

Secondary Side Considerations for the BOLT Flight Experiment

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The Boundary Layer Transition (BOLT) Flight Experiment is preparing for launch in the Spring of 2020. Final designs decisions have been made to allow fabrication of hardware. The secondary side experiment, which was initially proposed to be a roughness experiment, was selected instead to be an investigation of step effects to provide better synergy with the primary side. Numerous design decisions have influenced the decision to revise and refine the goal of the secondary side, which is now to investigate the effects of rearward-facing steps. The present paper focused on the BOLT secondary side flight experiment, providing details of the key inputs and decisions made to finalize the flight vehicle and instrumentation.

I. Nomenclature

M	Mach number	u	freestream velocity
Re	unit Reynolds number (1/m or 1/ft)	k	trip height (mm/in)
x	longitudinal distance from the nose (mm/in)	δ	boundary layer thickness (mm/in)
L	model reference length from nose to end of body (mm/in)	Subscripts:	
α	vehicle angle of attack (deg)	θ	momentum thickness (mm/in)
β	vehicle sideslip (deg)	kk	all properties evaluated at the trip height
ρ	density	ke	all properties except k evaluated at the boundary layer edge
μ	viscosity	e	boundary layer edge

II. Introduction

The Boundary Layer Transition (BOLT) Flight Experiment was initiated in 2017 with the John Hopkins University Applied Physics Laboratory (JHU/APL) as the principal investigator. BOLT is sponsored by the Air Force Office of Scientific Research (AFOSR) and is intended to succeed the Hypersonic International Flight Research Experimentation (HIFiRE) boundary-layer transition (BLT) flights. With increasing geometric complexity, each BLT flight has sought to build upon the success of the former, first starting with HIFiRE 1 on a straight cone, then HIFiRE 5 on an elliptic cone, and now BOLT, a highly three-dimensional body with concave surfaces and swept leading edges. The intent of BOLT is to use state-of-the-art numerical transition prediction tools, combined with ground-test data, to design, build, and fly a high-quality boundary layer experiment on a sounding rocket at hypersonic conditions. Reference 1 provides a recent

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review of BOLT, which provides details about the mechanical design, including the need for joints to maintain structural and thermal integrity of the vehicle throughout the planned trajectory. Based on an in-depth 3D thermal analysis of the proposed mechanical design for expected flight conditions, the BOLT Flight Geometry was selected to be made up of three parts of differing material: (1) an iridium-coated titanium zirconium molybdenum (TZM) nose-tip, (2) a stainless steel isolator section, and (3) an aluminum aft section. The first joint, between the TZM and stainless, is located at 82.55 mm (or 3.25 in) from the nose, while the second joint, between the stainless and aluminum, is located at 184.15 mm (or 7.25 in) from the nose. Figure 1 provides a view of the assembly in parts, showing the three sections of the main forebody. These joint locations, near the front of BOLT, were selected fairly early in the design cycle of the mechanical hardware. Additional details of BOLT and its experimental campaign can be found in Refs. 2 - 5. For the previous HIFiRE flights, similar nose-tip joints were flown, see Refs. 6 - 9. Different materials in each part mean differential thermal growth at the joints during flight. As was done on HIFiRE, the joints were selected to be rearward-facing (RF) steps on the launchpad (what is referred to by the team as the “cold-wall” condition) with the size of the step selected to always be RF during the flight test window as the parts heat up.

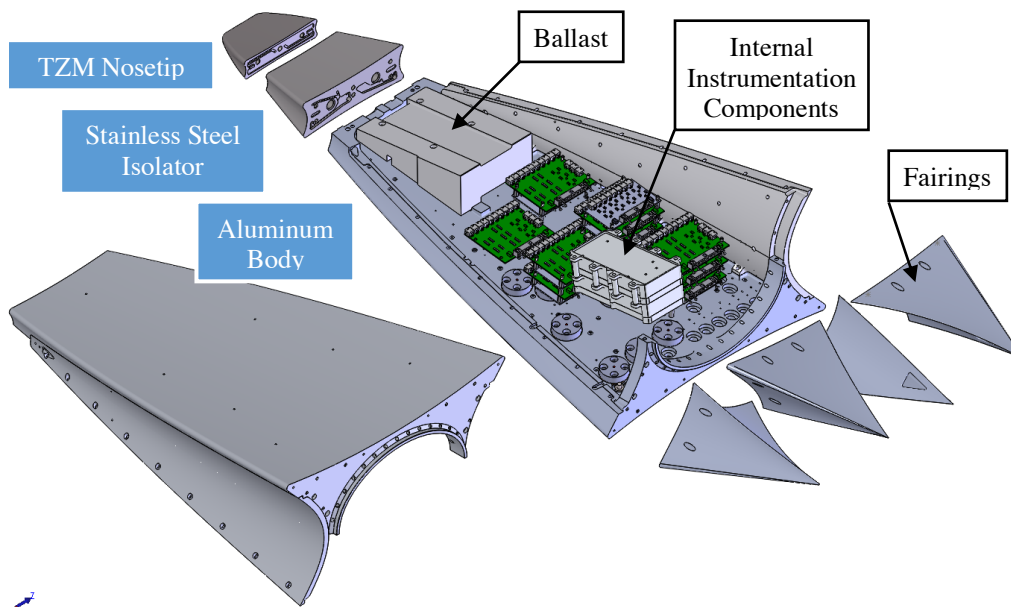


Figure 1. Exploded view of assembly showing the three main sections of the forebody.

