Orbiter Return-To-Flight Entry Aeroheating

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Introduction

The Columbia accident on February 1, 2003 began an unprecedented level of effort within the hypersonic aerothermodynamic community to support the Space Shuttle Program. During the approximately six month time frame of the primary Columbia Accident Investigation Board activity, many technical disciplines were involved in a concerted effort to reconstruct the last moments of the Columbia and her crew, and understand the critical events that led to that loss. Significant contributions to the CAIB activity were made by the hypersonic aerothermodynamic community(REF CAIB) in understanding the re-entry environments that led to the propagation of an ascent foam induced wing leading edge damage to a subsequent breech of the wing spar of Columbia, and the subsequent break-up of the vehicle. A core of the NASA hypersonic aerothermodynamics team that was involved in the CAIB investigation has been combined with the United Space Alliance and Boeing Orbiter engineering team in order to position the Space Shuttle Program with a process to perform in-flight Thermal Protection System damage assessments. This damage assessment process is now part of the baselined plan for Shuttle support, and is a direct out-growth of the Columbia accident and NASA's response. Multiple re-entry aeroheating tools are involved in this damage assessment process, many of which have been developed during the Return To Flight activity. In addition, because these aeroheating tools are part of an overall damage assessment process that also involves the thermal and stress analyses community, in addition to a much broader mission support team, an integrated process for performing the damage assessment activities has been developed by the Space Shuttle Program and the Orbiter engineering community. Several subsets of activity in the Orbiter aeroheating communities support to the Return To Flight effort have been described in previous publications (CFD?, Cavity Heating? Any BLT? Grid Generation?). This work will provide a description of the integrated process utilized to perform Orbiter tile damage assessment, and in particular will seek to provide a description of the integrated aeroheating tools utilized to perform these assessments. Individual aeroheating tools will be described which provide the nominal re-entry heating environment characterization for the Orbiter, the heating environments for tile damage, heating effects due to exposed Thermal Protection System substrates, the application of

Computational Fluid Dynamics for the description of tile cavity heating, and boundary layer transition prediction. This paper is meant to provide an overall view of the integrated aeroheating assessment process for tile damage assessment as one of a sequence of papers on the development of the boundary layer transition prediction capability in support of Space Shuttle Return To Flight efforts.

Integrated Aeroheating Analysis Tools

Accurate aeroheating environment definition is critical to the successful and safe re-entry and landing for any spacecraft. In the case of the Space Shuttle Orbiter, there is a heritage of aeroheating environment definition that was developed for the Space Shuttle Program (SSP) via extensive wind tunnel testing and calibration to STS 1-5 flight data. Subsequent to the STS-107 accident, Return to Flight (RTF) efforts within the Orbiter aeroheating community have been primarily focused on developing the engineering understanding and tools necessary to support Thermal Protection System (TPS) damage assessment. In addition, significant effort has been invested supporting the development of repair capabilities, which will be briefly discussed later in this paper. The engineering tools required to support a TPS damage assessment process for the Orbiter must not only be reasonably accurate, they must also support an analyses timeline of roughly one day. For this reason, prompt delivery of very efficiently obtained and accurate results, the aeroheating analysis tools utilized must be considered as part of a package with an associated process. The aeroheating tools that support this process include the XF0002, Cavity Heating, Catalytic Heating, RTF Boundary Layer Transition (BLT), Rapid Analysis CFD and Vehicle Breech Heating tools. Although there is significant effort underway to improve our ability to model the aeroheating environments induced by breeches in Orbiter TPS, this tool is principally used to support Probabilistic Risk Assessments (PRAs) in order to make Program level decisions on acceptable risk. Each of the remaining five tools in this list will be discussed in this section in order to describe their functionality and background, information will be provided to describe the data required as inputs, and a brief description will be given illustrating how the aeroheating analyses support the thermal and stress communities.

The backbone of the Orbiter aeroheating environment definition is provided via characterization of the nominal smooth body heating. The smooth body definition here is meant to distinguish between an undamaged TPS and a damaged TPS. The Orbiter engineering community has had tools in place since early development stages which provide an accurate characterization of the heating environment. The methodologies employed in these tools is consistent with the principal engineering techniques in use in the late 1970's, e.g. simplified representations of a flow field which rely on closed form flow geometry frameworks. [Reference Haney?] Examples of these techniques are stagnation heating, flat plate, tangent wedge, cone and swept cylinder methodologies. These methods were utilized to develop flight data calibrated heating representations for XXX locations on the Orbiter. Each of these locations is referred to as a Body Point (BPT), and the tools which encapsulates the BPTs is referred to as XF0002. (BPTs or BPs?) The heating environment provided by this tool must support thermal analyses which analyze the time dependent energy balance due to surface convective heating (or cooling), surface thermal radiation exchange and conduction. Note that LEO re-entries with the Orbiter do not present a significant flow field radiation contribution to the total heating, and it is neglected. Since the primary tool that XF0002 provides data to is a three dimensional thermal math model (3D-TMM), the aeroheating environment must be defined in terms of a surface temperature. For this reason, XF0002 generates the heat flux at four surface temperatures using a temperature based heat transfer coefficient. The 3D-TMM software then linearly interpolates on the four wall heat flux values using the time dependent thermal response as an input. The heat transfer coefficient basis of XF0002 is important to recognize because it has ramifications on the implementation and accuracy of other tools, e.g. Cavity Heating, that will be discussed in the following paragraphs.

