Boundary Layer Transition Results From STS-114

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Abstract

The tool for predicting the onset of boundary layer transition from damage to and/or repair of the thermal protection system developed in support of Shuttle Return to Flight is compared to the STS-114 flight results. The Boundary Layer Transition (BLT) Tool is part of a suite of tools that analyze the aerothermodynamic environment of the local thermal protection system to allow informed disposition of damage for making recommendations to fly as is or to repair. Using mission specific trajectory information and details of each damage site or repair, the expected time of transition onset is predicted to help determine the proper aerothermodynamic environment to use in the subsequent thermal and stress analysis of the local structure. The boundary layer transition criteria utilized for the tool was developed from ground-based measurements to account for the effect of both protuberances and cavities and has been calibrated against flight data. Computed local boundary layer edge conditions provided the means to correlate the experimental results and then to extrapolate to flight. During STS-114, the BLT Tool was utilized and was part of the decision making process to perform an extravehicular activity to remove the large gap fillers. The role of the BLT Tool during this mission, along with the supporting information that was acquired for the on-orbit analysis, is reviewed. Once the large gap fillers were removed, all remaining damage sites were cleared for reentry as is. Post-flight analysis of the transition onset time revealed excellent agreement with BLT Tool predictions.

Nomenclature

C	empirical curve coefficient
M	Mach number
Re	unit Reynolds number (1/ft)
Re_L	length Reynolds number based on L
p	pressure (psi)
T	temperature (°R)
x	longitudinal distance from the nose (in)
L_{Ref}	model reference length from nose to body-flap hinge line (9.7 in)
k	roughness element height (in)
K_{EQ}	equivalent roughness height from distributed TPS steps and gaps (in)
x, y, z	Shuttle coordinate system (in)
L,W,D	cavity dimensions, length, width, and depth (in)
α	model angle of attack (deg)
δ	boundary layer thickness (in)
θ	momentum thickness (in)

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Re_θ	momentum thickness Reynolds number

Subscripts

∞	freestream static conditions
t1	reservoir conditions
t2	stagnation conditions behind normal shock
e	local edge condition
aw	adiabatic wall
w	model surface
tr	transition onset
inc	incipient
eff	effective

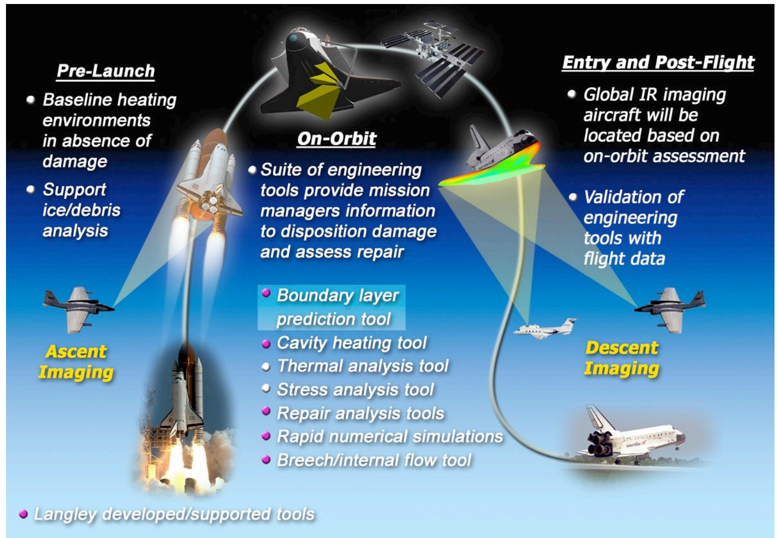


Figure 1. Aerothermal mission support tools developed for the RTF damage assessment process

Introduction

New analytic (engineering based) tools were developed to evaluate Shuttle Orbiter thermal protection system (TPS) damage in concert with a new capability to conduct "on-orbit inspections and repair, when indicated," as recommended by the Columbia Accident Investigation Board's (CAIB) final report[1]. Figure 1 provides a graphic showing the damage assessment capability and new tools[2] developed for the first Shuttle Return to Flight (RTF) mission, STS-114. Several engineering teams independently developed, matured, and certified their tools for use by the Shuttle program in the time between the initiation of the RTF effort in December 2003 and STS-114 launch in July 2005. Collectively, these tools allow informed decisions to be made of TPS damage and whether the vehicle is safe to fly as is or to repair.

One of the initial tools in the TPS damage analysis process is the boundary layer transition (BLT) Tool[3], which was developed for predicting transition onset, thus establishing the proper heating environment (either laminar or turbulent) to use with the subsequent analyses listed in Fig. 1. Using mission specific entry trajectory data (altitude, velocity, angle of attack, yaw, air density, air temperature, etc.), the BLT Tool determines the local boundary layer parameters at each critical damage site and thus the predicted time of transition onset based on the developed BLT empirical correlations. The program is a Fortran code and can be run on most computer systems. The experimental database used to develop the empirical correlations for the tool was based on simplified tripping elements and cavities on scaled wind tunnel models.[4] Computational solutions at both wind tunnel and flight conditions were generated to develop the BLT correlation and then extrapolate to flight.[5] The tool incorporates a database of computed boundary layer parameters that cover a range of nominal trajectories for entry and utilizes an interpolation scheme to extract specific local properties for determining the boundary layer transition onset during the entry trajectory from the observed damage and/or repair locations and geometries. Calibration of the BLT Tool has been carried out by comparison of predicted transition results to several of the historical high Mach number flight cases.[6] Due to the limited scope of the historical flight data, in particular the lack of detailed cavity and gap filler information prior to entry into the earth's atmosphere, a larger uncertainty has been placed on this process until detailed and calibrated results are obtained in up-coming flights.

The present paper provides a description of the use of the BLT Tool in support of RTF and a post-flight analysis of the STS-114 data as direct feedback for tool calibration, and is intended as part of a series of six papers on boundary layer transition research for RTF. The following five references are the companion papers. Reference 2 provides an overview of the new tools brought on line in support of the aeroheating analysis for RTF. Reference 3 provides an overview of the integrated effort that was involved with developing and certifying a BLT correlation methodology for estimating transition onset for the Orbiter windward surface on entry. Reference 4 describes the experimental database that was obtained to support BLT Tool development for RTF. Reference 5 discusses the boundary layer properties interpolation tool developed for both the BLT and Cavity Heating Teams. And lastly, Ref. 6 reviews some of the historical Orbiter flight data utilized to calibrate the BLT Tool.