The primary goal of the BOLT flight experiment is to measure natural boundary layer transition onset on the baseline geometry. Therefore, the joints, as designed and built into the vehicle, should not interfere with the instability breakdown process on the primary side of the vehicle, which contains a majority of the critical instrumentation. The primary side joint steps should be kept small (details to be discussed later) in order to not adversely affect the natural transition process, but some uncertainty remains. There was an additional objective for BOLT to measure boundary layer transition in the presence of intentional roughness, which was to be conducted on the side opposite the primary (which is referred to as the secondary side). However, after some consultation with the broader team, and to address the inherent uncertainty with which the joints on both sides could impact the results, the secondary side objective evolved into an intentional exaggeration of the secondary side joint step to better understanding of the effect of RF steps on boundary layer transition. While other options were initially considered to satisfy the “roughness” goal for the BOLT secondary side, the government review team at the Preliminary Design Review (PDR) felt that additional data on the joint-step effects on BLT would provide better return on investment.

For clarity, the steps being discussed here are considered quasi two-dimensional (2D) since the joints are nearly perpendicular to the flow direction. However, this is not to imply that the height of the step will be

uniform all around the circumference of the joint, as might be implied by calling it 2D. Despite this discrepancy, the steps here are labeled as 2D to reflect the notion that any disturbance created by the step should behave more 2D-like (with a mostly uniform separation and reattachment along the span), and not at all like what would occur with a three-dimensional (3D) trip that energizes the local vorticity (and creates large nonuniformities across the span).

In preparation to finalize the design of the BOLT flight vehicle, a fast-paced test entry was formulated and conducted in Purdue's Boeing/AFOSR Mach 6 Quiet Tunnel (BAM6QT) to look at the effect of both forward and rearward facing steps, see Ref. 10. The BAM6QT test was conducted to gather some preliminary data for identification of allowable forward-facing (FF) and RF steps for flight. The data were limited but suggested RF steps are much less likely to promote early BLT, which substantiated previous decisions to use RF steps on HIFiRE, as well as here on BOLT. Largely influenced by the uncertainty associated with 2D step effects on BLT in hypersonic flight, the decision was made to utilize RF steps on all joints and to size the steps based on consideration of the differential thermal growth of each part such that the steps always remain RF throughout the test windows (both ascent and descent). Ultimately, the BAM6QT study provided guidance for the final decisions on the sensitivity of boundary layer transition due to 2D steps.

Concurrent with the Purdue BAM6QT test entry, a transient thermal analysis coupled with nonlinear structural finite element model (FEM) was accomplished (see Ref. 1) on the proposed mechanical design, to predict how much thermal growth would occur during the entire flight trajectory, and more importantly the differential growth at the joints. The worst-case differential growth for both joints was used to size rearward facing steps at the joints with some margin, to ensure that the steps would always remain rearward facing. The primary side joints are intended to be as small as possible but still remain always rearward facing, while the secondary side will be intentionally exaggerated to provide additional insight into the boundary layer transition threshold in flight due to 2D RF steps. Details as to the selected steps sizes for both sides will be discussed in later sections. *The specific objective for this paper will be to provide a review of the secondary side experiment and describe how it supports the overall goals of the BOLT flight project.*

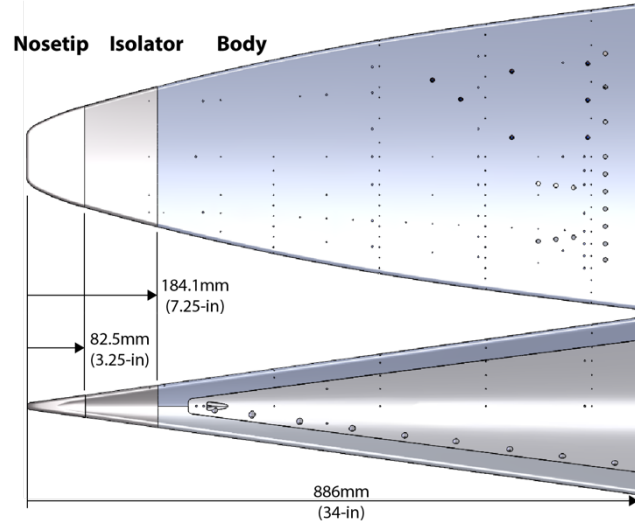


Figure 2. Planform view of flight geometry showing location of the joints.

III. BOLT Flight Vehicle & Joint-Steps

BOLT has been designed with two interface joints (between the sections) that are roughly within the first 20% of the total flight geometry length, as shown in Fig. 2. The first joint, between the nosetip and isolator, is referred to as the upstream joint, while the second, between the isolator and main body, is referred to as the downstream joint. As mentioned in Ref. 1, the hardware had to be finalized soon after the Critical Design Review (CDR), which occurred 18 months after kick-off of the project. The FEM analysis of the thermal response of the parts was accomplished just before CDR. Those results set the step heights on

the primary side, in order to ensure the step remained RF during the key experimental test windows during ascent and descent. They also influenced the size of the steps on the secondary side, with consideration of the BAM6QT results. Note, that the PDR and CDR were roughly 3 months apart, and that the many of the key decisions on how to proceed on the secondary side were made coming out of PDR, and had to be finalized at CDR. Thus, the secondary side experiment was formulated in a very short timeframe.

