Air Force Research Laboratory Robust Scramjet Program: Validation of Truncation Philosophy for 3-D Scramjet Inlets

Trent M. Taylor, Thomas D. Wolf, Ronald R. Springer, and Stephen M. D'Alessio

Ground testing of a medium-scale scramjet engine in semifreejet mode will require development of a technique for truncating 3-D inlets to provide confidence that the performance and operability of a full-length inlet is accurately represented. Truncation is necessary because of the test section size limitations of current hypersonic test facilities. A method was developed by APL, under the Air Force Research Laboratory Robust Scramjet program, to truncate a streamtraced 3-D inlet. Correlations were also developed to relate flow parameters between the full-length and truncated inlets that yield similar performance and operability. A pair of subscale inlets (baseline and truncated) have been designed and fabricated to be tested at the NASA Glenn Research Center 1- by 1-Foot Supersonic Wind Tunnel to verify this truncation methodology and correlation. This TRuncated INlet Test (TRINT) was concluded in the fourth quarter of 2011; the test covered a range of Mach numbers at various angles of attack and included evaluation of inlet performance during backpressured runs (i.e., an attached operating combustor was simulated). Analysis of the results is still pending, and if acceptable performance and operability similarity were demonstrated in the test, this truncation approach can be used for future Robust Scramjet engine demonstration tests.

MOTIVATION

Freejet testing of an integrated engine system (i.e., engine system is immersed in the supersonic flow) becomes increasingly difficult as the size of the engine increases. The length of the system can become too large to fit in the test section, and the blockage area of the inlet can prevent the facility from maintaining the desired operating condition. If the inlet can be truncated, the total length of the test article can be reduced, which, in turn, reduces blockage in the wind tunnel. However, if the flow properties (pressure, temperature, velocity, etc.) and inlet performance are significantly impacted by this truncation, then the test data for the engine are no longer valid. A carefully designed truncation methodology can minimize the differences so that integrated engine performance can be measured. Truncating an inlet can be a relatively straightforward process for a 2-D inlet, as seen in Fig. 1. The flow properties downstream of the first ramp on the 2-D inlet can be easily found with computational fluid dynamics (CFD) or experimentation. The first ramp can then be removed, and its flow turning can be replicated by lowering the inlet angle of attack (AOA). The wind tunnel must be set to the appropriate flow conditions, i.e., station M_1 versus M_0. The isolator is the constant area section downstream of the compression ramps. This is the portion of the inlet where the pressure rise required for combustion is contained and one of the places where flow properties will be examined. The current designs being considered for use in the Robust Scramjet program all use inward-turning 3-D inlets. Inward-turning inlets are designed to compress the flow in a 3-D manner as opposed to planar compression of pure ramp inlets. The advantage of the inward-turning engine concepts is a lower wetted surface area per unit mass flow processed by the engine. This feature inherently leads to lighter structures, lower heat loads, and fewer frictional losses within the propulsion system. On a 3-D inlet, flow is being compressed in all directions and there is no meaningful plane to remove as there is in a 2-D inlet. No known program to date has examined methods for truncating a 3-D inlet and conducted tests to determine the validity of the approach.

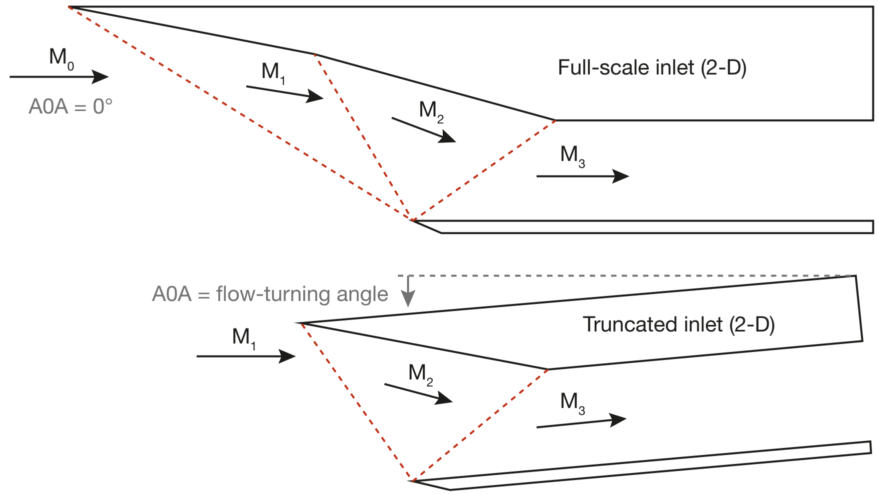

Figure 1. Truncating a 2-D inlet.