BLT Tool Overview

The BLT Tool predicts transition onset on the windward surface during entry and was newly developed in support of RTF. BLT prediction is based on mission specific trajectory and damage/repair (either cavity or protuberance) information that allows informed disposition of the damage sites. The BLT criteria utilized for the tool were developed from ground-based measurements to account for the effect of both protuberances and cavities (see Ref. 4) and have been partially calibrated against flight data. Using computed boundary layer edge conditions to correlate the results, specifically the momentum thickness Reynolds number over the edge Mach number and the boundary layer thickness, curve coefficients (C) of 27, 100, and 900 were adopted to conservatively predict transition onset for protuberances based on height, and cavities based on depth and length, respectively (see Ref. 3). The output of the tool is a determination of the predicted transition onset times for each damage site, which then allows selection of one of the pre-flight developed aeroheating environments for use with the subsequent analyses (see Ref. 2). The current tool provides mission support not previously captured by the original K_{EQ} roughness criteria[7].

The BLT Tool can be used pre-launch to assess flight trajectories with nominal roughness, in orbit to assist in damage disposition analysis, and for entry to predict transition onset times for locating airborne infrared (IR) measurement assets (for instance NASA WB-57 aircraft to be discussed subsequently).

The Fortran program requires mission entry trajectory data (altitude, velocity, angle of attack, yaw, air density, air temperature, etc.) and damage site locations and dimensions to determine the local boundary layer parameters used for predicting transition onset for each damage site. A companion tool, called the wedge tool (described in Ref. 6), is used to predict the zone of influence behind each damage/repair site, thus providing any potential interactions between the various damage sites.

The BLT Tool is intended for use on the windward surface only. The computational approach is presently limited to between Mach 6 and 20 (see Ref. 5) and the database for flight is additionally limited to the angle of attack bounds identified in the Shuttle Operational Data Book. The use of this tool outside of these limits is not advised. The present boundary layer transition methodology is based on scaled wind tunnel models and has only been partially compared to flight data with the highest Mach number at the time of transition onset of 18. Due to the limited scope of the historical flight data in regards to detailed cavity and gap filler information prior to entry, a larger uncertainty should be placed on this process until detailed and calibrated results are obtained in up-coming flights.

Mission Support

Launch

Space Shuttle Discovery launched from NASA's Kennedy Space Center on July 26, 2005, shown in Fig. 2, ending a two-and-a-half year wait for the historic return to flight mission. During this test mission, a variety of goals were accomplished while also learning some important lessons. For instance, a large piece of insulating foam broke off the External Tank (ET) during ascent providing an indication of the difficulties associated with the elimination of debris sources. The first of two Return-to-Flight missions, STS-114 included new on-orbit maneuvers, tests of new equipment and procedures, and a first-of-its-kind spacewalking repair of the TPS. Using the new Orbiter Boom Sensor System (OBSS), unprecedented up-close inspections of the TPS were acquired. The OBSS is comprised of a set of instruments, including video and a Laser Dynamic Range Imager, on a 50-ft extension attached to the

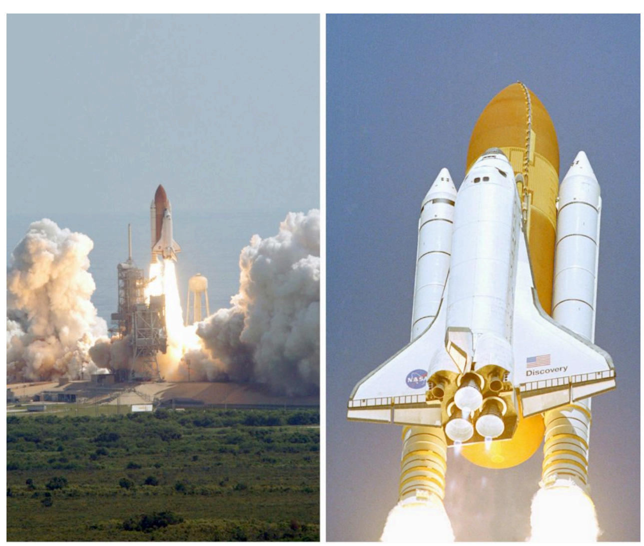


Figure 2. Launch of Discovery on July 26, 2005 during STS-114

Remote Manipulator System. The collection of new data included, on flight day three, the first-ever "rendezvous pitch maneuver" (RPM) as the orbiter approached the International Space Station (ISS) for docking.

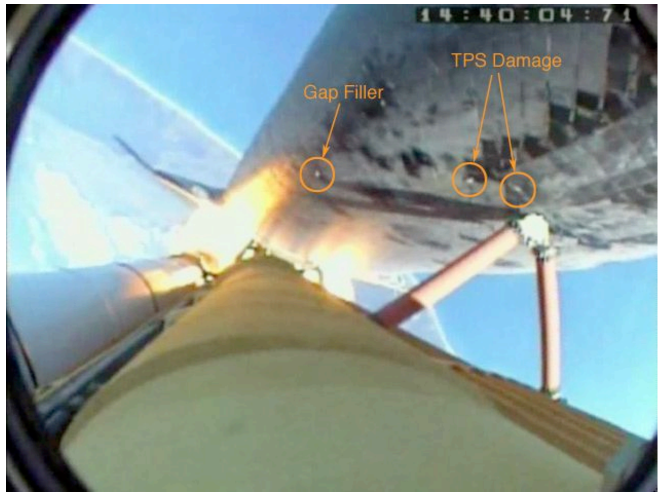


Figure 3. View from new ET camera during launch of Discovery during STS-114 on July 26, 2005

Debris shedding from the ET during launch was the programs principal concern and much work was completed in preparation for this mission to improve launch imaging. In fact, the RTF requirement to only launch during daylight hours was to increase visibility for imaging.[1] The ground-based long-range cameras were all improved and fine-tuned, NASA airborne assets (WB-57) were added, and new video systems were installed on-board the ET. The video feed from the ET showing the underside of the vehicle captured the dramatic and alarming large debris separation mentioned earlier (which contributed to the decision to delay the next RTF mission, STS-121). Also the new ET camera provided an early indication of windward surface damage to the TPS (an image captured from the video is shown in Fig. 3), although it was not clear during the launch if the white spots observed on the TPS were due to tile damage or protruding gap fillers. Post-launch assessments have since identified that the circled white spot near the center of the image is one of the gap fillers that will be identified during the RPM. The video shows that this gap filler was forced out during launch, perhaps due to the high acoustic loading (vibrations) during lift-off or the high dynamic loading (drag) that occurs approximately one minute after lift-off. Also, the image shown in Fig. 3 indicates the specific time (2 minutes, 5.71 seconds after liftoff) that the damage site on the nose landing gear door formed. The left circle (of the two marked as TPS Damage) is tile material debris just after liberation from the surface (gone in the next image of the video) and the resultant cavity left behind on the door is within the circle to the right. While the ET continues to be the primary debris source of concern as the program gets ready for the next mission, clearly other debris sources such tile or gap filler material from the Orbiter, should also be considered.

