Boundary Layer Transition Flight Experiment Overview and In-Situ Measurements

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In support of the Boundary Layer Transition Flight Experiment (BLT FE) Project, a manufactured protuberance tile was installed on the port wing of Space Shuttle Orbiter *Discovery* for the flights of STS-119, STS-128 and STS-131. Additional instrumentation was installed in order to obtain more spatially resolved measurements downstream of the protuberance. This paper provides an overview of the BLT FE Project. Significant efforts were made to place the protuberance at an appropriate location on the Orbiter and to design the protuberance to withstand the expected environments. A high-level overview of the in-situ flight data is presented, along with a summary of the comparisons between pre- and post-flight analysis predictions and flight data. Comparisons show that predictions for boundary layer transition onset time closely match the flight data, while predicted temperatures were significantly higher than observed flight temperatures.

Symbols

BF_{CFD}	Heating augmentation ("bump") factor predicted by CFD, dimensionless
k	Adjustment ("knock down") factor, dimensionless
M_e	Mach number at the edge of the boundary layer, dimensionless
Re_θ	Reynolds number based on momentum thickness, dimensionless
$\dot{q}$	Heat flux, Btu/ft^2-sec
$\dot{q}_{XF0002}$	Heat flux prediction provided by XF0002, Btu/ft^2-sec
σ	Standard deviation

Introduction

The design and ultimate weight of any vehicle entering a planetary atmosphere is affected by the amount of thermal protection system (TPS) required for safe and successful entry. One of the design drivers to TPS sizing is the time during the entry at which the boundary layer transitions from laminar to turbulent flow. The study of boundary layer transition (BLT) has been a significant effort for many decades, but the specific physics-based mechanisms that cause hypersonic BLT are poorly understood. This lack of understanding hinders designers in making accurate predictions of when the boundary layer will become turbulent and affects the sizing or the understanding of TPS robustness. If the geometry of a vehicle is known, engineers can obtain ground-test data from wind tunnels to develop engineering correlations[1-4]. However, one of the major weaknesses in a ground-based correlation approach is lack of understanding of the differences between wind tunnel and flight environments and how those differences affect BLT. In addition to the difficulties in predicting the onset of BLT, hypersonic turbulent heating predictions have also proven to be very challenging in many cases. Very little data exists to verify turbulent heating prediction models at low Reynolds numbers and hypersonic conditions.

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Following STS-107, the Orbiter Damage Assessment Team (DAT) was established with a charter to assess the effects of ascent and on-orbit damage and impacts upon the ability to perform safe re-entry[5]. A substantial testing and analytical tool development activity was undertaken to characterize the aeroheating, thermal, and stress implications of damage on the Orbiter material temperatures, tile factors of safety, and structural margins. The more notable aeroheating tools developed included the BLT Tool[3, 5-7] and the Cavity Heating Tool[5, 8]. In addition, the ability to rapidly produce Computational Fluid Dynamics (CFD) simulations of damage scenarios was also developed[9, 10].

During STS-114[11], an unprecedented repair spacewalk was performed to remove two protruding gap fillers because the risks associated with the uncertainties in early BLT and resulting heating effects were determined to be higher than the risks for spacewalk itself. As a result of these uncertainties with BLT and turbulent heating predictions, a flight test using a protuberance on the Orbiter to purposefully trip the boundary layer at a prescribed Mach number was proposed in November 2006[12].

Several other flight experiments were also proposed including an experiment to obtain measurements in a tile cavity and to obtain temperature measurements in the shock-shock interaction region on the Orbiter wing leading edge. A flight experiment that was reduced in scope from original proposals was ultimately approved and funded by the Space Shuttle Program (SSP). Many motivations exist[5] to obtain flight test data of this kind including a strong desire to obtain data to improve modeling capabilities and increase the potential for physics-based understanding, and to effect new-vehicle designs. Although early proposals included installing experiment hardware on all three Orbiter vehicles, the protuberance tile and augmented instrumentation package was only installed on one Orbiter, OV-103 (*Discovery*).

It should be noted that the flight experiment received strong advocacy from the SSP Manager, the Orbiter Project Office manager, and the NASA Engineering and Safety Center. It is interesting to note that strong Program Manager advocacy was also required for flight experiments on the first five flights of the SSP, which served as the initial Orbiter flight tests.

Participation in the planning and execution of the BLT FE included personnel from Johnson Space Center, Kennedy Space Center, Ames Research Center, Langley Research Center, the United Space Alliance, and the Boeing Company. Disciplines involved included experts in hardware, ground operations, aerothermodynamics, aerodynamics, flight controls, thermal analysis, structural analysis, trajectory design, operations, loads & dynamics, impact test & analysis, instrumentation, avionics, software, materials & processes, manufacturing, Safety & Mission Assurance, and robotics. Representatives from the Astronaut Crew Office also participated.

Because the number of flights on the remainder of the SSP manifest was limited, implementation of the flight test required rapid planning. In order to accelerate planning, the Systems Requirements Review and Preliminary Design Review were held concurrently in June 2007 to formally define the flight test scope and review initial plans. A Critical Design Review was held in January. In order for the flight experiment protuberance and augmented instrumentation to be installed, approval was required through nearly every level of SSP management. Re-entry for the first flight of the experiment, STS-119, occurred on March 28, 2009. Re-entry for the second flight experiment, STS-128, occurred on September 11, 2009. Re-entry for the third flight experiment, STS-131, occurred on April 20, 2010.

An activity complementary to the BLT FE led by NASA Langley was also undertaken to image the Orbiter during re-entry using infrared detectors. The Hypersonic Thermodynamic Infrared Measurements (HYTHIRM)[13, 14] team imaged the Orbiter on STS-119, STS-128 and STS-131 (in addition to STS-125 and STS-132).

An overview of the three flight experiments, a brief presentation of the data obtained, and a discussion about potential future flight tests on the Orbiter is presented in the sections that follow.

Experiment Design Overview

Protuberance Placement

Because the Space Shuttle Orbiter is a manned vehicle, safety is the top priority in all aspects of the experiment design. For any disturbance (protuberance, cavity, etc) on the Orbiter windward surface, a wedge of turbulent flow emanates downstream of the disturbance after BLT onset. The flow within this turbulent wedge can increase the heating over laminar levels by several times. During each flight of the Space Shuttle, damage occurs on the Orbiter surfaces due to ascent debris. Because some areas of the Orbiter are more prone to damage due to ascent debris than others, this was taken into account in the placement of the protuberance. Damage to the protuberance or the turbulent wedge downstream of the protuberance due to ascent debris could affect mission success and safety. In addition to the likelihood of damage, consideration was also given to the fact that certain areas of the Orbiter have more structural capability than others. An increase in heating due to the presence of the protuberance and associated wedge could reduce structural margins due to thermal gradients. The team placed the protuberance in an area that had sufficient margin to withstand the increase in heating due to turbulence.

With all these factors in mind, the protuberance location was chosen to be on the port wing, outboard and downstream of the main landing gear door (see Figure 1). This location avoids higher-risk impact sites due to ice frost ramps and other foam sources on the starboard side of the external tank. A risk study was performed and found that the risk of critical damage in the turbulent wedge downstream of the protuberance was less than 1 in 10,000.

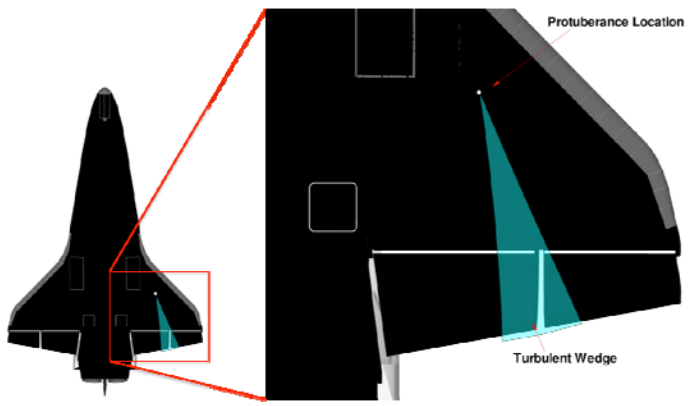

Figure 1: Selected protuberance location and predicted turbulent wedge

Protuberance Design

An incremental approach to the flight test program was decided upon early in the planning stages in order to ensure safety given the uncertainties in the prediction of BLT onset and associated effects on the TPS. As a point of reference, the earliest known BLT on the Orbiter occurred at approximately Mach 18 during the re-entry of STS-28[15]. The first flight on STS-119 targeted a BLT onset of approximately Mach 15 while the second and third flights on STS-128 and STS-131 targeted approximately Mach 18. The height of the protuberance was derived using the Orbiter BLT Tool, Version 2[6] with the Re_θ/M_e correlation using the best estimate correlation coefficient. The flown protuberance height was 0.25" for STS-119 and 0.35" for both STS-128 and STS-131.

A sensitivity study was performed to understand the effect of trajectory on predicted BLT time. The range of BLT onset Mach numbers predicted for a sample of trajectories are shown in Table 1 using the STS-119 protuberance height. The Best Estimated Trajectory (BET) shown for each applicable mission was derived from Orbiter navigation data. The average BLT onset Mach number prediction time for all of the trajectories is 15.5, with the earliest prediction at Mach 16.6 and the latest prediction at Mach 14.9.

Aerothermal, thermal, and stress analysis was performed for the protuberance, the area immediately surrounding the protuberance, and the downstream regions within the turbulent wedge. The aerothermal analysis was performed using nominal Orbiter heating predictions from XF0002[7], used to provide nominal Orbiter heating environments. Heating augmentation factor predictions due to the protuberance and associated vortex heating were derived using CFD. The Data Parallel Line Relaxation (DPLR) code[16] was used to for the augmentation factor predictions. Details on the specific CFD analyses performed in support of the flight experiment are discussed in Reference 17. Supporting arc jet testing and arc jet test environment calculations are detailed in Reference 18 and 19, respectively.

Table 1: Predicted BLT onset Mach numbers for a 0.25" protuberance

Trajectory	BLT Onset Mach Number
Generic ISS Return	16.6
STS-114 BET	15.7
STS-115 BET	15.2
STS-116 BET	15.2
STS-117 BET	14.9
STS-118 BET	15.6
STS-120 BET	15.3
STS-121 BET	15.7

The nominal Orbiter heating and CFD results were combined using a heating augmentation ("bump") factor methodology. These aerothermal environments were then used as a convective heating boundary condition for thermal analysis. Thermal analysis to account for conduction through the TPS materials to the structure and to account for radiation between surfaces was performed using SINDA and TRASYS[20, 21], respectively. Stress analysis was performed using standard DAT tools and methods. Additional details on the analysis are presented later in this paper.

