Implications and Conclusions

1. There is uncertainty associated with the lack of analysis and test for these small particles. While the engineering data is insufficient to clear these items, the NESC concurs with the SSP's prioritization and risk characterization.

2.4 Recommendations

1. Represent the 60 debris source/target pairs as a distribution on the risk matrix with those that push the risk into the catastrophic consequence column explicitly identified.

2. Assess additional testing or hydrocode analysis to ensure smaller particle sizes in these higher velocity regimes are not a threat.

3.0 Foam Debris from the External Tank

3.1 Assessment of Engineering Data

1. An extensive database of voids has been assembled from dissected foam from previously sprayed tanks, primarily ET-94, and from numerous high-fidelity witness panels sprayed using the new manual spray method. The database includes voids found in all types of foam used on ET-120/ET-121.

2. An ET Project investigation identified cryoingestion as the most probable root cause of the debris liberation observed in flight history data for the LH_2 tank-to-intertank flange location. The critical region of the flange has been redesigned, including a significantly improved manual spray process. Based on the dissection data from witness panels, the new spray process yields foam with far fewer voids and smaller voids than were recorded in the dissection data for the old foam. In addition, component panels with the geometric features of the LH_2 intertank flange joint and loads representative of the vehicle flight environment were tested and did not exhibit divots due to cryoingestion. (Reference: Test Report 809-9630, "Flaw Tolerance of Enhanced Flange Closeout", Lockheed Martin Space Systems Company, 04/15/2005).

3. An extensive database has been generated to describe the cohesive failure of foam due to thermal vacuum, cryopumping, and cryoingestion conditions. A failure methodology based on principles of fracture mechanics has been developed and verified through a comprehensive test program.

3.2 Limitations and Gaps

1. The dissection data from ET-94 is not sufficient to establish LH_2 tank-to-intertank variability of manually sprayed foam that was not removed from ET-120/ET-121.

2. BX-250 is the predominate manually sprayed foam for tanks produced through ET-120. After ET-120, the manually sprayed foam is BX-265. BX-265 replaced BX-250 due to environmental issues with the blowing agent in BX-250. BX-265 is being applied in all redesign/rework areas. ET-94 was set aside as a dissection/test article, therefore, most of the dissection data for comparison with "as-built" manually sprayed foam is BX-250 (overall about 75 percent of the process defects in the dissection data in ET Report 809-9440 are BX-250). Whether defect process yield from BX-250 foam is comparable to BX-265 foam has not been established. A simple comparison of all process defects from the dissection database reveals a greater percent of larger defects in the BX-265 than the BX-250 samples. For cylinders, 8 percent of the defects have a length greater than 1-inch in the BX-265 sample, whereas 4 percent are greater than 1-inch in the BX-250 sample.

For slots, about 7 percent of the width of the defects is greater than 0.5 inches in the BX-265 sample, whereas 4 percent are greater than 0.5 inches in the BX-250 sample. The chemical composition of BX-265 was modified in the attempt to maintain similar handling characteristics as BX-250, such as rise-time and overlap time. The foams are applied at distinct component temperatures — BX-250 around 110° F and BX-265 at about 155° F. A limited number of thermal vacuum test panels were fabricated using the discontinued BX-250. The divoting of these panels is enveloped by the results from the testing with BX-265.

3. Statistical analysis of data by the NESC shows that neither the 1.4 times "max observed" estimate nor the 99th percentile Normal distribution estimate of the "max expected" is a bounding estimate. The fits were made to the truncated dataset, i.e., no voids below the dissection recording limit, and this effect was not accounted for in the fit.

4. The "foam end-to-end best estimate" is not really end-to-end. It is another C/E study with most FOS and larger conservatisms removed. A better idea of total risk could be derived from a study that probabilistically combines all factors with uncertainties that reflect the state of knowledge on each factor. To really be "end-to-end", such a study should include the probability of releasing a large piece of foam and the probability of the foam hitting a critical area.

5. The limited test data at the smaller void depths and smaller void sizes is insufficient to accurately define the divot/no-divot failure curve. Also, the cases of replicate tests are insufficient to characterize material level data scatter. The divot/no-divot failure curve is used more like the design allowable in a limit load stress analysis than a fracture toughness value in a damage tolerance analysis. Therefore, uncertainties in material variability and data scatter should be treated like the development of "A" basis design allowables.

3.3 Assessment of Foam on RCC Environment (E) "Best Estimate" Logic

1. Calculating "E", the foam on RCC environment, is a multi-step analysis:

   a. Determine "best estimate" ET void defect size.

   b. Notionally place defect at maximum depth that will result in a divot using ET provided divot/no divot curves – constrained by the maximum foam depth.

   c. Calculate divot volume assuming divot is a frustum.

   d. Determine maximum KE impact from Monte Carlo analysis of density variation and Debris Transport Analysis (DTA).

2. The "best estimate" analysis selected an ET foam insulation defect size. For the most part, this was the maximum of the following three elements:

    a. Maximum defect observed from dissection data.

    b. 99 percentile of a Weibull distribution fit to the dissection data.

    c. 99 percentile of a Normal distribution fit to the dissection data.

    There were exceptions to this rule and, in at least three cases, the defect size used in the "best estimate" was less than the maximum observed in the dissection data. Based on this "quasi-deterministic" method of computing a "best estimate" using a defect value less than the maximum observed is not supportable. However, an alternative and potentially less conservative approach is to conduct a Monte Carlo-based probabilistic analysis using a distribution of defects.

3. Only process defects were considered. Geometric defects were not considered as their depth was too deep for a divot to form. This assumption has been verified.

4. The divot thicknesses were calculated using the "Limit" divot/no-divot curves. "Limit" curves include a 0.9 material knockdown factor, but the 1.25 FOS was removed. (The knockdown factor of 0.9 has been confirmed to be appropriate based on fracture toughness test results. Also, the adjustments to the BX-265 "Limit" divot/no-divot curve for NCFI-24-124 and PDL 1034 foams have also been demonstrated to be appropriate based on fracture toughness data). Using the "Limit" divot/no-divot curve rather than the ultimate curve with the 1.25 FOS is acceptable for determining the "best estimate" value of E. However, the system level FOS (C/E) should be at least greater than 1.4.

5. The values used for KE were the maximum values from the debris transport Monte Carlo analysis.

6. The "best estimate" value of E assumes an ET foam defect will cause a divot, the divot will always be aerodynamically transported to the Shuttle, and the divot will always hit the Shuttle on the apex of the RCC.

7. The "best estimate" value of E is based on the sealed void divoting mechanism. The cryoingestion and cryopumping mechanisms are included in the certification rigor estimates of C/E, but are not included in the "best estimate".

3.4 Engineering Assessment of Physical Realism of Debris Sources

The ET Project has considered three divoting mechanisms:

1. Cryoingestion-induced divoting.
2. Cryopumping-induced divoting.
3. Sealed void divoting.

Cryoingestion-induced divoting is limited to the LH_2/intertank flange area where foam voids at the substrate can communicate with the intertank N_2 purge gas. Cryopumping-induced divoting has been assessed for locations on the tank where the substrate is cold enough to allow the condensation of air (the LH_2 tank) and where it reaches a temperature of at least -320°F during the first 130 seconds of ascent (the first barrel of the LH_2 tank). Cryoingestion and cryopumping divoting use the same divot/no-divot curve to assess the divot mass and critical void size.

Sealed void divoting is ameliorated by low local temperatures that reduce the void pressure (increasing the critical defect size).

A fourth divoting mechanism not considered by the ET Project, "air enrichment" divoting, can also occur. Here, the void temperature during tanking is not cold enough to condense ambient air, but is cold enough to concentrate the air in a venting void. The vent must be sized to act as a highly resistive leak in the correct size range. That is, it allows air to leak into the void (due to temperature induced pressure differences) over the 6-hour time period prior to launch that the tank is at cryogenic temperatures, but not allow any appreciable amount of air to leak back out of the void during the ascent. The worst case condition prior to launch will be air at 1 atmosphere (atm) and sub-ambient temperature. If the leak path size is in the correct range, increases in the void temperature during ascent could result in void pressures well above 1 atm. Even if the void temperature does not increase during the critical foam release period (80< Mission Elapsed Time (MET) <130 seconds), a leak path size in the correct range could result in a void pressure approaching 1 atm during ascent.

An examination of each of the foam debris source locations on the ET and their possible divoting mechanisms is provided below:

LO_2 Tank Acreage (use-as-is foam). The LO_2 Tank Acreage is machine sprayed foam. Because the dissections have uncovered no defects in machine sprayed foam, this area is not considered to be at risk for divoting.

LO_2 Ice/Frost Ramps (use-as-is foam). The ice/frost ramps are poured in place over the pressurization line brackets. Most of the ice/frost ramp is poured over machine sprayed foam.

Only a small area (approximately a 1-inch margin around the base of the pressurization line bracket) of the poured foam contacts the substrate. The ice/frost ramp is at risk of sealed void divoting. Air enrichment-induced divoting is also possible.

LO$_2$ PAL Ramp (use-as-is foam). The PAL ramp is applied as a hand spray over machine sprayed foam. First, the rind of the machine sprayed foam is removed, then Conothane is applied over the machined foam, and finally the PAL ramp is manually sprayed on. This location is at risk of sealed void divoting. Air enrichment induced divoting is also possible.

LO$_2$/Intertank Flange (use-as-is foam). The flange closeout is a hand spray. This location is at risk of sealed void divoting. It is also at risk of air-enriched void divoting.

Intertank Acreage (use-as-is foam). The intertank acreage is machine sprayed, machined to minimum thickness, and then punctured. The thin foam and perforation limit the size of divoting to a size within acceptable limits.

IT Ice/Frost Ramp (use-as-is foam). The ice/frost ramps are poured in place over the pressurization line brackets and machine sprayed foam. Only a small area (approximately a 1" margin around the base of the pressurization line bracket) of the poured foam contacts the substrate. This location is at risk of sealed void divoting. Because the intertank is relatively warm in the area of the ice/frost ramps, little air enrichment can occur.

LH$_2$/Intertank Flange (new foam). The LH$_2$/Intertank Flange closeout is hand sprayed over the bare substrate. Sealed void divoting is possible. Voids at the substrate are susceptible to cryoingestion from the intertank purge gas and to cryopumping from the ambient air. Venting voids not in contact with the substrate are susceptible to air enrichment.

Bipod (new foam). Sealed void divoting can occur. Voids in this closeout are susceptible to cryoingestion from the intertank purge gas and to cryopumping from the ambient air.

Forward LH$_2$ PAL Ramp (new foam). The PAL ramp is applied as a hand spray over machine sprayed foam and the hand sprayed flange closeout. Sealed void divoting can occur. Venting voids are also susceptible to air enrichment.

Aft LH$_2$ PAL Ramp (use-as-is foam). The PAL ramp is applied as a hand spray over machine sprayed foam. Sealed void divoting can occur. Venting voids are also susceptible to air enrichment.

LH$_2$ Ice/Frost Ramps (use-as-is foam). The ice/frost ramps are poured in place over the pressurization line brackets and machine sprayed foam. Only a small area (approximately a 1" margin around the base of the pressurization line bracket) of the poured foam contacts the

substrate. This location is at risk of sealed void divoting. The ice/frost ramps forward of station 1290 experience substrate heating before 130 seconds MET and are at risk of cryopumping induced divoting from voids at the substrate. Venting voids in the body of the foam of all the ice/frost ramps are at risk of air enrichment induced divoting.

LH$_2$ Tank Acreage (use-as-is foam). The LH$_2$ Tank Acreage is machine sprayed foam. Because the dissections have uncovered no defects in machine sprayed foam, this area is not considered to be at risk for divoting.

Cryoingestion must be assessed because it is a possible defect mechanism. The defects found in the lead and trail spray panels and in the V&V sprays for the improved closeout at the LH$_2$/Intertank flange must be assessed for the three factors that are required to cause divoting:

1. The presence of a flow path to the intertank purge gas.
2. The defect size in relation to the divot/no divot curves.
3. The probability that the flow path is in the critical range to support void filling during tanking and pressurization from ullage gas heating during ascent.

Cryopumping is not a probable divoting mechanism. The lack of voids in the machine sprayed foam eliminates cryopumping as a concern in the acreage foam. No voids were found in the LH$_2$/intertank flange closeout lead and trail spray panels, or V&V sprays in locations that would be cold enough to allow cryopumping. Also, no voids were found in the LH$_2$ ice/frost ramp dissections in locations susceptible to cryopumping.

Air enrichment is also not a probable divoting mechanism. Analysis of the air enrichment that occurs during the 6.5 hour pre-launch hold and the pressure difference between the void and the atmosphere during ascent show that a narrow range of small (on the order of 0.001 inch or less) cracks will result in significantly more pressurization than is the case for sealed voids. Larger cracks allow the voids to vent during ascent. Smaller cracks effectively seal the voids against air enrichment. Owing to the narrow critical range of extremely small cracks, this failure mechanism is considered to be improbable.

The most probable divoting mechanism for the ET foam is sealed void divoting. The probability for individual locations must be assessed based on the void distribution in the non-machine sprayed foams and the void depths. The possible and most likely foam loss mechanisms for each location are summarized in Table 3.4-1.

Table 3.4-1. Divoting Mechanism Summary

		Cryoingestion	Cryopumping	Sealed Void	Air Enrichment
LO$_2$ Tank Acreage	use-as-is	-	-	-	-
LO$_2$ Ice/Frost Ramps	use-as-is	-	-	most probable	improbable
LO$_2$ PAL Ramp	use-as-is	-	-	most probable	improbable
LO$_2$/Intertank Flange	use-as-is	-	-	most probable	improbable
Intertank Acreage	use-as-is	-	-	-	-
IT Ice/Frost Ramps	use-as-is	-	-	most probable	-
LH$_2$/Intertank Flange	new closeout	likely low probability but must be assessed	low probability	most probable	improbable
Bipod	new closeout	likely low probability but must be assessed	low probability	most probable	improbable
Forward LH$_2$ PAL Ramp	new closeout	-	-	most probable	improbable
Aft LH$_2$ Pal Ramp	use-as-is	-	-	most probable	improbable
LH$_2$ Ice/Frost Ramps	use-as-is	-	low probability	most probable	improbable
LH$_2$ Acreage	use-as-is	-	-	-	-

3.5   Implications and Conclusions

The SSP implemented a three-tier process for evaluating foam debris impact C/E. The process evolved from a certification rigor "WOW" analysis to a "best estimate" analysis, and then to a Monte Carlo-based probabilistic analysis to quantify risks.

The "best estimate" analysis should include a system level FOS impact C/E of at least 1.4. Any foam debris case not meeting a "best estimate" C/E of 1.4 should be further analyzed with a Monte Carlo-based probabilistic method to quantify the remaining risks.

3.6   Recommendations

1.   Perform an end-to-end Monte Carlo-based probabilistic analysis for the foam debris cases that do not have a "best estimate" impact C/E of at least 1.4.

2.   Cryoingestion should be included in the Monte Carlo-based probabilistic analysis of the foam debris cases that do not satisfy the system level "best estimate" impact C/E of at least 1.4.

4.0   Ice Debris from the External Tank

4.1   Assessment of Engineering Data

Controls to Mitigate Ice

To some extent, ice debris is controlled by the Launch Commit Criteria (LCC). The LCC has been established such that the launch cannot take place if the ice criteria are exceeded without approval of a formal LCC waiver. The updated criteria for return to flight (RTF) include an expanded No Ice Zone to protect the Orbiter windows. The LO_2 feedline bellows acceptance criteria is intended to limit ice formation to a level that does not result in unacceptable damage to vulnerable TPS and structure. A visual inspection requirement has been established based on a 0.3-inch ice in an 8-inch arc. However, this requirement was established by the 0.053 lbm requirement that has recently been shown to be unacceptable. The NESC expects the LCC to be revised to reflect the positive benefit from implementing ice mitigation design changes to the LO_2 feedline bellows joint. There are other locations of ice formation that are less threatening to the Orbiter.

Examination of Bellows Ice and Tile Damage Flight History Data

The flight history was examined for cases of bellows ice debris. Thirty three (33) flights were examined where bellows ice could be observed in separate photographs and video imaging. Of these documented cases, eighteen (18) percent of the bellows did not lose any ice. One bellow lost all its ice. The average ice lost was about 16 percent per bellow.   The flight history data was also examined to identify possible damage from ice impacts to the Redesigned Solid Rocket Motor (RSRM), SRB, or Orbiter. The general conclusion was that ice debris and damaging impacts are common. There does appear to be an Orbiter right side bias to the potential impacts thought to be caused by ice. Damaging ice impacts appear to be more likely to occur when pre-launch environment has low-to-medium relative humidity. Finally, damaging ice impacts occur on both "typical" and "light ice" conditions.

There is an extensive database on impact damage to tile. Approximately 16,000 cases of damage to tile have been recorded. Of these cases, only about 2,000 are well documented, with only 300 cases documented with photographs. These latter cases comprise a dataset that is referred to as the "platinum dataset". This database was recently re-examined in an attempt to identify the damage cases most likely due to ice impacts. The features of tile damage recorded in the platinum dataset were compared to the features of ice damage documented from impact testing. (Test results show that foam damage tends to be broad and shallow whereas ice damage tends to be narrow and deep). Four cases of significant damage referred to as "close calls" were found. One of these cases was attributed to ablator debris from the SRB nose cap. This is viewed as a well understood anomaly and corrective actions were taken to prevent reoccurrence. A second

case was attributed to cork debris from the SRB. The remaining two cases are likely from ice debris. These four damage states are referred to as close calls because they were so severe that if the impacts had occurred in slightly different locations, the vehicle may not have survived re-entry.

Ice Impact Test Data

The data from full-scale ice-on-RCC impact tests is very limited. The test results show that ice impacts cause more RCC coating loss and delamination than does foam. Orbiter ice impact threshold capabilities for WLE panels are considerably less than maximum-possible and best-estimated ice environments. The cases analyzed are feedline bellows ice drip lip and feedline bracket yoke base fitting ice. The "best estimate' C/E for Panel 12 is 1.11 and 0.45 for the feedline bracket ice and feedline bellows ice cases, respectively. The end-to-end analysis does not support an assured control level.

Ice Formation and Liberation Tests

Testing is underway to determine the characteristics of ice that forms on the LO_2 feedline bellows (mid and aft locations without a heater to prevent ice formation) and feedline brackets that may be liberated during launch and ascent. The bellows tests were conducted to compare ice formation and liberation on the original bellows design to the redesigned drip lip configuration. The original test program was not planned with the objective of developing a comprehensive, quantitative database on ice liberation for the probabilistic analysis of ice debris impacts on the Orbiter. Likewise, the bracket ice formation and liberation test programs (in-progress) are limited to six planned tests. While somewhat limited in scope, the data generated from these test programs will be an essential benchmark on the debris distributions used in the probabilistic analysis. (See Section 10.)

Nose Cap and Windows

There is no ice debris transport mechanism (TM) identified to the Orbiter nose cap and chin panel. Windows are protected by the No Ice Zone or not threatened by other ice with no transport mechanism (TM).

4.2   Limitations and Gaps

1.   Limited ice-on-RCC impact testing has been conducted. Ice is not fully characterized to support testing and model development. The density of ice is still being studied and the development of impactor test specimens is still under development. This data is also needed to support the development of the impactor model used in the LS-DYNA[©] code to simulate ice-on-RCC or ice-on-tile impact events.

2.   The redesigned feedline bellow drip lip has not been demonstrated to liberate less ice than the original design. (The decision to use heaters at the forward bellows location to prevent ice formation is being implemented).

4.3   Implications and Conclusions

The engineering work is incomplete to support flight rationale for expected ice debris from the mid and aft feedline bellows and the feedline brackets. A probabilistic analysis will be conducted to estimate the level of risk due to expected ice debris from the feedline mid and aft bellows and the feedline brackets. (See Section 10.)

5.0   Debris with No Transport Mechanism

5.1   Assessment of Engineering Data

The SSP has identified a large number of debris sources that are cleared with a flight rationale based on having no TM to the Orbiter TPS (RCC or tile), windows or other vulnerable structure. Of the 173 sources in the expected debris table, 20 sources are identified with no TM to the tile, 65 with no TM to the RCC, and 71 with no TM to the Orbiter windows. The rationale for clearing these debris sources was a combination of analysis and assessment. "Analysis" indicates that an actual DTA was completed to determine whether the debris source could hit the TPS or windows. "Assessment" indicates that an engineering estimation of no TM was made based on general knowledge of vehicle flow fields without specific DTA. Special attention was paid to ensuring that this debris would not be at risk of being entrained in the re-circulation flow fields in the aft part of the vehicle at the base of the ET behind the ET attach structure. For the DTA cases, a WOW debris transport was used in determining if there was a mechanism for TM.

The debris cleared by "assessment" are generally from sources which are very far aft on the stack, such as RSRM slag, SRB hold down post debris, etc., relative to the vulnerable structure (TPS or RCC).   As an example for windows, debris sources aft of XT 1104 are aft of the Orbiter windows, and, therefore are reasonably assessed as having no TM to the windows. Masses range from SRB separation motor ejecta on the order of 10^{-5} lbm up to SRB aft skirt web froth-pak/instafoam debris up to 0.5 lbm. The legitimacy of the debris masses was not evaluated, as the critical element of this rationale is the transport of debris, not the mass. Small masses (<0.0002 lbm) are propulsive in nature and, therefore, do not fall into the general <0.0002 lbm mass accepted risk category. This hazard is classified as improbable/catastrophic (green).

5.2   Limitations and Gaps

The limitation of this argument lies in the modeling and understanding of the Orbiter flow fields. Several of these debris sources were eliminated on the basis of engineering judgment without any specific computational effort. Additionally, no data or summary of results were provided for review of these conclusions.

5.3   Implications and Conclusions

Given the location of the debris sources in question, and the relatively well understood nature of the flow fields in these areas, "no TM" appears to be a sound rationale for the items identified.

6.0   Debris Transport Analysis (DTA)

6.1   Assessment of Engineering Data

The DTA relies on five primary data sources and inputs. These are combined through the DTA, which outputs the mass, velocity, location and angle of predicted debris impacts. These parameters are then combined to yield the impact KE used to establish E in the C/E calculation.

1.   The DTA utilizes a combination of the ET foam test data and assumptions to establish the debris shape, mass, density and volume. The DTA also utilizes the results of the extensive foam dissection database of voids assembled from previously sprayed tanks, primarily ET-94, and the resulting divot/no-divot curves established via the ET thermal vacuum divot generation testing. The divot shape is assumed to be a 60-degree half angle truncated cone or frustum, which approximates the ET thermal vacuum foam divots and yields a conservative mass for a given divot size. The density is based on the ET Project's provided mean measurement/calculation per foam application or part. The resulting debris particle mass and volume are then calculated from the above data and assumptions by tying the divot thickness and inner diameter to the ET divot/no-divot data. As applied in the WOW analysis, the ET certification allowable mass (documented as the Vol. X requirement) is assumed at the mean foam density. The volume is then related to the ET data using the "ultimate" (FOS of 1.4 included) divot/no-divot line. For the "best estimate" analysis, the ET Project defined that the maximum void size is set to the frustrum inner diameter. The volume is then calculated using the "limit" (FOS of 1.0) divot/no-divot line. The resulting "maximum expected mass" is generated using a mean density with a $\pm$3-sigma variation in the Monte Carlo analysis.

2.   The initial foam release conditions, debris release location, time, pop-off velocity and angle, are inputs for the DTA. Combined with the debris mass and flight condition variations, these initial conditions produce millions of debris source locations and trajectories in the Monte Carlo analysis.   Debris release location is assumed to be "uniformly" distributed across the ET for each foam application, or part and results in what is essentially a survey of all potential debris release locations. Both WOW and the "best estimate" DTA use the same distribution of release location cases. The debris release time is focused on that portion of the ascent trajectory, Mach 2.2 to 3.0, shown to maximize the resulting KE *(combination of maximum dynamic pressure conditions (maximum debris acceleration) and largest relative velocity, yielding the peak potential ΔV – debris to launch vehicle).* Both WOW and "best estimate" DTA assume debris release times at four discrete Mach numbers — 2.2, 2.5, 2.75 and 3.0. The debris pop-off velocity and angle complete the initial release condition definition. Both the WOW and "best estimate" DTA use a pop-off velocity defined from an empirical fit of thermal vacuum test data derived from video analysis (0 to 300 fps) $\pm$30 fps. The curve-fit

provides pop-off velocity as a function of debris mass. In general, the release angle is assumed to be perpendicular to the surface ±10 degrees. However, some foam applications (e.g. ice/frost ramps) are varied by larger amounts accounting for geometric considerations.

3.   The debris aerodynamic model is simplified to provide drag for ballistic trajectory DTA and approximate lift to establish the debris cross-range. The breakup of the foam debris has also been investigated. The debris drag model for the frustum shape is based on extensive Computational Fluid Dynamics (CFD) analysis validated with wind tunnel, ballistic tunnel, and F-15 flight test data.   The analysis provides drag as a function of debris particle orientation, which results in a nominal drag value for an oscillatory orientation and maximum drag value for the frustum aligned axially into the flow direction and a minimum drag value for edge on flight condition. The debris lift effects are estimated by CFD analysis and validated with limited wind tunnel test data correlation. The analysis bounds the limited test data. Debris particle lift is treated as a dispersed cone around a zero-lift trajectory. The WOW DTA uses the test-validated CFD nominal drag level. The "best estimate" varies drag from nominal to broadside value over a uniform distribution in the Monte Carlo analysis. The CFD analysis derived lift levels are varied from a mean value by ±2-sigma. As an additional consideration, F-15 flight testing and wind tunnel testing indicates that foam debris breakup is very unlikely at expected release conditions and is, therefore, not modeled in the DTA.

4.   The DTA relies on the CFD analysis to produce the flow field to transport the debris. The STS launch vehicle flow field is provided as a function of Mach number from 0.6 to 5.0, angle-of-attack, and angle-of-sideslip to cover the range of conditions in the debris transport sensitive portion of the ascent trajectory. Based on recommendations of previous NESC peer-reviews, extensive wind tunnel test (on-surface and off body) data has been used to validate CFD results and the simulated flow fields. Geometric models (both test and analysis) were updated to more accurately represent STS launch vehicle configuration at a very high fidelity for debris transport. The geometric modeling is impressive in detail. The maximum error in global flow field velocity is estimated at less than two percent and is not considered a significant source of error or limitation of the DTA.

5.   The actual flight conditions (Mach, angle-of-attack & sideslip, dynamic pressure, and velocity) for debris release are provided by the results of Guidance Navigation and Control (GN&C) simulation of STS launch vehicle trajectories. For WOW DTA, the GN&C simulation sampled 150 wind profiles for a June launch that have been scaled to produce a high dynamic pressure trajectory (and therefore yield maximum debris acceleration conditions). The "best estimate" DTA is tied to nominal STS-114 trajectory conditions.

6.2   Limitations and Gaps

1. **Foam Shape, Density, Mass & Volume.**   The assumed frustum debris shape results in a conservative mass estimate (includes volume not seen in typical divots). The DTA ties the foam debris calculations to the ET Project's provided divot/no-divot curves yielding foam debris at a fixed volume with a maximum thickness assumed. Holding this volume constant and varying the mass yields an intermediate range of ballistic numbers resulting in a spread of KE levels per debris source location. However, density effects on divot/no-divot curves are not included. Overall, this is a conservative approach to debris size and mass resulting in increased predicted levels of KE.

2. **Release Conditions.** The release conditions applied affect both the resulting impact KE and range of impacts.   Foam debris release is assumed at the worst-case flight conditions (i.e., producing maximum KE) and is not necessarily directly tied to a thermal and structural foam failure analysis. This produces a conservative KE result. Currently, data provided by the ET Project to adjust the foam release conditions are incomplete. (Note: Data will be provided for the identified foam cases to be assessed by probabilistic analysis. See Section 10.) Pop-off velocity is based on video analysis at relatively low frame rate. The resulting uncertainty in the calculation is incorporated with the bounding curve.

