Current Hypersonic Research in the USA

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INTRODUCTION

The potential benefit of an operational hypersonic system has driven continued research in the United States in basic and applied technologies. The goal is to progress beyond the demonstration of core principals, and begin to utilize hypersonic flight within the atmosphere to deliver revolutionary capabilities.

The X-43A program delivered clear and convincing evidence that the propulsive principles of hypersonic flight are understood. For the first time the test, analysis, and design tools that evolved over 40 years of research were brought together to yield a working hypersonic air-breathing vehicle. The hydrogen fuelled vehicle accomplished all of its validation objectives, performing flawlessly at Mach numbers near 7 and 10 in two successive flights. The engine produced thrust at Mach 7 in excess of drag to yield positive acceleration, and at Mach 10, produced sufficient thrust to balance drag, or cruise. As the prime contractor for NASA, ATK GASL had the unique perspective of seeing the complete program from start to finish. Although very important, these flights are only a first step on a long path to an operational capability.

There is more work to be done in the optimization and maturity of designs for hypersonic engines. As compared to rocket propulsion which currently achieve most of the hypersonic missions of interest, hypersonic air-breathing propulsion is extremely immature. This most common criticism of air-breathing propulsion together with an as of yet unjustified perception of high cost, has hindered funding for applications development.

Over the past 10 years, ATK-GASL has worked to advance hypersonic propulsion technologies by increasing maturity, identifying more practical, lower cost designs, and transitioning from ground test to flight test. Our objective is to develop a line of engine designs, aligned with envisioned mission requirements, and with a focus on manufacturability at an affordable cost in production. We have identified propulsion system components, integrations, as well as practical ground and flight test strategies to push the technological maturity, and accumulate in-flight operational experience.

An evaluation of the National Aerospace Initiative by a National Research Council committee in 2004 identified four critical and enabling technologies that must be matured to TRL 6-7 (System/Sub-systems Prototype Evaluation in a Relevant/Operating Environment) to support future missile systems, aircraft systems and access to space systems:[1]

- Air-breathing propulsion and flight test,
- Materials, thermal protection systems (TPSs), and structures,
- Integrated vehicle design and multidisciplinary optimization, and
- Integrated ground testing and numerical simulation/analysis.

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Our research has focused to some degree on each of these areas. This lecture will review specific examples that have addressed these needs.

HYPERSONIC ENGINE RESEARCH PROGRESS

Depending on the mission scenario for the vision vehicle design, the propulsion cycle, engine configuration and the choice of fuel for the engine vary. Figure 1 shows a collection of hypersonic engine systems for which ATK GASL has played a significant role and that have been carried through significant ground tests or to flight test: the X-43A, HyTech, ATK TTRJ, and Dual Combustor Ramjet. These scramjet designs utilize a variety of inlet concepts ranging from planar two-dimensional to highly three dimensional designs. Likewise, combustor geometries also vary from high aspect ratio (width / height) rectangular to circular.

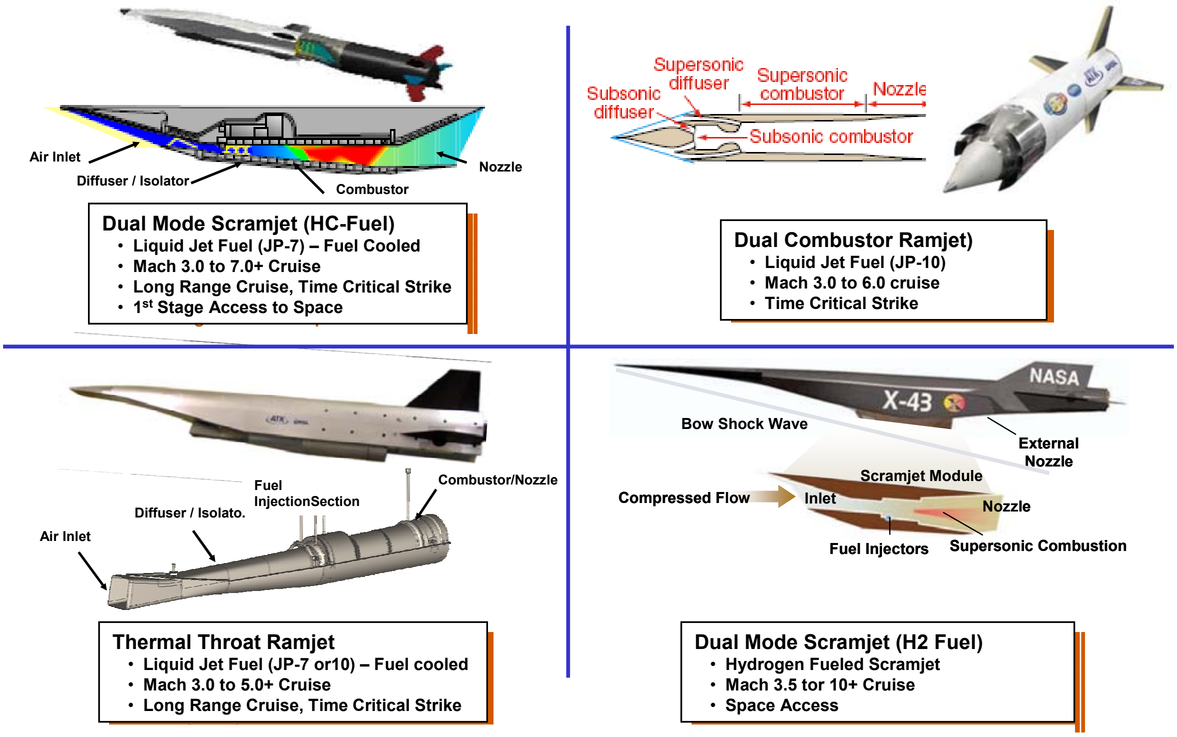

Figure 1. Hypersonic propulsion cycle and fuel choice depend on the speed range and intended mission among other parameters.

During the National Aerospace Plane (NASP) program era in the late 1980's to early 1990's, two-dimensional inlet / rectangular combustor geometries became the baseline for which significant tool and technology development was performed. The principle reasons for selection of this engine architecture were driven by the desire to maximize the airbreathing portion of the flight envelope for a Single-Stage To Orbit (SSTO) vehicle AND the need to build a flight vehicle in 5 years. These requirements drove the following considerations:

- Multi-Disciplinary Optimization (MDO) techniques necessary to optimize engine/vehicle integration demanded utilization of tools capable of rapid design iteration. Although Computational Fluid Dynamics (CFD) capabilities were maturing rapidly, analysis for two-dimensional designs was considered to be more advanced at the time than for other, more generalized shapes.

- High engine efficiency over a very wide Mach number range (M = 0 to 15+) required significant variable geometry in both the inlet, combustor and nozzle section to optimize engine contraction ratio, combustion efficiency, and nozzle expansion ratio. The need to rapidly develop engines for a flight vehicle drove the architecture to two-dimensional planar which allows the most straightforward movement of engine walls to accomplish the needed variable geometry in a vehicle integrated configuration.

Since the NASP era, which ended over 10 years ago, several factors have changed the hypersonic landscape. Although SSTO is still the dream of some, most of the hypersonic community has adopted a more pragmatic approach that focuses on the following configurations and missions:

- A first stage of a Two-Stage-To-Orbit (TSTO) concept that utilizes either a turbine or rocket-based accelerator as well as a rocket-stage for orbital insertion. The fuel of choice varies, but again most vision applications do not require scramjet operation above about Mach 8-10.

- A cruise aircraft which uses similar, although much larger scale, ramjets or scramjets that again operate between Mach 3+ up to Mach 7 or 8.

- A hydrocarbon-fueled ramjet or scramjet powered long range cruise missile, boosted via a solid rocket to Mach 3-4 and with ultimate airbreathing speed capability between Mach 5 and 8.

- A gun-launched air-breathing powered projectile capable of very long range. Packaging of this configuraiton in gun-tube diameters and use of high density fuels presents unique challenges in the ramjet-scramjet design space.

The energy required for a ramjet or scramjet to ultimately accelerate a vehicle to Mach 5 or even Mach 10 from a takeover condition of about Mach 3 is a fraction of the requirement imposed by NASP. Therefore, the need for optimum engine efficiency via extreme engine flowpath geometry variations gives way to other considerations of weight, surface area, volume, simplicity and affordability for the more pragmatic applications envisioned today.

Another factor that has changed the post-NASP landscape is the evolution of CFD and processing capability allowing MDO-based optimization of engine and vehicle configurations with much more general shapes. Significant effort is underway in the US and abroad to develop stream-line traced inlets and engine/airframe integrations with both superior inlet recovery and vehicle lift / drag characteristics. This capability has been enabled via development of CFD algorithms, computer processing capability and design automation tools to the point that development of geometries, grid generation and computation for generalized shapes now take a fraction of the time relative to two-dimensional geometries of the NASP-era.

These factors have also opened up the design space for combustors, and isolators which connect these unique inlets to the combustor. As the highest pressure, highest temperature component in any airbreathing engine, optimization of the combustor within performance, weight, surface area, volume, simplicity and affordability factors mentioned earlier is key to enabling practical scramjet systems.

Following the demise of NASP in 1994, evolution of the two-dimensional engine architecture design methods, tools and technology continued via both the NASA Hyper-X and the USAF HyTech programs. Today, we have demonstrated this technology in flight via the Mach 7 and 10 flights of the hydrogen fueled X-43A. Additionally, the HyTech program has demonstrated, via ground test, the viability of flight-weight two-dimensional hydrocarbon fuel-cooled scramjets. The next step, bringing these systems to flight, will occur via the USAF X-51 program with flights scheduled in late 2008 / early 2009.

During this period, 3-dimensional engine architectures continued to make advances with attention on more specific applications. The Johns Hopkins Applied Physics Laboratory continued development of the Dual Combustor Ramjet concpet that utilizes a round scramjet combustor.[2] This concept has had extensive ground testing and was flight tested at Mach 5.5 conditions by ATK GASL in 2005. In the gun-launched area the ScramFire projecitle was successfully flight tested in 2003.

X-43A

ATK GASL worked together with NASA to execute the design and fabrication and flight test of the X-43A flight vehicle and propulsion systems. Following in the footsteps of the NASP program, the X-43A engine design was derived from a vision 200-ft Global Reach vehicle.

Scaling to the 12-foot long X-43A vehicle (Figure 2) was executed by NASA using a series of Cycle code and CFD code methods.[3] The propulsion system architecture is predominantly two-dimensional and allows for a movable cowl door that is opened to initiate and facilitate started supersonic flow through the engine. The smaller scale results in higher heat loads on a per-unit area basis which made the thermal/structural design of the engine challenging. The following discussion concerns the implementation of the engine design and the fuel supply system. The details of the X-43A mission are presented in reference [4]

Figure 2. X-43A Engine and Fuel System were built as separate units and assembled to the vehicle. The fuel system delivered gaseous hydrogen and pyrophoric Silane for ignition.

