Short Duration Propulsion Test and Evaluation (Hy-V) Program

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Abstract
The Short Duration Propulsion Test and Evaluation (SDPTE) Program and the Hy-V Program have recently been combined with the aim of examining the influence of ground test facilities on scramjet performance. The combined program includes both research and educational activities that are being conducted by a consortium of university, industry and government participants. The objectives of the combined program are to; 1) Resolve ground testing issues related to the effects of test medium on dual-mode scramjet engine performance, 2) Resolve ground testing issues related to the duration of the test flow on dual-mode scramjet engine performance, and 3) Educate and motivate a new generation of aerospace engineers through student participation and research. This paper provides an overview and status of the combined program but focuses on objectives 1) and 2). The ground testing issues associated with these objectives are being examined using a range of facilities. These include a continuous-flow direct connect facility, a freejet blowdown facility and an impulse facility. By testing in a range of facilities, the effects of combustion generated test medium vitiates and test flow duration on the operation of two dual-mode scramjet flowpaths will be examined. The experiments will focus on flowpath operation at conditions equivalent to a flight Mach number of 5. However, some Mach 7 freejet testing will also take place. The program will conclude with a Mach 5 flight experiment of both scramjet flowpaths aboard a sounding rocket such that differences between ground and flight performance data can also be isolated.

1. INTRODUCTION

The development of design tools and technology for scramjet propulsion is dependent on wind tunnel testing. The success of this development depends on adequately simulating scramjet operation such that ground based databases can be accurately related to flight. These flight conditions can be generated using a number of different types of wind tunnels. For example, the propulsion testing for the AFRL/DARPA X-51A scramjet engine demonstration program was performed in the NASA Langley 8-ft High Temperature Tunnel (8-ft HTT)[1]. This facility is a combustion heated wind tunnel that burns methane in order to adequately match flight stagnation enthalpies. The X-51A engine also has lineage testing in the ATK GASL Test Bay IV (TBIV) Facility. This facility routinely burns hydrogen for heating the test flow. Together with AEDC's APTU Facility, which burns isobutane, these facilities are capable of relatively large scale testing of scramjet propulsion systems. However, combustion heated

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facilities vitiate the heated air with combustion products that include the major species of water when burning hydrogen, and additionally carbon dioxide, when burning a hydrocarbon. Minor species such as OH and NO, amongst others, are also present. These combustion products have both thermodynamic and chemical kinetic effects on scramjet combustion and have been shown to affect dual-mode scramjet (DMSJ) operation[2], reduce scramjet thrust[3], modify autoiginition[4] and enhance operability[4]. Since these products are not normally present in atmospheric air, their effects on scramjet performance and operation must be taken into account. Attempts have been made to account for the effects of these vitiates[5], however, there is no clear compensation method as major and minor species can have opposing effects[6].

Above a flight Mach number simulation of about eight, shock heated facilities are used for scramjet testing in place of combustion heated facilities. For example, Mach 10 propulsion tests for NASA's X-43A Hyper-X Program[7] were performed in the NASA HYPULSE facility at ATK GASL. Such facilities do not vitiate the test flow with combustion heated products. However, the shock heating process creates trace amounts of NO and O in the air flow and the test duration is typically 5 to 10 ms. This test time is four to five orders of magnitude shorter than for the 8-ft HTT, ATK GASL TBIV and APTU facilities. Although NO and O can affect combustion, the effects on scramjet performance are minimal[8,9]. However, given the short test time of shock heated wind tunnels, facility, flow and combustion establishment times must be taken into account. For example, with such test duration limits, there is uncertainty as to whether these facilities can adequately simulate the development of a thermal throat or boundary layer separation[10]. This is particularly relevant for DMSJ operation which often involves operation with a thermal throat and a large amount of boundary layer separation. The wall temperature boundary conditions are also typically three to five times colder for a scramjet tested in a shock heated facility than in a combustion heated tunnel. The performance of a scramjet in a shock heated facility has been compared with that in a combustion heated wind tunnel and reasonable agreement was found[10]. However, disagreement was greatest as stoichiometric equivalence ratios were approached. Shock heated facility scramjet data have also been compared with that of flight at Mach 8 conditions and encouraging comparisons were obtained[11]. Although facility-to-facility and facility-to-flight comparisons have taken place, there is no clear compensation method should test flow duration affect scramjet performance during testing in shock heated facilities.

The method of test medium heating on the ground can affect scramjet performance and operation and these effects must be taken into account when developing design tools and extrapolating results to flight. Of the ground test facilities available for practical sized system testing over the scramjet operational envelope, the test flow vitiates of combustion heated facilities and the test flow duration of shock heated facilities are, therefore, of particular concern. With this in mind, the Short Duration Propulsion Test and Evaluation (SDPTE) Program has recently been initiated and has been combined with the Hy-V Program[12]. The goal of the combined program is to examine the influence of ground test facilities on scramjet performance, particularly with respect to how test medium vitiation and test flow duration affect the performance and operation of a dual-mode scramjet. The combined program includes both research and educational activities that are being conducted by a consortium of university, industry and government participants. The SDPTE Program is led by ATK GASL and encompasses much of the research activity of the combined program. The Hy-V Program includes a similar research component but is more highly focused on the goal of university education and student outreach. The Hy-V Program consortium consists of the University of Virginia, Virginia Tech, Aerojet, NASA and the NASA Sounding Rocket Operations Contract (NSROC).