DEVELOPMENT OF 3-D INLET TRUNCATION METHODOLOGY

For the 3-D streamtraced inlets considered in this truncation investigation, the Busemann flow field (see Fig. 2) was selected as the parent flow. The baseline inlet was derived by tracing streamlines through the top portion of this flow where inlet surfaces are defined as the streamlines first turn from their original axial direction. The truncated inlet is made by removing portions of the baseline inlet at a higher flow-turning angle. This Busemann flow field is characterized by internally contracting,

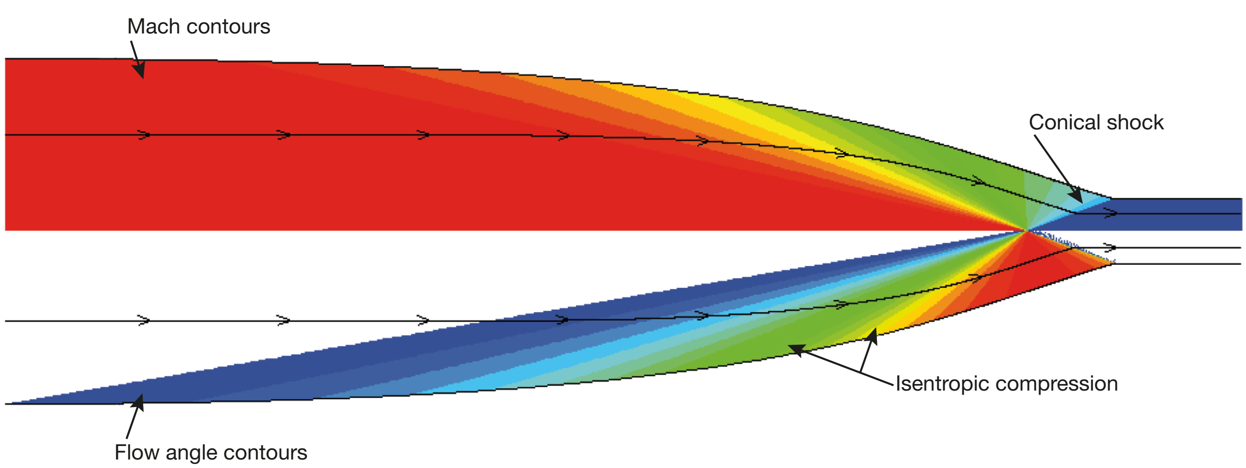

Figure 2. Busemann inlet. (Reproduced from Ref. 4 with permission of the American Institute of Aeronautics and Astronautics.)

conically symmetric flow that uses isentropic compression and terminates in a conical shock that realigns the flow to the axial direction, as shown in Fig. 2. The Busemann inlet has naturally high on-design performance because the forward compression occurs isentropically. The principal disadvantage of the Busemann inlet from a practical point of view is that its internal contraction significantly exceeds the Kantrowitz[1] starting constraint for inlets of interest. In supersonic inlets, a normal shock (or series of high-strength shocks) can set up in the forward part of the inlet and will deflect much of the mass flow from flowing down the inlet. An inlet with these high-strength shocks and low mass flow rates is labeled as unstarted. The Kantrowitz starting constraint defines an area ratio of the inlet that is necessary to have the shock system pass through the inlet and allow the mass to flow down the inlet, i.e., to start the inlet. Streamline tracing within the Busemann inlet provides the opportunity to leverage the high performance of Busemann design while avoiding the high internal contraction.

The parent Busemann inlet flow is generated from a solution of the Taylor–Maccoll[2] equations. In the present work, a method similar to that shown by VanWie and Molder[3] was used to solve the equations and derive the Busemann flow field. The process starts by assuming a Mach number and total pressure loss at the exit of the inlet. The conical shock strength can then be determined, and the flow field is then integrated backward through the inlet using the Taylor–Maccoll equations until the flow becomes aligned with the freestream. A Fortran program was written for this work to numerically integrate the equations using a Runge–Kutta method to find the inlet inflow conditions. The inlet exit conditions were then iterated using a bracketing method to find the parent flow field that had the desired inflow Mach number and contraction ratio (ratio of the entrance area to exit area).

Having defined the axisymmetric parent flow field, a locus of points defining the cross-sectional perimeter of the desired inflow shape was placed in the freestream of a 3-D representation of the axisymmetric flow field. Then, streamlines were traced through these points using a Fortran program. The resulting streamlines define the 3-D walls of the inlet that would produce the same inviscid flow field as the parent flow field. As the streamlines travel through the parent flow, some of them do not begin to turn from the freestream condition until they travel into the inlet (see Fig. 2). This portion of the streamlines does not need to be replaced by solid surfaces. This lowers the surface area of the inlet and lowers viscous losses. For example, the streamlines that are placed near the symmetry line do not begin to turn until far into the inlet and cause the resulting 3-D inlet shape to be cut back. This method allows the flow to spill (i.e., not enter the engine flow path) at lower off-design Mach numbers and aids in creating a low Mach number starting inlet.

With the streamtubes defined, the 3-D streamlines were read into a grid-generation program as databases. These were used to create a surface mesh and then a 3-D mesh. This method was tested and verified by solving the 3-D mesh in a CFD code with a calorically perfect and inviscid gas, which are the assumptions of the Taylor–Maccoll equations. Both an inlet with a circular inflow and circular outflow profile and an inlet with a square inflow and square outflow profile were solved in the CFD code. The total pressure losses and inlet exit Mach numbers closely matched the values predicted by the Taylor–Maccoll equations and conical shock equations. Total pressure is defined as the pressure that results from slowing the flow to zero velocity in an isentropic (adiabatic and reversible) manner. Shock waves and viscous losses will reduce the total pressure of the flow. A series of cross-flow slices was visualized from inflow to exit of the inlet, and a conical shock shape was observed in both the inlet with a circular profile and the inset with a square profile.