With a framework already in place for providing smooth baseline heating via XF0002, the challenge to the Orbiter aeroheating community during RTF was to develop a framework to provide heating environments for damaged TPS. The engineering framework utilized to accomplish this for RTF is based on the utilization of bump factors. This phrase is used to describe an implementation whereby the nominal four wall heat fluxes from XF0002 is augmented by additional multiplicative factor(s) which account for local geometry changes due to damage or repair, surface catalytic changes due to different surface materials from exposed TPS substrate or repairs. It is important to understand that a phenomenalogically consistent implementation of bump factors within the XF0002 framework requires that they be treated as augmentation factors to the heat transfer coefficient. This is phenomenalogically different than considering the augmentation factors as increments in heat flux. This is because the fundamental assumption of a temperature based heat transfer coefficient is that a linear approximation in surface temperature is made for the convective heat flux relationship. All surface temperature effects, to first order, are thus accounted for in this framework. All other effects such as localized geometry, flow physics, Reynolds number dependencies, surface catalytic properties, etc. are captured via the heat transfer coefficient term. In other words, the heat transfer coefficient is a linear efficiency term for converting a temperature potential into a heat flux. Further higher order accuracy in temperature, such as surface catalysis, are modeled within XF0002 by having temperature dependent heat transfer coefficients via the four wall heat fluxes. Thus, because the XF0002 implementation is fundamentally a heat transfer coefficient methodology, the Cavity Heating and Catalytic Heating tools should also operate in this framework if the tools are to be self-consistent.

The primary characteristic of tile damage that needs to be implemented into the aeroheating environment definition is the effect of the change in local geometry. Ascent debris, such as foam or ice, typically creates tile impact sites that have a length on the order of inches and depths ranging up to the order of one inch. Historically, the Orbiter aeroheating community assessed tile damage with a conservative methodology based on two dimensional aeroheating and thermal assessments. Due to the change in perspective in the SSP in regard to ascent debris because of the STS-107 accident, and the promotion of TPS damage assessment into a mandatory disposition process during missions, the level of accuracy required has mandated a concerted effort to reduce conservatism in the entire damage assessment process. The Orbiter aeroheating community, in light of this, invested over two years of intense effort to improve the basis of our ability to provide tile damage cavity heating. These efforts are currently planned to end before December, 2006. Strategic emphasis has been placed on the characterization of laminar cavity heating definitions since the historical cavity heating basis came from high Reynolds number, mostly turbulent wind tunnel data. In addition, engineering judgment also motivated this strategy because the largest improvement in accuracy and thus reduction in conservatism was believed to be possible by improving the laminar cavity heating environment definition. Initial goals to also improve the turbulent cavity heating framework have not been borne out, in large part due to the significant investment required to achieve the current improvements in laminar heating.

RTF improvements in the laminar cavity heating framework have been develop via a significant test program in the NASA-LaRC hypersonic aerothermodynamic facilities. This test program involved multiple wind tunnel entries into the Mach 6 and Mach 10 air tunnels and utilized thermographic phosphor coated ceramic wedge configuration test articles. Parametric data on cavity geometries and local boundary layer properties have allowed the Orbiter aeroheating community to develop a sound engineering basis for laminar heating within cavities. Cavity Heating tool implementation is linked to the wind tunnel data acquired via thermal phosphor technique nominal data acquisition and data reduction. Thus the actual heating levels established in the wind tunnel testing rely on the NASA-LaRC thermal phosphor system development activities. RTF efforts to characterize the heating uncertainty associated with the acquired test data were also critical in defining the Cavity Heating tool implementation. Since the NASA-LaRC developed thermal phosphor technique reduces the measured temperature rise into a non-dimensional temperature based heat transfer coefficient, consistency with the XF0002 heat transfer coefficient framework is ensured. The determination of cavity heating augmentation factors from the wind tunnel data involved the selection of an in-situ upstream reference location for non-dimensionalization of the cavity heating, as well as the heating in the immediate vicinity of the cavity. Obtaining the essential wind tunnel data on laminar cavity heating has enabled the characterization of three phenomenological categories of laminar cavity heating: shallow cavities, Everhart cavities and traditional closed (not defined?) cavities. Shallow cavities are defined as having a depth to boundary layer ratio of less than 0.3 and are characterized by minimal perturbation to the nominal undamaged heating level, even within the cavity. Everhart cavities, named after the lead of the NASA-LaRC wind tunnel test program on cavity heating, are characterized by slight streamline curvature which leads to decreased heating in the cavity (approximately a 0.6 augmentation factor), and moderate increased in the heating to the edge of the forward facing downstream cavity edge (augmentation factors of approximately 1.6). Everhart cavity classification includes a definition that the cavity length to local boundary layer thickness is less than 10, and the cavity length to depth ratio is less than 15. Closed cavities are characterized by significant perturbations to the flow field, including the generation of substantial stream wise vorticity. Closed laminar cavities have not been as well characterized during the RTF activity due to the complexity of the heating effects for this cavity category, and because of the damage severity needed to exhibit a closed laminar cavity behavior.

