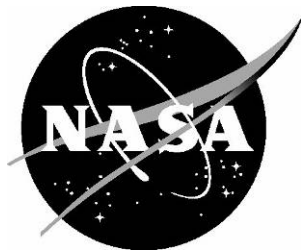


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NESC-RP-05-104/05-011-E



Inspection of the Math Model Tools for On-Orbit Assessment of Impact Damage Report

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December 2007

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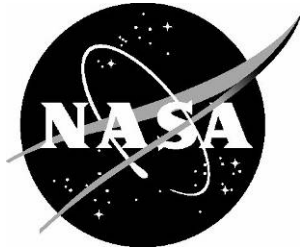
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September 15, 2005
[Revised November 28, 2007]

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Approval and Document Revision History

Approved:	_____ Original signature on file NESC Director	_____ 9/22/05 Date
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Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineer's Office	9/22/05
2.0	Added Appendix A. Inserted a reference in Section 3.0, RCC Damage Growth Tool, to point to the Appendix.	Principal Engineer's Office/NASA Technical Fellows Office	11/28/07

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Appendix A. Preliminary Findings Peer Review – RCC Damage Growth Tool, April 22, 2005


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List of Acronyms


AOA	angle-of-attack
atm	atmosphere
BC	Boundary Conditions
BLT	Boundary Layer Transition
bp	Body Point
BSM	Booster Separation Motor
C	Capability
C/E	Capability/Environment; Capability Margin
CATIA	Computer-Aided Three-Dimensional Interactive Application
CFD	Computational Fluid Dynamics
CHFT	Catalytic Heating Tool
CHT	Cavity Heating Tool
cm	centimeter
D	depth
DAT	Damage Assessment Team
DTA	Debris Transport Analysis
DVR	Design Verification Review
E	Environment
EC	Elevon Cove
EOM	End of Mission
ET	External Tank
ETD	External Tank Door
FEA	Finite Element Analysis
FEM	Finite Element Model
FOS	Factor of Safety
fps	feet per second
FRCS	Forward Reaction Control System
FRIC	Fibrous Refractory Composite Insulation
g	gram
GN&C	Guidance Navigation and Control
HRSI	High-temperature Reusable Surface Insulation (Black Tile)
HS	Half Span
HWISS	Heavy Weight International Space Station
I/F	Ice/Frost
IC	Initial Conditions
IPSS	Impact Penetration Sensor System
IT	Intertank
K	roughness element height
KE	Kinetic Energy

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L	length
LAP	Lower Access Panel
lbm	pounds mass
LCC	Launch Commit Criteria
Lcrit	critical dimension
Leff	thermally affected length
LESS	Leading Edge Structural Subsystem
LESS PRT	Leading Edge Structural Subsystem Problem Resolution Team
LH ₂	Liquid Hydrogen
LN ₂	Liquid Nitrogen
LO ₂	Liquid Oxygen
LRSI	Low-temperature Reusable Surface Insulation
m/s	meters/second
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
OBSS	Orbiter Boom Sensor System
OCCB	Orbiter Configuration Control Board
OEX	Orbiter Experiment Support System
OML	Outer Mold Line
OMS	Orbiter Maneuvering System
OPO	Orbiter Project Office
OVEI	Orbiter Vehicle End Item
PAL	Protuberance Air Load
PDL	Process Data Logging (FoamMix®)
PE	Performance Enhancement
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

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SIP	Strain Isolation Pad
SLD	Stress, Loads and Dynamics
SOASD	Smooth OML Aerothermal CFD Solution Database
SRB	Solid Rocket Booster
SSP	Space Shuttle Program
SSP MMT	Space Shuttle Program Mission Management Team
SSS	Space Shuttle System
STS	Space Transportation System
SwRI	Southwest Research Institute
tbar	equivalent skin thickness
TM	Transport Mechanism
TMM	Thermal Math Model
TPS	Thermal Protection System
TSAT	TPS Status Assessment Tool
V&V	Verification and Validation
VTLE	Vertical Tail Leading Edge
WLE	Wing Leading Edge
WOW	Worst-on-Worst

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EXECUTIVE SUMMARY


In Spring of 2005, the NASA Engineering Safety Center (NESC) was engaged by the Space Shuttle Program (SSP) to peer review the suite of analytical tools being developed to support the determination of impact and damage tolerance of the Orbiter Thermal Protection Systems (TPS). In response to this request, the NESC formed an independent review team with the core disciplines of materials, flight sciences, structures, mechanical analysis and thermal analysis.

The Math Model Tools reviewed included damage prediction and stress analysis, aeroheating analysis, and thermal analysis tools. 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. In addition, the tools are used together in an integrated strategy for assessing the ramifications of impact damage to tile and RCC.

The NESC teams conducted a peer review of the engineering data package for each Math Model Tool. The peer review process also included a review of 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 and among various tools and the propagation of uncertainties from the initial definitions of the impact event to the predictions of damage. This report contains the summary of the team observations and recommendations from these reviews.

As a part of these reviews the NESC made several recommendations regarding opportunities to improve the validation, expand the application and understand the accuracy of these math models. Many of these recommendations were accepted and addressed real time by the model developers. Any recommendations that remain open are summarized in Section 16 of this report, and will be provided to the Orbiter Project Office (OPO) for consideration as a part of their post-flight tool development and improvement initiatives.

The NESC recognizes the considerable amount of effort that the NASA and contractor technical community has put into the development and verification of these analytical tools over the last 2 ½ years. Overall, the team found that these tools represent a vastly improved analytical capability than was previously (pre-*Columbia*) available to the SSP for the resolution of debris impact issues on the orbiter. While there is always the opportunity to improve analytical tools in terms of validation and correlation, range of applicability and quantification of analytical uncertainty; these tools were all found to be suitable for application to STS-114 under the restrictions and limitation documented by the developers. These restrictions and limitations were all clearly documented and presented to the OPO at the Orbiter Configuration Control Board (OCCB) as a part of the base-lining of these tools for use in STS-114.

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1.0 INTRODUCTION

A combination of new and existing Math Model Tools have been developed to determine the impact tolerance and damage tolerance of the Orbiter Thermal Protection System (TPS) (tile and reinforced carbon-carbon (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 (Table 1.0-1). In addition, the tools are used together in an integrated strategy for assessing impact damage to tile (Figure 1.0-1) and RCC (Figure 1.0-2).

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 and among various tools and the propagation of uncertainties from the initial definitions of the impact event to the predictions of damage. The following content was requested 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.
- Validation & Verification (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 individual tool engineering readiness peer reviews are summarized in the following sections.

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1.1 Definitions

Definitions of various terms used in this report are presented below.


Verification and Validation:

Verification

- An item meets its requirements (National Space Transportation System (NSTS)-07700-10-1).
- The process of ensuring that an activity, design, product, or service complies with the baselined requirements document (Boeing PRO-6191).
- The process that ensures that a product meets its specified requirements through testing, analysis, inspection, demonstration, or through their combination (Boeing BPI-3475).
- For this “tool” review, the verification definition related to computational simulations by Oberkampf and Roy, 2005 is more appropriate.
 - The process of determining that a model implementation accurately represents the developer’s conceptual description and specifications - deals with mathematics and numerics, and provides evidence that the model is solved correctly. Two types of verifications need to be considered. These are Code verification and Solution verification.

Validation

- The process of ensuring the product/service conforms to customer needs and meets its intended purpose in its operating environment (NSTS-07700-10-1, Boeing PRO-6191).
- For this “tool” review, the validation definition related to computational simulations by Oberkampf and Roy, 2005 is more appropriate.
 - The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model - deals with physics; provides evidence that the correct model is solved – *Physics-based modeling and analysis*.

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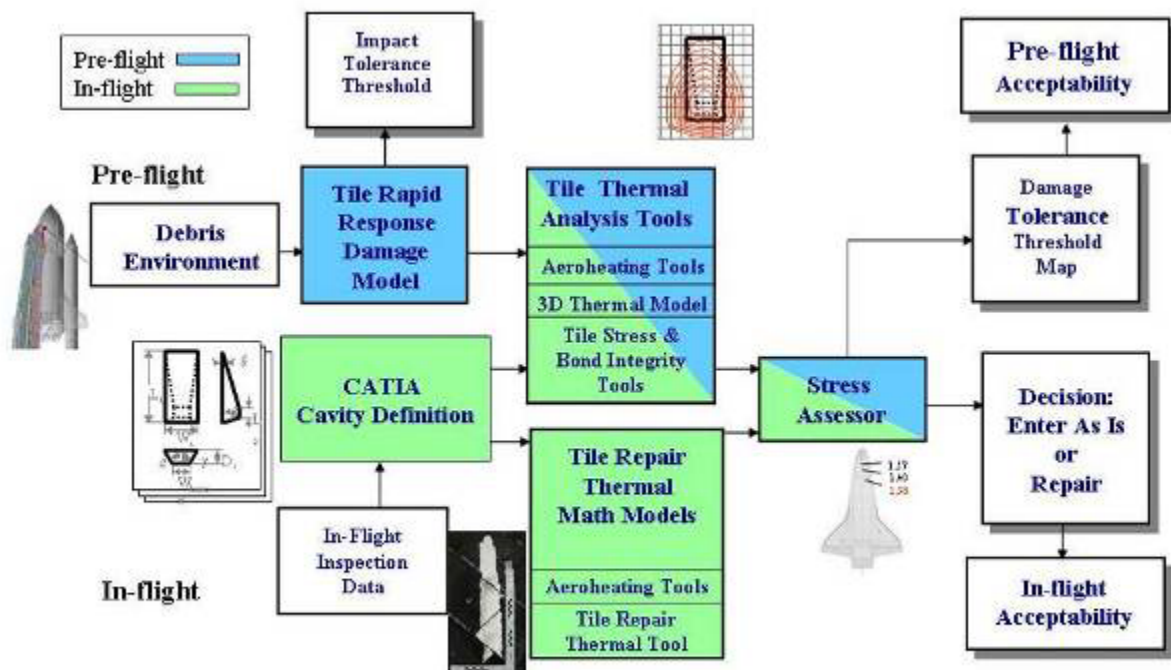



Figure 1.0-1. Tile Tools for Pre-Flight and On-Orbit Damage Analysis

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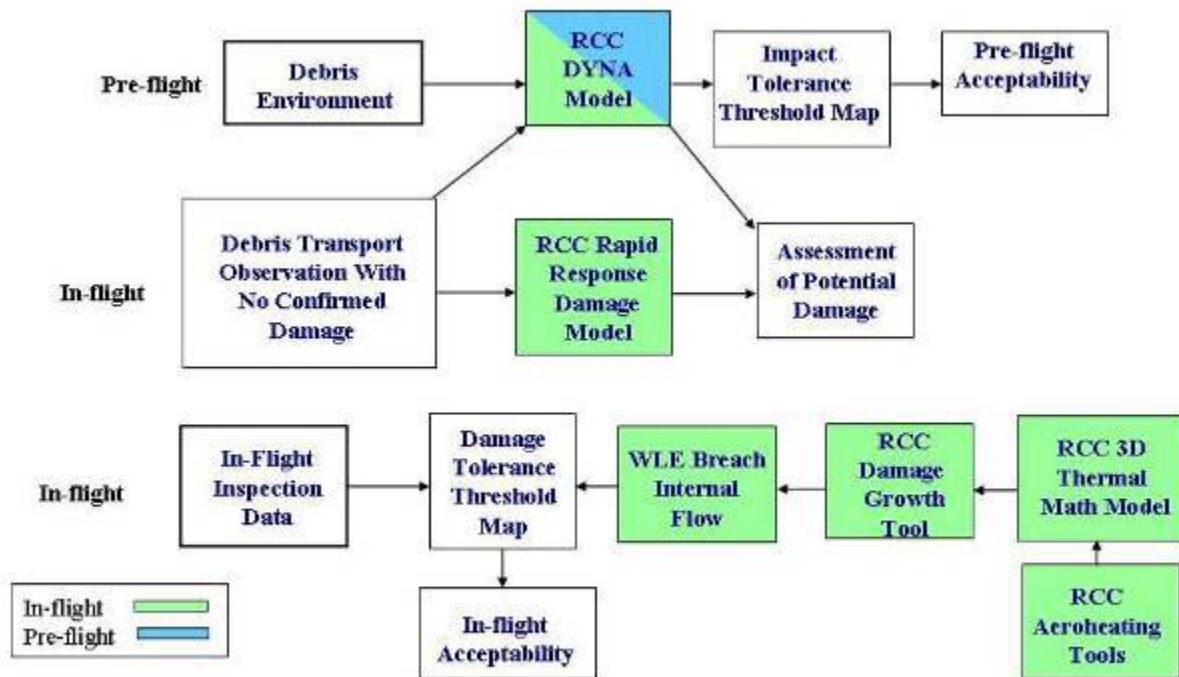


Figure 1.0-2. RCC Models for Pre-Flight and On-Orbit Damage Analysis



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Table 1.0-1. 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 ¹	N				X
	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	
	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 ¹	N				X
	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

¹ Note that tile repair tools, while included in this table of tools were not a focus of this review and are not considered a certified analytical capability for STS-114.

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2.0 IMPACT TOOLS

In this section, two tools for RCC impact debris assessment, LS-DYNA[®] and IMPACT2, are discussed. Then, the results of a Mini-mission Simulation conducted at NASA Johnson Space Center (JSC) on July 21-22, 2005 are presented.

2.1 RCC DYNA MODEL

This tool review involves the review of the FEMs analyzed by the application of LS-DYNA[®] software to impact foam and ice debris on RCC wing leading edge (WLE) panels and is *not a review of the LS-DYNA[®] software*.


Peer Review Team Members

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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 RCC WLE panels. Two indicators were defined as criteria for damage detection in the LS-DYNA[®] simulations. The first criterion is referred to as the “1-to-5 elements out” criterion that results in a through-crack-like damage state. The second criterion is referred to as the “onset of NDE detectable damage” criterion. This damage mode is assumed to occur when the minimum value of history variable 3 (minHV3) on the MAT58 material model in LS-DYNA[®] reaches a value of 0.002. LS-DYNA[®] correlations are performed with small flat panel and full-scale WLE 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 using “onset of NDE detectable damage” criterion. Test results clearly identify the RCC WLE impact threat due to debris, which had not been known previously. Testing is performed on specific panels (small flat panel and full-scale WLE panels) and included several impact locations on these panels. The LS-DYNA[®] FEMs and analyses were validated using these test results.

First, various steps involved in computational simulation validation are outlined. Next, the validation requirements for the LS-DYNA[®] analysis along with the reviewers’ comments are presented.

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Steps involved in computational simulation validation are as follows:

1. Accurate definition and representation of configuration to be analyzed.
2. Basic shape, surface definitions, thickness variations.
3. Appropriate level of spatial discretization (finite element meshing).
4. Appropriate structural idealizations (1-D, 2-D, 3-D).
5. Resolution of local gradients.
6. Inclusion of relevant geometrical details including offsets, cross-sectional properties.
7. Adequate mesh refinement, appropriate element selection.
8. Accurate definition and representation of material properties and their distribution.
9. Material types, orientations:
 - a. Homogeneous, layered or textile; polymeric or ceramic; metallic or non-metallic.
 - b. Appropriate modeling of material response elastically as well as damaged or degraded or aged.
10. Nonlinear effects, differences in tension and compression, strain-rate effects, temperature effects, damage initiation and propagation, fracture and delamination.
11. Accurate definition of boundary conditions and initial conditions (including external loading and contact).
12. Appropriate modeling of boundary conditions and initial conditions (including external loading and contact).
13. Appropriate definition of various coordinate systems.
14. Accurate solution of discrete system of equations including specific analysis procedures based on finite element results.
15. Numerical convergence, time step size, modal truncation.
16. Quantitative correlation of primary solution variables:
 - a. Displacements, rotations, forces, moments, reactions.
17. Quantitative correlation of secondary variables:
 - a. Stresses, strains, energies.
18. Qualitative visual correlation of deformation states.
19. Understanding of the post-processing, visualization features being used.

Table 2.1-1 summarizes the computational simulation validation steps along with the reviewers' comments. Table 2.1-2 summarizes the validation requirements for the LS-DYNA[®] analysis models along with the reviewers' comments.



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Table 2.1-1. LS-DYNA® Analysis and Modeling Validation Review

Requirements	Comment
Geometry Definition	Geometry based on CATIA models from Boeing HB; mid-surface geometries generated by Boeing Seattle
Material Definition & Layout <ul style="list-style-type: none"> • RCC • Foam • Ice • PDL 	<ul style="list-style-type: none"> • RCC data from Loral report (not part of data packet); interpolated ultimate stress and strain values from values given for 19-, 25-, and 38-ply laminates. • Foam is complex and includes knit lines for foam layers – BX-250, BX-265. Density is about 2.5 lbs/cft. Unloads elastically. • Ice has heavier density (45-57 lbs/cft). Thin slabs of ice are used in the tests. • PDL foam has heavier density than BX foams (about 3.5 lbs/cft). This foam is crushable and do not unload elastically.
Boundary Conditions (BC), Initial Conditions (IC), Loading, & Contact Definitions and Modeling	<ul style="list-style-type: none"> • BCs assumed pinned at lug attachments, no fittings or backup structure included in production runs; this assumption supported by results from the model complexity studies. • ICs assumed as debris projectile velocity, impact location and orientation. • No mechanical, thermal, or air loads applied. • Contact defined between T-seal and Panel and between impactor and target.
Material Modeling <ul style="list-style-type: none"> • RCC • Foam • Ice 	<ul style="list-style-type: none"> • RCC modeled using MAT58; required input data beyond known RCC material response data (i.e., assumes a response in post-ultimate region up to 10% strain based on LS-DYNA® input, not in data pack). • Foam modeled using MAT83; data obtained from drop tower tests; production runs used cryogenic foam model. • Ice modeled using MAT155 based on an equation of state.
Coordinate Systems	Developed to support material layout, contact definition and impact location and orientation.
Finite Element Model (FEM) Development	<ul style="list-style-type: none"> • FE meshing by Boeing Philadelphia; performed basic FE model check via PATRAN tools and other manual model checkout steps; mesh sensitivity; nominally 0.2-inch element edge element size chosen for production runs; production runs primarily performed by Boeing Philadelphia; selected quality check runs performed by NASA LaRC. • Model complexity studies considered for apex foam impact (2 panels and T-seal, panel and T-seal, and panel alone) with results indicating no significant difference, hence models of the panel alone were used in the production runs.


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Requirements	Comment
Numerical Solution Accuracy	Mesh sensitivity noted for contact and progressive damage modeling; sensitivity to material variations noted as significant.
Quantitative Correlation of Primary Variables	Contour plots of resultant displacement.
Quantitative Correlation of Secondary Variables	Contour plots of stress; time histories of energies and contact force.
Qualitative Correlation of Global Response	End-state deformation and damage plots.
Parametric Studies	Various impactor orientations and impact location and combinations of panels and T-seals. Correlation with tests. <ul style="list-style-type: none"> • Beam coupon test simulations • 6" x 6" panel test simulations • 6" x 12" panel test simulations • Full-scale foam impact test simulations – Panels 6L & 8L during CAIB, Panel 9L (A, B, C) and Panel 16RDT

Subsequently, LS-DYNA[®] is 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 RCC WLE panels. Numerous “productions runs” were performed to develop a database of threshold KE levels for all WLE panels and associated T-seals for foam and ice debris. These productions runs were then used to establish the capability, or “C”, of the RCC panels for the flight rationale in terms of threshold KE levels for the onset of NDE detectable damage for use in the certification process.

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 current LS-DYNA[®] analysis models. As such, the current model is incapable of predicting delamination.
2. The LS-DYNA[®] analysis models use 2-D shell finite elements. The RCC constituents (carbon-carbon substrate and surface coatings) are not explicitly modeled. The SiC outer layers and the CC substrate are modeled using smeared (or apparent) materials properties based on the Loral data (Report No. 221RP00614 Rev. A, October 12, 1994). As such, the current LS-DYNA[®] analysis model is incapable of directly predicting coating loss.

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3. LS-DYNA[®] analysis models can only be used to predict the “onset of NDE detectable damage” or threshold of damage. These analyses 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 threshold KE values obtained using the “1-to-5 elements out” criterion. The scale factor is determined by finding the KE value that result in a minimum HV3 value of 0.002.
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 a few of the RCC WLE panels are not available for the nose cap and chin panel. Additionally, the LS-DYNA[®] FEMs for the nose cap and chin panel are not verified with full-scale testing.
6. The small mass effect for foam on the kinetic energy (KE) 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, assumed to be 0.03 lbm. This factor appears to be analytically derived and empirically correlated with the LS-DYNA[®] predictions based on a range of impact debris masses. This factor has not been validated using test data. This equation is not applicable for use for nose cap and chin panel components.
7. A similar small mass effect for ice on the KE is assumed to by a factor $(m_1/m_2)^{0.3}$ where m_1 is the mass of the debris and m_2 is a reference mass, assumed to be 0.02 lbm. This factor appears to be analytically derived and empirically correlated with the LS-DYNA[®] predictions based on a range of impact debris masses. This factor has not been validated using test data. This equation is used for nose cap and chin panel components also.


Observations

1. RCC material properties have wide scatter. The LS-DYNA[®] material model is based on empirical material model (MAT 58) with tuned parameters (SLIMIT=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-shaped impactors with length aligned with velocity trajectory present 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 for the RCC WLE panels. The RCC impact response panels 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 small flat panels and full-scale WLE panels.

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Recommendations

1. The scope of intended use and the associated limitations of the debris on RCC analyses need to be clearly documented. **(Demonstrated during Mini-Sim)**
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. **(Completed July 18, 2005)**
3. Engineering data are needed to validate the nose cap and chin panel FEMs and predictions – mesh sensitivity, material orientation, etc. **(In Work** - Impact testing of the RCC nose cap was initiated on July 7, 2005 at Southwest Research Institute (SwRI)).
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. **(open)**
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. **(Partially Completed, July 18, 2005)**
6. RCC material characterization data including: effects of aging (or conditioning), strain-rate effects, failure modes and mechanisms, fracture toughness, and 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[®]. **(open)**
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. **(open)**
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. **(open)**
9. Completion of documentation in the LS-DYNA[®] Data Pack. **(open)**

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2.2 RCC RAPID RESPONSE DAMAGE TOOL – IMPACT2

Function(s) of Tool

The intended use of IMPACT2 for pre-flight and on-orbit impact damage assessment is to provide insight beyond the LS-DYNA[®] production run matrix with sensitivity analyses to small variations in impact location, debris mass, and impact orientation. For pre-flight assessment, IMPACT2 use would be to assess last-minute concerns immediately prior to launch. For on-orbit assessment, IMPACT2 use would be to assess RCC WLE 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 approach used by the IMPACT2 tool is to extract vibration mode shapes from a FEM of the RCC WLE panel (no T-seal) and to perform a modal solution of the impact event with the mode acceleration procedure used of stress recovery. Stress recovery at pre-selected points are compared with material stress allowable values and correlated with the LS-DYNA[®] production run predictions. The FEMs are currently based on the historical NASTRAN models (“certified” models) developed during the original development program 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). Table 2.2-1 summarizes the validation requirements for IMPACT2 along with the reviewers’ comments.