<u>Rendezvous Pitch Maneuver</u>

On Flight Day 3, a new procedure to acquire high-resolution images of the Orbiter to assess the state of the TPS after launch was performed. After the initial approach to the Station, Discovery performed a slow pitch about the lateral axis while astronauts on-board ISS took photographs with high-resolution cameras (an example is shown in Fig. 4). The pictures were then transmitted to the Damage Assessment Team (DAT) on the ground for processing and analysis. Locations were determined from the tile layout and the dimensions were estimated, as indicated in Fig. 5 for the primary TPS damage sites for STS-114. The naming convention shown identifies each damage site by the TPS zone number in which it resides, along with a sequential number based on the number of damages within each zone. Figure 4 also includes two inset photographs of the protruding gap fillers identified during the RPM. The green markers shown in Fig. 5 identify the damage sites that were found to be less than the 2-in criteria (and thus too small to be a concern), while the red and orange locations indicate the sites with

Figure 4. Gap fillers identified from RPM images

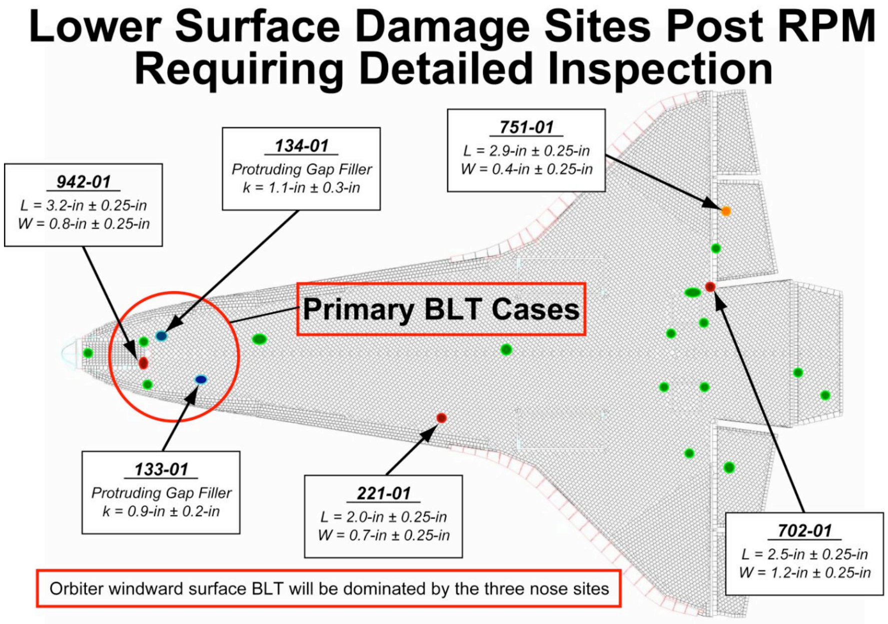


Figure 5. Damage sites identified from the RPM

dimensions greater than the 2-in, thus requiring further inspection using the OBSS laser scanning system[2]. The blue symbols indicate the gap filler sites that were also requested to be further imaged during the focused inspection process. The three identified sites circled near the nose were expected to be the biggest concerns, from a BLT perspective, due to both the location and size of the damage.

The aerothermal analysis process starts with the BLT assessment when the damage site information, from the DAT review of the RPM photographs, is released near the end of the third day. Note the relatively large uncertainty associated with estimating the damage dimensions using long-range photographs, as indicated in Fig. 5. The large uncertainty combined with the fact that no cavity depth information is provided by the RPM photos provides support for the request for detailed OBSS scan data. The OBSS attached to the end of Discovery's robotic arm carried out a survey of select areas of the TPS near the end of flight day 4. Table 1 provides a comparison of the estimated dimensions from the RPM analysis to the more accurate OBSS results (and then finally to the measurements made after landing, if available) for the primary damage sites shown in Fig. 5. The original uncertainty associated with the RPM estimates were greatly reduced by the scans of the cavity sites, however the gap filler scans by the OBSS proved inconclusive. As will be seen in the next section the large uncertainty associated with the gap filler protrusion height estimates had a significant impact on the eventual uncertainty associated with the BLT Tool prediction times (and ultimately on the decision to remove them).

Table 1. Comparison of key damage site dimensions from multiple sources

Damage Site	Location (in)	RPM Estimate (in)	OBSS Scan (in)	Ground Measurement (in)
942-01	X = 378.9 Y = 13.6 Z = 285.9	L = 3.2 ± 0.25 W = 0.8 ± 0.25	L = 3.07 ± 0.06 W = 0.72 ± 0.04 D = 0.33 ± 0.04	L = 3.07 W = 0.71 D = 0.30
221-01	X = 860.6 Y = 124.4 Z = 284.6	L = 2.0 ± 0.25 W = 0.7 ± 0.25	L = 2.20 ± 0.04 W = 0.85 ± 0.04 D = 0.27 ± 0.04	L = 2.0 W = 0.8 D = 0.4
702-01	X = 1377.2 Y = -125.4 Z = 268.76	L = 2.5 ± 0.25 W = 0.4 ± 0.25	L = 2.39 ± 0.06 W = 1.37 ± 0.05 D = 0.19 ± 0.04	L = 3.0 W = 0.5 D = 0.03
751-01	X = 1405.3 Y = -253.9 Z = 282.8	L = 2.9 ± 0.25 W = 0.4 ± 0.25	N/A	L = 3.5 W = 0.25 D = 0.1
134-01	X = 408.0 Y = -25.4 Z = 284.1	k = 1.1 ± 0.3	Scan inconclusive	Removed in orbit
134-01	X = 475.9 Y = 59.4 Z = 285.3	k = 0.9 ± 0.2	Scan inconclusive	Removed in orbit