In summary of the Cavity Heating tools development, implementation of the aeroheating environment definition for these three cavity frameworks has been performed to provide a capability to the SSP. Nominal heating levels were established via data acquired in the LaRC Mach 6 and 10 air facilities by utilizing the thermal phosphor technique. Wind tunnel uncertainties were also characterized based on the thermal phosphor data acquisition and reduction techniques. The ground testing and engineering development activity involved in the Cavity Heating tool activity is the most significant effort that was undertaken by the Orbiter aeroheating community. Significant reductions in conservatism have resulted due to this investment. However, because the ground testing environment is a simulation, not a duplication, of the flight environment, a ground test to flight extrapolation effect was characterized with Computation Fluid Dynamics (CFD) tools exercised on the Orbiter configuration at flight conditions, as well as the NASA-LaRC wind tunnel conditions. Navier Stokes simulations have been conducted for specific wind tunnel runs, and the local flow conditions and cavity geometries were scaled to the Orbiter configuration at flight conditions in order to perform this assessment. The CFD software and methodology utilized in this assessment will be described later in this paper. Minimal effects were demonstrated for shallow cavities. Moderate flight extrapolation effects were demonstrated for Everhart cavities. However, significant increases in heating augmentation factors have been demonstrated in the analyses of laminar closed cavities at flight conditions. The trend illustrated from the Navier-Stokes simulations at flight condition for closed laminar cavities emphasized to the Orbiter aeroheating team the significant challenges remaining to fully characterize, via an engineering correlation, closed laminar cavity heating. A conservative engineering correlation has been implemented into the Cavity Heating tool for Orbiter damage assessment support, however challenges remain if a more accurate representation of closed cavity heating trends is desired. At this time, there is no intention of continuing the development of the Cavity Heating tool in order to improve the closed laminar cavity engineering correlations employed in supporting the SSP.

It is of vital importance to establish a confidence level in the aeroheating environment definition for tile damage cavities which is appropriate to the risk assumed by a Shuttle crew and NASA if a tile damage can not be cleared as safe for entry. Significant effort has been devoted during RTF to establish the Cavity Heating tool as the first tier of aeroheating environment definition for the in-flight tile damage assessment process. This first tier is an engineering framework which must be capable of supporting an integrated engineering re-entry analyses for multiple tile damage sites. Studies of Orbiter tile damage flight history indicated prior to STS-114 that this assessment process needed to be capable of supporting up to ten tile damage sites in a time frame of approximately one day. This motivation dictated that a rapid analyses engineering tool be staged to disposition the necessary number of damage sites. That tool is the Cavity Heating tool. However, because this is an engineering tool which relies on an engineering basis developed via ground test data on representative tile damage geometries at appropriately scaled local flow conditions, there is a very real possibility that additional conservatism exists in its implementation than what is desirable given the potential risks involved. For these reasons, the Orbiter aeroheating team has also invested much effort during RTF to put into place a second tier, high fidelity tile cavity heating framework.

A second tier of cavity heating environment definition implies a higher fidelity, more accurate, and thus lower conservatism result. The only means the hypersonic aerothermodynamic community has available to develop this type of environment definition is through the use of hypersonic nonequilibrium chemistry Navier-Stokes solvers. However, this community has never had to support the development of aeroheating environments in a timeframe consistent with a Space Shuttle flight timeline. The demands placed on the CFD process, the engineers involved and the computational platforms is of a scale not typical of traditional hypersonic CFD application. Shortly into the RTF activity, though, a strong motivation to have such a capability in place for mission support developed within the Orbiter aeroheating team. In order to turn this motivation into a reality, hypersonic aerothermodynamic CFD experts from NASA-ARC and NASA-LaRC took two of the nations premier re-entry heating Navier-Stokes tools and developed the necessary framework of corollary tools and processes. NASA-ARC performed this development around the DPLR software. NASA-LaRC developed this capability around the LAURA software. The development of rapid grid generation techniques specifically tailored to tile damage assessment, the ability to perform CFD simulations on sub-domain(s) in proximity to a damage site, massive parallelization, and an ability to initialize these sub-domain(s) with an initial undamaged nominal vehicle solution have all proven to be indispensable for executing an analyses of this nature. This framework thus requires a CFD repository of prepositioned flow field solution along the Orbiter re-entry corridor for both DPLR and LAURA. Beyond the development of this Rapid Analysis CFD process to support Orbiter missions, the single most important development during RTF was the acquisition of the Columbia SGI based supercomputing system by NAS at NASA-ARC. Without this computing platform it is extremely unlikely that the Orbiter aeroheating community could now be in a position to satisfy the need to perform a high fidelity CFD based tile damage heating assessment along the laminar portion of the Orbiter re-entry trajectory. Yet, with this computational platform in place, the Orbiter aeroheating CFD team perform a benchmark study in early 2005 which executed CFD analyses on ten tile damage sites in a 24 hour timeframe. That exercise, which relied on the Columbia supercomputing system, proved that this type of analyses was now possible.

As the SSP approached STS-121, the Orbiter aeroheating team is positioned with the personnel, CFD process and prepositioned Orbiter configuration hypersonic CFD repository necessary to execute two tile cavity Rapid Assessment CFD simulations for the laminar portion of the Orbiter re-entry in less than 18 hours. This assessment is designed to perform a high fidelity comparison of the Cavity Heating tool tile damage augmentation factors to CFD based simulations with the DPLR and LAURA software. Results of this assessment will be utilized by the Orbiter aeroheating team during Shuttle missions to establish a recommendation in regard to the level of conservatism remaining in the Cavity Heating tool for the two most critical tile damage sites. However, at this time, the results of the Rapid Assessment CFD process are not capable of being supplied directly to the thermal modeling community. Any potential adjustment of the cavity heating environment for a 3D-TMM assessment must be incorporated manually into the Cavity Heating tool. For this reason, direct assessment of the re-entry thermal response with the Rapid Analysis CFD process is not considered part of the nominal flight support process. Having the capability to execute this high fidelity analyses ensures that the Orbiter aeroheating community is positioned to employ all practical means of ensuring that an appropriate level of conservatism exists in the aeroheating environments associated with a tile damage assessment.