The engine is manufactured as a self-contained unit Figure 3.[5] It incorporates a rectangular flowpath, and is of airframe-integrated design where the vehicle forebody and afterbody provide external compression and expansion surfaces which are continuations of the internal compression and expansion surfaces within the engine. It operates on gaseous hydrogen fuel with a silane igniter; to provide sufficient run time the hydrogen and hydrogen/silane igniter mixture are stored at 8500 and 4500 psi, respectively. The Glidcop engine section is attached to a stainless steel strongback, which in turn connects it to the airframe. A key feature of the engine is the actuated inlet cowl door, which protects the internal flowpath during boost, opens for engine operation, and then closes again during the vehicle descent from the test point. Both the cowl and the vertical leading edges of the engine are sharp-edged and water-cooled for thermal protection during boost and engine operation. Zirconia coating is used on the forward section of the engine cowl and in key places throughout the engine for additional thermal protection. The vehicle subsystems also incorporate a nitrogen purge system, which additionally provides cooling of certain vehicle subsystems during the flight test phase.

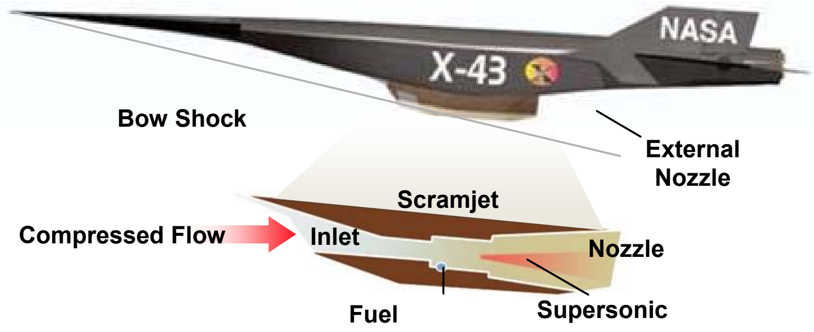

Figure 3: The X-43A Vehicle and predominantly two-dimensional propulsion flowpath

Results of the X-43A flight and ground tests yielded new confidence in the ability of design and analysis tools: cycle, computational, and test assets to effectively develop a hypersonic engine of desired performance. Figure 4 shows a comparison of engine pressures as measured in the NASA Langley 8-Foot High Temperature Tunnel as compared to flight data.[3] The tunnel is combustion heated using methane fuel and the test gas is consequently vitiated with products of hydrocarbon combustion. Despite these test gas composition differences, the comparison shows the data to be very consistent. Although this level of agreement is encouraging, the configuration and operating condition dependence of this result must be further considered.

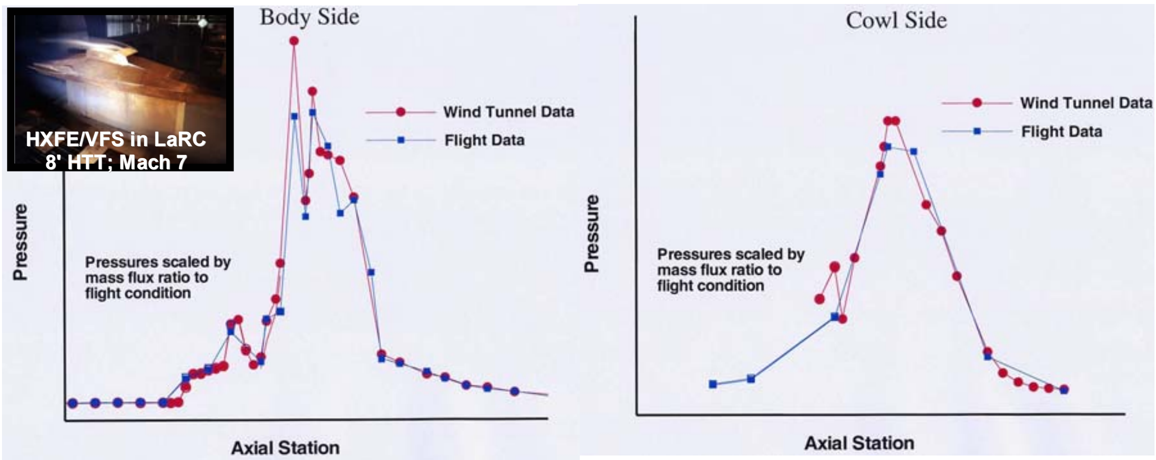

Figure 4. Pressure data from the X-43A compared to flight data showed remarkably good agreement with ground test data from combustion heated, arc heated, and shock heated facilities.

HyTech and X-51 Scramjet Programs[6]

The US Air Force HyTech and subsequent X-51 programs are focused on development and flight test of a scramjet engine with a storable liquid hydrocarbon fuel in an endothermic cycle. Supporting technologies including inlets, composite leading edges, heat exchangers, and flame-holding devices, were all developed early in the HyTech program. These developments were followed by a full-scale demonstration of the engine design in a heavy-weight, heat-sink flowpath called the Performance Test Engine (PTE), shown in Figure 5 at test in the ATK GASL Test Bay 6 Blowdown facility. General architecture of the engine is also shown in Figure 5 of a Direct Connect test article.

Figure 5. Inlet starting and performance of the USAF HyTech engine were demonstrated over the Mach 4-6 in the ATK GASL Leg 6 blowdown facility. The architecture of the engine is shown in the direct connect test article at the right.

More recent efforts are focused on developing flight-weight engines that feature fuel-cooled walls operating in an endothermic cycle, Figure 6. Fuel is pumped from a holding tank through all four walls of the engine to provide cooling. In the process of cooling, the fuel (JP-7) is vaporized and eventually is partially cracked. This highly reactive vapor is then directed to any or all of the five fueling sites in the engine via flowcontrol valves capable of handling the high temperature gas. The practical limit of this process is coking limit of the fuel. Since coking within the cooling channels must be avoided at all costs, temperatures are controlled to values safely below the coking temperature. This limits the hydrocarbon fueled scramjet engine to approximately Mach 8.

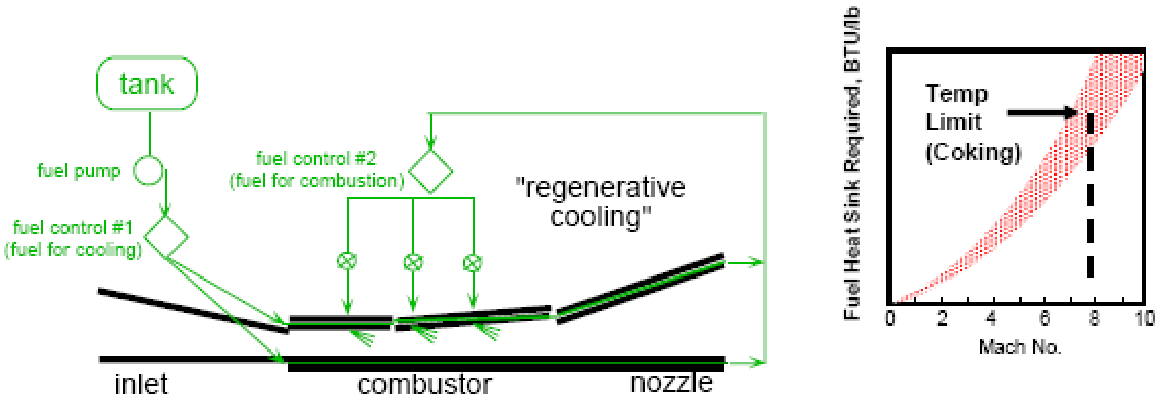

Figure 6. A schematic of a regenerative fuel cooled engine. As the flight Mach increases the thermal load increases. For liquid hydrocarbons the fuel coking limit occurs at about Mach 8.

Subsequent test of the HyTech engine were conducted in the Ground Demonstration Engine Number One (or GDE-1) also run at ATK-GASL and most recently in the GDE-2 engine tested at the NASA LaRC 8'HTT. The objective of these programs was to demonstrate the thermal response and the structural durability of the fuel-cooled construction. In GDE-1 the engine was operated in an "open loop" manner where separate fuel lines provided for fuel cooling and for combusted fuel. The fuel introduced to the combustor is first passed through a facility heater where the fuel is vaporized and partially cracked, simulating passage through the engine. This mode of operation was required since it was required that the engine be "over-cooled" initially until fuel distributions could be accurately determined. In each test series the engine was cooled at three times the expected flow rates and then at progressively reduced rates until a cooling flow rate was achieved that matched fueling requirements of the combustor. In the GDE-2 engine tests the fuel was standard JP-7 fuel in a closed-loop configuration at Mach 5 conditions to both cool engine hardware and fuel the engine's combustor[7].

TheX-51A flight program will carry the GDE engines through flight test, Figure 7. This flight program will demonstrate the operation of the endothermically fueled scramjet engine using a single flowpath and fixed-geometry inlet. The waverider derived vehicle will be launched on an ATACMS Booster to accelerate the test vehicle to a scramjet takeover Mach number of 4.5 with the scramjet engine further accelerating the vehicle to approximately Mach 7. The engine features a 9-in wide flowpath.

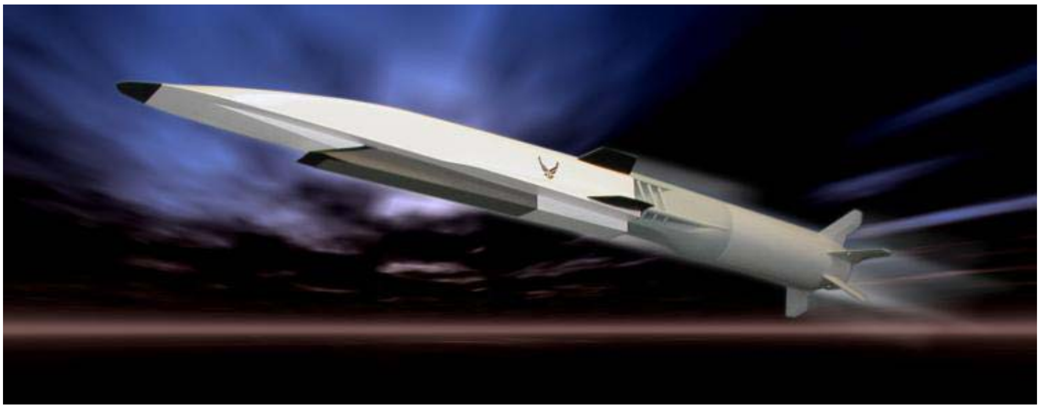

Figure 7. The X-51A will flight test the US AF HyTech engine with first flight scheduled for 2009

Dual Combustor Ramjet

The Dual Combustor Ramjet (DCR) propulsion system has been developed by John-Hopkins Applied Physics Laboratory. In the DCR , a subsonic combustion ramjet is used as the pilot to a scramjet engine, enabling efficient operation over a wider range of supersonic and hypersonic Mach numbers using logistically suitable fuels.[8] This novel combination of subsonic and supersonic combustion in a combined flowpath (Figure 8) attacks the challenging problem of liquid fuel evaporation and combustion without regenerative fuel cooling as in the Hytech engine. The overall combined flowpath architecture can be packaged into a missile type configuration with a round combustor[2], and is a notable excursion from the generally two-dimensional configurations discussed previously.