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Table 2.2-2. IMPACT2 Analysis and Modeling Validation Review

Requirements	Comments
Configuration (geometry) Definition	No electronic geometry; discrete FE geometry is the basis.
Material Definition & Layout <ul style="list-style-type: none"> • RCC • Foam • Ice 	<ul style="list-style-type: none"> • RCC thickness distributions approximated. • Foam not explicitly included. • Ice not explicitly included.
BC, IC, Loading, & Contact Definitions	Panel/T-seal combination has point constraints with stiffness coefficients representing attachment fittings and backup structure.
Material Modeling <ul style="list-style-type: none"> • RCC • Foam • Ice 	<ul style="list-style-type: none"> • RCC modeled as general anisotropic elastic material; material layout not described. • Foam modeled as nonlinear springs. • Ice modeled as point force with pulse load.
BC, IC, Loading, & Contact Modeling	BCs treated using diagonal matrix input at grid point (DMIG) terms. Loading is due to nonlinear forcing function generated by foam model; panel/T-seal contact treated using linear springs and multi-point constraints (MPC).
Coordinate Systems	Many coordinate systems due to assumed contact modeling approach.
FEM Development	Relatively coarse NASTRAN FE mesh (element edge length ~2.0 inches); mostly 2D shell elements; element lengths are 10 times the DYNA models

Assumptions and 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 configurations involving only the RCC WLE panels.


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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 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 for the debris and impact events considered. If the convergence is based on the convergence to the value obtained from the complete FEM (i.e., the historical NASTRAN FEM) 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.
5. IMPACT2 predictions based on the historical NASTRAN FEMs are correlated with the LS-DYNA[®] predictions. Sensitivity of the IMPACT2 results to changes in the underlying FEM used for generating the free vibration mode shapes and subsequent stress recovery has not been demonstrated.

Recommendations

1. Demonstrate the rapid response of IMPACT2 using 6” x 6” and 6” x 12” flat panels. **(open)**
2. Validate IMPACT2 with 6” x 6” and 6” x 12” flat panel test data. **(open)**
3. Demonstrate the rapid response tool application for the nose cap and chin panel structures. **(open)**
4. Provide a complete data pack of all analyses, data, and results for archival purposes and traceability. **(open)**

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2.3 IMPACT TOOLS SIMULATION

A Mini-mission Simulation (abbreviated colloquially as Mini-Sim) was conducted at NASA JSC on July 21-22, 2005. The purpose of the Mini-Sim was to assess the performance of the RCC Debris Impact Assessment team, the communication process between and among team members, and the performance of the three sets of tools (the database of results from the LS-DYNA[®] production runs, the use of IMPACT2, and detailed LS-DYNA[®] runs on a specific configuration).

Two scenarios and three simulated impacts were presented to the LS-DYNA[®] and IMPACT2 teams:


Scenario 1: Pre-launch assessment of an ice ball.

Scenario 2: Post-launch or early mission assessment with two hits to the RCC panels on ascent.

The Pre-launch scenario was based on debris transport analysis (DTA). The ice ball would strike RCC WLE panels in the range of Panels 9-11. The decision was made that the most likely impact was on Panel 10 for a 0.0035 lbm ice-ball with a speed of 791 feet per second (fps). The teams were required to assess the damage and make a recommendation of "GO/NO GO" to the Leading Edge Structural Subsystem Problem Resolution Team (LESS PRT). IMPACT2 results and results from the DYNA production runs both indicated that the impact event exceeded the RCC panel capability. Both the teams gave a "NO GO" for launch decision to the LESS PRT. The LESS PRT concurred with that decision. The IMPACT2 team demonstrated their rapid response feature. This part of the Mini-Sim took 90 minutes on July 21, 2005.

The Post-launch (early mission ascent) scenarios were two BX-265 foam hits: (1) on Panel 9 at 4.5 inches below the apex, mass of the foam divot was 0.023 lbm, and the velocity was 1155 fps - with velocity oriented with debris-Alpha=16 degrees and debris-Beta=10 degrees; and (2) an impact on Panel 17 at 0.5 inches below the center of the apex, mass of the foam divot was 0.036 lbm with velocity of 1130 fps with velocity oriented with debris-Alpha=0 degrees and debris-Beta=0 degrees. These Mini-Sim events were confirmed by imagery data and impact sensor data.

The IMPACT2 team had 2 hours to analyze the cases and then report the results to the RCC Debris Impact Assessment Team. The DYNA team had 24 hours to perform computations and report. In addition, the Team used the results from the LS-DYNA[®] production runs to estimate the severity of the impact events. All teams reported in time and their recommendations were consistent. For case 1, all teams showed positive margins; for case 2, all teams showed negative margins. However, the positive margins were less than the confidence bounds on the results; hence, the team recommended that detailed inspections be performed on both panels. This decision is needed by flight day 2 and 7 hours (T+55 hours) in order to be write the chit for

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detailed inspection. The LESS PRT then recommended inspection of both the panels. As Panel 9 is in the HOT zone for re-entry, inspection is required even when positive margins are calculated.

Recommendations

1. Communication among the IMPACT2 team, the DYNA team and LESS PRT needs to be improved. The angles for debris-Alpha and debris-Beta were misinterpreted by the team members and the need for graphic depiction of these angles was identified. **(open)**
2. Margin reporting by the teams need to be consistent in terms of units and metrics. The team needs a consistent basis of working the issues and reporting results. **(open)**
3. Team members should use certification rigor as basis of all results reported to the LESS PRT. **(open)**

Lesson Learned

1. Rapid response feature of IMPACT2 was demonstrated. The DYNA team demonstrated that a truncated-conical-shaped divot can be modeled in real-time and LS-DYNA[®] runs can be made to predict the onset of NDE detectable damage.

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3.0 RCC DAMAGE GROWTH TOOL

Peer Review Team Members


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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.

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.

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3. 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. Conservatism - 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.

Observations


1. Input Parameters:

- a. Delamination Extent - The assumption that the delamination extends 1-inch beyond the perimeter of any observed outer mold line (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

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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 flight¹ 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. V&V:

- a. Arcjet Testing - Based on stagnation testing of impact-damaged RCC panel, the 0.020 inch 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.


¹The statement of conservatism is based on a verbal description of a high fidelity FEA, 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.

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- b. Conservatism - 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.

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. 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.

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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.

Refer to Appendix A, Preliminary Findings Peer Review – RCC Damage Growth Tool (April 22, 2005).

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4.0 TILE RAPID RESPONSE DAMAGE MODEL (ICE)

Peer Review Team Members


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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 DTA parameters (mass, velocity and angle of impact). The ice on tile model was developed by SwRI, with Dr. James Walker as the development team lead. 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 Stress, Loads and Dynamics (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 CTH¹. 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.

As developed, the model 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 into 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

¹Eulerian refers to the equations solved by the code - CTH is a fully three dimension Eulerian finite-volume hydrocode. Eulerian means that the mesh stays fixed and the projectile moves through the mesh, rather than the mesh deforming.

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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.

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 degrees.
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 centimeter (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.


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Limitations:

1. Projectile mass range: 0 to 1 pound (453 grams (g))
2. Impact velocity: 80 to 1500 feet/second (fps)
3. Impact angle: 5 to 90 degrees
4. Maximum validated predicted cavity depth: 3 inches
5. In the region of 60 to 90 degrees impact angle, the model is only valid for $L/D_{\perp} \geq 2.5$, 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 g (3" × 1.5" × 1.5"), and the highest velocity tested was 1000 fps. 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.]*

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 (Observation 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.

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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.

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. **(complete)**
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. **(open)**
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. **(open)**
4. Present rationale for entry angle equaling impact angle (and contrast with foam-on-tile model rationale for assuming otherwise). **(open)**
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). **(open)**
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. **(open)**
7. Provide evidence to verify the assumption # 8 – that the glass layer of the tile is assumed to not provide noticeably more strength. **(open)**
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. **(in work)**

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



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Table 4.0-1. Analysis Validation Review Assessment Worksheet

Requirements	Comment	Requirement (conservative or nominal)
Geometry Definition	Assumptions 1, 2, 3, & 4; See comments.	Unknown; data not adequate to determine level of conservatism for these assumptions.
Material Definition, Layout, & Modeling • Ice	Ice material characteristics provided.	Nominal values used for "nominal" model.
BC, IC, Loading, & Contact Definitions & Modeling	See Observation 4.	Unknown effect.
FEM Development (including coordinate systems)	Not presented; should be eventually.	
Numerical Solution Accuracy	Not presented; should be eventually.	
Quantitative Correlation of Primary Variables (penetration depth)		Conservative
Quantitative Correlation of Secondary Variables	Not presented.	
Qualitative Correlation of Global Response	Adequate.	N/A
Parametric Studies	Further studies on CTH high-velocity needed.	N/A

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5.0 TILE RAPID RESPONSE DAMAGE MODEL (FOAM)


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Function(s) of Tool

There are rapid response damage models for both foam and ice debris damage on tile. These models generate a damage geometry (depth, length, width, entry, wall and exit angles) based on DTA parameters (mass, velocity and angle of impact). The only calculated parameter is depth of penetration. All other outputs are either simple functions of depth, or constants. The foam on tile model was developed by Boeing and is an empirical curve-fit based on over 500 shots of projectiles at tile. The damage penetration that is generated by the model envelopes 95 percent of all test data, and greater than 85 percent of flight data¹. Tests cover a significant range of projectile masses (0.002 to 0.4), projectile angles (5 degrees to 60 degrees), velocities (200-2900 feet per second (fps)) and impactor materials (BX-265, PDL, and NCFI). However, this matrix of tests was not developed utilizing any testing optimization techniques (i.e., Taguchi) and, in many cases, provides limited data at any given combination of parameters. BX-250 was never shot as a part of the test matrix, but has been assumed to be enveloped by BX-265 based on similarity of material stress-strain properties. Testing does include both pristine and aged tile, and tile arrays both with and without gap fillers, although the majority of data is on new panels without gap fillers. Most of the testing was conducted with High-temperature Reusable Surface Insulation (HRSI) (black tile); however Low-temperature Reusable Surface Insulation (LRSI) (white tile) was tested for comparison. Current proposed limits on tool usage do allow interpolation and limited extrapolation from specifically tested combinations of parameters.

¹ Significantly more than 85 percent of the historical data is captured by the model; however the V&V requirement was to envelope 85 percent.

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Assumptions and Limitations

Key Assumptions:


1. The tool assumes that the projectile always impacts with the length aligned with the velocity vector. This results in an “edge” or “flat” impact which transmits the maximum amount of energy in the minimum area, thereby doing maximum damage.
2. The tool does not account for projectile tumbling.
3. The model assumes all impactors are “brick” shaped vs. divot shaped.

Key Limitations:

1. 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.
2. 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.
3. Mass less than or equal to 0.4 pounds per meter (lbm) can be analyzed; however, masses less than 0.002 do not receive any benefit of reduction in damage threshold velocity, because there was no testing conducted in this regime.
4. Angles less than or equal to 60 degrees can be analyzed; however, angles less than 5 degrees are analyzed at 5 degrees.
5. Velocity less than 2,900 fps can be analyzed, within the restriction of not penetrating the densification layer. Obviously, for larger masses and higher angles at this velocity, there will be deep penetration.


Observations

1. There is a lot of scatter in the test data for foam 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

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depth is not that unusual and, for a few cases, there is almost 1-inch of scatter on depth of penetration.

2. For high angles (>30 degrees) and high mass (>0.2), the slope of the velocity damage depth curve is very high; therefore, for small changes in velocity (~20 percent) you can get significantly greater damage (from 0 to ~0.5-1.0 inch).
3. The foam on tile rapid response model is more conservative in the lower mass regimes, where it generally provides a conservative representation of threshold velocity. In the higher mass regimes (0.2 lbm and greater), the model can overpredict threshold velocity, and so sometimes there is as much as 0.25-0.5 inches of damage where the model would predict none.
4. For foam on tile with a 5-degree impact angle there is only one complete set of data. A set of data exists at 0.2 lbm for a range of velocity, and produces a well defined threshold. At 0.022 lbs there are only 3 data points, none of which exceed the threshold, so there is no real comparison of analysis to test for this mass and angle combination, other than that the threshold behavior appears conservative. For 0.13 lbm there are two data points, neither of which exceeds the threshold. Therefore, there is no real comparison of analysis to test for this mass and angle combination, other than to observe that the threshold may be conservative. However, based on the fact that these two data points occur in very close proximity to the analytical threshold, the data scatter, and the trends regarding threshold, this may not indicate conservatism with regard to the threshold.
5. A tile shear out failure mode appears to sit right in the middle of the critical range of parameters characterized by test (i.e., for example at 0.022 lbs and 2,000 fps). This failure mode is caused by a “smart” piece of debris that, based on tests to date, requires an impactor to hit a single tile with a critical combination of mass and velocity. The result is that a weak shear plane in the tile gives way and a large part of the whole tile is removed to the densification layer. This is significantly more damage than the model predicts at the given impact parameters (i.e., mass and velocity), as it is a fundamentally different failure physics than the other test data enveloped.
6. It is not clear how placards or limitations will be integrated into the model to ensure damage is not manifested as the more severe tile shear out or tile out failure mode.
7. Tile aging effects are based on samples of tile which were flown only six times.
8. Foam on tile models are empirical curve-fits and, while based on a significant total number of shots (500+), the number of shots at any given set of parameters is relatively

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small (~3) and there is significant scatter in the data. Therefore, the bounds of tool use should be clearly delineated and not extrapolated without additional verification.

Recommendations

Return-to-Flight (RTF)


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. **(in-work)**
2. The assumption of “no tumbling” as a conservative assumption in the model needs to be substantiated. **(in work)**
3. The assumption of a “brick” shaped divot enveloping other impactor shapes should be substantiated. **(completed via LS-DYNA[®] assessment)**
4. The “corners of the box” for which the foam on tile model is considered applicable, should be compared to CTH or LS-DYNA[®] hydrocode predictions. **(in work)**
5. Additional test data should be generated on small mass PDL foam impacts to tile. **(complete)**
6. Tile shear out and tile out zones should be clearly defined. **(complete)**

Post-RTF


7. Additional data should be gathered at 5 degrees for low mass impact damage prediction. A test set with more velocities for lower (0.022) and mid (0.13) range masses should be considered, as well as larger masses (0.4), if that is still a legitimate mass out of latest transport analysis. **(open)**
8. Additional test data should be gathered on RCG and substrate properties for aged tile. The tile tested should be more representative of fleet leader tile (~30 flights) to validate the assumption that tile aging occurs early in the life of the tile and does not continue to degrade properties as a function of age. **(in-work)**

Conclusions

Overall, this model does a satisfactory job of predicting key tile damage parameters. In general, it is conservative, which is appropriate given the scatter in the data. The model is most heavily

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populated with data in the lower mass, lower impact angle regime which will be most useful for flight. Completion of RTF recommendations should result in assurance of conservative prediction for even the extremes of the range of applicability. Post-RTF recommendations would result in additional confidence in model output.

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6.0 CAVITY HEATING TOOL

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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 Orbiter Project Office (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 CHT capabilities reduces the unnecessary conservatism and increases the fidelity of this historical method.

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


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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 thermal math model (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.

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 >15degrees, 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 90° is conservative and plays a minor role in augmentation factor predictions. This is supported by a limited available wind tunnel data for non-90 degree angles (angles of 90, 45, 25, and 6 degrees 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 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.

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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 BLT 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.

Observations

1. The NESC peer review's 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 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 return-to-flight (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

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engineering judgment from aeroheating, thermal, stress and TPS should be involved in establishing the cavity dimensions based on this rule.

Recommendations

The CHT peer review highlighted nine (9) 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 7.0. 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. **(closed)**

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 CFD for 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

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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).* 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 Space Shuttle tiles are necessary. **(closed)**

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 Space 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 cavities must be pursued before analysis 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 , Me , 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. **(open)**

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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 BLT Tool, the turbulent methodology which was developed early in the Space Shuttle Program (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. **(in work)**

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 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 CHT team using the data in hand. Two, the Me 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

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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. **(open)**

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 Draft Final 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 CHT 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 are eliminated, the tile gap effect, as established by test, should be employed **(open)**. 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. **(closed)**

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 **(open)**. In the longer term, further analysis, testing, and/or CFD results are

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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. **(open)**

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. **(open)**

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 CHT 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 those that they are consistent throughout the process. This should be provided as part of the end-to-end validation exercise. **(closed)**


9. Reliance on “50/50 Rule” to Establish Cavity Depth

The cavity modeling team is given the “50/50 Rule” 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

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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 members from the CHT, BLT, TMM, and CATIA modeling teams and compared with the actual damage in establishing the cavity dimensions based on this rule. **(closed)**

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7.0 CFD FOR CAVITY HEATING: SMOOTH BASELINE

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Function(s) of Tool

The Space 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 (i.e., 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.

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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 (AOA). 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 CHT and the BLT prediction tools. The SOASD is to be used pre-flight in support of damage tolerance assessment activities, historical data reconstruction (i.e., 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, Me 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 Space 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

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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.


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 AOA 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 computer-aided design (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.
4. For modeling efficiency, the entire Orbiter is modeled with the boundary conditions of a uniform Reaction-Cured Glass (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 leeward side.
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, AOA 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

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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.

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 SOASD 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 SOASD 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.

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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.


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 noted above. 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 Tool Draft Final 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 , Me , Te , 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 (**in work**).

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 should 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. (**in work**)

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2. Comprehensive Uncertainty Quantification

The CFD for Cavity Heating Tool Draft documentation did not adequately address comprehensive uncertainty quantification. The report did not give adequate treatment to the separation of uncertainty contributors including: numerical uncertainty (i.e., truncation error or mesh resolution, scheme accuracy, and convergence accuracy), physical model uncertainty (i.e., chemistry models, real-gas transport models, surface properties), geometric uncertainty (i.e., geometry accuracy), post processing uncertainty (i.e., 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 the updated documentation provided to the peer review team. **(closed)**

3. Clear Assumptions, Objectives and Limitations


Greater clarity on the assumptions should be 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. **(closed)**

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. **(closed)**

Instrumentation uncertainty is not quantified in the boundary layer report and thus cannot be properly addressed. However, 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. **(in work)**

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 a 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. **(closed)**

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8.0 CFD FOR CAVITY HEATING: FLIGHT TRACEABILITY


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Function(s) of Tool

At the time of the NESC peer review, the CFD for Cavity Heating: Flight Traceability analysis is intended as a supporting study for the tile CHT. The CHT serves as the primary predictor of local heating augmentation that occurs within and around any encountered 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 and structure. 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. An obvious concern is that heating bump factors, at high-enthalpy real-gas flight conditions, will not correlate to boundary layer parameters in the identical manner they do at tunnel conditions. The implication is that the heating bump factors predicted by the CHT might prove to be a poor estimate of the actual heating to the damaged tile. These 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, this CFD based study is simply a supporting effort, providing greater insight for the correlation of heating bump factors occurring at flight conditions.

Under the current study, CFD solutions for idealized 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 present, the CHT (version 2) also idealizes all cavities as rectangular. Again, the

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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.

Assumptions and Limitations

Several key assumptions should be noted when interpreting the results of this study.


1. It is assumed that the CFD methods used in this study are able to quantitatively assess detailed local heat-flux differences related to idealized cavity geometries.
2. These differences are reported as heating bump factors both at tunnel and flight conditions which are computed on the basis of the ratio of (local heat-flux) / (reference heat-flux). *Note: Heating bump factors use a ratio of direct radiation equilibrium heat-fluxes and not a ratio of heat transfer coefficients.*
3. At wind tunnel conditions, the CFD solutions are computed using iso-thermal walls.
4. At flight conditions, CFD solutions are computed using non-conducting, RCG catalytic, radiation equilibrium boundary conditions, with emissivity set at 0.89. *It should be noted that these are not the correct conditions for exposed cavity surfaces. However, proper treatment would require extensive coupling between the thermal math, and the tile thermal and the CFD models, which are currently unavailable.*

Several key limitations of the study are as follows:

1. This is only a study, and the CFD tools do not represent a certified capability for on-orbit in flight application.
2. Results from the study should only be used for feedback to the CHT and process.
3. Only flows aligned with rectangular cavities were examined.
4. The observed findings for pressure gradients are not currently confirmed with any experimental data.

Major uncertainty contributors to this study involve the following:

1. The calculated boundary layer thickness and surface heating at tunnel and flight conditions from the CFD have inherent uncertainty (reference Section 7.0, CFD for Cavity Heating: Smooth Baseline).

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2. Interactions between emissivity, catalysis, radiation and conduction on cavity heating levels, especially at flight conditions, are complicated coupled physics that are not entirely captured by the CFD study assumptions.
3. Cavity geometries are modeled with sharp edges in CFD calculations.
4. CFD results are for steady-state converged solutions. Any inherent unsteadiness is not properly modeled or captured.

Observations

An independent Peer Review Panel was established by the tool developers and augmented with NESC designees. The group was chartered to assess the Flight Traceability study results for supporting STS-114 RTF. The peer review team's observation is that, overall, the level of effort put forth by the NASA External Aerothermal Analysis Team is appropriate for the role that CFD is playing in assessing the Orbiter CHT. A concern central to the present study is "whether the heating bump factors evaluated at cold tunnel conditions translate to equivalent bump factors at flight conditions".

As previously noted, the CHT uses boundary layer parameters (δ , θ , Me and Re) and tile cavity relative dimensions (H/δ , L/δ , and W/δ) to determine correlations for heating bump factors. By using the boundary layer parameters and relative dimensions, flight-observed damage is mapped to equivalent tunnel cavity cases to determine local heating bump factors. The wind tunnel results support the idea of dividing the laminar portion of the database of experimental solutions into three families based on the boundary and relative dimensions. These are classified as *Shallow*, *Everhart* and *Closed* cavities. For each of the three families, separate estimates of the local cavity heating bump factors were developed and implemented in the CHT, based strictly on the wind tunnel data. The CFD Flight Traceability study provided assessments for each of the three families as well as cavities located in regions of pressure gradients and/or streamline curvature. The primary findings and observations of the study are summarized below:


1. In general, the flight CFD solutions for all cavity types show regions in the cavity with significant increase in bump factor when compared to equivalent tunnel CFD solutions. *Accepting assumptions, this increase between tunnel and flight is the most significant finding for this preliminary CFD study.*
2. For Shallow cavities and Everhart cavities, recommended cavity heating maps are presented attempting to bound the observed flight increases. *Note: For Shallow cavities, the bounding values are less than the CHT $BF=1.0$ on the cavity floor. For Everhart cavities, the bounding values exceed the CHT $BF=0.62$ over the last 25 percent of the cavity floor.*

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3. For Closed cavities, the CFD study has not provided enough cases to provide recommended Hybrid Bloom Filter (HBF) maps. However, very significant bump factor heating increases are observed in flight compared to tunnel for closed cavities.
4. A very limited set of CFD solutions for streamwise and spanwise pressure gradients indicate that while streamwise pressure gradients alone do not significantly alter either the peak or averaged bump factors, spanwise pressure gradients can produce significant increases in peak bump factor values, but do not alter average values.
5. The current study should be considered as a preliminary look at cavity heating traceability. The heat flux based bump factors predicted at flight must be studied using an integrated approach including downstream tools.
6. A very significant short coming for the validation of current cavity heating CFD estimates is the lack of high resolution, high quality experimental data for cavity heating.