It was also of interest to the Robust Scramjet program to examine inlets that undergo shape transition from the inflow to exit of the inlet—namely, those inlets whose cross-section transitions from a square shape to a circular shape. Various methods were examined for this shape transition and its impact on inlet performance. The main focus of this current work is to examine truncation methods, so further details on the shape transition study can be found in Ref. 4. The optimal method found is in this study was used to generate the baseline inlet geometry used in this truncation study.

As the flow is compressed in the forward section of the inlet, the amount of flow-turning (deflection from the axial direction) increases. The truncation method developed for the Robust Scramjet program uses the streamlines of the baseline inlet and truncates these lines at an increased turning angle such that the inlet profile is changed but the geometry downstream of the truncation remains the same. The method starts with the streamlines of the baseline inlet and then removes the leading portions of the inlet up to a surface that is at a larger flow-turning angle. Thus, the truncated inlet surfaces are kept as a subset of the baseline surfaces.

Once the baseline inlet flow was determined, a process was then developed to find inflow conditions for the truncated inlet that would provide similar flow properties to the isolator. The truncated inlet's inflow conditions were found by keeping total temperature constant from the baseline inlet flight profile. A freestream Mach number was estimated for the truncated inlet, and then the total pressure was adjusted to keep the mass capture of the two inlets the same. The stream-thrust-averaged 1-D flow parameters were then tracked through the truncated inlet and compared with the baseline profile, as shown in Fig. 3. Notice here that the lines for the truncated inlet start farther downstream, showing

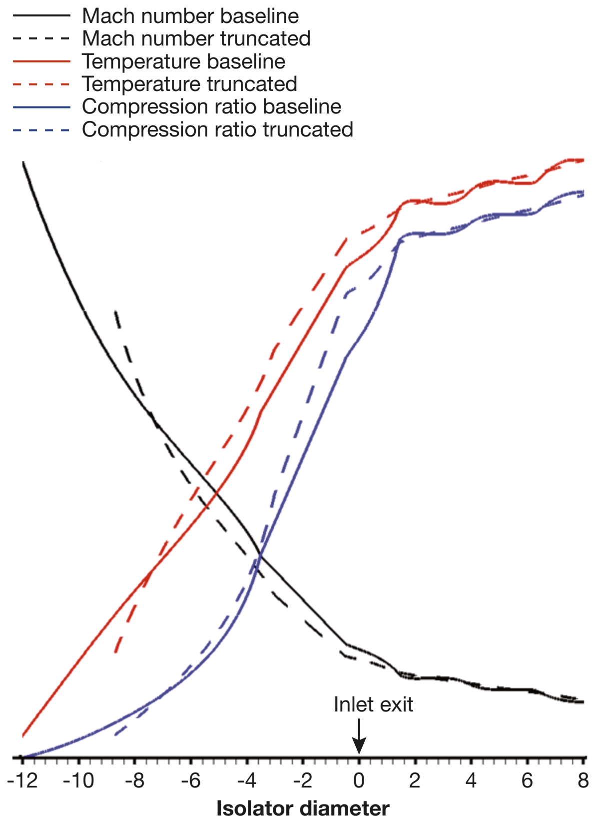

Figure 3. 1-D flow property profile through the inlet.

the length reduction with respect to the baseline inlet. The reference pressure in the figure is the same for both inlets and corresponds to the freestream static pressure of the baseline inlet. Although the initial Mach number is lower and the temperature and pressure conditions start higher for the truncated inlet, the exit flow properties should be comparable to the baseline inlet. The truncated inflow Mach number was updated, and the process was repeated until inlet exit properties comparable to the baseline inlet were achieved.

The 3-D truncation method produces a shock structure mismatch in the isolator, as shown in Fig. 4. In Fig. 4, the isolator shock structure produced by the baseline inlet is shown on the top, and that produced by the truncated inlet is shown on the bottom. The reflection pattern for the truncated inlet is farther downstream compared with the baseline case. This shift occurs because the decreased length of the truncated inlet results in a larger impact than lowering the incoming Mach number (thus increasing the first reflection angle). The impact of this phase shift in the shock reflections will be examined during the test program.

The corrections used to find the inflow conditions for the truncated inlet were plotted, and correction correlations were made by interpolating between points. These correlations can be used to determine truncated inflow conditions at arbitrary Mach numbers.

WIND TUNNEL FLOW CONDITION

The NASA Glenn Research Center 1- by 1-Foot Supersonic Wind Tunnel (1 × 1 SWT)[5] cannot replicate flight enthalpies and can only run discrete Mach numbers based on the available nozzles. It is a common practice to not test supersonic inlets at flight enthalpies because the energy requirement can be quite large for high-Mach-number flow. Freestream Reynolds number or dynamic pressure is generally used as a matching parameter between ground and flight in these types of facilities. The 1 × 1 SWT heats the air just enough to keep oxygen from condensing out of the flow at Mach 5 and 6. Because of the facility test section size, the medium-scale (one that processes 100 lbm/s, also called 10×) engine size was designed at a one-eighth scale. It was decided to try to match the Mach number and Reynolds number from flight conditions to tunnel conditions and run Mach numbers 6, 5.5, 5, 4, 3.5, and 3. The desired baseline flow conditions were found by using the chosen Mach numbers and operating the inlet at a constant flight dynamic pressure of 71.8 kPa (1500 psf). The flight conditions were then converted to Reynolds numbers per foot for comparison with the 1 × 1 SWT capabilities. The desired Reynolds numbers per foot also had to be multiplied by eight to account for the scale of the model. (The Reynolds numbers per foot for the 1 × 1 SWT need to be eight times higher than flight because the characteristic length is eight times shorter.) This process directly determines the desired Mach number and Reynolds number per foot for the baseline inlet, but a few extra steps are needed to determine the tunnel flow conditions for the truncated inlet.