The three aeroheating tools characterized to this point, XF0002, Cavity Heating and Rapid Assessment CFD provide the principal components necessary to define the convective laminar heating environment for tile damage assessment. However, two other tools are also needed to complete the heating environment definition. The Catalytic Heating tool provides a definition of the catalytic heating effect due to a difference in surface material properties between the nominal and damaged TPS. And, the RTF BLT tool provides a framework to predict the time of BLT.

Representation of catalytic heating effects for damaged Orbiter TPS is a key aspect of aeroheating environment definition. Damaged TPS which is characterized by the Catalytic Heating tool includes tile substrate, e.g. no Reaction Cured Glass (RCG) coating, and damaged Reinforced Carbon Carbon (RCC), e.g. exposed carbon-carbon substrate. (This discussion could perhaps benefit from a sketch and discussion of the tile structure in depth?) Representation of the catalytic heating effect for RCC and tile repairs are also characterized by this tool, but will not be discussed here. Arc jet testing conducted at NASA-ARC on various tile substrates (LI-900, LI-2200, FRCI-12) was conducted during RTF. Results from that testing have been used to define a preliminary catalytic heating framework. The data obtained at NASA-ARC indicates that tile substrate materials exhibit slightly less catalytic heating than RCG. Thus an assumption has been made that exposed tile has the same catalytic heating properties as RCG, and the nominal baseline heating definition for RCG coated tiles represented in XF0002 is adequate. However, this conclusion and the assumption to use RCG surface catalysis properties is dependent on the emissivity utilized for arc jet data reduction. And it has been well established that exposed tile substrates do not have the same surface emissivity properties, and emissivity characterization of tile substrates is not as mature as for RCG. For these reasons, arc-jet activities are continuing at NASA-JSC in an effort to improve the emissivity and surface catalytic modeling for tile damage. In addition, analytical efforts have been performed to characterize the surface catalytic heating effect for damaged RCC with exposed carbon-carbon substrate (Rochelle references). Engineering approximations assuming a fully catalytic surface for exposed carbon-carbon form a framework to provide location specific factors to augment the heating provided via XF0002 for RCC regions of the Orbiter TPS. Potential issues with providing a heat transfer coefficient consistent methodology for the fully catalytic heating to localized RCC damage are not without merit. However, from an engineering perspective a simple augmentation factor framework has proven to be expeditious, and it has been demonstrated to show acceptable comparisons to arc-jet RCC damage growth tests performed in the NASA-JSC ARMSEF facility.

Beyond the framework necessary to generate the convective heating environment for tile damage analyses, prediction of BLT time in the re-entry is essential for a complete representation of the re-entry environment. The implementation of XF0002 requires that the time of transition onset during re-entry be defined apriori. Yet, the prediction of BLT due to off-nominal TPS (e.g. damage or protruding gap fillers) can not be assessed apriori due to the lack of damage definition. For this reasons three discrete BLT times have been defined to represent times of transition that can span the re-entry corridor. The latest transition time utilized corresponds to the SSP defined Commit To Flight (CTF) roughness. The CTF roughness is used for all certification rigor Orbiter re-entry assessments. A second, slightly earlier, transition time is also utilized and the third, earliest pre-staged transition time, corresponds roughly to the extent of Orbiter BLT flight history. The CTF roughness corresponds to BLT near Mach 11, the next earlier transition time corresponds to approximately Mach 15, and the third transition time corresponds to approximately Mach 18. One additional comment on the intermediate transition time is warranted. Examination of Orbiter flight history, in part, was utilized for selection of the intermediate transition time near Mach 15. Approximately 60% of the Orbiter flight history demonstrates BLT times later than the intermediate transition time, yielding a reasonable confidence level that an individual Orbiter re-entry will transition later that approximately Mach 15. With the propositioning of XF0002 results for these three BLT times, assessments of BLT due to tile damage essentially come down to a multiple choice question during an in-flight assessment. However, the capability to perform flight specific BLT prediction is supported by the RTF BLT tool.

Development of the RTF BLT wind tunnel database led to the largest number of wind tunnel runs conducted for any of the RTF re-entry heating wind tunnel test programs. The BLT testing programs conducted at NASA-LaRC in their hypersonic wind tunnels supported the development of two mature BLT prediction capabilities. One capability supports BLT prediction for protuberances, and the second capability provides a BLT prediction capability for tile damage. Data acquired to support the SSP baselined capability which supported STS-114 were all acquired at NASA-LaRC facilities. Continuing efforts, post STS-114, will provide additional hypersonic Orbiter BLT data on approximate tile damage cavities via NASA-LaRC facilities. In addition, approximate tile damage cavity and discrete protuberance BLT data is being acquired during 2006 via the MH-13 Orbiter Hypersonic Heating test being conducted at the CUBRC LENS hypersonic shock tunnel. Current BLT prediction support for Orbiter re-entry is based on a momentum thickness based Reynolds number divided by the boundary layer edge Mach number (Re-theta/Me) versus protuberance height non-dimensionalized by boundary layer thickness (k/delta) correlation. The RTF BLT tool provides an engineering framework to interpolate (Frank's tool?) to points along a flight specific trajectory and provide the boundary layer properties necessary to predict BLT using this Re-theta/Me methodology. In addition, a corollary capability has been developed to evaluate a downstream turbulent region of influence, by assuming a ten degree cone half-angle propagated along boundary layer edge streamlines defined with solutions from the aforementioned CFD repository. This turbulent influence Wedge tool is used to evaluate tile damage site specific BLT, in the event that a tile cavity or protruding gap filler is predicted to lead to early transition which only affects a subset of tile damage locations.