The peer review team found that the conclusions were well supported and that the recommendations for future work address the identified limitations of the current work. As noted, the main significant finding from this study is that the CFD analysis results show that for all cavity types, there exist regions in the cavity with significant increases in bump factor when compared to equivalent tunnel CFD solutions. Extending this finding to the wind tunnel-based CHT, could result in the finding that the CHT under predicts the actual heating observed in an Orbiter tile cavity damage scenario. However, at this point, the CFD of the experimental configurations while providing increased fidelity remain un-validated, with no experimental data presented along with the CFD for the wind tunnel cases.

The initial data package included no validation by comparison with benchmark quality experiments of either the codes DPLR or LAURA CFD tools for hypersonic cavity heating. *(Note, that a single preliminary comparison with archived experimental data using the DPLR code was generated during the review period and did show excellent agreement between the analysis and test results).* It should be noted that the code (LAURA) to code (DPLR) comparisons are a means of verification and not validation. Similar solutions do not necessarily indicate a low uncertainty, due to the different physical modeling in the codes. However, these comparisons do help to verify that the coding of the two physical models do not contain significant errors. To substantiate the accuracy of the physical models, a comparison with experimental data is required. This is lacking in the current study. The comparisons of CFD results with the analytic CHT method are in the gray area between validation and verification. As for validation of the CFD analysis method, further effort is required before direct application to on-orbit damage assessments can be considered. The CFD tools can provide insight into trends and physics with fully 3-D solutions and using parametric studies. However, these studies must be grounded with experimental data before the validity of the conclusions drawn from the trends can be established.


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The CHT uses boundary layer thickness as the input normalization length scale primarily as a selection of which model to use: "Shallow", "Everhart" or "Closed" cavity heating model. With a free-stream at the edge of a boundary layer, subject to both vertical and pressure gradient effects and complicated with real-gas effects, finding the edge of the boundary layer from 3-D flight Navier-Stokes calculations can be problematical. The flow conditions most relevant to the cavity are those affecting the separating streamline coming off the lip of the front wall of the cavity. The most appropriate conditions affecting this streamline likely are due to the inner boundary layer than for the boundary layer edge. Thus, either displacement thickness or momentum thickness may prove to be a better length scale to delineate the different cavity heating models as conditions vary from wind tunnel to flight. Noting that the experiments are all for cavities in a flat-plate without these complicating effects, the determination of which boundary layer thickness parameter that best extends flat-plate cavity experience to flight conditions may yet be unresolved.


Lastly, one very important preliminary conclusion of the Flight Traceability study is that the CHT model for "Closed" cavities under predicts heating for at least some flight conditions. Minor damage will typically be of the "Shallow" or "Everhart" cavities, but the worst damage will be of "Closed" type. The number of flight conditions where "Closed" cavities were looked at with both the CHT and CFD is relatively small. This needs to be expanded to establish the extent by which this possible under prediction by the CHT would affect the integrated heat load.

Recommendations

1. Develop experimental tests to provide good validation data for low-enthalpy tunnel condition cavities: heating values, surface shear stresses, oil flows and other diagnostics of detailed local physical phenomenon. It is recommended that additional experiments be performed to provide adequate validation data for both the CHT and CFD heating tools. These experiments should be designed in collaboration with CFD and CHT analysts to ensure they provide the proper type of information needed for model validation. **(in work)**
2. Explore the feasibility of obtaining quantitative test data for local laminar cavity heating at high enthalpy conditions. *Note: Extension of Recommendation 1 in Section 7.0.* **(in work)**
3. Follow-on work is needed to understand the sensitivities for the integration of CFD computed heating bump factors with downstream tools: Heat transfer coefficient basis, TMM, Emissivity, Catalysis, Radiation exchange, and Conduction. *Note: This analysis was initially addressed as part of the end-to-end process.* **(in work)**
4. It is recommended that the proposed CFD bump factor maps be tested through the tile thermal and structural tools to examine if differences between the CHT and the CFD values yield significant changes in the results. **(open)**

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5. Perform a greater number of flight solutions for Closed cavities and those encountering significant pressure gradients to more fully evaluate the preliminary results of this study. **(open)**
6. The following expansions of the Flight Traceability study should be considered within the priorities of the Aerothermal team's activities: **(in work)**
 - a. Perform a more comprehensive validation of CFD's predictive ability for local cavity heating at both low and high enthalpy conditions.
 - b. Perform a CFD study of tile cavity edge radii to understand the relationship of heating spikes to edge radii.
 - c. Perform an independent CFD parameter study for H/delta, L/delta, L/W, and other parameters such as Medge, Re-theta, etc. *(The current study only matched wind tunnel parameter settings and did not provide comprehensive coverage).*
 - d. Examine the dependence of heating bump factors on the entrance and exit angles.
 - e. Examine of the dependence of heating bump factors on the orientation to the flow of various types of cavities.

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9.0 CATALYTIC HEATING TOOL: DAMAGED

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Function(s) of the Tool

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

$$\text{Final Local Heating} = \text{Catalytic Heating Augmentation Factor} * \text{Baseline Heating}$$

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 Orbiter Experiment Support System (OEX) flight data (STS-2, 3 and 5),

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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 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.

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*).

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

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, i.e., 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.

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

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 noted above. The following recommendations have been developed from 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. **(in work)**

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

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used throughout the analysis by the CHFT, the TPS TMM, and other associated models be verified as the same values **(closed)**. Additionally, it is recommended that additional test and analyses be conducted to improve confidence in emittance values for uncoated tiles. **(open)**

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. **(open)**

4. Bare RCC Catalysis

Catalysis of reacting surfaces, i.e., 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 considered for further investigation 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. **(open)**

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10.0 BOUNDARY LAYER TRANSITION (BLT) PREDICTION TOOL

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Function(s) of Tool

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 debris 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 corresponding Mach number for output.

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 in the process to assist the disposition decisions regarding which damage sites require further assessment. *(i.e., 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).*

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 flow field predictions. Currently, a BLT threshold of no earlier than 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

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methodology for flight above this historical observed limit for early Orbiter BLT. Overall the tendency of the BLT is conservative in that BLT is set at the earliest of the three allowable times.

Assumptions and Limitations


A peer review was conducted at NASA Langley on March 8th and 9th 2005 with the objective of reviewing the development of predictive tools to support disposition of the TPS damage and repair, and to provide comments as to the applicability of those tools to support STS-114. The peer review team was presented with an overview of the RTF perspectives and requirements of the BLT task along with a review of the recent mission simulation results. A review of the databases associated with prediction of the Orbiter flow field attachment line determination was conducted. Additionally, a review was conducted of the data on protuberances, cavities, and ablation (associated with a tile patch repair) the BLT team was using to establish new prediction techniques. Correlation results were provided for protuberances and cavities as well as flight data and comparisons using the prediction tools.

Based on this review, the following assumptions and limitations were noted:

1. Based on historical flight observations, a BLT threshold of no earlier than Mach 18 is assumed.
2. The cavity prediction technique assumes that the protuberance correlation approach is applicable to cavity-based transition. It is also based on limited ground test data with an even more limited set of Space Shuttle Orbiter flight data to compare against.
3. Attempting to have the cavity technique in a form similar to the protuberance correlation approach may not be the best correlation approach for cavities.
4. The ablation technique has significant weaknesses in that it has not yet reached the stage of actually being a prediction technique or correlation. However, based on the information presented, it is not clear that the levels of ablation out-gassing that would occur during re-entry from a potential tile repair, and their axial location were properly simulated in the limited ground test that was conducted. The correlation parameters were viewed as not adequate and recommendations were made on a better approach.

Observations

1. The peer review team recognizes that a tremendous amount of effort has been dedicated by the NASA team regarding the effects of TPS damage on BLT and the attempts to correlate newly acquired wind tunnel test data in support of RTF schedules.
2. Based on the information presented to the team, it was determined that there were not any tools that were significantly deficient to the effect that they could not be used to support


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STS-114. However, it was also determined that the tools were not acceptable to be used for STS-114 exactly as presented; nor were the tools considered to be at an end state requiring no further development to support future flights. Recommendations were made to address these deficiencies in time for STS-114.

3. The team observed the protuberance prediction technique had been developed further than either the cavity or ablator prediction techniques. However, each wind tunnel test provided data with different correlation levels.
4. Regarding use on STS-114, the protuberance prediction correlation needs to incorporate a limited set of Space Shuttle Orbiter flight data to augment the ground-based prediction correlation.
5. The computational techniques and engineering codes were considered to have acceptable uncertainties to support RTF. Continued improvement and incorporation of higher order physics results or correlations into the engineering codes are encouraged.
6. The cavity prediction technique has significant weaknesses. Attempting to have the cavity technique in a form similar to the protuberance correlation approach may not be the best correlation approach for cavities.
7. For the cavity prediction technique, the Re_θ/M_e versus D/δ (where D is the damage depth) may not be best considered the primary prediction technique and modifications should be performed.
8. The ablation technique has significant weaknesses in that it has not yet reached the stage of actually being a prediction technique or correlation. The data should be evaluated using a more appropriate correlation technique.
9. Test data for developing the correlations was not gathered at AOA greater than 40 degrees.
10. Testing roughness on small models (0.75 percent scale) may have limitations and larger model testing may be required for further development.

Recommendations

The peer review team found that the level of maturity on the different approaches varies and that the correlation approaches should be updated, to a limited extent, to support STS-114. Continued development efforts are recommended for the BLT prediction tools, particularly with respect to the cavity and surface blowing transition prediction capabilities. The following recommendations were developed from the results of the review.

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1. Roughness Requirements

The various step and gap requirements used on the Orbiter and the associated equivalent roughness values were explained along with the values associated with transition at Mach 14 and Mach 18. It was unclear as to the margin around the Mach 18 transition time and it was not evident that a study had been performed to assess the impacts of earlier transition occurrence to a fully turbulent flow, i.e., prior to Mach 18.

Recommendation:

An effort should be expended to understand the uncertainty associated with transition occurring prior to Mach 18, regarding impact on the vehicle. **(open)**

2. Flight Data


A review of the flight data involving transition was presented and discussed regarding the impacts on surface heating and back face temperatures. It was unclear why there was a large difference in surface temperature on instrument VO7T9674 for STS-28 and STS-93. It was also unclear why there appears to be a higher frequency of large roughness induced transition post STS-70.

Recommendation:

Transition data on all flights prior to STS-25 should be included in the correlation development. **(closed)** *Note: There is no thermocouple data available from STS-5 through STS-25. Only the already assessed STS-1 cavity near the wheel well door appears to have caused early transition.*

3. Attachment Line

The attachment line location defines the regions on the Orbiter lower surface, where if transition occurs as the result of damage or TPS repair, it would tend to be washed outboard and thus not impact the Orbiter lower surface. It was viewed as an indicator rather than a hard and fast rule. A concern was with the assumption that the attachment line could be used to define the influence zone within which damages can trigger the early downstream BLT. The approach assumes that the flow originates only from the nose stagnation point, thus resulting attachment lines make the effective influence zone too small. *(Note: Original Orbiter roughness maps were based on interpretation of data from many sources and allowed for transition spreading across vehicle streamlines).* It might be more appropriate to use wind tunnel roughness induced transition data to identify where the separating regions should be and then to validate using existing flight test data.

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Recommendation:

Consider the effects of AOA from 45 to 30 degrees in evaluating turbulence spreading as well as Mach 18 real gas effects rather than $M=6$ perfect gas estimates. **(open)**

4. Protuberances


The protuberance correlation established an engineering prediction technique that could be used to determine the impact of protuberances on transition. The approach was to correlate wind tunnel test data from three NASA Langley wind tunnels (20-inch $M=6$, 31-inch $M=10$, and the 20-inch CF4) and limited AEDC $M=8$ test data. BLT tripping points were simulated based on TPS tiles protruding from the OML using various heights of Teflon tape on a 10-inch long Orbiter model. The baseline correlation was Re_{θ}/M_e versus K/δ . The initial correlation was based on the 20-inch $M=6$ tunnel results. Incorporation of wall temperature effects and momentum thickness, $(K/\theta)(T_w/T_e)$, were used to achieve an alternate correlation with less wind tunnel test data scatter.

Recommendations:

1. Incorporate additional analyses identified into the initial correlation of Re_{θ}/M_e versus K/δ prior to STS-114. These include using a limited amount Space Shuttle Orbiter flight data to verify the correlation trends; separation of the incipient and effective transition data to allow for determination of uncertainty levels; and, review of roughness data from early in the SSP. **(closed)**
2. Future work should consider testing of additional roughness shapes and locations; further evaluation on the impact of the wall temperature and consideration for testing larger models. **(open)**

5. Cavities

The cavity correlation is used to assess TPS tile gouges relative to BLT. The approach was to attempt to correlate cavity transition data along the lines used for the protuberance data, i.e., Re_{θ}/M_e versus K/δ where a cavity dimension, either depth (D) or length (L) was substituted for 'K' (roughness element height). Use of the D/δ correlation relies on having cavity depth information provided while on-orbit. In addition, the correlation approach had only one point on the correlation line, raising concern of the correct slope. The D/δ correlation if extended to very small values of D/δ resulted in transition less severe than the smooth body flight experience. The cavity correlation is significantly less mature than the protuberance correlation, based on limited wind tunnel test data and without incorporating any flight data. The approach does not necessarily capture either

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the physics of the transition phenomena or historical correlation techniques. The cavity technique as presented possesses significant limitations.

Recommendations:


With these changes, this correlation could be applied, with caution, to STS-114.

1. Incorporate flight data into both D/δ and L/δ correlations to either develop a new trend line or verify the existing trend line. The D/δ correlation needs to be modified so that when extrapolated to small values it approaches smooth body transition. Since cavity depth information may not be available on-orbit and the L/δ correlation may be a better choice. In addition, similar to the recommendations made for the protuberance correlation, the incipient and effective transition data needs to be correlated separately and uncertainty bands developed for each **(closed)**. *Note: Ongoing work will address the use of an effective length rather than the geometric length as currently implemented in the correlation. The effective length will change based on the orientation of the flow to the alignment of the cavity.*
2. Re-examination at the STS-1 flight data to determine when incipient transition occurred. This should be attempted using thermal analyses of aft fuselage bond line data. **(closed)**

6. Ablation

The ablation correlation determines the impact of out-gassing/mass flow from the STA-54 cavity repair and whether the out-gassing was sufficient to impact BLT above and beyond the roughness generated by the STA-54 repair. The intent was to correlate data similar to the protuberance data (Re_θ/M_e) versus a blowing parameter instead of K/δ . Wind tunnel testing was conducted varying mass flow, porosity of the orifice, and density of the gas. Based on the wind tunnel data and the prediction of mass flow rates from a STA-54 tile repair on the fuselage at 60 percent length, it appeared that out-gassing would not be an issue during flight.

This was the least developed of the approaches and it is unclear whether the conclusions drawn are correct. It was not clear if the blowing rate from the 60 percent body length location used would represent the worst blowing on the windward surface. A station closer to the Orbiter nose would have been more appropriate, based on available supersonic/hypersonic test data.

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Recommendations:


1. The limited wind tunnel test data needs to be re-correlated against more traditional correlation parameters, *i.e., using a normalized blowing rate such as $(\rho v)_w/(\rho u)_e$* , to verify that the expected blowing level is being scaled properly. In addition, the blowing rate needs to be verified that it is representative of the hottest region just behind the nose cap on the Orbiter. The impact of blowing at locations further forward on the Orbiter need to be tested as well as the combined effects with roughness. *Note: available literature on ground test data indicates that downstream transition is more sensitive to blowing near the nose than from a downstream source.* Until this is resolved this approach has significant limitations. **(open)**

7. Computations

The computational portion of the BLT tool is an interpolation through a data base of computational solutions that output the boundary layer edge and surface quantities for the windward Orbiter surface. These quantities are used with the developed transition correlations to predict transition due to a given TPS damage site. The approach used within the computational tool involved interpolating within the data base using trajectory parameters and user input quantities ($x, y, z, Re, M, \alpha, V_\infty, \rho_\infty$), and then scaling to account for differences in Reynolds number. The data base is currently based on a combination of Navier-Stokes and Two-Layer (Euler + Boundary Layer) computational solutions. The code provides surface pressure, laminar heat rate, and boundary layer edge properties such as $\theta, \delta, Re_\theta/M_e, T_w/T_e$, etc. This tool is used by the BLT team to provide the flow transition time and associated K_{eq} that will be used for aerothermal/thermal evaluations of the damage locations. The tool uses α and Mach number interpolation of a given trajectory based on two reference trajectories of STS-107 and ISS heavy weight mission.


Based on the information provided, there did not appear to be any significant issues in this area. The use of the presented engineering tool to predict flow field properties for BLT estimation appeared to have acceptable uncertainties for STS-114.

One minor concern was that by mixing the solutions from the dissimilar codes could create the possibility of introducing data discontinuity, thus producing unrealistic analytical problems when used by non expert users. It is important to maintain consistency between the code/tool used to correlate transition data and to predict transition on both STS-114 and on future flights. It is also important that these engineering tools continue to be advanced by adding more flow field physics based on calculations from the higher order CFD codes.

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Recommendation:

Data continuity in data matrices should be thoroughly checked before releasing the code. Continual enhancement of the data bases should be sought to improve the accuracy of the outputs by continuously employing more physics accounted for CFD results. **(closed)**

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11.0 3-D ACREAGE TILE THERMAL MODEL

Peer Review Team Members

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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.


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).

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

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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.

2. Damage Location to Flight Data Comparison


A survey of historical tile damage to the Space 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 Room Temperature Vulcanizing (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/Strain Isolation Pad (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.

3. Uncertainty of Uncoated (Damaged) Tile Area Hemispherical 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, but 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.

4. Inter-Tile Gap Heating

The 3-D TMM does not simulate the individual 6” x 6” Space 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

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(not on the heating). Boeing claimed that this new approach is equivalent and produces conservative results.

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. **(complete)**

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. **(open)**

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. **(open)**

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12.0 SPECIAL CONFIGURATION THERMAL MODELS

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12.1 Elevon Lower Cove 3-D Thermal Math Model (TMM)

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.

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.

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

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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).

- 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.

Recommendations

- Perform arcjet testing for comparison with the model. **(open)**
- Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. **(open)**
- Expand the 3-D model to include thermocouple locations (where available) from early flights. **(open)**


12.2 Forward Reaction Control System (FRCS) Canopy 3-D TMM

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.

Assumptions and Limitations

- 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.
- 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.

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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.

Recommendations

1. Perform arcjet testing for comparison with the model. **(open)**
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. **(open)**


12.3 WLE Panel 9 Lower Access Panel (LAP) 3-D TMM

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.

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.

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

Recommendations

1. Perform arcjet testing for comparison with the model. **(open)**
2. Modify the 2-D or 3-D TMM to more closely match configuration/property differences between models. **(open)**
3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. **(open)**


12.4 Main Landing Gear Door (MLGD) 3-D TMM

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.

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

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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.

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.

Recommendations

1. Perform arcjet testing for comparison with the model. **(open)**
2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between model. **(open)**
3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. **(open)**

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12.5 Vertical Tail Leading Edge (VTLE) 3-D TMM

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.

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.

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.

Recommendations

1. Perform arcjet testing for comparison with the model. **(open)**

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2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. **(open)**
3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. **(open)**

12.6 Forward Window # 3 Perimeter 3-D TMM

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.

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.

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.

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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.

Recommendations

1. Perform arcjet testing for comparison with the model. **(open)**
2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. **(open)**
3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. **(open)**

12.7 External Tank Door (ETD) 3-D TMM

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.

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 2,400 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 to -50°F. The model also uses a constant thickness for the door which in reality is not the case.

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.

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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.

Recommendations

1. Perform arcjet testing for comparison with the model. **(open)**
2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. **(open)**
3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. **(open)**


12.8 Nose Landing Gear Door (NGLD) 3-D TMM

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.

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 683° F which is well below the 1500° 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.


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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 20° F/40° 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.

Recommendations

1. Perform arcjet testing for comparison with the model. **(open)**
2. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. **(open)**
3. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. **(open)**

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13.0 TILE STRESS TOOL – RTV BOND LINE (45 DEGREES)


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Function(s) of Tool

The tile stress and RTV bond tool is a new tool and is one of a series of computer tools developed to evaluate on-orbit tile damage. Stress analysis equations have been programmed to calculate entry factors of safety (FOS) for the lower surface new 6" x 6" LI-900 HRSI (black) acreage tiles with damage oriented at 45 degrees. Failure modes include tension at the RTV bond, compression and shear in the LI-900, and shear in the SIP. RTV bonds subjected to temperatures greater than 650°degrees F lose all tensile strength; however, the strength recovers after an initial reduction at temperatures between 470°F and 650°F.

Entry airloads, aerodynamic pressures, vibro-acoustic dynamic loads, tile damage dimensions, bond dimensions, material properties, and structural out-of-plane deflections are used to calculate corresponding FOSs. Airloads are tabulated for Mach numbers from 25 to 0.4 and downstream tile pressures and applied to the damaged acreage HRSI tiles. Entry random vibration levels, maximum 9.0 g (3.0 g's at 3-sigma) during TAEM are applied at the center of mass of the tile. Initially, default OOPD from the TIPS database for Performance Enhancement (PE) loads for TAEM are used, and then updated with OOPD from the stress assessor tool or non-linear finite element analysis (FEA). The determination to utilize non-linear FEA is made by the stress analysis, based on a manual review of the stress assessor tool output. The bondline stress tool is essentially a post processor to the TMM where temperatures at thermal nodes from critical Mach numbers, calculated by and obtained from the 3-D TMM tool, are superimposed on a tile damage map. This process allows for the damage to each tile to be categorized as single tile, multiple tile aft, multiple tile center, multiple tile side or multiple tile forward (see Figure 13.0-1). A rectangular area subjected to temperatures greater than 650°F is deleted from the bonded 5" x 5" footprint. Material properties are adjusted for temperature.