First, a truncated inlet inflow Mach number was chosen from the list of nozzles at the 1 × 1 SWT and then converted to the corresponding baseline flight Mach number using the correlations previously

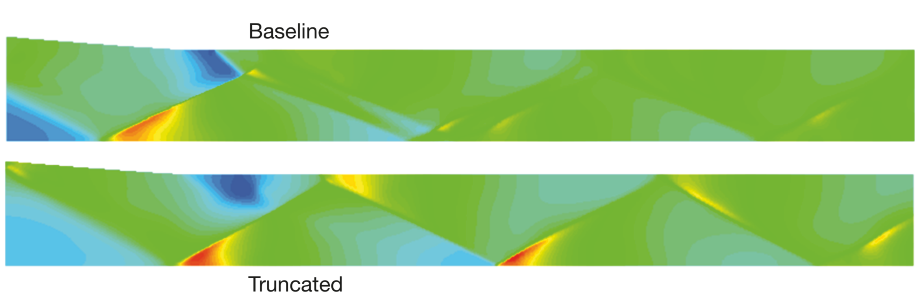

Figure 4. CFD of Mach 6 pressure contours in the isolator.

described. The corresponding baseline Mach number was then used with the constant flight dynamic pressure of 71.8 kPa (1500 psf) to find the other flow properties. The resulting total pressure was then multiplied by the total pressure correlation factor (described in the *Development of 3-D Inlet Truncation Methodology* section), and the static pressure was recomputed. The desired Reynolds number per foot to match (based on the computed flight conditions) was then calculated and multiplied by eight in a similar manner to that used for the baseline inlet.

The desired Mach and Reynolds numbers per foot for both inlets were then plotted against the tunnel capabilities map and are shown in Fig. 5. The desired "flight-matched" conditions, indicated by the yellow and green symbols, were outside the capabilities of the tunnel in all cases.

All of the flight-matched Reynolds numbers for both inlets were scaled by the same value until all of the points were within the tunnel capabilities, as shown in Fig. 5. It is necessary to use the same scale for all conditions because they are related through the correlating curves and consistency between the conditions needs to be maintained as much as possible. The same scaling must be used, otherwise the Reynolds numbers (and boundary layer profiles) will not match between the truncated and baseline inlets and there will be no way to evaluate the effectiveness of the truncation methodology.

The NASA 1 × 1 SWT personnel provided recommendations for the temperature settings for each of the Mach number conditions. Ideally, total temperature would be held constant between the corresponding conditions of the baseline and truncated inlets to be consistent with the assumption made while determining the previous correlations. However, because of the heating requirements at high Mach numbers, a compromise had to be made for this test. Therefore, the total pressure was set, given the total temperature requirements, to match the Reynolds numbers shown in Fig. 5. A 60-run test matrix was originally made that included all of the flow conditions and included running 0° and 2° of sideslip (yaw). Because of funding limitations, the first tunnel entry is limited to 20 runs and eliminates the sideslip and some Mach conditions.

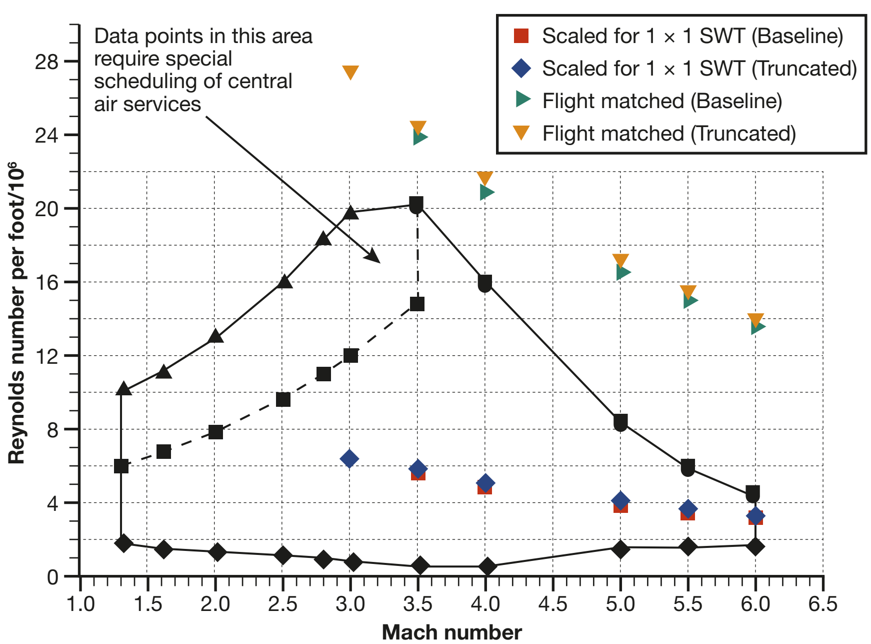

Figure 5. Tunnel operating conditions.