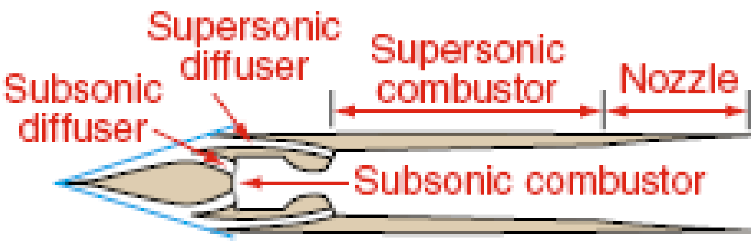

Figure 8 The Dual Combustion Ramjet (DCR) uses a subsonic combustor to pilot a supersonic combustor.

Recently, a Dual Combustor Ramjet propulsion system was implemented in support of a flight test program at ATK GASL. The objective of this program was to develop a low-cost Free-Flight Atmospheric Scramjet Test Technique (FASTT). This concept uses sounding rockets and their mature launch support infrastructure to ferry scramjet powered payloads to hypersonic flight conditions.

One major objective of the program was to compare ground test engine performance and operability data for comparison to flight data. A freejet test article was built at the same scale as the flight engine and tested in the ATK GASL Test Bay 6 Blowdown Facility. The test article shown in Figure 9 was designed for multiple tests of approximately 30 seconds duration. A predominantly heat sink design approach was used with construction from heavy-weight copper and nickel alloys. Water cooling was necessary for certain high thermal load combustor regions.

Figure 9. The DCR freejet test article installed I the ATK GASI test facility in preparation for testing at Mach 5.5.

The design requirements for the flight test called for on condition operation at approximately Mach 5.5 for 30 seconds. Throw weight considerations precluded copper construction, so a combination of high temperature nickel alloys and ablative linings were used for thermal management. Fuel was stored in a bladder system and pressure fed via regulated gas supply. The engine was instrumented for pressure and temperature measurement. Ignition was provided by a small solid-propellant gas generator that ignited the subsonic ramjet leg of the dual combustor.

The successful flight test will be described subsequently. From an engine perspective all objectives were met. Following separation from the booster system, and shroud disposal, fuel flow was initiated and the igniter system initiated combustion. Two levels of fuel flow were used. The initial rate was set near stoichiometric in the ramjet pilot combustor to assure robust ignition. This was fooled by a higher flow to achieve fuel rich conditions in the ramjet, as needed to fuel the supersonic combustor.

Correlation between flight to ground data underway. Preliminary comparisons show excellent agreement when heat losses are accounted in the different test articles.

Gun-Launched Scramjet

A series of Gun Launched scramjet designs were executed to demonstrate the feasibility of subscale gun-launch as a means to provide low-cost scramjet free-flight data[9]. Gun-launch was used to accelerate a projectile to scramjet take-over speeds and for flight in an atmospherically controlled ballistic range. The objective vehicle was a nominal 20-inch diameter missile operating over Mach 6-8. Pressure-Dimension (p-D) scaling rules were adopted to set conditions in the range to achieve comparable engine operation to the full scale vehicle in flight at altitude.

The engine design for the projectile was driven by the requirements for packaging within the constraints of a hypervelocity launch tube of 4” to 8” diameter, capability to withstand the gun set back acceleration, projectile stability in flight, and need for a self contained fuel system, and onboard instrumentation and telemetry.

Initial design iterations focused on a 2-dimensional derived annular configuration wrapped around a cylindrical centerbody as shown in Figure 10. These designs proved difficult to optimize for both performance and strength for the gun-launch environment. Subsequent successful designs like that shown in Figure 11 used multiple 3-dimensional engine modules positioned around the centerbody, allowing for more optimal structure to support compression in the projectile axis direction.

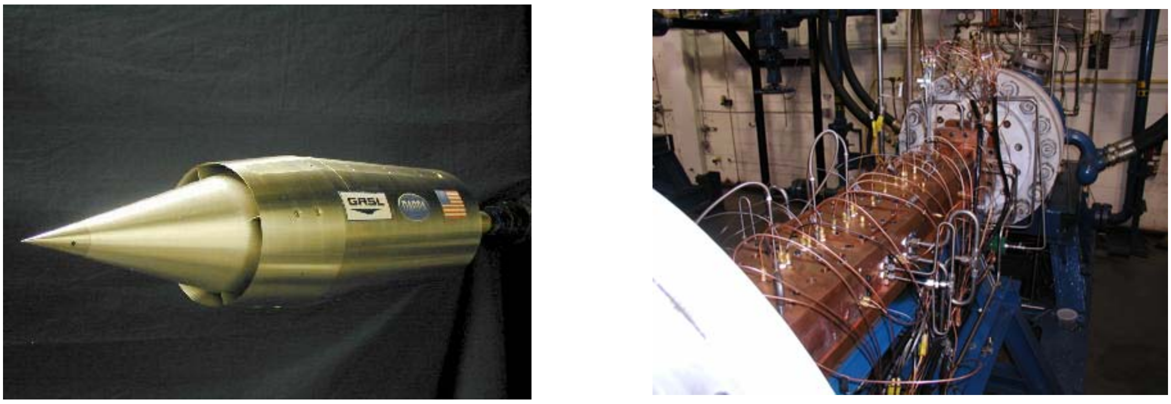

Figure 10. Initial configurations for a gun-launched scramjet featured a predominantly annular engine design that did not offer sufficient strength for high G loads. A direct connect test rig was used subsequently to develop a fully 3D engine configuration

Figure 11. The gun-launched projectile design used eight scramjet wrapped around a cylindrical centerbody with fuel tank and delivery system.

The projectile design had eight scramjet engines mounted around cylindrical centerbody It included an onboard fuel storage and operating ethylene fuel system. The set-back accelerations in the gun-tube are in the range of 10,000 G, and were a significant driver on the projectile design. The overall integrated projectile was verified computationally including aerothermal and structural loads. The propulsion design was carried out using a mix of CFD and cycle codes and then verified experimentally in direct-connect wind tunnel tests.

Direct connect wind tunnel tests were performed to evaluate the combustor and isolator designs and to build a comparative performance database with which to compare flight data. The engine design was tested using a 7x scale model in the GASL Test Bay I direct-connect facility to determine modes of operation and fueling strategies. To correctly capture the performance of the engine, the facility conditions were set using pressure-dimension scaling, using the same methodlogy as between the range and the objective vehicle. Experiments showed that while the flow path and flame-holding strategies were adequate for the current application, the fuel injection pattern needed to be re-designed to improve engine performance. Subsequent testing with modified injection schemes validated the alteration.

NEW DIRECTIONS IN HYPERSONIC ENGINE RESEARCH[10]

The combination of revised requirement for hypersonic flight vehicles and the advancements in computing capability has resulted on a renewed focus on non-rectangular isolator and combustor geometries for near term practical scramjet propulsion systems. From a surface area and structural weight point of view, circular cross sections offer the most benefit. However, the performance characteristics of scramjet ducts are often characterized in terms of length / diameter due to the natural formation of shock trains and the fuel injection and mixing characteristics associated with isolator and combustor ducts, respectively. Without due care, the net result could be the requirement for a much longer circular vs. high aspect ratio (width / height) two-dimensional duct to obtain the same performance, thus negating the benefits of cross-section.

Isolator and Combustor Geometry Considerations

To examine flow area and structural weight benefits, a finite element analysis for a combustor duct operating at typical scramjet conditions with combined pressure and thermal stresses was performed. The scale of the duct utilized is typical of a missile-scale system. It should be noted that these trends are scale dependent, with slightly different trends exhibited at larger scales. The analysis ground rules and assumptions are summarized below:

- Flowpath area held constant at 10 in2
- Wall thickness held constant at 0.15 in
- 30% of material removed for cooling passages
- Material is Inconel 718
- Stress limit is 65 ksi (80% yield point strength at 1300°F)
- Deflection limit is 2% area change
- Pressure in flowpath is 100 psi
- Thermal Gradient is 400°F

The analysis results are shown in Figure 12. Also shown is the typical wall cross-section which represents a 0.15 inch thick cooled wall constructed of Inconel 718. From these results, it can be seen that circular cross-sections provide 13% less wetted or surface area to flow area than square and 25% less than a typical 3:1 aspect ratio rectangular duct. Reductions in wetted to flow area benefit from both a friction drag and heat transfer point of view. Similarly, circular ducts provide a 12% and 30% reduction in weight per length than square and 3:1 aspect ratio rectangular ducts, respectively. Benefits between elliptical versus rectangular ducts tend to diminish to about 5% in both surface area and weight as aspect ratio approaches 3:1. Another potentially more significant benefit of circular or very low aspect ratio elliptical ducts is the lack of a requirement for back structure. That is, the relatively thin cooled wall is able to support the required loads and deflections without exceeding stress limits. The addition of back structure can significantly increase weight per unit length (factor of 2) and is required for any high aspect ratio rectangular or elliptical duct. As mentioned previously, these results are scale dependent. The case shown represents an approximately 3.5 inch diameter duct. However, scaling studies performed to similar constraints have shown that circular ducts up to about 36 inches in diameter can be designed to meet similar requirements without back structure.

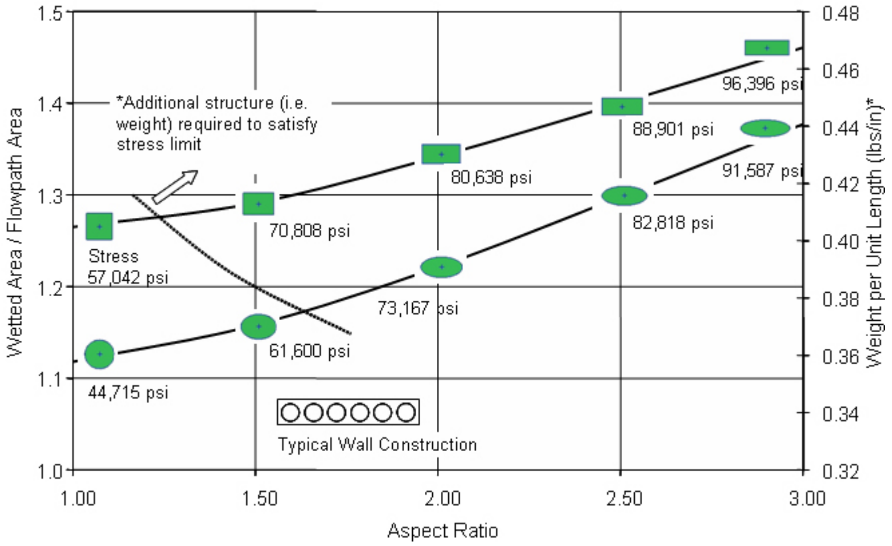

Figure 12: Wetted area and structural weight per unit length trends for two-dimensional and circular elliptical ducts

Although circular geometries show clear benefits in terms of wetted area and weight per unit length, care must be taken to manage overall length in order to achieve a system benefit. Performance characteristics for both isolators and combustors are often characterized in terms of Length / Diameter (L/D) or Length / Height (L/H). Example isolator and combustor characteristics are shown in Figure 13.