The primary side joint RF steps were determined based on the FEM analysis, with some conservative margin to insure the steps remain RF during the entire trajectory. Figure 3 provides the FEM-determined optimal cold-wall step heights for both joints of the primary side, and also shows the axial distribution of the RF steps along the joints. In this figure, the view is of the side of the geometry, where the flow would be from left to right. The main experiment surface is visible on the upper portion of the image, and the side “gutter” is visible on the lower portion of the image. As shown, the step height does vary azimuthally around the joint but is always largest on the swept LE itself, which is the location chosen to represent the steps. As noted in the figure, the upstream RF step was fixed at 0.008-in high, while the downstream joint was 0.007-in. The downstream joint was selected to be the linchpin for comparison to the secondary side, becoming the control height, and thus, is subsequently referred to as a “1x” step.

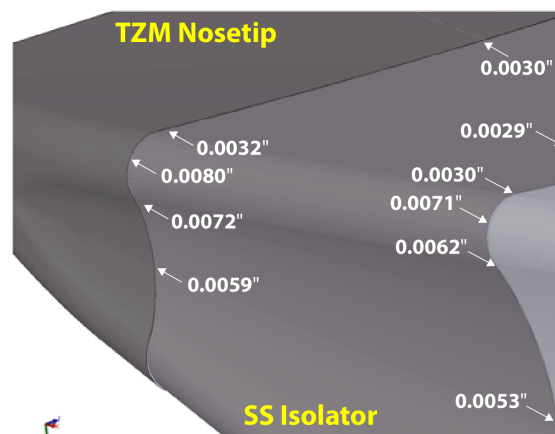


Figure 3. Primary side RF step distribution based on FEM analysis.

For the secondary side, the decision was made soon after PDR to create an even bigger RF step at the downstream joint by choosing some multiple larger than the primary side. The exact multiple was to be based on the BAM6QT data, which was initiated and completed within the few months between PDR and CDR. The focus on RF step effects on the secondary side was a recommendation from the review team coming out of PDR, and this decision was largely justified when reviewing the Purdue BAM6QT results and the large uncertainties associated with interpreting those results for the flight vehicle. Another secondary side decision, this one made at the CDR, was that the steps would be notionally mirrored on both sides of centerline (at least for planning purposes), thereby intending to provide some measure of repeatability data. Of course, manufacturing issues could result in some variation across the span, and the intent is to document the as-built step sizes as detailed as possible before flight. The team is presently pursuing detailed measurements of all the joint steps, as the vehicle has finally been fully assembled in preparation for shipment to the launch provider.

The original CAD design, of course, was baselined based on the ideal situation for a perfectly smooth surface with no steps at the joints. Inclusion of joint-steps required modifications to the original CAD file. To build in precise, well-controlled steps during fabrication, a plan was adopted whereby the isolator section was lengthened while continuing the contour, as shown in Fig. 4. Lengthening the isolator in this manner provides an easy way to build in controlled steps at each joint, as shown in the figure. A small amount of lengthening, say on the order of 0.050-in corresponds to less than 2% growth in the length of the part. A further modification to specifically tune the secondary side to the desired larger step requires a local skim cut of the aluminum surface across the span and a gradual taper of the surface back into the original lines. The amount of aluminum to be skimmed from the secondary side surface should be small, on the order of

a few thousands of an inch (notionally only 2% of the skin thickness). Figure 5 provides an image of the CAD file of the conceptual secondary side step, with the blue surface indicating the extent of the surface to be skimmed and contoured back to the original OML surface.

The decision to revise the goal of the secondary side to be a 2D RF step experiment was predicated on the added synergy to the primary side. While a roughness experiment, such as the originally-planned test of discrete trips, would have been considered valuable flight results, they would not have provided any insight into the impact of the steps that were being planned for the primary side.

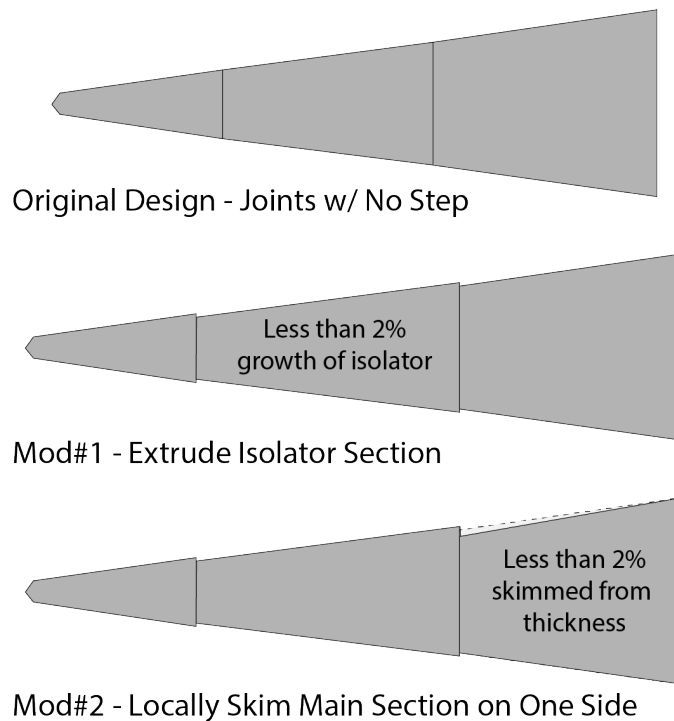


Figure 4. Schematic showing fabrication plan to build in well-controlled steps.