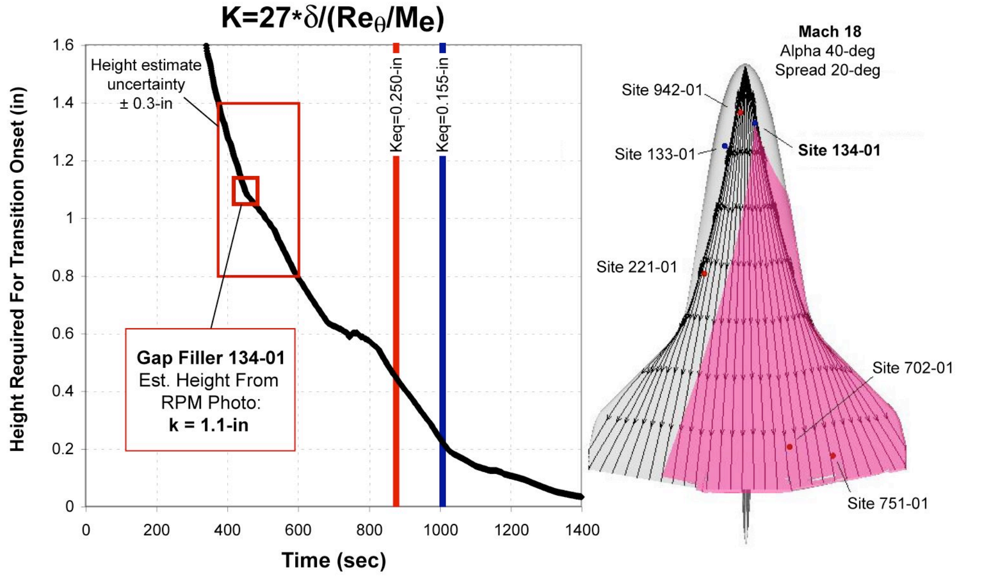


Figure 6. BLT assessment for gap filler 134-01

BLT Analysis

The aerothermal analysis, which was initiated on flight day 3, was required to be complete by flight day 6 for final review by the Mission Management Team (MMT). Accounting for the time necessary to double check results and develop charts, the initial entire aerothermal assessment needed to be conducted within about 24 hours. The following is the BLT analysis conducted in support of this process on the primary sites identified by the DAT and shown in Fig. 5. The turbulent wedge spreading results[6] shown in the subsequent figures are based on a 10-deg half angle spreading on the surface streamlines from a 40-deg angle-of-attack solution that conservatively shows potential downstream influence to other damage sites. BLT Tool output is plotted to show the critical dimension (height, length, or depth) predicted to cause transition onset for each site of interest as a function of time along the entry trajectory. The estimated damage dimensions, including uncertainties, are located on the calculated allowable roughness dimension threshold to determine the time, and therefore the freestream Mach number, at which transition onset is predicted to occur. Also shown on the BLT output plot are the times corresponding to K_{eq} (see Ref. 7) values of 0.250-in (red line representing a Mach 18 transition) and 0.155-in (blue line representing Mach 15 transition), which are the standard times of transition used pre-flight to generate the aeroheating environments for each mission. Note that based on a combination of the computational approach (discussed in Ref. 3) adopted for the BLT Tool and the range of calibration flight cases, any transition times earlier than ~800s (Mach 20) is beyond the accepted range of the BLT Tool. At the time of the tool development this limit seemed acceptable as the earliest transition Mach number previously was below 19 (STS-28 and 73).

For gap filler 134-01 (shown in Fig. 6), the location was found to be just within the portside attachment line (indicated by the outboard limit of the streamlines shown) such that the downstream influence of transition would be felt asymmetrically over a large portion of the windward surface and the wing leading edge on the port side. Most importantly, the estimated height of this gap filler protrusion exceeded the previous worst-case protrusion (which was based on a post-flight measurement only) by nearly a factor of two. Based on the output from the BLT Tool, this height and location corresponds to a very early transition time, roughly 450s (~Mach 25) with an uncertainty band (based on the uncertainty in the height estimation, ±0.3-in, from the RPM photos) of roughly ±75s. As mentioned previously, transition this early is outside the accepted limit for the tool, requiring extrapolation beyond both the computational and calibration ranges of the tool. The impact of this will be further discussed in a subsequent section. Note that the wedge tool shows that gap filler 134-01 will influence damage sites 702-01 and 751-01, and the analysis of these two sites had to account for these early transition onset times in the event that the gap fillers were left as is (eventually the decision was made to remove the gap fillers, also to be discussed subsequently).