The protuberance tile was fabricated using Boeing Replacement Insulation (BRI)-18 tile material. BRI-18 is an advanced, high-density tile with high temperature capability, but includes more damage impact resistance capability. BRI-18 tiles are often coated with a Toughened Unipiece Fibrous Insulation (TUFI) coating that further enhances damage tolerance. For the flight experiment protuberance tile, TUFI coating was applied to all regions of the tile with the exception of the protuberance itself. The protuberance was not TUFI-coated in order to improve the ability of an astronaut to remove the protuberance in the unlikely event of a repair Extra-Vehicular Activity (EVA). Repair procedures and tools developed during STS-114 were reviewed and evaluated for their ability to perform the tile protuberance removal. An illustration of protuberance removal for a protuberance prototype is shown in Figure 2. More information about the protuberance tile design can be found in Reference 22.

Figure 2: Tile protuberance prototype being cut by an EVA hacksaw[23]

One of the main requirements in the design of the protuberance was that the protuberance remain shape-stable through the entry. This is critical because the historical Orbiter BLT onset data due to protruding gap fillers have significant uncertainty due to the protuberance height. As a tile reaches the material capability temperature, it begins to change shape or slump. Because of this, aeroheating and thermal analysis drove the design for the protuberance shape. Nearly ten different design iterations were assessed and two shapes were tested in the Johnson Space Center (JSC) arc jet facility. The shape was designed so that heating levels would be relatively constant along the length of the protuberance. A photograph of the final design is shown in Figure 3. The length and width of the protuberance installed on the vehicle were 4.0” and approximately 0.4”, respectively, for all three flights. The protuberance was machined into the tile such that the leading edge was oriented at an angle of 45±3˚ relative to the predicted local flow streamline. This uncertainty was determined graphically using installed hardware pictures that were then scaled onto CFD solutions together with a tile layout.

Figure 3: Final protuberance shape

The predicted tile temperatures due to vortex heating just downstream of the protuberance drove the team to replace three LI-900 tiles with LI-2200 tiles, which have a higher surface temperature capability. A schematic showing the different tile materials in the region of the protuberance is shown in Figure 4. Additional details about the changes to the TPS can be found in Reference 22.

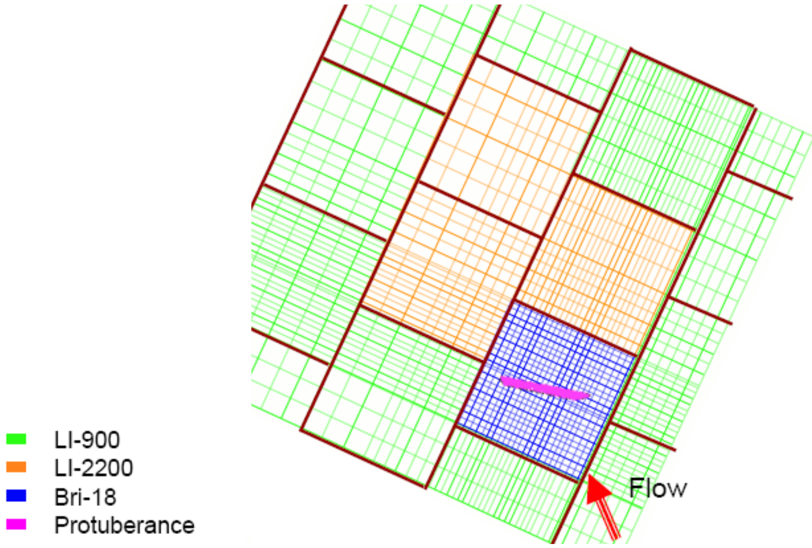

Figure 4: Tile materials used in the vicinity of the protuberance tile

Catalytic Coated Tiles

In addition to BLT and turbulent heating at high Mach numbers, another aerothermodynamic phenomenon that is not clearly understood is the potential coupling effect between turbulent flow and a catalytic material. Current best practices in human-spaceflight assume that turbulent and catalytic heating are additive. However, some have hypothesized that the heating would be significantly less than an additive model would predict. Because the Orion backshell TPS is being designed using fully-turbulent heating and because Orbiter tile (which is partially catalytic) has been baselined as the after-body tile material, resolution to the question about turbulent-catalytic coupling could aid in the design of Orion.

During STS-2, STS-3, and STS-5, several tiles were coated with a nearly fully catalytic material and instrumented to measure the effect of catalycity on the tile surface temperature[24-27]. However, these flights experienced BLT relatively late in the trajectory where catalytic effects are not as pronounced. In order to best assess the turbulent-catalytic coupling effect, turbulence should be experienced at relatively high Mach numbers where non-equilibrium effects are more prominent. Because one of the prime objectives of the BLT flight experiment was to trip the boundary layer at relatively high Mach numbers, a relationship to the turbulent-catalytic coupling question was apparent.

NASA-JSC solicited the help of engineers at NASA-Ames who were involved in the flight experiments on STS-2, STS-3, and STS-5. A new formulation for the catalytic coating was established and tested based on similar material constituents as for the previous catalytic tile flight tests. The catalytic coating was then applied to two tiles on *Discovery* located adjacent to one another for the STS-128 flight. The tiles were placed in close proximity to ensure similar environments were experienced to simplify analysis of the data following the experiment. A figure showing the coating applied to the tiles is shown in Figure 5. The apparent bumps in the figure were not as pronounced as they appear in the figure. Actual inspection of the coating showed the surface-plane deviations were minimal. A single tile was coated for the STS-131 flight of *Discovery*.

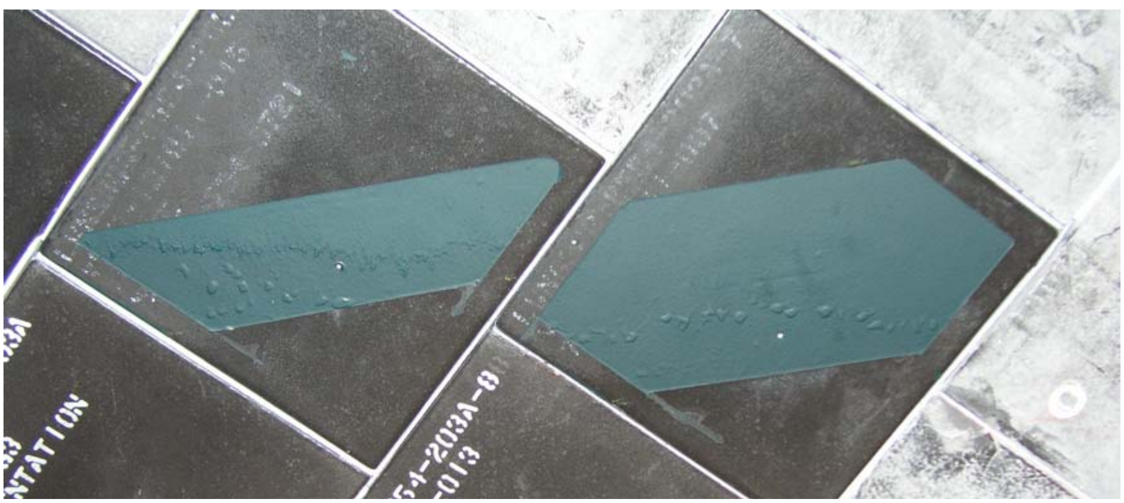

Figure 5: Catalytic Coated Tiles on STS-128.

Trajectory Design

The actual design of the Orbiter re-entry trajectory was not modified for the flight experiments. However, extensive coordination took place with flight design personnel, flight dynamics officers, and the Ascent-Entry Flight Techniques Panel to communicate potential impacts of Orbiter maneuvers on the flight experiment data. During entry the Orbiter executes a series of roll maneuvers. These roll maneuvers have been hypothesized to effect BLT onset because of the angle of attack and sideslip modulation associated with them. The team established desired ‘cut-off’ intervals on either side of the predicted BLT onset Mach numbers in order to avoid roll reversals during that period of the re-entry. A flight rule related to the flight experiment was established that allows for de-orbit burn modification to occur if the cut-off intervals are violated for the primary entry opportunity on the first day for which an entry is attempted. In practice, these intervals did not drive mission decisions during STS-119 or STS-128. During STS-131, the flight rule was used to obtain Flight Director approval for a retrograde separation and orbit adjustment that pushed the End of Mission (EOM) crossrange outside of the BLT FE crossrange cutout.

Instrumentation Overview

Prior to installation of the flight experiment hardware, *Discovery* had a total of 6 existing surface thermocouples on the windward surface of the vehicle. None of these previously available measurements were located downstream of the protuberance in the expected turbulent wedge. In order to adequately capture the heating levels and extent of the turbulent wedge, additional instrumentation was required. Exact placement of the thermocouples was carried out using the wedge tool[15, 28] using a wedge half angle of 7.5˚. The wedge tool is an analytical tool that uses predicted streamlines from CFD solutions to estimate the geometric extent of the turbulence downstream of a disturbance.

Figure 6 shows a sketch of the location of the instrumentation for STS-119, STS-128 and STS-131. White symbols represent instrument locations active for STS-119, STS-128 and STS-131. Because some of the instruments were not used for all of the flights, instruments that were active for STS-119 only are colored purple, for STS-128 only are colored green and both STS-128 and STS-131 are colored yellow. The catalytic coated tiles have boxes or triangles surrounding their location, for the tiles that were coated for both STS-128 and STS-131 or STS-128 only, respectively. It is important to note that the flight experiment team was limited to ten active thermocouple measurements because of data acquisition system (DAS) constraints in the wing region. Three holes were drilled into the Orbiter wing structure to run thermocouple lead wires between the DAS hardware and the outer surface of the vehicle. Additional information about the instrumentation system can be found in Reference 22.