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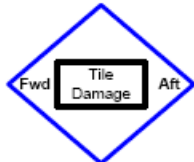
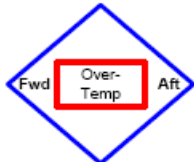
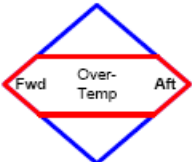
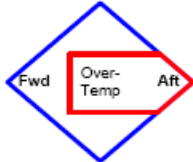

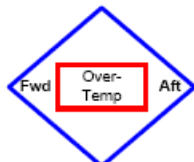
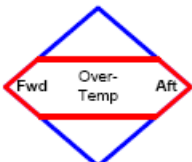
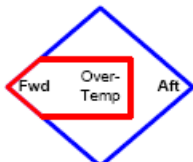

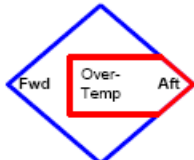
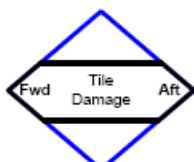

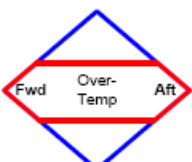
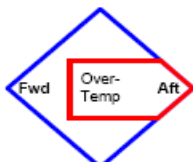
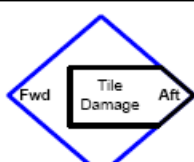
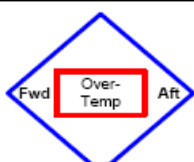
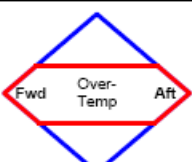
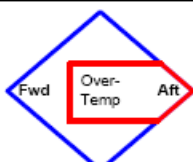
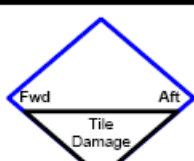
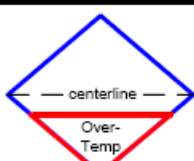
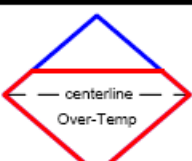

TILE	RTV		
 Single Tile Damage	 Interior O/T	 Exterior O/T	 Int/Ext O/T
 Multiple Tile Damage Aft Tile	 Interior O/T	 Exterior O/T	 Ext/Int O/T
 Multiple Tile Damage Aft Tile (continued)	 Int/Ext O/T		
 Multiple Tile Damage Center Tile	 Interior O/T	 Exterior O/T	 Int/Ext O/T
 Multiple Tile Damage Forward Tile	 Interior O/T	 Exterior O/T	 Int/Ext O/T
 Multiple Tile Damage Side Tile	 RTV burnout lower than centerline	 RTV burnout higher than centerline	

Figure 13.0-1. Categorization of Tile Damage for Analysis

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The RTV bondline tool code was originally developed and checked out at Boeing in Huntington Beach, California in a Microsoft Excel© format. In an effort to improve computational efficiency, the code was migrated to Boeing Houston and integrated with the 3-D TMM. An implementation datapack was provided to describe how the RTV bond stress equations interface with the 3-D TMM TPS screening program and the process for choosing the model configuration, loads, etc; checks during the program (internal and by user); and output examples during their verification/validation exercise. The integration required that the code be turned into a FORTRAN subroutine called by the 3-D TMM. The RTV bond subroutine also contains the code to perform the interpolations of the pressure and material property databases that are used during the analysis process.

Assumptions and Limitations

1. The on-orbit inspection will not be able to detect any internal tile damage; therefore, the structural integrity of the damaged tile above the densified layer is not considered.
2. Tool applies only to new lower surface 6" x 6" HRSI acreage tiles (LI-900 and FRCI-12) with 0.160" and 0.90 SIP.
3. Damage is assumed to have an orientation of 45 degrees with respect to the tile.
4. Orbiter Vehicle End Item (OVEI) Specification FOS required is 1.40. Analysis calculates the actual FOS.
5. The damaged overtemperature SIP is located at the center, which was verified to be conservative.
6. The overtemperature area of the RTV bondline is assumed to be rectangular for computational efficiency.
7. If the RTV overtemperature area exceeds 75 percent of the bondline footprint, the tile is assumed to be failed.

Observations


1. Worst-case (Lowest FS) tends to be when the overtemperature area is directly under the damage and when the damage/overtemperature is centered in the tile causing larger moments to the remaining bond area. The offset forward/aft area causes a higher moment such that MC/I may dominate.
2. The secant modulus is adjusted linearly for temp effect in the OOPD calculation (i.e., softness lowers deflection).
3. The FOS failure modes are only RTV bond tension, LI-900 compression and shear, and SIP shear. These are the dominant failure modes if the remaining tile undamaged assumption exists.

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4. The RTV bond and tile stress tool has not been correlated to any test data, but validated to be within 10 percent of FEA.
5. The integrated (FORTRAN subroutine) program validates within 2 percent of the stand-alone (Excel) program.

Recommendations

1. The tool inputs/outputs and effects on adjacent tools should be understood through a comprehensive end-to-end tile damage analysis tool check. **(complete)**
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. **(complete)**
3. RTV bondline failure is the critical failure mode identified on the damage map for many vehicle zones; however, it is the least validated of all the models. Efforts should be made to better validate the performance of the RTV/Tile/SIP system under elevated temperature. **(open)**
4. The assumption of secant modulus and shear allowable at 625° F being extrapolated just as flatwise tension to 15 percent of value at 450° F should be validated by test. **(open)**
5. The tool should be expanded for upper surface acreage tile and penetration perimeter tile, if possible. **(open)**
6. The effects of aged tiles should be included. **(open)**
7. This tool has already been used for pre-flight assessment in the development of the foam on tile and ice on tile damage maps, as well as the on-orbit (2²/3rd) criteria tile damage map. Thus, the restriction that it be used only for on-orbit assessment should be lifted. **(open)**

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14.0 STRESS ASSESSOR TOOL

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Function(s) of Tool

The stress assessment tool was developed to provide a capability to define damage tolerance of the Orbiter vehicle skin structure due to the local temperature increase resulting from Orbiter damage. The 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 based on 6.0 and Performance Enhancement (PE) certification loads cycle data combined with the increased thermal loads due to damage in order to define structural margins of safety and out of plane deflections. The results will then be utilized to support a vehicle safe to enter “as-is” or repair decision. The tool is applicable for pre-flight and real time on-orbit assessment. The analysis is based on maintaining an ultimate structural FOS of 1.4 (Orbiter Vehicle End Item (OVEI) Specification Requirement).

Assumptions and Limitations

1. The tool can only analyze the Orbiter bottom skin and the Orbiter Maneuvering System (OMS) pod structure, which includes the following types of construction:
 - a. Mid fuselage sheet stringer.
 - b. Mid fuselage/wing glove area sheet stringer.
 - c. Mid fuselage/wing carry through area waffle panel.
 - d. Aft fuselage waffle panel.
 - e. Elevon/wing honeycomb skins.
 - f. Forward fuse/chine sheet stringer.
 - g. MLGD honeycomb.
 - h. OMS pod composite honeycomb skin.


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2. The body flap and NLGD acreage construction is not specifically modeled, and most leeward (upper fuselage) areas of the vehicle and their representative types of construction are not covered by these tools.
3. Temperature limits are assumed to be 350° F on the bottom skin, and 250° F on the OMS pod. Model performance is not validated beyond these temperatures.
4. Damage is assumed to be “small” in comparison to critical panel dimensions so as to preclude significant boundary effects. This critical dimension (Lcrit) varies for each type of construction and zone on the vehicle. The “thermally affected length” (Leff) is assumed to be twice the corner-to-corner dimension of the damage. Leff is then compared to Lcrit to establish if damage can be considered within the valid application of the tool.
5. Structural response is assumed to remain linear; therefore, large out of plane deflection problems may have to be resolved with non-linear computational capability outside of the current Stress Assessor suite of tools. In cases where out of plane deflections exceed 0.040 inches non-linear analysis using NASTRAN Finite Element Analysis (FEA) is considered.
6. The tool assumes no significant damage cavity growth during entry which may not be conservative, particularly for damages which are susceptible to “worm holes”, or burrowing.
7. These models represent general, acreage behavior of types of construction. Many design details are absent from these models and, therefore, are not represented in the final solution. If damage occurs near one of these design details (critical seals, penetrations, structural splices), location specific modeling may be required to meet mission analysis needs.
8. Tool assumptions were reviewed for appropriateness per the Analysis Validation Review Assessment Worksheet shown in Table 14.0-1.

Observations

General

1. Tools are derived from closed form solutions, which capture changes in stress and loads due to thermal gradient, and compute out of plane deflections based on geometry of the local area. Many of the tools depend on automated Excel spreadsheets or calls to certification codes (i.e., “Waffle” and “PASCO”) as subroutines to compute margins.
2. Several data bases and programs are scripted together to provide the complete “Stress Assessor” capability.

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3. Models have generally been validated against FEM solutions, or hand calculations. Correlation requirement is ± 10 percent; however, in general, the tools perform much better than this criterion (typically within ± 5 percent).
4. In an infinite plate, strain produces a ratio of compression and tension zones (or K factor) of 0.5. In reality, as the panel-to-damage ratio gets smaller (less like an infinite plate), the zone ratio increases. For the range of panel-to-damage ratios considered valid for this analysis, Boeing established 0.6 as a more appropriate ratio of compression to tension zones through the use of NASTRAN FEA at various panel to damage ratios.
5. Models address both local (i.e., crippling, local buckling) and global panel (i.e., general instability, panel buckling) load effects due to increased thermal loads.
6. General quality checks have been run on all tools to ensure that as temperature and damage dimension increase, that margin and out of plane deflections respond in a rational fashion.

Sheet Stringer Construction - Wing

7. Wing assessment is conducted by thermal comparison only, since descent stress puts tension into the lower wing. Therefore, mechanical loads are not additive to gradient driven, compressive loads.

Sheet Stringer Construction – Mid Fuselage, Wing Glove

8. Models represent structure as either equivalent skin thickness (t_{bar}) or actual geometry as appropriate for the particular computation.

High Curvature Sheet Stringer Construction - Wing Glove and Forward Fuselage


9. Modeling of high curvature areas, such as the Wing Glove and parts of the Forward Fuselage, incorporate correction factors due to the redistribution of load due to the radial deflection of these curved geometries. This methodology was developed and utilized as a part of the original certification of these structural assemblies.
10. Loads are adjusted and panels are analyzed as flat plates.
11. Forward Fuselage utilizes certification analysis programs in the computation of margin.

Waffle Construction – Mid and Aft

12. Utilizes certification analysis programs “Waffle” and “PASCO” in the computation of margin.

Honeycomb Construction – Elevon, Intermediate Wing, MLGD

13. Stress-based computation rather than loads.

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14. Elevon and mid wing region utilizes elevon derived certification analysis program for margin computation; however, additional equations are required for out of plane deflections.
15. Orthotropic NASTRAN panels were used to simulate the structure and validate tool output for out of plane deflections.

Recommendations

1. The stress assessor tool 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)**
2. Better define the tool analysis range as it relates to the damage site. **(complete)**
3. Most of the analytical equations used to calculate the delta loads resulting from the damage sites have been verified. Need to verify the remaining analytical equations. **(complete)**.
4. Verification of correction factors for curved surfaces. **(in-work)**
5. An independent review of the NASTRAN models used to validate assumptions in the tool is needed. **(open)**
6. Provide capability for electronic transfer of out of plane deflections to the 3-D TMM. **(closed)**
7. Provide capability to determine NLGD stresses and out of plane deflections. **(open)**
8. Need to perform several end-to-end runs to validate the tool. **(complete)**
9. Expand the capability of the tool to include other areas beside the bottom skin and OMS pod. **(open)**
10. An independent review of the out-of-plane deflections non-linear FEA models is needed. **(open)**
11. An independent review of the NASTRAN models used for honeycomb structure (elevon, mid-wing, MLGD) is needed. **(open)**



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Table 14.0-1. Analysis Validation Review Assessment Worksheet

Requirements	Comments	Conserv./Nominal
Geometry Definition		
Mid Fuse sheet stringer	Simplified Geometry	Predictive
Mid Fuse/Wing Glove sheet Stringer	Simplified Geometry	Predictive
Mid Fuse/Wing Carry Thru Waffle	Simplified Geometry	Predictive
Aft Fuse Waffle	Simplified Geometry	Predictive
Elevon/Wing Honeycomb	Simplified Geometry	Predictive
Fwd Fuse/chine	Simplified Geometry	Predictive
MLGD honeycomb	Simplified Geometry	Predictive
OMS pod fwd skin panels	Inner & Out face sheets assumed at the same temperature	Unconservative
Damage Cavity	Idealized cavity received from thermal tools	Conservative
Material Definition		
	Bottom skin structure, 350° F;OMS Pod 250° F temperature 2024-T81 Aluminum face sheets for Honeycomb structure	Nominal
Key Assumptions		
	Combines existing loads database with loads associated with increased temperatures from the thermal assessment tool to create input loads for the analysis tools.	Nominal
	Temperature provided by thermal group	Nominal
	Margin of Safety, out of plane deflections for bottom skin structure underneath tile and OMS pod structure	Nominal
	Body flap, RCC panels, thermal barriers, and vertical tail cannot be analyzed using this tool.	Unconservative
	Ultimate factor of safety 1.4 per OVEI spec.	Nominal
	Thermal effective length, $L_{eff} = 2 \cdot (L^2 + W^2)^{.5}$, up to overall panel length or width	Conservative
	No significant cavity growth during entry	Unconservative
	Wing assessment by thermal comparison, not by Stress Assessor tool	Unconservative, no out of plane deflections

Requirements	Comments	Conserv./Nominal
BC, Loading	Body flap assessment not by Stress Assessor tool	Unconservative, no out of plane deflections
	For mid-fuselage region, Lower Wing Carry Thru certification analysis program used.	Nominal
	For aft-fuselage region, Waffle and Pasco programs used.	Nominal
	For elevon and mid wing areas, elevon certification analysis program used.	Nominal
	For MLGD areas, a certification analysis program used.	Nominal
	Curved panel theory for the forward fuselage and wing glove based on Timoshenko "Theory of Plates and Shells"	Nominal
	Using PE/6.0 certification database for pre-launch assessment	Nominal
	Using Modified (with reduced mechanical & ISS derived thermal cases) database.	Nominal
Numerical solution Accuracy	Thermal loads determined	Nominal, equations verified
	Using PE/6.0 loads replicate certification case margin within $\pm 1\%$ OMS Pod analysis replicate certification case margin within $\pm 4\%$	
Analysis Trend Check	Varying temperature change while maintaining damage size	Nominal
	Varying damage size while maintaining temperature change	Nominal
Quantitative Correlation	K value - under thermal loading the ratio between comp./tension zone -0.6 rather than 0.5 for NASTRAN	Conservative
	Tension/Compression	Verification of the elevon honeycomb structure and the mid fuselage was by NASTRAN FEA
Correlation of Global Response		
Parametric Studies	See historical reconstruction	

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15.0 INTEGRATED TOOLS FOR END-TO-END COMPUTATION OF TILE DAMAGE

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Background

Previous sections of this report have dealt with the review, verification and validation efforts on *individual* tools. Ultimately, the performance of the suite of tools must be evaluated in an end-to-end fashion in an attempt to establish the accuracy of the final solution. The correctness of the analytical output will be a product of both the quality of the input and the accuracy of the computed output which is passed from tool to tool. Therefore, the end-to-end review focused not only on the final tool output, but the interactions between tools and the processes for assuring data integrity between tools (particularly for manual input data).

Function(s) of Tool

The damage assessment tools are used in two capacities by the SSP: preflight and on-orbit (see Figure 15.0-1). The end-to-end review was focused principally on the on-orbit application of the tools; however, the tools are the same tools. The difference in application centers on the description of the damage shape. In both applications, there are three basic components to the assessment:

1. Describing the shape of the damage for analysis
2. Determining the effect of the damaged TPS configuration on local heat rate relative to the undamaged state
3. Performing analysis of the resulting TPS and structural system performance against five criteria:
 - a. RTV bondline temperature.
 - b. RTV bondline stress.

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- c. Structural temperature.
- d. Structural margin.
- e. Structural out of plane deflection.

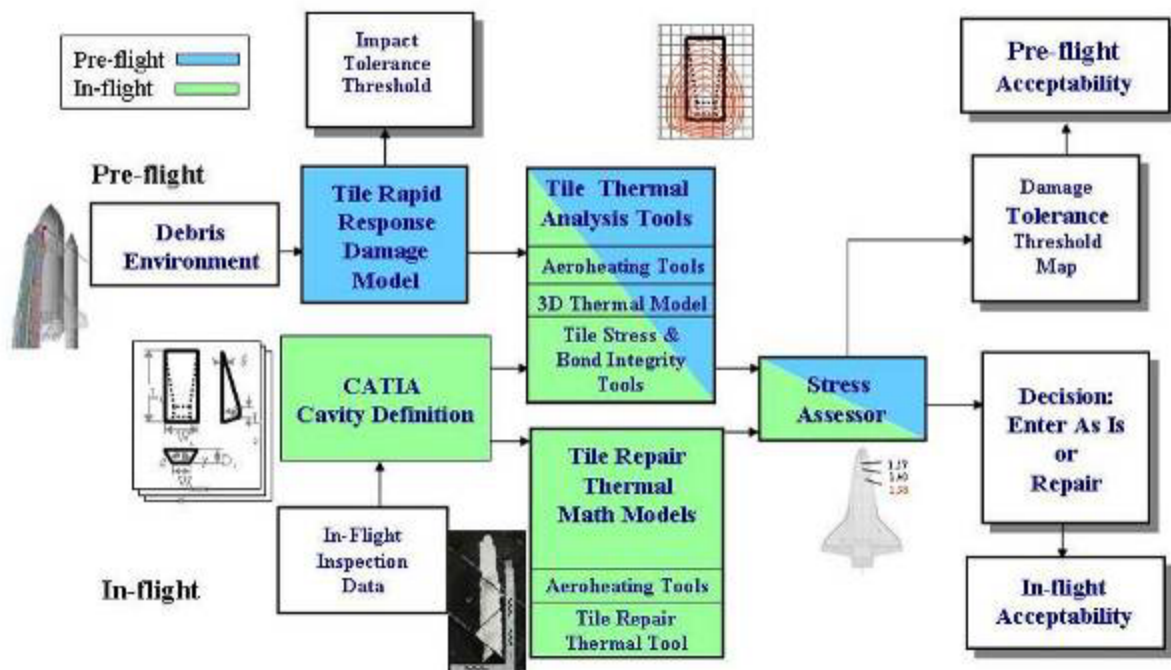



Figure 15.0-1. Flow of Data Defining Environment, Modeling Damage, Analyzing Capability and Culminating in the “Damage Tolerance Threshold Map”

Preflight

The tools are used pre-flight to support RTF rationale, and probabilistic computation of risk of critical impact. This application of the tools produces 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 approximately 33 zones, and determining the maximum allowable penetration depth using a combination of several analytical models including:

- Rapid Response Damage Model (ice and foam on tile)
- Cavity Aeroheating Augmentation Tools
 - Boundary Layer Transition Tool


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- Cavity Heating Tool
- Thermal Analysis Tools
 - 3-D TMM
- Stress Assessment Tools
 - Stress Assessor
 - RTV Bond Tool

On-Orbit

The tools were primarily developed to support on-orbit “return as is” or repair decisions by the Space Shuttle Program Mission Management Team (SSP MMT). In this application, the rapid response tile damage models are not required, as the damage geometry is described through a series of on-orbit inspections. These inspections include photographs taken during the Roll Pitch Maneuver and focused, laser inspections using the Orbiter Boom Sensor System (OBSS). While exact damage geometry is defined as a 3-D point cloud, a process is used to define a simplified cavity definition, otherwise known as the “shoebox” (see Figure 15.0-2). Therefore, the on-orbit tool suite includes:

- Simplified Cavity Definition Tool
- Cavity Aeroheating Augmentation Tools
 - Boundary Layer Transition Tool
 - Cavity Heating Tool
- Thermal Analysis Tools
 - 3-D Thermal Math Model (TMM)
 - Special Configuration 3-D tools
 - *Repaired Tile Tool (TRAP/CHAP/STG)*
- Stress Assessment Tools
 - Stress Assessor
 - RTV Bond Tool

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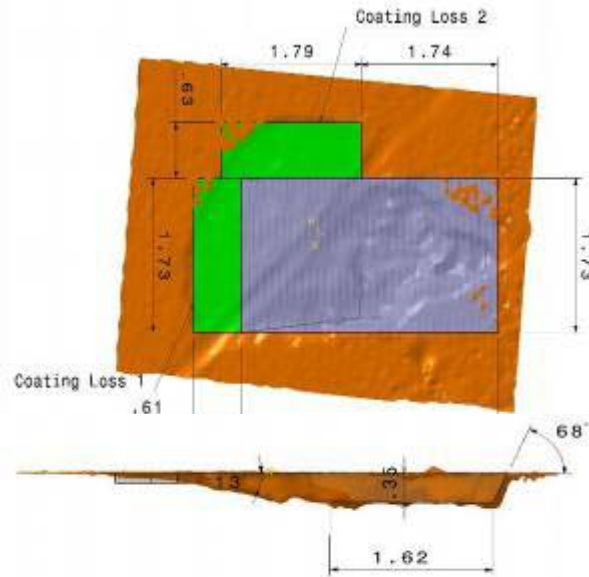



Figure 15.0-2. Simplified Impact Geometry

While the analysis of tile repair is a part of on-orbit evaluation capability, it was not considered a part of the NESC individual or end-to-end tool reviews. These tools are neither certified, nor baselined for use on the STS-114 mission.


Analysis Process Flow

The analytical process flow was assessed through the review of several reports, spreadsheets, and briefings which document the analysis execution:

1. "TPS Damage Assessment Script".
2. "Product Spread Sheet".
3. "Damage Assessment Analysis Data Transfer Files".
4. "TPS Tools List Spread Sheet", June 24, 2005.
5. "STS-114 Operations Integration Plan for Thermal Protection System Assessment", June 9, 2005.
6. "Analytical Tools Requirements Document for On-Orbit Debris Damage and Repair Assessment", NS05HB022, Revision A, June 2005.
7. "Tile Repair Program Analytical Tools Interface Control Document", NS05HB023, Revision NEW, June 28, 2005.

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The tile damage assessment process delivers analysis in a specific order with handoffs of data in a specific format. For in-flight assessments, actual cavity dimensions are defined by the OBSS. The OBSS output is damage location and volume, represented as a 3-D point cloud, which is fed to the Damage Assessment Team (DAT) to begin the analysis process. The point cloud is used by the simplified cavity definition tool to establish the geometry for analysis based on a “50/50 rule”. This draws the plane of the simplified damage walls and floor with 50 percent of the volume of the damage inside the plane and 50 percent of the volume of the damage outside the plane. This is effectively the “average” plane, and smoothes out local surface features which are not anticipated to affect the global behavior. The BLT time is a function of location and depth of damage, and is used to identify the aeroheating time history. The cavity heating tool then provides any required aeroheating augmentation factors. The TMM uses output from the simplified cavity definition tool, the aeroheating, and the associated augmentation factors as input to calculate temperature time history at specified locations. The stress assessor tool and the RTV bondline stress tools use the temperature and gradient information from the TMM to establish margins of safety at critical load events during reentry (i.e., Mach 5, TAEM, and Touch Down). The flow of data for on-orbit analysis is summarized in Figure 15.0-3. While much of the process is automated, there are several interfaces that are accomplished through manual user input.