TEST OBJECTIVE: DETERMINE VALIDITY OF THE TRUNCATION METHODOLOGY

The main objective of the testing is to determine whether the truncation methodology produces a truncated inlet with operability and flow characteristics similar to a full-length inlet over a range of Mach numbers and AOAs.

Compare Starting and Bleed Performance

Both inlets, baseline and truncated, will be run over a range of Mach numbers, and the starting performance will be compared. Using previous CFD, it was determined that flow bleed will be needed to keep the inlet started at low Mach numbers. The amount of bleed necessary to maintain a started inlet will be compared through the correlations to determine whether the truncated inlet has similar performance. Bleed will be accomplished by two methods: a starting door that is left slightly open and a starting door that is fully closed but has a bleed hole pattern. Several starting doors have been made to test different bleed hole patterns. Trend lines will be made for each inlet across the tested Mach range to compare flow similarity between various bleed configurations.

Compare Backpressured Operability

The inlets will be backpressured, and the operability of the inlets will be compared. Trend lines will be made for each inlet for performance metrics, such as peak pressure rise on the cane curve and inlet spill profiles with respect to Mach number. Backpressuring the inlets simulates the pressure rise at the exit of the isolator because of the heat release in the combustor. The cane curve is a common plot made that demonstrates inlet performance. It is generated by plotting points of backpressure versus mass flow rate through the engine. As the pressure is increased, the mass flow rate processed by the engine initially remains constant, and a vertical line of points is created on the plot. Eventually the inlet begins to spill flow out of the inlet as the pressure is increased and creates a curve on the line of points (the curve on the line looks like a cane). This shows the highest pressure rise that an inlet can tolerate by the engine before performance is impacted (by loss of mass through the engine). The Mach number for the truncated case will be converted to the corresponding baseline Mach number to see how the designs compare. High-frequency pressure transducers will also be placed at the inlet close-out, the inlet throat, and the end of the isolator to gather transient data during inlet unstart.

Compare Flow Profiles

Data from a flow rake, positioned at the inlet exit for the runs with no backpressure and at the isolator exit for the backpressured runs, will be used to estimate total pressure recovery. These data will also be used to determine flow distortion and evaluate whether similar flow profiles would be provided to the isolator and combustor in a full engine test.

Validate CFD Predictions

A large database comprising wall pressure data and flow profiles at various Mach numbers and AOAs will be used to validate CFD for both inlet designs and to build confidence in using this truncation methodology to design inlet components for future freejet test articles.

TRUNCATED INLET TESTS INLET MODELS, INSTRUMENTATION, AND TUNNEL INTEGRATION OVERVIEW

The wind tunnel models for the TRuncated INlet Tests (TRINTs) were designed for operating temperatures that approach 458 K (365°F) and tunnel total pressure of up to 160 psia. On the basis of these worst-case operating conditions, the 1 × 1 SWT user manual[5] was used to evaluate the tunnel starting and operating loads. This document also provided guidance for model scaling based on tunnel blockage criteria. The TRINT inlet models are at a one-eighth scale. The baseline model has a blockage of 22.9% at –1° AOA (orientation for minimal frontal profile) and 0° sideslip with the bleed door closed. If the starting door needs to be fully opened to start the inlet (20°), then the maximum blockage of the tunnel is 26.7%.

Figure 6 shows a drawing of the model installation on the facility sidewall plate. This whole assembly on the sidewall is attached to the rest of the test section. In Fig. 6, the flow would be coming from the bottom right and then flow through and around the inlet opening. The flow that is captured by the inlet is ducted out of the tunnel through the 4-in. pipe flange and goes to a mass flow measurement station. The 1 × 1 SWT tunnel test section is approximately 12.0 in. tall, 12.2 in. wide, and 52 in. long. Therefore, the size of the TRINT inlet models did not allow for much flexibility in positioning inside the test section. Taking into consideration AOA positioning extremes as well as maximum bleed door openings, the model was mounted so that the leading edge of the baseline inlet was never closer than 2.00 in. from the sidewall. Fore and aft positioning of the model was limited because of the span between the model mount strut and the exhaust duct, both of which protrude through the test section sidewall. The model was positioned as far aft as possible, putting the leading edge of the baseline inlet 2.50 in. forward of the entrance plane of the tunnel test section.