Considering the research and educational goals of the SDPTE and Hy-V Programs, the specific objectives of this work are to; 1) Resolve ground testing issues related to the effects of test medium on dual-mode scramjet engine performance, 2) Resolve ground testing issues related to the duration of the test flow on dual-mode scramjet engine performance, and 3) Educate and motivate a new generation of aerospace engineers through student participation and research. The ground testing issues are being examined using three facilities. A continuous-flow, direct connect experiment will be performed using the University of Virginia Supersonic Combustion Facility (UVaSCF). This facility is electrically

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heated and thus provides high enthalpy air that is free of combustion generated vitiates. However, the facility has the capability of adding water and carbon dioxide to the flow to simulate hydrogen or hydrocarbon combustion heating and thus the effects of vitiates can be examined. Test times in this facility are unlimited, but practically are on the order of two hours. Based on the flowpath currently installed in this facility, a freejet ground test article is being designed for the ATK GASL TBIV facility. At Mach 5 enthalpy, the TBIV facility can be run in regenerative storage heater and combustion vitiated modes. Both hydrogen and hydrocarbon fuel will be used during vitiated testing. Test times in this facility are typically of the order of 30 seconds. Finally, a series of short duration freejet ground tests will be conducted using the HYPULSE facility located at ATK GASL. These tests will be run with clean air, and additionally, using air that is artificially vitiated with water and carbon dioxide in order to simulate combustion heating. Tests at Mach 7 enthalpy are also planned in the TBIV and HYPULSE facilities. In each of the tests, the same test article, instrumentation and analysis procedure will be used for the vitiated and non vitiated tests. This will minimize as many variables as possible and allow the effects of the test medium vitiation to be accurately isolated. Additionally, by testing the same flowpath geometry at the same scale in each facility, other facility effects such as test flow duration will be able to be examined. Over the three facilities, test flow duration will vary by six orders of magnitude. The program will culminate with a captive-carry Mach 5 flight experiment of two DMSJ flowpaths aboard a sounding rocket such that differences between ground and flight test can also be isolated.

This paper focuses on the research aspects of the combined SDPTE and Hy-V Programs and provides an overview and status of the work. The paper begins with a description of the flowpath design for the new combined program. Planned ground testing activities and flight testing activities are then discussed. Finally, a description of the program management is presented, as well as a brief description of how the program integrates university student activities.

2. FLOWPATH DESIGN

The test articles for the ground and flight experiments are based on the University of Virginia direct-connect DMSJ configuration[13]. A schematic of this configuration is presented in Fig. 1(a). The flowpath consists of a two dimensional Mach 2 nozzle, a constant area isolator and a rectangular combustor. An unswept 10-deg. compression ramp is used to inject hydrogen fuel into the combustor at a Mach number of 1.7. The combustor has a 2.9-deg. divergence on the wall that houses the fuel injector. The isolator has a 25×38 mm (1×1.5 in.) cross section and the normal height of the ramp is 6.4 mm (0.25 in.). Flow exits to atmosphere 367 mm (14.4 in.) downstream of the base of the ramp. A fuel igniter port is located 24.6 mm (0.97 in.) downstream of the ramp. This port is used to ignite the DMSJ by momentarily introducing the combustion products of a hydrogen-oxygen detonation driven system. Reference 13 provides further details of the DMSJ configuration. During testing in the UVaSCF, the configuration has demonstrated performance sensitivity to water and carbon dioxide vitiation[2,6,12]. Testing is typically limited to fuel equivalence ratios in the range of 0.1 to 0.5.

In order to meet the objectives of the combined SDPTE and Hy-V Program, and to package the University of Virginia DMSJ into a practical freejet and flight test article, the test article concept has seen several design changes over concepts previously reported[12]. These include changes to the DMSJ forebody, inlet, isolator, combustor and exhaust. The freejet and flight test articles now include two flowpaths, A and B, as depicted in Fig. 1(b) and 1(c), respectively. Flowpath A retains many of the characteristics of the University of Virginia direct-connect DMSJ. However, Flowpath B has been modified to enable operation at higher equivalence ratios. In order to balance aerodynamic loads in flight, both flowpaths now share a common forebody and inlet design. The forebody consists of a two-dimensional geometry with a 10-deg. half angle wedge and a 0.76 mm (0.03 in.) radius leading edge. The forebody half angle was reduced in comparison to previous concepts in order to reduce the risk of inlet unstart induced by the cowl shock system, particularly at low flight Mach numbers. To additionally reduce the risk of unstart, the inlet design was changed. The shock trap design has been replaced with a two-dimensional inlet that captures the cowl shock system. The cowl leading edge also has a 5-deg. droop. This results in the cowl generating two weaker shocks rather than a stronger single

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shock which reduces the adverse pressure gradient experienced by the forebody boundary layer and reduces the likelihood of separation. In addition, the cowl has been located such that the cowl shocks strike the body side of the flowpath downstream of the forebody shoulder. These new inlet design features reduce the risk of inlet unstart at the low end of the flight Mach number range that will be encountered in flight. In order to ensure the inlet is self starting, the inlet side walls have a 30-deg. leading edge sweep and the inlet has a contraction ratio of 1.3 at the side wall closeout. This contraction ratio is below the Kantrowitz self-starting limit[14] of 1.43 for a flight Mach number of 4. With the current forebody and inlet design, the new Mach number at the entrance to the isolator is in the range of Mach 3 to 3.25, depending on the effectiveness of the shock cancellation at the forebody shoulder. Also, in order to ensure a turbulent boundary layer on the forebody in flight, the flight payload will incorporate a boundary layer trip that is based on the trip adopted by the Hyper-X program[15]. The trip will consist of a swept ramp in a repeating pattern across the forebody at 264 mm (10.4 in.) from the forebody leading edge. Natural transition will be exploited in the freejet ground testing.

In order to increase operating margin and reduce the likelihood of combustor and inlet interaction at the new flowpath Mach number, the isolator length has been increased to 418 mm (16.47 in.). This length was based on empirical research on shock train lengths in rectangular isolators[16,17].

As mentioned above, combustor design changes have also been incorporated. So that vitiation and short duration effects can be examined over a greater fuel equivalence ratio range than previously tested at the University of Virginia, additional area relief has been added to the combustor for Flowpath B and additional fuel injection stations have been added to both flowpaths. The combustor for Flowpath A is essentially the same as the University of Virginia direct connect configuration. However, a pair of sonic, flush-wall fuel injectors has been added to each side wall, 6.35 mm (0.25 in.) above and below the isolator centerline. Two axial stations are currently under consideration, 189 and 227 mm (7.43 and 8.93 in.) downstream of the ramp fuel injector. Downstream fuel injection has also been added to Flowpath B. In a similar arrangement to Flowpath A, options at 22 and 60 mm (0.87 and 2.37 in.) downstream of the ramp injector are under consideration. In order to provide more combustor area relief, Flowpath B has a 6.35 mm (0.25 in.) step at the base of the ramp fuel injector and a 5.8-deg. divergence on the injection wall. For both flowpaths, the ramp fuel injector will act as the location of primary fuel injection and flame stabilization. It is anticipated that the adopted design will enable Flowpath A and B to operate to fuel equivalence ratios approaching 1.0 without inlet interaction.