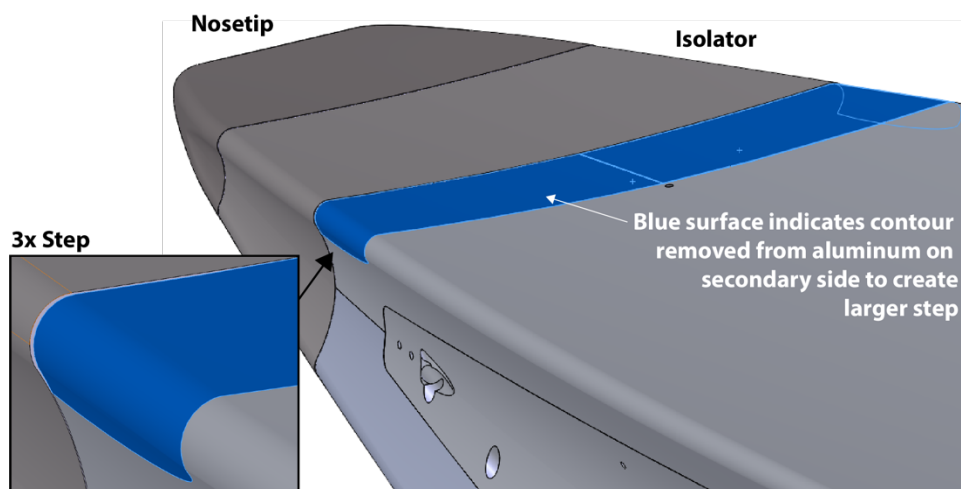


Figure 5. Image of the CAD file showing the secondary side 3x step.

IV. Numerical Methods

The correlations to be presented in this paper were extracted from laminar computational fluid dynamics (CFD) simulations performed by JHU/APL. The CFD cases at wind tunnel conditions were solutions previously generated to support the on-going ground test campaign, which included several entries into the Purdue BAM6QT with the 33% scale model.³ Several CFD solutions were previously available at Purdue freestream conditions corresponding to tunnel stagnation pressures of 620, 827, 965, 1069, and 1172 kPa (90, 120, 140, 155, and 170 psia), with all solutions at a nominal stagnation temperature of 160°C (392°F). At the time of the newer step effects test, the BAM6QT was operating at a maximum quiet stagnation pressure nearer to 1,103 kPa (160 psia). As such, the majority of the runs were started at this initial stagnation pressure with the corresponding results analyzed at an instantaneous stagnation pressure of 149 +/- 2 psia.¹⁰ The CFD results from 1069 kPa stagnation pressure freestream conditions, corresponding to a unit freestream Reynolds number of 11.4e6/m (3.5e6/ft), were thus selected to compare against the data as this Reynolds number most closely matched the reported Reynolds number of the experimental data of 11.3e6/m (3.4e6/ft). The CFD solutions at wind-tunnel conditions were not repeated for the actual as-tested freestream conditions of the experiment, since the Reynolds number was within one percent of the actual value.

The flight cases also were solutions completed ahead of time to cover a variety of nominal flight trajectory points.² These flight cases were performed with a constant isothermal wall temperature of 400K (260°F), originally to support a variety of flow analyses and calculation of heat transfer rates for transient thermal analyses. In reality, the wall temperature distribution will vary throughout flight, however, a 400K wall temperature was largely close to the expected bulk temperature of the aluminum frustum components throughout the majority of flight. The nominal expected temperature distribution in flight is shown in Figures 11-15 in Ref. 2, but does depend largely on assumptions for transition and will ultimately depend on the final as-flown trajectory realized in the flight experiment. With regards to calculation of the step correlations at flight conditions, the global 400K isothermal wall temperature boundary condition will result in cooler temperatures locally at the swept leading edge, particularly during the final few seconds of flight during the descent experiment window where temperatures are expected to approach 550K. Due to the cooler wall temperature in the simulations, the local boundary layer at the swept leading edge for the 400K isothermal wall CFD cases will be thinner than expected at the end of flight. Thus, correlations extracted from the flight cases near the end of the descent experiment may be conservative in terms of allowable steps, since in reality, the boundary layer at the swept leading edge may be thicker.

Both the wind tunnel and flight cases used for calculation of the correlations were completed on a smooth-wall configuration for the nominal flight attitude of zero angle of attack and yaw, although a limited number of CFD solutions were available at nonzero angles-of-attack and yaw. Non-zero cases are shown in Ref. 10 and are used primarily to trace streamlines to compare against the experimental data from the Purdue entry.

The grid used for these computations was created using the GoHypersonic LINK-3D structured grid generation software. The grid is 17.1 million cells for the quarter geometry and contains ~250 wall-normal cells with clustering for greater than 100 points within the boundary layer. Mean flows were generated with the Metacomp CFD++ flow solver. JHU/APL post-processing tools were used to calculate the correlation parameters by extracting a wall-normal boundary layer profile at each surface node location from the laminar mean flow solution. The boundary-layer edge properties were extracted from the wall-normal height defined as the edge using the first point to reach 99.5% of the freestream total enthalpy. Because the boundary-layer thickness varies significantly with azimuthal location around the swept leading edge, it is difficult to precisely extract step height correlations unless the precise step height distribution around the leading edge is known (which is also difficult to measure). As such, the correlations reported in this paper were calculated using the locally largest measured step on the swept leading edge, using boundary layer properties evaluated at the minimum boundary-layer thickness around the swept leading edge. By using these conservative assumptions to report the correlations, some measure of conservatism is built into the calculation of allowable step heights in flight particularly for the primary experiment steps.

Streamlines were created in Tecplot using the extracted Cartesian velocity components at the boundary-layer edge (99.5% total enthalpy). These streamlines were initially seeded from points of interest (such as the swept leading edge) to examine the predicted downstream location of transition onset.