Key interface points for the 1 × 1 SWT facility include a mass flow meter, located outside the tunnel test section,

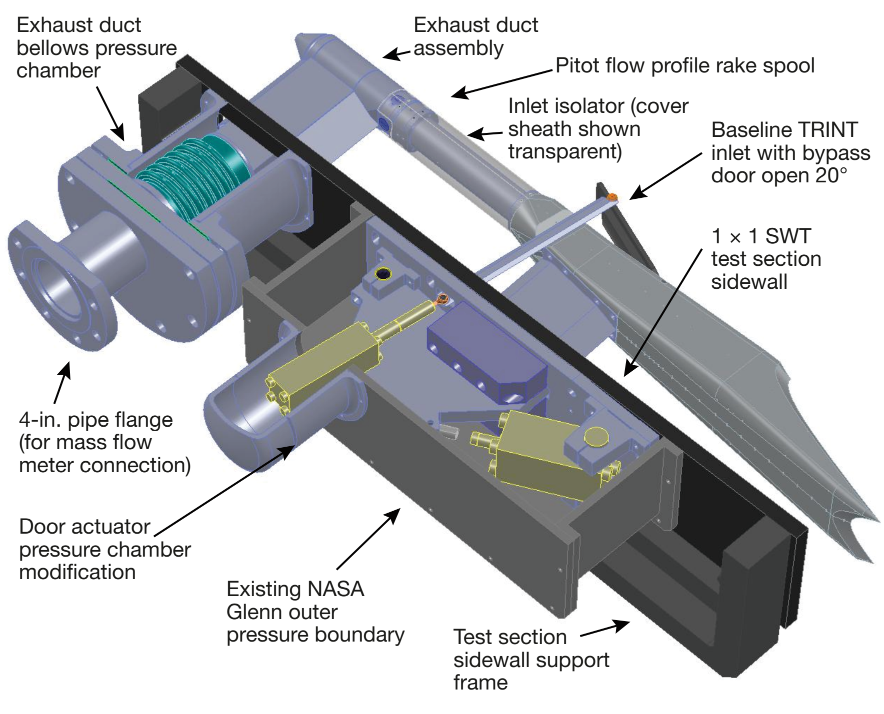

Figure 6. Installation drawing.

as well as an instrumentation interface port, located just downstream of the test section. Tunnel logistics make the model easiest to mount through the tunnel sidewall. Model mounting required two protrusions through the test section sidewall, one for the model mounting strut and another for the exhaust duct mass capture. Because of the rotating motion of the model required for AOA adjustment, these sidewall protrusions were difficult to seal. For this reason, a separate outer pressure boundary was created for each of these protrusions. The model mount strut, along with the AOA and bleed door adjustment mechanisms, make use of an existing outer pressure chamber, which required minor modifications for hydraulic actuator clearance, as well as hydraulic and control system feed-throughs. The aft exhaust duct protrusion required a unique design, incorporating a bellows that both maintained the test section pressure boundary and allowed the inlet capture gases to be diverted to the mass flow meter while not restricting the rotating motion of the AOA adjustment mechanism. The model instrumentation is bundled and directed aft along the longitudinal axis of the model then turned toward the sidewall just aft of the test section. The instrumentation bundle exits the tunnel through a single port sealed with an adhesive.

A starting door is incorporated into the bottom of the inlet. This door can also be modified so that flow can bleed out through slots or holes for the runs at low Mach. The door position was located as close as was practically possible to the inlet crotch and extends to just beyond the start of the constant area section. The door position is such that there is a small internal contraction before the door opens up enough to allow flow to expand freely into the test section. This contraction is slightly above the Kantrowitz criterion at Mach 3, but the criterion has been found to be conservative, and there is also a short axial distance before the internal contraction is relieved by the door. As a result, inlet starting is not expected to be a problem. The area relief provided by the door was sized to ensure that there was a flow area increase in the internal portion of the inlet up to the start of the constant area section. The bleed door is hydraulically actuated with a closed-loop feedback control and can be positioned at any opening angle from 0° to 20°. The door actuation mechanism was incorporated into the overall AOA actuation scheme so that door position feedback remains the same regardless of AOA positioning. Four door blanks were manufactured as part of the fabrication effort. These doors are easily interchanged and can be readily modified to evaluate different bleed flow concepts.

Mounted to the aft face of the inlet assembly is a constant area isolator section followed by a flow field profile rake insert spool. The rake insert spool and the isolator section can be interchanged so that a flow field profile can be obtained closer to the start of the constant area section. The flow field profile rake has a total of 21 pitot probes, as well as 8 static wall measurements. In addition to taking a centerline pitot measurement, the rakes take measurements along area rings at 10, 30, 50, 70, and 90% of the flow area. Static pressure measurements are taken at the probe tip plane, at each probe insert location, and at 45° from each probe insert location. A drawing of the rake spool is shown in Fig. 7.

Beyond the rake spool component, the flow is captured in the exhaust duct where the flow diverges before being turned slightly more than 90° and being ducted through the test section sidewall. The exhaust duct connects to a bellows, allowing for AOA adjustments, before connecting to a standard 4-in. pipe flange. This flange is connected to the 6-in. piping that leads to the mass flow meter.

The inlet model assembly is mounted to the outer test section sidewall by means of a strut that attaches to the assembled inlet halves. This strut is the main structural load path that carries all starting, operational, and unstart loads. The strut is pinned to a mounting plate that is fixed to the sidewall. The pin, which allows for AOA rotation, carries all loading, fore and aft, as well as any pitch loads. The strut also passes through two stabilization blocks that take out any model side loads. The strut rotation is controlled by means of a hydraulic actuator with a closed-loop feedback control and can be positioned at any opening angle from –2° to 4°. The bleed door actuation system is mounted directly to the strut so that door position is independent of AOA positioning. The entire strut mounting plate is pinned to the test section sidewall and has sufficient clearance in the mounting holes to allow for a rotation from 0° to 2°. This yaw positioning capability needs to be done manually but is easily accomplished by gaining access to the strut assembly outer pressure chamber.