As can be seen in Fig. 1(b) and (c), the DMSJ flowpaths terminate with a side exhaust. The flow is turned through an expanding duct and the flow is exhausted out into the freestream flow. This turn was necessitated by the size of the existing flight payload shroud and the fact that the flight experiment will be conducted in a captive carry mode. The exhaust configuration has been designed to minimize flow separation and backpressure on the combustor. The exhaust turn has a nominal radius of 152 mm (6 in.) and the exhaust wall is inclined at 13-deg. and 20-deg. to the payload axis for Flowpath A and B, respectively. These angles were chosen so that the exhaust exit dimensions and location are the same for both flowpaths.

3. GROUND TESTING

Ground testing will take place in the University of Virginia Supersonic Combustion Facility (UVaSCF), the ATK GASL Test Bay IV (TBIV) facility and the NASA HYPULSE facility at ATK GASL. The UVaSCF is an electrically heated facility that can be run with clean air or air that is artificially vitiated with the major vitiation combustion products of water and carbon dioxide. TBIV can be operated in vitiated or storage mode at Mach 5 and vitiated at Mach 7. HYPULSE is a shock heated facility that is normally run with an air test gas. However, it can be run in modes with hydrogen and carbon dioxide addition that result in test gas compositions similar to vitiated facilities.

Table 1 presents a list of test medium composition for Mach 5 and Mach 7 simulation for a range of facilities, together with the composition for the UVaSCF and that of flight. It can be seen that, for Mach 5 simulation using a combustion heater, water levels vary between 5% and 12% by mole and carbon dioxide varies between 4% and 5% by mole, depending on the fuel type. For Mach 7, up to 24% water

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or 9% carbon dioxide may be present, again depending on fuel type. The ground testing for the combined SDPTE and Hy-V Program will focus on the vitiation effects of hydrogen and isobutane combustion.

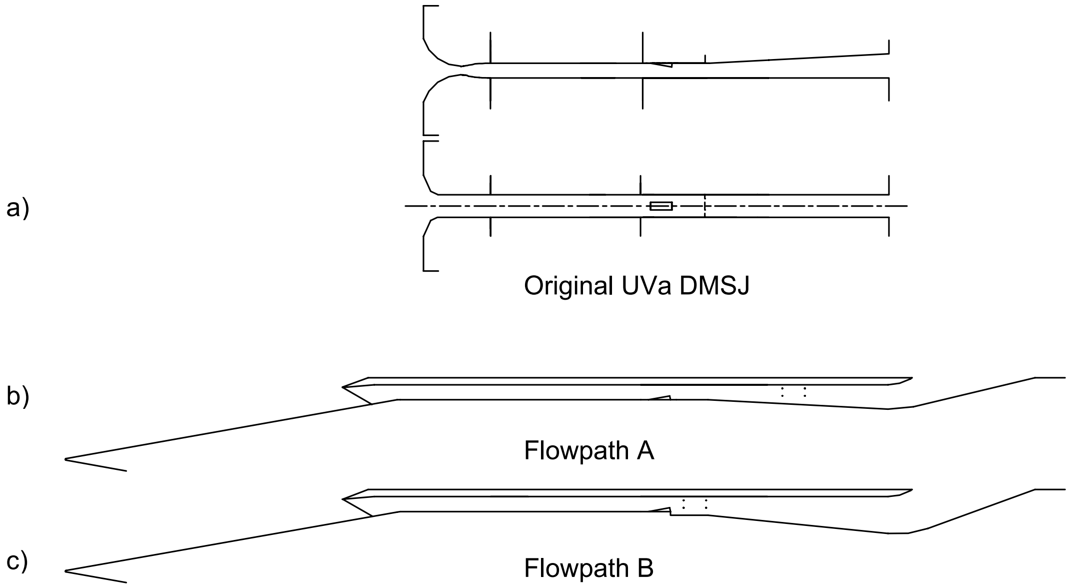

Figure 1. DMSJ flowpath geometries for, a) original University of Virginia direct connect rig, b) SDPTE (Hy-V) payload Flowpath A, and c) SDPTE (Hy-V) payload Flowpath B.

Table 1. Estimated test medium composition for combustion, shock and electrically heated facilities for Mach 5 and 7 simulation compared with flight.

Facility	**Heater type**	**Test medium composition (% mole fraction)**							
		Mach 5				**Mach 7**			
		H_2O	CO_2	N_2	O_2	H_2O	CO_2	N_2	O_2
AEDC APTU	Isobutane combustion	5.4	4.3	68.6	21.0	11.4	9.1	57.9	21.0
NASA 8' HTT	Methane combustion	8.7	4.4	65.2	20.9	18.2	9.1	51.3	20.8
ATK GASL TBIV (booster mode)	Hydrogen combustion (among others)	12.1	-	66.2	21.0	24.3	-	54.2	21.0
NASA HYPULSE	Shock	-	-	78.1	21.0	-	-	78.1	21.0
UVaSCF	Electrical	-	-	78.1	21.0	-	-	-	-
Flight	-	-	-	78.1	21.0	-	-	78.1	21.0

The ground testing matrix for the program is presented in Table 2. Typical flow duration times are listed, together with the expected flight test window duration. It can be seen that the ground testing will focus on Mach 5 simulation. The testing at the University of Virginia will be in direct connect mode, whereas the testing in TBIV and HYPULSE will be freejet. Freejet and semi-freejet tests will take place at Mach 7 in TBIV and HYPULSE. Anticipated test times will vary between 6 ms and 2 hrs.