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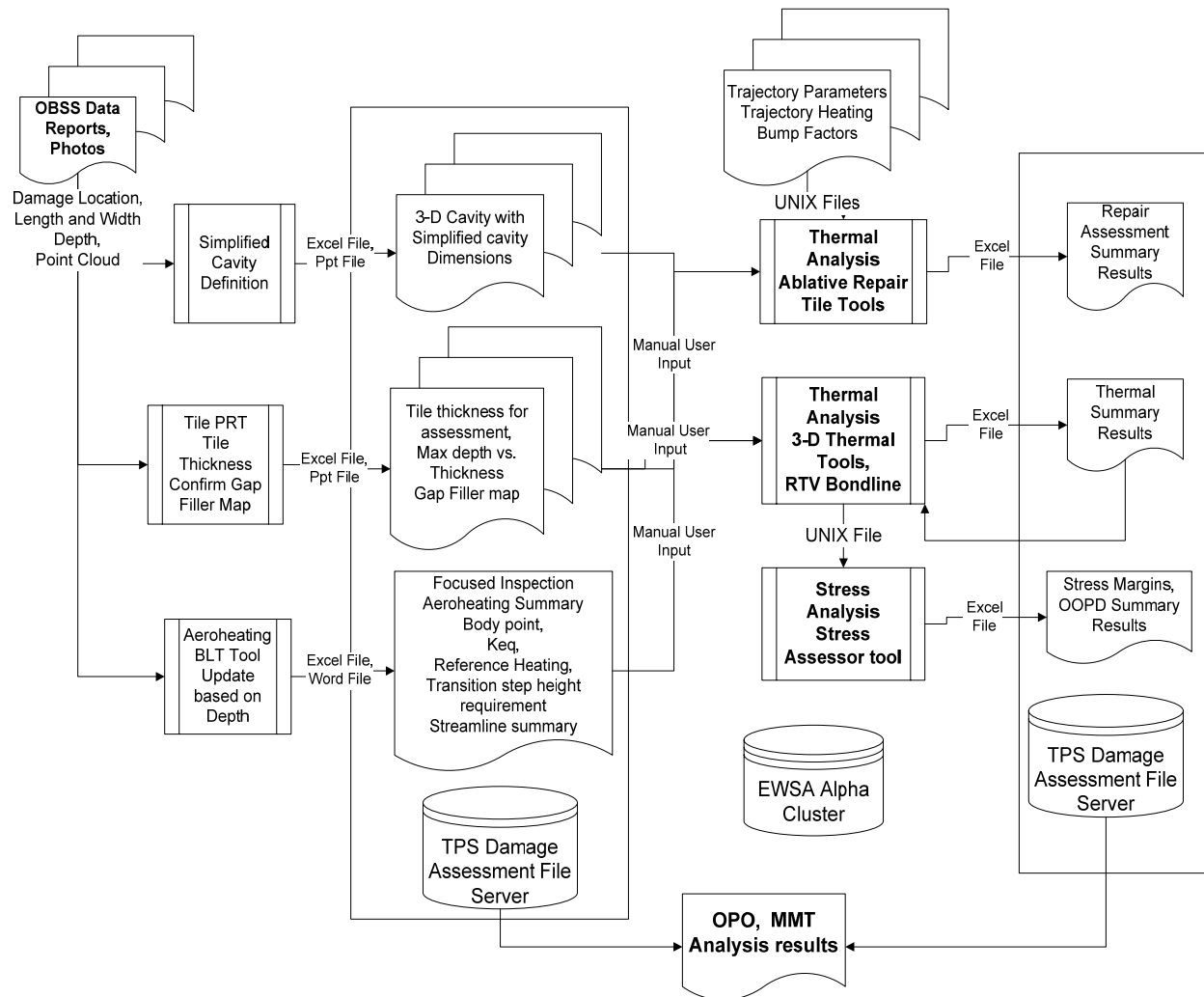



Figure 15.0-3 On-orbit TPS Damage Assessment Data Flow

Accuracy and Uncertainty

The accuracy of the tool performance was measured principally against a series of historical reconstructions. Eleven historical reconstructions were completed from a candidate list of 19 damages (see Figure 15.0-4). These 19 damages were selected from the “Platinum Database” as representative damage across all zones of the vehicle with sufficient data (PRACA data, measurements, photos, post-landing reports, etc.) available to make at least qualitative comparison with the analytical predictions possible. The downselect from 19 to 11 cases was based principally on the quality of the data available to define the geometry of the historical damage, and the quality of TPS documentation and structural condition after damaged tile

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removal. No “Platinum Database” historical damage was located sufficiently close to vehicle instrumentation (i.e., thermocouple or strain measurements) to anchor analytical results in a quantitative way to flight history.

Damage geometry for these reconstruction cases was sometimes based on nothing other than a 2-D image of the damage. This led to significant uncertainty in the most appropriate “shoebox” geometry. Therefore, multiple cases (best estimate, best case, worst case) for geometry of the cavity were run. In all cases, the historical reconstruction showed that with a “reasonable” set of assumptions about the cavity geometry, the entry environment conditions, and the material properties, the tools would predict an outcome which qualitatively correlated to the flight outcome. Therefore, it is expected that with an accurate definition of cavity geometry, the analytical tools can provide a reasonable representation of system behavior. It also showed that for 2 or 3 cases, that a recommendation to repair would have been made to preserve the full FOS for re-entry. A complete summary of this methodology and results is available in the briefing entitled, “Historical Data Reconstruction Assessment Using Tile Damage Analytical Tools”, OCCB S064065R1, presented at the July 5, 2005 OCCB.

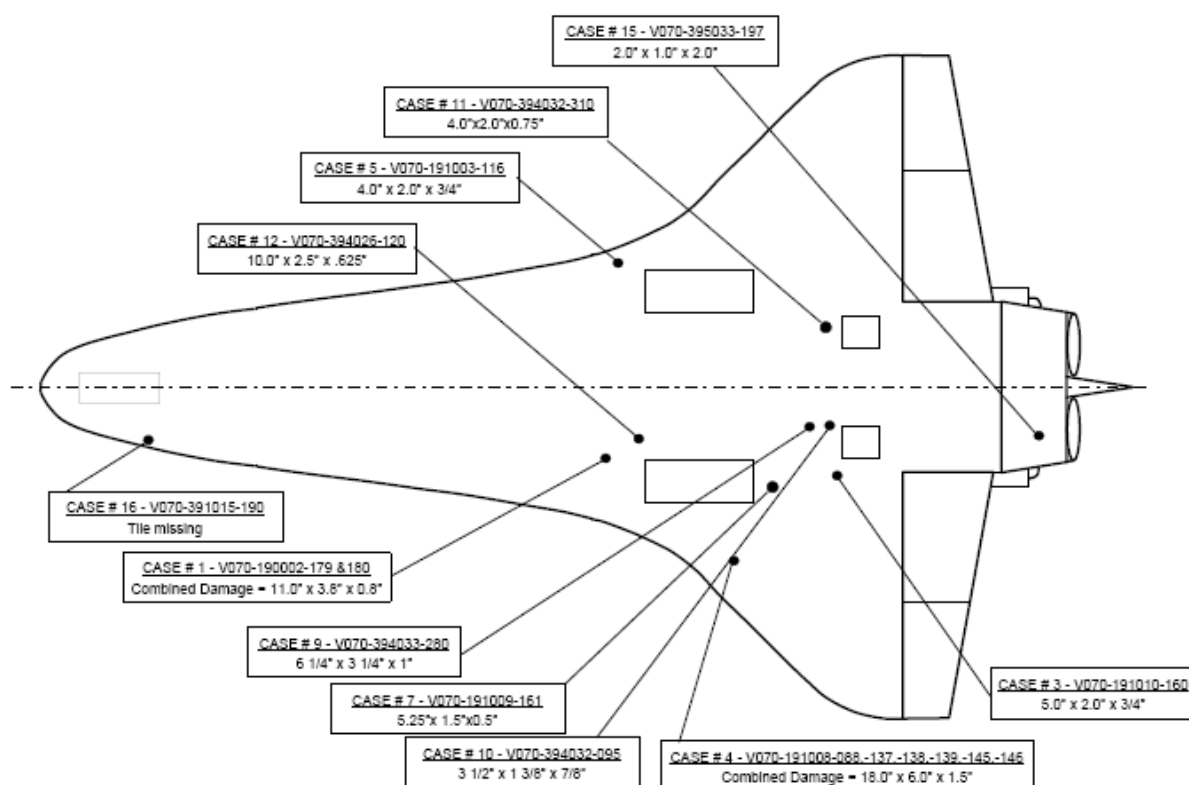



Figure 15.0-4. Eleven Damage Sites used in Historical Reconstruction Analysis

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The uncertainty inherent in the solution remains a significant question. Preliminary analysis has been conducted by Ares Corporation at the direction of Boeing. Initial attempts to quantify uncertainty and sensitivity have focused on approximately 10 variables of interest. These variables were selected because of the anticipated sensitivity of the result to the selected parameter, and because of the availability of data to describe possible variation of the parameter being evaluated. Uncertainty distributions evaluated included:

- Cavity depth
- BLT time
- Thermal conductivity
- Surface emissivity
- Ultimate tensile stress
- Interpolation between body points
- BLT correlation
- Heat rate augmentation: flat regions
- Heat rate augmentation: high pressure gradient regions
- K-Factor for thermal expansion calculation

Simplified models were developed to extrapolate the relationships established by running the detailed models (i.e., relationship between heat rate and back face temperature). Monte Carlo analysis was then run to obtain distributions on critical output data (i.e., structural temperature, RTV bondline temperature, structural FOS). The summary of this methodology and preliminary assessment is available in the briefing entitled, “Status Report on Uncertainty Analysis of the Tile Damage Assessment Process”, Bell, Madera, Benjamin, SSP PRCB, July of 2005. Further detailed assessment of the uncertainty is planned.


Assumptions and Limitations

Limitations and assumptions for the individual tools are identified in the appropriate sections of this report. However, there is an overarching limitation on surfaces/locations where tools may be applied. The tools may be used, and are test-verified for acreage tile areas, such as:

- Lower surface acreage
- Lower surface elevon acreage
- Lower surface body flap acreages

Tools are available, but not test verified, for other areas, such as:

- Wing Glove/Chine

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- Vertical Stabilizer Leading Edge
- Forward Reaction Control System
- Window Frame Periphery
- Elevon Cove
- Forward OMS tiles
- Lower surface seals (MLGD, NLGD and ETD)
- Leading Edge Structural Subsystem (LESS) carrier panels


Observations

Process


1. The analysis tool input and output requirements are adequately documented in the Analysis Tool Requirements Document for On-Orbit Debris Damage and Repair Assessment.
2. The majority of tool interface issues have been mitigated or eliminated through simulations and table top reviews.
3. The DAT has assigned a Damage Assessment Analysis Coordinator to facilitate communication and data transfer between analysis groups during the damage assessment process.
4. Maturity of the TPS Status Assessment Tool (TSAT) site (where DAT data is stored and disseminated) is undemonstrated and could result in some issues with timeliness of data transfer.

Integrated Application of Analysis Tools

5. The preflight application of these tools has inherent conservatisms that make an *a priori* determination of capability very restrictive. These conservatisms are related to analyzing with “certification rigor”, and making bounding assumptions for physical, geometric and computational simplicity. Many of these conservatisms are either removed or significantly reduced in a damage-specific, mission-specific application.
 - a. The use of certification trajectory and re-entry parameters (HWISS return trajectory, maximum Orbiter weight, maximum G’s and sink rate, and 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.

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- b. 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.
- c. 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.
- d. 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).
- e. 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.
- f. 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.
- g. 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.
- h. 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.

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- i. 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.
 - j. 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.
6. OBSS measurement accuracy for tile damage is currently baselined at ± 0.25 inches. However, development testing indicates it may do as well as ± 0.10 for HRSI in good lighting conditions.

Historical Reconstruction

7. Historical reconstruction cases do not cover the area of OOPD sensitivity in the forward mid fuselage.
8. Models can explain Orbiter survival with historical damage given a reasonable interpretation of input cavity geometry and a known BLT environment.
9. Historical reconstruction analysis used the mission-specific flight profile, including reconstructed BLT time. While this did not exercise all of the analytical tools, it was necessary to get the most predictive result out of the analysis. Utilization of the full suite of aeroheating augmentation tools would have resulted in a more conservative environment for many of the damage cases (due to earlier boundary layer transition); therefore, a more conservative prediction of damage, and potentially more recommendations to repair.
10. Small deep impacts lead to analysis that may or may not predict local overtemperature conditions. This is highly dependent on the proximity to gaps and the presence of wormholes. Regardless, these types of impact are not an issue for global failures that the Damage Assessment Team is most concerned about.
11. Sintering tools were removed from the tool set during development. However, TMM shows temperatures in excess of the tile single use values (2800-3100F). Whether the model is conservative or unconservative in these regimes is unknown.

Uncertainty Analysis

12. This uncertainty analysis is a good start towards understanding uncertainty even though limited do to the lack of incorporation of actual computational tools.

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13. The preliminary assessment indicates that there is quite a large amount of uncertainty in the estimates of tile to SIP bond line temperature and, therefore, predicting RTV failure. This sensitivity is not as pronounced at the structural interface due to the thermally isolating effects of the RTV and SIP; however, the resulting spread in FOS computation is not negligible. For example, for a specific body point (1100), a FOS of 1.4 is actually more accurately described as between 1.3 and 1.9.
14. Results appear to be biased in conservative direction in most cases.
15. Uncertainties are all assumed to be independent, but some are actually coupled.
16. There is really insufficient information available from this preliminary uncertainty analysis to draw any firm conclusions with respect to the overall accuracy of the analysis methodology.


Recommendations

Process

1. A more rigorous process to ensure the quality and integrity of manually input data must be implemented prior to flight. **(complete)**
2. Graphical display of thermal analysis results should be considered for implementation during the analytical process as a part of the QA and solution verification process. **(open)**
3. Develop standard coordinate system nomenclature for damage reference (i.e., center of damage vs. center of simplified damage vs. tile centroid) to ensure accurate communication and utilization of damage geometry. **(complete)**
4. A back-up capability should be provided for the Stress Assessor tool suite. **(in-work; ECD 9/2/05)**

Integrated Application of Analysis Tools

5. The implementation of the catalycity lookup table in 3-D TMM should be verified, as this is a new capability since the last simulation. **(open)**
6. The role of CFD in real-time mission support applications should be clarified. **(complete; pitch C. Campbell)**
7. Confirm that a bump factor is not applied in cooling region. **(complete)**

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8. Evidence indicates that using 1.0 bump factor for shallow cavities is very conservative. Further evaluation with CFD and test is required. **(open)**
9. Additional CFD sensitivity studies are recommended including, but not limited to:
 - a. Everhart Cavity analysis. **(open)**
 - b. Turbulent cavity assessments (CFD all laminar in/laminar out). **(open)**
 - c. Lower Mach number studies (i.e., M=12 lower end of catalytic effects, M=3 effects of negative heating and bump factor). **(open)**
 - d. Bump factor sensitivity (heating rate ratio, heat transfer coefficient ratio, emissivity, catalytic surface effects). **(open)**

Historical Reconstruction


10. Historical reconstruction case 9 has shown unusual behavior in the bondline stress tool which should be investigated. **(complete)**
11. Redo Historical Reconstruction #1 (Best Estimate) following the preflight process for determining aeroheating augmentation to gain a better understanding of effect of BLT assumptions on analysis. **(complete)**
12. Re-evaluate the platinum dataset to try to find a case for historical reconstruction in the OOPD sensitive area. **(complete – none available)**

Uncertainty

13. A better understanding of uncertainties and sensitivities to input parameters is critical when making re-entry decisions, particularly those that may result in accepting reduced margins for re-entry. Preliminary results would indicate large uncertainties on bond line temperature, which currently drives many of the capability limitations. These uncertainties should be further explored. **(in work)**
14. Parameters that are identified as primary drivers of analytical uncertainty should be assessed for further analytical and test efforts to narrow the uncertainty bands on the analytical results. **(open)**
15. Quarter inch uncertainty on cavity depth is probably too large based on OBSS demonstrated accuracy, and ± 0.1 would be more appropriate for conditions expected on-orbit. **(in work)**

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16. Emphasis should be given to establishing the uncertainty associated with the cavity geometry simplification process. **(open)**
17. Reasonable attempts should be made to incorporate appropriate correlation of factors rather than assuming they are all independent. **(open)**
18. Revisit list of significant input parameters to identify the most meaningful contributors. **(open)**

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16.0 CONCLUSIONS AND RECOMMENDATIONS OF FORWARD WORK

The NESC recognizes the considerable amount of effort that the NASA and contractor technical community has put into the development and verification of these analytical tools over the last 2-½ years. Overall, the team found that these tools represent a vastly improved analytical capability than was previously (pre-*Columbia*) available to the SSP for the resolution of debris impact issues. While there is always the opportunity to improve analytical tools in terms of validation and correlation, range of applicability and quantification of analytical uncertainty; these tools were all found to be suitable for application to STS-114 under the restrictions and limitations documented by the developers. These restrictions and limitations were all clearly documented and presented to the OPO at the OCCB as a part of the base-lining of these tools for use in STS-114.

As a part of these reviews, the NESC made several recommendations regarding opportunities to improve the validation, expand the application, and understand the accuracy of these math models. Many of these recommendations were accepted and addressed in real time by the model developers and, as such, are identified as “closed” in the body of the report. Recommendations that remain open are summarized in Table 16.0-1 with the NESC point of contact. These recommendations will be provided to the Orbiter Project Office (OPO) for consideration as a part of their post-flight tool development and improvement initiatives.




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Table 16.0-1. Remaining “Open”, “In Work” and “Partially Complete” Recommendations from the NESC Peer Review of Impact Damage Assessment Tools


Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
RCC DYNA	2.1, 19	Engineering data are needed to validate the nose cap and chin panel FEMs and predictions – mesh sensitivity, material orientation, etc.	In Work	I. Raju
RCC DYNA	2.1, 19	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.	Open	I. Raju
RCC DYNA	2.1, 19	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.	Partially Completed, July 18, 2005	I. Raju
RCC DYNA	2.1, 19	RCC material characterization data including: effects of aging (or conditioning), strain-rate effects, failure modes and mechanisms, fracture toughness, and 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 [®] .	Open	I. Raju
RCC DYNA	2.1, 19	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.	Open	I. Raju

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
RCC DYNA	2.1, 19	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.	Open	I. Raju
RCC DYNA	2.1, 19	Completion of documentation in the LS-DYNA [®] Data Pack.	Open	I. Raju
IMPACT2	2.2, 22	Demonstrate the rapid response of IMPACT2 using 6" x 6" and 6" x 12" flat panels.	Open	I. Raju
IMPACT2	2.2, 22	Validate IMPACT2 with 6" x 6" and 6" x 12" flat panel test data.	Open	I. Raju
IMPACT2	2.2, 22	Demonstrate the rapid response tool application for the nose cap and chin panel structures	Open	I. Raju
IMPACT2	2.2, 22	Provide a complete data pack of all analyses, data, and results for archival purposes and traceability.	Open	I. Raju
IMPACT Tools Simulation	2.3, 24	Communication among the IMPACT2 team, the DYNA team and LESS PRT needs to be improved. The angles for debris-Alpha and debris-Beta were misinterpreted by the team members and the need for graphic depiction of these angles was identified.	Open	I. Raju
IMPACT Tools Simulation	2.3, 24	Margin reporting by the teams need to be consistent in terms of units and metrics. The team needs a consistent basis of working the issues and reporting results.	Open	I. Raju
IMPACT Tools Simulation	2.3, 24	Team members should use certification rigor as basis of all results reported to the LESS PRT.	Open	I. Raju
RCC Damage Growth Tool	3.0, 28-29	Input Parameters. Delamination Extent - Validated on-orbit NDE techniques should be developed for determining	Open	S. Labbe

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
RCC Damage Growth Tool	3.0, 28-29	<p>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.</p> <p>Input Parameters. 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.</p>	Open	S. Labbe
RCC Damage Growth Tool	3.0, 28/29	<p>Model Physics. 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.</p>	Open	S. Labbe
RCC Damage Growth Tool	3.0, 28-29	<p>V&V. 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. .</p>	Open	S. Labbe
RCC Damage Growth Tool	3.0, 28-29	<p>V&V. Conservatism - 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.</p>	Open	S. Labbe

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Tile Rapid Response Damage Model (Ice)	4.0, 33	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.	Open	J. Kramer White
Tile Rapid Response Damage Model (Ice)	4.0, 33	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.	Open	J. Kramer White
Tile Rapid Response Damage Model (Ice)	4.0, 33	Present rationale for entry angle equaling impact angle (and contrast with foam-on-tile model rationale for assuming otherwise).	Open	J. Kramer White
Tile Rapid Response Damage Model (Ice)	4.0, 33	Provide evidence of solution verification. 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).	Open	J. Kramer White
Tile Rapid Response Damage Model (Ice)	4.0, 33	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.	Open	J. Kramer White
Tile Rapid Response Damage Model (Ice)	4.0, 33	Provide evidence to verify assumption # 8 – that the glass layer of the tile is assumed to not provide noticeably more strength.	Open	J. Kramer White

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Tile Rapid Response Damage Model (Ice)	4.0, 33	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.	In Work	J. Kramer White
Tile Rapid Response Damage Model (Foam)	5.0, 38	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	J. Kramer White
Tile Rapid Response Damage Model (Foam)	5.0, 38	The assumption of “no tumbling” as a conservative assumption in the model needs to be substantiated.	In-Work	J. Kramer White
Tile Rapid Response Damage Model (Foam)	5.0, 38	The “corners of the box” for which the foam on tile model is considered applicable should be compared to CTH or LS-DYNA [®] hydrocode predictions.	In-Work	J. Kramer White

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Tile Rapid Response Damage Model (Foam)	5.0, 38	Additional data should be gathered at 5 degrees for low mass impact damage prediction. A test set with more velocities for lower (0.022) and mid (0.13) range masses should be considered, as well as larger masses (0.4), if that is still a legitimate mass out of latest transport analysis.	Open	J. Kramer White
Tile Rapid Response Damage Model (Foam)	5.0, 38	Additional test data should be gathered on RCG and substrate properties for aged tile. The tile tested should be more representative of fleet leader tile (~30 flights) to validate the assumption that tile aging occurs early in the life of the tile and does not continue to degrade properties as a function of age.	In-Work	J. Kramer White
Cavity Heating Tool	6.0, 43-48	Augmentation Factors for Non-Rectangular Cavities. Additional understanding of the effects of non-rectangular cavities must be pursued before analysis can be accomplished with data already available. 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.	Open	S. Labbe

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Cavity Heating Tool	6.0, 43-48	Laminar Wind Tunnel Test Data Base. 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.	In Work	S. Labbe
Cavity Heating Tool	6.0, 43-48	Application to Limited to Windward Side Damage. 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.	Open	S. Labbe
Cavity Heating Tool	6.0, 43-48	Tile Gap Effects. 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 are eliminated, the tile gap effect, as established by test, should be employed.	Open	S. Labbe
Cavity Heating Tool	6.0, 43-48	Pressure Gradient Effects. 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.	Open	S. Labbe