Although no grid resolution study was performed for this effort, the results from this grid have compared favorably to separate mean-flows computed by Texas A&M and the University of Minnesota. Additionally, the correlation parameters such as edge conditions have been spot-checked against those computed in US3D to ensure accurate calculation.

V. Purdue Test Program

As the plan to focus on RF steps on the flight vehicle secondary side was being formulated just after PDR, the decision was made to quickly arrange a wind tunnel test entry to directly investigate step effects under quiet tunnel conditions. Testing that had been done for BOLT up to that time had included a few runs dedicated to joint/step effects by virtue of wrapping small shim strips to the standard JHU/APL model that was making the rounds of various facilities.⁴ Shims temporarily attached to the surface meant that both FF and RF steps were present during those particular runs, resulting in a combined test of both, and not directly relatable to flight. The decision was made to investigate step effects systematically, by building a series of new nose tips designed to provide the steps of interest, but only one step at a time (not FF with RF). Chynoweth, et al. (Ref. 10) provides a complete review of that test entry, so only relevant details from that study that pertain to BOLT secondary side flight experiment decisions will be discussed here.

For the Purdue BAM6QT step test entry, the existing JHU/APL model was modified by building a new suite of nose tips intended to provide systematic and well-controlled variation of the step at the joint between the nose tip and the rest of the model. The nose tip joint for that model was in the region of the two joints for the flight configuration, but not in the exact location. Nine new nose tips were built, one to be a replacement smooth step and the others to provide FF and RF steps of ± 0.762 , ± 0.152 , ± 0.254 , ± 0.508 mm (± 0.003 , ± 0.006 , ± 0.010 , and ± 0.020 -in). Figure 6 provides a sketch of the contours at the joint with the various nose tips, showing the range of FF and RF steps that were fabricated. The nominal smooth nose tip is shown in black, while the various colored lines illustrate the range in steps, based on the maximum value at the swept leading edge (LE). Note, that this plot also shows the axial step variation along the joint, based on the maximum value at the swept LE. Instrumentation for the BAM6QT entry included both infrared (IR) and temperature sensitive paint (TSP), as well as high-frequency pressure gauges at nine locations to provide an additional measurement of boundary layer (BL) behavior.

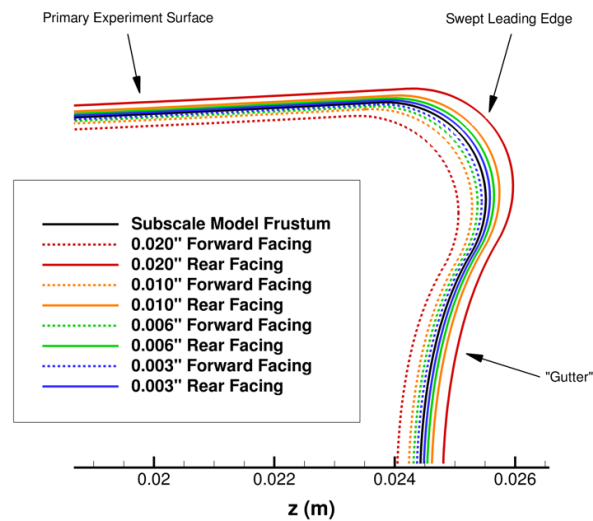


Figure 6. Purdue study to investigate step effects at nose-tip joint.

All results from the BAM6QT step test entry data were acquired near a stagnation pressure of 1027 kPa (149 psia) and a stagnation temperature of 160°C (392°F). The initial data were acquired at the nominal

pitch and yaw ($\alpha, \beta = 0^\circ$), but most of those results showed minimal effects due to steps. The data were primarily acquired under quiet flow conditions. While systematic trends of transition onset and movement were not observed, these results provide a conservative indication of step sizes and conditions that are not likely to cause early BLT at the nominal flight inclinations and were used as conservative thresholds. To further explore the transition onset trends, off-nominal conditions of angle of attack and yaw were also studied and are reported in Ref. 10. It should be noted that the correlations that were developed from the BAM6QT results are considered conservative as applied to flight, as the correlations were extracted from the last known laminar cases using the maximum height on the swept LE as well as the minimum BL thickness. Furthermore, the CFD cases used to extract the BL properties were completed based on cold-wall conditions ($T=400K$). The actual temperatures in flight would be expected to thicken the BL in comparison to the calculations. To correlate the BAM6QT results, BL properties were extracted from smooth-wall CFD solutions at tunnel conditions when transition was observed and compared against historical correlations, as shown in Table 1. Figure 7 provides a sample image providing the calculated Re_{kk} distribution near the nose based on a step height of $k=0.020"$. The results captured in the table reflect an RF step of $0.020"$ showing no effect (and thus, a minimum of 6200), while the FF step of $0.006"$ (or Re_{kk} of 1500) was large enough to have an effect. This suggests almost a 4-to-1 ratio in terms of the tripping effectiveness of an FF step in comparison to the RF step. The data in the Purdue entry provided initial insight into step-induced transition effects, and ongoing research at Purdue is planned to gather more precise step-induced transition data on BOLT.