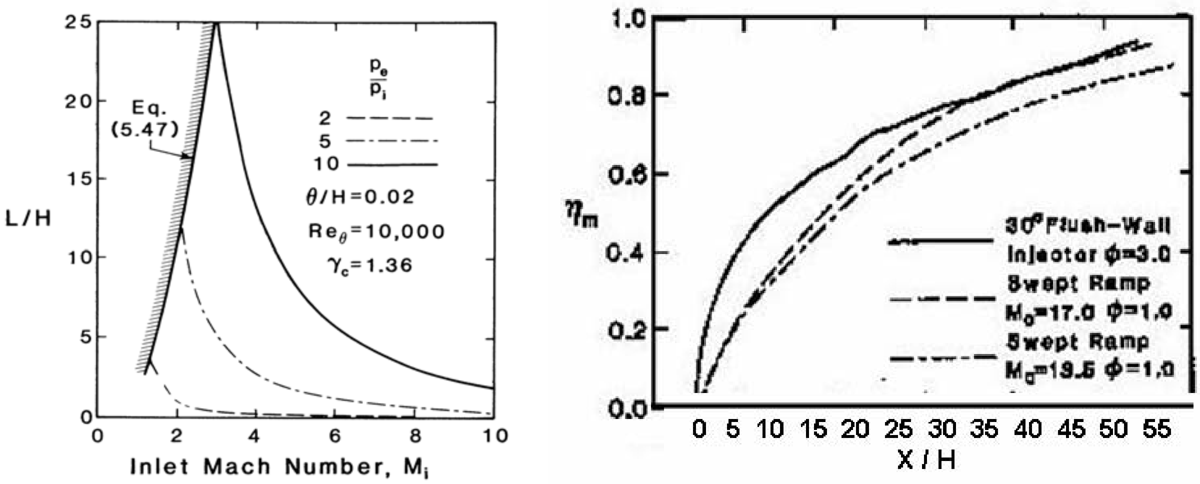

Figure 13: Isolator L/H requirements vs. inlet Mn for various pressure ratios and Combustor (fuel) mixing efficiency vs. normalized length

For the same duct constraints in the previous example and range of typical L/D or L/H, Figure 14 shows the trends for overall wetted surface area (surface area x length) as a function L/D for circular ducts or L/H for 3:1 aspect ratio elliptical or rectangular ducts. Recall that previously shown, circular and elliptical geometries result in reduced surface area per length. However, at comparable L/D or L/H, the total wetted area, due to length, actually increases by 1.5X for circular vs. 3:1 aspect ratio rectangular ducts. This clearly overwhelms the benefits previously shown from a surface area perspective and typically results in unmanageably long component lengths. However, the weight benefits derived from elimination of back structure could still favor the circular geometry for configurations where system benefit is more highly sensitive to weight than wetted area or length constraints. This wetted area and length effect can be largely mitigated through the use of high aspect ratio elliptical ducts which result in a 1.1X increase in surface area for 3:1 elliptical vs. rectangular ducts. However, recall the wetted surface area per length benefits were less pronounced between elliptical and rectangular, and again, both require back structure to meet stress requirements.

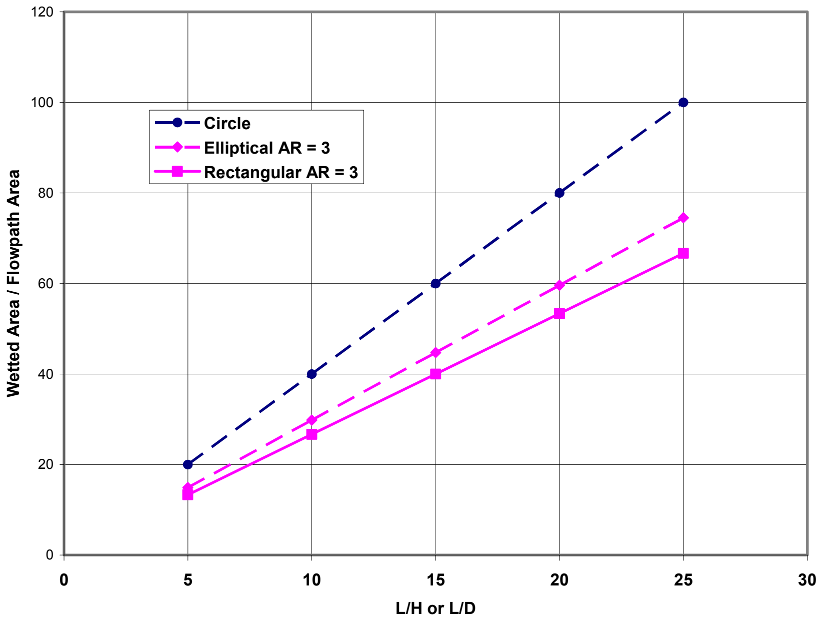

Figure 14: Total wetted surface area as a function of Length / Height or Length / Diameter for circular and high aspect ratio elliptical and rectangular geometries

To take the maximum advantage of circular cross section geometries, one must decouple the engine performance from the duct L/D constraints. For combustion systems, this can be accomplished by the inclusion of in-stream fuel injection elements. A notional arrangement shown in Figure 15 accomplishes this decoupling by reducing the injection characteristic dimension or "gap" between the injection devices. The closer the gap, the shorter the combustor. However, care must be taken to properly balance overall combustor length against the additional stream drag imposed by the injector elements.

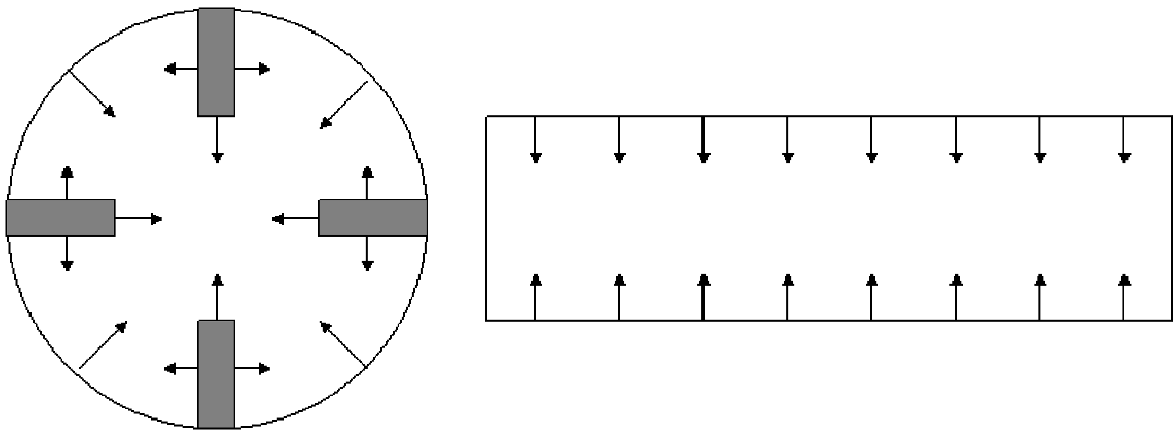

Figure 15: Alternate fuel injection strategies using in-stream fuel elements may be employed for circular ducts to achieve similar distribution characteristics to wall injected rectangular ducts.

Another significant advantage of circular cross-section ducts and combustors, in particular, is their amenability to conventional manufacturing processes. Sections are readily machined via lathe, drill and wire electro discharge machining methods. Semi-finished sections can then be stacked on a mandrel and welded together with minimal thermal distortion. Figure 16 shows an ATK manufactured cooled-combustor section which was fabricated and put into test less than 6 months after the design was initiated. Description of testing for this hardware is described in the following section.

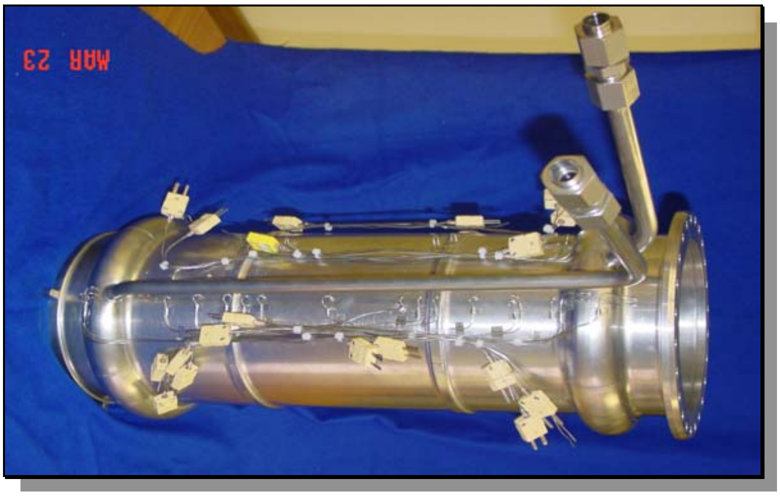

Figure 16: ATK rapid prototyping processes applied to circular combustor geometries resulted in clean sheet design to fuel-cooled flight-weight hardware in less than 6 months

Test Validation Activities

In order to evaluate performance and operability and to validate design tools for circular cross-section isolators and combustors. ATK GASL designed and fabricated a direct-connect isolator / combustor rig tested at the NASA Langley Research Center (LaRC) Direct Connect Scramjet Test Facility (DCSTF) in Norfolk Va. The configuration, named the Pilot Technology Development (PTD) rig, is shown installed in the DCSTF in Figure 17.