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Cavity Heating Tool	6.0, 43-48	Pressure Gradient Effects. It is 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.	Open	S. Labbe
CFD for Cavity Heating: Smooth Baseline	7.0, 53-55	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. 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 , Me , T_e , T_w , Pr and y 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.	In Work	S. Labbe
CFD for Cavity Heating: Smooth Baseline	7.0, 53-55	Flight Boundary Layer Thickness. It is 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, such tests should be performed to survey the boundary layer thickness at high enthalpy conditions.	In Work	S. Labbe
CFD for Cavity Heating: Smooth Baseline	7.0, 53-55	Instrumentation uncertainty is not quantified in the boundary layer report and thus cannot be properly addressed. However, 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.	In Work	S. Labbe

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
CFD for Cavity Heating: Flight Traceability	8.0, 59-60	Develop experimental tests to provide good validation data for low-enthalpy tunnel condition cavities: heating values, surface shear stresses, oil flows and other diagnostics of detailed local physical phenomenon. It is recommended that additional experiments be performed to provide adequate validation data for both the CHT and CFD heating tools.	In Work	S. Labbe
CFD for Cavity Heating: Flight Traceability	8.0, 59-60	Explore the feasibility of obtaining quantitative test data for local laminar cavity heating at high enthalpy conditions.	In Work	S. Labbe
CFD for Cavity Heating: Flight Traceability	8.0, 59-601	Follow-on work is needed to understand the sensitivities for the integration of CFD computed heating bump factors with downstream tools: Heat transfer coefficient basis, TMM, Emissivity, Catalysis, Radiation exchange, and Conduction. <i>Note: This analysis was initially addressed as part of the end-to-end process.</i>	In Work	S. Labbe
CFD for Cavity Heating: Flight Traceability	8.0, 59-60	It is recommended that the proposed CFD bump factor maps be tested through the tile thermal and structural tools to examine if differences between the CHT and the CFD values yield significant changes in the results.	Open	S. Labbe
CFD for Cavity Heating: Flight Traceability	8.0, 59-60	Perform a greater number of flight solutions for Closed cavities and those encountering significant pressure gradients to more fully evaluate the preliminary results of this study.	Open	S. Labbe

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
CFD for Cavity Heating: Flight Traceability	8.0, 59-60	<p>The following expansions of the Flight Traceability study should be considered within the priorities of the Aerothermal team's activities:</p> <ul style="list-style-type: none"> • Perform a more comprehensive validation of CFD's predictive ability for local cavity heating at both low and high enthalpy conditions. • Perform a CFD study of tile cavity edge radii to understand the relationship of heating spikes to edge radii. • Perform an independent CFD parameter study for H/delta, L/delta, L/W, and other parameters such as Medge, Re-theta, etc. <i>(The current study only matched wind tunnel parameter settings and did not provide comprehensive coverage).</i> • Examine the dependence of heating bump factors on the entrance and exit angles. • Examine the dependence of heating bump factors on the orientation to the flow of various types of cavities. 	In Work	S. Labbe
Catalytic Heating Tool: Damaged	9.0, 64-65	<p>Future Enhancements. 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 catalyticity and emittance of RCC repair materials should be measured. The emittance assumptions for other materials must be reviewed and updated as required.</p>	In Work	S. Labbe

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Catalytic Heating Tool: Damaged	9.0, 64-65	Emittance. Additional test and analyses should be conducted to improve confidence in emittance values for uncoated tiles.	Open	S. Labbe
Catalytic Heating Tool: Damaged	9.0, 64-65	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.	Open	S. Labbe
Catalytic Heating Tool: Damaged	9.0, 64-65	Bare RCC Catalysis. Catalysis of reacting surfaces, i.e., bare RCC, may be a misnomer and referring to this as fully catalytic heating might be an invalid concept. It is recommended that this phenomenon be considered for further investigation 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.	Open	S. Labbe
BLT Prediction Tool	10.0, 68-73	Roughness Requirements. An effort should be expended to understand the uncertainty associated with transition occurring prior to Mach 18, regarding impact on the vehicle.	Open	S. Labbe
BLT Prediction Tool	10.0, 68-73	Attachment Line. Consider the effects of AOA from 45 to 30 degrees in evaluating turbulence spreading as well as Mach 18 real gas effects rather than M=6 perfect gas estimates.	Open	S. Labbe
BLT Prediction Tool	10.0, 68-73	Protuberances. Future work should consider testing of additional roughness shapes and locations. Further evaluation is recommended on the impact of the wall temperature and consideration for testing larger models.	Open	S. Labbe

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
BLT Prediction Tool	10.0, 68-73	<p>Ablation. The limited wind tunnel test data needs to be re-correlated against more traditional correlation parameters, <i>i.e., using a normalized blowing rate such as $(\rho v)_w / (\rho u)_e$</i>, to verify that the expected blowing level is being scaled properly. In addition, the blowing rate needs to be verified that it is representative of the hottest region just behind the nose cap on the Orbiter. The impact of blowing at locations further forward on the Orbiter need to be tested as well as the combined effects with roughness. Until this is resolved this approach has significant limitations.</p>	Open	S. Labbe
3-D Acreage Tile Thermal Model	11.0, 76	<p>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 bands 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.</p>	Open	H. Rotter
3-D Acreage Tile Thermal Model	11.0, 76	<p>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.</p>	Open	H. Rotter
Special Configuration Thermal Models	12.0- 12.8	12.1 through 12.8 listed below.	See below	H. Rotter

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Elevon Lower Cove 3-D TMM	12.1, 78	<ul style="list-style-type: none"> Perform arcjet testing for comparison with the model. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. Expand the 3-D model to include thermocouple locations (where available) from early flights. 	Open	H. Rotter
Forward Reaction Control System (FRCS) Canopy 3-D TMM	12.2, 79	<ul style="list-style-type: none"> Perform arcjet testing for comparison with the model. 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. 	Open	H. Rotter
WLE Panel 9 Lower Access Panel (LAP) 3-D TMM	12.3, 80	<ul style="list-style-type: none"> Perform arcjet testing for comparison with the model. Modify the 2-D or 3-D TMM to more closely match configuration/property differences between models. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. 	Open	H. Rotter
Main Landing Gear Door (MLGD) 3-D TMM	12.4, 81	<ul style="list-style-type: none"> Perform arcjet testing for comparison with the model. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between model. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. 	Open	H. Rotter

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Vertical Tail Leading Edge (VTLE) 3-D TMM	12.5, 82	<ul style="list-style-type: none"> Perform arcjet testing for comparison with the model. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. 	Open	H. Rotter
Forward Window # 3 Perimeter 3-D TMM	12.6, 84	<ul style="list-style-type: none"> Perform arcjet testing for comparison with the model. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. 	Open	H. Rotter
External Tank Door (ETD) 3-D TMM	12.7, 85	<ul style="list-style-type: none"> Perform arcjet testing for comparison with the model. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. 	Open	H. Rotter
Nose Landing Gear Door (NGLD) 3-D TMM	12.8, 86	<ul style="list-style-type: none"> Perform arcjet testing for comparison with the model. Modify either the 2-D or 3-D TMM to more closely match configuration/property differences between models. Expand the 3-D model to include thermocouple locations (where available) from early flights to either confirm or improve the TMM. 	Open	H. Rotter

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Tile Stress Tool	13.0, 90	RTV bondline failure is the critical failure mode identified on the damage map for many vehicle zones; however, it is the least validated of all the models. Efforts should be made to better validate the performance of the RTV/Tile/SIP system under elevated temperature.	Open	J. Kramer White
Tile Stress Tool	13.0, 90	The assumption of secant modulus and shear allowable at 625° F being extrapolated just as flatwise tension to 15 percent of value at 450° F should be validated by test.	Open	J. Kramer White
Tile Stress Tool	13.0, 90	The tool should be expanded for upper surface acreage tile and penetration perimeter tile, if possible.	Open	J. Kramer White
Tile Stress Tool	13.0, 90	The effects of aged tiles should be included.	Open	J. Kramer White
Tile Stress Tool	13.0, 90	This tool has already been used for pre-flight assessment in the development of the foam on tile and ice on tile damage maps, as well as the on-orbit (2"/3") criteria tile damage map. Thus, the restriction that it be used only for on-orbit assessment should be lifted.	Open	J. Kramer White
Stress Assessor Tool	14.0, 94	The stress assessor tool 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	J. Kramer White
Stress Assessor Tool	14.0, 94	Verification of correction factors for curved surfaces.	In-Work	J. Kramer White
Stress Assessor Tool	14.0, 94	An independent review of the NASTRAN models used to validate assumptions in the tool is needed.	Open	J. Kramer White

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Stress Assessor Tool	14.0, 94	Provide capability to determine NLGD stresses and out-of-plane deflections.	Open	J. Kramer White
Stress Assessor Tool	14.0, 94	Expand the capability of the tool to include other areas beside the bottom skin and OMS pod.	Open	J. Kramer White
Stress Assessor Tool	14.0, 94	An independent review of the out-of-plane deflections non-linear FEA models is needed.	Open	J. Kramer White
Stress Assessor Tool	14.0, 94	An independent review of the NASTRAN models used for honeycomb structure (elevon, mid-wing, MLGD) is needed.	Open	J. Kramer White
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Process. Graphical display of thermal analysis results should be considered for implementation during the analytical process as a part of the QA and solution verification process.	Open	J. Kramer White
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Process. A back-up capability should be provided for the Stress Assessor tool suite.	In-Work; ECD 9/2/05	J. Kramer White
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Integrated Application of Analysis Tools. The implementation of the catalycity lookup table in 3-D TMM should be verified, as this is a new capability since the last simulation.	Open	J. Kramer White

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Integrated Application of Analysis Tools. Evidence indicates that using 1.0 bump factor for shallow cavities is very conservative. Further evaluation with CFD and test is required.	Open	J. Kramer White
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Integrated Application of Analysis Tools. Additional CFD sensitivity studies are recommended including, but not limited to: a. Everhart Cavity analysis. b. Turbulent cavity assessments (CFD all laminar in/laminar out). c. Lower Mach number studies (i.e., M=12 lower end of catalytic effects, M=3 effects of negative heating and bump factor). d. Bump factor sensitivity (heating rate ratio, heat transfer coefficient ratio, emissivity, catalytic surface effects).	Open	J. Kramer White
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Uncertainty. A better understanding of uncertainties and sensitivities to input parameters is critical when making re-entry decisions, particularly those that may result in accepting reduced margins for re-entry. Preliminary results would indicate large uncertainties on bond line temperature, which currently drives many of the capability limitations. These uncertainties should be further explored.	In Work	J. Kramer White

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Uncertainty. Parameters that are identified as primary drivers of analytical uncertainty should be assessed for further analytical and test efforts to narrow the uncertainty bands on the analytical results.	Open	J. Kramer White
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Uncertainty. Quarter inch uncertainty on cavity depth is probably too large based on OBSS demonstrated accuracy, and ± 0.1 would be more appropriate for conditions expected on-orbit.	In Work	J. Kramer White
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Uncertainty. Emphasis should be given to establishing the uncertainty associated with the cavity geometry simplification process.	Open	J. Kramer White

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Model	Reference (section, page)	Recommendation	Status	NESC Point of Contact
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Uncertainty. Reasonable attempts should be made to incorporate appropriate correlation of factors rather than assuming they are all independent.	Open	J. Kramer White
Integrated Tools For End-To-End Computation of Tile Damage	15.0, 108-110	Uncertainty. Revisit list of significant input parameters to identify the most meaningful contributors.	Open	J. Kramer White

Appendix A. Preliminary Findings

Peer Review – RCC Damage Growth Tool

April 22, 2005

Scope

An engineering data package for each math model tool will be peer-reviewed, including the interface (input/output data requirements and hand-offs) with any other tool. The inspection will also include the end-to-end integrated strategy for using the tools to assess impact damage.

The objective of the peer-review is to determine if the tools and the end-to-end strategy are suitable to support STS-114. This objective will be achieved by independently reviewing the engineering data packages with the content outlined below. The following was provided for this peer review:

- Key assumptions: test and analysis results supporting the assumptions
- Limitations: test and analysis results demonstrating the rationale for the limit
- Verification and Validation (V&V): complete set of V&V results (tests and analyses) mapped to specific requirements
- RCC Damage Growth Tool:
 - Description
 - Assumptions and limitations
 - Description of model input and output

RCC Damage Growth Tool Assumptions

The peer review was conducted assuming the current RCC damage growth tool was limited to: (1) time-to-breach assessments and (2) ascent debris impact. The current tool will not be used for RCC hole growth assessment.

Summary

The team have concluded that the engineering interpretation of the experimental data is adequate to establish the RCC impact damage requirement, that coating loss with delamination is the critical RCC damage level in support of the flight rationale development. However, the peer-review team concludes that 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. This is of critical importance for WLE locations where the tool currently predicts pass vs. fail.

(NESC assessment of the arcjet test results provided suggest that the wedge test time to breach is considerably less than stagnation test time to breach for similar initial damage states). In addition, the verification and validation 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 team views the tool maturity level as developmental in nature as opposed to a certified 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 assessments of damage to RCC. 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.

Note: The statements above are specific to the time to breach calculations that represent the RTF applicability of the tool. It is understood that the hole growth application of the tool (post breach) must be upgraded to include the wedge test results because of the additional physics involved in this damage propagation on the WLE RCC.

Content

- 1.0 RCC Damage Growth Tool - Input
 - Fact Sheet - RCC Damage Growth Tool - Input
- 2.0 RCC Damage Growth Tool – Model Physics
 - Fact Sheet - RCC Damage Growth Tool – Model Physics
- 3.0 RCC Damage Growth Tool – Verification and Validation (V&V)
 - Fact Sheet - RCC Damage Growth Tool – V&V
- 4.0 Peer Review Team Members

1.0 RCC Damage Growth Tool - Input

Finding 1.1, 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 finding is of concern because this assumption directly impacts the accuracy of the tool output “Equivalent IML Hole Diameter”. For STS-114, the damage growth will not be predicted, however, in the future, if the output “Equivalent IML Hole Diameter” is required, the validity of this assumption is of importance.

In the V&V of the RCC Damage Growth Tool, the extent of delamination for arc jet 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. Furthermore, the current capability for on-orbit NDE does not exist, and the predictive capability of the tool relies on the 1-inch assumption.

Limits to tool application: The tool has limited predictive use pending on-orbit validated NDE techniques to determine extent of delamination.

Recommendations: Continue validation of on-orbit NDE techniques for determining extent of delamination by cross-sectional analysis CT scans or cross-sectional destructive evaluation of impact damaged RCC.

Finding 1.2, Mid-plane Delamination*. The assumption that one delamination occurs in any RCC panel showing OML damage may not adequately represent the actual damage state within the RCC. RCC impact damage may result in multiple ply separations beneath the OML damage site. This finding is of concern because this assumption may affect the accuracy of the tool output “Cavity Burn-Thru Time (sec).” Multiple delamination planes may result in faster RCC burn-through times than those predicted by the RCC Damage Growth Tool. If burn-through is already predicted by the current version of the tool, then this finding does not require action. 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, the validity of this assumption is of importance.

Limits to tool application: This tool may be limited to predicting recession rates in those cases where delamination has occurred on only one plane. No method for determining the number of delaminations on-orbit is available. The tool has not been validated for cases where the number of delaminations is known.

Recommendations: The tool should be modified so that burn-through times can be calculated for multiple delaminations. The sensitivity of the modified RCC Damage Growth Tool to multiple delaminations should be examined. The modified tool should be used to determine whether multiple delaminations beneath OML damage of types 3, 4, and 5 will result in faster burn through times. If the number of delaminations affects the

* This finding is based on the assumption that the RCC mass loss curve has been established for undamaged RCC as per DIR 3-56700/RCC/1-0001 and J of ThermoPhysics and Heat Transfer 9[3] 478-485 (1995).

predicted RCC burn through time, the following recommendations are made. The number of delaminations should be quantified by non-destructive or destructive cross-sectional analysis for impact tested panels with varying impact angles to develop a database for predicting number and location of delaminations resulting from impact damage. The tool should be validated for arc jet test samples of varying known number of delamination planes.

Fact Sheet - RCC Damage Growth Tool - Input

Fact Sheet, Input Finding 1.1

Available data on RCC subjected to controlled impact damage have been examined to evaluate these assumptions. Two studies on RCC impact damage were found for evaluation.

1. 6" x 6" RCC panels were impacted at Glenn Research Center for verification of the LS-DYNA© model. These panels were impacted at two impact angles 45° and 90°. BX-265 foam debris weighing between 0.0043 and 0.0067 lbm impacted the RCC at velocities between 1952 and 2440 fps. Hard ice debris weighing between 0.0185 and 0.0198 lbm impacted RCC at velocities between 498 and 858 fps. Only data pertaining to those 18 panels showing damage on the front face were examined here. After impact testing, the samples were examined by NDE techniques. Dark areas were assumed to be delaminations and the estimated areas of delamination are reported on the Orbiter TPS Impact Testing Data Archive website <http://hitf.jsc.nasa.gov/hitfpub/archive/admin2.cfm> (password required).
2. Portions of wing leading edge panel 9LB and 9LC (zero flights) were also impact tested for verification of the LS-DYNA© model. Only data pertaining to those targets showing damage on the OML were examined here. Five targets on these panels showed visual OML damage. The impact angle for these targets varied between 23.5 and 45.1°. The foam debris velocity varied between 1425 and 1778 fps, while the ice debris velocity varied between 1099 and 1213 fps. The foam debris weighed 0.044 lbm and the hard ice debris weighed 0.026 lbm. Length and width of delamination were estimated from NDE and reported at the above website. For the purpose of comparison to delamination area based on the 1-inch assumption, the delamination area from NDE was assumed to be length times width (rectangular area of delamination).

Delamination areas for the eighteen 6 x 6 inch panels and 5 targets of panel 9L showing visual front face or OML impact damage were estimated assuming delamination extended 1" in all directions from any visual damage. Estimated delamination areas were then calculated using Photoshop plug-in functions. These areas estimated based on the 1-inch assumption were compared to those estimated from NDE results. An example of the 1-inch assumption analysis is shown in Figure 1.

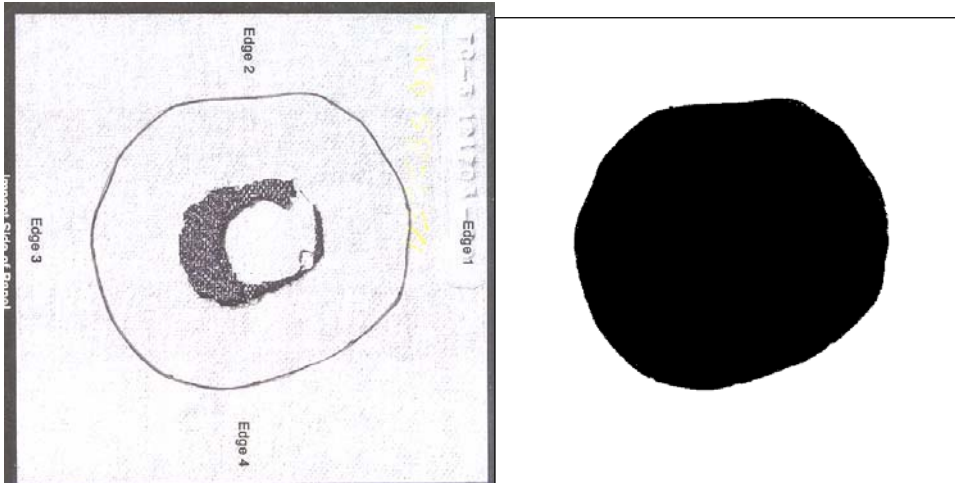


Figure 1. 6 x 6-inch RCC panel 20-4 showing estimated delamination extent 1 inch around front face damage with corresponding delamination area analysis shown in black.

A comparison of the delamination area estimated based on the 1-inch assumption to that estimated from NDE was made for 22 samples. Little correlation between the two methods is observed, as seen in the following plot. The 1-inch assumption is in better agreement for foam-induced damage than for ice-induced damage. Trends in impact angle also seem worth exploring. However, from these results (Figure 2) it can only be concluded that one or both of these techniques is inadequate to determine delamination areas. Ultrasonic and thermographic NDE techniques may not always discern between delamination and other types of damage accumulation.

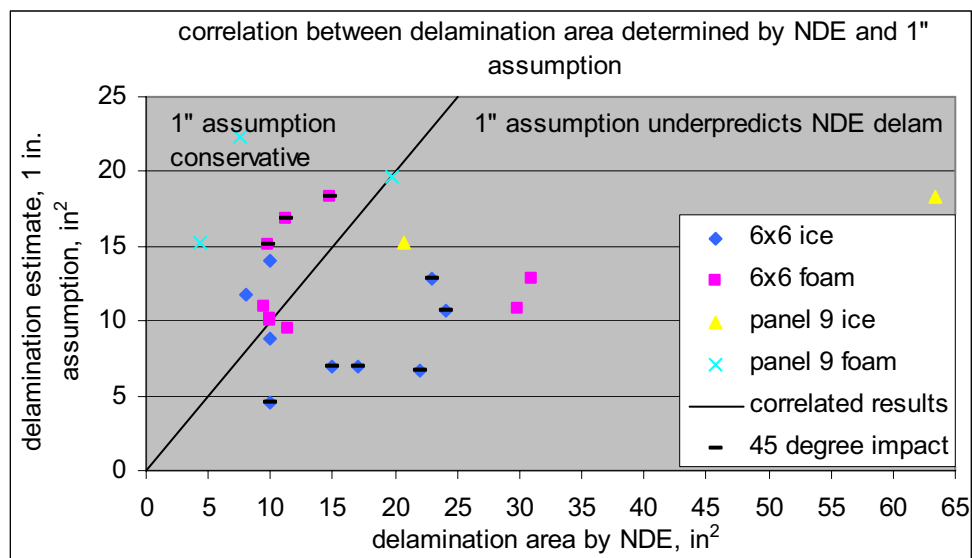


Figure 2. Correlation between delamination area determined by NDE and the 1-inch assumption for impact tested RCC used in LS-DYNA© validation.

Next, cross-sectional CT scan results for some of the 6 x 6-inch panels were obtained from the above mentioned Orbiter TPS Impact Testing Data Archive website. The delaminations due to impact damage are clearly seen by this technique as shown in Figures 3a and 3b. The four panels showing front face impact damage are marked with an asterisk. It can be seen that the delaminations extend to the edge of the panels in some cases, indicating delaminations beyond the 1-inch assumption perimeter. These results may not be representative of ascent impact damage for the following reasons. These panels were all impacted with foam projectiles at 90° impact angles, so damage at other impact angles may differ from that observed here. Second, curvature and edge effects differ between the 6 x 6-inch and actual WLE panels. The 6 x 6-inch panels are a better model of the apex region of the WLE panel than the top or bottom of the WLE panels, as assessed by stress-strain behavior in LS-DYNA© modeling[†] of impact. Despite these differences between the 6 x 6-inch panels and WLE panels, the 6 x 6-inch CT cross-section results do raise questions about the validity of the 1-inch assumption in the RCC Damage Growth Tool. More information about the extent of delamination of impact damaged RCC as well as the validity of on-orbit NDE techniques is needed.