3. **Debris Aerodynamics.** Modeled divot shapes are idealized representations (spheres, cubes and for foam frustums) of actual debris. The assumed debris shape is fundamental to the resulting aerodynamics. This necessary assumption is a limitation to the DTA overall accuracy. Debris lift is based on a bounding CFD analysis not validated due to limited test data. An assumed 2-sigma variation in lift is applied.

4. **Ice Aerodynamics**. Currently based on CFD analysis of assumed shape without test data validation (limited testing is planned prior to RTF). Breakup of ice is not quantified at this time and requires validation testing (planned prior to RTF).

6.3   Implications and Conclusions

1. **Foam Shape, Density, Mass & Volume.** The worst case combination of low density and resulting increased volume for a fixed mass is not covered in the DTA. This is offset by the assumed shape resulting in larger volume divots than typically generated in ground-based testing.

2. **Release Conditions.** Both the timing and distribution of foam release result in the most conservative estimate of potential debris impacts. The pop-off velocity data contributes to the large areas of potential debris impacts.

3. **Debris Aerodynamics.** The assumed frustum shape is representative of typical foam divots adding conservatism and realism to the DTA. The lift cone dispersion results in large areas of potential debris impacts.

4. **Ice Aerodynamics.** Given the current concerns regarding ET LO_2 feedline bellows ice, test validation of the CFD-generated aerodynamics is required.

7.0   Re-Entry Burn-Through of the WLE RCC

7.1   Assessment of Engineering Data

An empirical tool to predict RCC damage growth after an impact event was developed from arcjet test data. The RCC Damage Growth Tool is used to determine: acceptable damage criteria for the Orbiter RCC; the rationale for RCC damage repair; and to establish the on-orbit RCC inspection criteria. The following paragraphs describe the assessment of the suitability of the arcjet test data and the resulting empirical tool to support the flight rationale.

Any empirically predictive analysis tool is limited by the extent that the environments used for tool development correspond to those encountered during flight. The RCC Damage Growth Tool was developed and validated using only stagnation arcjet test data. It is well documented that there are substantial differences between the arcjet and flight environments. The RCC Damage Growth Tool is based on the assumption that the performance of RCC can be characterized as a function of temperature and pressure only from stagnation flow arcjet test data. This critical assumption, that the arcjet testing based stagnation flow produces conservative results compared to flight, has not been substantiated by a V&V program.

Given the impracticability of obtaining realistic flight data, the validation claim depends on the degree to which arcjet conditions match flight conditions. Since none of the RCC WLE surface experiences stagnation heating, the conservatism claim requires critical evaluation. A mismatch of test and flight conditions may exist if RCC damage growth is sensitive to crossflow environmental factors that stagnation testing cannot reproduce. One means of evaluating the sensitivity of the tool to deviations from stagnation is to expose specimens to crossflow conditions (i.e., flow with substantial shear) and compare the test results to both stagnation results and predictions. Wedge tests were designed to produce crossflow data by reducing the specimen angle-of-attack relative to the flow axis. If stagnation quantities are sufficient to characterize damage growth, then the wedge testing, at the same stagnation temperatures and pressures, should produce results (time to breach and hole growth rate or size) similar to those from stagnation testing.

7.2   Limitations and Gaps

The current RCC Damage Growth Tool is validated only for stagnation flow cases. Its level of conservatism and application to non-stagnation cases has not been validated.

7.3   Implications and Conclusions

The engineering interpretation of the experimental data is adequate to establish the RCC impact damage requirement ― coating loss with delamination ― in support of the flight rationale

development.   However, the reliance on only the stagnation test experimental data as the empirical basis of the Math Model Tool *for time to breach predictions* may not be conservative. This reliance brings into question the accuracy of the time to breach predictions on the WLE where it has not been demonstrated that stagnation flow is a reasonable approximation for damaged RCC environment. This is of critical importance for WLE locations where the tool currently predicts pass versus fail. In addition, the V&V program has not adequately addressed this modeling deficiency. Finally, the uncertainty in the results from the tool has not been quantified to establish a basis for the pass/fail criterion. Because of these findings, the NESC views the tool maturity level as developmental in nature as opposed to a certified/validated engineering tool. Therefore, the results of the tool must be interpreted by an experienced subject matter expert (i.e., the tool developers) to support management decisions regarding on-orbit RCC damage assessments. Addressing the wedge flow test results in the time to breach predictions and establishing an end-to-end uncertainty level are considered essential requirements to reliably apply the tool for on-orbit assessments.

7.4   Recommendations

1.   Additional arcjet tests, including wedge flow tests, with specimens containing actual impact damage rather than simulated impact damage, are required to establish the level of conservatism in using the RCC Damage Growth Tool for all vehicle locations and impact damage cases.

8.0   Impact Capability of the Orbiter RCC

8.1   Assessment of Engineering Data

1.   The significant effort expended on impact testing and analysis has greatly expanded the understanding of the impact capability of RCC.

2.   RCC material data are based on the 1994 Loral Report plus material testing performed post-*Columbia*. New data is consistent with previously developed RCC design data.

3.   Finite element model (FEM) simulations using LS-DYNA$^{©}$ code provide analysis results based on empirically-derived material data input definitions that qualitatively correlate with observed test behavior.

4.   LS-DYNA$^{©}$ correlations are performed with flat panels and WLE panel (9L) tests. Maximum deflections correlate to within 10 percent and damage maps, using the "1-to-5 elements out" criterion, qualitatively correlate with test data. (The deflection time histories for the 6" x 6" flat panels seem to correlate up until damage initiates and deviates after that point. The charts in Section 4.2.1a of the data pack indicate resultant displacement errors of 20 percent).

5.   Test results clearly identify the RCC impact threat due to foam and ice debris, which had not been previously characterized. Testing was performed at several locations on specific panels (flat and full panels). The LS-DYNA$^{©}$ analysis was validated using these test results. LS-DYNA$^{©}$ was then used to analyze other panels and panel locations to evaluate capability against foam and ice debris impact.

6.   Parametric studies have been performed on the impact behavior of the WLE RCC panel apex region using rectangular foam and ice impactors. The rectangular foam brick with its length aligned with velocity trajectory presents the worst case. The square block of ice with the large face impacting tangent to the panel produces the largest damage.

8.2   Limitations and Gaps

1.   LS-DYNA$^{©}$ can only be used to predict the "onset of NDE detectable damage" or threshold of damage. LS-DYNA$^{©}$ cannot be used to predict damage growth because the material damage model in LS-DYNA$^{©}$ does not accurately model all forms of RCC damage. Furthermore, the LS-DYNA$^{©}$ damage parameter value that predicts the threshold of damage in WLE RCC panels is very close to he damage parameter value that predicts a through-the-thickness crack. Therefore, the LS-DYNA$^{©}$ predictions lack the fidelity necessary to show that the RCC is damage tolerant.

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2. The small mass effect is assumed to vary by a factor $(m_1/m_2)^{0.2}$ where m_1 is the mass of the debris and m_2 is the mass of the WOW estimate. This factor appears to be derived analytically and empirically-correlated with the LS-DYNA[©] prediction based on m_2, 0.03-lbm in most cases. This factor needs to be validated using test data. Bounds on correctness of this factor have not been established, especially as size limits are approached. Also, this factor does not appear to be valid for the nose cap.

3. The material orientation changes continuously on the surface of the doubly curve shell nose cap. As such, orientation of elements appropriate to the material orientation is very difficult to achieve. Only one FEM for the nose cap exists and as such the fidelity of the finite element solution is not well established.

4. Because of the different RCC material (laminate) configuration in the nose cap, the NESC has no assurance that the failure modes exhibited by the WLE panels are the same as those for the nose cap. The pads (ply drops) used to achieve the required thickness of the nose cap are highly susceptible to initiating delaminations for out-of-plane loads, such as those produced by debris impact.

8.3 Assessment of "Best Estimate" Logic for RCC

Note: Presented at the DVR, April 7-9, 2005.

1. The reported "knock-down factor" on C for "no NDE detectable damage" is in fact a *requirement*. The damage requirement changed from the through-the-thickness crack ("1-to-5 elements out") to "onset of NDE detectable damage" as a result of the RCC burn-through tests and analyses.

2. Furthermore, the C computation should be adjusted by 0.56 rather than 0.69 to meet the damage onset requirement. The basis for this value is to account for the uncertainty and variability in the RCC material property data and the LS-DYNA[©] material model used to simulate the RCC response. Recent analyses indicate the velocity factor should be 0.75 (0.5625 on KE) and ***not*** 0.83 (0.69 on KE).

3. The "best estimate" of capability must include an adjustment to account for the higher density and stiffness for PDL foam (a factor of 0.8 is used on KE).

4. Using observation #2 above, an example calculation for the bipod closeout foam debris case (Panel 12) is as follows:

- Predicted using 10 percent aging only; Lowest C/E Panel 12 – 1494 ft-lbs (ft-lbs)

- Onset of NDE detectable damage (0.5625) – 1494*0.5625 = 840 ft-lbs

- Material properties ("best estimate" and MPM) (1.22) – 840/1.22 = 689 ft-lbs

- Mass adjustment for small masses: $(0.0107/0.03)^{0.2}*689 = 560$ ft-lbs.

This revised value is 23 percent lower than the reported value of 686 ft-lbs presented at the DVR on April 8, 2005. Table 8.3-1 presents the comparison of the NESC values computed to the SSP's DVR values (as described above).

Table 8.3-1. Comparison of "Best Estimate" C-Values and C/E-Ratios

Tank Location	C-Values, ft-lbs		E-value, ft-lbs	C/E Ratios	
	NESC Values	SSP DVR values		NESC Values	SSP DVR values
LO_2 Acreage (Ogive)	388	475	180	2.2	2.6
LO_2 Flange	533	652	587	0.9	1.1
Intertank Acreage	405	496	164	2.5	3.0
LH_2 Flange	489	599	339	1.4	1.8
LH2 Acreage	401	491	134	3.0	3.7
LO_2 Ice/Frost Ramps (PDL)[1]	337	636	622	0.5	1.0[2]
Intertank Ice/Frost Ramps (PDL)[1]	337	636	437	0.8	1.5[2]
LH_2 Ice/Frost Ramps (PDL)[1]	334	632	395	0.9	1.6[2]
LO_2 PAL Ramp	481	590	353	1.4	1.7
LH_2 Forward PAL Ramp	481	590	306	1.6	2.0
LH_2 Aft PAL Ramp	482	590	296	1.6	1.9
Bipod Closeout	560	686	607	0.9	1.1

[1] PDL high density foam adjustment 20 percent (a factor of 0.8 is used on KE)
[2] NESC cannot reproduce these computed numbers

8.4   Implications and Conclusions

1.   The RCC laminate, used in both the WLE and nose cap TPS, is not a damage tolerant material system. RCC is characteristically a brittle system with significant variability in material properties. RCC properties are dependent on temperature, conditioning, and coating parameters used in both the fabrication and operational use. These variabilities need to be accounted for in the RCC damage threshold predictions. Limitations on the LS-DYNA$^{©}$ prediction of the onset of NDE detectable damage for RCC structures also need to be included as engineering uncertainties.

2.   The SSS C/E should be at least 1.4, which is consistent with the FOS-specified value in NASA STD-5001 which is 2.0 for composite structure with discontinuities and 1.4 for uniform composite material. As the impact capability is computed for uniform regions of the RCC, which are not dominated by discontinuity stresses, the value of 1.4 seems more appropriate.

8.5   Recommendations

1.   Perform a sensitivity study to mesh refinements. Also, the sensitivity to mesh refinements and material orientations in the elements near probable impact locations would provide insight on important variables in the behavior of the nose cap.

2.   Impact tests of the nose cap and test/analysis correlation of results are needed to validate the analysis predictions.

3.   The "best estimate" value of C should be computed using material properties that accounts for material variability inherent in RCC and the end-of-life aged RCC properties.

9.0   Impact Capability of Orbiter Tile

Tile debris flight rationale falls into the following five categories.

1.   No Transport Mechanism (Section 9.1)

2.   Damage Tolerance (Section 9.2)

3.   Analysis of Historical Flight Damage (Section 9.3)

4.   Probabilistic Flight Rationale (Section 9.4)

5.   Accepted Risk Based on Previous Flight History (Section 9.5)

6.   Other (Tile Over Critical Seals and Penetrations) (Section 9.6)

The strengths, weaknesses and knowledge gaps for each of these rationales are discussed in the sections below.

9.1   No Transport Mechanism

The discussion of no transport mechanism as flight rationale in general is detailed in Section 5.0.

9.2   Damage Tolerance

9.2.1   Assessment of the Engineering Data

This methodology describes the allowable tile damage depth for the Orbiter's lower surface on a "damage map". This map is constructed by dividing the Orbiter lower surface into 31 zones, and determining the maximum allowable penetration depth using a combination of several analytical models (see Figure 9.2-1) including:

- Rapid Response Damage Model

- Aeroheating Tools

- 3-D Thermal Math Model (TMM)

- Tile Stress and Bondline Integrity Tool

- Structural Stress Assessment Model

Figure 9.2-1. Flow of Data Defining Environment, Modeling Damage, Analyzing Capability and Culminating in the "Damage Tolerance Threshold Map"

There are Rapid Response Damage Models for both foam and ice impacts on tile that generate a damage geometry (depth, length, width, entry, wall and exit angles) based on DTA parameters (mass, velocity and angle of impact). The foam on tile model was developed by Boeing and is an empirical curve-fit based on over 500 impacts of foam projectiles on tile. The resulting curve is fit to envelope 95 percent of all test data. Tests cover a range of projectile masses (0.002 lbm to 0.04 lbm), projectile angles (5 degrees to 60 degrees), velocities (200-2900 fps), and impactor materials (BX-265, PDL, and NCFI). BX-250 was not utilized as a part of the test matrix, but has been assumed to be enveloped by BX-265. This assumption is based on the similarity of the two material stress-strain properties. Testing does include both High-temperature Reusable Surface Insulation (HRSI) (black) and Low-temperature Reusable Surface Insulation (LRSI) (white) tile, pristine and aged tile, and tile arrays both with and without gap fillers. Current proposed limits on tool usage do allow extrapolation beyond specifically tested combinations of parameters.

The ice/ablator Rapid Response Damage Model was developed by Southwest Research Institute (SwRI) and is based on equations derived from first principles of physics. The equations of

motion are integrated forward in time until the impactor speed drops below the crush velocity (i.e., it comes to rest), or the impactor is forced back to the tile surface. The tile resisting stress is modeled as a function of the Hugoniot stress and the tile crush strength. The Hugoniot stress is the stress as a function of particle velocity along the idealized one-dimensional planar impact. Approximately 350 impacts of ice and ablator on tile have been used for validation to ensure that the proper fundamental physics are being represented in the models. Tests cover a significant range of projectile masses (up to 0.25 lbm), projectile angles (5 degrees to 90 degrees), velocities (200 fps-1000 fps) and impactor density (ablator, dense ice, low density ice). The material properties are scaled, or "softened", to ensure that 95 percent of the test data is enveloped. The scaling of the material properties is consistent with the type of scatter seen in the material properties test program. In addition, because of the nature of this type of modeling, additional test data was generated on large strain stress-strain behavior for tile material. Current proposed limits on tool usage do allow significant extrapolations in impact velocity (up to 1500 fps) for dense ice and ablator. Additional efforts are underway to provide the basis for other extrapolations for ablator and low density ice on angle of impact. SwRI uses CTH hydrocode models with their Rapid Response Impact Model to support extrapolations as required.

In the case of both the foam and ice impact, the resulting damage is represented as a simplified, or shoebox, geometry (see Figure 9.2-2). Simplified, cavities average the irregular shapes of real cavities for ease of analysis and representation. This simplified geometry is necessary to maintain consistency with the wind tunnel test configurations used to derive the cavity heating augmentation factors.
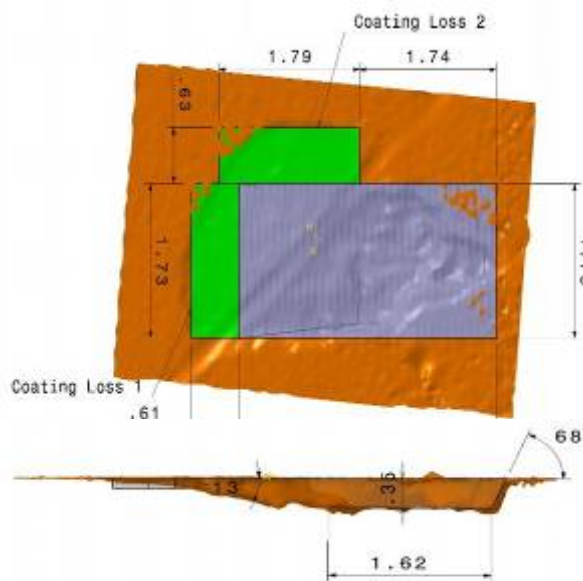
Figure 9.2-2. Simplified Impact Geometry

The change in the nominal Orbiter surface aerodynamic heating profile produced by damaged tile TPS is then defined through the application of a series of Aerothermal Tools (see Figure 9.2-3). This suite of Aerothermal Tools is used to determine the aeroheating augmentation factors and the appropriate Aerothermal environment needed to support the thermal analysis of damaged tile regions. Heating profiles in the damage region are modeled by assigning a baseline ("undisturbed") heating value near the damage and applying augmentation factors to the nominal heating value for the effected regions in and around the TPS damage site. The process defines the damage site heating levels as a function of time along the entry trajectory. As a final Aerothermal step, a catalytic heating augmentation factor to account for changes in damaged surface properties is also defined.

The Aerothermal analysis is initiated with the damage location and geometry information which is input to the Boundary Layer Transition (BLT) Prediction Tool. From this information, the BLT Prediction Tool is used by aeroheating analysts to provide the Cavity Heating Tool (CHT) with the appropriate transition Mach number, which is needed to determine the boundary layer state. Then, the appropriate cavity heating methodology can be used. To establish the expected time of BLT during entry, the BLT Prediction Tool uses the observed damage and/or repair locations and geometries to determine the most appropriate roughness value for each damage site. The selected transition Mach number (corresponding to the roughness value selected) is then provided to the CHT for augmentation factor methodology. In addition, the transition time must be provided to the 3-D TMM for selection of the appropriate Aerothermal baseline environment, on which to apply the augmentation factors.

Once the transition Mach number input is established, the CHT will draw on information provided by the Smooth Outer Mold Line (OML) Aerothermal CFD Solution Database (SOASD). The SOASD will be used to generate the boundary layer parameters (i.e., boundary layer thickness) needed by the CHT to accurately predict the cavity heating augmentation factors. Given the damage location and geometry, the BLT Mach number, the trajectory free stream flight conditions and the boundary layer parameters, the CHT uses a wind tunnel test-derived database to generate heating augmentation factors at every TMM node location requested at each time point in the trajectory. Damaged tile and/or repair materials will have different catalytic heating properties due to changes in surface properties. The Catalytic Heating Factor Prediction Tool (CHFT) provides additional augmentation heating factors as necessary to the TMM. Thermal analysis is then performed using the 3-D TMM.

Figure 9.2-3.   Simple Aeroheating Tool Flow Diagram

The 3-D TMM Tool was developed to take the aerothermal input and to predict the temperature response of Orbiter lower surface acreage TPS tile materials and structure. The 3-D TMM Tool temperature predictions are limited to lower Orbiter body surface acreage tile. The undamaged TPS tile accuracy is 5°F on the maximum structure temperatures as a result of uncertainties that can be attributed to the material thermal properties. Model accuracy will be affected by damage cavity geometry modeling (simplified cavity geometry). The tool is verified by arcjet test data as well as flight temperature measurements.

The 3-D TMM Tool predicts time history of tile and structure temperatures and structural thermal gradients for areas with damaged tile. Exceedances of material temperature limits can be identified and tile bond pass/fail criteria for entry can be evaluated in a timely manner.

A set of Special Configuration Math Model Tools (SCMMT) was developed to predict the temperature response of Orbiter tile and structure configurations. The damage sensitive areas are: perimeter seal locations around Orbiter doors, forward windows, forward vertical tail leading edge, forward reaction control canopy, and elevon lower cove. These Orbiter areas are known to not be damage tolerant for foam and ice impacts; therefore, thermal analyses pre-launch is not required and SCMMT are not applicable to development of flight rationale. The SCMMT are used only for on-orbit damage assessment.

The Tile Stress and Bondline Integrity Tool is used in conjunction with the 3-D TMM to determine bondline failure at the tile to primary structure interface. They are performed using classical stress analysis methodologies. Stress analysis equations have been programmed to calculate entry FOSs for the lower surface 6" x 6" LI-900 HRSI (black) acreage tiles with damage oriented at 45 degrees. Failure modes include tension at the Room Temperature

Vulcanizing (RTV) bond, compression and shear in the LI-900, and shear in the Strain Isolation Pad (SIP). RTV bonds subjected to temperatures greater than 650°F are assumed to lose all tensile strength; however, the strength recovers after an initial reduction at temperatures between 470°F and 650°F.

Temperatures at thermal nodes from critical Mach numbers are superimposed on a tile damage map. Any areas of temperature greater than 650°F are simplified to a rectangular geometry and deleted from the bonded 5" x 5" footprint of the tile. Then, input aerodynamic pressures, 21.3 g (7.1 g's at 3-sigma) vibro-acoustic dynamic loads, tile damage dimensions, loss of bond dimensions, material properties, and structural out-of-plane deflections are used to calculate corresponding FOS.

The Structural Stress Assessment Models then use the output from the 3-D TMM to determine the reduction in structural margin and increase of out-of-plane deflection due to increases in thermal gradient at the local damage site. This is conducted with classical stress analysis methodologies utilizing calculating thermal expansion. The local temperature increase resulting from Orbiter damage is converted into thermal loads, and is then used to analyze Orbiter stresses due to these loads. The tool is capable of combining the existing mechanical loads with the increased thermal loads to define structural margins of safety and out-of-plane deflections. There are several different models to represent the various types of Orbiter structure. The models are validated to FEM and hand calculations.

The models are interconnected with a script which takes required input and transfers model output as required. The final product is Orbiter lower surface "damage map", defining the maximum damage depth that can be tolerated in each of the 31 zones. The resulting damage thresholds are based on conservative, bounding, and certification rigor assumptions. Originally planned as the core rationale for acreage tile, this methodology has very limited use in the deterministic computation of C/E because the current 1st generation damage map is so conservative in the calculation of C. Many damages incurred during flight history, which survived re-entry without identified vehicle degradation, exceeded the vehicle capability as identified in the certification rigor, or 1st generation, damage tolerance map. However, the damage analysis tools and the resulting certification rigor damage map are still imbedded in the flight rationale in the Analysis of Historical Flight Damage (Section 9.3) and Probabilistic Assessment (Section 10.0) methodologies detailed below. Therefore, some discussion of their conservatism is appropriate.

Sources of conservatism in this methodology include, but are not limited to:

1.   The use of certification trajectory and re-entry parameters (Heavy Weight International Space Station (HWISS) return trajectory, maximum Orbiter weight, maximum G's and sink rate, End of Mission (EOM) sun, etc.). These types of conservatisms can be

significantly reduced for any given mission by using mission-specific parameters such as trajectories and weights. Operational constraints can also be imposed on G's and sink rate to reduce heating in contingency conditions.

2. Non-case-consistent margins (minimum tile thickness, maximum heating and minimum structural margin for an entire zone @ one location). This is a practicality associated with having to analyze the entire lower vehicle surface. Areas of the vehicle are grouped by similar tile thickness and similar structural configuration. There are options available to reduce this conservatism, such as averaging minimum capabilities over a percentage of the zone, so as not to be inordinately penalized by a local minima or maxima across the entire zone.

3. Damage cavity definition with a goal of exceedance of only 1/100 cavities (95 percent depth, 95 percent length, 95 percent width => 99 percent+ overall cavity volume; conservative wall angle assumptions). This conservatism is removed when these tools are used in an on-orbit scenario, as tile damage geometry becomes a measurable parameter from inspection. For a less conservative pre-flight assessment, percentages of test data enveloped could be reduced. Recommendations to reduce cavity definition parameters may be supported by the evaluation of actual flight data damage geometry, such as the "Platinum" dataset.

4. Treatment of orientation and impact angle. A foam projectile is assumed to always impact in the worst possible orientation (smallest edge first) to induce the greatest amount of damage. An ice projectile is assumed to always impact in the worst orientation excluding a flat piece of ice impacting flat. This latter ice scenario was deemed unrealistic, as ice does not form in large flat sheets when attached to the Orbiter. Also if the projectile can hit with any orientation, then the probability of it hitting within 12 degrees of flat is a low probability of occurrence (roughly 2-sigma). All projectiles are assumed to impact with a 90 degree beta angle (alpha is defined by the DTA).

5. Tile bondline failure model simplifications and limited allowables drive many locations to premature bondline overtemperature and failure. These models conservatively locate tile damage in the center of the tile, so as to localize heating on one tile footprint.

6. Aerothermal environments include several conservative assumptions. The cavity heating augmentation factors are based on rectangular cavities (90 degrees entrance / exit angles), which yield higher "bump factors"; catalytic heating factors bound rather than fit test data; BLT time is set to a bounding equivalent roughness that tends to initiate "early" transition.

7. The 3-D TMM Tool does not simulate the individual 6" x 6" Orbiter tiles and has no inter-tile gap heating. This is accounted for with a conservative heating augmentation factor of 1.2.

9.2.2   Limitations and Gaps

1.   The limitations and gaps in the development of the damage map, and its use in the flight rationale, are driven by the limitations and gaps of the individual tools. These are discussed in detail in Appendix C.

9.2.3   Implications and Conclusions

1.   Modeling methodology has been subjected to sufficient peer-review to understand the basic workings of all models, assumptions, limitations and key parameters passed between the models. Details on the functions, limitations and assumptions associated with each model are discussed in detail in Appendix C.

2.   The damage tolerance methodology used in the production of the 1st generation damage map incorporates all the standard, certification rigor methodology and factors. Therefore, the reliability is believed to be quite high.

9.2.4   Recommendations

1.   Tool certification for use both in-flight and as a part of the flight rationale should include a thorough end-to-end validation. This validation should emphasize interfaces between tools, demonstrating understanding of modeling accuracy and uncertainty, as well as end-to-end correlation to both test and historical damage (in-work).

2.   Tile damage analysis models should be brought in-house to NASA to enable additional evaluation and independent tile damage risk trades through structured, parametric model sensitivity studies (in-work).

3.   The generation of a less conservative, predictive damage map should be produced for quantification of pre-flight risk of tile acreage catastrophic damage and compared to flight history for the purposes of model validation (in-work).

9.3 Analysis of Historical Flight Damage

9.3.1 Assessment of the Engineering Data

This methodology attempts to understand flight history, characterize historical damage, demonstrate the capability of models to recreate flight like damage, and incorporate improvements in the debris environment.

Historical ascent damage is categorized into three families:

1. Popcorning Damage.
2. Larger, Distributed Damage.
3. ET umbilical Debris Environment.

The methodology culminates in the analysis of seven representative scenarios. These scenarios are a combination of popcorning and divoting debris, and the resulting damage to the Orbiter TPS vehicle under a typical transport environment.

Popcorning Damage

The rationale provides sufficient data to show that the typical flight damage occurring along the chine/glove area is most likely traced to small, popcorning foam, primarily off the ET intertank acreage. A reasonable debris liberation model and reasonable DTA parameters utilized with both the 50 percent and 95 percent damage model produces a similar distribution of damages as seen in the flight history. The debris shedding frequency in the debris liberation model was developed on five flights worth of data, and the debris geometry was based on STS-95. The DTA looked at both nominal and no transport dispersions to understand sensitivity to dispersion and utilized typical dispersions (nominal drag, nominal lift and nominal pop off velocity) as a best representation of a "typical" flight. These "typical" transport parameters are then utilized with a foam debris "best estimate" and a 50 percent damage model to extrapolate typical debris damage that could be encountered on STS-114. This damage is then compared to the certification rigor damage map to ensure that anticipated popcorning damage is within vehicle capability.