The baseline inlet is instrumented with 118 static pressure taps. Because of the shortened length inherent in the truncated design, there are only a total of 90 static

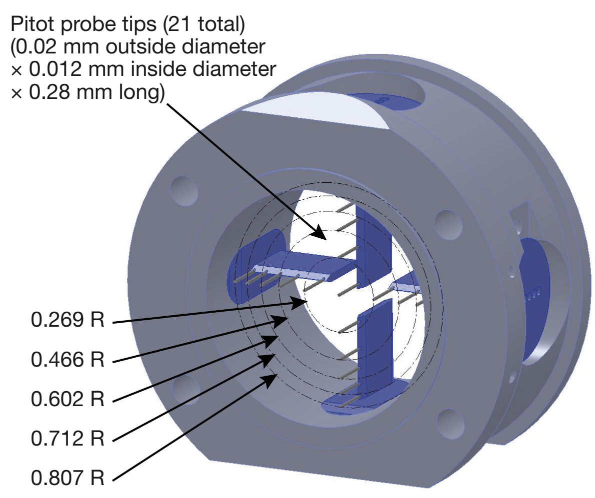

Figure 7. Rake spool drawing. R, radius.

tap locations. The majority of these taps are in the same locations as the baseline inlet, with some movement due to the difference flare angles near the notch. The isolator has a total of 52 static pressure taps, with 21 located every half inch along the upper and lower centerlines. The TRINT inlet models also incorporate three high-frequency pressure transducers (Kulite P/N XCE-093). Positioning of the transducers is as close to the lower wall centerline as possible, with one located near the inlet crotch, one located near the isolator entrance, and the third located near the isolator exit.

TEST PROCEDURES

Mass flow measurements and temperature readings at the mass flow measurement station are used to determine when the tunnel and model have reached steady state at the current operating condition. Each run starts with the inlet at –2° AOA, and the door will be put to full open to start the inlet (starting position). Each flow condition is run through the AOA range from –2° to +4° in 1° increments. Wall pressure, mass flow rate, and flow distortion (with a pitot rake) are measured at each point. Additionally, dynamic pressure sensors and Schlieren images are used to determine whether the inlet has started, as well as to check for inlet unstart when the inlet is backpressured. Dynamic pressure sensors, located in the isolator and at the throat of the inlet, are used to estimate the speed of the shock system as it progresses upstream in the isolator and induces inlet unstart during runs where backpressure is applied.

Calibration and Performance Runs

From previous CFD results, bleed is necessary at low Mach to keep the inlet started once the door is closed. Multiple bleed configurations are to be calibrated before the inlet can be backpressured. The first configuration is using the standard door, which does not contain holes or slots for bleed. After the inlet starts with the door fully open, it is moved toward the closed position but will remain slightly (cracked) open. If the inlet unstarts (i.e., the door was closed too much), then the door is moved back to the fully open position to restart the inlet and the process is repeated. Once a door position is found that keeps the inlet started at all AOAs, it is swept through the AOA range while mass flow measurements are taken, flow distortion is measured with the flow rake, and wall pressure distributions are recorded. After the range of runs is made with the standard door, the low Mach conditions are rerun with bleed configurations. Two additional doors will be brought to the test with different bleed hole patterns/sizes. An additional, unmodified door is at the facility for contingency purposes. After the door is changed out, the tunnel will be started and the door will be put in the fully open position to start the inlet. The door will then be closed. If the inlet remains started, it will again be swept through the AOA range while mass flow rate, flow distortion, and wall pressure distribution are recorded. If the inlet fails to remain started, then a door with a larger total bleed area will be installed and the process will repeat. If both leaving the door cracked open and the door with bleed holes have similar profiles of mass flow rate and flow distortion, then both ways are to be tested in the operability runs involving backpressure and cane curve refinement.

Operability Runs

These runs focus on establishing a well-defined cane curve. The mass flow plug will be configured so that its nominal travel distance has approximately five increments. The mass flow plug is run through these increments, taking mass flow measurements, flow profiles with the rake, and wall pressure distributions at each plug position. After the inlet unstarts, the mass flow plug will be put to its fully opened position and the door is opened to restart the inlet. The increment that caused unstart is noted, and then data are taken at several additional finer mass flow plug settings near inlet unstart to develop a well-defined inlet cane curve. This process is to be repeated at each AOA. High-frequency pressure transducers are also used in these runs to record the unsteady phenomena during inlet unstart.

CURRENT TEST PROGRAM STATUS

The baseline and truncated inlet models have been fabricated and instrumented as shown in Figs. 8 and 9. Final edits are being made for the data reduction document that is used to program the data acquisition system

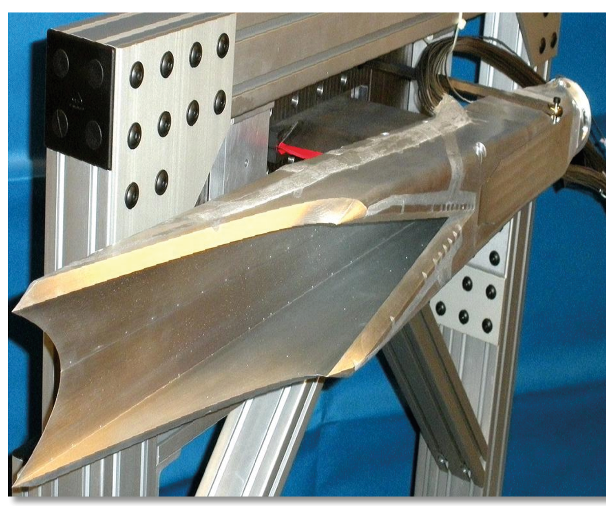

Figure 8. Baseline inlet.