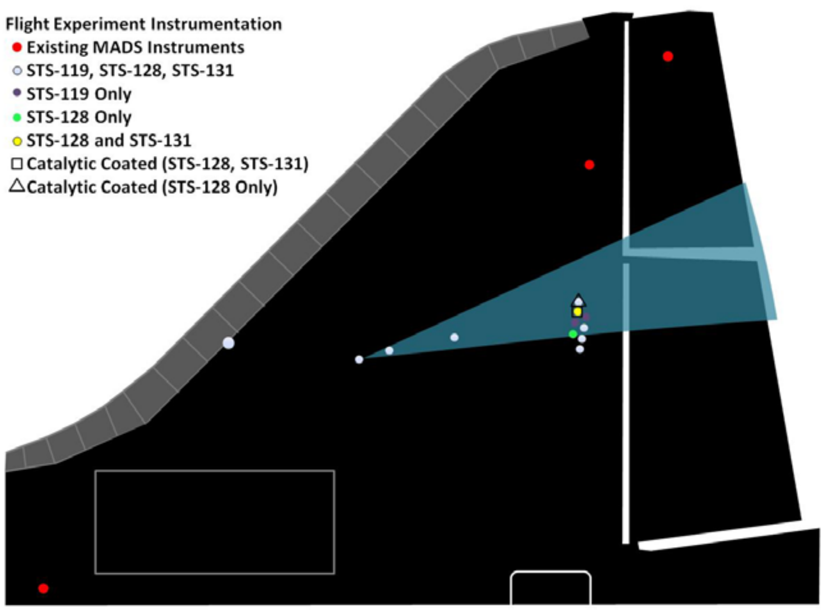

Figure 6: Instrumentation locations for STS-119, STS-128 and STS-131.

The differences in instrumentation layout between STS-119, STS-128 and STS-131 were implemented to (1) obtain higher resolution on the turbulent wedge angle and (2) to take measurements in the two catalytic coated tiles during STS-128 and single tile catalytic tile during STS-131. For STS-128, the catalytic coated tiles were placed as near to the center of the predicted wedge as possible and adjacent to one another. The thermocouples were placed in the tiles in different locations relative to the leading edge of the coating application. One thermocouple was placed as close to the leading edge as possible while the other was in the middle of the coating application for the other tile. For STS-131, a single tile was utilized with two thermocouples; one near the leading edge and one in the center. The thermocouples were placed in this manner to measure the catalytic jump due to a mismatched material[29] and to measure the general catalytic behavior of the coating, respectively.

For the purposes of comparison to HYTHIRM data and computational predictions, the uncertainty levels associated with the thermocouple measurements were assessed. The components that contribute to the overall uncertainty include a precision uncertainty due to the bit resolution and recording steps in the measurement system, a MADS stability precision uncertainty, and a calibration curve precision uncertainty. In combination, these precision uncertainties are estimated to be ±20˚F. In addition to this precision uncertainty, there is also a known bias uncertainty due to installation effects. It is estimated that the actual tile surface temperature is approximately 20˚F hotter than the values reported by the thermocouple measurement due to the thermocouple placement slightly below the actual tile surface. This bias effect is location dependent as each thermocouple is installed at a slightly different depth. Team members plan to perform additional analysis in the future to more precisely characterize this bias effect.

STS-119

Pre-flight STS-119 Analytical Predictions

Pre-flight predictions for the area downstream of the protuberance were performed for two general regions. The first region considered the area from the protuberance and aft to the end of the vehicle. A graphical representation of the area is illustrated in Figure 6, where the areas within and surrounding the turbulent wedge were analyzed. This analysis considered the global effects of the wedge turbulent heating on thermal and structural margins and was performed using standard Orbiter analysis tools. These analyses predicted acceptable thermal and structural margins for the predicted BLT times, even when considering the thermal gradients that exist across the turbulent wedge.

The second analysis region only considered the area immediately surrounding the protuberance, shown pictorially in Figure 4. The intent of this analysis domain was to capture any adverse local effects due to the protuberance and associated vortex heating on the thermal and structural margins. As discussed previously, the local aeroheating analysis was carried out using a combination of XF0002 and CFD. The CFD solutions were provided for select trajectory points and are discussed in Reference 17. Thermal and structural analyses were also performed, as discussed previously.

A summary of the predicted material temperatures is presented in Table 2 for the pre-flight (predicted) STS-119 trajectory and a generic, conservative, International Space Station (ISS) return trajectory, assuming BLT takes place upstream of the protuberance at approximately Mach 8. Other trajectories were also analyzed but are not shown. In the case of the generic ISS return trajectory, a material temperature waiver was required for the protuberance as the predicted temperature of 3028˚F exceeded the single-use limit for BRI-18 by 128˚F. Notwithstanding this tile surface over-temperature prediction, acceptable tile factors of safety and structural margins were predicted.

Table 2: Maximum STS-119 predictions for STS-119 & generic ISS trajectories.

Material	**Peak Temperature (˚F)**	
	STS-119 Pre-Flight	Generic ISS Return
Protuberance	2892	3028
Protuberance tile acreage	2720	2720
LI-2200 tile	2535	2724
LI-900 tile	2312	2529
Room Temperature Vulcanizing (RTV)	419	533
Aluminum structure	152	187

Mission Overview

Space Shuttle *Discovery* launched from Kennedy Space Center (KSC) on March 14, 2009. The mission consisted of 4 spacewalks to continue construction of the ISS. The Orbiter was docked to the ISS for 10 days. During the mission, the crew delivered and installed the final ISS truss segment, known as S6. The final pair of power generating solar array wings were also delivered and successfully installed. All prime objectives of the mission were achieved and following undocking, the ISS was ready to house a six-member crew. *Discovery* landed safely at KSC on March 28, 2009.

A post-flight review of the thermocouple data showed a relatively early (~Mach 11.5) asymmetric BLT event on the starboard side of the Orbiter during the STS-119 re-entry. This asymmetric event was also observed in HYTHIRM imagery[12, 13] as shown in Figure 7. The infrared imagery was obtained from a Navy NP-3D aircraft approximately 25 nautical miles away from the Orbiter while the Orbiter was near Mach 9. The HYTHIRM imagery proved to be very useful in conjunction with the wedge tool and the thermocouple data to help isolate regions that might have caused the flow disturbance, though no out-of-tolerance steps or protruding gap fillers were identified during post-flight inspection to have been the cause of the asymmetric BLT event.

STS-119 Flight-Experiment Data Overview

For convenience during the discussion of the flight data, the labeled flight experiment thermocouples are shown in Figure 8. Thermocouple time traces are shown in Figure 9 and Figure 10. Only the data associated with the flight experiment-specific thermocouples is shown. The thermocouple data is plotted in two different plots for the sake of clarity. Figure 9 shows the thermocouple data associated with the flight experiment thermocouples that are furthest aft, while Figure 10 shows the data for thermocouples farther forward and on the protuberance. The data is plotted using the post-flight BET. Temperatures are plotted versus time from Entry Interface (EI), the time at which the Orbiter altitude is 400,000 feet. Angle of attack and roll angle profiles for the re-entry are also shown.

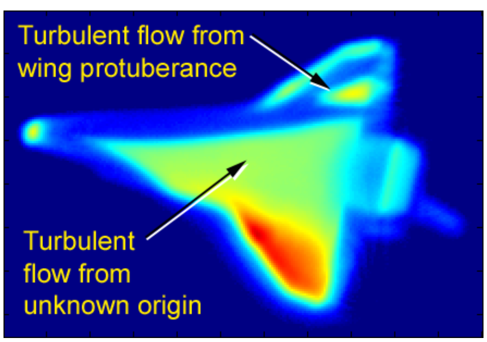

Figure 7: HYTHIRM imagery from STS-119. See References 13, 14

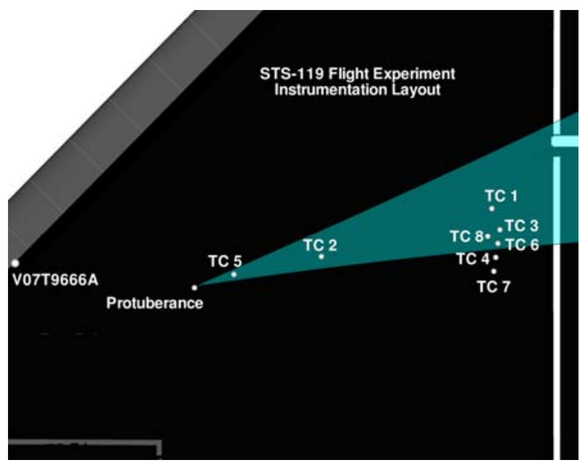

Figure 8: Thermocouple labels for STS-119.

A cursory glance at the aft thermocouple traces in Figure 9 shows that temperatures did not exceed 2000˚F. Peak temperatures were experienced during the turbulent portion of the entry. Temperatures during the laminar portion of the trajectory were consistent with each other, with peak laminar temperatures between approximately 1500 and 1600˚F. Thermocouple 1 (hereafter referred to as TC 1) is located at the center of the predicted wedge and shows the earliest sign of BLT at 969 seconds. This corresponds to a Mach number of 15.6. BLT time was selected based on the earliest time that temperatures departed from laminar levels. It should be noted that the process of selecting BLT time can be somewhat subjective, depending on the data under consideration.

The thermocouple data also indicates that the turbulent wedge progresses inboard (and presumably outboard on the opposite side of the wedge), as expected, with TCs 3, 8, and 6 showing BLT very soon after TC 1. TCs 4 and 7 show transition times much later than the other aft thermocouples. These two thermocouples appear to have been correctly placed outside the turbulent wedge. Based on these observations, the turbulent wedge half angle is approximately 7.0˚. This value was derived by determining the angle between two rays. The first ray was defined using the wedge tool seeded by the TC 5 location. The inboard edge of the predicted wedge with an angle sufficient to affect TC 6 (but not TC 4) was defined as the first ray. The second ray was defined as the streamline passing through TC 5 predicted by a smooth-body CFD solution.