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The intent of the ground testing is to minimize as many variables as possible in order to highlight and focus on the two main variables; test medium and test duration. Ideally, one test article would be built and tested in all the facilities, thereby eliminating any differences between the test articles. However, standard test article design practices differ for each type of facility. For instance, design features developed to minimize data uncertainty in pulse facilities (e.g. close coupled pressure transducers), are not necessarily compatible with design features developed to deal with the heat loads of longer duration blowdown facilities (e.g. water cooled walls). The design effort goes up significantly to simultaneously address all the idiosyncrasies of different facility types. Certain requirements may not even be possible to accommodate in all facilities. For example, a water cooled copper leading edge works well for the TBIV facility but might have a short service life if it is impacted by an occasional metal diaphragm fragment that is generated by the HYPULSE tunnel. As such, it was determined that 'standard' designs should be used for each facility test article. To minimize test article differences for the freejet testing, the design team duplicated as many parts as possible and then only fabricated one set of these parts. Basically, it was decided that the HYPULSE test article will be built first and tested. It will then be disassembled and reassembled, using many of the same parts, to construct the TBIV test article.

Table 2 Ground testing matrix for the SDPTE (Hy-V) Program.

Facility	Characteristic	Mach 5			Mach 7		
UVaSCF	Mode	Direct connect	Direct connect	Direct connect	-	-	-
	Test medium	Dry air	H_2 vitiation	Isobutane vitiation	-	-	-
	Test time	2 hr	2 hr	1 hr	-	-	-
ATK GASL TBIV	Mode	Freejet	Freejet	Freejet	-	Semi-freejet	Semi-freejet
	Test medium	Dry air	H_2 vitiation	Isobutane vitiation	-	H_2 vitiation	Isobutane vitiation
	Test time	30 sec.	30 sec.	30 sec.	-	30 sec.	30 sec.
NASA HYPULSE	Mode	Freejet	-	Freejet	Freejet	Freejet	Freejet
	Test medium	Dry air	-	Isobutane vitiation	Dry air	H_2 vitiation	Isobutane
	Test time	6 ms	-	6 ms	7 ms	30 ms	7 ms
Flight	Mode	Free flight	-	-	-	-	-
	Test medium	Atmosphere	-	-	-	-	-
	Test time	11 sec.	-	-	-	-	-

A. University of Virginia Supersonic Combustion Facility Experiment

The University of Virginia Supersonic Combustion Facility is an electrically-heated supersonic wind tunnel that is capable of simulating flight Mach numbers to 5. The facility has a continuous flow capability that allows unlimited duration testing. Including warm up and warm down periods, tests are usually conducted over a 5 to 6 hour period with steady state test conditions typically held for 1 to 2 hours. Since the facility is electrically heated, it does not have a freestream that is vitiated with combustion heater vitiates. However, the major combustion vitiates of water and carbon dioxide can be added to the freestream. Therefore, the clean air of flight or a hydrogen or hydrocarbon vitiated test medium can be simulated.

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Air heating is achieved via a 300 kW, 14-stage electrical resistance heater that is supplied with compressed air by an oil-free compressor and desiccant air dryer system. In order to vitiate the flow, water, in the form of steam, and carbon dioxide can be added to the air flow in the vicinity of the facility heater. The temperature of the air is controlled at the point of steam addition so that condensation does not take place. The steam is supplied by an electrical boiler and carbon dioxide is supplied by two heated cylinders. Makeup oxygen is added to the flow, prior to heating, in order to maintain an oxygen mole fraction of 21%. The facility vitiation subsystems have recently been upgraded to allow the Mach 5 simulation vitiate levels of Table 1. Reference 6 provides further details of the facility and vitiation capabilities.

Mach 5 enthalpy direct-connect testing with the DMSJ configuration of Fig. 1(a) is currently underway for clean air and air vitiated with water and carbon dioxide levels equivalent to hydrogen and methane combustion. This work is being performed as part of the Hypersonics Project of the NASA Fundamental Aeronautics Program. However, as discussed above, risk reduction activities have led to flowpath design changes for the current program. The DMSJ geometry in the UVaSCF will therefore be modified to match the new SDPTE and Hy-V flowpath. In order to minimize test article changes, the new geometry will be configured to match Flowpath A. Figure 2 presents a schematic of the new configuration. As can be seen in the figure, the existing isolator and combustor will be reused, however, a new isolator extension and a Mach 3 nozzle will be fabricated and implemented. Design of these components is currently underway. Since the University of Virginia combustor tests have a one atmosphere back pressure that interacts with the most downstream end of the combustor, downstream fuel injectors will not be implemented in this test article. Experiments with the new configuration will be conducted with 48 wall static pressure taps and 16 wall temperature probes.

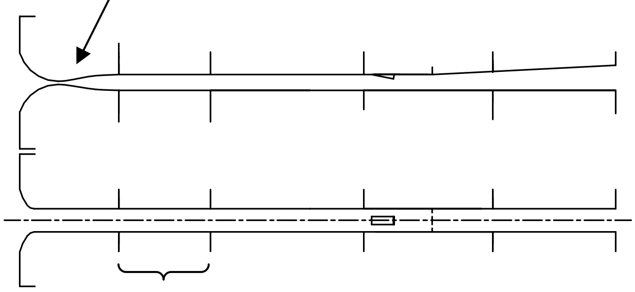

Figure 2. New direct connect Flowpath A configuration to be tested in UVaSCF for SDPTE (Hy-V) Program.

B. ATK GASL TBIV Experiment

The TBIV facility uses a storage heater to provide clean, dry air to Mach 5 conditions, and a booster heater with oxygen replenishment to provide vitiated air to Mach 8 conditions at total pressures of up to 1500 psi (10 MPa). The altitude and flight Mach number simulation capabilities at several dynamic pressures are indicated in Fig. 3. The booster heater can burn hydrogen, methane or isobutane fuel to provide the vitiated air conditions. Blow-down test duration ranges from 30 seconds to 60 minutes, depending on test conditions and/or model structural limitations. Facility run times are generally limited to less than two minutes for tests at flight Mach numbers from 6 to 8 where it is necessary to exhaust into a vacuum sphere. Tests simulating flight at Mach 2.5 to 4.0 can exhaust to atmosphere and can therefore run for longer periods. Engine models are mounted in TBIV on a force balance suspended in the 4 ft (1.2 m) diameter by 10 ft (3 m) long test cabin.