9.3.2 Limitations and Gaps (Popcorning Damage)

1. The methodology for determining the popcorning debris environment (mass, frequency and Mach number) for STS-114 extrapolations is unclear.

2. This methodology describes "typical" popcorning damage expected on a given flight. There is no rationale to define risk of a-typical damage, or to establish if historical damage covers a significant percentage of what could be encountered. Some sensitivity can be established through the use of a 95 percent damage map. However, it has been pointed out that this is only one-third of the debris, transport, capability computation, and defining the tails of the damage distribution, and is probably more accurately established at the system level.

3. This assessment is based on the first revision of the "certification rigor" or "1st generation" damage map. The tools which generate this map have been significantly updated since the NESC assessment was completed.

Larger, Distributed Damage

The cases of larger, distributed and less frequent impact damage are assumed to be from larger foam and ice debris.

A forward extrapolation for STS-114 large divots was conducted, similar to the work conducted on popcorning. However, five additional scenarios are developed which focus on larger debris sources from areas such as flanges, bipods, and ice/frost ramps. These scenarios are intended to be representative or typical, not necessarily bounding. Large debris source sizes are limited based on tank improvements and dissection data. Utilizing dissection data and expectations for improved performance based on redesign, all areas of potential larger foam liberation are shown good except the LO_2 ice/frost ramps. Even with limited debris size (0.007 lbm is used based on historical loss, versus 0.017 lbm maximum possible), the ice/frost ramps produce unacceptable damage in the forward part of the vehicle adjacent to the nose cap. While these comparisons are relative to the certification maps, some damage is projected to be equal to, or greater than, the thickness of the tile. Therefore, some relaxation on conservatisms will be required to show positive margins on even an improved capability map.

When tile margin is evaluated for scenarios other than LO_2 ice/frost ramps, there are still some areas with very low or negative capability. This may be inappropriately driven by Ogive foam popcorning, but that is uncertain based on the level of information available for review at this time. This marginal capability indicates that perhaps other foam/TPS source/target pairs should be treated in a probabilistic fashion to more accurately quantify the risk of catastrophic failure.

9.3.3 Limitations and Gaps (Larger, Distributed Damage)

1. Arguments regarding ice are technically weak, and mostly anchored in simplistic attempts to correlate launches with high ice build-up to damage. From a lack of correlation, ice is assumed to not be a major contributor to damage. This conclusion

lacks substantive evidence and rigorous correlation efforts. It ignores the possibility that moderate ice launches may produce less dense ice which liberates more easily during ascent and actually causes greater damage.

2. Some flight history data was presented to support the argument that the reduction in large divots from critical tank areas will "cut the tail off" the distribution of damage depths and widths. However, the connection between the provided data and the desired conclusion is unclear.

ET Umbilical Debris Environment

Aft damage is characterized as being very repeatable and insensitive to events which have traditionally generated significantly more vehicle damage (i.e., STS-87). The damage is attributed to being dominated by recirculation effects in this area, and the debris source is the ET umbilical baggie and local ice.

9.3.4   Limitations and Gaps (ET Umbilical Debris Environment)

1. While intuitively reasonable, the argument of the damage being due to the recirculation environment is circumstantial. The chaotic flow field would make any type of historical reconstruction impossible.

2. If the hypothesis that the recirculation environment and the ET umbilical baggie and ice are the sources of damage is accepted as reasonable, then no evidence is offered about potential for non-typical debris damage; nor is the statistical representation of the population of damage seen thus far around the ET doors, or Orbiter capability to withstand typical damage in this area.

9.3.5   Implications and Conclusions

1. A flight rationale has been constructed which gives confidence that for typical debris there is lower, but still unquantified probability, of a catastrophic hazard for foam on tile.

2. The argument with regard to the probability of non-typical debris damage is lacking and does not sufficiently characterize the risk.

3. With this methodology, the LO_2 ice/frost ramps continue to produce unacceptable damage (C/E significantly below 1). Therefore, the SSP will pursue a risk assessment analysis for this source/target pair.

9.3.6   Recommendations

1.   The methodology for determining the popcorning debris environment (mass, frequency and Mach number) for STS-114 extrapolations should be clearly documented.

2.   The "certification rigor" or "1st generation" damage map should be updated to incorporate the baselined version of all the analysis tools (in work). These assessments should also be conducted again to ensure flight rationale remains valid.

3.   The flight rationale for tile damage needs to include a quantitative analysis of the risk from ET umbilical ice and baggie debris.

4.   All foam debris sources (including popcorning) should be incorporated into a probabilistic model for assessing the risk to tile from foam debris damage. This would describe the probability of having a non-typical debris damage event which is where the risk exists, not in typical debris damage.

5.   The flight rationale for seals and penetration needs to be updated, including the risk from popcorning debris.

9.4   Probabilistic Flight Rationale

9.4.1   Assessment of Engineering Data

A Monte Carlo-based probabilistic model has been developed to establish the likelihood of producing LO_2 ice/frost ramp debris and resulting damage which exceeds the certification limits for tile. The details of this methodology are provided in Section 10.0. In this assessment, the damage generated by the debris is characterized as a distribution that is constructed from the 50 percent damage model (mean fit of impact damage test data) and the 95 percent damage model (envelopes 95 percent of impact damage test data) with a Normal distribution. From a capability perspective, this methodology utilizes a certification rigor damage map to assess the capability of the vehicle.

9.4.2   Limitations and Gaps

1.   The relationship between the 50 percent damage model and the 95 percent damage model is assumed to be a Normal distribution.

2.   From a capability perspective, this model utilizes the certification rigor damage map. Therefore, the same observations made in the Damage Tolerance section (Section 9.2) regarding the generation of this capability map apply.

9.4.3 Implications and Conclusions

1. From a capability perspective, this model utilizes the certification rigor damage map. Therefore, the same implications and conclusions made in the Damage Tolerance section (Section 9.2) regarding the generation of this capability map apply.

9.4.4 Recommendations

1. Utilization of a Normal distribution to relate the 50 percent and 95 percent damage model should be verified from test data (Verified).

2. A Monte Carlo-based probabilistic analysis that includes the distribution of foam defects as well as the Monte Carlo debris transport analysis should be conducted to determine the likelihood of an impact which exceeds the tile damage tolerance capability (In work).

3. A more realistic approach to the Monte Carlo-based probabilistic analyses would incorporate a distribution for capability as well as environment. In the event that this type of distribution can not be readily established, a less conservative approach to the capability map could be generated (3rd generation) that would provide a more realistic assessment of risk to the vehicle (In work).

9.5 Accepted Risk Based on Previous Flight History

This is the rationale presented for a family of debris sources for which the SSP has not determined damage tolerance. Mostly composed of booster separation motor (BSM) insulator and propellant debris, and SRB separation debris, these sources are on the order of 10^{-7} and 10^{-8} lbm. They are accepted strictly on their low mass, without analysis or test.

9.5.1 Limitations and Gaps

This rationale is based strictly on flight history, with no analysis or test.

9.5.2 Implications and Conclusions

1. There is uncertainty associated with the lack of analysis and test for these small particles. While there an absence of engineering data to clear these items, the NESC concurs with the SSP's prioritization and risk characterization.

9.6   Other (Tile Over Critical Seals and Penetrations)

9.6.1   Assessment of the Engineering Data

The OPO has provided an assessment of critical seals which are at risk of debris damage. This assessment examined special tile configurations associated with the following:

1.   Main Landing Gear Doors (MLGD)

2.   Nose Landing Gear Doors (NLGD)

3.   ET Door

4.   Elevon Cove (EC)

5.   WLE Carrier Panels

The impact and damage tolerance of seal areas is assumed to be identical to acreage areas except in overhang and lip areas (areas where tile extend out from structure unsupported). This is a conservative assumption as these perimeter tiles are tougher, denser FRCI-12 and LI-2200 materials. Threshold velocity for damage to FRCI-12 has been demonstrated by test to be approximately 20 percent higher than LI-900. Impact limits within 1-inch from either side of the thermal barriers of the MLGD, NLGD and ET doors, and within 1-inch from the overhang on the forward elevon cove, have a maximum capability defined by the acreage tile impact tolerance (no damage) limits. There is no ice threshold for impact tolerance. Therefore, any ice impact within 1-inch of the thermal barriers for the MLGD, NLGD and ET doors, and within 1-inch from the overhang edge on the forward elevon cove tiles, is unacceptable. It is also assumed to result in critical damage. Ice impacts are also considered critical on the WLE carrier panels. These restrictions are supported by test results of both acreage and special configuration tile test articles.

9.6.2   Limitations and Gaps

1.   These conclusions are based on a very small number of tests.

2.   Arguments regarding the low likelihood of ET door damage on ascent are inconsistent with recirculation environment present in this area.

3.   The assessment lacks any determination of damage probability occurring in critical locations within 1-inch of seals and overhangs.

9.6.3 Implications and Conclusions

The accepted risk for a debris impact to a critical seal or penetration is incomplete.

9.6.4 Recommendations

1. Critical seal and penetration zones should be incorporated into the probabilistic assessment as separate zones. This would allow the extraction of impact probability which exceeds capability for these zones. This method of implementation would allow the probability of impacting a seal area to be rolled up in the overall probability of critical impact.

2. The flight rationale for seals and penetration needs to be updated, including the risk from popcorning debris.

10.0 Probabilistic Analyses of Foam and Ice Debris Impacts on RCC and Tile

10.1 Foam Debris Impact on RCC and Tile

10.1.1 Assessment of Engineering Data

The SSP contracted with The Aerospace Corporation to conduct an end-to-end Monte Carlo-based probabilistic analysis of the most critical ET foam debris cases. Only those debris cases with values of C/E "best estimate" below 1.5 will be analyzed (refer to Table 8.3-1). These are:

- LO_2 and intertank ice/frost ramps
- LO_2 intertank flange
- LH_2 intertank flange
- LO_2 PAL Ramp
- Bipod Closeout

Any potential foam debris from the LH_2 PAL Ramp and the LH_2 ice/frost ramps were enveloped by the above Monte Carlo probabilistic-based analysis of the LO_2 PAL ramp and LO_2 ice/frost ramps, respectively. Foam debris from the acreage areas were analyzed using the WOW analysis. Figure 10.1-1 depicts the foam locations and the respective analysis methods.

LH2 Ice/Frost Ramps
(SLA 561/ PDL; T531)

Bipod Closeout
(BX265 / PDL; T540)

LH2 PAL Ramp
(BX250/265/ PDL; T529)

LO2 PAL Ramp
(BX250/265/ PDL; T529)

LH2 Tank Acreage
(NCFI 24-124;T523)

LO2 Tank to Intertank Flange
(BX2 250; T542)

LO2 Tank Acreage
(NCFI 24-124;T521)

LH2 Tank to Intertank Flange
(BX 265; T525)

Intertank Acreage
(NCFI 24-124; T522)

(2) LO2 / Intertank Ice/Frost Ramps
(SLA 561/ PDL; T531)

Monte Carlo
Worst on Worst
Enveloping

Figure 10.1-1. ET Tank Foam Area and Foam Debris Analysis Methods

The Aerospace Monte Carlo methodology consists of five steps/models as outlined in Figure 10.1-2. This methodology has been individually peered-reviewed. A brief summary of each model follows.

Foam Void Predictive Model (Void Distributions)	→	Foam Debris Generation (Physics divoting model)	→	Foam Transport Model	→	Orbiter Impact Algorithms	→	Orbiter Damage Analysis
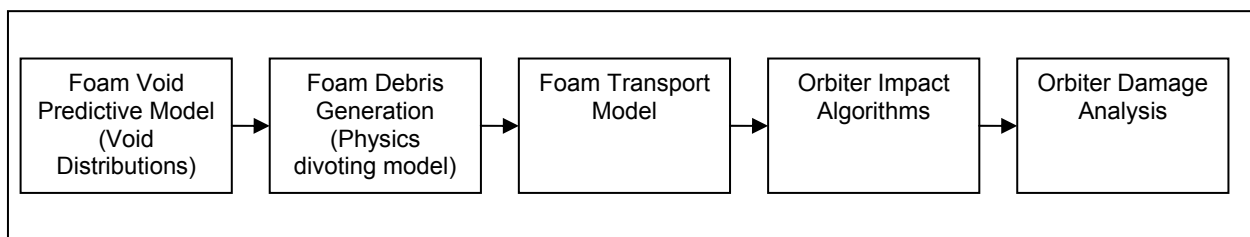
Figure 10.1-2. Foam Debris Monte Carlo Analysis Methodology

The *Foam Void Predictive Model* randomly distributes voids within the foam based on foam void size and void number distributions. These distributions are based on the foam dissection database.

The *Foam Debris Generation Model* is a physics-based model used to determine if a divot will form and, if so, its size, shape, mass, time of release and pop-off velocity. As part of the Monte Carlo probabilistic-based analysis, this model uses distributions of the foam material properties (strength, density, etc.). Two separate heating trajectories are used: nominal and hot. This model has been verified by ET Thermal Vacuum divot testing.

The *Foam Transport Model* transports divots as a function of divot location, shape, mass, and pop-off velocity; vehicle ascent velocity; and atmospheric density. This model has been verified by comparison with high fidelity 6-DOF CFD solutions.

The *Orbiter Impact Algorithm Model* utilizes a high fidelity model of the Orbiter to determine if a divot will impact the Orbiter based on the divot trajectory.

The *Orbiter Damage Analysis Model* determines the Orbiter damage based on debris KE and Orbiter RCC material property distributions.

10.1.2 Limitations and Gaps

The Monte Carlo methodology, input distributions, and physics models have all been independently peer-reviewed and verified by test data and/or independent analyses. However, the overall end-to-end Monte Carlo probabilistic-based analysis numerical results have not been independently reviewed. The limitations previously identified in Sections 3.2 and 3.5 also apply to the Monte Carlo probabilistic-based analysis. This limitation is not viewed as a constraint to RTF.

10.1.3 Implications and Conclusions

In general, the Monte Carlo analysis is conservative as the divot generation assumptions produce an excessive number of divots, the transport assumptions bias impact velocities are high, and the damage map allowables are survivable. The Monte Carlo results for each set of sources and targets are listed in Table 10.1-1. Due to the mathematical method used to aggregate the risks, the aggregate results are pessimistic.

Table 10.1-1. Foam Debris Risks For Nominal Trajectory
(Source: Presented by the SSP at the DVR on June 24, 2005)

Source ＼ Target	Ice/Frost Ramps	LO₂ PAL	LO₂ Flange	LH₂ Flange	LH₂ Flange Cryo.	Bi-Pod	Aggregated Reliability	Aggregated Probability
RCC	>0.9999+	>0.9999+	>0.9999+	>0.9999+	>0.9999+	>0.9999+	>0.9999+	<1 in 10,000
Standard Tile	0.9976	0.9999	0.9997	0.9999	0.9999	1.0000	0.9971	~1 in 350
Special Tiles and Seals	0.9962	0.9999	0.9963	0.9999	0.9999	1.0000	0.9925	~1 in 130
Aggregate	0.9938	0.9999	0.9960	0.9999	0.9999	1.0000	0.9896	~1 in 100

10.1.4 Comparison of Monte Carlo results with Flight History

The Aerospace Corporation Monte Carlo analysis identified the most likely contributor to foam-induced damage as the ice/frost ramps. However, the model predicted divoting at a much higher rate than had been previously documented from the ET separation photographs (only a single 3-4 inch divot was identified in 161 post-ET-82 ramps that were imaged). Therefore, a review of the ET separation photos for ISS flights was performed by the NESC. Figure 10.1-3 shows the foam loss from ramps 5-9 for STS-100. The figure contains circles scaled to 1, 2 and 3 inch diameter for size comparison. The photograph shows evidence of foam loss in the size range predicted by the Aerospace analysis. Ramps 6 and 7 each show multiple instances of foam loss.

In addition to the single large ice/frost ramp divot (out of 161 ramps imaged) previously documented, the separation photos of ISS missions show fairly frequent small (on the order of 1 to 3 inch diameter) losses of foam from the middle LO₂ ice/frost ramps. The rate of loss at these locations is in line with that predicted by the Aerospace Corporation in their Monte Carlo analysis.   However, because the photographs show no foam loss from ramps lower on the LO₂ tank and on the intertank, the overall probability of not exceeding the allowable impact loads on tile is lower than that predicted by the Monte Carlo analysis.   In a first order sense, the Aerospace results for tile impacts from ice/frost ramp divots are at most an order of magnitude conservative.

Figure 10.1-3. STS-100 Ice/Frost Ramps 5-9

10.2 Analysis of Ice Debris Impact on RCC and Tile

10.2.1 Assessment of Engineering Data

The SSP contracted with Boeing to conduct an end-to-end Monte Carlo-based probabilistic analysis of expected ice debris from the feedline bellows, feedline brackets, and the umbilical. The locations of the feedline bellows, feedline brackets and umbilical, along with the flight rational methodology approach, are shown in Figure 10.2-1. Figures 10.2-2 and 10.2-3 show the specific location of the feedline bellows and brackets, respectively. Ice from the forward bellows, which has the greatest possibility of causing damage due to its forward location, has been mitigated by installation of a heater to prevent ice formation. Residual ice from the forward bellows is controlled by LCC.

XT 1129: Probabilistic
XT 1377: Probabilistic
XT 1623: Enveloped (risk ≤ 1377)
XT 1871: Enveloped (risk ≤ 1377)
XT 1923: Enveloped (risk ≤ 1377)

Bracket Ice

Bellows ice

XT 1109 (Fwd): LCC for residual ice
XT 1979 (Mid): Probabilistic
XT 2026 (Aft): Enveloped (risk ≤ Mid)

Umbilical Ice
Design, Flight History
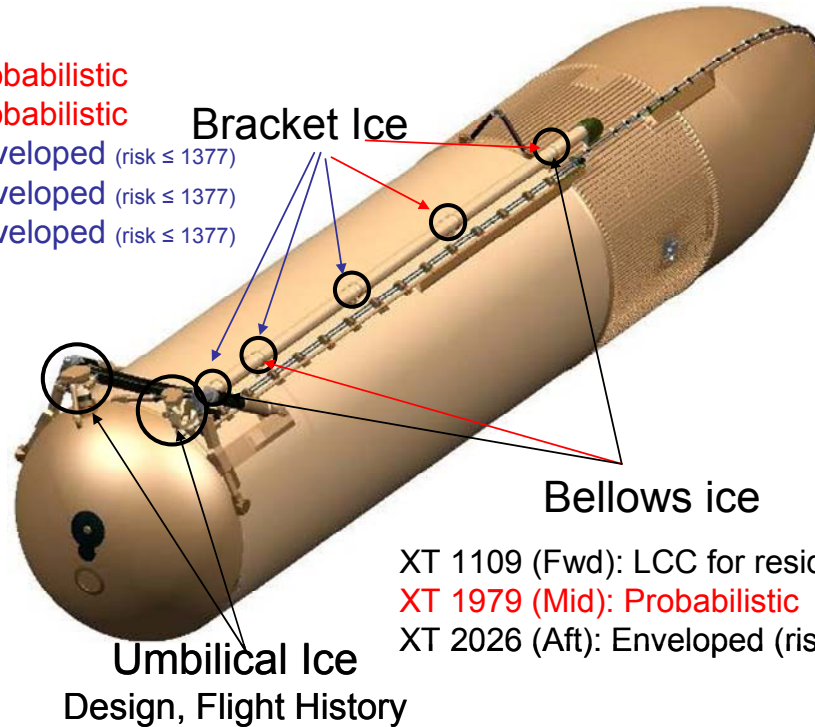
Figure 10.2-1. Ice Source Locations and Flight Rationale Methodology

Fwd Bellows XT1106   Mid Bellows XT1979   Aft Bellows XT2026
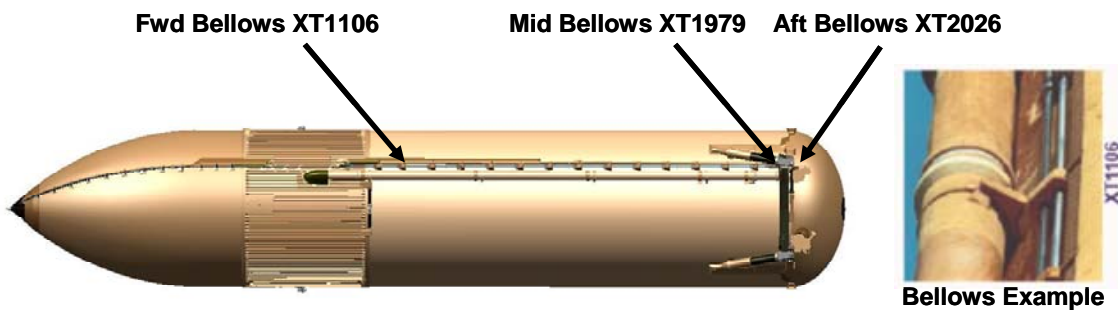
Bellows Example

Figure 10.2-2. Feedline Bellows Locations and Bellows Ice Example

XT1129   XT1377   XT1623   XT1871   XT1923

Bracket Example

Figure 10.2-3 Feedline Bracket Locations and Bracket Ice Example

To reduce the number of Monte Carlo simulations required to analyze bracket ice on tile, the SSP opted to apply a deterministic evaluation as a filter. Only ice on tile, which failed a 50 percent tile damage depth, was further analyzed using Monte Carlo techniques. No rigorous engineering data or test data supports the use of 50 percent tile damage depth as an appropriate tile capability.

The Boeing Ice Monte Carlo methodology consists of four steps/models as outlined in Figure 10.2-4. This methodology has been individually peered-reviewed. A brief summary of the individual models follows.

Ice Growth & Liberation Mass Distribution Rate of Release	→	Ice Transport Model	→	Orbiter Impact Algorithms	→	Orbiter Damage Analysis
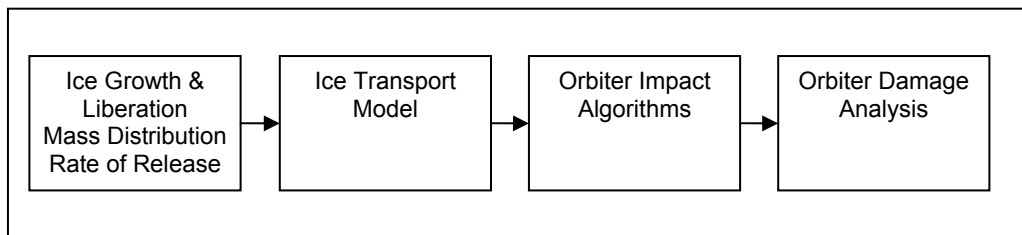
Figure 10.2-4. Ice Debris Monte Carlo Analysis Methodology

The *Ice Growth and Liberation* testing has been performed on both a feedline bellows mock-up and a feedline bracket mock-up. These tests do provide an input for the maximum amount of debris released but, due to inherent limitations, cannot provide reliable mass distributions or rate of release data. The tests can be used comparatively to provide relative information. The mass distributions used in the Monte Carlo were bounding cases, and several rates of release distributions were used in a parametric study to provide sensitivities.

The *Ice Transport Model* has been verified by comparison with NASA high fidelity 6-DOF CFD solutions. The transport model did not include rebounding ice particles off other surfaces (rebounding turned off).

The *Orbiter Impact Algorithms* utilize a high fidelity model of the Orbiter and algorithms in the BUMPER code. The BUMPER code has been independently verified.

The *Orbiter Damage Analysis* determines Orbiter damage based on the *foam* impact damage map. For a given depth of damage, this provides a much greater width of damage than what is to be expected from flight history and experimental test data. Use of the foam impact damage map is conservative.

10.2.2 Limitations and Gaps

The physics of ice growth and resulting material properties, ice liberation, fracture, debris transport, and impact kinetic energy are currently not well understood. Furthermore, definitive test data to anchor the probabilistic analysis is not available. Therefore, the degree of uncertainty in the quantitative risk levels estimated by the probabilistic analysis will be difficult to quantify. Confidence in the results can be increased by using appropriate bounding estimates for the distribution and ice debris release times.

No rigorous engineering data or test data supports the use of 50 percent tile damage depth as an appropriate tile capability filter.

Ice on special tiles and seals were not analyzed. Ice from the umbilicals relied on flight history for a flight rationale basis.

10.2.3 Implications and Conclusions

Due to the inherent lack of knowledge of ice growth, fracture, and liberation, the Boeing Monte Carlo used bounding and conservative assumptions resulting in very conservative results in a parametric study. Assuming an exponential mass distribution and lift-off to uniform rate of release distribution yields, the following probabilities are listed Table 10.2-1.

Table 10.2-1. Summary of Ice Damage Monte Carlo Analysis
(Source: Presented by the SSP at the DVR on June 24, 2005)

Source Target	Bracket XT 1129	Bracket XT 1377	Mid Bellows XT 1979	Aft Bellows XT 2026
RCC	<1 in 100,000	<1 in 1,000,000	No transport	No transport
Standard Tile	1 in 1,000	1 in181	1 in 100	1 in 1,000
Special Tiles and Seals	No analysis	No analysis	No analysis	No analysis

10.3   Summary of Foam and Ice Debris Monte Carlo Analyses

The NESC participated in the peer-reviews of the Aerospace and Boeing analyses. These reviews included the methodologies being implemented in each analysis code and the input data used in the analyses. The end-to-end predictive capability of the Aerospace and Boeing probabilistic analysis codes, independently-developed, should be verified and validated. Ongoing peer-reviews are accomplishing the validation requirement, but more work is required for verification. The NESC suggests that verification could be achieved by comparing the analysis results from the two codes for a minimum of one debris case.

11.0   Hazard Analysis and Risk Assessment

The 3x4 risk matrix shown in Figure 11.0-1 will be used to assign a risk level to each debris case. The Likelihood of Occurrence is assigned by assessing the controls that are in place to mitigate the risk. Severity is an assessment of the most severe hazard effects. Expected debris is classified as Catastrophic. Therefore, the key to assigning risk is the level of controls available to mitigate the risk. The controls available to mitigate foam debris are essentially those that are inherent in the ET design. A variety of controls are being evaluated to mitigate ice debris. The risk is a joint probability of the Likelihood and Severity.

The levels of Likelihood of Occurrence are defined as follows:

Probable: Expected to happen in the life of the program. Controls have significant limitations or uncertainties.

Infrequent: Could happen in the life of the program. Controls have significant limitations or uncertainties.

Remote: Could happen in the life of the program, but not expected. Controls have minor limitations or uncertainties.

Improbable: Extremely remote possibility that it will happen in the life of the program. Strong controls in place.

The levels of Severity are defined as follows:

Marginal: Hazard could result in a mishap of minor nature inflicting first-aid injury to personnel and/or damage to flight or ground equipment which can be tolerated without abort or repaired without significant program delay.

Critical: Hazard could result in serious injury to personnel and/or damage to flight or ground equipment which would cause mission abort or a significant program delay.

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.

Tables 11.0-1 and 11.0-2 are summaries of the engineering data supporting the flight rationale for the RCC and the tile, respectively. Figure 11.0-2 shows the Orbiter RCC locations referred to in Table 11.0-1 and the Orbiter tile locations referred to in Table 11.0-2. The interpretation of these data will result in the assignment of each debris case to a risk level.

11.1 Risk Assessment for Foam Debris

The Aerospace Corporation has conducted Monte Carlo-based probabilistic analyses of the most severe foam debris sources (LO_2 ice/frost ramp, LO_2 intertank flange, LH_2 intertank flange, LO_2 PAL Ramp, and Bipod Closeout). The Aerospace Monte Carlo-based probabilistic model used methodologies that have been peer-reviewed and validated by comparison to other analysis results and ground test data. In addition, the input distributions used in the analyses have also been peer-reviewed. However, the overall end-to-end Monte Carlo analysis has not been verified. One potential verification method would be a comparison of flight history with a Monte Carlo analysis for the LH_2 intertank flange with the previous foam design. **While the end-to-end predictive capability (numerical results) has not been verified, the results of sensitivity studies and comparison to flight data suggest that the results are conservative.** Based on the results of these analyses and an assessment of the controls for each foam source, the NESC concurs with the SSP that the likelihood of debris from each foam source exceeding the critical impact capability for RCC is Improbable. The NESC concurs with the SSP that the likelihood of foam debris exceeding the critical impact capability of Tile is either Remote or Infrequent, depending on the foam source. The highest computed risk is for tile seals and penetrations, which is not overly conservative relative to flight history, and furthermore, has not been fully characterized. **The NESC has concluded that the probabilistic results, supplemented by additional engineering data, physics considerations, and the level of control over debris liberation, provide a reasonable engineering foundation for a flight rationale for STS-114 based on accepted risk due to expected foam debris.**

11.2 Engineering Considerations that Support the Flight Rationale for Foam Debris

1. The bipod ramp was eliminated and several manual spray closeouts were redesigned (the bipod closeout, the first ten feet of the LH_2 tank PAL ramp, and the LH_2 tank-to-intertank flange closeout).