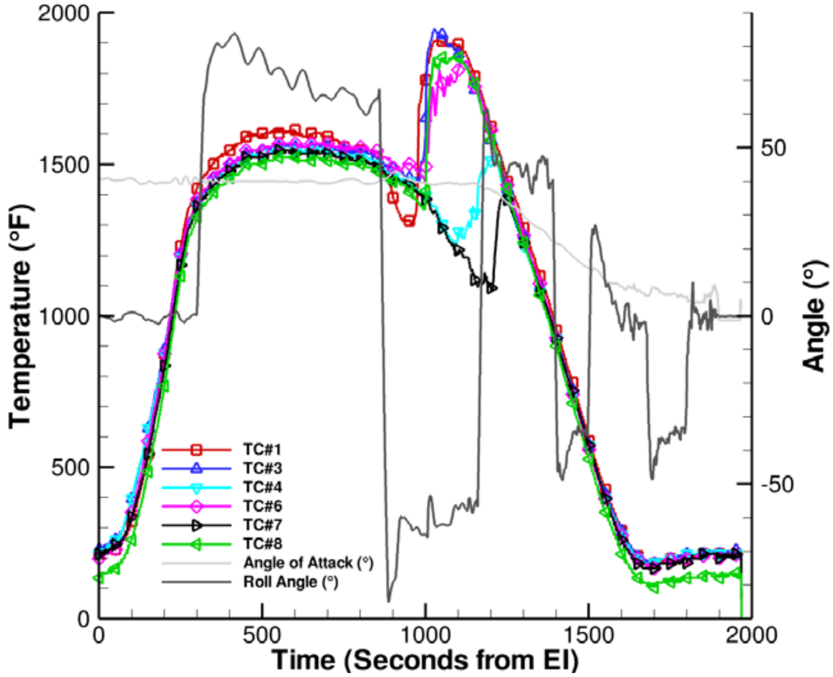

Figure 9: STS-119 data for aft thermocouples

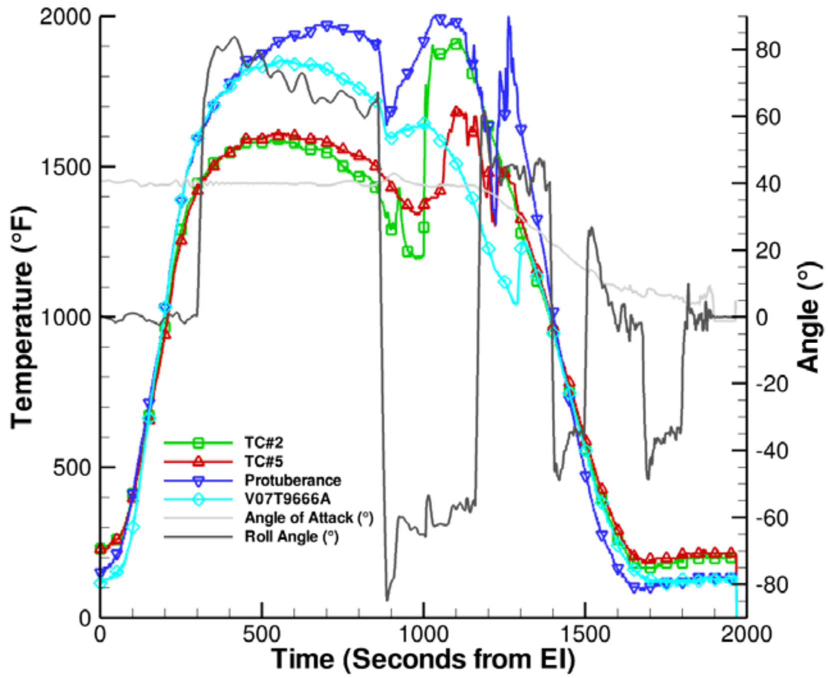

Figure 10: STS-119 data from “forward” thermocouples

Figure 10 shows the thermocouple traces for the remaining flight experiment thermocouples. As can be seen, the maximum temperature was approximately 2000˚F and was experienced by the protuberance. As expected, the protuberance temperature was higher than the downstream temperatures during all portions of the trajectory. Due to the location of V07T9666A just downstream of the wing leading edge, it is not surprising that this thermocouple registered temperatures higher than TCs 2 and 5. TCs 2 and 5 have very similar temperatures during the laminar portion of the trajectory. As expected, TC 2 experiences BLT first, followed by TC 5 and finally the protuberance. This is consistent with the turbulent front traveling upstream with time. Since TC 5 represents the measurement closest to the protuberance, it is considered to be a measure of the time for fully effective BLT due to the protuberance. Based on the BET, TC 5 experienced BLT at Mach 13.1 (1045 seconds). The protuberance itself experienced BLT at Mach 7.7 (1224 seconds). The reference thermocouple (V07T9666A) experienced BLT at approximately Mach 6.4 (1291 seconds).

An interesting signature is observed in some of the thermocouple traces shown in Figure 10. At approximately 850 seconds there is a sharp drop in temperature in the protuberance and V07T9666A measurements. By examining the roll angle data in the same figure, one can see that this time corresponds to a vehicle maneuver in the form of a roll-reversal. Close examination of the plot also reveals a slight change in angle of attack associated with the roll-reversal. This thermocouple behavior associated with vehicle maneuvers has been observed on many previous Orbiter flights for the V07T9666A measurement. At approximately 900 seconds, TC 2 has an abrupt rise in temperature and then quickly drops to levels consistent with previous trends. The cause of this behavior is currently not understood, but it has been hypothesized that the vortex emanating from the protuberance passed over TC 2 in this time frame as the Mach number and aerodynamic attitude changed.

Following the flight of STS-119, the tiles downstream of the protuberance were examined by TPS and material experts. Based on experience with the behavior of tile coating, it was determined that none of the tiles affected by the flight experiment exceeded a temperature of 2500˚F. However, some of the tiles did exhibit deposits that provided clues as to the vortex heating structure downstream of the protuberance (Figure 11). Because of these observations, it was concluded that TC 5 was not actually located in the peak vortex-heating region as originally desired. Using these post-flight observations and heating distributions predicted by CFD, the thermocouple was relocated for STS-128.

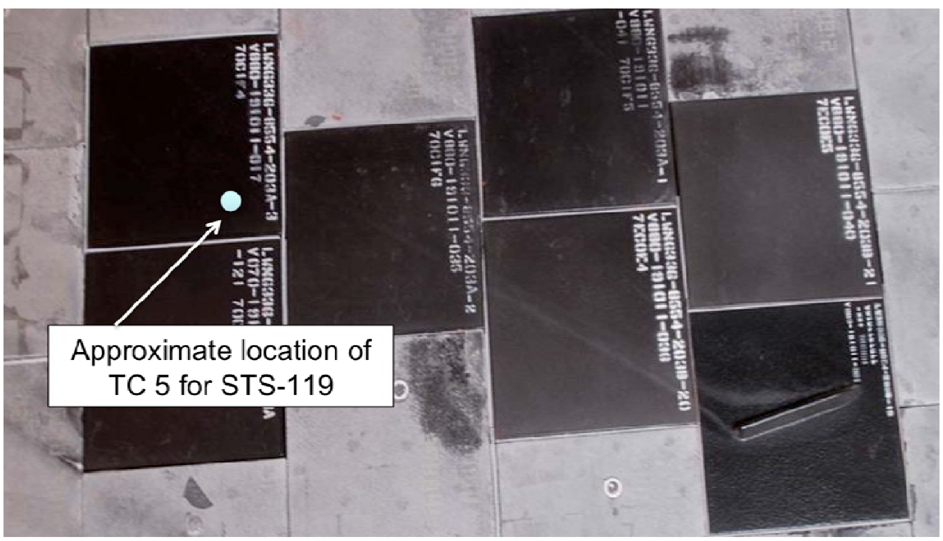

Figure 11: STS-119 post-flight photo showing streamline structure

The protuberance tile was removed from the vehicle in a non-destructive manner and was sent to material experts for additional study. The tile was scanned pre- and post-flight to assess the protuberance shape change. Comparing the pre- and post-test scan results shows that the protuberance did not change shape appreciably. The observed geometry changes were between 0.0074 and 0.0212 inches, depending on location. The uncertainty in this measurement is not currently characterized because of difficulties in alignment when the measurements were taken.

Flight Data and Analysis Prediction Comparisons

Because analysis would play such a vital role in providing rationale for the safety of follow-on flight experiments, extensive comparisons between the STS-119 flight data and analysis predictions were performed. These comparisons included the predicted BLT onset time and material temperatures versus observed onset time and temperatures.

Comparisons between predicted and earliest observed BLT onset times were very favorable. As discussed in Reference 6, the predicted onset Mach number for a 0.25-inch height using the STS-119 BET was Mach 15.4. The observed BLT Mach number at TC 1 was Mach 15.6. This is within the ±1-σ prediction uncertainty of the BLT Tool.

Comparisons between predicted and observed temperatures were not as favorable as the BLT onset time comparisons. Of particular note was the predicted temperature on the protuberance (2892˚F based on the pre-flight STS-119 trajectory) versus the maximum reported temperature on the protuberance (2011˚F). This nearly 900˚F difference equates to a difference in heat flux of over a factor of four. The ability to compare predictions to actual flight data was less precise for the tiles surrounding the protuberance because of the sparseness of the instrumentation. However, material experts stated that the tile coating temperature did not exceed 2500˚F, as mentioned earlier. This is in contrast to the maximum pre-flight prediction of 2720˚F for the protuberance tile acreage. This represents a difference in heat flux of at least 1.4 times. It is, however, believed that the temperatures were actually much lower than 2500˚F. The cause of the large discrepancy between predicted and observed temperatures is currently unknown. However, three hypotheses for the cause of the discrepancy have been tendered: (1) non-continuum effects[30], (2) gross errors in the prediction of the boundary layer profile or extent of the separation upstream of the protuberance and (3) errors in the prediction of the thermal response.

Analysis in Support of Flight Experiment #2

In order to ensure that the second flight (using a protuberance height of 0.35-inches) would not impact safety or vehicle integrity, additional analysis was required. In considering the analysis performed, it is important to point out two important facts: (1) there was no readily-available explanation for the large discrepancy between temperature prediction and observation on STS-119 and (2) due to the flight manifest, a very quick decision was needed as to which protuberance height should be installed. The team had on the order of one month to review the STS-119 data, revise models, and perform an adequately rigorous analysis.