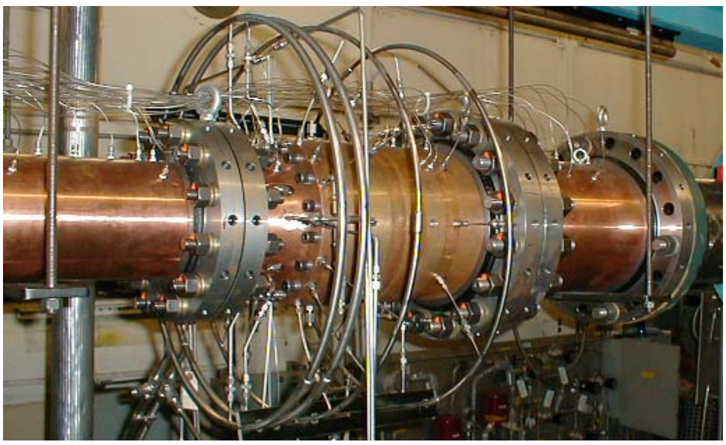

Figure 17: ATK circular cross section PTD rig installed in the NASA LaRC DCSTF

Both heavyweight heat sink and fuel-cooled hardware tested for a total of 72 minutes of combustion time over Mach 3.8 to 5.4 conditions and a range of dynamic pressures from 1000 to 3000 psf. Ignition and combustion were obtained on both ambient and heated fuel; the latter supplied initially by an external heater (open loop) and then via the fuel-cooled engine hardware for subsequent closed-loop testing. Conventional JP-10 fuel was used for most of the tests although subsequent testing on JP-7 showed negligible fuel sensitivity. Excellent combustion efficiency was obtained via a novel proprietary piloting and injection system design within 3 to 5 combustor L/D. Pre-combustion shock train lengths within the isolator section ranged from 3 to 8 L/D depending on flight condition and fuel equivalence ratio.

The flight-weight, fuel-cooled combustor was tested for a total of 23 minutes of hot (combustion) time, with individual tests of up to 2.5 minutes each to achieve thermal equilibrium. Combustor wall and fuel temperature measurements have been used to validate / calibrate both environment definition and heat transfer models. Post-test inspection shows the hardware is in excellent condition with no traces of either thermal distress nor fuel coking.

Following the highly successful PTD test series, ATK has designed, fabricated and tested a flight-weight fuel-cooled freejet engine utilizing a circular cross-section combustor mated to a rectangular, fixed geometry inlet. The engine in test at ATK GASL is shown in Figure 18 including a flight weight fuel pump. Demonstration of this engine and its critical subsystems establishes the near-term reality of lightweight, highly efficient, air-breathing engines capable of propelling vehicles at hypersonic speeds.

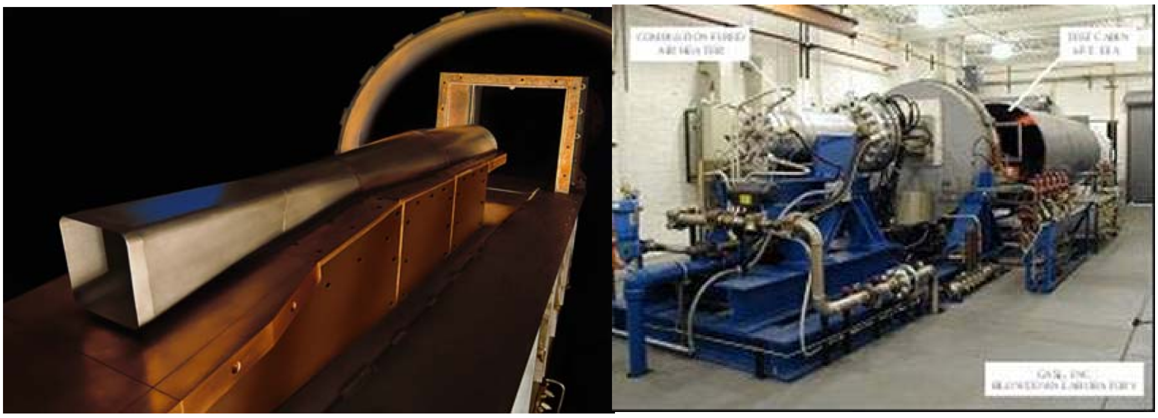

Figure 18: Flight-weight engine installed for freejet test in ATK GASL Test Cell 6

To support these near term goals, ATK's engine integrates several existing low-risk technologies to produce a near term high speed engine solution. The engine is fueled and cooled using an existing kerosene fuel, JP-10. Use of existing materials and established manufacturing processes allowed the ATK team to bring this high speed engine from concept to flight-weight hardware and subcomponents, to verification testing in just 2 years. The engine is capable of thrust-to-weight ratios of greater than 15 without the need for exotic materials.

RECENT PROGRESS IN HYPERSONIC FLIGHT TEST

Like the architecture of hypersonic engines, the Hypersonic Flight Test landscape has changed significantly from the NASP vision. The NASP concept was a fully reusable vehicle from the outset that would take-off from a runway and accelerate to orbital speeds without staging and return. An envelope expansion approach was to be used to achieve higher speeds incrementally while testing and validating the vehicle operating characteristics. This large "delta v" requirement drove the vehicle to be very large and the cost to be unaffordable. The envelope expansion flight development approach, although still most preferred, became impractical for even less capable vehicles just able to break into the hypersonic regime because of the relatively large vehicles and price tags they incurred.

Since the end of the NASP program, as more near term vehicle concepts and applications have been identified, a robust hypersonic flight test program in the US has been advocated by several advisory and research boards[11]. In 2003, these activities culminated in the The National Aerospace Initiative (NAI). The NAI was the started by the Director of Defense Research and Engineering, (DDR&E), with the objective to build a roadmap for combined Department of Defense and NASA resources and support a robust hypersonic development and flight demonstration program. The goal was to achieve incrementally increased flight Mach number per year, reaching Mach 12 by 2012.

The path to this objective was already paved by several on-going programs, such as X-43A, X-51A and HyFly. These focused on validation of design methods in flight utilizing air-launched rocket boosters to achieve hypersonic insertion conditions, thus allowing hypersonic air-breathing "payload" vehicles to be sized for powered flight over a relatively narrow speed range. To date non of these smaller vehicles have packaged landing or recovery equipment which is a notable shortcoming, but the overall program cost for these small vehicles can be kept modest despite the need for a new vehicle for each flight.

Ground to Flight Test Transition

Flight is the ultimate application of hypersonic propulsion development activities and therefore it is the only real test of the technology. The relatively high cost of flight test, coupled with the inability to easily recover and reuse flight test articles, has made extensive ground test the most appealing approach for practical technology development. Ground test in the hypersonic regime is compromised by limitations in facility size, energy, and test duration as well as vitiation of the test media. These issues have been at least partially understood and modeled to a degree such that development via ground test has continued. These practical considerations have driven most development programs to extract as much data and reduce as much risk as is practically possible in ground test, with flight test being held as an ultimate but necessary step.

The most appropriate point in a program to transition from ground to flight test is a crucial determination for hypersonic development. If an inexpensive approach to flight test were to be available, it would be possible to transition to flight test earlier in a development program. This would allow flight data to be compared with ground data, examine operability of key subsystems in flight, and feed back to the design activities for the future flight system, reducing risk and delivering a better optimized final product.

Cost for both Ground and Flight tests grow with the size, scale, and complexity of the test as indicated in Figure 19. For ground test, component tests of combustors or inlets are the least expensive. Complete engine tests are more expensive requiring larger facilities and having added complexity. Complete vehicle tests are more expensive still, and for hypersonic aero-propulsion there is little hope of large scale ground testing of hypersonic airplanes in the future. Large scale component testing, like an aircraft size combustor may be possible, but testing integrated performance will await ultimate flight test.

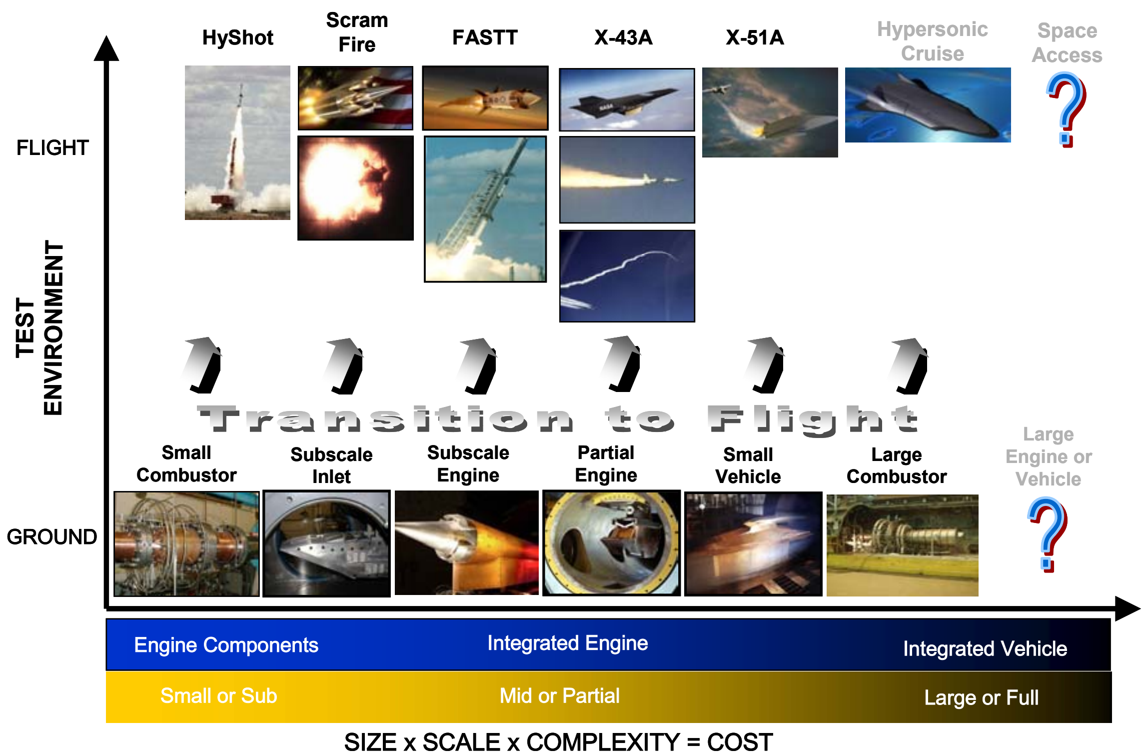

Figure 19. The transition from ground to flight test can occur at numerous points in the size, scale, and complexity domain. Less expensive flight test options foster earlier transition opportunities.

In flight a very similar story holds: size and complexity drive cost. The programs listed span recent, near-term, and envisioned flight programs. The Australian HyShot program is listed as the least expensive as it was a flying component (combustor) test. The ScramFire, FASTT and X-43A Programs were integrated vehicle tests of increasing scale and complexity. The X-51 program will attempt to fly for multiple minutes and accelerate over multiple Mach numbers. Long duration hypersonic cruise airplanes, and access to space vehicles are not currently planned for flight test, but will be significantly more complex and costly.

At what technical maturity level should the transition from ground to flight occur? At what scale should ground tests be run to prepare for flight? At some point in the future it will be necessary to leap forward from component and subscale ground tests to larger-scale more complex flight tests.