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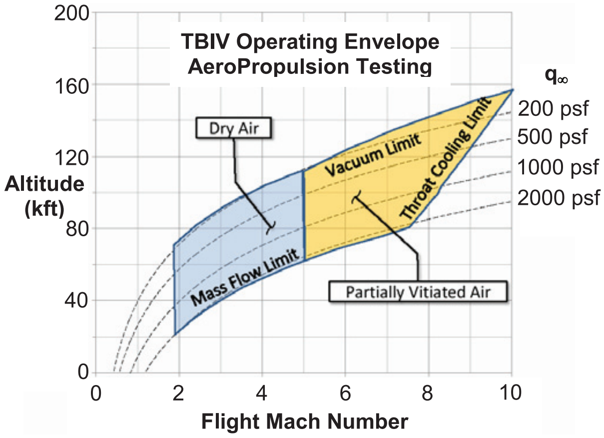

Figure 3. TBIV Operating Map.

The TBIV test article for this program is an all Oxygen-Free High Conductivity (OFHC) copper, heat sink model with water cooled leading edges for the forebody, flowpath inlets and pedestal prow. The forebody is a single piece construction with a single circuit, gun drilled water cooling passage. The forebody has pressure measurement locations that lead up to the centerline of the two flowpaths, A and B. As can be seen in Fig. 4, Flowpaths A and B are mounted side by side. This arrangement was required due to facility nozzle test rhombus size and facility blockage considerations. Each flowpath has four zirconia coated walls with gun drilled, water cooling passages along the leading edges. These walls are dowel pinned together, oven brazed and then final machined to make a fully sealed subassembly capable of withstanding the maximum operating conditions of the Mach 7 tests. Pressure measurement locations are along the centerline of each flowpath with multiple off centerline locations as well. Several thermocouple measurements are also located throughout both flowpaths. Fuel injection locations are from of the aft face of the body side ramp and at several side wall locations downstream. Each flowpath has independent fuel control systems to provide the appropriate fuel distribution for the given test conditions.

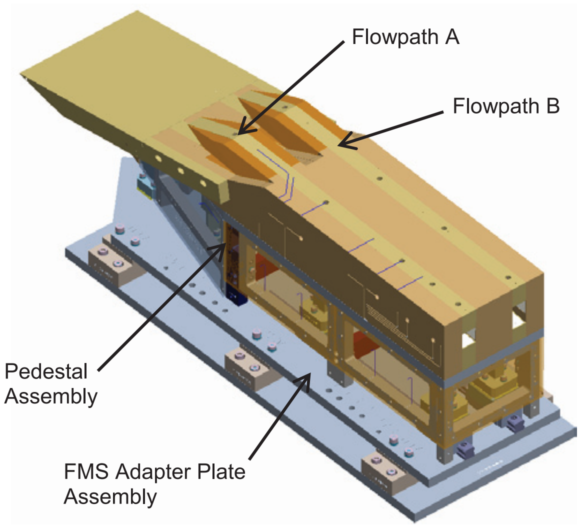

Figure 4. TBIV test article with Flowpaths A and B side by side.

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The entire forebody and flowpath configuration mounts to a vertical pedestal assembly that positions the test article within the facility nozzle test rhombus. The pedestal is the same pedestal that will be used during the HYPULSE experiments described in the next section. The stainless steel leading edge of the pedestal will be replaced with a water cooled copper leading edge but all other parts will be reused. The pedestal serves the same function as for the HYPULSE experiments and acts as a protective conduit for all instrumentation, water cooling and fuel lines. The pedestal mounts to the same plate that will be used in HYPULSE. However, in TBIV the plate acts as part of the Force Measuring System (FMS) such that all test article axial thrust and drag forces can be measured with load cells.

The instrumentation layout between the HYPULSE and TBIV test articles are very similar. Some compromises were made where fuel injection sites, water cooling passages, heat flux gauges and manufacturing seams all competed for similar space, but in general, instrumentation sites closely resemble those on the University of Virginia test article and those planned for the flight test article. Table 3 shows a general comparison of instrumentation between the subject test articles.

Table 3. Comparison of instrumentation among SDPTE (Hy-V) test articles.

	TBIV	**HYPULSE**	**UVaSCF**	**Flight**
Pressure Transducer Channel Limitation	256	120	128	144
Current Pressure Tap Configuration	52 per flowpath	52 per flowpath	48	60 per flowpath
Thermocouple Configuration	34	5 heat flux	16	44 limit, 32-36 designated for flowpaths

C. HYPULSE Experiment

The NASA HYPULSE facility is a shock-heated, free- jet facility that operates in the reflected-shock tunnel (RST) mode for aeropropulsion and aerothermal testing at flight conditions from Mach 5 to 10 and in the shock-expansion tunnel (SET) mode for flight conditions from Mach 12 to 25. The capabilities of the facility are depicted in Fig. 5. In the reflected-shock tunnel mode, HYPULSE offers very useful capabilities, which complement those of the blowdown tunnels, in the Mach 5 to 10 range. For example, it can provide higher total pressures (to 5000 psia) to simulate higher flight dynamic pressures at Mach 8, or to follow a constant dynamic pressure trajectory of 1000 psf from Mach 7 to 10. HYPULSE also offers clean, dry air data to evaluate contaminant effects from combustion- or arc-heated tunnels.

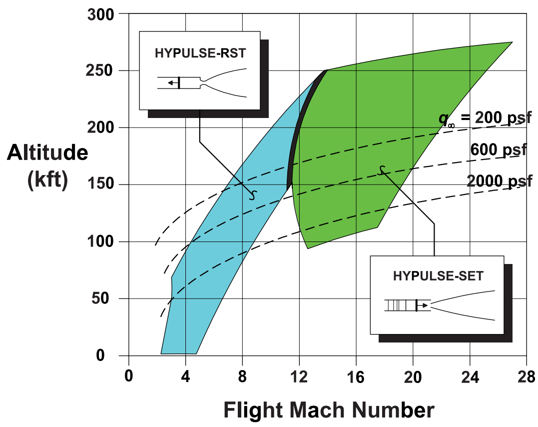

Figure 5. HYPULSE Shock Tunnel Operating Map.