The five capabilities briefly discussed above provide the framework for Orbiter re-entry heating tile damage assessment. The XF0002 software provides nominal smooth baseline Orbiter heating along a complete re-entry profile and is a heritage capability. The Catalytic Heating tool provides simple augmentation factors to define the relative effect of exposed TPS substrate. The Cavity Heating tool provides an engineering framework of cavity heating correlations to support a first tier of capability. A second tier of cavity heating capability is supported via the Rapid Assessment CFD process. And, the fifth capability is provided by the RTF BLT tool, which supports BLT prediction for cavities and protuberances. These tools provide the combined aeroheating support necessary to execute an Orbiter re-entry heating assessment. Yet, these capabilities are only one aspect of the integrated analyses necessary to determine the viability of a damaged Orbiter for re-entry. Downstream of the aeroheating capability, in a serial process, are a thermal analyses and a stress analyses. The real metrics of performance for the Orbiter TPS and structure are generated by the thermal and stress technical communities. The tile system key performance metrics which are characterized by these disciplines are TPS surface temperatures, tile/bond line temperatures, Tile/RTV margins and structural sub-system margins. An integrated aeroheating/thermal/stress assessment is required to yield a characterization of these performance metrics. The flight support process that ties these three engineering communities together will be described further in the next section.

The aeroheating tools described in this section are not only used to support the in-flight process to disposition tile damage. Several pre-flight activities must also be supported via the integrated aeroheating/thermal/stress analyses which is characterized as the Damage Assessment Team (DAT) analyses. The two most significant of these activities are the mission risk assessment due to ascent debris such as foam or ice shed from the External Tank, and a pre-flight On-Orbiter Inspection Criterion (OOIC). The ascent debris risk assessment has been executed for STS-11 and STS-121 based on the combined results of an ascent damage occurrence assessment and a re-entry damage response assessment. Ascent debris is evaluated for its likelihood to generate TPS damage, and the likelihood of catastrophic re-entry consequences due to the damage is assessed to develop a PRA. Results of the PRA activity are then utilized by the SSP to determine if the risks associated with these topics is acceptable. The pre-flight OOIC activity is an input for the in-flight DAT assessment. Due to the scope of effort required to disposition any single TPS damage site during a mission, a high-confidence safe-for-entry damage threshold has been defined by the OOIC. This threshold is the result of a parametric DAT analyses which defines a maximum tile damage length that can be confidently cleared as safe-for-entry. For STS-114, the OOIC was evaluated by the DAT analyses for an STS-114 flight specific set of parameters and yielded a damage length of two inches for windward acreage tile. Significant updates to the DAT analyses tools implemented since STS-114 will lead to a revised STS-121 OOIC for a generic International Space Station (ISS) mission profile, thus yielding an OOIC that can be applied to any future Shuttle missions to the ISS. Due to the implications the OOIC carries for the in-flight DAT process, and the criticality of an efficient DAT process the OOIC and DAT processes will be discussed more in the next section.

Tile Damage Assessment Flight Support Process

Individual tools from multiple disciplines are required to perform a re-entry TPS assessment. The uniqueness of a re-entry TPS assessment that must be performed during an Orbiter mission, in a response time which is appropriate with a flight, sets it significantly apart from the fashion in which the aerothermodynamic, TPS and stress communities typically perform. Development of the combined DAT analyses for performing tile damage assessment during a Shuttle mission timeline was a major undertaking by the SSP during RTF. Multiple organizations have been involved in the development and successful execution of this process. Principal technical support from the stress analyses community included individuals from NASA-Johnson Space Center, Boeing-Houston, Boeing-Huntington Beach, Boeing-Kennedy Space Center. Thermal analyses technical support has been mostly provided by Boeing-Houston and Boeing-Huntington Beach. Aeroheating community support has been provided by NASA-Johnson Space Center, NASA-Ames Research Center, NASA-Langley Research Center, Boeing-Houston, Boeing-Huntington Beach and Jacobs-Sverdrup in Houston. TPS community technical support is provided by the significant vehicle hardware team at Kennedy Space Center which includes NASA, Boeing and USA, as well as expertise from the NASA-Johnson Space Center. These organizations provide the technical expertise to execute the DAT analyses, and in order for this team of engineers to efficiently perform the tile damage assessment activity some of the team remains at their respective home organization locations, and most of the team consolidates their manpower in Houston during a Shuttle mission.