Because no readily available explanation has been determined to explain the analysis discrepancy, an ad-hoc approach was selected to derive "knockdown" factors in order to match the STS-119 data. The team felt relatively confident in the ability of the CFD predictions to accurately describe the distribution of heating. However, the magnitude of the combination of the undisturbed and heating augmentation factors was in question. Following their derivation, the knockdown factors were applied to the STS-128 pre-flight certification analysis with the assumption that the knockdown factors were appropriate for use with the 0.35-inch protuberance. While 0.25-inch protuberance CFD solutions were used for the STS-119 reconstruction and knockdown factor derivation, 0.35-inch protuberance CFD heating distributions were used for the STS-128 certification analysis[17]. These distributions were used in combination with the undisturbed heating, CFD heating augmentation factor magnitudes, and derived knockdown factors. Equations 1 and 2 describe the relationship between the different parameters.

$$\dot{q} = \dot{q}_{XF0002}\left[\left(BF_{CFD} - 1\right)k + 1\right] \qquad \textbf{Equation 1}$$

$$\dot{q} = \dot{q}_{XF0002}\left[BF_{CFD} \cdot k\right] \qquad \textbf{Equation 2}$$

In these equations, $\dot{q}$ represents the heat flux applied, $\dot{q}_{XF0002}$ represents the undisturbed Orbiter heating predicted by XF0002, BF_{CFD} is the unadjusted heating augmentation factor predicted by CFD, and *k* is the knockdown factor derived using STS-119 data.

For the STS-128 certification analysis, the BLT time needed for the prediction was derived using a generic ISS return trajectory, a protuberance height of 0.35-inches, and the Re_θ/M_e correlation in the BLT version 2 tool[6]. In order to accurately describe the heating immediately downstream of the protuberance, a fully effective BLT time was required. This time was derived using available fully effective wind tunnel data correlations that were calibrated to the STS-119 fully effective BLT time based on TC 5. The formulation of the correlation and the calibration to the flight data were very similar to that carried out for the BLT tool[6]. For the heating distributions and unadjusted augmentation factor predictions, CFD solutions were available at Mach numbers of 20, 18, 15, and 12. Linear interpolation was carried out on the values for *k* and BF_{CFD} for points in the trajectory between the available CFD solutions.

Results of the analysis are shown in Table 3. The analysis associated with the STS-128 pre-flight trajectory assumed that an upstream disturbance caused transition on the BLT FE protuberance to occur at Mach 16.2. The analysis also limited the baseline Orbiter and protuberance turbulent heating based on observations from STS-119, STS-121, and STS-28. The results for the Generic ISS Return trajectory assume a nominal (~Mach 8) upstream transition.

In the case of the generic ISS return trajectory (which was used for certification of STS-128), a material temperature waiver was required for the protuberance as the predicted temperature of 2925˚F exceeded the single-use limit for BRI-18 by 25˚F for 25 seconds. Rationale for the appropriateness of the waiver was based on the fact that (1) the predicted time of the over-temperature condition was relatively short (2) a certification-level (conservative) trajectory was being used for the assessment and (3) despite the surface over-temperature condition, acceptable tile factors of safety and structural margins were predicted. It was also believed that the analysis was still slightly conservative, even after the adjustments made following STS-119.

Table 3: STS-128 predictions for pre-flight STS-128 and generic ISS return trajectories.

Material	**Peak Temperature (˚F)**	
	STS-128 Pre-Flight	Generic ISS Return
Protuberance	2799	2654
Protuberance tile acreage	2995	2925
LI-2200 tile	2887	2890
LI-900 tile	2450	2475
RTV	444	489
Aluminum structure	161	186

STS-128

Mission Overview

For STS-128, Space Shuttle *Discovery* launched from Kennedy Space Center on August 29, 2009. The mission consisted of 3 spacewalks and the Orbiter was docked to the ISS for 9 days. The three spacewalks consisted of, among many other tasks, replacing experiments outside the European Space Agency's Columbus laboratory and installation of a new ammonia storage tank for ISS cooling. The Orbiter also carried with it the 4.5-ton Multi-Purpose Logistics Module (MPLM), which was filled with supplies for the ISS. All prime objectives of the mission were achieved. *Discovery* landed safely at Edwards Air Force base in California on September 11, 2009.

Similar to STS-119, examination showed that *Discovery* had again experienced an early asymmetric BLT event. Unfortunately for the flight experiment, this asymmetric event took place upstream of the port wing. Figure 12 shows the turbulent wedge for an assumed disturbance location in addition to the thermocouples and associated BLT Mach numbers on the vehicle. The asymmetric event initiated at approximately Mach 13.6. The effects of this upstream event unfortunately make it challenging to interpret portions of the flight experiment data. HYTHIRM observations at closest approach were prior to the time at which the asymmetric wedge was indicated by the thermocouple data. As a result, observations of the asymmetric wedge similar to

STS-119 are not available as shown in Figure 13. The exact cause of the early asymmetric BLT event is unknown notwithstanding a focused effort to inspect the vehicle for out-of-specification steps, gaps, and for missing gap fillers.

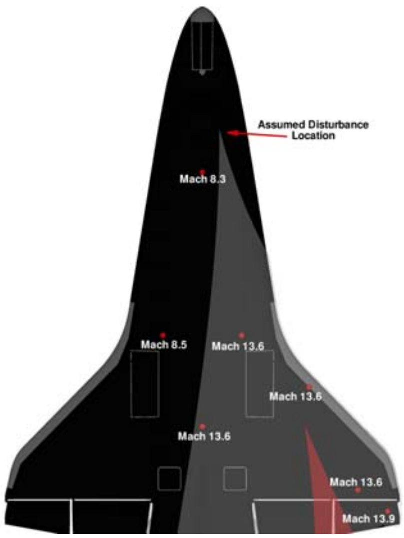

Figure 12: Post-flight reconstruction of asymmetric BLT event.

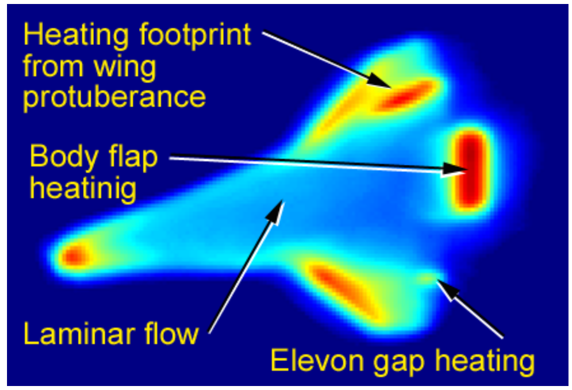

Figure 13: STS-128 HYTHIRM imagery[13, 14]

Flight Data Overview

For convenience during the discussion of the flight data, the labeled flight experiment thermocouples are shown in Figure 14. Thermocouple time traces are shown in Figure 15 and Figure 16. Similar to the STS-119 presentation, the thermocouple data are plotted in two different plots for the sake of clarity. Figure 15 shows the thermocouple data associated with the flight experiment thermocouples that are furthest aft, while Figure 16 shows the data for thermocouples farther forward and on the protuberance. The data is plotted using the post-flight BET.

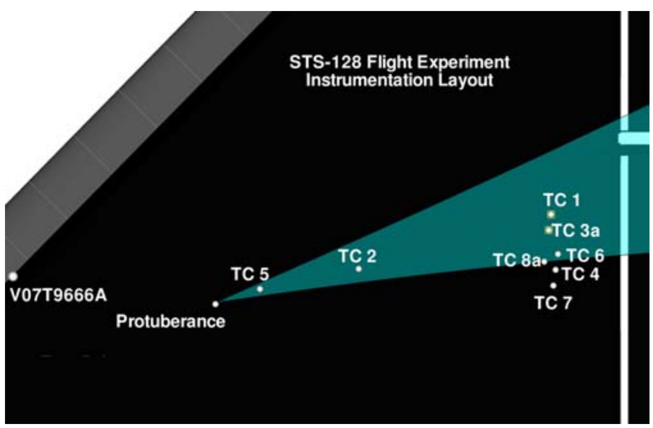

Figure 14: Thermocouple labels for STS-128.

A cursory glance at the aft thermocouple traces in Figure 15 show that temperatures did not exceed 2000˚F, with the peak temperatures experienced during the turbulent portion of the entry. With the exception of TC 1 and TC 3a, temperatures during the laminar portion of the trajectory were all similar with peak laminar temperatures between approximately 1500 and 1600˚F. In fact, the traces for TC 4, TC 6, TC 7, and TC 8a lie nearly on top of each other through the entire re-entry. It should be noted again that both TC 1 and TC 3a had catalytic coating applied to the surface. As such, the elevated temperatures in relation to the other aft thermocouples are expected. It is also worthwhile to note that because of the thermocouple placement at the leading edge of the catalytic coating, it was also expected that TC 3a would exhibit a higher temperature than TC 1. The magnitude of the temperature levels and the trends with time for TC 1 and TC 3a, however, are somewhat troubling. While a physics-based explanation for the drop in temperature seen prior to 900 seconds during the laminar portion of the trajectory is possible due to the reduction in non-equilibrium heating potential as the altitude and Mach number are reduced, the behavior of TC 1 and TC 3a during the turbulent portion of the re-entry is not understood. As can be seen, the traces appear to be very noisy. Additional and more detailed assessments of the heating in Stanton number space (not shown) also cast some doubt on the measurement validity in the turbulent regime. This was a disappointment to the flight test team since obtaining coupled turbulent-catalytic heating behavior at high Mach numbers was one of the prime objectives of the STS-128 BLT FE.

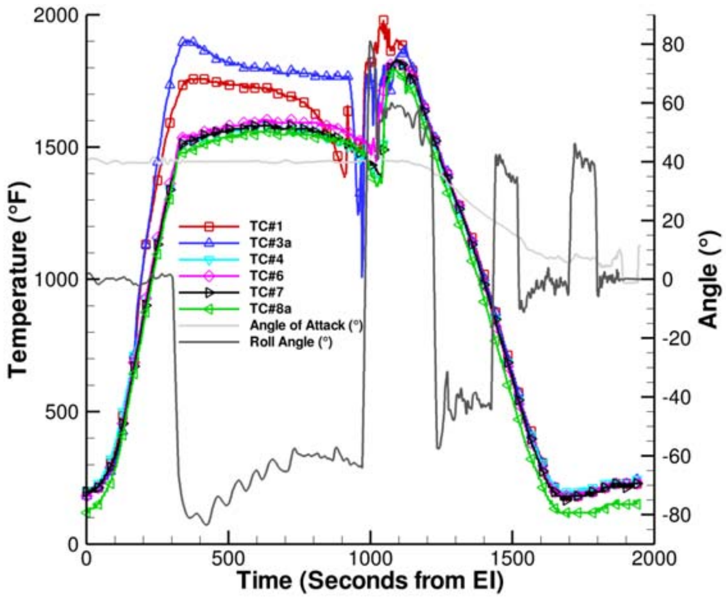

Figure 15: STS-128 data for aft thermocouples

TC 1 is located at the center of the predicted wedge and shows the earliest sign of non-laminar behavior at 913 seconds. This corresponds to a Mach number of 17.5 based on the BET. The thermocouple data then indicates that the turbulent wedge progresses inboard, as expected, with TC 3a showing the next sign of non-laminar behavior. However, there appears to be a delay in BLT of approximately 60 seconds between TC 3a and TCs 6, 8a, 4, and 7. Based on this information, it appears that the turbulent wedge was initially very narrow before widening later in the trajectory. It is important to note, however, that the upstream asymmetric BLT event most certainly effected wedge angle observations. This is evidenced by the fact that during STS-119, TCs 4 and 7 showed transition times much later than the other aft thermocouples, clearly indicating that they were outside the turbulent wedge. In this case, TC 4 and TC 7 appear to have experienced transition due to the asymmetric event although it is hard to draw conclusions as to whether or not BLT at these locations was first caused by the BLT FE protuberance or by the unknown upstream disturbance. Based on these challenges, the turbulent wedge half angle was not formally assessed for STS-128.