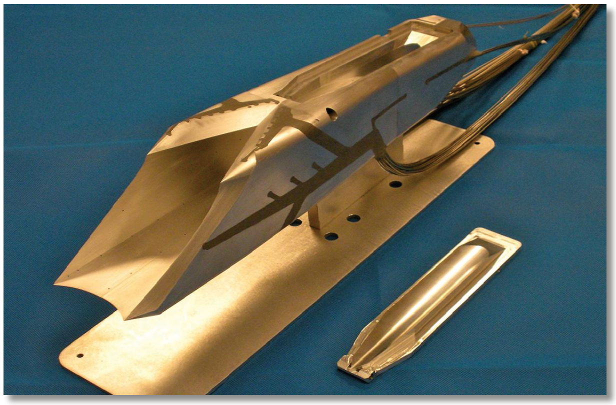

Figure 9. Truncated inlet.

and process the test data. Boundary layer trips have been sized for the model. A turbulent boundary layer is required in the internal portion of the inlet because a laminar boundary layer will easily separate from the shock reflections and unstart the inlet. An epoxied grit will be used and was sized for the Mach 6 conditions; this single size will be used for all test conditions. A portion of the test matrix has been completed, and the rest will be completed in the last quarter of 2011.

ACKNOWLEDGMENTS: We acknowledge Dr. Daniel Risha, Dr. Charbel Raffoul, Dr. Christopher Murawski, and Dr. Thomas Jackson of the Air Force Research Laboratory Robust Scramjet program for administrating this effort and providing guidance throughout execution of the task. We also want to acknowledge Ms. Heidi Wilkin and Dr. Mark Hagenmaier of the Air Force Research Laboratory for funding this effort and for their contributions in the inlet design. Mr. Wayne Hawkins, Mr. Wade Burfitt, Dr. Roy Schulz, and Mr. Steve Bancroft of Arnold Engineering Development Center (AEDC) at Arnold Air Force Base also provided guidance for this test. Funding was also provided by the Department of Defense Test Resources Management Center Test and Evaluation, Science & Technology (DoD TRMC S&T/T&E). Dr. Charles Trefny and the personnel of the 1 × 1 SWT at the NASA Glenn Research Center were of great help in developing the tunnel integration and data reduction plans for this task.

REFERENCES

[1]Kantrowitz, A., and Donaldson, C., "Preliminary Investigation of a Supersonic Diffuser," National Advisory Council for Aeronautics Report Advance Confidential Report L5D20 (1945).

[2]Anderson, J., "Conical Flow," Chap. 10, *Modern Compressible Flow with Historical Perspective*, 3rd Ed., McGraw-Hill, New York, p. 370 (2003).

[3]VanWie, D., and Molder, S., "Applications of Busemann Inlet Designs for Flight at Hypersonic Speeds," *Aerospace Design Conf.*, Irvine, CA, paper AIAA 92-1210 (1992).

[4]Taylor, T., and VanWie, D., "Performance Analysis of Hypersonic Shape-Changing Inlets Derived from Morphing Streamline Traced Flowpaths," in *Proc. 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conf.*, Dayton, OH, paper AIAA 2008-2635 (May 2008).

[5]Soeder, R. H., Stark, D. E., Leone, J. F., and Henry, M. W., *NASA Glenn 1- by 1-Foot Supersonic Wind Tunnel User Manual*, NASA/TM-1999-208478/Rev1 (1999).

The Authors

Trent M. Taylor is the task lead for the TRINT program and is a member of the Senior Professional Staff in the Aerospace Systems Design Group (KVD) within APL's Force Projection Department. Dr. Taylor designed the streamtracing and shape-changing methods used to design the baseline inlet, developed the truncation methodology, and is leading the test series at the NASA facility. **Thomas D. Wolf** is a member of the Senior Professional Staff and also part of KVD. Mr. Wolf was the mechanical designer for both inlet models and instrumentation and led the facility integration and coordination with the NASA facility. **Ronald R. Springer** is a Senior Professional Staff member in KVD and the Project Manager for the Robust Scramjet program. Dr. Springer aided in both the development of the data reduction plan and running the test series. **Stephen M. D'Alessio** is a Principal Professional Staff member and the Program Manager for the Robust Scramjet program and other programs in the Force Projection Department's Advanced Weapons Technology portfolio. Mr. D'Alessio also helped to coordinate the facility integration and test plan. For further information on the work reported here, contact Trent Taylor. His e-mail address is trent.taylor@jhuapl.edu.

The *Johns Hopkins APL Technical Digest* can be accessed electronically at **www.jhuapl.edu/techdigest**.