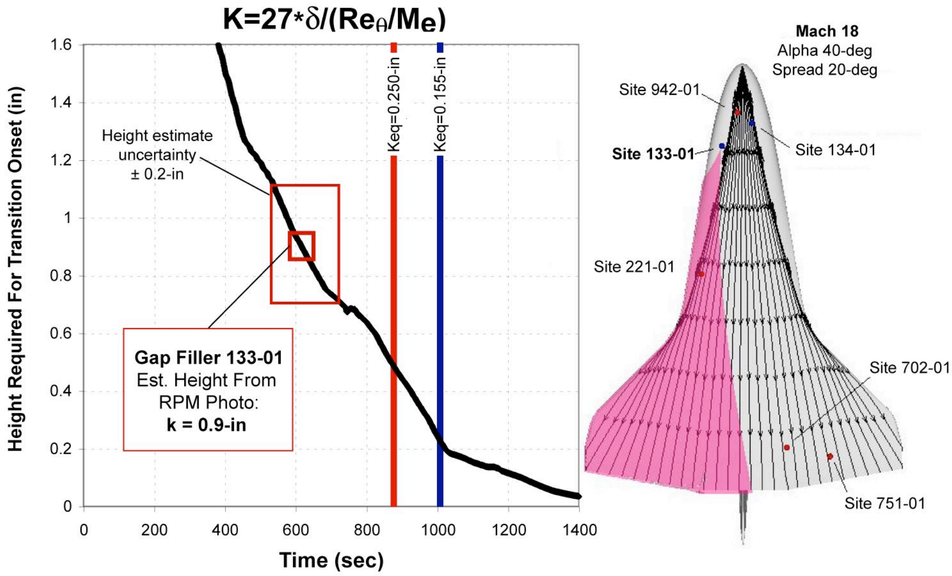


Figure 7. BLT assessment for gap filler 133-01

For gap filler 133-01 (shown in Fig. 7), the location was found to be just outside the starboard attachment line, and that based on the conservative estimate of 10-deg of turbulent spreading the downstream impact of transition would be felt asymmetrically over roughly the other half of the windward surface and the wing leading edge on the starboard side. Further analysis of turbulent spreading lead to the conclusion that if the wedge half-angle was less than 7.5-deg (which is considered nominal for flight) then the turbulent wedge would likely not spread back within the attachment line, thereby having no effect on the windward surface or the wing leading edge. However, this gap filler protrusion was also estimated to be nearly as large as 134-01, again nearly double the previous worst-case protrusion. The initial output from the BLT Tool indicates that this height and location also corresponds to a very early transition time, roughly 600s (Mach 24) with an uncertainty based on the height estimation uncertainty only of roughly ±75s. This transition time is again outside the accepted range for the tool. Note that the wedge tool results shows that gap filler 133-01 will influence damage sites 221-01, and the subsequent analysis had to account for potential for an early transition onset time.

As mentioned previously, both gap fillers were scanned with the OBSS in hopes of reducing both the height and the estimation uncertainty. Unfortunately, the gap filler scan results were inconclusive, so the initial prediction of onset time could not be updated. An assessment of the reliability of these early transition predictions was conducted with a critical eye towards the degree of extrapolation. The existing high Mach number flight data used to calibrate the tool were reexamined in hopes of identifying any method to quantify the level of uncertainty with the present results being so far beyond the tool's range. An adjustment to the accepted calibration constant, based on the notion that the original STS-73 data had been misinterpreted provided a means to alter the predicted transition onset times to 745s (~Mach 22) and 790 (~Mach 21) for 134-01 and 133-01, respectively (however with still a large uncertainty band ±Mach 2.5). The previous evaluation of STS-73 was based on the gap filler height measured on the runway, which was bent over such that the total height above the surface was 0.6-in, while when straightened the gap filler was 1.4-in high. Using the unbent height along with the transition onset time for that flight provided an alternate calibration curve coefficient (C=50), which resulted in the adjustment to the predicted transition time. Also, independent experts were consulted during the mission for outside opinions on these early transition time predictions from the BLT Tool. Unfortunately, all independent assessments came back with roughly the same order-of-magnitude estimate for transition onset, providing a sanity check but little relief to the perceived conservatism of the BLT Tool. A flight history review reveals that many gap fillers have been noted as bent over on the runway based on the post-flight inspections. A spirited and healthy debate occurred over whether gap fillers this large might bend over or burn away early in the trajectory, thus reducing the protrusion height, and the transition Mach number, down towards the historical limit. Unfortunately, a structural assessment of the gap filler material response under aeroheating loads was not available during the mission to support or dismiss this speculation.

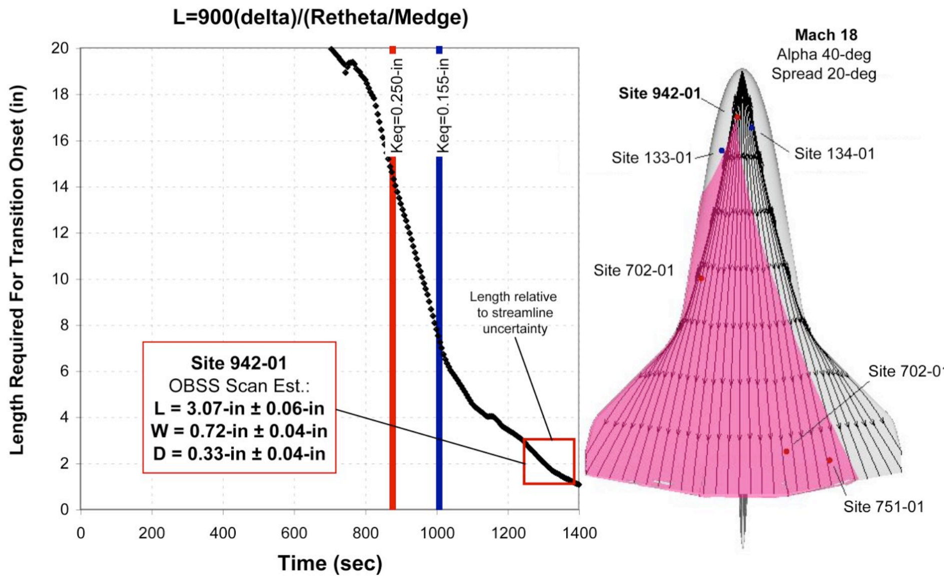


Figure 8a. BLT assessment for cavity site 942-01 based on length

The BLT Team also investigated damage site 942-01 during the mission, due its relatively large size and far-forward location. A comparison of the lengths and widths listed for each cavity identified in Fig. 5 distinguishes 942-01 as one of the larger cavities. The location on the nose landing gear door, which was just inside of the starboard attachment line (as identified in the turbulent wedge plot shown in Fig. 8a) provided the potential to affect a large portion of the windward surface. The initial RPM estimate, listed in Table 1, provided length (3.2 in) and width (0.8 in) only. Based on the initial length estimate only, a transition time of 1225s was predicted. When the new OBSS scan updates became available and the length was reduced to 3.07 in, the transition onset time prediction was modified to 1240s. Also, OBSS provides the additional dimension not previously available, the depth. Based on the depth of 0.33 in, a predicted transition onset time of 1245s was obtained. Thus, if the gap fillers are removed, the predicted transition onset time would be relatively close to the nominal transition times for this vehicle (~Mach 8) based on the last damage site (known about during the mission) near the nose, site 942-01. Note that based on the BLT Tool output for 942-01, the length or depth required to predict transition onset near Mach 18 (the red K_{EQ} line) is approximately 14 and 1.6 inches, respectively.