Figure 16 shows the thermocouple traces for the forward and protuberance thermocouples. As is shown, the maximum temperature from the measurements was just below 2600˚F and was experienced by the protuberance. Examination of the thermocouple traces for these forward thermocouples shows unexpected behavior for several of the thermocouples.

During the early portion of the trajectory it can be seen that the protuberance thermocouple exhibits the highest temperature and has a laminar peak relatively early in the re-entry at approximately 350 seconds. Unexpectedly, the temperature then steadily decreases until rising again after reaching a temperature of about 1300˚F at approximately 850 seconds. Just before

1100 seconds, the thermocouple signal drops-out completely. It then rises to the maximum temperature (presumably a turbulent value) at around 1150 seconds. Protuberance BLT was assessed to have taken place at 1041 seconds (Mach 13.6) due to the upstream disturbance. One observation that leads to the conclusion that the protuberance thermocouple is suspect during the laminar portion is that the temperature during this portion of the re-entry for STS-128 is lower (0.35" protuberance) than the laminar temperature for STS-119 (0.25" protuberance). This observation cannot be explained from a fluid dynamics perspective. However, post-flight examination of the protuberance surface by material experts seems to corroborate the maximum (~2600˚F) temperature measured by the thermocouple due to visual changes in the tile surface.

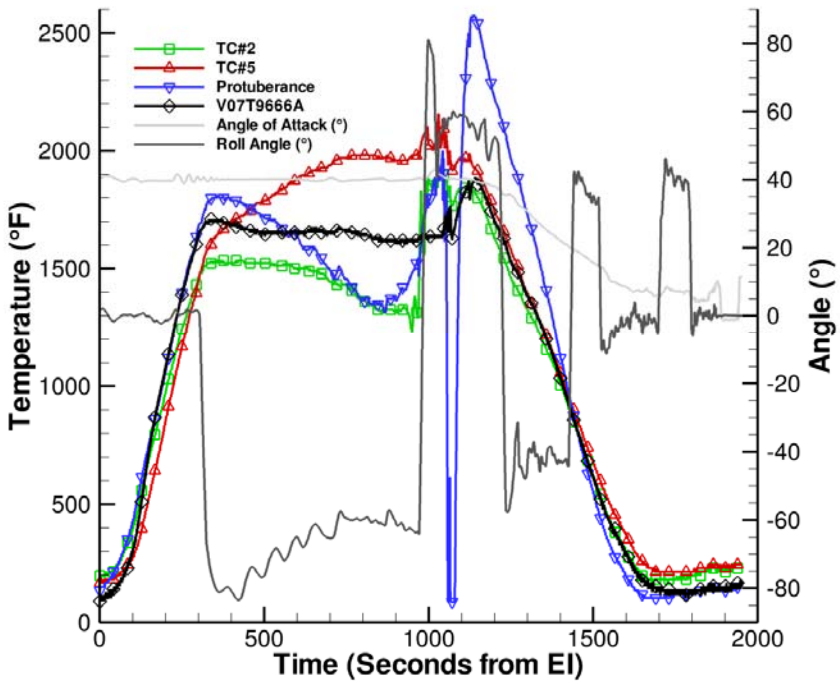

Figure 16: STS-128 data for forward thermocouples

TC 5, located just aft of the protuberance, experienced a continual rise in temperature over the course of the early portion of the trajectory. This behavior is attributed to the relocation of the measurement into the vortex-scrubbing region. Presumably, this vortex heating interaction to the surface masks any clear interpretation of the BLT time, although it was estimated at 1021 seconds (Mach 14.2). The small temperature spike immediately prior to 1021 seconds is attributed to a vehicle maneuver.

TC 2 exhibits behavior similar to the protuberance thermocouple. It reaches a laminar peak relatively early in the trajectory and then steadily decreases before experiencing a rapid rise in temperature. The rapid rise in temperature is assumed to have been caused by transition from the BLT FE protuberance. V07T9666A seems to exhibit relatively nominal behavior in contrast to the discontinuous behavior observed on STS-119.

The cause for the measurement anomalies observed on STS-128 is currently unknown, although similar behavior has been seen on previous Orbiter missions. This behavior has been observed on nearly all tile surface temperature measurements (wing, fuselage, OMS pod). Preliminary studies have shown a possible correlation with roll angle. Ground operations and instrumentation personnel have assessed the system but have found nothing out of the ordinary. It is most often assumed that the thermocouple circuit has intermittent connectivity or that the measurement is real and there is an unexplained aerodynamic or fluid dynamic effect causing the observed behavior in the data. Additional hypotheses are also being considered. These include Radio Frequency (RF) coupling due to the 'antenna' arrangement of the tile thermocouples, a direct voltage or current coupling flow to the thermocouple circuit, and a semi-conductor based Schottky diode effect. The flight experiment team has been coordinating with the Orion technical community in hopes to prevent similar anomalous, non-temperature related measurement effects on Orion.

Following the flight of STS-128, tiles downstream of the protuberance were examined by TPS and material experts in a manner similar to STS-119. Based on experience it was determined none of the downstream tiles exceeded a temperature of 2500˚F. This information has proven useful in post-flight reconstruction activities. A close-up runway photograph of the protuberance is shown in Figure 17.

Figure 17: Post-flight runway photograph of STS-128 (0.35-inch) protuberance.

The protuberance tile was removed from the vehicle in a non-destructive manner and was sent to material experts for additional study. The tile was scanned prior to and after the mission with Optigo and Metris systems and was scanned again on a bench top using an Optigo measuring device to assess the protuberance shape change. A maximum flattening on the protuberance of 0.016" was measured. In addition, the two catalytic coated tiles were removed from the vehicle and have been replaced with new LI-900 tiles. The catalytic coating did exhibit some coating flaking and RCG coating imperfections on the aft portion of the coating footprint (see Figure 18).

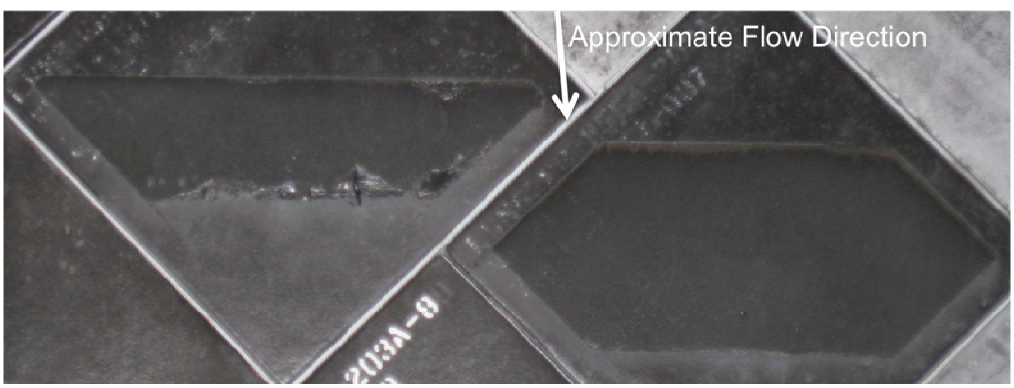

Figure 18: Post-flight runway photograph of catalytic coating following STS-128.

Flight Data and Analysis Prediction Comparisons

Comparisons between predicted and earliest observed BLT onset times were again very favorable. As discussed in Reference 6, the predicted onset time for a 0.35-inch height using the BET was Mach 17.4. The observed BLT onset time at TC 1 was Mach 17.5. This is within the ±1-σ prediction uncertainty of the BLT Tool[6].

Comparisons between predicted and observed temperatures for STS-128 were improved over the comparisons for STS-119. However, the analytical predictions were found to be higher than actual measurements. The ease of making comparisons is complicated by the upstream asymmetric BLT event. The available analysis results of most applicability to the flight data comparison are the results assuming an upstream BLT at Mach 16.2 (see Table 3). For that case, the predicted temperature on the protuberance was 2799˚F versus the maximum-recorded temperature on the protuberance of 2562˚F. Similar to STS-119, the ability to compare predictions to actual flight data was less precise for the tiles surrounding the protuberance because of the sparseness of the instrumentation. However, material experts have stated that the tile coating temperature did not exceed 2500˚F. This is in contrast to the maximum pre-flight prediction of 2995˚F for the protuberance tile acreage. However, it is believed that the temperatures were actually much lower than 2500˚F and so the over-prediction is more severe than this initial comparison suggests. It is also important to note that the analysis summarized in Table 3 is for an earlier BLT event than that experienced on STS-128 (Mach 16.2 in the analysis vs. Mach 13.6 in flight).

Due to the better placement of TC5, it is believed that future analysis predictions will be more accurate for the tile acreage surrounding the protuberance. However, in order to obtain ideal data to improve predictions in the peak vortex-heating region, an instrument would need to be placed within the vortex footprint immediately downstream of the protuberance.

Analysis in Support of Flight Experiment #3

Due to the thermocouple anomaly experienced during STS-128 and the subsequent difficulty in determining peak laminar temperatures on both the protuberance as well as the rest of the tile acreage within the turbulent wedge, the decision was made to re-fly the 0.35-inch protuberance. Because this was a re-flight of an already analyzed boundary layer trip configuration, significantly less additional analysis was required in preparation for the third flight, STS-131.