ATK GASL has conducted three flight test programs in the past 4 years. These programs ranged over two orders of magnitude in program complexity and cost. Each used a different flight test method and had widely different sophistication and completeness in the supporting ground programs. These programs serve as examples of the great variety of options that exist for flight test and the types and value of data that can be extracted.

ScramFire – Ballistic Range Flight Test Technique

The ballistic range test technique for scramjet-integrated vehicles provides a short-duration flight at actual altitude conditions[12]. The vehicle is mounted in a gun and fired into a range, which is evacuated to match flight static pressure at altitude. Scaling is required since the range lacks static temperature control to match the temperature at altitude. The vehicle accelerates in the gun barrel and enters the range at the specified flight velocity. The on-board engine is then ignited and the vehicle proceeds under powered flight conditions until it impacts the far wall of the range. During this test time, data is taken via on-board and off board sensor systems to evaluate engine and vehicle performance.

Demonstrations of this flight test technique have been performed on a scramjet engine integrated into a cylindrical vehicle for Mach 6-8 flight conditions. To execute these tests a complete design and development of a scramjet-integrated projectile was undertaken including the verification of the structural design through FEM analyses, the verification of engine performance through engineering performance codes and wind tunnel data, and five flight tests in G-Range, a light gas gun facility at the Arnold Engineering Development Center (AEDC), Figure 20.

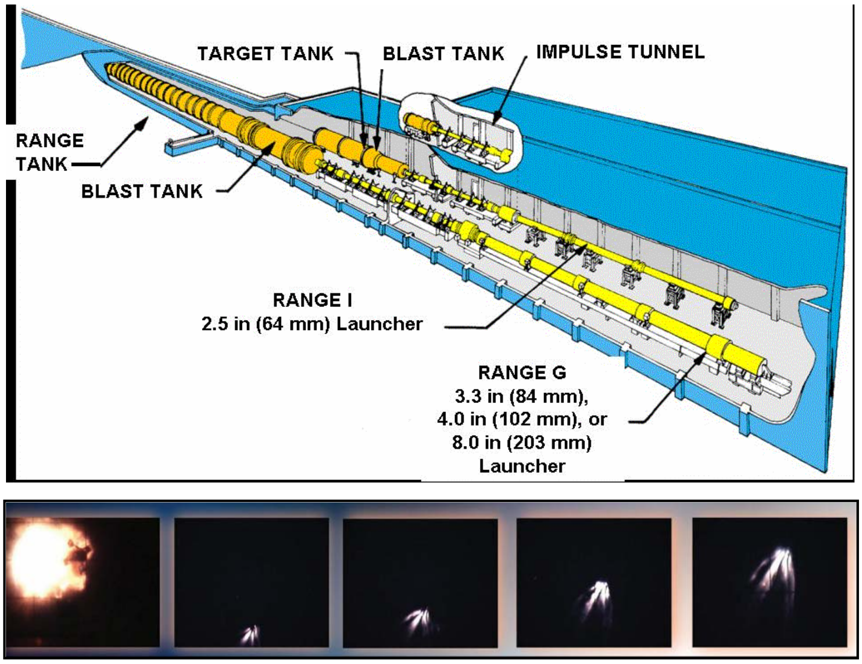

Figure 20. The Arnold Engineering Development Center , G-Range Facility. High speed video images of the Scramjet Projectile in powered flight in the range.

The cylindrical projectile and the integrated scramjet engine were designed specifically for this flight test demonstration program. The engines operated as dual-mode scramjets using ethylene fuel in a self-contained and actuated fuel supply system. The projectile is nominally 4-inch diameter and weighs approximately 20 lb. The projectile design included that of the internal and external flow lines, structure, telemetry system and associated onboard instrumentation, aerodynamic stability system, weight and balance. The projectile diameter is sized to fit in the AEDC G-Range four-inch launch tube and the structure is sized to survive launch loads. A picture of a projectile design is seen in 10.

The structural design is primarily driven by the high acceleration loads (10,000 G design condition) encountered during launch. As a result, the goal of the design was to achieve a simple structure capable of withstanding the launch loads. Consequently, the projectile is comprised of a minimum of overall components, including nonstructural components that include valves, telemetry system and associated instruments.

Onboard instrumentation and telemetry (TM) are employed to make direct measurements of engine performance in flight and transmit the information to a ground station for collection and post test analysis. The high g capable, miniaturized TM units include an 8 channel transmitter, encoder, signal conditioner, antenna, and power supply, Figure 21. The package included five pressure transducers, two projectile flight axis aligned accelerometers, and a battery voltage transducer.

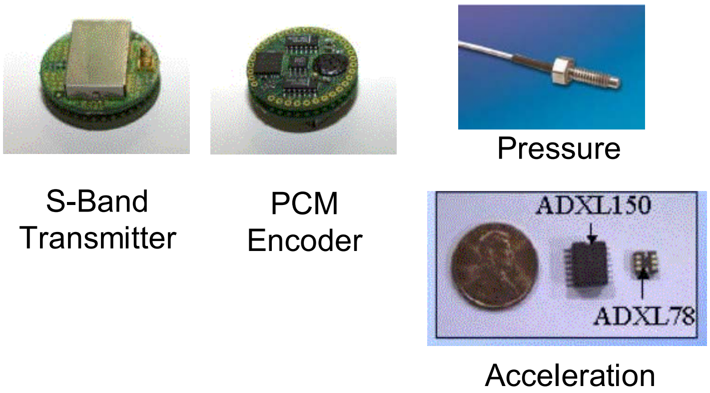

Figure 21. Eight Channel, G-hardened telemetry system, pressure sensors and accelerometers used for on-board measurements of the scramjet projectile.

Off-board instrumentation included IR, visible, and UV still imagery and spectral sensors spaced along the range to image both the projectile, the density field, and the emission of combustion products. Framing cameras were used in the visible and the IR to capture the time evolution of the flight.

Figure 22 shows a plot of axial acceleration at the projectile center of gravity versus flight time. This data contains residual high frequency response to the set-forward acceleration that occurs when the projectile leaves the gun muzzle. This vibration dominates the measurement during the early portions of the flight with amplitudes exceeding the range of the accelerometers. Subsequently, the axial acceleration data appears, in the mean, to rise from a low value to a higher value between 0.299 and 0.312 seconds, indicating acceleration due to scramjet operation. As indicated by annotations, the acceleration at 0.299 seconds closely matches the engine-off performance prediction. For comparison to the maximum acceleration measured, the stoichiometric engine performance is also shown as an annotation to the plot. The measured acceleration rises to approximately cruise conditions, in the mean, at 0.31 seconds. Late in the flight the projectile achieves significant incidence angle indicated on the right axis of the plot and determined from flash laser photographs along the range. This attitude results in a flight at angle of attack that ultimately causes in inlet unstart. This is detected by on-board pressure measurements in the inlet (not shown). At this point the axial acceleration suddenly drops at 0.312 seconds.

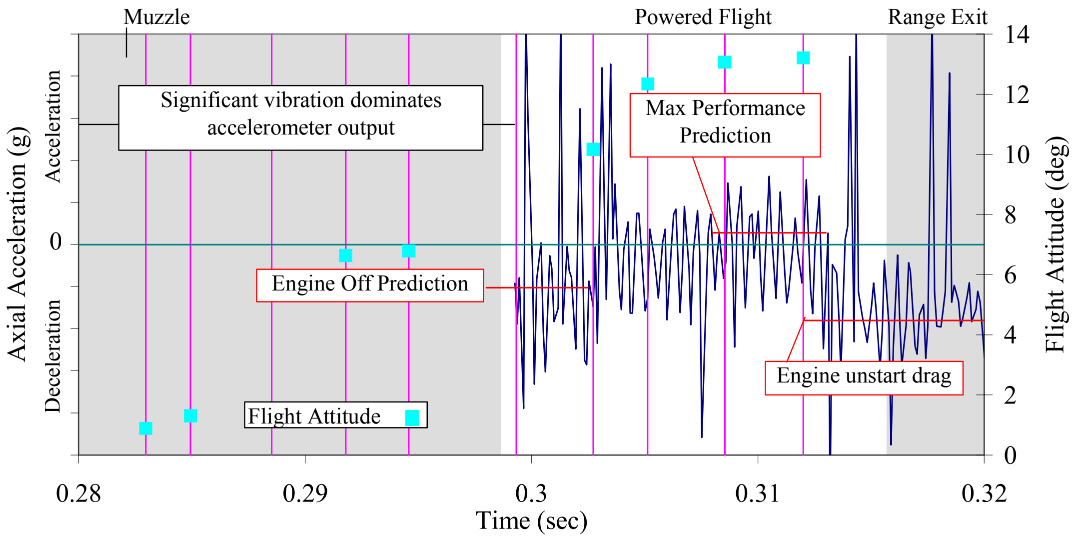

Figure 22. Acceleration measured in the projectile axial direction and flight attitude during launch and free flight. Predicted accelerations are shown for fuel off, fuel on, and engine unstart conditions.

Free Flight Atmosphere Scramjet Test Technique (FASTT)

This program set out to demonstrate the use of ground launched ballistic rockets as a low-cost solution to launch scramjet integrated vehicles to flight test conditions[13]. Such an approach can provide an affordable path for maturing hypersonic air-breathing components and systems in flight. Whereas the traditional approach to full-scale development has been to perform subscale and full-scale ground testing prior to full-scale flight testing, usually using an air-launched, fully-guided booster system, this approach takes a different path.

The FASTT approach uses an unguided, sounding rocket booster stack to carry a scramjet vehicle payload to desired insertion conditions in the atmosphere. There exists in the US are a broad range of launch assets along with a significant and mature infrastructure for launching, tracking, and transmission and reception of data. The combination allows for relatively affordable flight test of hypersonic test vehicles at small to moderate scale.

For the initial demonstrations, a two stage stack was selected with a separable payload vehicle. Launch operations were conducted at the NASA Wallops Flight Facility located on the Eastern shore of Virginia. A suppressed ballistic trajectory was chosen that inserts the payload at a velocity of approximately Mach 6 at near horizontal elevation angle. A scramjet engine powered payload was designed weighing approximately 300 lb, 11-inch diameter with an overall length of about 8 feet. The engine was derived from the Dual-Combustor Ramjet concept and fuelled with liquid JP-10 The engine and airframe was instrumented with approximately 150 transducers including pressure, temperature and redundant 3-axis accelerometers. The separated payload flies its own ballistic arc and over approximately 30 seconds transits less than 5000 ft altitude, such that the vehicle flight conditions are nearly constant.