2. ET automated spray foam (LO_2, LH_2, and intertank acreage) debris sources have been eliminated from concern for all Orbiter RCC and tile locations by the certification rigor (WOW) deterministic analysis. Also, some Orbiter WLE RCC panels and tile locations can be eliminated from concern using the WOW or best estimate deterministic analyses for all foam debris sources.

3. Divot/no-divot cohesive failure methodology is conservative. (Test panels contained artificially machined voids with cut edge rather than natural voids. The idealized void geometry in the divoting tests are worst-case simulations of the actual orientations of naturally occurring voids in foam. Also, the failure curve is bounding to all divot data which is conservative for densities greater than the minimum).

4.   Component tests with flight hardware geometry (geometry of intertank flange regions) and simulated flight loads environment did not divot, for both as-sprayed foam panels and panels with artificially-induced voids.

5.   Component qualification tests for redesigned bipod closeout region did not liberate large divots (test panels were as-sprayed foam, no artificially-induced voids). Voids in qualification test panels are smaller than some of the voids in similar locations found in the V&V section data.

6.   Tile capability map used in the C/E deterministic calculations and in the probabilistic analyses are conservative.

7.   Flight history demonstrates damage tolerant attributes of tile.

8.   Physics of cohesive failure of foam, debris transport analysis, and Orbiter impact capability are well characterized and experimentally verified.

9.   Distributions and assumptions used in the end-to-end probabilistic analyses render a moderate-confidence upper bound risk assessment. (For some debris sources, probabilistic analysis may be inconsistent with past flight history).

10.   Ascent and on-orbit assessment capability for STS-114 and repair capability on future flights has the potential to mitigate risk.

11.3   Risk Assessment for Ice Debris

The Boeing Company conducted Monte Carlo-based probabilistic analyses of ice debris from the ET feedline bellows at the forward, mid, and aft locations, and at the ET feedline brackets at locations 1129 and 1377. (Ice debris from ET umbilicals has not been rigorously analyzed). While ice liberation tests of a feedline bracket have been conducted, the limited results do not provide an adequate test basis for building distributions of the debris mass. Furthermore, limitations in simulating the actual flight environment cast a doubt over the suitability of the test results to establish the time of ice debris release. Therefore, several different distributions of mass debris and several scenarios of time of release were used to estimate the probability of ice debris exceeding the Orbiter critical impact capability. A less conservative tile damage capability allowable (50 percent damage depth) was used in the ice analysis rather than the foam analysis. (This is unacceptable for deterministic analyses). The results indicate that the estimated likelihood of exceeding the critical damage capability for the RCC is Improbable. The estimated likelihood of exceeding the critical damage capability for tile is very high (Probable or Infrequent). (Seals and penetrations were not explicitly addressed in the probabilistic analyses). However, the Monte Carlo analysis results vary by **three orders of magnitude**, depending on

the input mass distribution assumption and the scenario for time of release, which could result in the risk being classified anywhere from Probable to Remote. In addition, a relative comparison between the bellows ice liberation test and the bracket ice liberation test suggests that significantly more ice is liberated from the bellows than from the bracket. Therefore, a reasonable qualitative argument can be advanced that eliminating the bellows ice has significantly lowered the overall risk to tile from ice debris. **Based on the available test data and analysis results, the NESC has concluded that the feedline brackets and ET umbilical ice debris environment is not sufficiently characterized or understood to assign the level of risk.**

11.4   Engineering Considerations that Supports the Flight Rationale for Ice Debris

1.   Installed heater on the forward bellows to eliminate ice formation. (The heater at the forward bellows has eliminated half the ice sources at the forward most ice debris location.) Ice debris risk to WLE RCC panels has been significantly mitigated.

2.   Bracket ice liberation tests suggest debris mass is small compared to forward bellows. Bracket geometry appears to constrain total mass liberated.

3.   Conservative assumptions about ice debris mass distributions and time of release results in bounding probability values (approximately 1 in 300), which are lower than the value (approximately 1 in 200) for forward bellows prior to installing the heater.

4.   Ice characterization tests have provided an understanding for evaluating tank ice and can be used to a limited extent to assess ice on the lower side of the bracket (the only view currently visible) and upper side of the bracket.

5.   Tile damage capability map is conservative.

6.   On-orbit assessment capability for STS-114 and repair capability on future flights has the potential to mitigate risk.

7.   Flight history demonstrates damage tolerant attributes of tile.

8.   Only a small fraction of recorded damage cases to tile appear to be from ice debris.

9.   LCC controls have the potential to limit the total amount of ice prior to launch (at least can tell the difference qualitatively between heavy ice and light ice).

11.5   Recommendations

1.   An evaluation of effective controls of ice debris from the ET umbilical ice should be completed prior to STS-114 and implemented via Launch Commit Criteria (LCC).

2.   An evaluation of effective controls of ice debris from the feedline brackets should be completed prior to STS-114 and implemented via Launch Commit Criteria (LCC). In addition, risk mitigation methods that can be implemented for subsequent missions to reduce overall program risks should be pursued as a high priority.

3.   Focus the flight test objectives to obtain engineering data during STS-114 to characterize the ice debris environment for the ET feedline brackets at locations 1129 and 1377, mid bellows, and ET umbilical. Additional ground tests should be conducted to supplement the flight test data.

4.   The end-to-end predictive capability of the Boeing and Aerospace probabilistic analysis codes, which were independently-developed, should be verified. One approach to achieving this verification is to compare the analysis results from the two codes for at least one debris case.
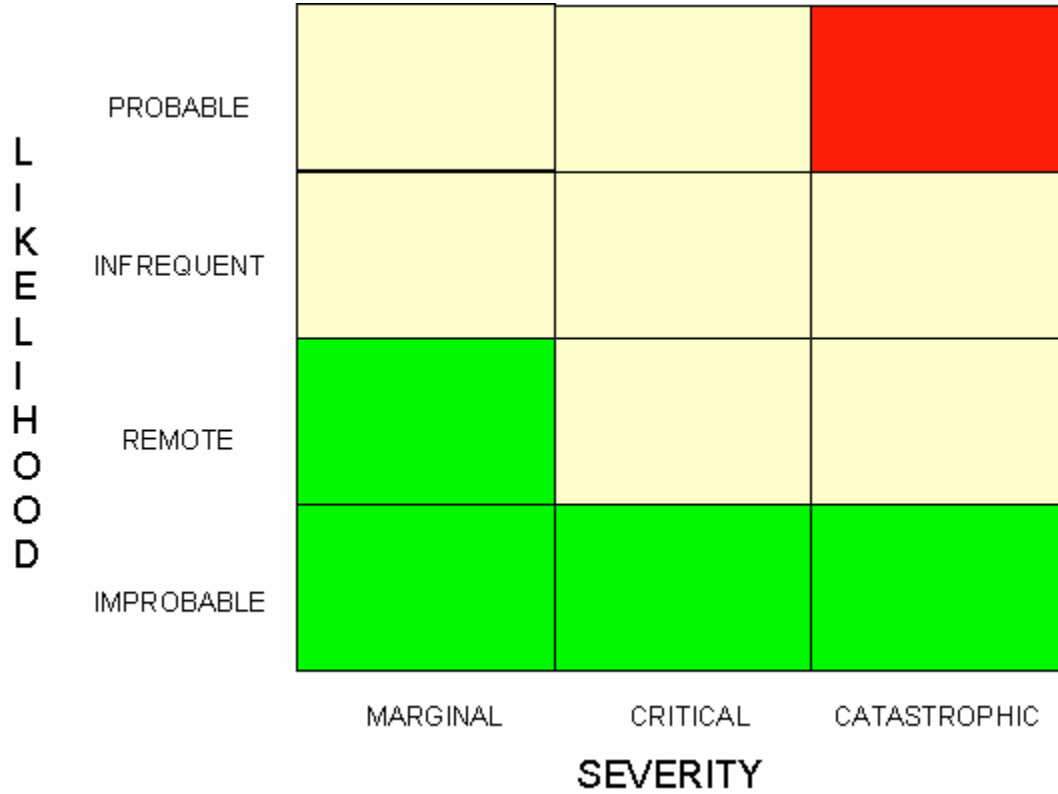
Figure 11.0-1. Hazard Severity and Likelihood of Occurrence with Controls in Place

Table 11.0-1. Critical Damage to Orbiter RCC and Tile to Expected Foam and Ice Debris from External Tank

Debris Sources by Tank Location	Redesigned or "Fly-as-is"	Is Large[1] Foam or Ice Loss Physically Realistic? (Yes/No)	Flight Evidence of Previous Foam or Ice Loss? (Yes/No)	C/E Certification Methodology (SSP DVR Values)		C/E "Best Estimate" Methodology (SSP DVR Values)		C/E "Best Estimate" Methodology (NESC Values)	Monte Carlo-Based Probabilistic Assessment (SSP DVR Values)	Monte Carlo-Based Probabilistic Assessment (SSP DVR Values)[2]
				WLE Panels 10-12	Nose Cap/ Chin Panel	WLE Panels 10-12	Nose Cap/ Chin Panel	WLE Panels 10-12	Aggregated All RCC	Aggregated All Tile
LO$_2$ Flange Foam	"Fly-as-is"	Yes	**No**	0.36	0.29	1.1	1.1	0.9	<1 in 10,000	1 in 250
LH$_2$ Flange[3] Foam	Redesigned	Yes	No Data	0.39	No TM[4]	1.8[5]	No TM	1.4	<1 in 10,000	1 in 10,000
LO$_2$ Ice/Frost Ramps Foam	"Fly-as-is"[6]	Yes	Yes (1)	0.24	0.12	1.0[10]	0.61	0.5[9]	<1 in 10,000	1 in 160
Intertank Ice/Frost Ramps Foam	"Fly-as-is"	Yes	**No**	0.28	0.52	1.5[10]	3.2	0.8[9]	Included in LO$_2$ I/F	Included in LO$_2$ I/F
LH$_2$ Ice/Frost Ramps Foam	"Fly-as-is"[7]	Yes	Yes (12)	0.38	No TM	1.6[10]	No TM	0.9[9]	Enveloped	Enveloped
LO$_2$ PAL Ramp Foam	"Fly-as-is"	Yes	**No**	0.41	0.26	1.7	1.6	1.4	Enveloped	1 in 10,000
LH$_2$ PAL Ramp Foam Forward	Redesigned[8]	Yes	No Data	0.39	No TM	2.0	No TM	1.6	Enveloped	Enveloped
Aft	"Fly-as-is"	Yes	Yes (2)	0.40	No TM	1.9	No TM	1.6	Enveloped	Enveloped
Bipod Closeout Foam[3]	Redesigned	Yes	No Data	0.37	No TM	1.1[5]	No TM	0.9	<1 in 10,000	<1 in 10,000
1377 Feedline Bracket Ice	"Fly-as-is"	Yes	No Data		No TM		No TM		<1 in 1,000,000	1 in 181
1129 Feedline Bracket Ice	"Fly-as-is"	Yes	No Data		No TM		No TM		<1 in 100,000	1 in 1,000
Mid (1979) Feedline Bellows Ice	Redesigned	Yes	Yes	No TM	No TM	No TM	No TM	No TM	No TM	1 in 100
Aft (2026) Feedline Bellows Ice	Redesigned	Yes	Yes	No TM	No TM	No TM	No TM	No TM	No TM	1 in 1,000

[1] Excludes small mass debris such as popcorning.
[2] Includes seals and penetration for foam, but not for ice.
[3] Susceptible to cryoingestion (nitrogen purge at intertank).
[4] No Transport Mechanism (TM).
[5] Cryoingestion and cryopumping failure mechanisms not included in "best estimate" E.
[6] Material changed on STS-79.
[7] Process improved beginning on ET-112.
[8] Massive aero ramp eliminated, foam applied at base of fitting.
[9] PDL high density foam adjustment 20 percent (a factor of 0.8 is used on KE).
[10] NESC cannot reproduce these computed numbers.

Table 11.0-2. Characterization of Foam Debris, DTA, and Capability Data for Damage to Tile

Orbiter Location	Location (See Figure 11.0-2)	Cert-WOW-Cert[1]	Ult-WOW-Cert[2]	Typical-Typical-Cert (95%)[3]	Typical-Typical-Cert (50%)[4]	Typical-Typical-Cert (95% w/o I/F ramp)[5]
Forward	BP_1100	0.19	0.21	0.39	0.40	1.04
	BP_1050	0.21	0.24	0.34	0.45	3.21
	BP_1074	0.13	0.15	0.26	0.41	1.07
	BP_2202	0.24	0.29	0.60	0.31	0.95
	BP_1202	0.13	0.15	0.34	0.71	1.64
	BP_1304	0.33	0.39	1.27	0.54	2.38
	BP_1351	0.06	0.07	0.35	1.76	3.92
	BP_2305	0.33	0.39	1.38	0.47	1.16
	BP_1450	0.07	0.08	0.39	1.77	3.81
	BP_2004	0.13	0.15	0.58	0.54	1.76
	BP_1607	0.42	0.50	2.49	0.76	1.42
	BP_2340	0.12	0.14	0.98	3.45	4.31
	BP_1602	0.05	0.06	1.35	1.75	3.33
	BP_1600	0.07	0.13	20.00	2.44	1.59
	BP_2420	0.39	0.46	2.62	HIGH	20.00
	BP_2350	0.11	0.13	1.85	3.83	4.55
	BP_1702	0.12	0.14	3.28	5.56	2.82
	BP_1700	0.07	0.10	16.67	HIGH	3.28
	BP_2620	0.24	0.28	2.72	HIGH	16.67
	BP_1800	0.09	0.10	2.46	7.14	4.72
	BP_2820	0.51	0.60	11.36	HIGH	2.46
	BP_2750	0.14	0.16	3.73	142.86	22.22
	BP_2540	0.13	0.16	3.42	50.00	3.73
	BP_2370	0.09	0.12	2.34	10.42	3.42
Aft	BP_1851	0.11	0.13	3.49	7.14	2.34

🟥	< 1.0
🟨	< 2.0

[1]Certification limit from NSTS 07700 determines size debris liberated into WOW dispersed trajectory with resulting damage based on a 95% damage model and compared to certification rigor capability map (i.e., 1st generation).
[2]Ultimate divot-no divot curve determines size of debris liberated into WOW dispersed trajectory with resulting damage based on a 95% damage model and compared to certification rigor capability map.
[3] "Best estimate" of expected foam debris based on 7 SE&I defined scenarios with liberation into nominal lift, nominal drag and nominal pop off velocity transport with resulting damage based on a 95% damage model and compared to certification rigor capability map.
[4]Same as 3, except damage based on a 50% damage model.
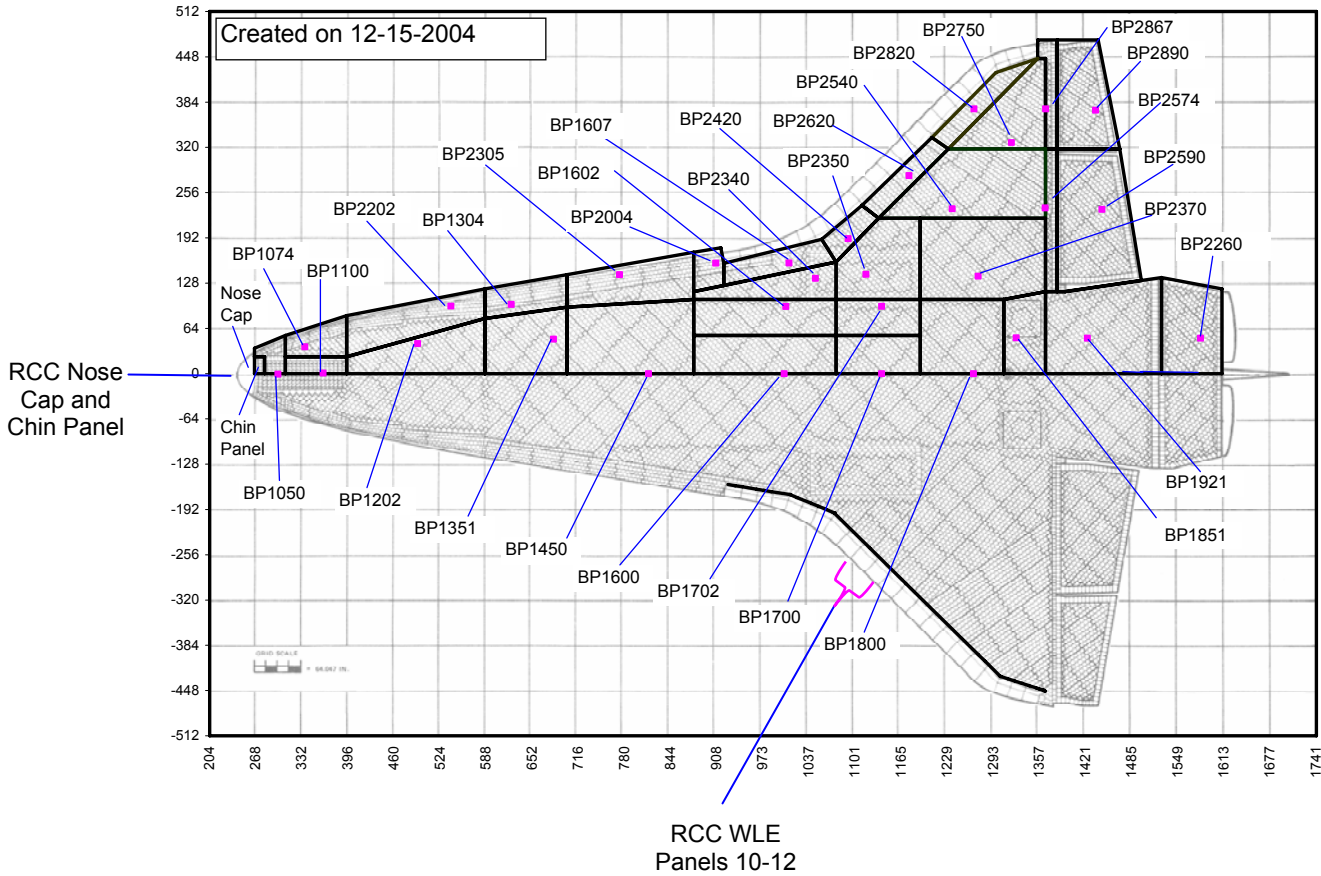[5]Same as 3, except removal of 3 scenarios dealing with typical ice/frost ramp debris

Figure 11.0-2. Mapping of Orbiter Body Points (BP) and RCC WLE Panels and RCC Nose Cap and Chin Panel

12.0   Conclusions and Recommendations

Since the loss of *Columbia* on February 1, 2003, the Space Shuttle Program (SSP) has significantly improved the understanding of launch and ascent debris, implemented hardware modifications to reduce debris, and conducted tests and analyses to understand the risks associated with expected debris. The STS-114 flight rationale for expected debris relies on a combination of all three of these factors.

A number of design improvements have been implemented to reduce debris at the source. The External Tank (ET) thermal protection system (TPS) foam has been redesigned and/or process improvements have been implemented in the following locations: the bipod closeout, the first ten feet of the liquid hydrogen (LH_2) tank protuberance air load (PAL) ramp, and the LH_2 tank-to-intertank flange closeout. In addition, the forward bipod ramp has been eliminated and heaters have been installed on the bipod fittings and the liquid oxygen (LO_2) feedline forward bellows to prevent ice formation. The Solid Rocket Booster (SRB) bolt catcher has been redesigned. The Orbiter reaction control system (RCS) thruster cover "butcher paper" has been replaced with a material that sheds at a low velocity. Finally, the pad area has been cleaned to reduce debris during lift-off.

The understanding of the sources and mechanisms that produce foam debris was established by a rigorous root cause investigation and the dissection of significant sections of foam removed from flight-ready ETs. Quantifying the risk associated with debris has been a major challenge. Activities included tests and analyses to predict expected/possible debris, transport tests and analyses to define debris trajectories and the velocity at impact, and tests and analyses to determine the impact capability of the Orbiter TPS components. These tests and analyses have addressed all types of ET foam and tank locations, ice from several locations on the ET, and butcher paper from the RCS thruster cover.

The SSP requested that the NASA Engineering and Safety Center (NESC) conduct a peer-review of the flight rationale for expected debris. The NESC assembled a multi-disciplinary team of subject matter experts to address each component of the proposed flight rationale. The team reviewed the debris sources data, transport test and analysis data, Orbiter impact capability test and analysis data, and the overall methodology to establish flight rationale and associated risks. The NESC peer-review began with the element level certification activities in 2004 and continued through the development of the end-to-end Space Shuttle System (SSS) level flight rationale in 2005. The NESC team has been working closely with the SSP team and has provided numerous recommendations throughout the review process on possible areas of improvement to the foam spray process, hardware redesign, and in quantifying the risks associated with expected debris. Virtually, all of the NESC recommendations have been implemented by the SSP team. This report documents the findings of the NESC peer-review of the flight rationale logic and conclusions. (Previously issued NESC position papers documented

the findings and recommendations regarding element level certification for expected debris). Provided below is a summary of the NESC findings for the principle elements of the flight rationale. The conclusions and recommendations are highlighted.

Physics of Foam Debris Generation: Each foam location on the ET has been assessed for susceptibility to large foam loss based on physical arguments about the type of foam, and the void temperature and pressure conditions during ascent. The large acreage locations, where the automated spray method is used, were eliminated from concern since no voids were found in these areas during dissection of foam on tank ET-94. Other locations can contain voids which have leak paths and may be susceptible to cryoingestion or cryopumping, depending on their location on the tank and the thickness of the foam. Divoting from sealed voids due to thermal/vacuum conditions is the most likely source of foam debris and can occur in every location on the tank with manually applied foam. **The NESC concluded that an analysis of each specific location on the tank that takes into account the local temperature, pressure, and location of voids is a valid method for determining the most likely divoting mechanism for each ET foam debris case.**

"Worst-on-Worst (WOW) Estimate" of the Impact Capability Margin (C/E): The WOW estimate of the C/E is actually the certification rigor methodology for structural design. C is the capability of TPS to survive the impact and E is the debris environment, both quantified in kinetic energy (KE) for impacts to the RCC and velocity for impacts to tile. The WOW estimate includes a 1.4 factor of safety (FOS) on C and a 1.25 FOS on E. The methodology compounds conservatisms that are included in each of the three analyses (debris liberation, debris transport, and impact capability) that must be combined to estimate the C/E. The minimum predicted impact C/E is well less than 1.0 for many WLE RCC panels, the RCC nose cap and chin panel, and many tile locations. **Therefore, the locations of the Orbiter with a C/E less than 1.0 are not certified for expected debris using the standard WOW approach.** To further address these locations, a "best estimate" approach was used to compute a less conservative estimate of the C/E. In addition, a Monte Carlo-based probabilistic analysis was used to quantify the risk for the most difficult cases.

"Best Estimate" of the Impact Capability Margin (C/E): The "best estimate" is a quasi-deterministic method. The capability and expected debris mass are point-values; and the debris transport analysis is the result of a Monte Carlo simulation. All FOSs used in the certification methodology are removed from the estimates of C and E. In addition, the expected debris mass has been reduced to the smaller mass debris due to the sealed voids divoting mechanism. The NESC concurs that the "best estimate" method is less conservative than the "WOW estimate" and is useful in understanding the level of risk due to expected foam debris. The system level FOS should be at least 1.4, if all other FOSs are removed from the C and E estimates. **A number of debris cases for RCC and tile do not have an impact C/E greater than 1.4 based on the "best estimate" method and several locations are below 1.0.**

Recommendation #1: The NESC concurs with the Delta System Design Verification Review (DVR) (April 26-27, 2005) finding that an end-to-end Monte Carlo-based probabilistic analysis will be conducted for the foam debris cases that do not have a "best estimate" impact C/E of at least 1.4.

ET Foam Debris Environment (E): The cryopumping and cryoingestion divoting mechanisms are included in the "WOW estimate", but <u>not</u> included in the "best estimate" of the debris mass. Divoting from cryopumping requires a "smart" leak path that is large enough to allow a void to fill with condensed air during the pre-launch hold, but is small enough to preclude venting as the air is vaporized during ascent. The results of component level tests simulating the flight environment support the supposition that divoting from cryoingestion and cryopumping are highly unlikely to occur. Therefore, the "best estimate" values of E are based on the smaller mass, but more likely debris caused by the sealed void divoting mechanism. The NESC concurs with the logic of not including cryoingestion and cryopumping in the "best estimate" of E used in the impact C/E because this is a quasi-deterministic method. However, all divoting mechanisms and all void data must be included in the Monte Carlo-based probabilistic analysis.

Recommendation #2: Cryoingestion should be included in the Monte Carlo-based probabilistic analysis of the debris cases that do not satisfy the system level "best estimate" impact C/E of at least 1.4.

Impact Capability (C) for RCC: The value of impact capability that corresponds to the onset of damage in RCC (or the NDE threshold for detectable damage) is a requirement, and should not be thought of as a knockdown factor to account for an uncertainty. The damage onset requirement was established by the arcjet burn-through tests and the analysis of the WLE and nose cap. The SSP based the "best estimate" value of C on only the as-fabricated properties of the RCC test panels. The NESC reviewed the engineering data and concluded that the value of C used in the "best estimate" must account for both expected material variability and end-of-life aged RCC. **Therefore, the NESC computed values of the "best estimate" impact C/E are approximately 20 percent lower than the SSP values.** In addition, the nose cap geometry and material are significantly different from the WLE RCC panels. No impact tests or arcjet burn-through tests have been conducted on the nose cap geometry or material. **The impact capability margins (estimated to be less than 1.0) for the nose cap and chin panel are based only on analytical results from math models that have not been verified to be accurate for the nose cap geometry and material.**

Recommendation #3: The "best estimate" value of C should be computed using material properties that accounts for material variability inherent in RCC and the end-of-life aged RCC properties.

Recommendation #4: Impact tests and arcjet tests should be conducted on the nose cap geometry and material to verify the analysis methodology and results used to develop the flight rationale.

RCC Burn-Through and Hole Growth Damage Requirements: After reviewing the engineering data supporting the RCC burn-through requirements and the RCC Damage Growth Tool used to develop the nose cap and WLE damage maps, the NESC concurs that the arcjet data is adequate to establish the RCC impact damage requirement for re-entry of STS-114 (0.020" coating loss for time to breach, and 0.020" coating loss plus a mid-plane delamination for hole growth). However, the experimental data from the stagnation flow arcjet tests are not sufficient to validate the tool for all impact damage cases and for vehicle locations subjected to crossflow flight conditions. Stagnation flow arcjet tests are a reasonable simulation of the nose cap flow conditions whereas properly designed wedge flow arcjet tests are a better simulation of the crossflow flight conditions of the WLE.   Therefore, the level of conservatism, uncertainty in results, and limitations on the use of the tool cannot be established for all vehicle locations and damage cases. Because of this shortcoming, the current tool should only be used by experienced subject matter experts such as the tool developers. Specifically, caution must be exercised in using this tool to predict hole growth.

Recommendation #5: Additional arcjet tests with specimens containing actual impact damage rather than simulated impact damage, particularly wedge flow tests, are required to establish the level of conservatism in using the RCC Damage Growth Tool for all vehicle locations and impact damage cases.