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The HYPULSE test article for this program is presented in Fig. 6. The article is an uncooled, aluminum and carbon steel model with leading edges of the forebody, flowpath inlets and pedestal prow made of stainless steel. The forebody is a single piece construction with an optional trip strip location 10.4 in. (264 mm) from the leading edge and pressure measurement locations that lead up to the centerline of the two flowpaths, A and B. As for the TBIV facility, the flowpaths are mounted side by side. For each flowpath, the cowl and two side walls make up a single cover plate which is assembled over a machined body wall to make a sealed subassembly capable of withstanding the maximum operating conditions of the Mach 7 tests. Pressure measurement locations for close coupled, high frequency, PCB pressure transducers are along the centerline of each flowpath with multiple off centerline locations as well. Heat flux gauge locations are along the body wall centerline throughout both flowpaths. These heat flux gauges will be used to confirm that the boundary layer is turbulent when it enters the inlet and also confirm that the HYPULSE flow is established given the uncertainty regarding flow establishment time of dual-mode scramjets. As in the TBIV test article, fuel injection locations in the HYPULSE test article are from the aft face of a body side ramp and at several side wall locations downstream.

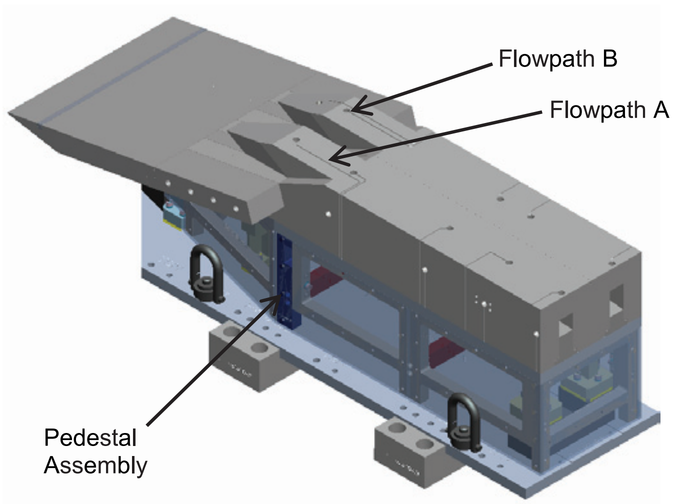

Figure 6. HYPULSE test article with Flowpaths A and B side by side.

The entire forebody and flowpath configuration mounts to a vertical pedestal assembly that positions the test article within the facility nozzle test rhombus. All pressure and heat flux instrumentation route from the flowpaths and forebody down through the pedestal, out to bulkhead fittings and back to the data acquisition and control system. Close coupled, fast acting fuel valves are also located within the pedestal and provide each flowpath with independent fuel control systems for the given test conditions.

4. FLIGHT EXPERIMENT

A. Payload Design

The Hy-V flight payload, shown in Fig. 7, is a cylindrical design with vertical and lateral symmetry. The design is based on a combination of design elements from the DARPA/ONR FASTT payload and a risk reduction study conducted early in the SDPTE program. The payload is comprised of seven major airframe components: forebody/inlets, spacer section, aft airframe, flowpaths A and B, antenna section, fuel storage and payload skins. Another crucial, but non-airframe component, is a pair of gas generators that will be used to ignite the flowpaths. The payload is designed to withstand launch (captive boost) and survive sine and random vibration acceptance testing without damage to the structure or subsystems. The targeted maximum payload weight is 214 kg (470 lbs), including shroud and ballast, and the targeted nominal test window duration is a maximum of 15 seconds.

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The overall design philosophy was to divide the payload into functional subcomponents so that an optimum weight material system could be selected for each component. Materials were selected and a Thermal Protection System (TPS) was incorporated as required such that active component cooling was not necessary. Due to the high external heat loads experienced throughout the flight trajectory, as well as those present in the combustor, various methods were adopted to minimize heat transfer to the payload structure. A deployable shroud will be used to minimize aerodynamic heating during the ascent phase. The nose tip, forebody and flowpath inlets are all constructed from Haynes 230 alloy, which retains sufficient mechanical properties at the expected temperatures. All outer mold line surfaces aft of the inlet are also protected by phenolic cork sheeting that is bonded to the payload skins. Additionally, a spacer section serves as a thermal transition from the forebody (Haynes 230) to the aft airframe (Aluminum).

The payload layout from tip to tail starts with the wedge forebody (10-deg. half-angle), with fences to ensure uniform flow entering the flowpath inlets. The flowpath inlets process the flow into two different isolator combustor flowpaths, Flowpath A on one side of the payload and Flowpath B on the other. Both flowpaths have a gas generator igniter just downstream of the base of a hydrogen fueled ramp. Side wall fuel injectors will be available to inject more fuel downstream of the ramp should the ground tests deem it necessary. Each flowpath exhausts its combustion products outward at a ramp angle of 13-deg. for Flowpath A and 20-deg. for Flowpath B. Internal to the central airframe section are two annular instrumentation bays where the majority of instrumentation, data acquisition and processing, and telemetry units are located. Further downstream is the aft airframe and antenna section. Finally, the transition airframe has a 10.8 in. (274 mm) payload, Radax joint at the forward end and a 14 in. (356 mm) Orion, Radax joint at the aft end. This section also houses a GLNMAC inertial navigation unit and a fuel delivery tank and control system.

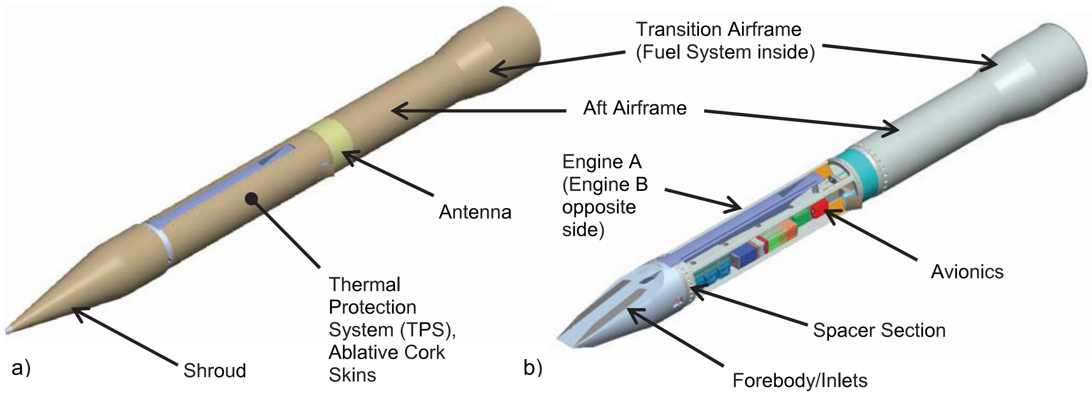

Figure 7. SDPTE (Hy-V) flight payload design, a) with shroud and TPS, and b) shroud and TPS removed.