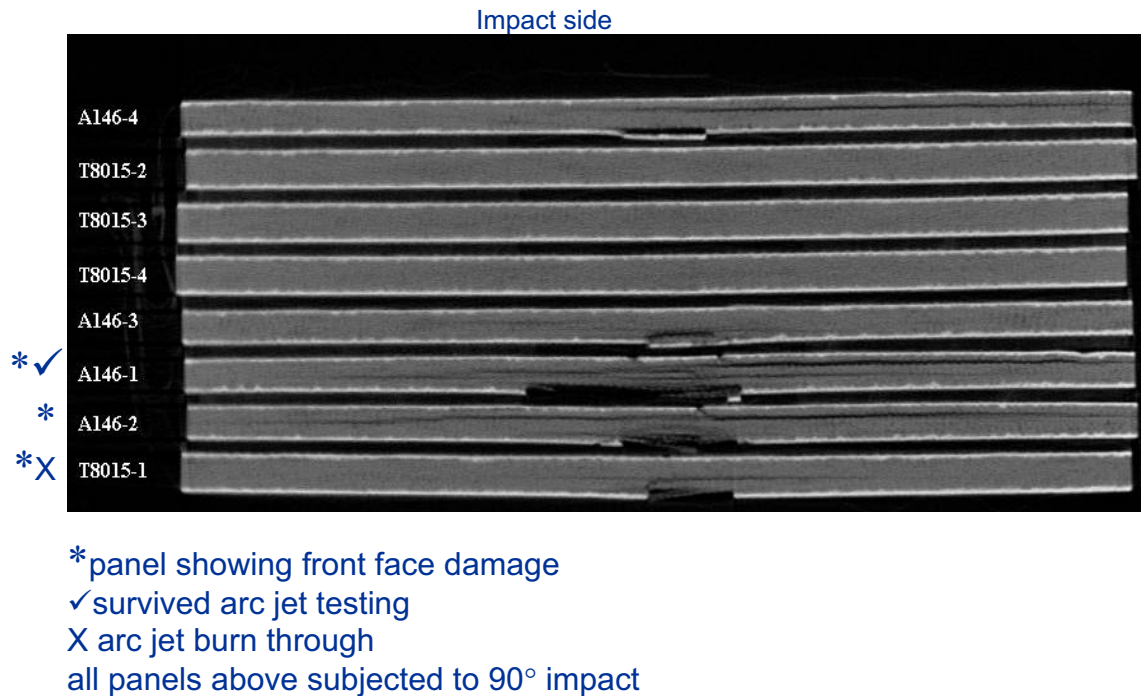


Figure 3a. Cross-sectional CT scans for 6x 6-inch RCC panels impacted for LS-DYNA© validation.

[†] Personal communication with Kelly Carney, NASA Glenn Research Center.

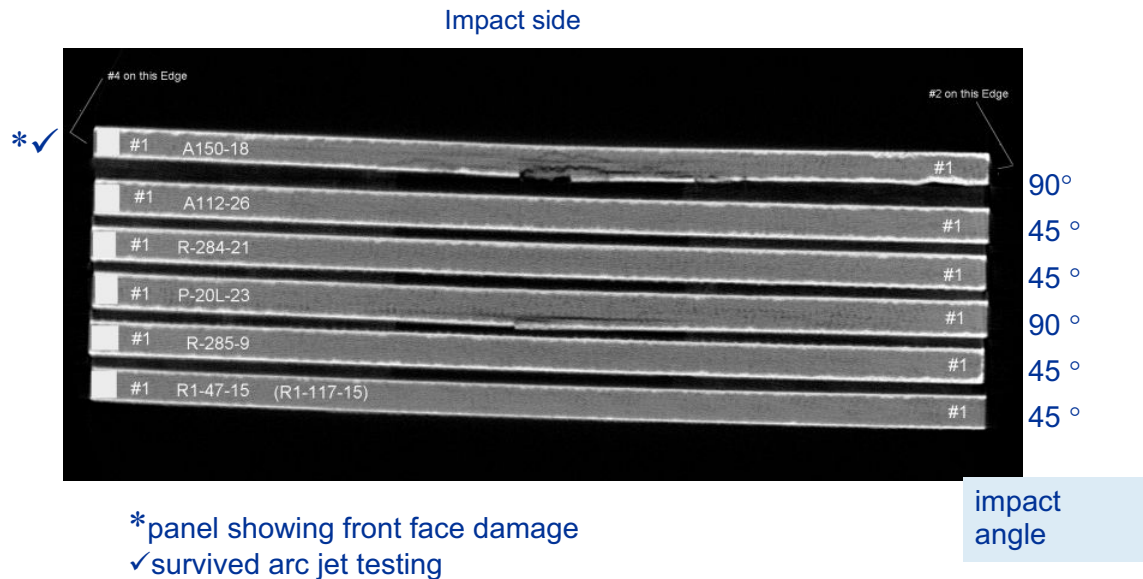


Figure 3b. Cross-sectional CT scans for 6 x 6-inch RCC panels impacted for LS-DYNA© validation.

Fact Sheet, Input Finding 1.2

The edges of the 6 x 6-inch panels subjected to impact damage have been photographed. The photographs can be found on the Orbiter TPS Impact Testing Data Archive website. Of the 18 6 x 6-inch panels showing front face damage, 9 showed edge delaminations. Only one delamination plane was seen on each edge at 35 ± 11 percent through thickness distance from the impact face to the back face. The range of through thickness distance of the delamination plane from the impact face was 13 to 46 percent. There was one exception to the above results. In this case there were two delaminations close to the OML and IML that were connected by a through thickness crack. Based on these results, it can be stated that for the 6 x 6-inch panels, when edge delamination occurs, one delamination plane is typically formed at about 1/3 the through thickness from the impact face *when observed at a lateral distance of 3 inches from the impact site*. Boundary conditions (edge effects) and curvature of the RCC can be expected to affect the nature of the delamination.

While the edge delaminations on the 6 x 6-inch panels are consistent with the assumption that OML damage results in one delamination at the mid-plane of RCC when observed at a lateral distance of 3 inches from the impact site, the cross-sectional CT scans indicate that multiple delaminations have occurred for 90° foam impact damage below the observed OML damage. Again, as described for finding one, it is not known if the delaminations observed for the 6 x 6-inch panels in the CT scan results can be generalized for other impact angles or for WLE panels. However, the sensitivity of the RCC Damage Growth Tool to multiple delaminations should be examined.

2.0 RCC Damage Growth Tool – Model Physics

Finding 2.1, Mass Loss Expression. 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 ablation. Therefore, the tool is not able to account for the augmented transfer rates that occur in damaged or breached regions. The Arrhenius expressions were developed to be conservative. However, they have been demonstrated to be conservative only for the range of environments for which data has been gathered. Since the mass transfer rates for the test do not cover the range of conditions for flight (or range of conditions in breach regions), it is not known if the method is conservative for all conditions that might occur. The diffusion limit plateau occurs for a non-dimensional ablation rate, not for a material recession rate. \dot{S} does not plateau because increases in recession rate can occur even during the diffusion limit plateau as a result of increased mass transfer rate.

Limitation: The application for the \dot{S} surface recession model is limited to the range of conditions (heating rates, mass transfer rates, and pressures) for which the data was gathered. Extrapolation to other conditions may yield inaccurate results. This limitation applies to both prediction of breach time and damage growth.

Recommendation: The \dot{S} expression needs to include mass transfer rate dependency. The current \dot{S} relationship attempts to include this effect by having a pressure term, but this is not adequate. The use of the pressure term does not account for the relative mass transfer variations and resultant recession rates.

Finding 2.2, Temperature and Pressure. Temperatures and pressures obtained from the validated Orbiter aeroheating tool may be incompatible with the recession rate correlations without a detailed assessment of the differences between the test and flight environments.

Limitation: Use of the recession rate correlations is limited to conditions within the test data envelope where temperature and pressure predicted by the aeroheating tools approximates that observed in the tests.

Recommendation: The fully catalytic temperature assumption of the aeroheating tools needs to be validated. At minimum, fully catalytic hot wall temperatures should be computed for the arc jet conditions of the RCC substrate recession measurements. These should be compared with the measured temperatures. Consequences to tool predictions due to any differences between the two temperatures should be assessed.

Finding 2.3, Catalytic Behavior. Temperature and pressure data with which the recession rates were developed lie outside most of the smooth OML temperature (both nominal and fully catalytic) and pressure range in flight. The validity of the correlations at flight conditions was not assessed. (Important: this finding has not been completely vetted by all team members.)

Fact Sheet - RCC Damage Growth Tool – Model Physics

Fact Sheet, Model Physics Finding 2.1

Damaged RCC interacts with the aerothermal environment through the thermochemical mechanisms of oxidation, ablation, and mass loss to accommodate the chemical energy present in the flow. Both temperature and mass loss are material responses to the aerothermal environment. Typically, the temperature is determined by coupling aerothermal boundary conditions to a material response model through a surface energy balance calculation. By correlating recession rate with only temperature and pressure, the recession rate is implicitly coupled to the particular aerothermal conditions under which the correlation was developed – in this case stagnation arc jet conditions. Temperature and pressure would be adequate to describe the recession rate if the surface is assumed to be in thermochemical equilibrium, both in the test and flight environments. Proper use of the correlation would be restricted to those conditions, which are unlikely to encompass the range of conditions encountered in flight for all possible damage scenarios.

The method in the damage growth tool used to predict ablation of the carbon-carbon is an Arrhenius expression that correlates material recession rate, \dot{S} , to local surface temperature, see page 17 of the Damage Growth Tool briefing. This expression includes a pressure dependency with recession rate also proportional to square root of pressure. This method cannot account for increased recession rates that may occur in damaged regions. As previously mentioned in Finding 1, augmented heating and mass transfer occur in damaged and breached areas. Figure 4 presents non-dimensional ablation rates, B_c' calculated for carbon-carbon. B_c' is defined as:

$$B_c' = \text{Mass removal rate/mass transfer coefficient}$$

These rates assume chemical equilibrium reactions of the carbon-carbon with the adjacent boundary layer gases. Actual rates may be somewhat less due to chemical kinetics, but these curves still illustrate the phenomena of interest. As shown in Figure 4, the diffusion limited plateau is pressure dependent and extends to 2500 K (4040 °F) and slightly beyond. This plateau indicates that the non-dimensional material removal rate does not increase with increasing surface temperature. However, the actual rate is given by:

$$\text{Mass removal rate} = B_c' \times \text{mass transfer coefficient}$$

The recession rate is then determined by:

$$\dot{S} = \text{Mass removal rate/carbon-carbon material density}$$

Therefore, the recession rate is directly proportional to the mass transfer coefficient. Any empirical method that predicts recession rate without mass transfer considerations must be based on data gathered at similar/representative mass transfer rates.

Note: This dependency on mass transfer rate is the reason Arrhenius expressions developed from oven test or radiant heating data are not applicable.

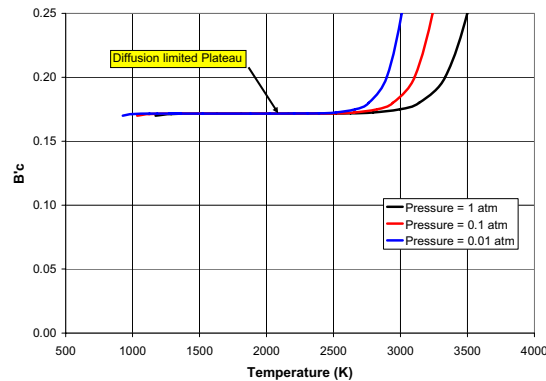


Figure 4. Non-dimensional Ablation Rates for Carbon-Carbon

Fact Sheet, Model Physics Finding 2.2

The developers have designed the damage growth tool to use validated Orbiter aeroheating tools to compute temperature and pressure at the damage location for a prescribed trajectory. Pressure is computed with XF0002, an aeroheating code maintained by Boeing. The code has been validated with flight and wind tunnel ground test data. Fully catalytic and nominal temperatures are computed with an RCC Thermal Math Model (TMM), which is presumed to incorporate material response physics for nominal RCC or a fully catalytic surface. Heating rates for the TMM are assumed to come from XF0002 outputs.

If the correlations are considered valid beyond the test environment, temperature and pressure inputs are required for their use with the damage growth tool. Being a response parameter itself, this temperature must be supplied by a thermal response model that does incorporate the aerothermal environment as an input. The material response model in the TMM does not incorporate the same thermochemical mechanisms implicit in the recession rate correlations. Instead, the TMM accommodates the chemical energy of the flow with catalysis only; oxidation, ablation, and mass transfer are not included when predicting the temperature response. In effect, the temperature response from a material model with one set of physics (the aeroheating tool) is treated as an input to a recession rate correlation with a different set of physics. The fact that the recession rate correlation was formulated to conservatively predict the measured arc jet test data does not address the inconsistent application of the two material response models.

The actual temperature response of the material may be greater since catalysis alone would not include the additional energy absorbed by the surface from oxidation.

However, these temperatures are then used to compute recession rates for an oxidizing and ablating material. Potential error in the recession rate estimation will exist at all conditions for which the temperature predicted by the aeroheating tool differs from the actual material temperature.

Fact Sheet, Model Physics Finding 2.3

The developers have designed the damage growth tool to use validated Orbiter aeroheating tools to compute temperature and pressure at the damage location for a prescribed trajectory. Pressure is computed with XF0002, an aeroheating code maintained by Boeing. The code has been validated with flight and wind tunnel ground test data. Fully catalytic and nominal temperatures are computed with an RCC Thermal Math Model (TMM), which is presumed to incorporate material response physics for nominal RCC or a fully catalytic surface. Heating rates for the TMM are assumed to come from XF0002 outputs.

The SiC recession rates were determined from mass loss and thickness measurements of test specimens exposed in arc jet tests. The recession rates were correlated with observed surface temperatures and pressures. These data were obtained at high heat flux conditions in a series of over-temperature tests. The temperatures and pressures reached in the SiC coating loss tests from NASA TP 104792 are shown in Figure 5. Mass loss was correlated with temperature but not pressure; only two pressure ranges appear to have been targeted. The correlation shown on p. 15 of the March briefing appears to contain additional data at higher temperatures. The RCC substrate recession rates were also determined from mass loss and thickness measurements in an over-temperature test series. They do include the $p^{0.5}$ correlation. The temperature and pressure points from TP 104792 are shown in Figure 6.

The damage growth tool is presumed to use nominal temperatures in the SiC correlation (though not explicitly stated) and fully catalytic temperatures in the RCC substrate correlation. On the OML, the higher of the two rates will be used (p. 19).

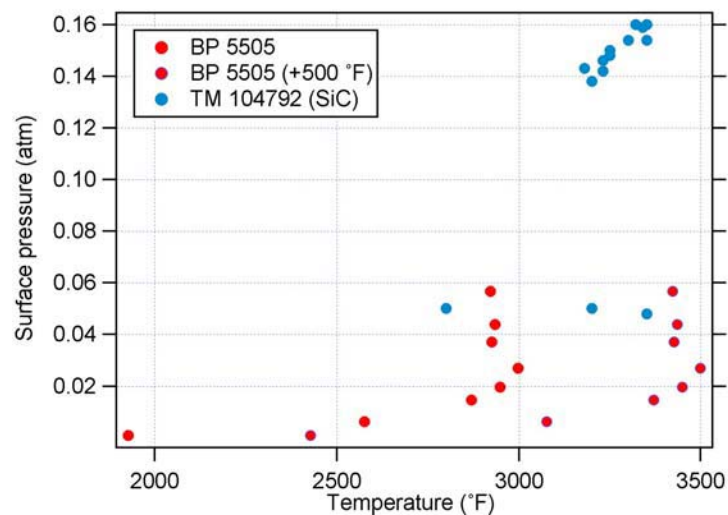


Figure 5. Comparison of temperature and pressure envelopes of data used for the SiC recession rate correlation and for body point 5505. Both nominal and fully catalytic BP 5505 temperatures are shown.

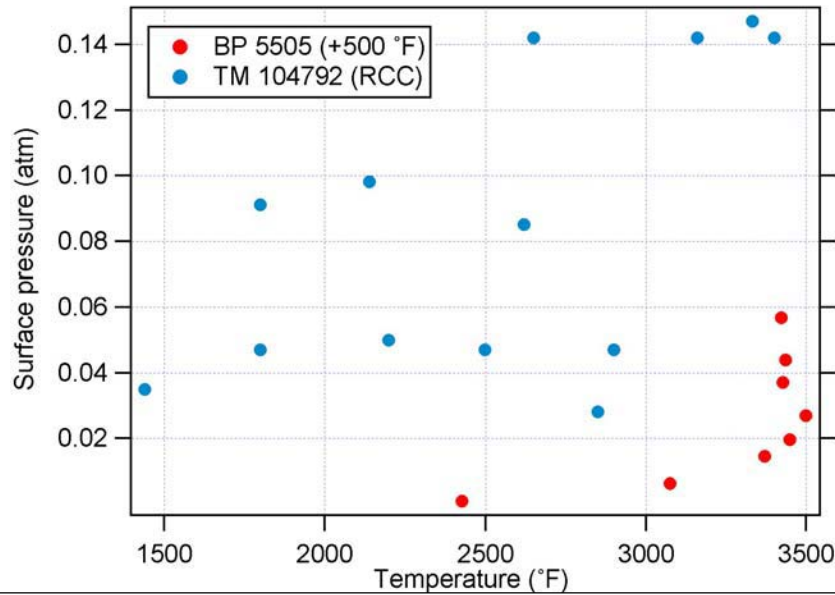


Figure 6. Comparison of temperature and pressure envelopes of data used for the RCC substrate recession rate correlation and for body point 5505. Fully catalytic BP 5505 temperatures are shown.

Shown in Figure 5 are smooth OML temperatures and pressures for body point 5505 around peak heating during entry. Both the nominal and fully catalytic temperatures are plotted. (The FC temperatures are the nominal +500 °F). BP 5505 is near the peak heating region on Panel 9 and is considered to be the point that experiences the highest heat flux (and temperature). Figure 6 shows the same fully catalytic BP 5505 temperatures and pressures.

All of the data used to develop the RCC substrate recession rate correlation lies outside of the flight range for BP 5505. Other points on the Orbiter will have lower temperatures, but both higher and lower pressures. In this most critical region, there is no overlap. Uncertainties in extrapolation have not been assessed.

3.0 RCC Damage Growth Tool – Verification and Validation (V&V)

Finding 3.1, Wedge Testing. The tool has been applied to validation test cases and appears to conservatively predict the onset of damage growth for stagnation cases. However, tool predictions have not been compared against the wedge test data acquired explicitly for tool validation purposes. This is of concern for two reasons. First, since the temperatures and pressures for which wedge samples were tested appear comparable to expected RCC flight conditions, the reasons for discounting wedge test data are not apparent. Second, the evident differences in response between stagnation and wedge test results indicate that wedge flow environments may impose additional stresses on RCC not present in stagnation environments. These additional stresses may not be captured by the current version of the tool.

Limits to tool application: The current tool is validated only for stagnation flow cases; its application to non-stagnation cases has not been validated. No metric for application conformance to validated environments has been developed. Current wedge test data 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.

Recommendation: The current version of the tool should be used to “predict” the results of existing wedge testing. This would both indicate the sensitivity of the tool to deviations from stagnation flow, and establish the validity of current substrate exposure limits in non-stagnation environments. Future testing and tool development should focus on those environmental factors, in both test and flight that are sensitive to deviations from stagnation flow. This may require consideration of critical variables other than temperature and pressure.

In particular, a map of the mass transfer rate on the wing leading edge should be developed and compared to the conditions generated in the stagnation arc heater tests. Regions where mass transfer rates exceed test levels should be identified. Special caution should be used when applying the tool in these regions.

Finding 3.2, Conservatism. The conservatism of the tool’s predictions varies with application. The tool output does not indicate the confidence or conservatism with which its predictions should be evaluated.

Limits to tool application: Although the 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.

Recommendation: the tool should be exercised to assess the sensitivity of tool predictions to likely uncertainties in the input parameters. Those uncertainties include the reasonable precision with which physical quantities can be measured, variations in hard-coded rate profiles and trajectory maps, and the potential for erroneous input of damage type, damage location, and flight trajectory. The results of this analysis should be bundled into the tool documentation.

Finding 3.3, V&V Test Data. 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 precludes systematic evaluation of tool sensitivity to test parameters. The existing test data is too sparse to allow statistical evaluation of the tool's predictive capability. Since no rationale for tool validation is described, it is not possible to evaluate whether the test data does or does not meet the validation requirements.

Limits to tool application: The arcjet data set neither fully envelopes nor representatively samples the range of parameters credibly present in flight. As a result, the tool is "valid" only for the very limited combinations of material conditions and flight environments actually tested. The small number of data points does not allow the use of statistical arguments to verify the tool's ability to interpolate or extrapolate from test data.

Recommendation: additional tool validation testing should be preceded with a concise description of test objectives and a test matrix that *deliberately* and *systematically* varies relevant specimen and facility parameters. The goal is to demonstrate that trends predicted by the tool are confirmed with validation data. This would allow situations not actually tested to be credibly simulated using extrapolation or interpolation of trends from the tool.

Several key objectives should be posed for future testing. The accompanying test matrices should be designed to vary single test parameters while holding other parameters constant. The following is a partial list of questions that form the basis of a credible validation claim:

- 1) How does time-to-breach vary with delamination size?
- 2) How does burnthrough recession vary with time at fixed conditions?
- 3) How does growth rate or hole size vary with test article angle of attack for a near-threshold SiC coating damage configuration?
- 4) How does final breach area vary with initial crack widths or exposed substrate area for fixed conditions?
- 5) Others.

Future claims of tool validation should be accompanied with analyses that compare these trends directly to those predicted by the tool.

Finding 3.4, Static Indentation Damage*. The model has been primarily validated for delaminations caused by static indentations (except for specimens 2131 through 2134, which all come from a single impact event). Impact damage from projectiles may be different from static indentations.

Recommendation: Correlate static indentation damage with projectile impact damage.

Finding 3.5, RCC Life-Cycle Properties*. The model has been primarily validated for damage on as-fabricated RCC (except for specimens 2131 through 2134, which all come from a single panel). Impact damage on flown RCC may differ from impact damage on as-fabricated RCC. An example of possible changes in flown RCC is sub-surface oxidation.

Recommendation: Correlate delamination behavior of impact damaged flown RCC to that of impact damaged as-fabricated RCC. Perform additional V&V on flown RCC or obtain additional interlaminar shear or across ply tension data that demonstrate the delamination behavior of RCC does not degrade appreciably with number of flights.