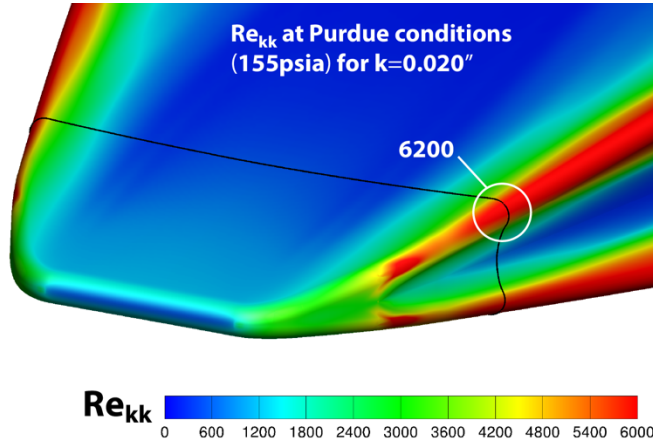


Figure 7. Calculation of Re_{kk} at WT conditions based on RF step of $k=0.020"$

Table 1. Purdue BAM6QT step test results with comparison against historical correlations

Correlation Type	Historical Correlation Constant (for Context)	Forward Facing +0.006" LE +0.002" CL Mostly lam at $\alpha=0^\circ$	Rear Facing -0.020" LE -0.008" CL Laminar at $\alpha=0^\circ$
$Re_{kk} \left(\frac{\rho_k u_k k}{\mu_k} \right)$	~340 for 3D (Ref. 11)	1500	6200
$Re_{ke} \left(\frac{\rho_e u_e k}{\mu_e} \right)$	~800 for 2D AL (Ref. 11)	550	1830
$\frac{Re_\theta k}{M_e \delta}$	32.6 for 3D (Ref 12)	20.9	70.0
$\frac{k}{\delta}$	N/A	2.0	6.8

The historical correlations that were used for this analysis include the roughness Reynolds number correlations of Reda (Ref. 11) based on both local BL profile information at the roughness height (Re_{kk}) and

edge properties (Re_{ke}) and the more recent Shuttle correlations (e.g., see Ref. 12) based only on edge properties ($Re_{ek}/M_e\delta$). The last one (k/δ) shown in Table 1 is not intended as a correlation, but was used primarily for context, for relating the step size to the local BL thickness at the swept LE. It should be noted that the three main correlations listed in the table do not match particularly well back to the historical values that were associated with each approach, as captured in the references (and shown in Table 1). Some of the differences may be attributable to the roughness types that were utilized in the original studies (most were three-dimensional type trips) while those examined for BOLT during the BAM6QT test were exclusively 2D steps. With this disparity in mind, these new correlation constants were treated strictly as a rough guide for BLT in flight due to large uncertainties associated with them.

VI. Design of the Secondary Side Experiment

One of the early design decisions coming out of PDR was to focus strictly on RF steps for all joints and to ensure that they stay RF during most of the flight trajectory. The FEM analysis was utilized to predict the thermal growth of the parts and was scrutinized to understand the uncertainties/margins involved. Based on FEM results, the RF steps at both the upstream and downstream joints on the primary side were selected to be a notional, cold-wall 0.178mm (0.007-in) RF step at the swept LE, which was designated a “1x step.” Note, that the thermal growth at both joints, while not identical, were with 15% of this notional value, as previously shown in Fig. 3. The 1x notation was adopted for ease of comparing the FEM results to the expected BLT behavior predicted based on the BAM6QT results and for relating the primary side steps to the secondary side. Figure 8 provides the results of the step correlations built from the BAM6QT results and trajectory point CFD solutions during ascent (a) and descent (b), including the results from the thermal growth analysis of the primary side steps. The horizontal axes on both plots represents the flight Reynolds number during the critical test window of ascent (Fig. 8a) and descent (Fig. 8b), and in both plots moving from left to right along this axis is equivalent to increasing time along the flight trajectory. The vertical axis is the step height, either FF if positive or RF if negative. The three correlations are also plotted, based on the BAM6QT results, as a threshold such that the region shaded green should indicate that no BLT is expected due to step effects, and the region between the three correlations shaded yellow as an indication of the potential for transitional behavior. Outside of the correlations, the grey regions, it is expected that step sizes of these magnitudes would very likely induce early BLT downstream; therefore, the turbulent region. Thus, during ascent, a 1x RF step (the blue dashed line) is initially within the yellow zone, meaning the step at the swept leading edges could be large enough to affect the measured BLT behavior downstream. By the midpoint of the ascent test window, the step size reduces to the point that it should be small enough to have no influence on transition. On descent, the 1x RF step stays completely within the green zone, thus suggesting no “step effects” on the primary side. As can be seen in these figures, the 1x RF step size was chosen based on the FEM results such that steps remain RF during the both experimental windows, as by the end of Fig. 8b the step size is nearly to zero. Although there was some concern about the initial step effects on the primary side during ascent, the project was not willing to reduce the cold-wall step size at the risk of developing an FF step later in the trajectory.

Note that on ascent, the vehicle will initially be all turbulent, then as the Mach number increases and the Reynolds number decreases, BLT on the vehicle will start to move backwards. Based on the primary side step, the expectation for “natural” BLT behavior will be delayed until about the midpoint of the ascent test window. The reverse happens on descent, where initially the vehicle starts at as all laminar, then gradually transition will move forward on the vehicle independently depending on the side. The large uncertainties with how the single set of BAM6QT data relates to flight was the driving factor on the secondary side becoming an RF step experiment, instead of a roughness-tripping experiment (as was initially intended).

