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Abstract

Third-generation reusable launch vehicle (RLV) systems are envisioned that utilize airbreathing and combined-cycle propulsion to take advantage of potential performance benefits over conventional rocket propulsion and address goals of reducing the cost and enhancing the safety of systems to reach earth orbit. The dual-mode scramjet (DMSJ) forms the core of combined-cycle or combination-cycle propulsion systems for single-stage-to-orbit (SSTO) vehicles and provides most of the orbital ascent energy. These concepts are also relevant to two-stage-to-orbit (TSTO) systems with an airbreathing first or second stage. Foundation technology investments in scramjet propulsion are driven by the goal to develop efficient Mach 3-15 concepts with sufficient performance and operability to meet operational system goals. A brief historical review of NASA scramjet development is presented along with a summary of current technology efforts and a proposed roadmap. The technology addresses hydrogen-fueled combustor development, hypervelocity scramjets, multi-speed flowpath performance and operability, propulsion-airframe integration, and analysis and diagnostic tools.

Introduction

The United States National Aeronautics and Space Administration (NASA) has established a strategic goal of creating a safe, affordable highway through the air and into space. Candidate third-generation reusable launch vehicle (RLV) architectures include single-stage and two-stage concepts which utilize airbreathing, combined-cycle and combination-cycle propulsion systems to take advantage of potential performance gains over conventional rocket-propelled concepts. An access-to-space roadmap has been established that focuses on airframe-integrated hypersonic airbreathing propulsion development through foundation technology investments, ground demonstration and flight validation. Successful implementation of this roadmap requires a robust technology development program to mature aspects of the propulsion system and integrated aero-propulsive vehicle performance through both analytic and experimental research.

Figure 1 shows a comparison of nominal specific-impulse values for airbreathing engine cycles vs. rockets. The dual-mode scramjet (DMSJ) forms the core of combined-cycle or combination-cycle airbreathing propulsion systems and provides most of the orbital ascent energy for single-stage-to-orbit (SSTO) airbreathing launch vehicle systems. The term “dual-mode scramjet” refers to an engine cycle that can operate in both subsonic combustion and supersonic combustion modes. Rocket-based combined cycle (RBCC) concepts are being studied which integrate rocket thrusters with the DMSJ flowpath for low-speed propulsion. Turbine-based combination cycle (TBCC) concepts are also being examined which integrate a gas turbine engine and DMSJ in a dual-flowpath configuration.

Hypersonic airbreathing propulsion research conducted by NASA spans over 40 years.[1-4] Historical work includes the hypersonic research engine (HRE), airframe-integrated scramjet ground testing and component development, the X-30 National Aerospace Plane (NASP) program, and, more recently, the Hyper-X (X-43) flight

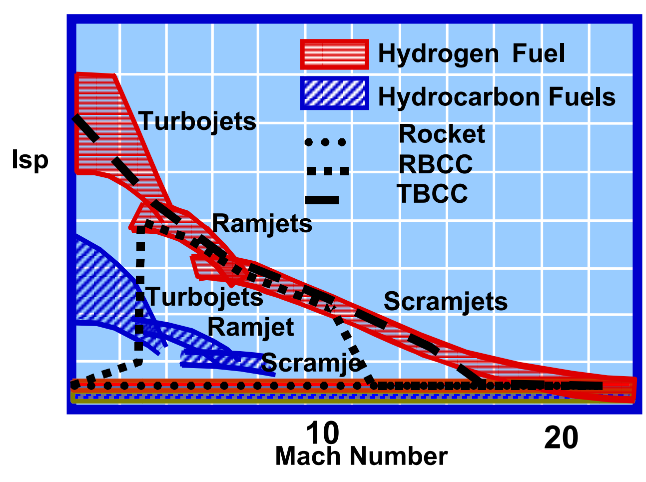

Figure 1. Airbreathing Propulsion Performance.

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demonstration project. This work has also included fundamental research in supersonic combustion flow physics, analysis tools and diagnostic methodologies.

Multidisciplinary research is required to develop efficient airbreathing and combined-cycle propulsion systems for airframe-integrated vehicles. These requirements include high-fidelity flow-field solution methods, physical models, rapid design capabilities and experimental techniques to develop flowpath performance, flow-field characteristics, chemical kinetics, thermal management and aero-propulsive interactions. Specific research goals are driven by systems analyses of candidate architectures and derived propulsion system performance goals. Current efforts and future technology goals include mid-speed (Mach 3-8) combustion flow physics and component development, hypervelocity (Mach 10-15) scramjet flow physics and flowpath performance, DMSJ and combined-cycle flowpath performance and operability, propulsion-airframe integration and computational and diagnostic tool development. Other enabling component technologies, such as high-temperature lightweight materials, seals actuation mechanisms, and engine subsystems are also part of the current program.

The paper will present a brief overview of historical airframe-integrated scramjet propulsion research along with a brief discussion of current research efforts within NASA. Technology shortfalls to develop Mach 3-15 scramjet propulsion flowpaths are discussed along with a proposed technology roadmap to address these shortfalls and accomplish strategic agency objectives.