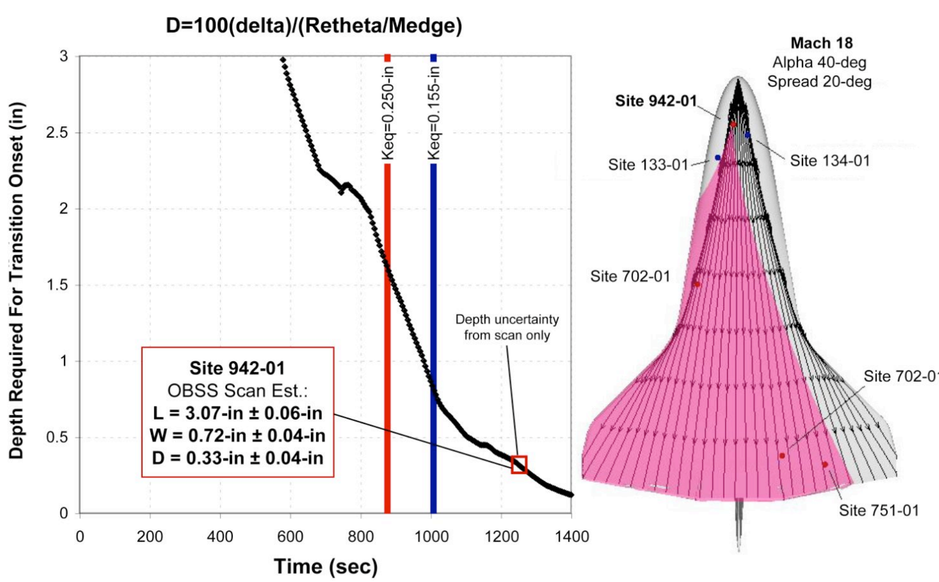


Figure 8b. BLT assessment for cavity site 942-01 based on depth

Extravehicular Activity

Based upon the cascade of uncertainties associated with the suite of analytic tools (BLT, thermal, and structural, etc.) for both the windward acreage tiles and the wing leading edge RCC panels, the decision was made by the MMT to utilize the ISS robotic arm to locate an astronaut near the gap fillers for removal during extravehicular activity (EVA) #3. The decision to attempt a repair was made easier by a well thought out operational plan that provided assurance that any safety concerns were minimized. Prior planning and forethought on how to secure an astronaut to the boom and the dynamics of moving a relatively large object around, and in close proximity to, the lower surface of the Orbiter alleviated most MMT concerns. Figure 9 shows photographs from this unprecedented EVA repair, in which Steve Robinson was able to easily and safely pull out both gap fillers.

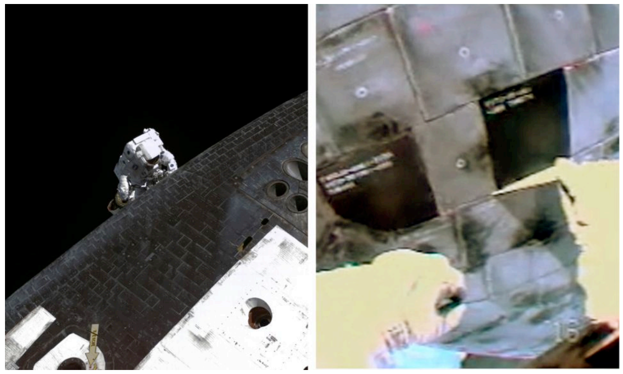


Figure 9. Removal of protruding gap fillers during EVA 3

During the discussion leading up to the decision to repair or not, some concern was raised about what if the gap fillers do not come out very easily. A back-up plan to utilize a makeshift hand saw to cut the gap filler down to the surface was adopted. The BLT Tool output was utilized to recommend the maximum height at which transition would occur no earlier than Mach 18 (0.4 in., see Figs. 6 and 7 for the height corresponding to the red K_{eq} = 0.250-in line). As it turned out, Steve Robinson had no trouble removing the gap fillers by hand, at one point mentioning that it took less than a pound and half of force to pull one of them out. As the gap fillers were being removed, red adhesive, which is supposed to be along the bottom edge of the gap fillers, could be seen smeared across the side. Having the adhesive along the side of the gap filler, with repeated exposures to higher temperatures, could compromise bonding integrity.

Entry IR

To supplement the limited number of discrete instrumentation on Orbiter Vehicle (OV)-103 (to be discussed subsequently), high altitude aircraft equipped with long range infrared (IR) imaging systems were to be used to obtain global aeroheating images during entry, hopefully near the time of transition. Previous attempts at imaging the Shuttle windward surface using IR had been attempted, initially using aircraft (STS-3)[8] and then ground-based systems (STS-96[9] and STS-103[10]). The current attempt was to take advantage of existing airborne assets to fly above the weather (mainly humidity) and minimize the slant range between the imaging system and the Orbiter. As depicted in Fig. 10, the two NASA WB-57 Ascent Video Experiment (WAVE) aircraft used during launch and a Missile Defense Agency Gulfstream II, referred to as HALO (High Altitude Observatory), aircraft were placed along the ground path at key points in the trajectory. The WB-57 is able to fly at an altitude of 60 kft., while the HALO flies at 48 kft. Based upon the BLT analysis of transition onset once the two large gap fillers were removed, transition was expected to be fairly nominal. The three aircraft were staged at Mach 7, 9, and 11, initially, in hopes of capturing an image showing a turbulent wedge (thus providing confirmation of the turbulent spreading angle and a direct indication of the source). Unfortunately due to weather concerns at the runway, reentry was waved off a total of 4 times over two days for landing at KSC until the final divert to Edwards Air Force Base in California. Naturally, the aircraft were not able to relocate in time to acquire these important images during the early morning landing on the west coast.

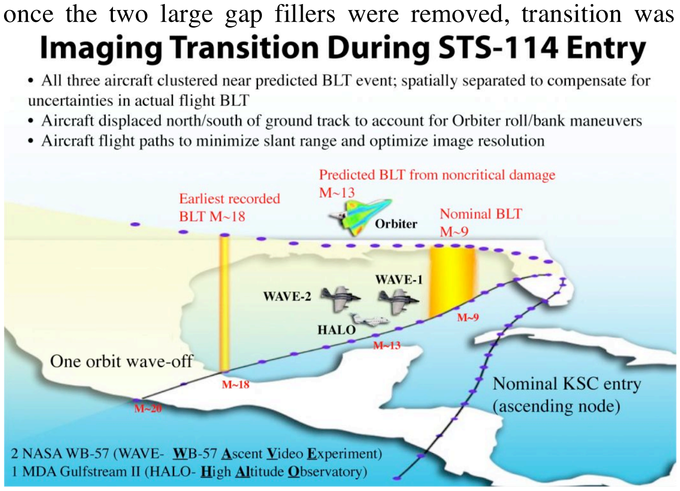


Figure 10. Pre-flight plan for entry IR image capture

Post-Flight

Transition Onset (TC Data)

Discovery (OV-103) has the fewest number of windward surface thermocouples of all the vehicles in the fleet, a total of five working thermocouples for this flight. A few weeks were required to retrieve and process the data from the Modular Auxiliary Data System (MADS), and the resulting temperature-time histories and transition onset times are indicated in Fig. 11. Relatively speaking, the transition onset time for this flight is considered nominal, with transition occurring at a Mach number below 8.