The process is illustrated in Figure 23. The two stage booster stack is rail launched at suppressed elevation angle, Figure 24. The three sets of fins on the stack and payload are canted to impart a low-rate spin during flight to offset any thrust axis misalignment from the intended ballistic arc. Booster and payload data are transmitted to the tracking station throughout the flight. After the first stage lofts the vehicle and separates, an interstage delay allows the vehicle to execute a gravity turn toward horizontal before the second stage is ignited. The second stage accelerates the vehicle to the insertion conditions, and upon burnout, the payload vehicle is separated. To protect the engine from aerodynamic heating during ascent it is covered by a clamshell-type shroud. This shroud is deployed shortly after separation and the engine is ignited to execute the scramjet powered portion of the flight test. After the engine fuel is expended, the vehicle coasts until splashdown where no recovery is attempted.

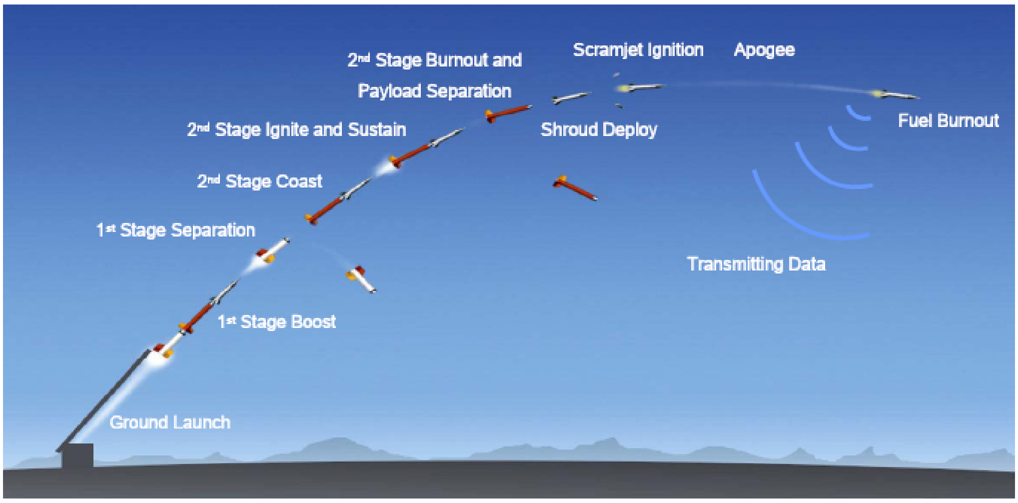

Figure 23. THe FASTT approach uses sounding rocket boost system to carry a scramjet powered vehicle to hypersonic test conditions along a ballistic trajectory

Figure 24. The payload vehicle and two-stage booster stack are rail mounted and launched along a suppressed ballistic trajectory.

The main features of the low-cost atmospheric flight test technique for scramjets are highlighted below:

- Low-cost sounding rocket boosters capable of carrying subscale hypersonic vehicles and scramjet engines to the required takeover conditions.
- Suppressed ballistic trajectory, with boost staging, to reach test conditions (altitude and Mach number) of nearly constant dynamic pressure, without the need for guidance, navigation, and flight control. This feature also avoids the requirement for a Flight Termination System, further simplifying the approach.
- Onboard instrumentation to measure engine pressures, temperatures, flow rates, heat flux, as well as health monitoring of critical systems.
- Data acquisition and telemetry system capable of conditioning measurement signals and transmitting data back to ground station.
- Electronic event sequencer to control in-flight events, including: separation events; shroud deployment; starting fuel flow; and engine ignition.
- Adapter flange for attaching scramjet engine and hypersonic vehicle payload to sounding rocket booster. This adapter will also incorporate a separation mechanism to initiate vehicle free-flight at the end of boost.
- Inlet shroud system that protects the payload inlets during the boost ascent phase. A shroud separation system deploys the inlet shroud after scramjet-payload separation, and prior to engine ignition.

In order to reduce the risks associated with flying a complex scramjet-integrated vehicle through an unproven trajectory with an unproven combination of flight hardware, surrogate payload missions were performed for booster performance testing and subsystems evaluation. Two surrogate payload missions were executed successfully and verified the booster capabilities and the full suite of payload instrumentation, power systems, and subsystems including the inlet shroud deployment, telemetry, and transponder tracking. Post-flight data analyses helped the flight test team to better understand launch vehicle tip-off and drag characteristics, and improved prediction capabilities to fine tune the successive launches to achieve the desired payload insertion point. In conjunction with a freejet ground test program that identified fueling schemes, demonstrated robust light-off, and provided a baseline engine data set to compare with flight data, flight vehicle airframe and fuel subsystems were integrated into flight hardware, and subsequently underwent successful preflight clearance testing.

The powered flight vehicle (Figure 25) was launched and inserted to free flight. Insertion occurred at an altitude approximately 10,000 ft lower than expected although at the correct Mach number. Figure 26 summarizes the pre-flight predictions and the achieved insertion conditions for the free flight vehicle (FFV). The discrepancy is not fully understood but appears to be a combination of rail tip-off and wind weighting. On-board systems performed as designed, and engine operation occurred including fuel-off tare, fuel ignition, throttle-up, and steady engine operation while critical engineering measurements were obtained. Sufficient measurements were taken for determination of engine cycle performance, and for comparison to ground test data. Preliminary comparisons to ground test measurements show good agreement. In flight the inlet eventually unstarted, producing unstable coning flight in which the engine was not able to recover stable operation.

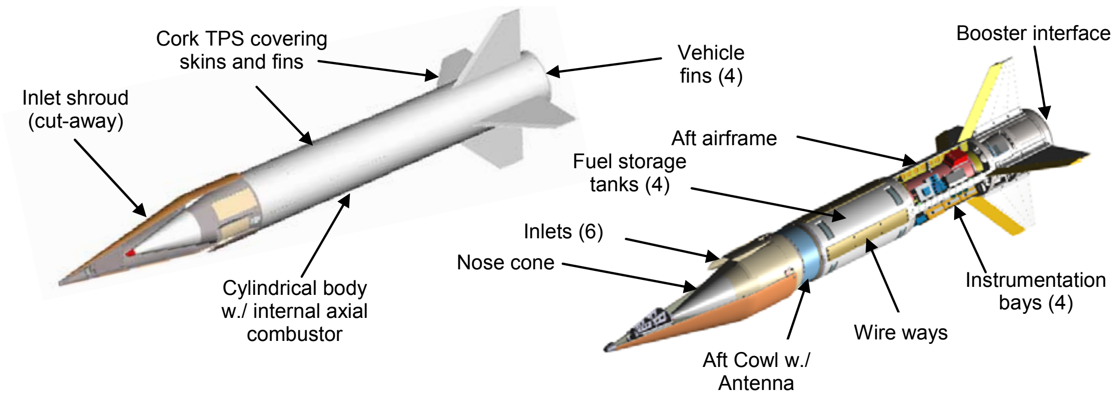

Figure 25. The Scramjet powered Free Flight Vehicle (FFV) and subsystems. The inlet shroud is deployed after separation exposing the engine to air flow.

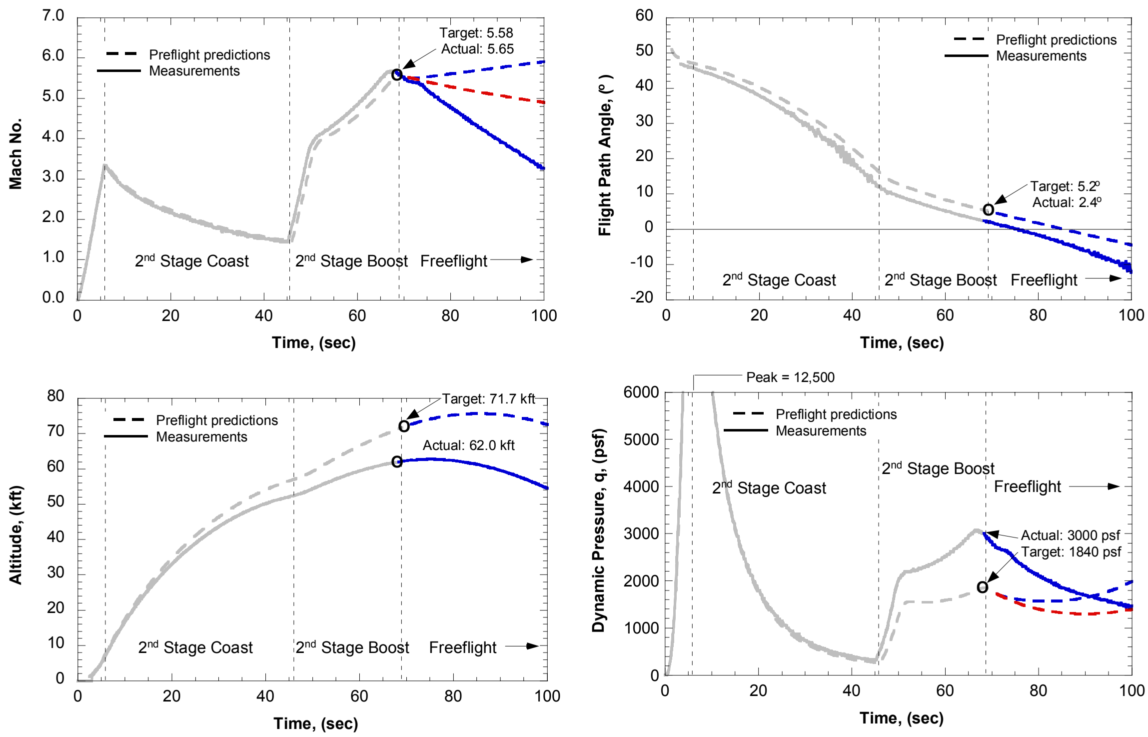

Figure 26. FFV trajectory data compared to preflight predictions. Left, top: flight deduced Mach No., right, top: flight path angle, left, bottom: altitude, right, bottom: calculated flight dynamic pressure.

Figure 27 shows important flight measurements during the sequence of events from booster thrust tail-off through engine operation on a single plot. The acceleration peaked at ~65 sec and then dropped off as the booster stage burned out. At 68.23 sec the vehicle deployed to free-flight, and 0.40 sec later the shroud was jettisoned. The Gas Generator (GG) pressure rose and steadied while the vehicle decelerated and a tare measurement was obtained for ~1.3 sec. By 70.0 sec the fuel flow rate was steady at the initial throttle setting however the GG pressure showed no sign of auto- ignition, until the sharp rise following the ignitor firing at 70.3 sec. The GG pressure steadied and a small delta acceleration was sensed. The fuel flow rate was increased to full flow rate and became steady by 71.1 sec and the GG pressure rose higher accompanied by a noticeable 2-g delta acceleration; however, the vehicle did not experience positive net acceleration resulting in a continuing slow decrease in flight Mach. The engine continued to burn until 73.1 sec when it experienced a disturbance from which it appears to initially have recovered, but then reverted to unsteady chugging, accompanied by acceleration tail-off. Subsequent analysis has identified a susceptibility to unstart of this particular inlet configuration that was flight tested.