The DAT analyses, however, is only one piece of a large choreography of in-flight mission support and technical analyses that is required. Critical functions for the DAT analyses are performed by organizations outside of the TPS, aeroheating, thermal and stress communities. The Imagery Operations Team performs all technical assessments of digital still photography and on-orbit damage site scanning. The Orbiter crew executes pre-planned activities to examine the TPS with the Shuttle Remote Manipulator System (SRMS) equipped with special hardware designed to obtain detailed information while in orbit. This special hardware, referred to as the Orbiter Boom Survey System (OBSS), includes digital photographic and laser based systems capable of providing two or three dimensional data on sites of interest. The ISS crew performs a digital photographic scan of the Orbiter outer surface while it performs the Rendezvous Proximity Maneuver (RPM) as it approaches the Space Station. The Mission Operations team integrates all the on-going activities of the planned Orbiter mission, while also supporting the data exchanges between the Orbiter and ISS crew that occur to support the DAT process. Each one of these teams and organizations is critical to successfully executing a mission, and to successfully performing the DAT process. Emphasis on the large effort that is required across the entire mission support team is key to this discussion, because it makes reference to the large scope of activity required. However, the principal focus of this paper is to present the aeroheating analyses process which supports an Orbiter mission. Therefore, the rest of this section will provide an overview of the integrated tile damage assessment process which includes the aeroheating discipline.

The nominal DAT analyses process begins with the Orbiter crew initiation of the RPM maneuver. As mentioned previously, the ISS crew performs a digital photographic survey of the Orbiter outer surface while it performs this end over end flip on ISS approach. The RPM maneuver is designed to provide line of sight observations by the ISS crew for the majority of the Orbiter surface. This maneuver happens, approximately, on the third day into a Shuttle mission. Upon successful docking to the ISS, initial greetings and protocols, results of the digital photographic survey conducted by the ISS crew are downlinked to the waiting Imagery Operations Team (IOT). Upon receipt of that data, the IOT begins a painstaking survey of these images in order to identify regions of black tile which show exposed, white, tile substrate. The IOT compares any discrepancies that are identified with the On-Orbiter Imaging Criterion (OOIC) which was mentioned in the previous section. The IOT currently utilizes a generic two inch OOIC damage length criterion for acreage tile damage. Exceedance of the generic OOIC damage length criterion during the IOT survey then becomes the first threshold that is crossed in identifying tile damage. Any and all tile damage sites that exceed the generic OOIC are referred to the mission support DAT for further review. In addition, for STS-121, the IOT will also perform a detailed survey of all RPM images in order to identify the presence of any protruding gap fillers (PGFs). Any PGFs identified which exceed 0.25 inches are also referred to the DAT for further review.

Upon receipt of RPM survey data indicating tile damages which exceed the generic OOIC damage threshold, the DAT performs a more detailed review of the damage lengths provided by the IOT. Details of the DAT pre-flight analyses which supported the OOIC definition are utilized in order to provide a more detailed review of all IOT identified damage sites. The next major step in the DAT process is the identification of tile damage sites that exceed the detailed OOIC limits, baselining of the RPM survey length and width for internal DAT processes, and a prioritization of the damage sites for further detailed assessment with the OBSS hardware. In parallel to the DAT activity to prioritize the tile damage sites, the aeroheating community moves into execution of their first analyses supporting the DAT. For each damage site identified by the DAT for further review, the aeroheating team executes three activities. The nominal smooth baseline heating for each damage site must be specified, so the team performs a survey which identifies the most appropriate Orbiter Body Point (BPT) model. The second analyses utilizes the Wedge tool in order to evaluate if any specific damage site will be downstream of the turbulent zone of influence emanating from any upstream damage site or PGF. The third activity executed by the aeroheating team involves an assessment of BLT due to the tile damage cavity. The BLT tool is utilized to predict the transition time for each damage site based on a correlation which uses the IOT defined cavity length as an input. Based on this assessment, an initial recommendation of transition time is made by the BLT team for each damage site.

Once the DAT has prioritized the tile damage sites, a joint review is conducted with the Reinforced Carbon-Carbon (RCC) community in order to submit a combined list of prioritized sites for OBSS survey. This combined OBSS survey list potentially includes both RCC sites, tile damage sites, leeside damage sites, and/or PGFs. It is submitted to the Mission Operations team for planning of SRMS/OBSS activities the following day, the fourth day into a Shuttle mission. When the Orbiter crew designated for OBSS surveys wakes up from their sleep period on their fourth day in space, the OBSS survey details are ready for them to begin. Upon commencement of the OBSS survey, a highly detailed process of SRMS positioning, OBSS hardware selection and data collection begins. OBSS scan data is transmitted to the ground and relayed to the IOT. For the tile damage sites, the IOT generates detailed reports which specify the tiles affected at each damage site, a rigorous assessment of data quality and geometry uncertainty, as well as locations for digital files which provide a three dimension cloud of data, referred to as a point cloud, which specifies the geometry of each damage site. Upon delivery of this report and the associated point cloud, the DAT begins its second phase of OBSS based tile damage assessment. This second phase involves detailed assessments by the aeroheating, thermal and stress communities, and involves a twenty-four hour around the clock effort to disposition each damage site.

The point cloud provides the geometry details required for the DAT analyses process by defining the damage geometry at each site. Although back up processes are in place which can utilize data from sources other than the point cloud, this is the preferred technique for geometry definition. The DAT utilizes the point cloud to generate a CAD description of the damage site, and an associated simplified cavity. The simplified cavity does not include all the geometry variations of a damage site, instead it is meant to portray a representative definition of the geometry which is adequate for the intended DAT analyses. Each damage site is investigated by a joint aeroheating/thermal/stress team supported by experienced CAD personnel who have generated hundreds of simplified cavities based on tile array impact testing. The simplified cavity representation includes the definition of a uniform depth, an angle representing the entrance into the damage site, an angle representing the exit from the site, as well as angles for each of the other two sides of a six-sided non-symmetric volume. Once this team develops simplified cavity representations for several damage sites, an integrated DAT review is conducted to approve the specifications for each simplified cavity. Once the specifications of the simplified cavity have been defined by the DAT, the combined areoheating/thermal/stress community begins their detailed analyses.