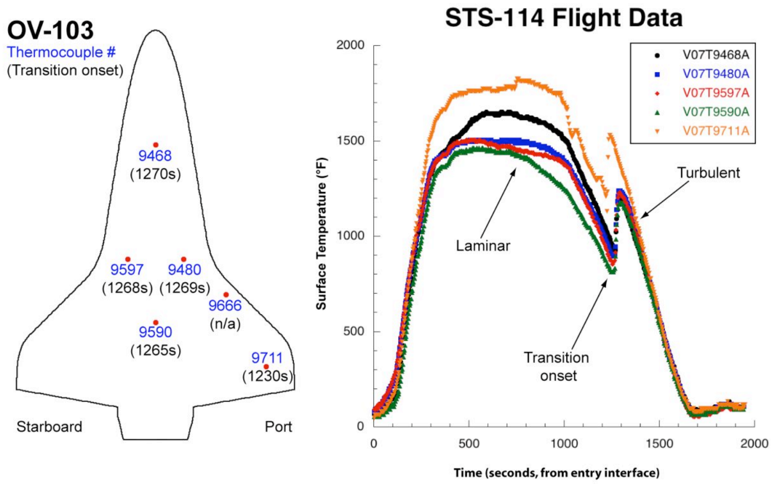


Fig. 11 Thermocouple locations for OV-103 and transition onset times for STS-114

Port side thermocouple (9711) showed the earliest transition onset time of 1230s. The central thermocouples showed a rapid movement of transition from the back to the front of 1265s to 1270s, respectively. It is interesting to note that if the entry imaging aircraft had been in position for the landing at Edwards, then it is likely one of the IR systems would have captured the transition process. Clear evidence of cause and effect and confirmation of the turbulent spreading angle would have been useful information for this post-flight assessment of STS-114.

Post-Flight Runway Inspection

The post-flight runway TPS inspection team at Edwards found nine additional gap fillers protruding, as noted in Fig. 12. These nine gap fillers had not been previously identified in orbit during the RPM photographic analysis. So the obvious question arises, why were these gap fillers not identified? Were the additional gap fillers too small to be noticed during the RPM process, or did they in fact protrude during entry or upon landing? Only three of the gap fillers identified as protruding on the runway were noted as potentially being out during the high heating portion of the trajectory due to the resulting flow pattern and burn marks around the trip. Of those three, only two have been since confirmed as protruding prior to entry from a more thorough review of the RPM photos. These two were small enough, both protruding 0.1-in or less, that they were missed during the mission.

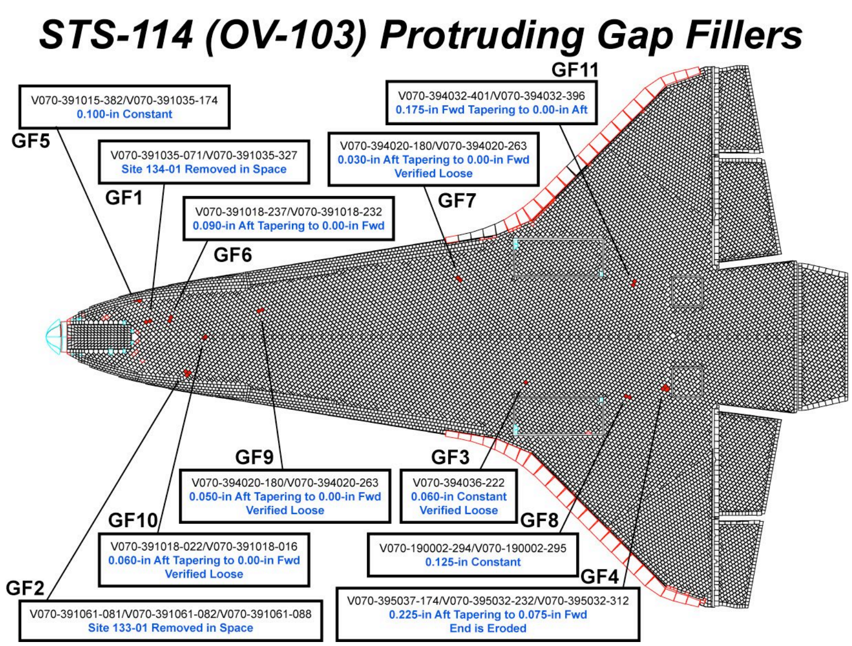
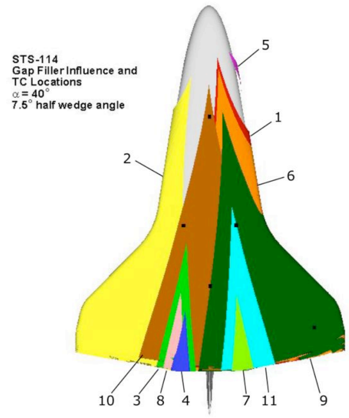


Figure 12. Protruding gap fillers on STS-114

Final BLT Analysis

Figure 13 provides the BLT Tool analysis results for all 11 protruding gap fillers identified in Fig. 12. Several of the gap fillers were in a position such that if they were indeed out during entry, the onset of transition would not have been picked up by the thermocouples (GF3, 4, 5, 7, and 8). If the airborne IR imaging systems had been in place for this entry, the earlier transition wedges missed by the lack of windward surface thermocouples could have been confirmed or refuted. The most intriguing gap filler is GF6 as it's location and height would suggest a transition onset time near what was actually identified with the STS-114 flight data, with the possible exception of the most forward thermocouple (9468). Alternatively, based on the BLT assessment of Site 942-01 (shown earlier), transition movement down the center of the fuselage, as indicated by the rapid forward progression of transition onset from TC9590 to TC9468 (within 5 seconds), may have been due to the cavity on the nose landing gear door. The slightly earlier transition onset time on the port wing (TC9711, roughly 30 seconds earlier than on centerline) may have been due to GF6. The noted rapid movement of transition tends to rule out an alternate explanation of nominal transition due to the distributed background roughness of the TPS (steps and gaps). Based on the computed movement of a constant value of Re_θ/M_e, transition onset would move more slowly across the four central thermocouples (on the order of 100s).