B. Payload Subsystems

The payload subsystems consist of an Event Sequencing System, a Power System, an Instrumentation, Data Acquisition and Telemetry System, an Inlet Shroud/Shroud Separation System, a Fuel System and an Igniter System.

1. Event Sequencing System

An electronic event sequencer will be used to trigger the following payload events autonomously during the mission profile: inlet shroud separation, fuel flow initiation and igniter system initiation. The event sequencer is a multi-function timer that can be programmed to control up to 30 events with a minimum of 100 ms spacing between events.

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2. Power System

The power subsystem provides and distributes power to all payload subsystems and incorporates a means of switching between ground and internal payload power. The available power must be sufficient to operate all subsystems from launch through to the end of fueled flowpath operation (15 seconds), as a minimum requirement, and with reserves to continue data collection and transmission thereafter. Power delivered to the subsystems will be regulated to within the required tolerances of the individual subsystem components. The payload contains two separate power control systems. The first power system provides power to all telemetry, instrumentation and data monitoring, multiplexing, and Radio Frequency (RF) transmission hardware. The second power system provides pyrotechnic initiation power and fuel valve power for all in-flight payload section events. Power is stored in rechargeable batteries. Battery packs are mounted directly to the payload airframe, while the rest of the components are mounted to avionics pallets.

3. Instrumentation, Data Acquisition and Telemetry

The types, location and accuracy of payload instrumentation must be sufficient to characterize the flight trajectory and flowpath operation (e.g., inlet(s) starting, subsonic combustion, supersonic combustion, etc.). It is desired to perform sufficient measurements to determine the flight condition from on-board measurements and to provide health monitoring of critical subsystems including instrument bay heating and skin thermal protection effectiveness. The instrumentation package includes individual pressure sensors, pressure scanning modules, B- and K-type thermocouples, thermistors, current and voltage monitoring circuitry, accelerometers and a magnetometer. Measurements of interest include nose tip pressures, forebody wedge and skin pressures, skin temperatures, and electronic component temperature monitoring. In addition, inlet pressure and temperature, gas generator pressure, isolator, combustor and exhaust nozzle axial pressures and combustor heat loss measurements will be taken. In all, the payload has 144 instruments including 120 pressure channels in four pressure scanning modules, 32 individual thermocouple sensors, six single axis accelerometers, a single 3-axis magnetometer, ten individual pressure transducers, two high frequency pressure sensors, and 29 various sensors and monitors for health monitoring capabilities.

The data acquisition system provides the necessary excitation voltages and signal conditioning for the onboard instrumentation package and uses Pulse-Code Modulation (PCM) format for data transmission. The system has the capability to sample and multiplex the channels for the instruments listed above. The data acquisition provides health monitoring via instrumentation system voltages and currents, squib fire current, instrument bay temperatures and relay and G-switch status monitors. All PCM multiplexed data are analog type and have an input range of 0 to +5 volts.

The telemetry system transmits the PCM output data stream to ground stations via an S-band transmitter/antenna. The telemetry system also transmits the ranging transponder signal to ground stations via a C-band transponder/antenna. The current choice for a dual-band antenna is a Haigh-Farr combination S and C-band Microstrip antenna that is designed to provide 360° antenna coverage to maintain the link with ground stations while rotating (the entire booster plus payload will have a spin rate of approximately 5 Hz). It is intended to transmit data starting on the launch rail up until the payload runs out of sufficient power. Once the ground umbilical is disconnected at lift off, there is no “off” switch. The antenna must be protected from the aerothermal environment throughout flight and this thermal protection must be as RF transparent as possible.

4. Inlet Shroud/Shroud Separation System

A shroud is used to protect the front of the payload during boosted ascent to the desired insertion point. More importantly, the shroud protects the forebody instrumentation and flowpath inlets during the boost stages, when it is desired not to have air pass through the scramjet flowpaths. Once the payload reaches its desired insertion point, the shroud halves are ejected, thereby exposing the inlets. The shroud was previously used on the FASTT Program and is designed and supplied by Systima Technologies, Inc. Systima has shroud heritage to the Theater High Altitude Area Defense (THAAD)

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missile defense system and experience in deployment in high aerodynamic environments to 16,000 psf.

5. Fuel System

The fuel system to be flown on the payload is a blowdown gaseous hydrogen system. The 3250 psi tank is housed in the transition section aft of the flowpaths. Gaseous hydrogen flow is controlled by an on/off valve, then regulated to maintain a constant pressure on a sonic venturi to provide measured flow rate to the flowpaths. Multiple sonic venturis will be sized according to the fueling schedule determined during the ground test phase of the program.

6. Igniter System

Fuel auto-ignition is not expected at the Mach 5 flight condition. Therefore, an igniter system is included in each flowpath. A commercially available Solid Propellant Gas Generator (SPGG) is the prime candidate for the igniter, with silane, spark or plasma torch igniter as secondary options. Ignition requirements have been defined based on the University of Virginia experiments conducted to date and will be verified in the freejet model ground testing to be conducted in GASL's TBIV facility.

C. Mission and Trajectory

The flight experiment will take place at the NASA Wallops Flight Facility using a Terrier (Mk-70), Improved Orion sounding rocket. The payload will be flown on the second stage Improved Orion in captive carry mode. Both stages are fin stabilized but unguided and are not routinely used for air breathing propulsion experiments that involve relatively high dynamic pressure. Therefore, in order to reduce dispersion from the target test conditions and reduce the total heat load through to the end of the test window, the combustion experiment will begin prior to the second stage burn out.