STS-131

Mission Overview

For STS-131, Space Shuttle *Discovery* launched from Kennedy Space Center on April 5, 2010. The mission consisted of 3 spacewalks and the Orbiter was docked to the ISS for 10 days. The three spacewalks consisted of, among many other tasks, installing a new Ammonia Tank Assembly (ATA) and retrieving Micro-Meteoroid Orbital Debris (MMOD) shields. The Orbiter also carried with it the Multi-Purpose Logistics Module (MPLM) *Leonardo*, which was filled with supplies for the ISS. All prime objectives of the mission were achieved. *Discovery* landed safely at Kennedy Space Center in Florida on April 20, 2010.

Unlike both STS-119 and STS-128, post-flight examination of thermocouple data showed that *Discovery* had not experienced an early asymmetric BLT event during the STS-131 re-entry. The vehicle experience BLT relatively late in the trajectory, at approximately Mach 6.8. Figure 19 shows the thermocouples and associated BLT Mach numbers on the vehicle. HYTHIRM observations at closest approach were at approximately Mach 15 and are shown in Figure 20.

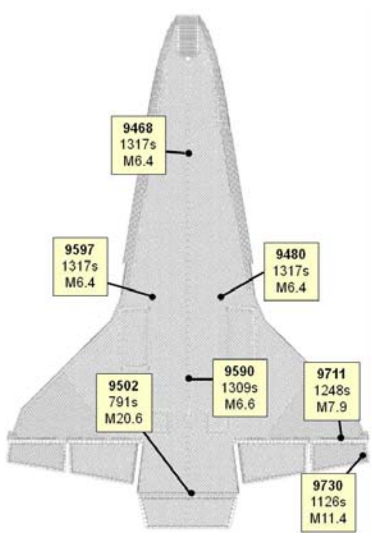

Figure 19: Post-flight reconstruction STS-131

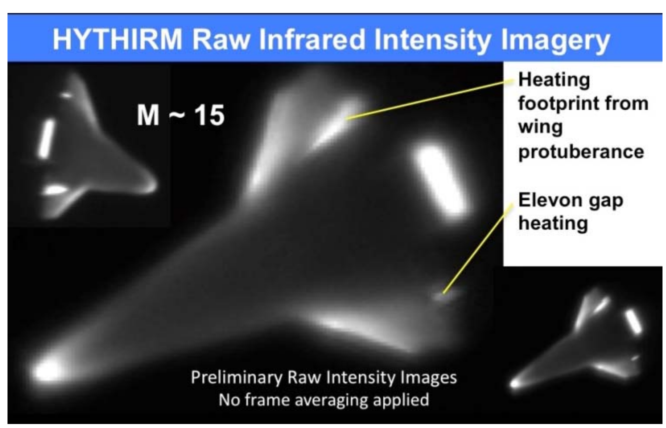

Figure 20: STS-131 HYTHIRM imagery[13, 14]

Flight Data Overview

For convenience during the discussion of the flight data, the labeled flight experiment thermocouples are shown in Figure 21. Thermocouple time traces are shown in Figure 22 and Figure 23. Similar to the STS-119 and STS-128 presentations, the thermocouple data are plotted in two different plots for the sake of clarity. Figure 22 shows the thermocouple data associated with the flight experiment thermocouples that are furthest aft, while Figure 23 shows the data for thermocouples farther forward and on the protuberance. The data is plotted using the post-flight BET.

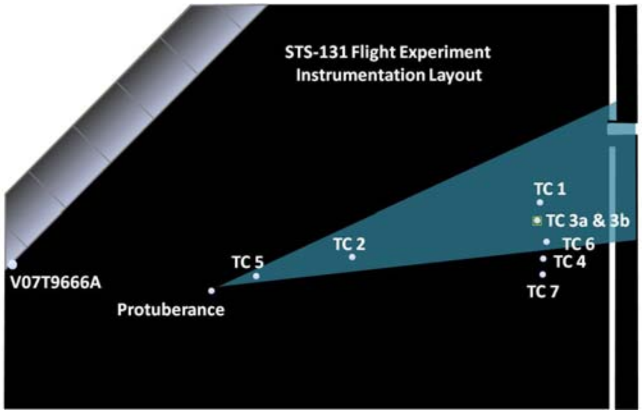

Figure 21: Thermocouple labels for STS-131.

A quick glance at the aft thermocouple traces in Figure 22 show that temperatures did not exceed 2000˚F, with the peak temperatures experienced during the turbulent portion of the entry. With the exception of TC 1, TC 3a and TC 3b, temperatures during the laminar portion of the trajectory were all similar with peak laminar temperatures between approximately 1500 and 1600˚F. It should be noted again that both TC 3a and TC 3b had catalytic coating applied to the surface. As such, the elevated temperatures in relation to the other aft thermocouples are expected. It is also worthwhile to note that because of the thermocouple placement at the leading edge of the catalytic coating, it was expected that TC 3b would exhibit a higher temperature than TC 3a.

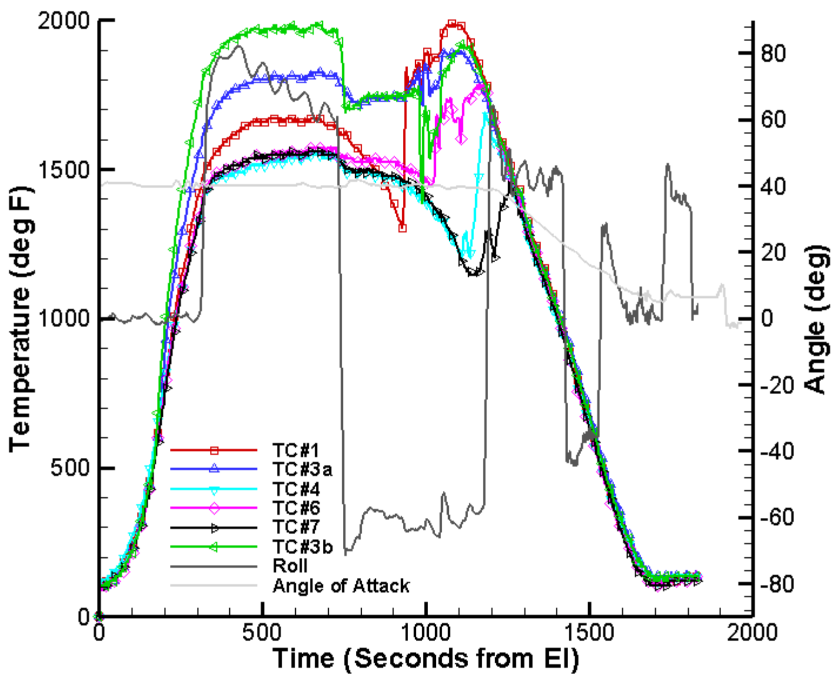

Figure 22: STS-131 data for aft thermocouples

TC 1 is located at the center of the predicted wedge and shows the earliest sign of non-laminar behavior at 929 seconds. This corresponds to a Mach number of 17.4 based on the BET. The thermocouple data then indicates that the turbulent wedge progresses inboard, as expected, with TC 3a and 3b (both Mach 15.1, 1012 sec) showing the next sign of non-laminar behavior, followed by TC 6 (Mach 14.8, 1022 sec). There appears to be a delay in BLT of approximately 90 seconds between TC 6 and TC 4 (Mach 12.0, 1109 sec) and another 50 seconds between TC 4 and TC 7 (Mach 10.5, 1157 sec). Based on this information, it appears that the turbulent wedge was initially very narrow before widening later in the trajectory. The turbulent half angle was measured based on the thermocouple observations as well as post flight visual inspections and determined to be approximately 7 deg. It should be noted that a number of the thermocouples exhibit the sudden drop or drifting behavior that was observed in the STS-128 data. The onset of the behavior coincides with initiation of roll reversal maneuvers.

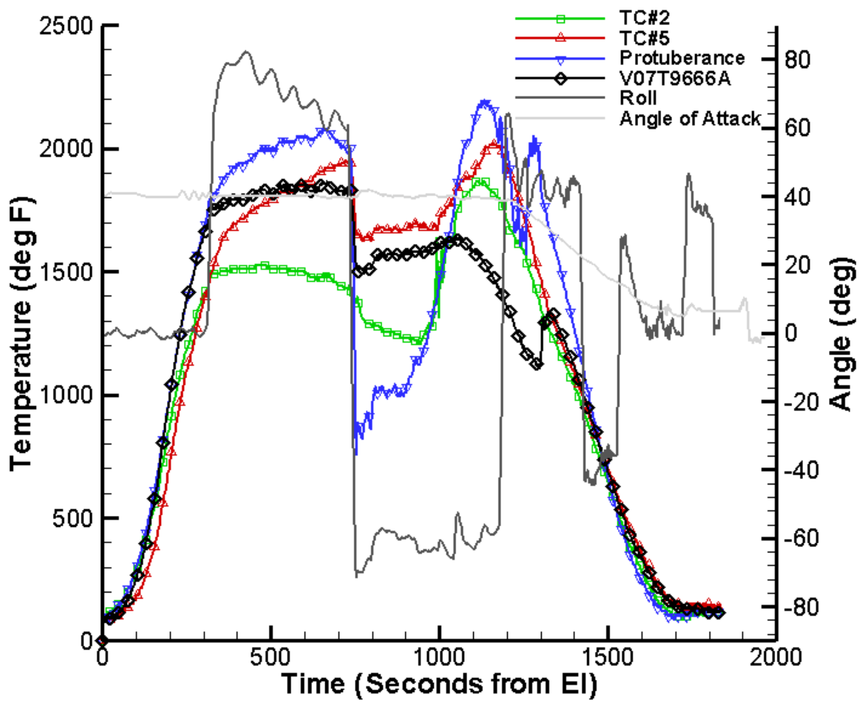

Figure 23: STS-131 data for forward thermocouples

Figure 23 shows the thermocouple traces for the forward and protuberance thermocouples. As is shown, the maximum temperature from the measurements was just below 2200˚F and was experienced by the protuberance. Examination of the thermocouple traces for these forward thermocouples shows the thermocouple anomaly behavior for several of the thermocouples. All of the forward thermocouples exhibit a drop in temperature at approximately 750 seconds, the same time that a roll reversal maneuver is initiated.