Inputs to the DAT analyses which have been defined at this point in the process include the Cartesian location of the damage site in Orbiter coordinates, the BPT for nominal reference heating, and the simplified cavity. Before the thermal community can execute the integrated aeroheating/thermal 3D-TMM, the BLT tool is utilized to make a final recommendation of transition time to use for each damage site. Influence due to PGFs or upstream damage sites is accounted for, and a BLT time is selected from the pre-flight established transition times. The default transition time utilized, in the event that nothing leads to the prediction of an earlier time of transition, corresponds to approximately Mach 15. With the definition of a BLT time, the 3D-TMM execution can begin with the other details established by the DAT. Because the 3D-TMM involves an integrated aeroheating/thermal analyses, upon completion of a 3D-TMM run for a specific damage site, quality assurance steps are undertaken by both the thermal and aeroheating communities to ensure that the analyses is adequate. In particular, the aeroheating community examines outputs from the Cavity Heating tool to ensure that the engineering correlations which support the cavity heating environment definition remain within valid envelopes. Included as part of the 3D-TMM execution is an assessment of the Tile/RTV bond margin, thus after the execution of the 3D-TMM several figures of merit are available to assess a damage site. The tile surface temperatures are checked to determine if multiple mission or single mission surface temperatures are exceeded, the RTV material temperatures are queried to establish if they have exceeded a multiple mission threshold, the Tile/RTV bond stress margins are reviewed and the structural temperatures are examined. A table summarizing each of these figures of merit, as well as the pending structural margin assessments, is tracked within the DAT to monitor the progress of integrated process. Once the 3D-TMM is given approval by the aeroheating and thermal analyses experts, the results are forwarded to the DAT for inclusion in the summary table and to the stress analyses community. At this point, the stress analyses community performs a detailed assessment of the structural margins and factors of safety in order to evaluate the integrity of the vehicle for a safe re-entry.

Another activity that begins with the DAT baselining of the simplified cavity definition, is the Rapid Assessment CFD process. For STS-121, this process has been staged such that two tile damage sites will be examined in an 18-hour allotted time. Prioritization of the tile damage sites is performed by the aeroheating team in order to identify the two damage sites to perform a second tier aeroheating environment analyses. A recommendation from the aeroheating team is made to the DAT for final approval before the CFD experts positioned off-site at NASA-ARC and NASA-LaRC begin their analyses. The eighteen hour allotted time is meant to coincide with an expectation of when the nominal aeroheating/thermal/stress assessment is completed. Upon delivery of the Rapid Assessment CFD results which compare the Cavity Heating tool environments to the CFD environments in the cavity site, the aeroheating team reviews the results and provides a recommendation to the DAT on the adequacy of the Cavity Heating tool results.

Upon completion of the entire DAT process involving the aeroheating, thermal and stress communities, the DAT reviews the combined results of the damage site assessments in order to provide a recommendation to the Orbiter Project and the Mission Management Team (MMT). The substance of this recommendation is a review of the figures of merit for each damage site, and a recommendation of whether the damage site can be dispositioned as safe for entry. The elapsed time between the delivery of OBSS point clouds to the DAT and the submittal of this recommendation is intended to be approximately twenty four hours. Upon receipt of this recommendation, the MMT reviews the available information on ISS hardware system performance and Orbiter hardware performance, and reviews the DAT recommendations from both the Tile and RCC assessments developed utilizing OBSS data. If a recommendation coming from the DAT and confirmed by the Orbiter Project is that the vehicle is not safe for entry, then the MMT must consider its options and balance the various risks of unprepared re-entry (e.g. use-as-is), repair or safe-haven. In order to provide some perspective on the current TPS repair systems being pursued by the SSP, information will be provided in the next section reviewing the four repair systems currently being planned for inclusion on STS-121.

Orbiter Thermal Protection System Repair

The Columbia accident, loss of its crew and the activities of the Columbia Accident Investigation Board (CAIB) have led to significant changes in the way we approach the Space Shuttle. As individuals we have a newfound awareness of the very real dangers of manned spaceflight and the personal dedication needed to ensure safe missions. As engineers we strive to utilize the available methods and techniques to provide a more accurate characterization of the details associated with re-entry. As advocates of manned spaceflight, we must recognize the benefits to continuing this human adventure as well as the risks that are associated with it. It is against this background that recommendations from the CAIB are taken by the aeroheating community that supports the Orbiter Project. A significant fraction of the United States aerothermodynamics community was involved in the CAIB effort, and the motivation to do everything within our means to avoid a similar accident during a future Shuttle mission is high. For this reason and others, the Orbiter aeroheating community has also been involved in responding to the CAIB recommendation to develop TPS repair capability, in addition to the efforts which have led to the damage assessment capabilities which are described in this work. Since the Columbia accident and the recommendation from the CAIB to develop TPS repair capabilities, the SSP has been involved in an extremely challenging and difficult activity to implement contingency repair capabilities for damage to the TPS. Leading up to STS-121, there are four TPS repair systems being prepared for flight. Two for tile repair and two for RCC repair.