Past Flight History: The data on debris generation and impact damage recorded from previous flights provides a compelling basis for a flight rationale for Orbiter acreage tile. However, it has less relevance for impacts on the Orbiter RCC. The recorded incidents of foam debris generation are documented from a limited number of cameras. So this information lacks the fidelity required to precisely define the debris mass. Also, a large database (about 14,000 cases) of actual damage to tile has been recorded over the life of the Orbiters. A subset of about 300 damage cases, referred to as the platinum dataset, are adequately documented to provide a benchmark for the computational methodology developed to predict tile damage. **The NESC concluded that the platinum dataset is also a valid basis for supporting the flight rationale.**

Tile and Structural Capability Models: A suite of Math Model Tools (Damage, Aerothermal, Thermal and Structural Analysis Tools) are utilized to describe the capability of the acreage Orbiter tile and structure. This description of capability is documented as a "damage map" and is utilized in various forms and versions throughout the flight rationale. The tools have been subjected to peer-review to understand the basic workings of all tools, assumptions, limitations and key parameters passed between the tools. The methodology, used in the production of the "certification rigor" or "1st generation" damage map, incorporates all the standard certification

rigor methodologies and factors. Therefore, the conservatism of the capability established is believed to be quite high.

Recommendation #6: Certification of tools for both in- flight and as a part of the flight rationale should include a thorough end-to-end validation. This validation should emphasize interfaces between tools, demonstrating understanding of modeling accuracy and uncertainty, as well as end-to-end correlation to both test and historical damage.

Recommendation #7: The generation of a less conservative, predictive damage map should be produced for quantification of pre-flight risk of tile acreage catastrophic damage and compared to flight history for the purposes of model validation.

Flight Rationale for Tile: Both the "WOW" and "best estimates" of the impact C/E for many tile locations are considerably less than 1.0. However, the Math Model Tools used to estimate these impact C/Es also conservatively overestimates the severity of some damage cases previously recorded in the flight history database. Flight history clearly illustrates the damage tolerance capability of acreage tile. Therefore, a flight rationale has been constructed which gives increased confidence in our understanding of the debris environment and indicates that for typical debris there is not a catastrophic hazard for foam impacts on tile (excluding seals and penetrations). However, the use of flight history is not sufficient to characterize the accepted risk if several cases of severe impact damage occurring in a noncritical tile location had occurred to a more critical close-by tile location.

Recommendation #8: A Monte Carlo-based probabilistic analysis that includes the distribution of foam defects as well as the Monte Carlo debris transport analysis should be conducted to determine the likelihood of an impact which exceeds the tile damage tolerance capability.

Risk Assessment for Foam Debris: The Aerospace Corporation has conducted Monte Carlo-based probabilistic analyses of the most severe foam debris sources (LO_2 ice/frost ramp, LO_2 intertank flange, LH_2 intertank flange, LO_2 PAL Ramp, and Bipod Closeout). The Aerospace Monte Carlo-based probabilistic model used methodologies that have been peer-reviewed and validated by comparison to other analysis results and ground test data. In addition, the input distributions used in the analyses have also been peer-reviewed. **While the end-to-end predictive capability (numerical results) has not been verified, the results of sensitivity studies and comparison to flight data suggest that the results are conservative.** Based on the results of these analyses and an assessment of the controls for each foam source, the NESC concurs with the SSP that the likelihood of debris from each foam source exceeding the critical impact capability for RCC is Improbable. The NESC concurs with the SSP that the likelihood of foam debris exceeding the critical impact capability of Tile is either Remote or Infrequent, depending on the foam source. The highest computed risk is for tile seals and penetrations,

which is not overly conservative relative to flight history, and furthermore, has not been fully characterized. **The NESC has concluded that the probabilistic results, supplemented by additional engineering data, physics considerations, and the level of control over debris liberation, provide a reasonable engineering foundation for a flight rationale for STS-114 based on accepted risk due to expected foam debris.**

Recommendation #9: The risk assessment for seals and penetration should be completed, including the threat from popcorning foam debris and ice debris.

Risk Assessment for Ice Debris: The Boeing Company has conducted Monte Carlo-based probabilistic analyses of ice debris from the ET feedline bellows at the forward, mid and aft locations and the ET feedline brackets at locations 1129 and 1377. (Ice and baggie debris from ET umbilicals has not been rigorously analyzed). While ice liberation tests of a feedline bracket have been conducted, the limited results do not provide an adequate test basis for building distributions of the debris mass. Furthermore, limitations in simulating the actual flight environment cast a doubt over the suitability of the test results to establish the time of release of the ice debris. Therefore, several different distributions of mass debris and several scenarios of time of release were used to estimate the probability of ice debris exceeding the Orbiter critical impact capability. A less conservative tile damage capability allowable (50 percent damage depth) was used in the ice analysis than the foam analysis. (This is unacceptable for deterministic analyses). The results indicate that the estimated likelihood of exceeding the critical damage capability for the RCC is Improbable. The estimated likelihood of exceeding the critical damage capability for tile is very high (Probable or Infrequent). (Seals and penetrations were not explicitly addressed in the probabilistic analyses). However, the Monte Carlo analysis results vary by **three orders of magnitude,** depending on the input mass distribution assumption and the scenario for time of release, which could result in the risk being classified anywhere from Probable to Remote. In addition, a relative comparison between the bellows ice liberation test and the bracket ice liberation test suggests that significantly more ice is liberated from the bellows than from the bracket. Therefore, a reasonable qualitative argument can be advanced that eliminating the bellows ice has significantly lowered the overall risk to tile from ice debris. **Based on the available test data and analysis results, the NESC has concluded that the feedline brackets, bellows, and ET umbilical ice debris environment is not sufficiently characterized or understood to assign the level of risk. To establish the flight rationale for STS-114, additional work is required to develop adequate controls for ice.**

Recommendation #10: A physics-based engineering analysis of the risk to tile from ET umbilical ice and baggie debris should be conducted to ensure that adequate impact capability exists for impact scenarios consistent with past flight environment.

Recommendation #11: An evaluation of effective controls of ice debris from the ET umbilical ice should be completed prior to STS-114 and implemented via Launch Commit Criteria (LCC).

Recommendation #12: *An evaluation of effective controls of ice debris from the feedline brackets should be completed prior to STS-114 and implemented via Launch Commit Criteria (LCC). In addition, risk mitigation methods that can be implemented for subsequent missions to reduce overall program risks should be pursued as a high priority.*

Recommendation #13: *Focus the flight test objectives to obtain engineering data during STS-114 to characterize the ice debris environment for the ET feedline brackets at locations 1129 and 1377, mid bellows, and ET umbilical. Additional ground tests should be conducted to supplement the flight test data.*

Recommendation #14: *The end-to-end predictive capability of the Boeing and Aerospace probabilistic analysis codes, which were independently-developed, should be verified. One approach to achieving this verification is to compare the analysis results from the two codes for at least one debris case*

Appendix A. Shuttle System Improvements to Reduce the Debris Environment

A.1 Forward Bipod Thermal Protection System Redesign

1. New baseline design change eliminates the bipod foam ramp.

    a) Structural verification tests have confirmed the performance of the modified fitting in defined flight environments.

    b) Wind tunnel testing has verified the TPS closeout performance when exposed to ascent aerodynamic and thermal environments.

2. Bipod fittings incorporate redundant heaters in the base of the bipod to prevent ice formation as a debris hazard.

    a) Thermal verification tests with the automated heater control performance validated based on bipod web temperature measurements.

3. Redesigned closeout application process to reduce complexity. Enhanced spray techniques and implemented additional process controls to reduce variability.

A.2 Liquid Oxygen (LO$_2$) Feedline Bellows Ice Elimination/Reduction Efforts

1. TPS "drip lip" option to address ice formation on the LO$_2$ feedline bellows.

    a) Drip lip diverts condensate from the bellows and significantly reduces ice formation by as much as 60 percent.

    b) Drip lip design is complete. Installation of additional foam to form the drip lip was installed before ET-120 and ET-121.

2. To further reduce ice formation, heater installed in forward bellows location.

A.3 Protuberance Air Load (PAL) Ramp

1. ET PAL ramps design assessment.

    a) Ramp foam loss in the history of the Shuttle on STS-4 and STS-7.

    b) Related to cryopumping of air into associated panels and pre-launch repairs.

    c) Subsequent changes in configuration and repair criteria reduced the potential for foam loss from this area. No further foam loss is believed to have occurred.

    d) Due to the size and location of the PAL ramps, placed them at the top of the priority list for TPS verification reassessment and NDE.

e) Verification data for the existing ramps were reassessed and determined to be valid.

2. Dissected similar hardware from ET-94 and conducted performance demonstration tests.

3. A 10-foot section of the LH_2 PAL ramp in the area of the LH_2/intertank flange was removed and replaced with improved foam application techniques and process controls.

4. NDE techniques are being used to gather engineering data following the foam application.

A.4 LH_2/Intertank Flange Closeout Redesign

RTF efforts to reduce potential for foam loss at the LH_2/intertank flange include:

1. Removing and replacing the LH_2/intertank flange foam in the critical debris zone.

2. Reversing the flange bolt installation to reduce the potential for voids created around the fastener as the closeout foam is applied.

3. Injection of foam into the stringer cavity minimizing voids over the flange nuts.

4. Point filling voids in the substrate at the intertank splice panels.

5. Reducing liquid nitrogen (LN_2) migration through the flange bolts by applying a barrier.

6. Reducing the complexity of the closeout foam spray by employing a four-step foam application process: stringer injection closeout; thrust panel rib pocket closeout; upper flange closeout; and lower flange closeout.

7. Removing and replacing the forward 10-foot section of the LH_2 PAL ramp using improved application techniques.

A.5   Solid Rocket Booster (SRB) Bolt Catcher Redesign

The bolt catcher assembly and related hardware was redesigned and qualified by testing as a complete system to demonstrate compliance with FOS requirements.

1. Redesign of the bolt catcher housing is fabricated from a single piece of aluminum forging that removes the weld, which was the weakest element, from the original design.

2. New energy-absorbing material and thermal protection selected.

3. Redesign and resizing of the ET attachment bolts and inserts.

4. Testing to characterize the energy absorber material.

5. Testing to determine the design loads.

6. Qualification tests demonstrated that the assembly complies with the FOS of 1.4.

7. Cork selected as the TPS material for the bolt catcher.

A.6 Other Debris Sources

1. Replaced the Orbiter Reaction Control System (RCS) thruster cover "butcher paper" with material that sheds at low velocity.

2. Cleaned up the pad area to reduce debris during lift-off.

A.7 Improvements to the Orbiter RCC

NDE: Improved NDE capabilities provide greater knowledge of the integrity of the Orbiter RCC parts prior to launch. The features of the NDE capability are:

1. The following systems are currently certified: X-ray, ultrasound (wet and dry), Eddy current, and computer-aided tomography scan.

2. Only Eddy current can be conducted without removing components from the vehicle.

3. Eddy current testing is useful for assessing the health of the RCC outer coating and detecting possible localized subsurface oxidation and mass loss. It reveals little about a component's internal structure.

4. All RCC components from the vehicles were removed and returned to the vendor facility for comprehensive NDE.

   a) Structural integrity and an estimate of mass loss were validated by off-vehicle NDE and destructive testing of flown RCC WLE components.

   b) The health of the associated attach hardware was also determined using a combination of visual inspection and NDE methods appropriate to identify critical size flaws inherent to the components.

WLE Sensor System: An impact warning system has been implemented on the WLE on STS-114. (It should be noted that the system that will fly on STS-114 is a developmental system). The system has the following features:

1. Accelerometer-based sensors on the WLE spar as an additional means to identify impact.

2. Includes 132 accelerometer measurements that will be acquired by 44 3-channel, high-rate, battery-powered data acquisition units located in the wing compartments.

3. Raw data will be post-processed within each acquisition unit to determine applicable windows of data that will be transmitted via radio frequency to relay units also located in the wing cavity.

4. Data will be relayed via RS-485 serial bus and radio frequency transmission to a laptop-based receiver unit in the crew cabin where the data will be stored in files.

5. Files are then routed through the Orbiter Communications Adapter and the Ku-band system to ground personnel for evaluation.

6. In the event that an impact is detected, engineers can determine the location of the sensor(s) that measured the impact and recommend a more focused inspection of the area later in the mission.

A.8   Orbiter Hardening

Phase I: Front spar "sneak flow" protection for the most vulnerable and critical WLE Panels 5 through 13. (Implemented for STS-114).

Phase II: "Sneak flow" front spar protection for the remaining RCC Panels 1 through 4 and Panels 14 through 22. (Project is in the final design phase. Implementation of the Phase II modifications may begin as early as one year after RTF).

Phase III: Replace WLE Panels with more robust RCC Panels. (This is a less mature option, but holds promise for increasing the robustness of the Orbiter).

Appendix B. List of Definitions

The definitions provided below are those developed by the SSP and documented in a Return to Flight (RTF) White Paper entitled, *"Return to Flight Rationale for Expected Debris Environments"*, written by B. H. Wendler, March 2005.

Debris Mass:

1) If larger than what the impact resistance indicates for a no-configuration change condition, then affects the thermal protection integrity;

2) Has a mass larger than what the impact tolerance allows and a probability of occurrence that is not controlled to an acceptable hazard level;

3) Does not have substantiating engineering proof or NSTS 07700 exemption to show that the mass will not exceed impact tolerance on vehicle surface structure.

The first case can be quantified by a margin calculation C/E. The second case requires probabilistic predictions.

Minimum Impact Tolerance (WOW): Based on assuming all input values that determine the impact tolerance capability has a no risk assumption. This means each input into the uncertainty branch has negligible uncertainty by taking an even more conservative value. FOS, "A" basis properties, worst case re-entry, end-of-life conditions, etc., are assumed at the worst case level. The full uncertainty considerations were to be enveloped and allowed to accumulate through the chain of engineering.

Maximum Predicted Mass (MPM): Three types of MPM debris exist.

1) Maximum certified levels of debris (e.g. allowable level of foam divot mass from ET ice/frost ramp in LO_2 tanks area);

2) Historical accepted mass levels are noted as the maximum observed mass; or

3) Design mass (1.4.5).

The second case involves items that did not undergo design certification review with uncertainty predictions or other predictive analysis. For example, ablation products, string, or other non-propulsive objects less than $0.0002lb_m$, where no debris transport, liberation model, or impact tolerance are known.

"Best Estimated" Mass: Maximum liberated debris size where it would be unlikely to be exceeded or experienced. The basis of this estimate consists of engineering analysis and test results that show adequate conservatism exists in the combined values assumed. Conservatism

relies on combining the uncertainties in an end-to-end approach. For example, the chain of engineering used to predict the mass liberated involved a greater than 2-sigma (conservative side) input on each value where 3 or 4 terms are combined as part of a much larger sequence of additional such combinations or WOW combinations. Some of the terms combined may not have distributed properties, but the predicted inputs have been "enveloped" over pass/fail test conditions.

These assumptions were anchored in either test data or more detailed simulation analysis results so that the uncertainties are bounded and a balanced input level that has conservatism could be established. If the impact site has a mass effect or other phenomena than just mass, the maximum estimated mass may reflect knowledge of the impact prediction conditions that include conservative estimates in impact angle, momentum transfers, or other terms in the capability over environment calculation.

Design Mass Limit: A maximum predicted mass level derived from engineering estimates of the mass the design could allow. It takes into consideration redesign, process changes, geometry constraint on size, testing on maximum density, or other key terms used to estimate the maximum mass.

Historical Mass Limit: A mass level derived from flight history known to shed with no special engineering disposition made prior to the Space Transportation System (STS)-107, but had design changes as part of RTF. These are listed to help show the level of improvements made during the RTF effort.

Capability over Environment (C/E): Capability is defined as the impact tolerance threshold that can be consistently expressed against a class of debris in a range of transport conditions. For example, RCC WLE material has a different capability expression for foam than for ice. It also is defined in engineering terms relative to the debris transport relative to the vehicle's state vector predicted conditions. Again, for RCC this is usually in terms of energy; however, for tile, it is expressed in terms of velocity. Because of this, certain environment conditions have to be included in the capability model to represent a worst-case condition, like angle of impact for RCC. The energy term stated for each wing panel includes knowledge of the worst-case angle impact. Environment is defined at the physical impact site initial conditions, typically relative velocity and local impact angle, and inertia plus any angular momentum terms if relevant. C/E ratio estimates with the common engineering term become dimensionless. Terms and assumptions for C/E are discussed in Section 3.0.

Impact Tolerance: The ability of the impact site to withstand an impact, without change to capability or configuration. The impact tolerance is typically dependant on the physical properties of the impact site, but also of the debris (i.e., ice will have a different impact tolerance than foam due to density, strength, and elastic/fracture properties).

Damage Tolerance: The ability to complete a mission even though the configuration, or capability of the design, has been altered by a debris impact.

Flight Rationale: Closure justification that satisfies acceptance of exception to what is required. In this case, it is a debris environment that has basis for risk acceptance or end-to-end acceptance.

Appendix C. Peer-Review of Math Model Tools

A combination of new and existing Math Model Tools have been developed to determine the impact tolerance and damage tolerance of the Orbiter TPS (tile and RCC) due to impacts from debris (primarily ice and foam from the ET). These Math Model Tools include damage prediction and stress analysis, aeroheating analysis, and thermal analysis. Some tools are physics-based and other tools are empirically-derived. But even the physics-based tools include empirical-based models, such as the damage model in the LS-DYNA$^{©}$ code. Each tool was created for a specific use and timeframe, including certification, real-time pre-launch assessments, and real-time on-orbit assessments (see Table C-1). In addition, the tools are used together in an integrated strategy for assessing impact damage to tile (see Figure C-1) and RCC (see Figure C-2).

The NESC conducted a peer-review of the engineering data package for each Math Model Tool. The peer-review also included the end-to-end integrated strategy for using the tools to assess impact damage. The end-to-end review addressed issues related to the data transfer between each tool and the propagation of uncertainties from the initial definitions of the impact event to the predictions of damage. The following content was provided in each engineering data package:

- Key Assumptions: Test and analysis results supporting the assumptions.

- Limitations: Test and analysis results demonstrating the rationale for the limit.

- V&V: Complete set of V&V results (tests and analyses) mapped to specific requirements.

- Desktop user instructions:
    - Description
    - Assumptions and Limitations
    - Detailed description of model input and output
    - Instructions for running the tool
    - Quality checks that ensure the results are valid

The objective of the peer-review was to determine if the tools and the end-to-end strategy are suitable to support STS-114. It should be noted that the NESC peer-review was not an independent software V&V. These tools are not part of the mission in-line decision-making process. Rather, the tools will be used by experienced, subject matter experts who will interpret the results and provide engineering analyses to the Mission Management Team. The results of the engineering readiness peer-review are summarized in the following sections.

Table C-1. RCC and Tile Math Model Tools

Models	New/Updated /Existing	Used for Pre-Flight C/E	Used Real-Time		
			Launch Go/No-Go	On-Orbit before Inspection	On-Orbit Use-as-is
RCC Damage Prediction Tools					
RCC DYNA Model	N	X		X	
RCC Rapid Response Damage Model	N		X	X	
RCC Aeroheating Tools					
Step/Ramp Heating	N				
WLE Breach Internal Flow Model	N				X
RCC Damage Growth Tool	N				X
RCC Thermal Models					
RCC 3-D Thermal Math Models	E				X
Tile Damage Prediction Tools					
Tile Rapid Response Damage Model (foam)	N	X	X	X	
Tile Rapid Response Damage Model (ice)	N	X	X	X	
Tile Aeroheating Tools					
Cavity Heating Database	N	X			X
CFD for Cavity Heating	N	X			X
Catalytic Heating Tool	N	X			X
Boundary Layer Transition Prediction Tool	N	X			X
Tile Thermal Tools					
3-D Acreage Tile Thermal Model	N	X			X
Repaired Tile Thermal Model	N				
Special Configuration Thermal Models	N				X
Tile Stress Tools					
Tile Stress Tool	N	X			X
Tile Bondline Integrity Tool	U	X			X
Stress Assessor Tool	N	X			X
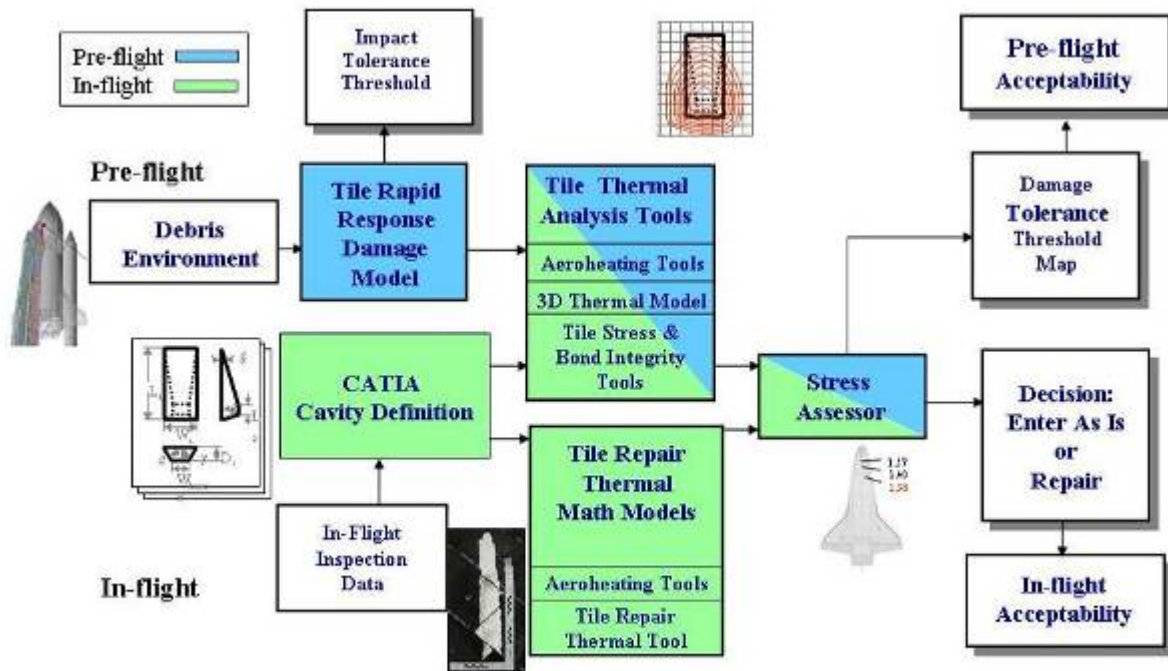
Figure C-1. Tile Tools for Pre-Flight and On-Orbit Damage Analysis
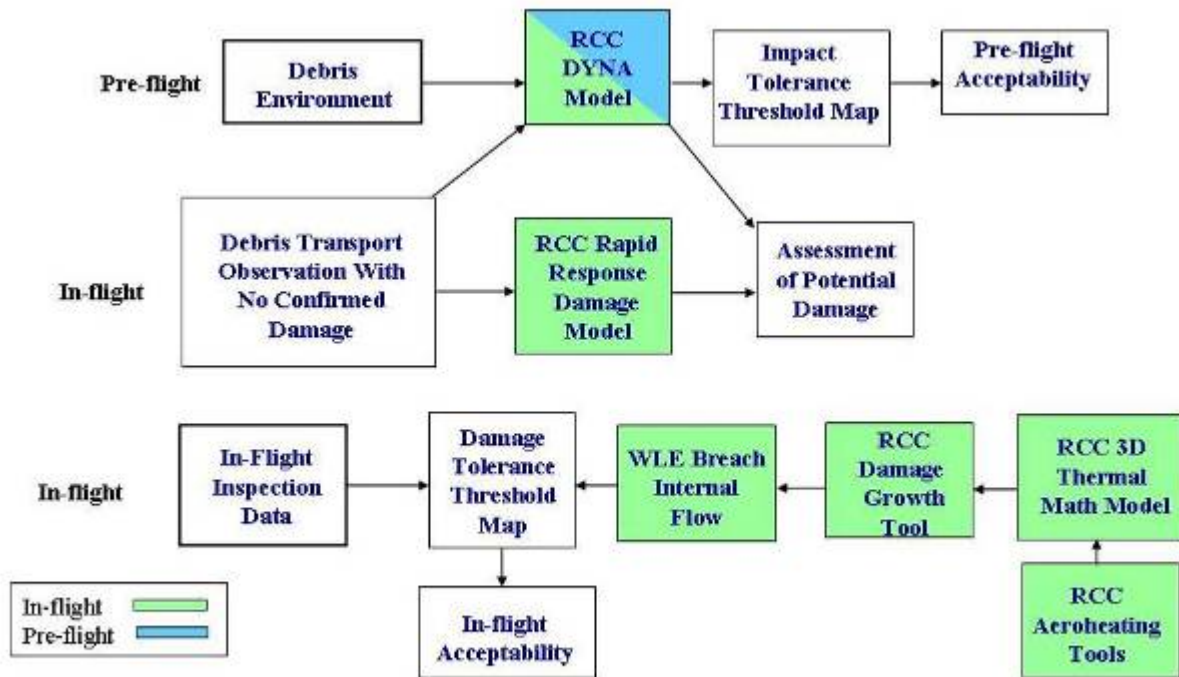
Figure C-2. RCC Models for Pre-Flight and On-Orbit Damage Analysis

C.1   RCC DYNA MODEL

This tool review involves the review of the application of LS-DYNA© software to impact of foam and ice on RCC and is *not a review of the LS-DYNA© software*.

C.1.1 Function(s) of Tool

Finite element simulations using LS-DYNA© code provide analysis results based on empirically-derived material data input definitions that qualitatively correlate with observed foam-impact test behavior of WLE RCC panels. LS-DYNA© correlations are done with flat panel and panel (9L) tests. Flat panel maximum deflections correlate to within 15 percent up to the onset of damage. Damage maps using the "1-to-5 elements out" criterion correlate qualitatively well with test data, as does test correlation of the "onset of NDE detectable damage". Test results clearly identify the RCC impact threat due to debris, which had not been known previously. Testing is performed on specific panels (flat and full panels) and at several locations on these panels. The LS-DYNA© finite element models and analyses were validated using these test results.   LS-DYNA© is then used to analyze other panels and for impact at other panel locations to evaluate the capability of the panels against foam and ice debris impact in lieu of full-scale testing of all WLE RCC panels. These results are then used to establish the capability, or "C", of the RCC panels for the flight rationale in terms of threshold KE.

C.1.2 Assumptions and Limitations

1. Delamination is a mode of damage that is observed in the RCC WLE panels due to impact loads. However, delamination is not modeled in the LS-DYNA© analysis. As such, the current model is incapable of predicting delamination.

2. The Program's LS-DYNA© analysis uses shell elements. The surface coatings are not explicitly modeled. The SiC outer layers and the CC substrate are modeled using smeared materials properties. As such, the current model is incapable of directly predicting coating loss.

3. LS-DYNA© can only be used to predict the "onset of NDE detectable damage" or threshold of damage – it cannot be used to predict damage growth because the material damage model used in the LS-DYNA© models does not accurately represent all forms of RCC damage. The approach to predicting "onset" is by scaling the LS-DYNA© predictions of "1-to-5 elements out" damage state.

4. Applicability of "onset of NDE detectable damage" criterion is currently based on panel apex foam impacts.

5. Analysis quality checks similar to those performed on the RCC WLE panels are not available for the nose cap and chin panel. Additionally, the LS-DYNA© finite element models for the nose cap and chin panel are not verified with full-scale testing.

6. The small mass effect is assumed to vary by a factor $(m_1/m_2)^{0.2}$ where m_1 is the mass of the debris and m_2 is a reference mass. This factor appears to be analytically arrived and empirically correlated with the LS-DYNA© prediction based on a range of masses. This factor has not been validated using test data.

C.1.3 Observations

1. RCC material properties have wide scatter. The material model is based on empirical material model (MAT 58) with tuned parameters (SLIMT=0.8, SLIMC=1.0 and ERODS=0.1). These parameters do not correspond to any physical material properties and are not derivable from the RCC material characterization tests.