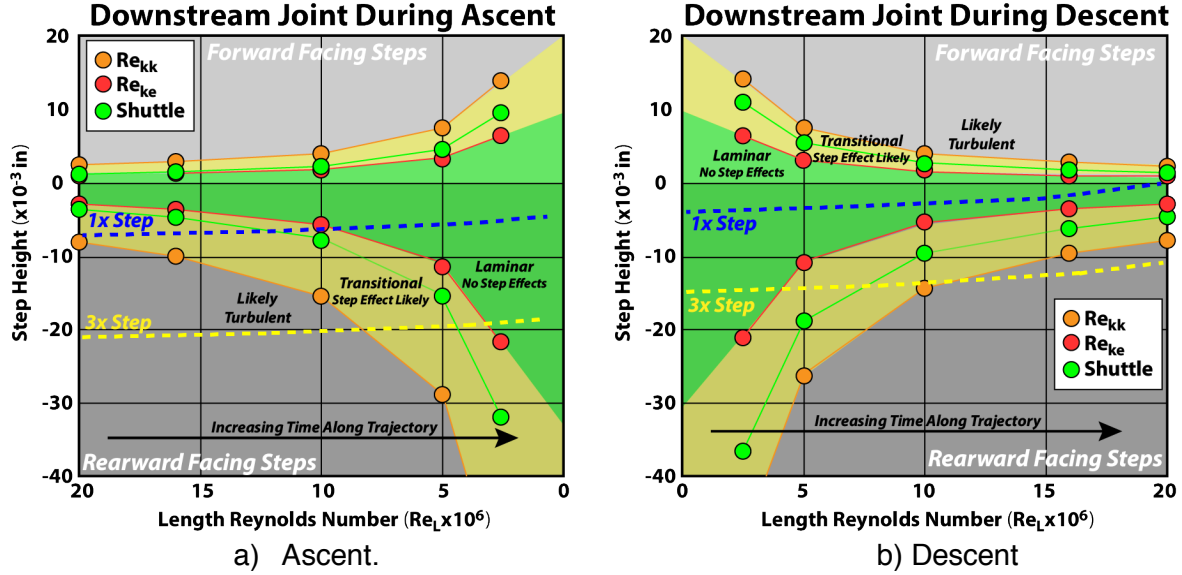


Figure 8. Comparison of correlations against expected step behavior.

Also plotted in Fig. 8 are an engineering estimation of how a 3x step (the yellow dashed line in both plots) would behave based on the 1x step FEM analysis. The thermal behavior of the material around the steps should be identical for both sides, thus, the slope of the two dashed lines are the same, just the starting point has been adjusted. A 3x step was seen as an ideal target for the secondary side experiment, based on the results in Fig. 8, due to the increased likelihood of seeing transition from the RF steps during both flight test windows, with sufficient separation in time between the primary and secondary sides. The 3x step, then, corresponds to a 0.533mm (0.021-in) high step at the swept LE for the cold-wall condition (start of flight). By the end of the descent flight window, the 3x step is expected to be on the order of around 0.254mm (0.010-in) high based on the thermal growth of the parts, which still should be large enough to adversely influence BLT. Also as previously mentioned, another decision made early in the process for the secondary side was to focus exclusively on the downstream joint, as this joint is nearest to most of the planned instrumentation (more on this later). In this way, only the aluminum section was impacted by the need for the additional machining required to allow for the larger step heights on the secondary side.

In summary, the goals of the secondary side experiment were revised to provide better synergy with the primary side. By investigating the effects of rearward-facing 2D steps on the secondary side, better clarity should be provided as to when the primary side is free of step effects. The primary side RF step was selected to be 0.007" high at the swept LE, based on the FEM analysis, while the secondary side was selected to be three times higher at 0.021".

VII. Flight Instrumentation

The final design decision to be made with regard to the secondary side experiment was a layout of instrumentation to capture the movement of BLT due to the steps. The number of sensors left available for the secondary side was small, as a predominance of the instrumentation that is to be flown on BOLT is dedicated to the primary side experiment. The secondary side was allocated 24 Medtherm coaxial thermocouples (T/Cs), as well as a few pressure gages. Sixteen of the 24 T/Cs were installed as dual sensors (provides both a top surface and a back-side measurement) to allow derivation of heat transfer at the surface, while the remaining eight were only top surface measurements. Figure 9 provides a sketch of the layout of the sensors for the secondary side. Note that the sensors are clustered outboard under the assumption that the steps at the swept LE will be the primary tripping point so the T/Cs are aligned with the streamlines coming from the downstream joint step at the swept LE. The distribution was laid out to provide symmetry on the secondary side (quadrant to quadrant) as well as to provide duplicates of locations on the

primary side for direct comparisons. There are an additional 14 in-depth T/Cs within the joints that are intended to track internal temperatures for conducting a post flight FEM reconstruction of the step behavior.

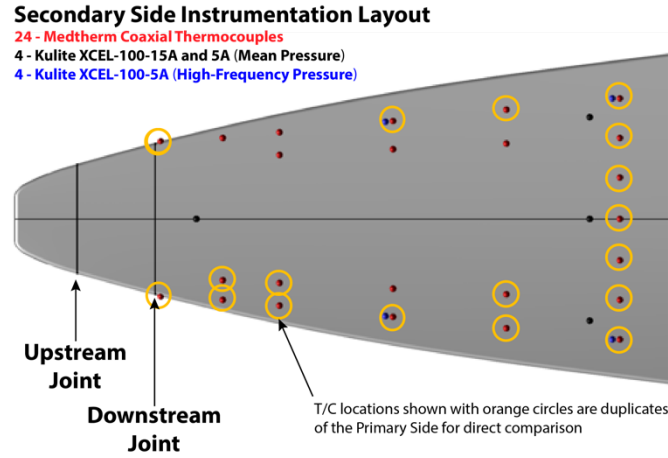


Figure 9. Instrumentation layout for the secondary side.