Post-Flight Gap Filler Analysis



GF#	X0 (in)	Y0 (in)	Z0 (in)	k (in)	BLT Tool Onset Time (s)	Notes
1	411	-26.5	284	Removed		
2	479	60.5	285	Removed		
3	1060	81.7	269	0.06	1270	
4	1301	87.5	265	0.075	952	1, 2
5	394	-62.1	296	0.1	1245	1, 2
6	449	-30.8	282	0.09	1250	
7	1245	-92.3	266	0.175	990	1
8	1234	102.9	267	0.125	1090	
9	604	-45.6	279	0.05	1330	
10	508	1.6	279	0.06	1315	3
11	936	-72.2	272	0.03	1380	

Notes: 1. Flow pattern noted on runway that suggest gap filler out during entry
2. RPM review confrimed gap filler was protruding but not noticed during mission
3. RPM review suggest gap filler may have been protruding on orbit

Fig. 13 BLT analysis of the gap fillers post-flight

Implications for STS-121

Post-flight, a review of the strengths and weaknesses of the BLT Tool as implemented for STS-114 has uncovered the necessity to develop a new version where the computational database is based on CFD instead of engineering solutions. This will remove the limitation of the computational method beyond Mach 20. However, the lack of any high Mach number transition data for calibration purposes will continue to limit the range of the tool. The next version of the tool will include additional ground-based data at Mach numbers up to 16 (obtained in the CUBRC LENS facilities in Buffalo, NY), as well as any additional existing flight cases that have been identified as quality calibration cases. Also, further refinement of the experimental databases obtained at NASA Langley Research Center facilities will continue. In the meantime, a case should be made to utilize an up-coming flight to include a controlled high Mach number transition experiment for reducing uncertainties regarding real-gas effects on the transition process at high Mach numbers.

On the vehicle processing side, a gap filler assessment group was established to determine the root causes for the gap filler protrusions during STS-114 in order to reduce the likelihood of reoccurrence during up-coming missions. As mentioned earlier, sidewall bonding was identified as a significant issue as the adhesive material that is smeared closer to the surface will be exposed to higher temperatures, thereby reducing long-term strength of bond. Pull tests on a random selection of gap fillers on the vehicles revealed this to be an issue of concern and that many of the gap fillers in place may be of questionable capacity. Therefore, the decision was made by the Space Shuttle Program to replace all gap fillers on the vehicles (a major undertaking), using an improved installation process and new pull test standard, as soon as possible to reduce likelihood of future protrusions. Due to the shear number of gap fillers to be replaced on each vehicle (roughly 15,800 as shown in Fig. 14), the lower surface was broken up into priority zones. Gap fillers within the Priority 1 zone were required to be replaced before the next flight, as this area had the biggest influence on the wing leading edge, both from a heating perspective as well as a debris source (gap filler liberation and subsequent impact on the wing leading edge). The remaining zones were to be completed as soon as possible, but if not done prior to launch the program recognizes that additional EVA's may be required as risk mitigation.

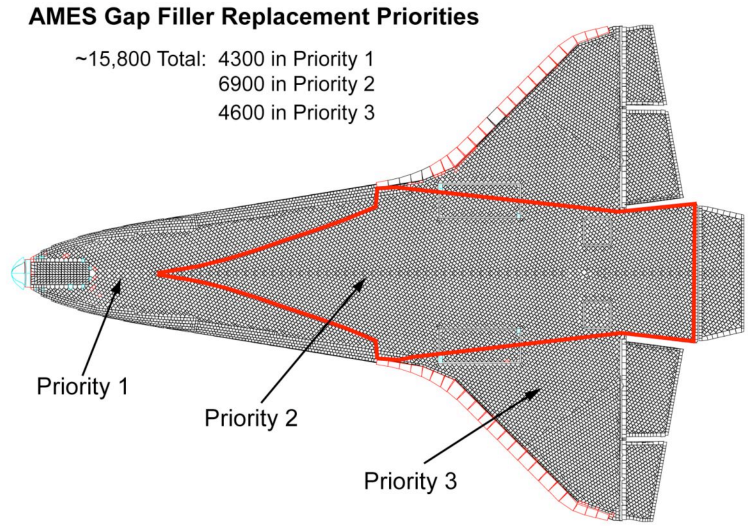


Fig. 14 Gap filler replacement priority

Summary

To support the Shuttle RTF effort, a predictive tool was developed for estimating the onset of boundary layer transition from deviations to the OML. The BLT Tool is the first step in the analysis process of the local TPS aerothermodynamics in order to allow informed disposition of damage for making recommendations to fly as is or to repair. This tool was developed in time to be implemented for the first RTF mission, STS-114, and thus was utilized during the decision process to send an astronaut out to remove the two protruding gap fillers of concern that were identified during the mission. Once these large gap fillers were removed the remaining damage sites were all cleared for reentry as is. Post-flight analysis of the resulting entry transition onset data revealed good comparison of the predicted times to that measured by the surface thermocouples, based on the remaining damage site on the nose landing gear door and a possible gap filler that was protruding on the runway, but can not be confirmed to be out prior to entry. Finally, a discussion of improvements to the BLT Tool for reducing uncertainties and to vehicle processing for reducing the likelihood of future gap filler protrusions was provided.

Acknowledgements

The present results could not have been accomplished with out the help of the entire BLT Team: Frank Greene, Ron Merski, Derek Liechty, Karen Bibb, Greg Buck, Harris Hamilton, Jim Weilmuenster, Chuck Campbell, Stan Bouslog, Gary Bourland, Dan Reda, James Reuther, Gerry Kinder Dennis Chao, Brian Anderson, Maria Barnwell, Steve Schneider, Rudy King, Mike Kegerise, and Cathy McGinley. Also, the following individuals have been very helpful with providing requested information or interpretation along the way: Cooper Snap, Dave Bretz, Steve Turner, and Armando Oliu.

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