2. Rectangular foam brick with length aligned with velocity trajectory presents the worst case for panel apex impact. The square block of ice, with the large face impacting tangent to the panel, produces the largest damage panels that are marginally more sensitive to ice impacts near panel ribs.

3. The LS-DYNA© model does not correlate the displacement time histories for full-scale test panels. In contrast, threshold velocities for damage initiation correlate within 10 percent with the test results on the flat and full panels.

C.1.4 Recommendations

1. The scope of intended use and the associated limitations of the debris on RCC analyses need to be clearly documented.

2. Engineering data to support the adjustment factor(s) used to convert from "1-to-5 elements out" criterion to the "onset of NDE detectable damage" criterion are needed.

3. Engineering data are needed to validate the nose cap and chin panel finite element models and predictions – mesh sensitivity, material orientation, etc.

4. Engineering data are needed for comparing full-scale panel test results with LS-DYNA© predictions (time-history plots of deflections and strains as well as end-state deformation patterns) - in particular, for Panel 9 tests that did not exhibit impact damage.

5. The small mass factor for BX and PDL foams need to be documented. Valid bounds of this factor need to be established, especially as size limits are approached.

6. RCC material characterization data including: effects of aging (or conditioning), strain-rate effects, failure modes and mechanisms, fracture toughness, load-unload behavior needs to be completed. These data will be useful in developing next generation material models that could be used with LS-DYNA©.

7. Investigation of through-the-thickness material layout (rather than smeared) such as discrete layer modeling of SiC outer layers and CC substrate needs to be undertaken.

8.   The effect of multiple strikes at the same (or nearly the same) location and KE levels using the LS-DYNA$^{©}$ tool needs to be quantified.

C.2   RCC RAPID RESPONSE DAMAGE MODEL

C.2.1   Function(s) of Tool

The intended use of IMPACT2 for pre-flight and on-orbit is to provide insight beyond the LS-DYNA$^©$ production run matrix with sensitivity analyses to small variations in location and impact angle. For pre-flight, IMPACT2 use would be to assess last minute concerns immediately prior to launch. For on-orbit, IMPACT2 use would be to assess panel damage due to reported debris strike(s) and document critical locations for subsequent LS-DYNA$^©$ analyses. Finite element simulations based on the IMPACT2 code are used to estimate the effect of debris impact on RCC WLE panels. The finite element models are currently based on the historical NASTRAN models ("certified" models) for the generation of free-vibration mode shapes. These mode shapes are used to perform a modal analysis with the forcing function defined to simulate the debris impact loading (i.e., nonlinear forcing function).

C.2.2   Limitations

1.   Application of this modeling and analysis approach for cases without LS-DYNA$^©$ collaboration introduces uncertainties that do not have clear bounds.

2.   Point or concentrated force application is an approximation of the impact event (may not accurately simulate the true contact problem, but should be conservative).

3.   Application of IMPACT2 is limited to RCC WLE panels; applications to the nose cap and chin panel have not been demonstrated.

C.2.3   Observations

1.   Foam model uses modal dynamics analysis with concentrated nonlinear force input. Foam impact force determined via coupled system analysis (force is a function of foam-panel relative displacement). Projectile is assumed to be prismatic and does not breakup.

2.   Ice model uses linear modal dynamics analysis with fluid jet concentrated impact force. Ice is assumed to be "prismatic". Ice impact force is determined from fluid jet impulse and is applied as a triangular-shaped time pulse.

3.   The IMPACT2 predicted threshold values of velocity are within 6 percent for hard ice and 11 percent for BX-265 foam compared with Panel 9 testing.   Comparing to LS-DYNA$^©$ predictions, the IMPACT2 predicted threshold velocities are within 15 percent and 20 percent for foam and ice impacts, respectively (excluding Panels 4 and 7). However, LS-DYNA$^©$ predictions themselves are within 15-19 percent of the test data. Therefore, uncertainties in IMPACT2 predictions could exceed 30 percent on threshold velocities of the test data.

4. Linear modal solution accuracy may be appropriate for onset predictions – assuming small deflections, lightly loaded panel.   Point or concentrated force application is an approximation of the impact event (may not accurately simulate the true contact problem, but should be conservative). Convergence of the modal solution is demonstrated. If the convergence is based on the convergence to the value obtained from the complete finite element model and a direct time integration procedure, then the 800-mode solution converges to the complete-model solution. The question that remains is whether the complete-model solution is itself a converged solution for this type of simulation.

C.2.4   Recommendations

1. Demonstrate the rapid response of IMPACT2 using 6" x 6" and 6" x 12" flat panels.

2. Validate IMPACT2 with 6" x 6" and 6" x 12" flat panel test data.

3. Demonstrate the rapid response tool application for the nose cap and chin panel structures.

4. Provide a complete data pack of all analyses, data, and results for archival purposes and traceability.

C.3   RCC DAMAGE GROWTH TOOL

C.3.1   Function(s) of Tool

The RCC Damage Growth Tool will be used to predict damage growth at impact damage sites, including time-to burn-through (breach) and hole growth, during entry and to develop the impact damage tolerance map for WLE and nose cap RCC.

C.3.2   Assumptions and Limitations

1.   Input Parameters:

   a.   Delamination Extent - The tool has limited capability for predicting an equivalent IML hole diameter pending development of on-orbit validated NDE techniques to determine the extent of delamination.

   b.   Mid-plane Delamination - Uncertainty in the predicted cavity burn-through time exists due to the limited number of arcjet samples from full-scale impact damaged RCC panels.

2.   Model Physics:

   a.   Mass Loss Expression - The tool, in its current state of development, acts as a conservative bounding estimation for predicting time to breach and damage growth.   Higher fidelity solutions are needed to avoid unwarranted conservatism in the prediction of material removal.

3.   Verification and Validation (V&V):

   a.   Arcjet Testing - The current tool is validated as conservative only for stagnation flow cases similar to the nose cap environment. Pending development of a wedge/crossflow tool, the stagnation tool has not been adequately validated as conservative for application to WLE environments that experience crossflow. Wedge test data for machined defects may indicate that the 0.020-inch substrate exposure threshold is unconservative at maximum heating, and that growth rates are larger than expected for stagnation cases. Given the small amount of available wedge data, the NESC is currently unable to conclude that machined-slot hole growth is atypical of impact-induced Types 4 or 5 damage.

   b.   Conservatisms - Although the stagnation tool appears biased toward conservative predictions, the safety margin decreases with increasing temperature. Because validation data is limited, an unskilled user may infer unwarranted confidence in tool predictions of untested configurations. Given the inherent uncertainties of certain tool inputs and assumptions, the tool requires use and interpretation only by subject matter experts.

C.3.3 Observations

1. Input Parameters:

   a. Delamination Extent - The assumption that the delamination extends 1-inch beyond the perimeter of any observed OML damage on an RCC panel may not adequately represent the extent of delamination. This observation is of concern because this assumption directly impacts the accuracy of the tool output "Equivalent IML Hole Diameter".

   In the V&V of the RCC Damage Growth Tool, the extent of delamination for arcjet samples was determined by ultrasonic through transmission and infrared thermography. The validation of the tool relies on the accuracy of ultrasonic and thermographic NDE techniques to accurately identify the extent of delamination. This accuracy has not been demonstrated due to limited data for extent of delamination of full-scale impact-damaged RCC panels as determined by NDE. Furthermore, the current capability for on-orbit NDE does not exist, and the predictive capability of the tool relies on the 1-inch assumption.

   Since on-orbit NDE is not currently available, delamination size will be estimated based on the 1-inch assumption. The tool developers acknowledge that this uncertainty will overshadow any uncertainty in other tool parameters.

   b. Mid-plane Delamination - The assumption that the worst case impact damage results in a single mid-plane delamination is reasonable based on the available evidence. Additional validation is needed to demonstrate that this assumption is conservative. This validation should be based on a comparison of tool predictions to time-to-burn-through determined for arcjet tests of full-scale impact damaged RCC panels. Without additional validation, this assumption introduces a measure of uncertainty into the predicted cavity burn-through time. If burn-through is already predicted by the current version of the tool, then this observation is irrelevant. However, if damage occurs in an area of the WLE that is predicted to survive re-entry with the current tool and the output "Cavity Burn-Thru Time (sec)" is required, then the validity of this assumption is critical.

3. Model Physics:

   a. Mass Loss Expression - The damage growth tool is empirically-based and does not capture the physics of an ablating material. The mass loss expression does not adequately couple the flow field and material physics to allow its use outside the range of test conditions for which it was developed. The Arrhenius expression used to predict material ablation does not account for the effect of mass transfer rate which is one of the primary driving parameters that causes material removal.

Instead, the tool simply uses pressure and temperature to determine the material recession rates. It appears that the recession correlations are based on test conditions that are conservative relative to flight[1] and, therefore, the tool is expected to yield conservative predictions for time to breach and damage growth. The level of conservatism is not readily ascertained because the primary variables that produce material recession are not specifically included in the calculations. It is important that the tool use the primary variables that effect material removal so that a more accurate surface recession prediction can be obtained. This approach would also allow for a more refined predictive tool that could be used for a sensitivity analysis.

4. Verification and Validation (V&V):

   a. Arcjet Testing - Based on stagnation testing of impact-damaged RCC panel, the 0.020" criterion for allowable coating damage or crack width appears valid. For more extensive damage, the stagnation tool appears to conservatively predict both the onset of damage growth and the ultimate IML damage area for stagnation arcjet cases. The tool designers claim that the stagnation tool conservatively predicts both the onset of damage growth and ultimate IML breach area for wedge test cases. However, this claim is not supported by the data supplied to the review panel. In fact, data for machined-slots in wedge specimens contradicts the conservatism claim.

   b. Conservatisms - The test series focused on development of conservative prediction capability rather than tool validation. As a result, the low repeatability of specimen preparation and test conditions hinders systematic evaluation of tool sensitivity to test parameters. The predictive conservatism of the (stagnation) tool varies with application to stagnation, or wedge cases and mode of induced damage. Also, the single cited comparison of equivalent stagnation (Run 2-2621-4, Model 1965) and wedge (Run 2-2651-4, Model 2035) cases is inadequate to establish the conservatism of either testing mode. The tool output does not indicate the confidence or conservatism with which its predictions should be evaluated.

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[1] The statement of conservatism is based on a verbal description of a high fidelity finite element analysis, including cavity radiation that has been conducted to establish that surface temperatures of 2960 °F at BP 5505 are consistent with peak flight heating conditions of approximately 70 BTU/ft2-sec for flight.

C.3.4 Recommendations

1. Input Parameters:

    a. Delamination Extent - Validated on-orbit NDE techniques should be developed for determining the extent of delamination. For STS-114, the current tool should only be used by an experienced subject matter expert, such as the tool developers, to predict hole growth.

    b. Mid-plane Delamination - Additional time to burn-through data should be obtained from arcjet tests of full-scale impact damaged RCC panels to determine whether the predicted burn-through times are conservative.

2. Model Physics:

    a. Mass Loss Expression - Future versions of the code should be more physics based and use the convective boundary conditions as the driving parameters which determine surface removal rates. Even if empirical expressions are selected, mass transfer rate should be used as a primary variable that determines material removal rates. This will result in a higher fidelity tool that more accurately predicts time to breach and damage growth.

3. Verification and Validation (V&V):

    a. Arcjet Testing - Impact-damaged wedge test data is urgently required for development and validation of a maximum damage criterion and a wedge/crossflow damage tool. Pending development and validation of a wedge/crossflow tool, the stagnation tool should be used to "predict" the results of existing wedge testing. This would indicate the sensitivity of the stagnation tool to deviations from stagnation flow, and establish the conservatism of the allowable damage criterion in non-stagnation environments.

        In addition, because achieving flight temperatures required testing at different heat fluxes for stagnation and wedge (and at heat fluxes far greater than those estimated for flight), there may be significant differences in the flow environments of both the stagnation and wedge configurations. Better understanding and quantification of these losses, and consideration of improved test configuration, is recommended.

    b. Conservatisms - More test data, for both stagnation and wedge cases, is required to test the sensitivity of tool conservatism to damage parameters. Additionally, the tool should be exercised to assess the sensitivity of tool predictions to likely uncertainties in the tool's assumptions. Those uncertainties include variations in damage locations, trajectory profiles, and the effects of multiple delaminations. The results of this analysis should be bundled into the tool documentation.

C.4   TILE RAPID RESPONSE DAMAGE MODEL (ICE)

C.4.1   Function(s) of Tool

"Rapid Response" damage models for both foam and ice debris damage on tile have been developed for the Space Shuttle Program. These models generate a damage geometry (depth, length, width, entry, wall and exit angles) based on debris transport analysis parameters (mass, velocity and angle of impact). The ice on tile model was developed by Southwest Research Institute (SwRI), with Dr. James Walker as the lead of the development team. The specific intended application is to evaluate the damage to both FRCI-12 and LI-900 tile from projectiles composed of ice of all densities possible in the environment.   It has been baselined for use in pre-flight and in-flight analysis by the Orbiter SLD panel. The estimate of the results is generated using 2-D analytical closed-form equations derived from the basic physics of the problem. These were validated by comparison with test and large scale numerical solutions using the Eulerian code CTH.   As with other analytical solutions to complex engineering problems, such as the Navier-Stokes Equation, simplifying assumptions are required to produce a tractable solution. The degree to which these assumptions are valid defines the usefulness of this analytical solution.

The model, as developed, uses nominal material values and other input parameters. Therefore, it would not be expected to envelope all of the test data, which captures all the variability in the parameters. To obtain a model that would be conservative without being excessively over-conservative, SwRI was directed to generate a model that would encompass 95 percent of the test data. This percentage level was deemed appropriate by NASA management compared with a traditional 3-sigma level of 99.86 percent in that other conservatisms were also built-in to the end-to-end debris liberation, transport, and impact scenario. A worst-on-worst-on-worst case calculation would result in unreasonable restrictions on tile capability. As the material properties are the primary source of uncertainty, SwRI decided that a reasonable way to achieve this goal was to apply a constant scale factor onto the material properties used in the nominal model. The value obtained after iteration was 0.615, and it was used to generate results and curves for this "95%" model.   This scale factor is in the same range as the spread of the strength characteristics of the tile by itself. These results along with the nominal model results have been documented and reported by SwRI.

C.4.2   Assumptions and Limitations

Key Assumptions:

1.   Cavity width is assumed to be twice the impactor width; the actual value is not calculated. *[The width was not systematically examined in either the analytical model or with CTH. Typically, the width is not as large as this factor. Data is presented to back up this assumption, but it is exceeded somewhat, occasionally by 100 percent.]*

2.   Assumes brick-shaped impactor.

3.   Entry angle is equivalent to impactor incident angle. [The foam on tile model does not make this assumption. The validation of this assumption has not been presented.]

4.   Sidewall angles and exit angles are assumed to be 90°.

5.   The model assumes the projectile impacts the target and never unloads (no rebound). *[This could potentially be unconservative, as the rebound gives more load transfer to the target (momentum transfer). By contrast, CTH does include unloading.]*

6.   The projectile is not rotating. *[Studies performed for foam on tile indicate that the possible rotational rates do not add significantly to the local impact velocity of ends of the projectile at these translational speeds.]*

7.   The impactor is assumed to have a curved lower leading edge of radius 0.25 cm to take into consideration ice fracture effects. This factor was empirically-derived.

8.   The glass layer of the tile is assumed to not provide noticeably more strength.

The material characteristics used for ice are as follows:

-   Modulus of Elasticity (E) = 8000 MPa
-   Shear Modulus (G) = 3000 MPa
-   Density = 0.914 g/cc (57 lb/ft3)
-   Poisson's ratio = 0.33
-   Flow stress = 2.0 MPa
-   Tensile strength = 1.0 MPa
-   Sound speed (c) = 2954 m/s

High strain compression curves were obtained from tests used for both types of tile.

Limitations:

1.   Projectile mass range: 0 to 1 pound (453 g)

2.   Impact velocity: 80 to 1500 ft/s

3.   Impact angle: 5° to 90°

4.   Maximum validated predicted cavity depth: 3"

5.   In the region of 60° to 90°, the model is only valid for $L/D \geq 2.5$, where D is the average of the width and height. *[The testing does not cover the ranges that are suggested above, but CTH was performed over those ranges. The largest mass tested was 100 grams (3" $\times$ 1.5" $\times$ 1.5"), and the highest velocity tested was 1000 ft/sec. SwRI has proposed the extension of the limits because CTH was performed up to these ranges. Although the analytical model predicts a much larger amount*

of damage than CTH at large velocities, it is reasonably validated. The CTH high velocity/high mass runs can be used to reliably identify any gross possible underpredictions, which it did not do.]

C.4.3   Observations

1. The ice on tile rapid response model is reliably conservative for all variations of the input parameters. There is a significant amount of validation by both experimental data and CTH numerical simulation. It appears in general to overpredict the damage by a significant amount in almost all cases. Since this is the case, the only assumption that could cause an underprediction by the analytical model (number 5) apparently is not significant.

2. There is a lot of scatter in the test data for ice impact on tile. In many cases there is 0.50-inch of penetration depth scatter for any given set of conditions, 0.75-inch scatter on depth is not that unusual and for a few cases there is almost 1-inch of scatter on depth of penetration.

3. The model is deterministic so uncertainties arising from variability in input data, such as material data for the tile and impact parameters (size and density of ice, impact speed and angle), are unaccounted for.

4. Eulerian models such as CTH do not have a capability to incorporate friction, which can be important for angled impacts.

5. The model does not predict the physics of "tile out" or "tile shear out". "Tile out" is a failure mode where the impacted tile fails at the densification layer with little surface damage, and the entire tile comes out down to the densification layer. "Tile shear out" is a failure mode where the impacted tile fails at a weak shear plane (45 degrees from surface to densification layer) and a large portion of the tile comes out down to the densification layer.

6. The model is only applicable to a predicted depth of penetration less than or equal to the densification layer. Once the impact is predicted to be into the densification layer, the physics changes and the model is no longer valid.

C.4.4   Recommendations

1. Tile damage analysis models should be brought in-house to NASA to enable additional evaluation and independent tile damage risk trades through structured, parametric model sensitivity studies.

2. An effort should be made to quantify how much the uncertainties from the input are propagated into the results. Sensitivity or response surface analysis could be a method to make this determination.

3.   There are some significant exceedances of the 2-to-1 crater width to projectile width factor in the high-density ice on LI-900 tile. A more complete explanation of why this is not important may be necessary.

4.   Present rationale for entry angle equaling impact angle (and contrast with foam-on-tile model rationale for assuming otherwise).

5.   Provide evidence of solution verification, i.e., "*The process of determining that a model implementation accurately represents the developer's conceptual description and specifications* - deals with mathematics and numerics; provides evidence that the model is solved correctly."[1] It is critical that the analytical model be quantitatively debugged by running the solution on simplified materials and/or short time frames that can be checked independently (outside of the solution code itself).

6.   Evaluate Lagrangian finite element solution of angled-impact problem, such as that applied with LS-DYNA$^©$, to assess effects that may have been missed by lack of a frictional coefficient.

7.   Provide evidence for assumption number 8 (glass tile layer not providing more strength).

8.   The decrease in the slope of the depth versus velocity curves for the CTH results for higher velocities (at all angles) should be examined in further detail. If this effect is accurate, then the analytical model predictions at these higher velocities are excessively conservative, which can lead to undesirable decisions.

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[1] Oberkampf, W., Roy, C., "Verification and Validation in Computational Simulations", AIAA Short Course, April 16-17, 2005

C.5   CAVITY HEATING TOOL

C.5.1   Function(s) of Tool

Space Shuttle Orbiter damaged tile regions must be analyzed by aeroheating, thermal, and stress groups to determine the effect of damage on safe re-entry. These damaged tile regions can cause a change in the nominal Orbiter surface heating profile. Heating profiles in the damage region are modeled by assigning a baseline ("undisturbed") heating value near the damage and applying an augmentation factor to the nominal heating value for the affected regions in or near the damage. The Cavity Heating Tool (CHT) is used to determine the aeroheating augmentation factors needed to support the thermal analysis of damaged tile regions.

The CHT uses wind tunnel test-measured heating augmentation factors to expand the historical 2-D turbulent engineering database to include fully laminar 3-D augmentation factors. In addition, the CHT provides 3-D turbulent augmentation factors and automated boundary layer property prediction capability to determine the properties needed for augmentation factor prediction. Historically, a 2-D turbulent cavity heating augmentation factor database has been used to support TPS damage analysis. This historical database is generally believed to be conservative, especially for the laminar portion of the entry trajectory. To reduce unnecessary conservatism, the CHT was developed to provide the OPO with more realistic augmentation factors in the laminar flow regime.

The CHT is capable of providing laminar and turbulent cavity heating augmentation factors for the Orbiter windward surface throughout a given trajectory. Laminar augmentation factors are derived from data obtained during recent wind tunnel testing performed at NASA Langley Research Center. Turbulent augmentation factors have been derived from the Reference Aeroheating Methodology. The following enhanced capabilities of the CHT reduce the unnecessary conservatism and increase the fidelity of this historical method.

1.   Provides time-dependent augmentation factors instead of applying a single conservative (Mach 18) value throughout trajectory.

2.   Expands the turbulent cavity heating augmentation factor database to include laminar factors (laminar factors are generally lower and apply over a significant portion of the re-entry trajectory).

3.   Applies more realistic heating distributions outside the cavity (non-linear vs. linear) based on wind tunnel test results.

4.   Full integration into the 3-D TMM allows for reduced analysis time requirements, providing more time for the critical decision-making process.

5.   The CHT is applicable for both pre-flight tile damage tolerance assessments and in-flight tile damage assessments.

C.5.2 Assumptions and Limitations (and Uncertainties)

Several key assumptions were made during the development of the CHT.

1.   Foremost is in the application of wind tunnel test derived augmentation factors as valid for flight conditions. The developers are conducting a flight traceability study using CFD analysis to show that CHT augmentation factors cover any wind tunnel-to-flight increment.

2.   The orientation of the damage site is assumed to be aligned with the local flow field on the vehicle surface, and no adjustments are made for crossflow cavities.

3.   The CHT was developed from test data on cavities aligned with the flow. Results from limited test data of cavities with crossflow do not, however, indicate any discernable trend that the distribution of augmentation factors would be altered. Note that for large crossflow angles > 15deg the heating becomes less severe because effective cavity length decreases. *(Adjustments are to be included in future versions after additional testing has been completed.)*

4.   It is assumed that an entry and exit angle of 90º is conservative and plays a minor role in augmentation factor predictions. This is supported by a limited available wind tunnel data for non-90º angles (angles of 90º, 45º, 25º, and 6º were tested). Also, the CHT was developed from test data on cavities with $1.0 < L/W < 12.5$ ratios. Width appears to play a minor role, especially for wider cavities.

5.   It is assumed that the derived laminar methodologies can be applied to regions on the Orbiter with Mach edge numbers (Me) below values tested in the wind tunnel. This is supported by data which shows no discernable Me trend for average cavity floor values and maximum heating augmentation factors for the non-transitional cavities in the range tested

A few key limitations have been noted in the development of the CHT.

6.   The tool is designed for local cavity augmentation factors – no factors further than one cavity length downstream are provided by the CHT. (Note that the additional downstream effects are addressed by the Boundary Layer Transition Prediction Tool).

7.   The updated CHT wind tunnel test results address only conditions of laminar flow over cavities. Turbulent flow over cavities is addressed by the historical method. Additionally, the automated results from the CHT are not valid for leeward surface, only windward surface application is appropriate.

8.   The CHT cannot be used for breach flows.

Uncertainty sources that contribute to the CHT overall prediction accuracy have been identified.

9.   The CHT relies on input from the CFD Smooth Baseline Tool to provide boundary layer property predictions. These boundary layer properties have uncertainties on the order of 15 percent. The CHT is based on wind tunnel test data, which includes its own source of uncertainty in addition to any for extrapolation to flight conditions. Tile gap effects are not included and it is suggested that an uncertainty factor of 20 percent be applied to account for these configurations.

10.   Results for wing glove and chine regions (high pressure gradient regions) will not be validated before flight. For these high pressure gradient regions, a 50 percent uncertainty factor is applied to the augmentation factors.

C.5.3   Observations

1.   The NESC peer-review assessment is that the CHT can be used for STS-114 with the accepted risk of recognized limitations, some significant, to the application and validity of the tool.

2.   The CHT peer-review did highlight several primary concerns from an end-to-end validation perspective. The first is in regards to Aeroheating data integration into the TMM. This should be reviewed and fully understood by both the CHT developers, the Aerothermal environments engineers, and the TMM users. This finding does not specifically affect the validity of the CHT, but is essential to the integrated analysis process and must be resolved prior to RTF. The second is the "50/50 rule" to establish the cavity geometry. Application of this simplification must be applied with caution as it affects the cavity dimensions which has a direct effect on the CHT augmentation factors and will be a first order effect in the TMM results. The combined engineering judgment from aeroheating, thermal, stress and TPS should be involved in establishing the cavity dimensions based on this rule.

C.5.4   Recommendations

The CHT peer-review highlighted eight (8) major findings and has provided specific recommendations to address each. Many of these findings address the recognized assumptions, limitations, and uncertainty factors addressed in Section C.5.2. The following recommendations have been developed from this peer-review regarding the CHT.

1.   **Lack of Validation for Flight Conditions**

There is a concern that the wind tunnel data are being used to predict flight conditions without a quantification of the uncertainties inherent in the extrapolation. Specifically,

the wind tunnel data does not reproduce the real gas non-equilibrium chemistry and the ratio of boundary layer edge temperature to wall temperature that occur in flight.

These real gas and wall temperature effects on the heating bump factors are not addressed in the documentation, but the effects need to be assessed. CFD solutions can and should be used to understand these effects. A direct comparison should be made by computing CFD solutions for a wind tunnel case and the corresponding flight case that the wind tunnel data is meant to predict. This process should be performed for a high Mach number case which will have the largest real gas effects, and a low Mach number case which will have the largest wall temperature effect. The differences between the wind tunnel CFD solutions and flight CFD solutions will provide an estimate of the uncertainty in the extrapolation process. This extrapolation will be partially addressed by the CFD For Cavity Heating: Flight Traceability study.

2.   Cavity Orientation Assumption in Wind Tunnel Data Base

The new CHT is based on measurements made with the axis of the cavity aligned with the local flow direction. Since most cavities are the result of impact damage during ascent in which the flow field is significantly different than during re-entry, it is likely that some misalignment between the local flow direction and the axis of the damage will exist. Additional understanding of the effects of crossflow cavities must be pursued before RTF and can be accomplished with data already available.

A series of 19 wind tunnel runs were made to investigate the effects of this misalignment. Some results are presented in the Cavity Heating Tool Draft Final Documentation. It is noted that the effect of cavity misalignment is to reduce the effective L/H which stabilizes the flow and reduces the resultant increase in heating level. Thus, ignoring the misalignment should produce conservative results, in that the computed bump factor will be higher than the physical value. Some quantification of this effect is necessary to prevent overly conservative results which could result in an unnecessary repair. *(It has been noted that adjustments are to be included in future versions after additional testing has been completed.)* However, the results of the 19 misaligned runs should be used to determine if a simple relationship between flow angle and bump factor reduction exists. Since the amount of data for misaligned cavities is relatively limited, incorporation of this relationship into the CHT is not recommended. However, this information should be developed to aid in the decision-making process which determines if repairs to the Shuttle tiles are necessary.

3.   Augmentation Factors for Non-Rectangular Cavities

The CHT relies on correlations obtained from wind tunnel tests of rectangular cavities with 90° entry/exit angles. Photographs of actual Shuttle tile damage indicate that these

cavities are typically irregular in shape with entry and exit angles that are shallower than 90°. There is a concern that application of the CHT to these non-rectangular cavities typical of actual flight damage may not produce conservative results. Additional understanding of the effects of non-rectangular must be pursued before RTF and can be accomplished with data already available.