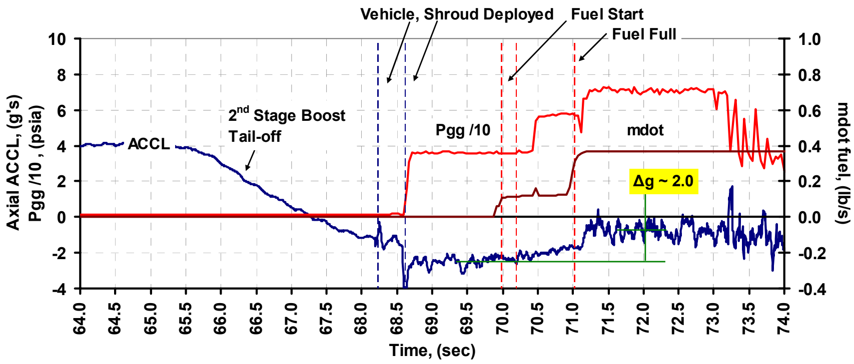

Figure 27: Axial acceleration, gas generator pressure, and fuel flow rate spanning from booster thrust tail-off through inlet unstart.

The FASTT approach is an effective technique for testing small to modest sized hypersonic propulsion vehicles in free flight because the suppressed ballistic trajectory allows for test durations of 10 to 60 seconds with minimal variation of altitude, and through proper fueling control, minimal variation of dynamic pressure. Further investigation of launch initiation phenomena is required to better aim at the insertion point, or the flight experiment must be made less sensitive to insertion point. This may be accomplished through fuel controls, for example. The approach can also be extended by adding booster or vehicle flight controls if desired, however it will thereby take on greater complexity.

X-43A Flight Tests

The X-43A program set out to demonstrate hydrogen fueled scramjet operations in a fully integrated aircraft system at Mach numbers of 7 and 10. ATK GASL was the prime contractor to NASA for the execution of the program and had overall responsibility for the detailed design and manufacture and support to flight test of the vehicles. The research performance aspects of the engine and vehicle design were the responsibility of NASA. The program was well described by the keynote speaker for this lecture series.[14] Here this activity will be briefly summarized for subsequent comparison and contrast with the gun-launched and FASTT approaches described previously.

The X-43A vehicle was a 12-foot long lifting body design, weighing about 3000 lb, with a fully integrated, hydrogen fuelled scramjet engine. The aircraft was designed statically stable and had full flight controls to maintain angle of attack and sideslip subsequent to separation from the booster stack, through engine cowl door opening, and engine start and shut-down. The vehicle also executed parameter identification maneuvers subsequent to scramjet function.

The boost system for X-43A was a modified Pegasus first stage that was air-dropped from the NASA B-52 (Figure 28). The Pegasus was fully controlled to execute a pull up from the air-launch altitude to the approximately 100,000 ft insertion point at Mach 7 or Mach 10. The vehicles were instrumented with over 300 transducers for pressure and temperature, and discrete local strain measurements. The flight management unit included accurate 3- axis measurements of translational acceleration and angular velocity, along with Global Positioning System (GPS) and control surface deflection measurements.

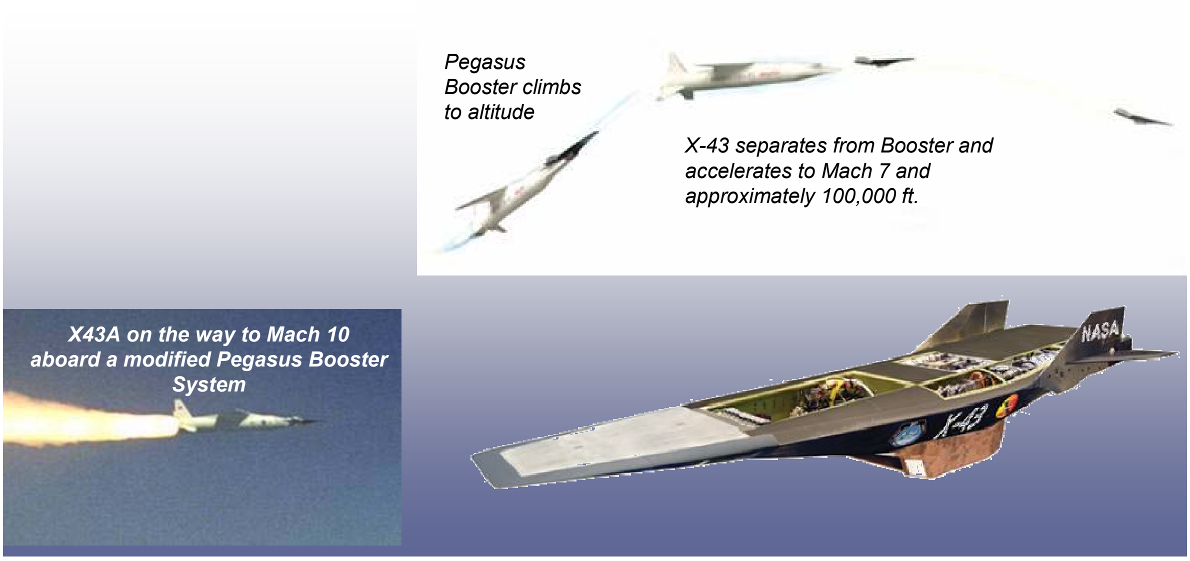

Figure 28. The X-43A vehicle and boost system on the way to Mach 7 for separation and flight test.

Flights 2 and 3 of the X-43A vehicles were successful in achieving all research objectives. Flight 2 at Mach 7 captured all engine and vehicle performance data and accelerometer data clearly indicated acceleration under scramjet power. Comparison of these data with the extensive ground tests database and predictive methodologies has shown all data to be within the stated uncertainties. The tunnel results including combustion heated, arc-heated, and shock heated all predict the flight results quite well without any systematic differences apparent. Flight 3 achieved a similar quantity and quality of data. Acceleration showed the vehicle to achieve cruise-level thrust at the peak of the fuel level of fuel flow. Comparisons to ground test in shock heated tunnels confirm the ability of these facilities to measure engine performance consistent with flight.

Comparison of Flight Test Approaches

Executed by ATK GASL during an overlapping period from 1998-2005, the X-43A, FASTT and ScramFire programs offer a insight to the execution and outcome of flight test programs with vastly different budgets, test article scales, and flight test infrastructure.

As compared to the traditional self-powered, envelope expansion approach to aircraft flight development, all three programs are very different, but similar to each other. They rely on non-integrated propulsion to achieve hypersonic flight speeds and scramjet takeover. Without the need for significant self-acceleration capability and the required fuel volume that entails, these test systems can be built in relatively small packages, keeping one parameter which drives overall program cost low.

On the other hand, these approaches are sometimes characterized disparagingly as "point designs" since they operate over only a very small range of conditions. This view fails to capture the significance of the need for free-flight data to feed back to the modeling, simulation, and design tools that have not yet been adequately exercised in flight. Before the three flight tests described here, there existed no data on fully integrated scamjet powered vehicles. The CIAM hydrogen fueled ramjet/scramjet test in 1998 and the HyShot hydrogen fueled combustor test in 2002 each captured important but limited data on engine performance. In neither case was thrust measurement attempted or practical in a configuration where the test article stays attached to the boost vehicle.

The three flight programs are compared in Table 1 across a range of flight test approach figures of merit. Comparison and trade of these and other merits are important during the planning phase of a flight program, when the desires of the research team are being constrained by budget realities. The trades that occur and the impact on the program are briefly described next.

Table 1. Comarison of technical and programmatic parameters from three different hypersonic flight programs

	Flight Mach	# Flights	Test Article Mass (lbm)	Inlet Span (in)	Test Duration (s)	Boost Insertion Mode	Flight Controls	Accel. Measured	# Data Channels (On-Board)	Off-Board Data	Ground Test Program	Success Criteria Met	Program Cost Range ($M)
X-43A	7, 10	3 1 Failed 2 Designs	3000	19	10	Air-Launched Controlled Boost	Active Vehicle and Engine	Yes	300+	Long Range Imaging	Inlet, DC FJ, Vehicle	All	$100-$200
FASTT	5.5	3 2 Surrogates	300	10	10	Ground Launch Ballistic Boost	Event Sequence Timer	Yes	150+	Long Range Imaging	DC & FJ	All (Engine Unstart Captured)	10-$15
ScramFire	6 to 8	9 1 Failed 3 Surrogates 3 Designs	20	4	<0.1	Gun Launch in Range Chamber	Inertial Off/On Valve	Yes	8	Multiple Close Range Imaging	DC	All	$1-$2

Flight Controls

Active flight control and software quickly accumulate costs. Consideration can be given to both the boost system and the test article. X-43A used full active controls on both elements, and also air-launched the booster from a manned airplane. Removing or simplifying controls reduces cost, and ground launch vs. air-launch avoids human rating systems for carriage on a piloted platform.

Ground Test Program Scope

Reducing or eliminating ground tests reduces costs with more reliance on computational simulations. Dynamic operability in flight can not be modeled, so eliminating ground tests incurs more risk. At a minimum and sufficient ground tests must be executed to assure the basic flight test objectives can be met. More robust ground campaigns as in the X-43A program bring value in comparison to flight test.

Experimental Design

Lower cost requires design adjustments, limits flexibility, and may cause some objectives to be sacrificed. To package a vehicle that can fly on an unguided stack requires the payload to be capable of being spun during boost which favors symmetric, non-lifting configurations. For gun-launch testing the test article must be capable of significant scaling to a small test article package, and be capable of withstanding the gun-launch G-forces. Conversely, cost-driven innovation can deliver dividends in packaging approaches that can deliver other dividends for the research program.

Risk

Lower cost ultimately requires acceptance of higher risk to the fundamental objectives. Adding iterations (more flights) and can lead to additional learning allowing more "unknown-unknowns" to become available for discovery

CONCLUSIONS

ATK GASL, with our NASA, DARPA, AFRL, and ONR sponsors and Contractor team partners, have been executing hypersonic engine research and transitioning from ground based research to flight test. We have examined a range of engine geometries since the end of the NASP program and with current missions focused on more narrow engine operating ranges and affordable, manufacturable designs for system applications, we have identified an engine architecture that offers robustness and simplicity. This engine is currently completing an extensive ground test program and flight test opportunities are on the horizon.

We have now executed flight programs over a range of complexity and costs that span two orders of magnitude. All flights programs included supporting ground test campaigns of varying scope and complexity. The flight programs met their intended objectives and delivered propulsion data needed to address key issues:

- Vehicle Acceleration – the final measure of propulsion effectiveness
- Ground to Flight performance comparisons, and predictive tool validation across multiple scales
- Design for integration and operability in flight

Remarkably good agreement has been seen between ground and flight data, although other Engine/vehicle designs may not be so robust. Future Flight Programs can baseline these successful programs, further refine approaches, and continue building a flight database.

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