The T/C locations shown in Fig. 9 were chosen based on smooth-wall CFD solutions (discussed previously) to track the surface streamlines for both nominal and off nominal conditions. Figure 10 provides the streamlines emanating from the swept LE region of the both the upstream and downstream joints in comparison to the T/C locations. The red streaks shown are from the LE region of the upstream joint, while the blue streaks are from the downstream joint. Expectations for flight are that the downstream joint should be the one to first influence BLT onset, however, the inboard set of T/Cs can be used to monitor which of the two joint are causing the disturbances.

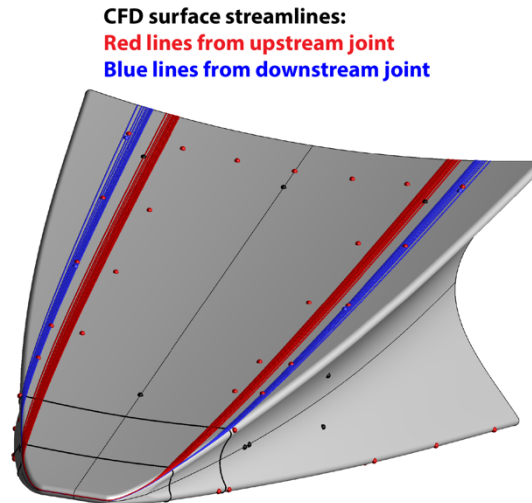


Figure 10. Surface streamlines emanating from both joints based on smooth-wall CFD for nominal pitch and yaw.

Figure 11 provides an assessment of the T/C locations in comparison to the smooth-wall surface streamlines for off-nominal pitch and yaw cases of 5 deg. For the windward and leeward pitch cases, the streamlines shift symmetrically, and only slightly, outboard or inboard, respectively, but within the region of coverage of the T/Cs. A more pronounced and asymmetric shift in surface streamlines is seen with the yaw case. The chosen instrumentation locations for the secondary side are sufficient for observing the disturbances that should emanate for the RF step at the swept leading edge. One final thing that still needs to be assessed is the impact to the surface streamlines based on computations done on a nonsmooth grid,

one that has the actual RF steps included. The expectation is that the impact to the surface streamlines will be small, but still needs to be verified, preferably before flight.

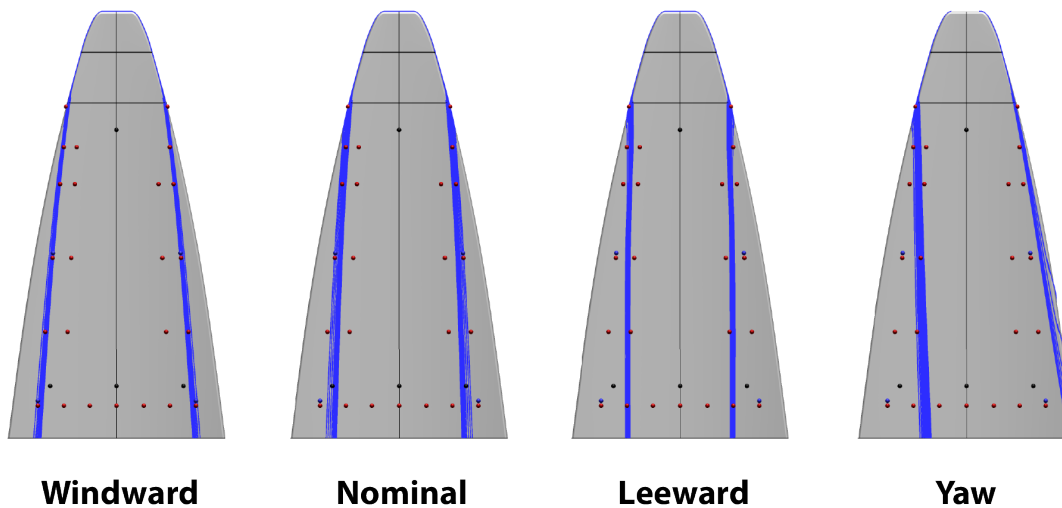


Figure 11. Surface streamlines emanating from the downstream joint based on smooth-wall CFD for off-nominal pitch and yaw.

VIII. Concluding Remarks

Details have been provided into the key decisions that were made during various project design reviews in leading to the final formulation of the secondary side experiment. Although the initial plan for the secondary side was to focus on three-dimensional boundary layer trips, the project decided soon after PDR instead to use the secondary side of BOLT to be a two-dimensional rearward-facing step experiment. In this way, information from the secondary side would then have more of a direct impact on the results for the primary side, since both would have rearward facing steps present. A wind tunnel experiment was conducted in the Purdue BAM6QT to better understand the impact of steps, both forward and rearward facing. The results from that test entry were used to determine the allowable step sizes for flight. Correlations were developed and used to scale the wind tunnel results to flight. The instrumentation layout for the secondary side was completed based on a review of the surface streamlines during nominal and off-nominal conditions in flight. The spanwise distributions of steps were intended to be consistent between the two halves of the secondary side in order to provide some sense of repeatability data. And most of the secondary side sensors were placed to be replicates of primary side locations, in order to facilitate direct comparisons. Even with the recent test results, there is still a large uncertainty with the effect of two-dimensional steps on boundary layer transition. Therefore, the BOLT project is of the opinion that these secondary side flight results will be significant and unique, provide valuable insight into the impact of steps at flight conditions.

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