This program will leverage the success of the FASTT Program in order to reduce risk. Apart from the fact that the payload for the current program will be captively carried, the mission profile is very similar. The flight will consist of several events that can be divided into two phases. The first phase, launch and ascent, will consist of first stage ignition, burn out and separation, and second stage ignition. The second phase, the experiment test window, will then commence towards the end of the second stage burn and will start with shroud deployment. Once flow is established in the two scramjet flowpaths, the fuel will be turned on and ignited using the gas generators. The experiment will be completed prior to apogee when fuel exhaustion occurs. In order to minimize cost, the payload will not be recovered. Data acquisition and telemetry will take place throughout the flight using the NASA Wallops Main Base Telemetry ground station. Radar and video tracking will also take place.

The nominal trajectory was chosen in order to meet the primary target test conditions of Mach 5, with a dynamic pressure of 1500 psf (72 kPa) and a rate of change of dynamic pressure near zero. The secondary target test condition is 1000 psf (48 kPa). These dynamic pressures were chosen to match ground test capabilities. Calibration to previous FASTT flights and trajectory optimization was initially performed using the three-degree-of-freedom Program to Optimize Simulated Trajectories (POST)[18]. Detailed six-degree-of-freedom simulations were then performed using the GEM code[19]. The GEM code has been calibrated against FASTT flights in preparation for detailed dispersion analyses. The Mach number, altitude and dynamic pressure for the nominal trajectory are presented in Fig. 8. Figure 8(a) shows the predicted Mach number and altitude variation with time, together with a time line of major flight events. Figure 8(b) presents the details of the Mach number and dynamic pressure variation over the test window. The test window starts with a primary test window of 11 sec., between shroud deployment and second stage burnout, in which the primary target test conditions are met. This is then followed by a secondary test window of 7 sec. in which the secondary test conditions are met. Following the test window, splashdown occurs at 210 sec. and 114 miles downrange of launch.

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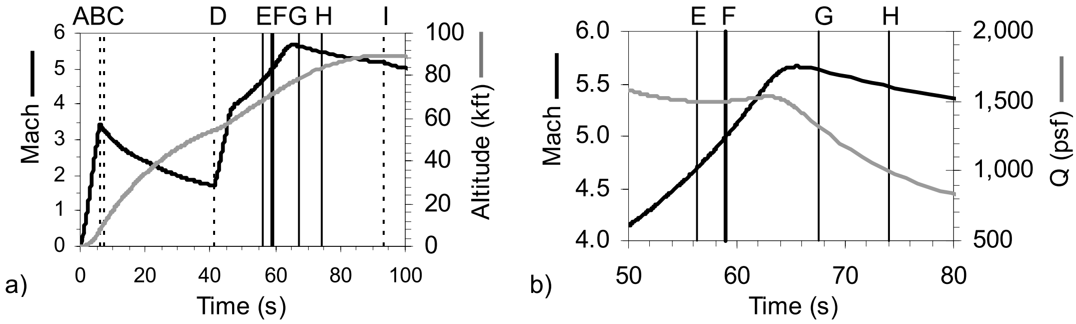

Figure 8. Predicted nominal trajectory for flight experiment, a) Mach number and altitude history, and b) Mach number and dynamic pressure, Q, during test window. Key; A: First stage ignition, B: First stage burn out, C: First stage separation, D: Second stage ignition, E: Deploy shroud, F: Primary target condition, G: Second stage burn out and primary experiment end, H: Secondary experiment end, and I: Apogee.

5. PROGRAM MANAGEMENT

A. Team

The combined SDPTE and Hy-V Programs are working collaboratively to successfully execute the ground and flight experiments. ATK GASL has the overall responsibilities for the SDPTE program, including planning and execution from concept, design development, testing and reporting to program close-out. The program is being executed while also ensuring a program-wide focus on safety, reliability, cost, schedule, and adequacy of systems, procedures, and people for long-term success. The SDPTE Program is a key effort of the Department of Defense's Advanced Propulsion Test Technology (APTT) focus area of the Testing and Evaluation/Science and Technology (T&E/S&T) Program sponsored by the Test Resource Management Center (TRMC). The SDPTE Program is subcontracting a number of organizations, including members of the Hy-V Program. The Hy-V Program consists of the University of Virginia, Virginia Tech, Aerojet, NASA and the NASA Sounding Rocket Operations Contract (NSROC). The Hy-V Program forms the focal point for university education and student outreach and is providing university personnel and students to the SDPTE Program. The SDPTE and Hy-V collaborative arrangement has resulted in university students working side by side with industry professionals. Based on this level of student involvement, NASA Wallops Flight Facility is providing the sounding rocket launch opportunity as part of the NASA Sounding Rocket Program's university-level student education program.

B. Management

The combined SDPTE and Hy-V program has adopted an Integrated Product Team (IPT) approach to efficiently execute the major projects within the program; namely, Design, Ground Test, Flight Test and Analysis. The IPTs are made up of cross functional members responsible for meeting all design, quality, safety, cost and schedule requirements, ensuring the mitigation and control of critical failure modes, performing potential problem analysis for the processes and products, evaluating and monitoring supplier's and subcontractor's ability to meet requirements and ensuring that all facility and tooling capabilities are adequate to meet program requirements.

Since communication is the key to program success, the SDPTE program uses Teamcenter Community, a UGS Corporation, commercial software package that provides a collaboration toolset to enable these IPTs to work more effectively. The IPTs can share documents from a common document library, eliminating the need to email files and manually integrate changes, manage action items through a community Task List and initiate an application sharing instant conference to enable all team members across the country to see what is being discussed from their computer screen.

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6. CONCLUSION

The combined SDPTE and Hy-V Programs will result in a comprehensive ground and flight database that will enable the isolation of the effects of ground based facility test flow vitiation and test flow duration on the performance of a dual-mode scramjet. The combined program is being conducted by a consortium of university, industry and government participants that includes a significant level of university student involvement.

The generated database will enable validation of analytical and computational tools for predicting dual-mode scramjet performance. However, the most important contribution of this program will be the comparison of test results from a large freejet blowdown facility, which is both vitiated and unvitiated, with results from a large freejet shock heated facility, which is also vitiated and unvitiated, and the subsequent comparison of the ground test data with that of flight in atmospheric air. It is anticipated that this comparison will significantly improve our understanding of the capabilities and limitations of testing in large facilities that are capable of scramjet system sized experiments. The comparison will also improve the accuracy of the prediction of scramjet performance when extrapolating ground based data to flight.

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