Although the tile system is not required to experience the same temperature environment on re-entry as the nose cap or wing leading edge RCC systems, it is an essential component of the TPS. As demonstrated during STS-107, compromising the integrity of the TPS system can lead to catastrophic results. And although the tile system itself does not experience surface temperatures as high as the RCC, the extreme temperatures within the shock layer of the Orbiter windward surface are only inches away. Critical damage to any TPS system can be characterized by three categories. The first category involves localized damage which by itself does not generate a catastrophic situation, but instead may generate a series of significant damage propagation which leads to an unsafe situation. The second category also involves localized damage which by itself does not generate a catastrophic situation, but requires only minimal damage propagation before leading to an unsafe situation. The third category of damage is severe enough that by its very nature it presents an unsafe situation. Examples of this third category would involve an incident like what happened on the STS-107 mission, or damage which has resulted in a penetration of the TPS system and outer skin of the Orbiter. Current tile repair options intended to fly on STS-121 involve a surface emittance enhancer referred to as an Emittance Wash, and a thin shell outer surface barrier referred to as a Tile Overlay. The Emittance Wash is an RTV based material with SiC particulate in it to serve as an emittance enhancer. The concept of Emittance Wash repair involves coating the tile substrate at a damage site in order to re-establish the high emittance characteristic of the black RCG coated tile. By design, this repair does not add any significant TPS thickness, it only raises the surface emittance. Thus, the Emittance wash repair would fall into the first category of repair identified above. The Tile Overlay is a thin Silicon Carbide plate with a gasket and multiple self-tapping fasteners. The concept involves orientation of the thin plate on a damage site, after placement of fibrous insulation into the tile cavity, and rotation of the self-tapping screws into undamaged tile around the damage site. Because this repair has the potential to restore the basic functionality of the tile, it is placed in the second category of repair. In regard to tile repair for the third category of damage, it is plausible that the Tile Overlay could work in a severe damage situation. However, significant risk would exist in its utilization for a damage in the most severe category.

Repairs for the RCC system on the Orbiter must withstand the extreme temperatures which require the use of RCC. Significant difficulties due to the nominal temperatures encountered in the nose cap and shock-shock interaction regions during the DDT&E activities for the two RCC repair systems currently being pursued. Both of the RCC repair concepts are analogous to the those for tile repair. A repair system which is applicable to the first category of damage, Crack Repair, utilizes an on-orbit curing material which essentially restores the surface integrity of the RCC. During re-entry, the Crack Repair material converts to a Silica based matrix which essentially serves as an oxidation barrier for the RCC substrate which is exposed at an RCC damage site. This repair method has been shown to show acceptable performance for small coating loss and/or small cracks. The second RCC repair system, Plug Repair, involves an approximately seven inch diameter, circular, thin Carbon Silicon Carbide (C-SiC) plate with a toggle bolt design to serve as a fastener. Repair operations with the Plug Repair would nominally involve positioning of the toggle bolt in the center of a penetration in the RCC, application of torque to the exposed head of a mechanism designed to draw the toggle bolt in, torquing of the bolt to a specified level to achieve as small a gap as possible at the interface of the C-SiC to the RCC, and subsequent application of the Crack Repair material to the perimeter of the Plug Repair in order to prevent flow underneath the repair. The Plug Repair system can be applied to the second category of damage described above, and potentially the third as well.

Various levels of confidence have been established for each of these four repair concepts. For Tile Repair, utilization of the Emittance Wash repair has a fairly high confidence. In addition, re-entry assessment analyses are positioned as part of the DAT process to determine if a repair of this type can provide sufficient improvement in vehicle safety to re-enter in an otherwise unsafe situation. However, due to its ability to only restore the surface emittance characteristic of the tile, and not return the overall insulation of the tile, its benefit is only incremental. The Tile Overlay system, although it shows potential for being applicable to more severe tile damage situations, is of the lowest maturity of any of the four repair concepts described. In addition, due to the complex issues being worked through and the need to establish as much capability for repair as possible, the Tile Overlay is currently only being developed for application to flat regions of the windward surface which do not include thermal barriers. Follow-on activities have been defined which could extend applicability of the Tile Overlay to curved regions and/or thermal barrier regions, but emphasis at this time is being placed on resolving the significant technical issues with its utilization in flat regions. The Crack Repair system for RCC damage has shown demonstrable capability for small RCC damage, thus it is only an incremental capability. Although analogous to the Emittance Wash, the analytical tools and testing basis for Crack Repair is not as mature as for Emittance Wash. Plug Repair is the only capability still being pursued for more sever RCC damage, and significant confidence has been developed for the extreme temperature conditions that it will encounter during re-entry. However, this repair system is currently limited in its coverage due to the variable curvature of the wing leading edge, the availability of only a limited number of plugs tailored to different curvatures, interference of the toggle bolt hardware with hardware beneath the RCC, and limits on the ability of a seven inch outer diameter to provide overlap in regions of hardware interference. In spite of the limitations and relative immaturity of these repair concepts in comparison to full rigor spaceflight hardware, the capabilities provided by these four potential repair concepts are significant. The repair teams that have developed these capabilities, with support from communities well beyond just the hypersonic aerothermodynamic community, have accomplished a feat that some thought was not possible when the CAIB issued their recommendation.

Summary

The Columbia accident,

Acknowledgements

The Columbia accident,