During the early portion of the trajectory it can be seen that the protuberance thermocouple exhibits the highest temperature and has a laminar peak at approximately 650 seconds. At 750 seconds the temperature then suddenly decreases over 1000 °F (at the same time as a roll reversal maneuver) before rising again. It then rises to the maximum temperature at around 1115 seconds. Protuberance BLT was assessed to have taken place at 1259 seconds (Mach 7.7). Post-flight visual examination of the protuberance surface by material experts corroborates that the temperature on the protuberance did not exceed 2600 °F.

TC 5, located just aft of the protuberance, experienced a continual rise in temperature over the course of the early portion of the trajectory. This behavior is attributed to the location of the measurement into the vortex-scrubbing region. This vortex heating interaction to the surface masks any clear interpretation of the BLT time, although it was estimated at 996 seconds (Mach 15.6).

TC 2 reaches a laminar peak relatively early in the trajectory and then steadily decreases before experiencing a rapid rise in temperature. The rapid rise in temperature is assumed to have been caused by transition from the BLT FE protuberance. V07T9666A seems to exhibit behavior similar to STS-119 and is nominal with the exception of the drop at 750 seconds that all of the thermocouples experienced.

The cause for the measurement anomalies observed on STS-131 is currently unknown, although similar behavior has been seen on previous Orbiter missions, including STS-128. Anomaly onset for all thermocouples on this flight seems to correlate with the initiation of roll reversals. In order to try to reduce the effects of the anomaly prior to this flight, ground crew thoroughly checked all wiring and connections. In this case, the first roll reversal occurred much later than in STS-128 (750 seconds compared to 350 seconds) allowing for significantly more laminar data to be collected. As a result, laminar heating levels are much clearer and offer more confidence than those from STS-128.

Following the flight of STS-131, tiles downstream of the protuberance were examined by TPS and material experts in a manner similar to STS-119 and STS-128. Based on experience it was determined none of the downstream tiles exceeded a temperature of 2500˚F. This information has proven useful in post-flight reconstruction. A runway photograph of the protuberance is shown in Figure 24.

Figure 24: Post-flight runway photograph of STS-131 (0.35-inch) protuberance.

The protuberance tile was removed from the vehicle in a non-destructive manner and was sent to material experts for additional study. The tile was scanned prior to and after the mission with Optigo and Metris systems and was scanned again on a bench top using an Optigo measuring device to assess the protuberance shape change. A maximum flattening on the protuberance of 0.01" was measured. In addition, the catalytic coated tile was removed from the vehicle and replaced with a new LI-900 tile. The catalytic coating seemed to hold up better on STS-131 as compared to STS-128. The leading edge appeared to be fully intact while the trailing edge did appear to have some material loss (Figure 25).

Flight Data and Analysis Prediction Comparisons

Comparisons between predicted and earliest observed BLT onset times were again very favorable. The predicted onset time for a 0.35-inch height using the BET was Mach 17.2. The observed BLT onset time at TC 1 was Mach 17.4. This is within the ±1-σ prediction uncertainty of the BLT Tool[6].

As with the previous flights, the analytical predictions were found to be higher than actual measurements. Predicted temperatures on the protuberance were 2799˚F, as compared to the maximum-recorded temperature on the protuberance of 2197˚F. Similar to the previous flights, the ability to compare predictions to actual flight data was less precise for the tiles surrounding the protuberance because of the sparseness of the instrumentation. Material experts have stated that the tile coating temperature did not exceed 2500˚F. This is in contrast to the maximum pre-flight prediction of 2995˚F for the protuberance tile acreage. However, it is believed that the temperatures were actually much lower than 2500˚F and so the over-prediction is more severe than this initial comparison suggests. It is also important to note that the analysis summarized in Table 3 is for a much earlier vehicle BLT event than that experienced on STS-131 (Mach 16.2 in the analysis vs. approximately Mach 6.8 in flight for the vehicle acreage).

Figure 25: Post-flight runway photograph of catalytic coating following STS-131.

Analysis in Support of Flight Experiments #4 and 5

As a result of the cleaner, though still somewhat compromised, STS-131 flight data, in addition to additional analysis, the rationale was developed to fly a 0.5-inch protuberance on the fourth BLT DTO FE flight, STS-133. A similar analysis procedure was used for the fourth flight as was used for the second flight, STS-128, when the protuberance height was increased from 0.25 to 0.35 inches. This included the use of the "knockdown factors," adjusted for the additional STS-128 and STS-131 data. Following their derivation, the knockdown factors were applied to the STS-133 pre-flight certification analysis with the assumption that the knockdown factors were appropriate for use with the 0.50-inch protuberance. While 0.35-inch protuberance CFD solutions were used for the STS-131 reconstruction and knockdown factor derivation, 0.50-inch protuberance CFD heating distributions were used for the STS-133 certification analysis. These distributions were used in combination with the undisturbed heating, CFD heating augmentation factor magnitudes, and derived knockdown factors.

For the STS-133 certification analysis, the BLT time needed for the prediction was derived using a generic ISS return trajectory, a protuberance height of 0.50-inches, and the Re_θ/M_e correlation in the BLT version 2 tool[6]. Results of the analysis are shown in Table 4.

Table 4: STS-133 predictions for pre-flight STS-133 and generic ISS return trajectories.

Material	**Peak Temperature (˚F)**
	Generic ISS Return
Protuberance	2944
Protuberance tile acreage	2533
LI-2200 tile	2527
LI-900 tile	2284
RTV	472
Aluminum structure	174

In the case of the generic ISS return trajectory (which was used for certification of STS-133), a material temperature waiver was required for the protuberance as the predicted temperature of 2944˚F exceeded the single-use limit for BRI-18 by 44˚F for 35 seconds. Rationale for the appropriateness of the waiver was based on the fact that (1) the predicted time of the over-temperature condition was relatively short (2) a certification-level (conservative) trajectory was being used for the assessment and (3) despite the surface over-temperature condition, acceptable tile factors of safety and structural margins were predicted. It was also believed that the analysis was still slightly conservative, even after the adjustments made following STS-119, STS-128 and STS-131.

Because of ground operations schedule constraints, a decision on the plans for the next flight experiment (currently planned for STS-133 in November 2010) was needed relatively soon following STS-131. Analysis was completed within two months and a recommendation from the BLT FE team was accepted by the SSP to fly a 0.50-in protuberance on STS-133.

In addition, a proposal to execute a scaled back version of the flight experiment (including the boundary layer trip and three or four thermocouples) was approved for STS-134, to be flown on OV-105, *Endeavour*. The protuberance will be the same height as STS-133, 0.5", and will allow for the team to collect data on a separate vehicle. One thermocouple will be wired with a different configuration, allowing the team to examine the effects of the wiring on the thermocouple anomaly. The launch is currently planned for February 2011.

BLT Hypotheses Discussion

As part of the discussion in Reference 5, the authors presented four hypotheses that Orbiter BLT flight-testing could address. These hypotheses are summarized below. See Reference 5 for a more complete discussion of the basis for each of the hypotheses.

A. BLT *cannot* be initiated with a discrete protuberance at hypersonic non-equilibrium entry conditions.
B. There *is not* a ground-to-flight environment scaling effect on discrete protuberance induced BLT at hypersonic non-equilibrium conditions.
C. High Mach number/high enthalpy non-laminar heating is *not* fully turbulent.
D. High Mach number/high enthalpy heating for turbulent boundary layers and surface catalysis interact and are thus *dependent* upon each other.

Based on the data obtained from the first three flights of the flight experiment, relatively clear conclusions can be stated about two of the hypotheses while additional data will be required for the other two.

Because the boundary layer was tripped at Mach 15.6 (STS-119), 17.5 (STS-128) and 17.4 (STS-131), the data from the flight experiment refutes hypothesis A. A discrete protuberance was placed on the Orbiter with sufficient instrumentation downstream to measure the effects of the protuberance. The instrumentation showed transitional behavior at hypersonic non-equilibrium conditions.

The data from the three flights also refutes hypothesis B, although not as directly as it refutes hypothesis A. The basis for this statement hinges on the methods used to develop the Version 2 of the BLT tool and the accuracy of the tool with respect to the observed BLT onset times from the flight experiments. As outlined in Reference 6, the tool was created by first developing a correlation methodology based on available ground test data. The correlation was then calibrated to the available Orbiter flight data. Reference 6 clearly shows that a significant adjustment to the ground-based correlation was required to match the flight data. The BLT tool predicted BLT onset for both flights of the flight experiment well within the 1-σ uncertainty bounds. Due to these factors, it can be stated that there *is* a ground-to-flight scaling effect on discrete protuberance induced BLT at hypersonic non-equilibrium conditions. Additional efforts to establish the confidence level on discrete protuberance incipient BLT will be assessed after all five flights of the Orbiter BLT Flight Experiment are completed.

Data obtained from the three flights of the flight experiment are not sufficient to confirm or refute hypothesis C. While comparisons[31] between the flight data and Navier Stokes based turbulent flow models (at hypersonic non-equilibrium conditions) show a divergence at higher Mach numbers, the question remains as to whether or not the turbulent flow models are the cause of the discrepancy or if the actual heating in the studied flight regime is not fully turbulent. The additional planned flights will help in future evaluations of hypothesis C. This hypothesis is also of significant interest to the Orion aerothermodynamics and TPS community, because the Orion after-body TPS are currently being designed to a turbulent and fully catalytic heating environment. Realization of reduced heating environments for the Orion after-body could either lead to improved performance with the existing design or reduction to the after-body TPS thickness to save weight.

Because of the thermocouple behavior observed on STS-128 and STS-131 for the catalytic coated tiles, data does not exist to refute or confirm hypothesis D. While the flight data did show the catalytic heating increment for laminar conditions, the behavior of the thermocouples during the turbulent regime makes it difficult to draw conclusions. The additional planned flights will help in future evaluations of hypothesis D.

Conclusions and Summary

In support of the Boundary Layer Transition Flight Experiment Project, a manufactured protuberance tile was installed on the port wing of *Discovery* on STS-119, STS-128 and STS-131. Additional instrumentation was also installed in order to obtain more spatially resolved measurements downstream of the protuberance. This instrumentation measured boundary layer transition and associated temperatures during flight. Comparisons of analytical predictions and the obtained flight data have shown that while BLT onset times have been accurately predicted using the engineering correlations, temperature has been significantly over predicted with respect to the measured temperatures. The reason for these discrepancies is currently unknown. To obtain additional data to increase understanding of BLT, turbulent flow, and gas-surface interactions, two additional flights of the flight experiment are currently in the planning stages and will be flown on STS-133, in November 2010 and STS-134, in February 2011.

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