The CHT correlations are based on data obtained in the NASA Langley 20-inch Mach 6 Air Tunnel for rectangular cavities of varying L/H, Re, M_e, and H/δ. In addition to these runs, a series of runs were made which included variations in planform, cross-section profile, and cavity orientation relative to the local free stream flow direction. The data presented within the Cavity Heating Tool Draft Final Documentation indicate that for a significant number of cases the Cavity Average and End Wall Peak bump factors for the non-rectangular cavities can exceed the bump factors for the rectangular cavities by non-trivial amounts.   The significance of the increase in the End Wall Peak bump factor may not be great, since this would result in enhanced heating only to tile material at the aft end of the gouge. However, an increase in the Cavity Average bump factor could conceivably result in a significant increase in heating on the floor of the damage site, and thus cause excessive temperatures in the vehicle structure.

It is recommended that these wind tunnel test results be re-evaluated to determine: a) the exact nature of the boundary/shear layer in the vicinity of these cavities, and b) a relationship between the enhancement in bump factor and the deviation of the geometry from the standard rectangular cavity.   It is likely that the first time this tool is used, the cavity will be significantly non-rectangular, and questions concerning the heating enhancements will have to be addressed.

4.   Laminar Wind Tunnel Test Data Base

The new CHT is based on a series of wind tunnel tests conducted in the NASA Langley 20-inch Mach 6 Air Tunnel for laminar flow over cavities. For conditions in which the flow is determined to be transitional or turbulent, based on the results of the Boundary Layer Transition Tool, the turbulent methodology which was developed early in the SSP is used. In the Cavity Heating Tool Draft Final Documentation, it states that the turbulent methodology is "generally conservative." An example of a case in which the turbulent methodology may not be conservative is presented in which, when the test results indicate transition from closed cavity laminar correlations to turbulent correlations, both the resultant bump factor and the heating rate decrease.

Some transitional and turbulent cavity cases were obtained in the wind tunnel tests. It is recommended that an investigation be conducted in which the turbulent cavity

methodology is applied to the transitional/turbulent wind tunnel cases to determine the extent to which this historical methodology is conservative.

5.   **Application to Limited to Windward Side Damage**

The CHT, as developed and implemented, is not directly applicable to the evaluation of leeside damage. The CHT team clearly recognizes this limitation and in fact discusses the arguments against application of the tool to leeside damage sites. The CHT database has been generated based on tests at conditions applicable to wind-side flow. The bulk of the tool relies on an assumption of attached laminar flow, whereas the leeside, during the high heating phase of the mission, will typically be dominated by turbulent and/or separated flow.

Having accepted these limitations, the CHT team, working with the aeroheating panel, formulated an approach to provide augmentation factors for leeside cavities. The concern is that the approach chosen will rely on several assumptions that may in fact be incorrect. One, the historical turbulent approach "generally assumed to be conservative" will be used. This assumption has yet to be validated by the cavity heating team using the data in hand. Two, the edge Mach number on which this turbulent formulation relies will be computed using CFD - based on CFD in a region considered to have relatively low confidence levels. These assumptions coupled with engineering judgment will be used to manually provide augmentation factors for the thermal analysis for damage sites on the leeside.

There can be many arguments made that leeside TPS damage is unlikely to prevent a safe return of the vehicle. The leeside TPS is generally over designed (i.e., structural temperatures are maintained well within the margins) and heating levels are fairly low relative to the wind-side and stagnation areas. While this statement is certainly true, an examination of the sensitivity of the structural margins to various augmentation levels of the nominal heating or loss of TPS on the leeside would provide some insight. The BLT Tool generally assumes that transition will not wrap around to the leeside if the damage is outside the attachment line. There have clearly been cases shown where the transition can sweep across the attachment line. The concern is that possible turbulence emanating from damage on the wind-side could raise the heating levels in the region of any damage on the leeside.

It is recommended that the CHT, BLT, and TMM teams perform sensitivity studies to assess the need for a leeside capability and provide some rationale for the engineering judgment that will necessarily be used for leeside damage should it occur.

6.   Tile Gap Effects

There is a concern that augmenting the local bump factor by a 20 percent uncertainty factor to account for tile gap effects on the cavity heating level is not sufficient. Historically, an adjustment on the local heating or tile thickness was used in regions with unfilled gaps to account for a possible impact on structural temperature levels. The concern is based on current arcjet experimental data presented in the Cavity Heating Tool documentation. The cavity heating data are presented for tests with and without tile gaps and show 14-48 percent increases in the heating factors due to the presence of a tile gap. Convincing arguments were presented concerning the credibility of the data and it is believed the low end of this range is more accurate. As a result of the questionable data, the cavity team recommended only a 20 percent increase in the bump factor for cavities in the presence of tile gaps.

It is recommended that a properly designed test be conducted after RTF so the tile gap effect on cavity heating can be quantified. As the tools mature and the end-to-end conservatism is eliminated, the tile gap effect, as established by test, should be employed. Additionally, verification that that 20 percent uncertainty factor is included in the TMM for this configuration is required as part of the overall end-to-end validation.

7.   Pressure Gradient Effects

There are no data for cavities in regions with pressure gradients. A 50 percent uncertainty was arbitrarily added based on engineering judgment to regions with high pressure gradients, but there is no rationale given for choosing a value of 50 percent. Engineering analysis to support this uncertainty factor was not presented.

It is recommended that before RTF, CFD results should be used to determine a value of the correction factor and the threshold value of the pressure gradient for which it is applicable. In the longer term, further analysis, testing, and/or CFD results are needed to quantify heating bump factors and uncertainties as functions of pressure gradient, body location, and free stream conditions. This objective should be added to the planned follow-on development testing to address crossflow and cavity shape effects.

It is further recommended that if cavity heating data are needed in a region with a pressure gradient during STS-114, that the heating bump factor be determined manually, using CFD solutions if at all feasible.

The following two recommendations address end-to-end validation arising from the CHT peer-review.

8.   Application of CHT Bump Factors into the TMM

A great deal of time and discussion during the CHT peer-review focused on the correct way to apply the bump factor obtained from the CHT to the TMM. As a result of a conversation with Boeing/Huntington Beach and previous interactions with the CHT development team, the NESC Cavity Heating Tool Peer-Review team has formed a rough understanding as to how the TMM manages the surface energy balance. If this understanding is correct, then applying the bump factor to the heating rate, interpolated from four surface temperature values, is an acceptable approach. Further investigation is required to conclusively address implementation issues regarding exactly how the CHT augmentation factors are used in concert with the baseline heating in the TMM.

It is recommended that an explanation from someone familiar with the TMM explain how the TMM solves the surface energy balance and how it uses the bump factors within this energy balance be provided. A simple sample solution would also be of great value. There is no need to take the process completely from the cavity wind tunnel data through the TMM calculations. Starting with a set of bump factors and applying them to the heating problem will be more than sufficient.   Additionally, this should address the application of the catalytic heating factors and verify which emissivity values are being used and that they are consistent throughout the process. This should be provided as part of the end-to-end validation exercise.

9.   Reliance on 50/50 "Rule" to Establish Cavity Depth

The cavity modeling team is given this rule of thumb to establish cavity depth in an automated fashion. This "rule" appears to be one that has been developed outside the purview of the CHT, but its application contributes to the geometric definition of the cavity, critical to the thermal analysis. There is no documentation of this rule within the CHT material and its genesis was unclear to the peer-review team. *Note: the rule is established in the Tile Repair Project Analysis Tools Requirements document.* The rule appears to effectively "smear" all remaining material on the cavity floor over the entire area of the cavity floor. It also appears that the 50/50 rule may be applied regardless of the size of the cavity. For a small cavity, the 50/50 rule is likely of little or no consequence. However, as the cavity size grows there could conceivably be a large area of minimally protected structure. It was not clear that there were any bounds associated with the 50/50 rule, beyond which human intervention would be required.   Application of this simplification must be applied with caution as it affects the cavity dimensions,

which has a direct effect on the CHT augmentation factors and will be a first order effect in the TMM results.

It is recommended that the 50/50 rule be utilized as first cut, with an established depth (or height of floor material) below which a flag will automatically be set to require intervention in the cavity modeling to accommodate this type of situation. Similarly, establish a maximum cavity area above which a flag would be set to require intervention. All cavity models should be reviewed by the combined engineering team including membership from the CHT, BLT, TMM, and CATIA modeling teams and compared with the actual damage in establishing the cavity dimensions based on this rule.

C.6 CFD FOR CAVITY HEATING: SMOOTH BASELINE

C.6.1 Function(s) of Tool

The Shuttle RTF provided a natural extension for application of high-fidelity Computational Fluid Dynamic (CFD) tools, not only to develop a comprehensive laminar, aerothermal database for the smooth configuration of the Orbiter, but also to investigate and assess the vehicle health effects for various types of TPS damage and proposed on-orbit repair strategies. In support of these activities, the establishment of an aerothermal database of laminar, real-gas Navier-Stokes CFD solutions that span a range of Orbiter entry flight conditions has been completed. The Smooth OML Aerothermal Solution Database (SOASD) is an essential resource for nominal (Smooth OML) pressure, heating particularly the boundary layer state information. The comprehensive set of aerothermal data provided includes not only surface pressures, shear forces, temperatures and heat fluxes, but also other quantities such as the fluid dynamic (e.g., edge Mach number) and thermochemical state of the flow at the boundary layer edge, and integral boundary layer parameters such as displacement and momentum thickness. The latter parameters are of use in determining, in an engineering sense, the onset of transition of the wall-bounded shear layer from laminar to turbulent. All of these required data are determined a posteriori from the computed CFD solutions.

The high-level inputs for the SOASD tool are the location and geometry of TPS damage or repair, and the flight Mach, Reynolds number and angle-of-attack. The tool then outputs the local conditions at each damage/repair site. These include the reference heat flux, temperature, pressure, and boundary layer parameters for use by the Cavity Heating Tool (CHT) and the Boundary Layer Transition (BLT) Prediction Tool. The SOASD is to be used pre-flight in support of damage tolerance assessment activities, historical data reconstruction (e.g. Platinum dataset activities), and the establishment of the 3"/1" imaging requirements verification. For real-time on-orbit mission support, the tool is used to assist in an informed damage disposition decision. The SOASD provides direct input to CHT and BLT Tools for Damage Assessment Team analyses. Additionally, it is foreseen that the CFD Process/Tools can be used to augment data and information available. This last application is not currently considered as part of the critical/primary path.

It should be noted that prior to STS-107, no previous detailed comprehensive CFD aerothermal analysis database for Orbiter entry flight conditions existed. The new SOASD represent the best efforts (state-of-the-art) calculations of accurate Orbiter entry flow-fields. The CFD analysis tools used in the study are the DPLR code from NASA Ames Research Center and the LAURA code from NASA Langley Research Center. Both codes represent modern implementations and methodologies for application to real-gas Navier-Stokes calculations. The two codes are applicable to both viscous, compressible, ideal-gas (tunnel conditions) and real-gas (chemically non-equilibrium, high enthalpy – flight condition) flows.

Damage Assessment Tools Using the CFD Smooth Baseline Database

This database is a resource directly needed by two primary TPS damage assessment tools that are to be used during all future flights in the event of observed damage. The first is the CHT which serves as the primary predictor of local heating augmentation within and around any observed tile damage. The CHT relies primarily on a large database of wind tunnel cavity heating experiments to establish predicted heating for a cavity based on boundary layer parameters (boundary layer thickness, edge Mach number and Reynolds number based on momentum thickness). To relate a particular damage observed on-orbit to the database of experimentally observed heating, boundary layer parameters are used by the CHT to perform the mapping. Thus, essential inputs to the CHT are the boundary layer parameters over the tile acreage region of the Orbiter OML as a function of the entry trajectory that the SOASD provides.

The BLT Tool will also be used during future Shuttle flights in the event of observed Orbiter TPS anomalies. The purpose of the BLT Tool is to predict, for an observed surface perturbation, the time during entry when the onset of transition to turbulence occurs as well as the extent (area) of the transition. Early transition to turbulence, experienced at sensitive locations on the Orbiter, produces extreme heating and may have catastrophic consequences. As in the case of the CHT, critical inputs to the BLT Tool are the boundary layer parameters as functions of entry trajectory and OML location. The SOASD provides this boundary layer information – particularly at the higher Mach numbers experienced during nominal peak heating.

C.6.2 Assumptions and Limitations

Several key assumptions have been made during the development of the SOASD.

1. The tool utilizes a set of 15 CFD solutions at points in Reynolds No-Mach space along a nominal Orbiter entry trajectory. Additional CFD solutions at off-nominal angle-of-attack solutions are provided at each trajectory point. It is assumed that this adequately captures the required variations necessary for the downstream (CHT & BLT) tools.

2. The CFD analysis tools utilized are based on the assumption that the flow is laminar, continuum mechanics is applicable, and the geometry is very close to that characterized in the current Orbiter CAD model.

3. For the application of the results of these calculations, it is assumed that the accuracies and uncertainties for boundary layer parameters at flight conditions are consistent with quantified accuracies and uncertainties for boundary layer parameters at tunnel conditions and heat-rate values at flight conditions.

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4.   For modeling efficiency, the entire Orbiter is modeled with the boundary conditions of a uniform RCG surface coated and non-heat conducting surfaces. This is assumed adequate to capture acreage wind-side tile parameters of interest.

5.   It is assumed that the grid resolution, numerical models, physics models, and surface characterization adequately replicate Orbiter entry conditions.

Several key limitations have been noted in the development of the SOASD.

6.   The database is intended for tile TPS application and the products from the database will only be used to determine aero, aerothermal and boundary layer parameters for smooth OML wind-side RCG tile acreage regions.

7.   The SOASD is specifically not to be used for locations on or very near the WLEs, the nose cone or the leeside.

8.   As noted in the assumptions, the products from the database are only applicable for the Orbiter under laminar flow conditions.

9.   The products from the database will only be used for the Orbiter under conditions in which the flight parameters match those represented along the nominal entry corridor covered by the Reynolds Number – Mach, angle-of-attack space captured in the computations.

10.   The products from the database must be used with the full understanding and acceptance of the quoted parameter based uncertainties. In particular flight boundary layer quantities, such as the boundary layer thickness, will be used with the accepted risk of the lack of substantial validation of defensible uncertainties. (i.e., no direct comparison of boundary layer thickness measurements – flight or ground test – and SOASD predictions are available).

Several uncertainty sources contribute to the overall prediction accuracy contained in the SOASD.

11.   CFD analysis solutions rely on proper grid resolution and quality as well as proper physical and numerical modeling. The calculations provided in the SOASD have been assessed for these uncertainty levels and documented. The accuracy and validation of the tool have been established by comparison of predictions of boundary layer properties at wind tunnel conditions. Traceability to flight is accomplished by comparison of flight heating rate data with the CFD analysis predictions. These form the basis for the validation of the SOASD predictions of boundary layer properties at flight conditions.

12. The flight data and tunnel experimental data both include uncertainties which are not accounted for in the comparisons.

13. The lack of high enthalpy boundary layer experimental data for direct comparisons requires the acceptance of an unquantified uncertainty in the flight predictions.

C.6.3 Observations

1. An independent Peer-Review Panel was established by the tool developers and augmented with NESC designees. The group was chartered to assess the SOASD tool readiness for supporting STS-114 RTF. The peer-review team's assessment is that the SOASD can be used to support STS-114 for damaged TPS assessment with the accepted risk of recognized limitations to the application and validity of the tool. The major findings of the peer-review team have been reported to the OPO. The NESC reviewers concur with these findings.

2. These major observations can be summarized in two primary findings. The first is in regards to the flight boundary layer thickness predictions. As noted previously, validation of the accuracy of boundary layer thickness predictions at flight conditions is based on comparisons at wind tunnel conditions and comparison of flight heat rate values. Therefore, the predicted boundary layer thickness at flight conditions in the SOADB does not have direct quantitative support for validation. Comparisons with flight data for heating rate and pressures are considered very good and suggest that the BLT predictions are relatively accurate for the regions of SOASDB applicability. Confirming the validity of this assumption is remaining open work. The NESC supports the pursuit of experimental boundary layer data at high-enthalpy, flight-like conditions, to improve validation rigor

3. The initial report did not adequately address comprehensive uncertainty quantification and did not give adequate treatment to the separation of uncertainty contributors including: numerical, physical model, geometric, post processing, experimental (instrumentation) and inherent system uncertainty. It was recommended that the report should also document uncertainty bias and maximum deviation. This has been addressed in an updated version of the documentation.

C.6.4 Recommendations

The SOASD Peer-Review highlighted a couple of major findings and has provided specific recommendations to address each. Many of these findings address the recognized assumptions, limitations and uncertainty factors addressed in Section C.6.2. The following recommendations have been developed from this peer-review regarding the SOASD.

1. **Flight Boundary Layer Thickness**

The boundary layer thickness accuracies and uncertainties at flight conditions in the SOASD are reliably correlated to accuracies and uncertainties of heating at flight conditions and boundary layer thicknesses at tunnel conditions. Validating the accuracy of boundary layer thickness predictions at flight conditions, based solely on these comparisons, is not well supported. As a result, the predicted boundary layer thickness at flight conditions presented in the CFD For Cavity Heating documentation does not have a quantitative support for validation and represents a significant assumption for the tool. It was recommended that further assessment of the validity of this assumption should occur as follow-on work that examines the relationship between δ, Re, M_e, T_e, T_w, Pr and γ through unit CFD tests for flat plates with and without high enthalpy. This should also be for the unit CFD tests for the Orbiter configuration at flight conditions to quantify the sensitivities of the solutions to various parameters. However, it is anticipated that hard validation of the boundary layer thickness at flight conditions will not be possible without high enthalpy experimental data. Therefore, it is also recommended that the possibility of obtaining high quality experimental validation data from a ground test facility for high enthalpy boundary layer thickness predictions be studied. If an experimental test proves feasible (i.e., considering resource and time constraints), such tests shall be performed to survey the boundary layer thickness at high enthalpy conditions. It should be noted that the need for this data was recognized by the OPO, which requested that a delta-funding requirement and test strategy be submitted for consideration.

2. **Comprehensive Uncertainty Quantification**

The CFD for Cavity Heating documentation did not adequately address comprehensive uncertainty quantification. The report did not give adequate treatment to the separation of uncertainty contributors including: numerical uncertainty (e.g. truncation error or mesh resolution, scheme accuracy, and convergence accuracy), physical model uncertainty (e.g. chemistry models, real-gas transport models, surface properties), geometric uncertainty (e.g. geometry accuracy), post processing uncertainty (e.g. calculation of the boundary layer edge location), experimental or instrumentation uncertainty, and inherent system uncertainty. It was recommended that the report address the above parameters and document uncertainty bias and maximum deviation in addition to the standard deviation. Much of this work has been completed and included in updated documentation provided to the peer-review team.

3. **Clear Assumptions, Objectives and Limitations**

Greater clarity on the assumptions are being made. The objectives/purpose of the database and the limitation/restrictions of the database should be included in the

documentation. This has been completed and included in updated documentation provided to the peer-review team.

4.   Other Issues, etc.

One reviewer noted confusion on the methodology for calculating the boundary layer edge. Additional descriptions shall be added to clarify the methodology. It is noted that the BLAYER utility calculates along gridlines and not an interpolated normal axis. An attempt will be made to calculate the orthogonality of these lines.

Instrumentation uncertainty is not quantified in the boundary layer report and thus cannot be properly addressed. However, a bit more discussion on this topic should be added. The added discussion should address the issue of why different methods were tried for the computation of tunnel free stream conditions.

Discussion needs to be added that describes the differences between the LAURA and DPLR implementation of the physical models, and how it is an exercise for future study to try and get the physical models precisely the same between the two codes. The chemical non-equilibrium portions of the two codes contain enormously complicated and extensive models to account for the non-ideal gas effects. Ensuring that these are done precisely the same in both codes would take a very long time. Also, the numerical dissipation schemes for the two codes are quite different making exact code verification studies impossible.

C.7   CFD FOR CAVITY HEATING: FLIGHT TRACEABILITY

C.7.1   Function(s) of Tool

Flight Traceability is intended as a supporting study for the ***tile cavity heating*** tool (refer to Appendix C.5). The *tile cavity heating tool* is to serve as the primary predictor of local heating augmentation that occurs within and around any observed tile damage. The heating augmentation products of the tile CHT, in turn, feed the tile thermal and structural assessment tools to analyze the impacts of any change in heating on the health of the Orbiter TPS. A noteworthy aspect of the CHT implementation is that the derived laminar flow cavity heating bump factors it provides are based entirely on low-enthalpy, ideal-gas, and wind-tunnel experiments. The mapping of this experimental database of cavity heating results is performed via the CHT by directly relating boundary layer parameters at tunnel conditions to those at flight. The obvious concern is that heating bump-factors at high-enthalpy real-gas flight conditions will not correlate to boundary layer parameters in an identical manner as they do at tunnel conditions. The implication is that the heating bump factors predicted by the CHT might either over or under estimate the actual heating. The Flight Traceability results are not intended to form a basis for determining the heating bump factors for a given cavity damage assessment on-orbit. Instead, the CFD study is simply a supporting effort, giving greater insight for the correlation of heating bump factors occurring at flight conditions.

Under the current study, CFD solutions for tile cavities are computed at both wind tunnel and flight conditions to understand the cavity heating bump factor relationships between the two. The study considers only laminar flows on rectangular cavities that are aligned with the flow. At the present, the CHT (version 2) also idealizes all cavities as rectangular. Again, the objective of the study is not to develop a comprehensive local heating CFD prediction database for Orbiter tile cavities, but to develop supporting evidence for the relationship between tunnel heating bump factors and flight heating bump factors for equivalent tile cavities.

The NESC peer-review has been completed and the results presented to the tool developers and SSP. However, the formal documentation of the peer-review is not complete as of the release date of this report. A separate report, "Inspection of the Math Model Tools for On-orbit Assessment of Impact Damage", will be prepared by the NESC that fully documents all of the tool peer-reviews.

C.8 CATALYTIC HEATING TOOL: DAMAGED

C.8.1 Function(s) of the Tool

1. For the hyper velocity entry of the Orbiter, the KE of the air molecules processed by the Orbiter bow shock relaxes into other energy modes, such as chemical and thermal energy. The high temperatures associated with this conversion of KE into chemical and thermal energy cause the air molecules to dissociate into their constituent atoms absorbing large amounts of the total available energy. When these atoms recombine into stable molecules at the surface of the vehicle, due to catalytic effects, the latent dissociation energy is released producing increased heating levels to the thermal protection system (TPS).

2. Different TPS surface materials can have different surface catalytic properties and can modify the rate at which these catalytic reactions take place. For example, because of increased surface catalycity, the surface heat rate will be correspondingly increased. The Catalytic Heating Tool (CHFT) provides these augmentation factors as enthalpy-dependent laminar heating augmentation factors for the damaged TPS Bare Tile and RCC substrate as well as the proposed TPS repair materials. Specifically, these are catalytic augmentation factors for uncoated tiles (LI-900, LI-2200, and FRCI-12), tile repair materials (emissivity wash and STA-54), damaged reinforced carbon-carbon (RCC) substrate, and RCC repair materials (NOAX – RCC Crack repair material, MCM-700 coated CSiC – RCC Plug repair material). The CHFT is used both for pre-flight damage tolerance and in-flight damage/repair assessments.

3. The catalytic heating augmentation factors defined are applied as follows:

   Final Local Heating = Catalytic Heating Augmentation Factor* Baseline Heating

   The development of these catalytic heating factors is based on arcjet test data from NASA ARC and JSC facilities. The basic approach was to determine maximum augmentation factors relative to heating for healthy (undamaged) coated tile and RCC. Damaged, uncoated RCC catalytic heating factors were developed using analyses that are validated by tile OEX flight data (STS-2, 3 and 5), and then verified by limited RCC arcjet data. The variation of factors with flight conditions was based on the OEX flight measurements on tiles that were coated with a highly catalytic material.

4. Several enhancements are provided by the CHFT. Previously, catalytic heating data for damaged, bare tiles were not available and the heating was assumed to be the same as the heating on healthy Reaction Cured Glass (RCG)-coated tiles. Data are now available to support this assumption. Additionally, analytical tools and limited test data are now available to quantify catalytic heating to damaged uncoated RCC and some candidate

RCC repair materials. However, data for the tile repair material, STA-54, does not yet exist (testing is planned).

5. Other factors that can affect the heating, such as damage geometry, are accounted for in other tools. The catalytic heating augmentation factor applies to the change in heat flux due to the change in catalytic recombination rates of the oxygen and nitrogen. Since the nominal (undamaged) material on the tile surfaces of the Orbiter is RCG, the black coating on the windward TPS tiles, the catalytic heating factor of other TPS, and TPS repair materials are given as a ratio to the RCG heat rate.

C.8.2   Assumptions and Limitations (and Uncertainties)

Several key assumptions were made during the development of the CHFT.

1. Foremost among these is that the arcjet data bound (place an upper limit on) the catalytic heating effect, and that the resulting heating factors can be scaled to flight. This flight extrapolation depends on assuming that the variation with total enthalpy of the catalytic heating factor is the same as that derived from the catalytic tile effects flight experiments on the OEX flights (STS-2, 3, and 5). In deriving the catalytic heating factors, an assumption regarding emissivity is required to adjust the radiative heating in the energy balance.

2. This assumption has a direct effect on the catalytic results. For the CHFT development, the nominal emissivity values were used by the Thermal Group in this data analysis.

3. There is limited available arcjet data to use as the basis for some catalytic heating factors *(Bare LI-900: Two test points – 1600 F & 1800 F on RCG; Bare FRCI-12 and LI-2200: Two test points – 2000 F and 2300 F on RCG; Emittance Wash: Four test points – 1600, 1800, 2000 and 2300 F on RCG).*

A few key limitations have been noted in the development of the CHFT for windward surface tiles, RCC surfaces, and to other materials tested.

1. The CHFT provides enthalpy-dependent heating augmentation factors for damage and repair materials for the laminar portion of the flight trajectory.

2. Turbulent factors are ignored.

3. The CHFT results are simplistic; and bounding heating factors are based on limited test data. As such, they should be considered as preliminary.

Sources of uncertainty that contribute to CHFT overall prediction accuracy have been identified.

4.   As stated, the catalytic heating factors were developed by bounding available data. Additionally, any uncertainty in emittance values directly affects the analysis of arcjet test data and values derived from these data.

5.   Emittance is typically difficult to determine, even to define. It directly affects the uncertainties in catalycity. Most importantly, the end-to-end analysis must use same emittance for flight predictions. For bare tiles, the emittance can be particularly difficult to define. Bare tiles are volume emitters, therefore, radiation comes from inside as well from the tile surface, however, the tiles are modeled with surface emittance only. The effect of neglecting the volume emittance of the tiles has not been quantified.

C.8.3   Observations

1.   The NESC peer-review team's assessment is that the CHFT (augmentation factor approach) can be used on STS-114 for damaged TPS with the accepted risk of recognized limitations, some significant, to the application and validity of the tool.

2.   Catalytic factors for damaged TPS (bare tile and RCC substrate) are based on the limited available testing. However, the analysis is acceptable for application on STS-114. The TPS bare tile assumptions and results appear reasonable and bounding. The bare/damaged RCC substrate also appears bounding. It should be noted that catalysis of reacting surfaces, e.g. bare RCC, may be a misnomer and referring to this as fully catalytic heating might be an invalid concept.

3.   It is more accurate to call this "augmented heating" since the process includes oxidation, combustion, mass injection, catalysis, etc., that occurs with "bare RCC".

4.   The catalytic factors for TPS repair (STA-54, RCC crack & plug, emittance wash) are based on limited and incomplete arcjet test data. The tile emittance wash and RCC crack repair catalytic factors are based on limited available arcjet test data and are reasonable and bounding. The analysis is acceptable for application on STS-114.

5.   For the tile repair material, STA-54, a good catalytic factor based on engineering data is not available. This is further compounded by lack of thermal property data. Therefore, no credible uncertainty analysis exists and the use of the present CHFT factors are suspect.

6.   For the RCC plug repair material, an average catalytic factor based on arcjet test data does not address the split line effects (boundary between plug and RCC), which could result in local increased heating. This potential increase in heating at the split line requires further assessment.