If the V&V incorporates results for RCC material with delaminations known to be representative of damage to flown RCC, these results would eliminate the concerns raised by this finding.

* This finding is based on the assumption that the RCC mass loss curve has been established for undamaged RCC as per DIR 3-56700/RCC/1-0001 and J of ThermoPhysics and Heat Transfer 9[3] 478-485 (1995).

Fact Sheet - RCC Damage Growth Tool – V&V

Fact Sheet, V&V Finding 3.1

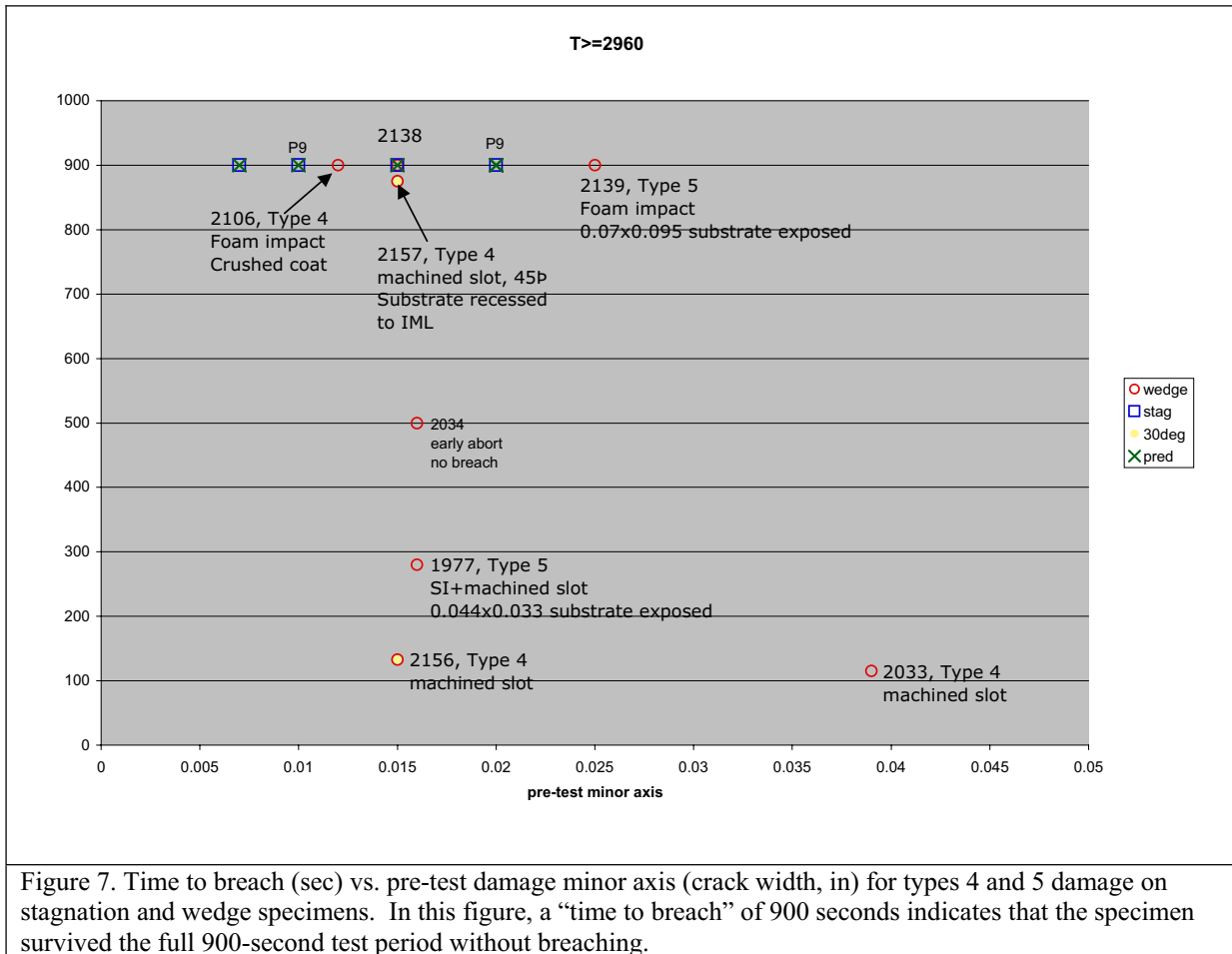
Any empirically predictive analysis tool is limited by the extent that the environments used for V&V correspond to those encountered during flight. As the designers have stated, this tool was developed and validated using stagnation arcjet test data. Although the designers are aware that there are substantial differences between the arcjet and flight environments, they have characterized the performance of their materials based on temperature and pressure only. Their critical claim is that the arcjet testing based only on temperature and pressure, in stagnation, produces conservative results compared to flight.

Given the impracticability of testing the tool against 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, by definition, reproduce. One means of evaluating the sensitivity of the tool to deviations from stagnation is to test specimens under crossflow conditions (i.e., flow with substantial shear) and compare the results to both stagnation results and predictions. The wedge tests, described in the test reports, 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 wedge testing, at the same temperatures and pressures used in stagnation, should produce results similar to those from stagnation testing.

The tool designers are to be commended for recognizing the importance of crossflow testing. However, the designers have declined to compare their tool outputs to the wedge test results, citing the inappropriateness of the tool to wedge data. Given that the wedge data was acquired for the explicit purpose of tool validation, it is not obvious to an independent evaluator why this comparison is inappropriate. From the test report JSC - 62928, DAMAGE TOLERANCE ARC JET TEST FOR REINFORCED CARBON-CARBON (RCC), page 6 (Summary), emphasis added:

The test data is being used to validate the RCC Damage Growth Tool as well as help define the damage tolerance capabilities for the wing leading edge (WLE) and nose cap regions of the Shuttle Orbiter. A total of **50 specimens were tested in both wedge and stagnation** in 5 phases of tests as well as the evaluation of coupons from a full scale RCC panel 9 damaged by foam impact.

Independent assessment of test data indicates that some wedge specimens show damage growth that is not expected from the stagnation data. Among other effects, machined slots of thickness <0.020 inch appear to grow in wedge testing; they did not grow in stagnation testing (Figure 7). This indicates that stagnation quantities, while possibly necessary determiners of RCC erosion, may not comprise a complete set of parameters that determine damage growth. Angle of attack, and related crossflow environmental parameters, may also influence both the onset and growth of RCC damage.



While the tool designers assert that the tool is validated only for stagnation effects, restricting actual use of this tool to stagnation regions would seem an unacceptable limit on tool application. Crossflow is present on every WLE panel, including the flow attachment and flow impingement (Panel 9) regions. Current data and analysis is

insufficient to assess the tolerance of tool conservatism to deviations from stagnation flow.

Aerothermal analyses have been conducted to better understand and quantify the test environments for the flat face test samples from which the RCC damage tool was developed. Centerline enthalpies were used to perform these calculations (Note: The data from Don Curry indicated significant differences between centerline and bulk enthalpy values). Figures 8 and 9 show the surface pressure and heating rate distributions calculated for the surface of the sample. All of these quantities are relatively uniform for the 2.8 inch central portion of the sample that constitutes the actual test specimen. A complete series of calculations were performed and are summarized in Table 1. The measured and calculated heating conditions compare reasonably well. The peak enthalpy condition that occurs at the centerline at least partially accounts for the slight over-prediction in heating condition. Included in this table is the mass transfer coefficient calculated for each of the test conditions. The transfer coefficients are all in the range from 0.0119 to 0.0158 lbm/ft²-s. This range is significantly lower than the transfer rates calculated for panel 9 during flight. In flight, at peak heating conditions, mass transfer rates are calculated to exceed 0.035 lbm/ft²-s. Therefore, the test conditions with the highest mass transfer rate are less than half the peak conditions experienced in flight.

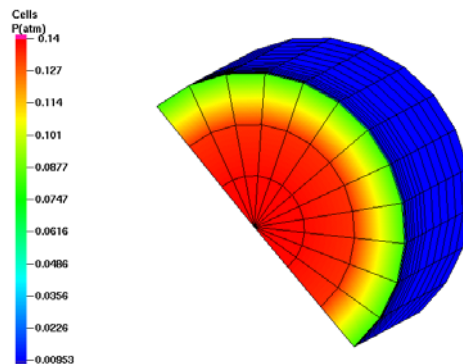


Figure 8. Flat Face Sample – Test 2 Predicted Pressures

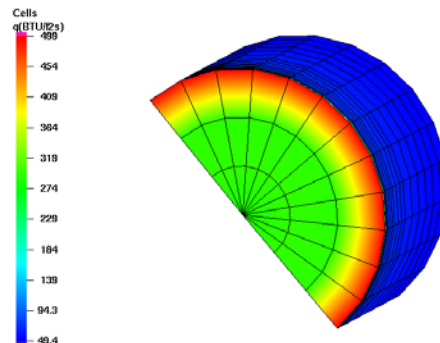


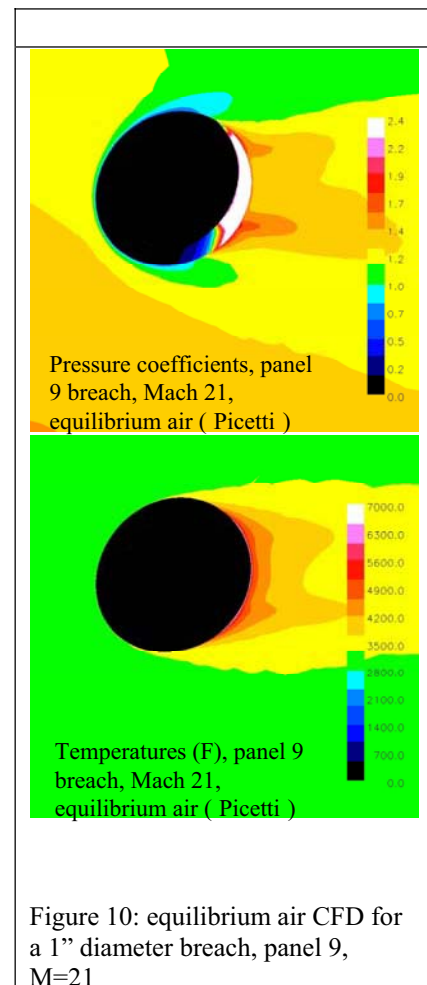
Figure 9. Flat Face Sample – Test 2 Predicted Heat Fluxes

Table 1. Comparison of Measured and Predicted Test Conditions

Test Case	Stagnation Pressure (atm)	Exit Diameter (in)	Distance from Nozzle Exit (in)	Centerline Stagnation Enthalpy (Btu/lbm)	Predicted Heat Flux (Btu/ft ² -s)	Measured Heat Flux Data (Btu/ft ² -s)	% Difference	Predicted Mass Transfer Coefficient (lbm/ft ² -s)
1	0.047	5	10.5	12036	157	147	6.80	0.013
2	0.070	5	10.5	12604	199	186	6.99	0.0158
3	0.049	5	10.5	9520	127	118	7.63	0.0133
4	0.036	10	10	21227	253	226	11.95	0.0119
5	0.043	10	10	17939	233	209	11.48	0.0129
6	0.061	5	10.5	9356	141	109	29.36	0.015
7	0.043	10	10	8068	102	94	8.51	0.0126

A further complication arises when considering crossflow effects: flow ingestion by a breach may produce substantial heating augmentation relative to even fully catalytic heating on a smooth surface. For flight application, the tool uses material temperatures and pressures derived from smooth-OML, certified analyses of flight trajectories, adjusted for surface catalycity changes with coating loss. However, the smooth-OML temperatures and pressures, derived for an attached flow over an unbroken surface, are unlikely to accurately reproduce the temperatures and pressures present with supersonic flow impinging onto the uncoated, fully-catalytic lip of a breach.

The tool appears to compensate for catalycity differences for surface coating loss. The tool does not appear, however, to account for flow impingement in the subsurface of a damage site. CFD analyses (Picetti/Boeing, Figure 10) of flight damage indicate that such flow is likely to substantially (and asymmetrically) augment the local temperatures and pressures, even in the absence of catalycity effects. (Actual surface temperatures would be somewhat lower due to multidimensional conduction and surface thermochemistry.) This augmentation will depend on the size, shape, and position of the hole. Enhanced heating would result in damage growth greater than predicted by the tool. Also, molten sealant appears to flow so as to self-heal crushed or slotted coatings. The shear forces driving liquid flow on the surface may vary strongly with angle of attack, an effect not captured by the current tool.



Fact Sheet, V&V Finding 3.2

This tool was developed using a chemical kinetics rate set for RCC erosion and a conceptual model for the RCC damage growth mechanism. The designers constructed this tool with the explicit intent to be conservative. Given the maturity level of the damage growth mechanistic concept, the desire for conservatism is understandable. However, an excessive application of conservatism may be undesirable for tool applicability, as it may drive a requirement for repair that would not result from a perfectly accurate tool. Another consequence of high implicit conservatism is the obscuration of potential weaknesses of the basic physical model, and associated paths for tool improvement.

The alternative to a highly conservative tool is a highly accurate tool that explicitly states the uncertainties in output quantities, based both on realistic uncertainties for input quantities, and on explicit evaluation of the fundamental accuracy of the physical model. Standard numerical techniques exist for propagating input uncertainties to outputs. The evaluation of fundamental model accuracy, through well-considered validation testing, is much more challenging. In this case, designing the model to be inherently conservative may be the only feasible strategy for assuring the overall tool conservatism.

Even if the model is a perfectly accurate understanding of damage growth, the uncertainties in required input properties may generate substantial uncertainties in the outputs. Uncertainties in user inputs include uncertainty in damage measurements and delamination areas. Uncertainties in hard-coded tool numerics include:

- Uncertainties in flight temp and pressure, caused by variations in atmospheric density and vehicle trajectory;
- Uncertainties in flight temp and pressure, caused by uncertainties in the certified trajectory analysis tool (for zero-uncertainty atmospheric density and trajectory);
- Uncertainties in reaction rates, even for precise arcjet conditions.

The accumulation of these uncertainties, when explicitly propagated through a perfectly modeled tool, may result in substantial uncertainties in damage growth predictions. The current tool accumulates uncertainties implicitly by biasing results in favor of high conservatism. However, the degree of total conservatism is not quantitatively assessed, nor is conservatism (and therefore risk) be assigned to specific inputs or model features. This reduces the ability to assess risk, and potential risk-mitigation techniques, based on tool assumptions or input precision.

The designers themselves have noted that the conservatism of the tool appears to decrease as test temperatures increase. It is possible that propagated uncertainties would be large enough, at high temperature, that error bars would intrude into non-conservative prediction space. This possibility can be probed by conducting sensitivity analyses of the tool. In some cases, input quantities could be varied simply by the amount of precision reasonably achievable in measurement (for example, the precision of a crack width measurement). For hard-coded quantities (for example, recession rates), reducing the values from “conservative” to “non-conservative” or “accurate” would allow compilation of conservatism as a function of manipulated quantity. Knowing the relative sensitivity

of tool predictions to different numerical components would greatly improve the ability of a user to assess the sources and limitations of tool conservatism.

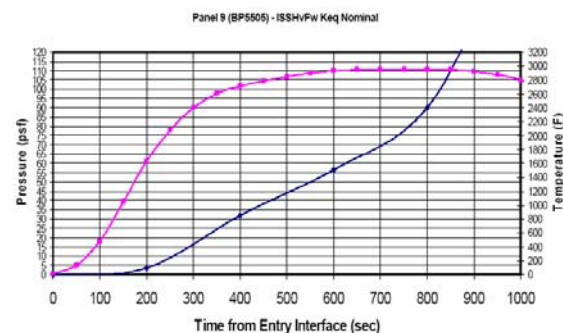
Fact Sheet, V&V Finding 3.3

The test series cited as validation (JSC – 62928) appears to be a mixture of elucidating damage growth mechanisms (developmental) and confirming tool predictions (verification and validation). The set of test data appears insufficient for either objective. Given the potential for five damage types, variable delamination, variable OML damage, and varying locations on the vehicle, the number of potential damage combinations is quite large. Even assuming the panel 9 impact specimens represent the maximum—rather than typical or minimum—damage from an impact, the range of test parameters barely spans the potential impact damage.

Within that span the small number of test samples is insufficient to compile meaningful reproducibility or trend statistics. At the 2960°F stagnation condition there appears to be only one pair of specimens between which only a single variable (including delamination, unmeasured prior to phase III testing) changes (2041, 2042). However, the report notes uncertainties about the preparation and testing of 2041. (Although the validation documents label 2041 as having Type 2 damage, the pre-test photo and description of preparation seem to indicate Type 1 damage. If the damage actually was Type 1, this result contradicts the assertion that Type 1 damage resists breaching.) Specimen series 2132, 2133 appear to be nearly identical specimens at nearly identical test conditions, but 2132 testing was ended 65 seconds short. Given the “significant surface activity” on 2132 (not seen on 2133), one can reasonably wonder if the extra 65 seconds of test would have made a more substantial difference in results. Specimen series 1949, 1899B, 1965 comprise a deliberate evolution of surface damage, but the extent of delamination was not measured. Damage type 3 was tested only once during the validation series, at 2500°F. Because it is difficult to either interpolate or extrapolate damage growth conclusions from the limited test data, it is difficult to assert that the tool could accurately predict damage not actually tested.

Other factors reduce the strength of the validation claim. The tool has been primarily validated for damage on as-fabricated RCC (except for specimens 2131 through 2134, which all come from a single panel) with statically-induced delamination. Impact damage on life-cycle aged RCC may differ from impact damage on as-fabricated RCC, and impact damage from projectiles may be different than that from static indentations.

Finally, the tool is designed to simulate damage growth rates for the complete entry temperature and pressure profile. In flight, temperatures and pressures vary with altitude or time following entry interface. However, no tests to date have varied the arcjet temperature and pressure to replicate the flight profile; the tests have all been performed at fixed arcjet conditions. Profile



Temp/pressure profile for selected trajectory, BP5505 (T in red)

testing would better evaluate the ability of the tool to accurately accumulate the effects of ablation rate changes with temperature, including time-dependent variations in both material catalyticity and boundary layer composition. Profile testing would also better capture the consequences of surface morphology changes (micro-cracking of the non-catalytic SiC coating, caused by mismatch of coefficients of thermal expansion for carbon and SiC), which may depend on rates of temperature change.

Fact Sheet, V&V Finding 3.4

Impact damage formed by static indentation and 90° projectile impacts has some similarity in that possible multiple delamination planes may be observed beneath the surface damage and loss of back-side coating has occurred. See for example the CT cross-section of panel A146-1 (Figure 3a) impacted with foam at a 90° angle and the macrograph of specimen 1900 with static indentation damage in Figure 11. The damage to the impact face appears different, with more coating crushing in the case of static indentation. CT cross-sections also show the extent of delamination may be larger for the projectile impacted panels.

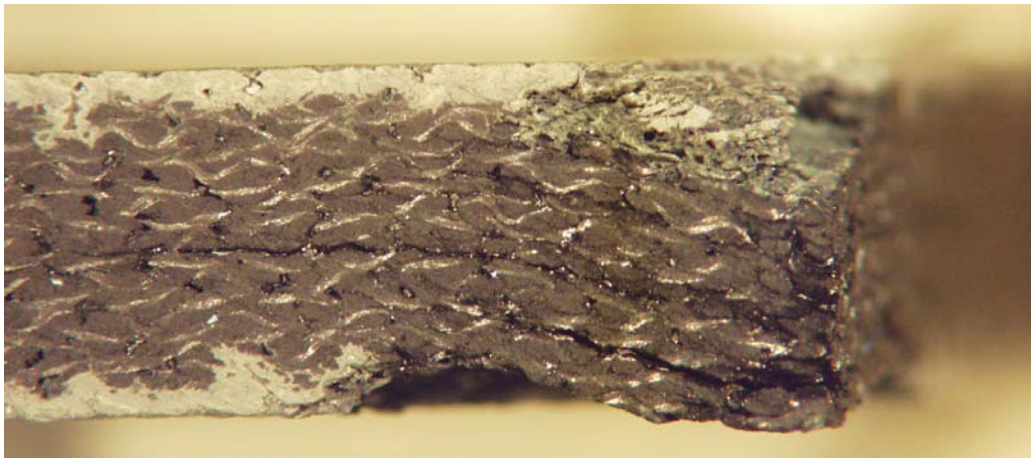


Figure 11. Macrograph of Section of Arc Jet Specimen 1900B

Fact Sheet, V&V Finding 3.5

Interlaminar shear data and across ply tension data were obtained from the RCC aging team for various panels of RCC (shown in Table 2). These two properties should be good indicators of delamination behavior. Unfortunately the data are incomplete, but currently there is no conclusive evidence that delamination behavior degrades substantially for flown RCC. Across ply tension data for as-fabricated RCC should be found for this comparison. Providing additional flown material is available, further measurements could be made to verify that delamination behavior will not degrade for flown RCC.

Table 2. Interlaminar shear and across ply tension data for as-fabricated and flown RCC.

age/treatment		interlaminar shear 0.25"x0.50", psi	interlaminar shear 0.25"x1.00", psi	across ply tension psi
8L top	26 flights	1964±75 (6)	1713±305 (6)	860±36 (7)
8L apex	26 flights	1873±373 (20)	N/A	759±71 (7)
8L apex, 3000°F	26 flights	2383±215 (3)	N/A	N/A
8L upper fragment	26 flights	N/A	1613±179 (3)	593±66 (3)
8L lower fragment	26 flights	N/A	1417±308 (3)	N/A
10L apex	OV102-19 flights	N/A	N/A	785±64 (12)
12R apex	OV102-15 flights	N/A	N/A	743±69 (6)
uncoated after TEOS, no SiC, no type A		1613±148 (12)	N/A	N/A
uncoated after TEOS, no SiC, no type A	after 3000F treatment	2243±69 (3)	N/A	N/A
as-fabricated with SiC, and type A		2094±284 (3)	N/A	N/A
as-fabricated with SiC, and type A	conditioned, 1000F, air 0.03lbm/ft ² mass loss	1212±414 (6)	N/A	177±24 (8)

of specimens shown in parentheses.

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14. ABSTRACT In Spring of 2005, the NASA Engineering Safety Center (NESC) was engaged by the Space Shuttle Program (SSP) to peer review the suite of analytical tools being developed to support the determination of impact and damage tolerance of the Orbiter Thermal Protection Systems (TPS). The NESC formed an independent review team with the core disciplines of materials, flight sciences, structures, mechanical analysis and thermal analysis. The Math Model Tools reviewed included damage prediction and stress analysis, aeroheating analysis, and thermal analysis tools. Some tools are physics-based and other tools are empirically-derived. Each tool was created for a specific use and timeframe, including certification, real-time pre-launch assessments. In addition, the tools are used together in an integrated strategy for assessing the ramifications of impact damage to tile and RCC. The NESC teams conducted a peer review of the engineering data package for each Math Model Tool. This report contains the summary of the team observations and recommendations from these reviews.					
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