7.   The nominal emittance assumption is a significant limitation to establishing the catalytic factors. Emittance is a major parameter in the energy balance equation that is used to

estimate the catalytic factor. The lack of accurate emittance data will drive catalytic factor uncertainties. The determination and use of emittance is one of the critical end-to-end analysis validation topics that must be addressed.

C.8.4 Recommendations

The CHFT peer-review has highlighted several major findings and has provided specific recommendations to address each. Many of these findings address the recognized assumptions, limitations, and uncertainty factors addressed in Section C.8.2. The following recommendations have been developed out of this peer-review regarding the CHFT.

1.   Future Enhancements

> Recommendations for continuing development of the CHFT were presented at the OCCB and recognized by the OPO, which requested that a delta-funding requirement be submitted for consideration. The NESC concurs with this course of action. Enhancements to consider should include replacing bounding factors with an engineering method of modeling catalytic heating as a function of surface temperature and of re-entry-gas energy-state. The characterization of STA-54 in arcjet tests should be completed. The catalycity and emittance of RCC repair materials should be measured. The emittance assumptions for other materials must be reviewed and updated as required.

2.   Emittance

> The development of the CHFT revealed that a major uncertainty in the catalytic heating effects stems from uncertainty in the emittance of the materials. Any uncertainty in emittance values directly affect the analysis of arcjet test data and values derived from these data. Emittance is typically difficult to determine. For bare tile, emittance can be particularly difficult to define. Bare tiles are translucent; therefore, radiation comes from inside as well as from surface of tile. Most importantly, the end-to-end analysis must use the same emittance for flight predictions. It is recommended that the emittance values used throughout the analysis by the CHFT, the TPS Thermal Math Models, and other associated models be verified as the same values. Additionally, it is recommended that additional test and analyses be conducted to improve confidence in emittance values for uncoated tiles.

3.   Split Line Effects

> The magnitude of the heating increase at the split line between coated RCC and the repair plug, and the resulting effect from the thermal analysis needs to be addressed. *(Actually, the increase in heating at material split lines is a problem to some degree for most of the materials with different catalycity covered in the CHFT).* However, the critical nature of the plug performance installed in the RCC is of primary concern. For the RCC plug

repair material, an average catalytic factor based on arcjet test data does not address these split line effects (boundary between plug and RCC), which could result in local increased effects. Prior to utilization of on-orbit repair materials for RCC, this potential increase in heating at the split line requires further assessment, including the estimates of the stated average catalytic factor.

4. Bare RCC Catalysis

Catalysis of reacting surfaces, e.g. bare RCC, may be a misnomer and referring to this as fully catalytic heating might be an invalid concept. The RCC substrate surface oxidizes, rather than promotes recombination of oxygen atoms. Surface reactions with nitrogen atoms are not addressed; and they are assumed essentially to be fully catalytic. As previously noted, it is more accurate to call this "augmented heating" since the process is essentially a coupling of gas physics and surface (bare RCC) physics phenomena. Two offsetting factors led the analysts to recommend assuming fully catalytic heating on bare RCC. Bare RCC oxidizes at entry conditions leading to increased heating due to the addition of heat of combustion. However, ablation or erosion of the surface tends to reduce the heating by blowing effects. A catalytic heating factor cannot rigorously consider these opposing effects, particularly since the factor includes an effect of discontinuous surface catalysis. However, due to the overall uncertainties, this approximation seems reasonable. It is recommended that this phenomenon be investigated further by measuring the heat flux to bare RCC in pure nitrogen, as well as an inert gas (argon) to discriminate between catalytic reactions from other reactions on the surface, and thus to identify actual catalytic heating factors.

C.9 BOUNDARY LAYER TRANSITION (BLT) PREDICTION TOOL

C.9.1 Function(s) of Tool

1. BLT from laminar to turbulent flow conditions results in a marked increase in surface heating to the Orbiter during re-entry flight. Damage from ascent impacts could result in conditions that promote early or asymmetric transition. The objective of the BLT Prediction Tool is to predict BLT time during re-entry based on damage and/or TPS repair information. High level inputs required to make the BLT time assessment include up-to-date trajectory information, detailed and accurate dimensions of the critical damage sites, and any repair concepts that are available. The BLT Prediction Tool provides a transition time or Mach number for output.

2. The BLT Prediction Tool can be used prior to entry to provide a prediction of transition onset, based on updated BLT correlation results, using flight trajectory and OML damage/repair information as inputs. The results of the BLT predictions are then used to assist the disposition decisions regarding which damage sites require further assessment. (e.g. a damage site downstream of a more forward damage site could be flagged for further assessment, if BLT predictions indicate the forward damage site would promote transition to turbulent flow).

3. The BLT Prediction Tool approach is based on a Fortran program that includes a database of computed boundary layer parameters that cover a range of nominal trajectories for entry and utilizes an interpolation tool to extract specific local properties used to predict the boundary layer state during the mission trajectory. The interpolation tool accesses a database of boundary layer conditions based on analytical predictions. Currently, a BLT threshold of Mach 18 is assumed, along with a higher uncertainty for the initial flights. This will be assumed until new detailed information can be obtained to further refine the use of ground-based methodology for flight above this historical observed limit for early Orbiter BLT.

The NESC peer-review has been completed and the results presented to the tool developers and SSP. However, the formal documentation of the peer-review is not complete as of the release date of this report. A separate report, "Inspection of the Math Model Tools for On-orbit Assessment of Impact Damage", will be prepared by the NESC that fully documents all of the tool peer-reviews.

C.10   3D ACREAGE TILE THERMAL MODEL

C.10.1 Function(s) of Tool

The TMM was developed to aid in the assessment of damage sustained by the Orbiter TPS during ascent. The TMM predicts the temperature response of the Orbiter's lower surface acreage TPS materials and structure at damaged locations. Results from the model serve as input to the structural/stress tools for margin assessments. Once a damaged location is analyzed, the model will be used as supporting information with flight experience to determine whether the damage is acceptable to fly "as is" or if a repair is necessary before re-entry is attempted.

C.10.2 Assumptions and Limitations

1. The TMM uses a constant thickness approach. A sensitivity analysis on this constant thickness approach was not performed. The thickness at the damaged location is used in the model, but no data was presented showing how the thickness varied over an analyzed location.

2. Cavity (damaged) heating augmentation factors were considered "out of scope" for the thermal reviewers. However, several items that would affect the augmentation factor were listed are still under investigation. These items include surface catalytic factors, gap heating inside cavity, porosity/permeability characteristic of uncoated silica, emittance of bare tile, and glazing and melting of RSI and wormholes.

3. Thermal model is just one component in the overall assessment. Considering that several items were considered "out of scope" for the thermal team, it was not clear how all reviews (stress, aeroheating, etc.) are being coordinated to ensure the integrated product is adequate (ensuring consistency between inputs and outputs).

C.10.3 Observations

1. Tile De-bonding in Flight Data Comparisons

    The fact that the model predicted tile de-bonding in flight data comparisons when de-bonding did not occur is a cause for concern. Boeing is updating the stress tool used to evaluate bondline integrity and will verify/validate the new tool. The thermal review team did not receive any information on how the thermal data is used by the stress tool to evaluate margin assessments. As such, we did not examine how the temperature data from the thermal TMM (which uses a constant thickness approach) is mapped onto the structural math models.

1. Damage Location to Flight Data Comparison

   A survey of historical tile damage to the Shuttle was performed and selected cases were evaluated. No temperature data was available (flight instrumentation) to compare TMM temperature results for these analyzed cases. Results for the three locations analyzed using the 3-D TMM indicated RTV bond failure limits would be exceeded in all but one case. Post-flight examination of the damaged sites revealed that tile loss did not occur. The thermal tool identifies how much of the tile/SIP bondline exceeds the bond failure criteria (RTV bond failure criteria requires that 50 percent of the tile RTV-560 footprint exceeds 625°F). Tile loss is highly dependent on flight load cases. To address this issue, Boeing is developing a new stress tool (to be embedded in the 3-D TMM). The stress tool identifies forces on the tile from flight loads and using the temperature data determines if de-bonding will occur.

2. Uncertainty of Uncoated (Damaged) Tile Area Hemspherical Emittance

   During the STS-107 investigation, M&P recommended using the TPSX database for uncoated tile emissivity values. TPSX data are theoretical projections based on room temperature measurements. TPSX tile emissivity data are significantly lower (at high temperatures) than previous values used in Boeing thermal models. Thus, TPSX data predicted conservative tile temperatures. Arcjet tests were performed at JSC to evaluate bare tile emissivity in the 2800°F range to assess this tile property change. Based on test data, M&P recommended continuing to use the TPSX data. For LI-2200, the TPSX data is lower than test data <u>but</u> this is not the case for LI-900 (test data is lower than TPSX – potentially non-conservative). Damaged tile has different surface properties (i.e., roughness, glazing, etc.) than pristine arcjet test samples and could result in different emissivity values than TPSX. Boeing stated that no sensitivity studies of emissivity have been performed to understand the criticality of this assumption.

3. Inter-Tile Gap Heating

   The 3-D TMM does not simulate the individual 6" x 6" Shuttle tiles and, thus, has no inter-tile gap heating in unfilled gaps. Gap heating is accounted for with a heating augmentation factor of 1.2. This augmentation factor is used in undamaged areas. The factor was identified using test data (Comparison of Orbiter STS-2 Development Flight Instrumentation Data with Thermal Math Model Prediction, 1982). In the past, the method used to account for gap heating was to apply a factor of 0.8 on the tile thickness (not on the heating). Boeing claimed that this new approach is equivalent and produces conservative results.

C.10.4 Recommendations

1. Damage Location to Flight Data Comparison

Re-run more flight Platinum history dataset comparisons to determine if 3-D TMM (with new embedded stress tool) still predicts tile loss and compare temperature predictions against the forensic evidence confirming the integrity of the bond.

2.   Uncertainty of Uncoated (Damaged) Tile Area Hemispherical Emittance

Perform an emissivity sensitivity analysis with 3-D TMM for various tile types, with guidance from M&P in defining uncertainty band to be used. If results show a high sensitivity, the Program needs to re-evaluate the use of the TPSX data. The Program should consider testing damaged tile (emissivity test) via a calorimetric thermal vacuum test of a tile sample.

3.   Inter-Tile Gap Heating

Perform inter-tile gap heating sensitivity analysis and compare results with test data. Justify value used by calculating the ratio of model sidewall heating to surface heating. This will not be an exact number, but should serve as a rough confirmation of the value used.

C.11 SPECIAL CONFIGURATION THERMAL MODELS

C.11.1 Elevon Lower Cove (EC) 3-D Thermal Math Model (TMM)

C.11.1.1 Function(s) of Tool

This model was developed to perform a thermal assessment of debris impact damage of the Elevon Lower Cove (EC) on flight specific missions and to provide entry temperature data for structural evaluation. The modeled area includes 56 percent Half Span (HS) – 77 percent HS of the EC. It extends one tile forward and aft in acreage areas, upward to the cove-closeout honeycomb panel and through the primary seal to the secondary seal curtain. The modeled area also includes the wing stub structure and TPS components between inboard and outboard elevons.

C.11.1.2 Assumptions and Limitations

1. The TMM can be used as an approximation for other EC sections. However this capability has not been validated. Major differences in the EC as you move along the wing (inboard to outboard) include tile thickness, rub tube diameter, and hinge location. Boeing stated modifications could be made in the future to incorporate more of the elevon into the model.

2. Flow past the primary and secondary seals is considered outside the scope of this TMM. If impact damage is extensive enough to create a flow path through the cove tiles and cause damage to the primary or secondary seals, it would automatically be considered as a case for repair.

C.11.1.3 Observations

1. A formal test program was not established for the 3-D TMM. Validation is accomplished by comparison with flight data and to the predictions of the existing certified 2-D undamaged model. There is no 2-D damaged model. Direct one-to-one comparison between the 3-D TMM and both flight data and 2-D certified undamaged model is difficult due to thermocouple locations and configuration differences. Boeing stated that the 20°F/40°F flight verification criteria was imposed prior to having a full understanding of the substantial changes that some areas of the vehicle had undergone since flight data was collected. In some instances there have been changes made that cause temperatures to be different by much more than 40°F. FRCI-12 tile material was not available for the early flights but half of the elevon leading edge tiles are now FRCI-12. Earlier flights used different configurations for the cove closeout and had no thermal barrier covering the honeycomb panel. There was also no flow restrictor present between the carrier panel and seal retainer panel on STS-3 (source of flight data)

2. Several 3-D/2-D comparison plots violated the 20°F validation criteria. Boeing stated that these variations can be explained by EC configurations differences between the models.

C.11.1.4 Recommendations

1. Perform arcjet testing for comparison with the model.

2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models.

3. Expand the 3-D model to include thermocouple locations (where available) from early flights.

C.11.2 Forward Reaction Control System (FRCS) Canopy 3-D TMM

C.11.2.1 Function(s) of Tool

This model was developed to predict temperatures on the forward portion of the FRCS Canopy. The tool will be used to evaluate the temperature response of the TPS tile, RTV, SIP, thermal barrier and structure due to damage caused by debris impact. The modeled area extends aft and upward from the forward-most corner of the FRCS cavity seal for approximately eight tiles in both directions.

C.11.2.2 Assumptions and Limitations

1. No internal FRCS components are modeled (i.e., thrusters, valves, tanks, lines, etc.). The current standard approach to flow path damage sites is to recommend repair. The capability to predict the temperature of internal components due to ingested air flow was not considered as part of the original task scope. Boeing stated that the model could be expanded to include these components. Similarly a breach beyond the thermal barrier could be simulated with model adjustments, but the accuracy of the predictions would be based on the capability to determine flow path impingement and heat rate deposition in the breach cavity.

2. To model another area the TMM would need to be modified for tile type, tile thickness, and underlying structure at that particular location. The TMM can be modified but predictions would carry the caveat that the model has been modified and not validated for the location.

C.11.2.3 Observations

1. A formal test program was not established for the 3-D TMM. Validation is accomplished by comparison with the existing certified 2-D undamaged model. There is no damaged 2-D model. No flight data is available for comparison. Due to differences between the 2-D and 3-D models, exact one-to-one comparison is not feasible. Therefore, comparisons are limited top surface nodes of the thermal barrier and tiles (considered as critical areas). Boeing stated that the lack of flight data was accepted by the technical community.

C.11.2.4 Recommendations

1. Perform arcjet testing for comparison with the model.

2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models to either confirm or improve the TMM.

C.11.3   WLE Panel 9 Lower Access Panel (LAP) 3-D TMM

C.11.3.1 Function(s) of Tool

This model was developed to perform a thermal assessment of the WLE LAP on flight-specific missions and to provide re-entry temperature data for structural evaluations of damage locations due to debris impact. The TMM is used to predict temperatures on the HRSI and FRCI tile, RTV, SIP, gap filler, horse collar, thermal barrier and supporting structure.   The 3-D TMM models the LAP for Panel 9, an aluminum frame that is bolted to the lower attachment, internal insulation, and part of the RCC panel which is in contact with the horse collar, and one row of adjacent Orbiter acreage tiles.

C.11.3.2 Assumptions and Limitations

1.   The model does not include the T-seal between RCC panels. The T-seal is considered part of the WLE RCC model.

2.   The model can be used as an *approximation* for other LAPs, but mechanical differences must be well understood. Differences include tile thickness variations and different heating rates. Different panels will present similar trends, but different peak values. Management will be made aware that the model was modified to simulate an area that has not been validated. Therefore, the results will need to show more margins from allowable temperature limits than the area for which the model has been validated to make a repair/no-repair decision.

C.11.3.3 Observations

1.   A formal test program was not established for the 3-D TMM. Validation is accomplished by comparison with flight data and to the predictions of the existing certified 2-D undamaged model. There is no 2-D damaged model.   Direct one-to-one comparison between the 3-D TMM and both flight data and 2-D certified undamaged model is difficult due to thermocouple locations and configuration differences.

2.   The flight data comparisons show differences greater than the 20°F/40°F flight verification criteria. Boeing stated that the 20°F/40°F criteria became imposed prior to having a full understanding of the substantial changes that some areas of the vehicle had undergone since the flight data was collected. In some instances, there have been changes made that cause temperatures to be different by much more than 40°F. Model had to be compared to flight data that is only "near" the modeled area and does not truly represent the actual modeled location.

3.   The 3-D model over predicts flight data (similar profiles) while the 2-D under predicts flight data (not similar profiles). The 3-D model does not compare favorably to the certified 2-D model. The 3-D model compares better than 2-D for maximum temperature

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comparisons. Boeing stated the 2-D model tends to under predict due to boundary assumptions.

C.11.3.4 Recommendations

1. Perform arcjet testing for comparison with the model.

2. Modify the 2-D or 3-D TMM to more closely match configuration/property differences between models.

3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM.

C.11.4 Main Landing Gear Door (MLGD) 3-D TMM

C.11.4.1   Function(s) of Tool

This model was developed to perform a thermal assessment of damage to the MLGD tiles. The TMM covers the forward 60 percent of the MLGD, the thermal barrier, and three surrounding rows of tiles. Critical components of the MLGD are the thermal barrier, pressure seal, RTV, SIP, and aluminum structure.

C.11.4.2 Limitations

1.   Flow past the thermal barrier is considered outside the scope of this TMM. The sidewalls of tiles on either side of the thermal barrier slant away at approximately 45 degrees. As such, damage 0.3" deep that reaches within 0.3" of the surface edge is considered a penetration that would cause flow past the thermal barrier. Any flow past the thermal barrier that would impinge on the pressure seal would be repaired.

C.11.4.3 Observations

1.   A formal test program was not established for the 3-D TMM. Validation is accomplished by comparison with flight data and to the predictions of the existing certified 2-D undamaged model. There is no 2-D damaged model.

2.   Direct one-to-one comparison between the 3-D TMM and both flight data and 2-D certified undamaged model is difficult due to thermocouple locations and configuration differences.

3.   The surface thermocouples temperature comparison with the 3-D TMM temperature predictions is conservative, but not so for skin thermocouple comparisons. Boeing stated that the predicted surface temperatures depend almost exclusively on heat flux input and emissivity. The over prediction of temperature at the surface is due to conservative heat flux data from the aeroheating subsystem. The temperature of the internal thermocouple trails the surface by about 500 seconds, and the cooling of the surface in the later stages of flight keeps the over predicted spike in temperature from impacting the aluminum skin temperature.

4.   The reason that the 3-D model predicts a lower temperature for the aluminum skin is that the honeycomb core of the door on OV-103 transmits more heat to the door interior than is transmitted by the unfilled void on OV-102 test data.

C.11.4.4 Recommendations

1.   Perform arcjet testing for comparison with the model.

2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between model

3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM.

C.11.5 Vertical Tail Leading Edge (VTLE) 3-D TMM

C.11.5.1 Function(s) of Tool

This model was developed to predict temperatures of the VTLE. The primary purpose of the tool is to evaluate the temperature response of the TPS tile, RTV, SIP and structure due to a debris impact. The model areas include 20 percent and 90 percent along the vertical tail span.

C.11.5.2 Assumptions and Limitations

1.   Other areas of the VTLE are excluded from the TMM. The justification is that temperature results indicate the temperature profile is highest at the 90 percent location along the vertical span.

2.   If impact occurs at a location other than the 20 percent and 90 percent areas, the 90 percent TMM is used to assess it for conservatism. If required, the model can be altered to reflect the damaged location. If this occurs, then additional margin as compared to allowable temperatures will be required to make repair/no-repair decisions. This capability is not validated and management would be made very aware that the model was being used outside of its original intended area.

C.11.5.3 Observations

1.   A formal test program was not established for the 3-D TMM.

2.   Validation is accomplished by comparison with flight data and to the predictions of the existing certified 2-D undamaged model.

3.   There is no 2-D damaged model.

4.   Direct one-to-one comparison between the 3-D TMM and both flight data and 2-D certified undamaged model is difficult due to thermocouple locations and configuration differences.

5.   TMM (at 20 percent and 90 percent) correlated with flight data at the 30 percent and 80 percent span location. Data presented shows flight data from the 80 percent span and TMM results from the 90 percent span. It is difficult to compare curves and highlight differences. Also, the flight data and TMM tile materials are not the same.

C.11.5.4 Recommendations

1. Perform arcjet testing for comparison with the model.

2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models.

3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM.

C.11.6   Forward Window # 3 Perimeter 3-D TMM

C.11.6.1 Function(s) of Tool

This model was developed to predict temperatures on the perimeter of the Forward Window #3 Periphery. It is used to evaluate the temperature response of the TPS tile, RTV, SIP, thermal barrier and structure due to damage caused by debris impact. The modeled area covers four tiles along the Orbiter centerline lower corner of the Forward Window #3.

C.11.6.2 Assumptions and Limitations

1.   Only four tiles modeled – other window periphery tiles may be analyzed with this model, but the configuration differences must be well understood. The modeled location was identified by the debris analysis team as a critical area. Boeing stated that there is a great deal of symmetry among the window periphery tiles so that the model can be adapted for other areas. Window configuration similarity is well understood. Management will be made aware that the model was modified to simulate an area that has not been validated, thus the results will need to show more margin from allowable temperature limits than the area for which the model has been validated to make a repair/no-repair decision.

2.   Breaches (caused by damage) beyond the thermal barrier can be simulated with model adjustments, but the accuracy of the predictions is based on the ability to define the flow path impingement and cavity heat rates. The current standard approach to flow path damage locations is to recommend repair.

3.   If damage is large enough to change the edge temperatures of the TMM (that is, TMM not sized properly), then a repair is recommended due to the criticality of the modeled location.

C.11.6.3 Observations

1.   A formal test program was not established for the 3-D TMM. Validation is accomplished by comparison with flight data and predictions of the existing certified 2-D undamaged model.

2.   There is no 2-D damaged model.   Direct one-to-one comparison between the 3-D TMM and both flight data and 2-D certified undamaged model is difficult due to thermocouple locations and configuration differences.

3.   Boeing stated that the V&V flight comparison criteria was adopted in advance of fully understanding some of the discrepancies the model would encounter relative to flight data.

4.   The 3-D TMM is built to current configuration data which differs from the original certified 2-D TMM.

C.11.6.4 Recommendations

1.   Perform arcjet testing for comparison with the model.

2.   Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models.

3.   Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM.

C.11.7 External Tank Door (ETD) 3-D TMM

C.11.7.1 Function(s) of Tool

The 3-D TMM covers the ETD, thermal barrier, and two rows of surrounding tiles. It uses the effective structure thickness for the fuselage and the thickness from the 2-D certified model for the door. Hinges and latch fittings are not modeled. The TMM performs a thermal assessment of damage to the door tiles and two rows of adjacent tiles on the wing/fuselage. Critical components of the ETD include the thermal barrier, pressure seal, RTV, SIP and aluminum/beryllium structure.

C.11.7.2 Assumptions and Limitations

1. Model does not include the hinge and latch fittings and the effects of vent door convective cooling.

2. Activation of the vent doors occurs at approximately 80,000 feet, at a velocity approximately 2400 feet/second and is continuous until landing.

3. TMM results under predict flight data prior to vent door opening and then over predict flight data after vent door opening.

4. The air temperatures at this altitude range from -90°F to -50°F. The model also uses a constant thickness for the door which in reality is not the case.

C.11.7.3 Observations

1. A formal test program was not established for the 3-D TMM.

2. Validation is accomplished by comparison with flight data and the predictions of the existing certified 2-D undamaged model.

3. There is no 2-D damaged model.

4. Direct one-to-one comparison between the 3-D TMM and both flight data and 2-D certified undamaged model is difficult due to thermocouple locations and configuration differences.

5. The flight data and 3-D TMM predicted results appear to be out of phase in the comparison plots. Boeing stated this "phase" difference is due to assumptions in the analytical aeroheating data. Specifically, the time peak heating and transition occurs.

C.11.7.4 Recommendations

1. Perform arcjet testing for comparison with the model.

2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models.

3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM.

C.11.8   Nose Landing Gear Door (NGLD) 3-D TMM

C.11.8.1 Function(s) of Tool

The NLGD 3-D SINDA TMM was developed to perform a thermal assessment of the NLGD on flight-specific missions and to provide entry temperature data for structural evaluations of damage due to debris impact. The 3-D TMM consists of the thermal barrier, one row of tiles adjacent to the thermal barrier, door acreage tiles, and aluminum structure. The model can predict re-entry temperatures and temperature profiles for the modeled components.

C.11.8.2 Assumptions and Limitations

1.   The TMM results in the supplied package show a temperature violation for the Inconel flexible spring. Boeing stated that this violation was corrected with 3-D TMM modifications. Specifically the addition of AB312 fabric, AB312 cord and changes to the Inconel spring configuration (based on SDS drawings).

2.   The current temperature is 683º F which is well below the 1500º F temperature limit. The current temperature was reported in correspondence from Boeing personnel addressing model review questions.

3.   The aft half of the NLGD will be modeled prior to the next flight (entire door not modeled in current version) and will go through a similar V&V process. Therefore, this model can be considered a work in progress.

C.11.8.3 Observations

1.   A formal test program was not established for the 3-D TMM.

2.   Validation is accomplished by comparison with flight data and to the predictions of the existing certified 2-D undamaged model.

3.   There is no 2-D damaged model.

4.   Direct one-to-one comparison between the 3-D TMM and both flight data and 2-D certified undamaged model is difficult due to thermocouple locations and configuration differences.

5.   The flight data and 3-D TMM predicted results comparisons appear to exceed the 20º F/40º F verification requirement. They do show similar profiles.   Boeing replied that additional detail was added to the 3-D TMM since the review package was presented.

6.   Model modifications (AB312 cord and ceramic sleeving covering the Inconel springs) have resulted in temperature predictions closer to the 2-D TMM. Based on the Boeing reply (flight data comparison rather than 2-D/3-D comparison), it is not clear if the flight data comparison plots show 3-D or 2-D TMM predicted temperature profiles.

7. The 2-D and 3-D TMM predicted comparison plots also exceed the 20° F criteria. Current model predictions (not in package reviewed) show the maximum temperature of the hottest Inconel spring as 683° F. The RTV and pressure seal are 33° F colder, and the aluminum skin is 26° F colder in the 3-D model than in the 2-D model. All predicted 3-D component temperatures are within material temperature limits.

8. Boeing stated that the differences between the 2-D and 3-D model predictions are well understood and result from material and configuration differences since the 2-D model was developed.

9. Boeing also stated that large differences in the maximum temperatures are still evident in the results. This is contradictory to the previous explanation.

C.11.8.4 Recommendations

1. Perform arcjet testing for comparison with the model.

2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models.

3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM.

C.12   TILE STRESS TOOL – RTV BOND LINE (45 DEGREES)

The NESC peer-review has been completed and the results presented to the tool developers and SSP. However, the formal documentation of the peer-review is not complete as of the release date of this report. A separate report, "Inspection of the Math Model Tools for On-orbit Assessment of Impact Damage", will be prepared by the NESC that fully documents all of the tool peer-reviews.

C.13 STRESS ASSESSOR TOOL

The NESC peer-review has been completed and the results presented to the tool developers and SSP. However, the formal documentation of the peer-review is not complete as of the release date of this report. A separate report, "Inspection of the Math Model Tools for On-orbit Assessment of Impact Damage", will be prepared by the NESC that fully documents all of the tool peer-reviews.

C.14   Assessment of End-to-End Tool Integration

A limited peer-review of the end-to-end, integrated computational capability has been completed by the NESC, including the tool interfaces (data transfer) and correlation to historical flight data, and the tile tools that were cleared for use on STS-114. However, the current estimate of the level of uncertainty in the final computation of the damage severity (aluminum structure temperature, RTV bondline temperature, and structural margin of safety) is significant and may not allow any relief of the 1.4 FOS.

The NESC peer-review has been completed and the results presented to the tool developers and SSP. However, the formal documentation of the peer-review is not complete as of the release date of this report. A separate report, "Inspection of the Math Model Tools for On-orbit Assessment of Impact Damage", will be prepared by the NESC that fully documents all of the tool peer-reviews.

Approval and Document Revision History

Approved:	Original Signature on File	07/07/05
	NESC Director	**Date**

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1.0	Initial Release	Principal's Engineer Office	07/07/05