Historical Background

Figure 2 shows a summary of scramjet engine research at NASA's Langley Research Center. The first major scramjet engine development project was the Hypersonic Research Engine (HRE), which began in the 1960's.[5] The goal of the HRE project was to flight test a flight-weight, regeneratively-cooled, hydrogen-fueled, axisymmetric scramjet engine on the X-15 research airplane. The project was re-directed to ground test research when the X-15 program was terminated. Several component and flowpath tests were conducted, including full-scale engine tests at NASA's Langley and Lewis Research Centers. The structural assembly model (SAM) was tested in the Langley 8-Foot High Temperature Tunnel (8-Ft. HTT) and the Aerothermodynamic Integration Model (AIM) was tested in the Lewis Plumbrook Hypersonic Test Facility (HTF).[6,7] These tests demonstrated performance and operability of a scramjet engine.

Following the HRE program, scramjet

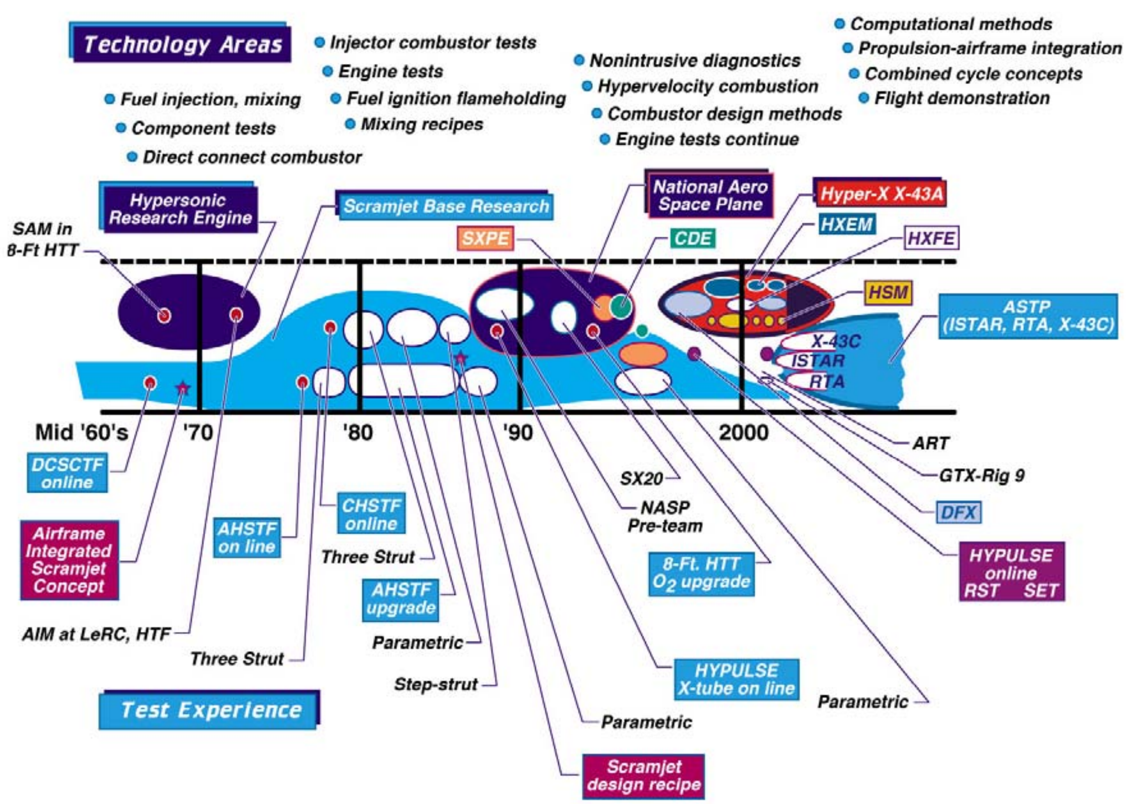

Figure 2. Historical summary of NASA scramjet engine research.

research within NASA was focused on airframe-integrated concepts. Research at NASA's Langley Research Center focused on modular, fixed-geometry concepts, such as the 3-strut engine, utilizing sidewall compression. Sub-scale engine tests in the 1970's demonstrated required thrust and operability for an airframe-integrated scramjet-powered system. Two additional engine test programs in the 1980's included the strutless parametric engine (SLPE) and the step-strut parametric engine (SSPE).

During the 1970's and 1980's, fundamental research in scramjet engine design and performance as well as supersonic combustion physics was conducted at NASA Langley.[8,9] These efforts included the development of empirical models for mixing-controlled combustion, isolator performance, ignition and inlet operability limits. Computational Fluid Dynamics (CFD) tools, including kinetics models for hydrogen-air combustion and other aspects of supersonic chemically-reacting flow physics modeling, were matured during this time frame. Diagnostic tool development to obtain calibration data for combustion models and characterize scramjet combustor flow physics was also conducted. Historical work in direct-connect component tests to mature combustor design and modeling tools is summarized in references 3 and 8. These include an investigation of a plasma torch as an ignition device source for hydrogen-fueled supersonic combustors and investigations of various fuel injector arrangements, including swept-ramp, expansion and compression ramps.

The National Aero-Space Plane (NASP) (X-30) program was initiated in the 1980's to develop a single-stage-to-orbit flight research vehicle. The X-30 concept proposed utilizing scramjet propulsion to Mach 25. While the NASP program did not flight test an SSTO vehicle, major technology contributions to scramjet propulsion were accomplished. These included development of comprehensive Mach 3-8 engine performance databases, hypervelocity scramjet performance and design methods, CFD and design tool maturation and propulsion-airframe integration. Tests of the sub-scale parametric engine (SXPE) were conducted at NASA Langley in the Arc-Heated Scramjet Test Facility (AHSTF).[10] The NASP Concept Demonstrator Engine (CDE), shown in figure 3, was tested in the Langley 8-Ft. HTT to demonstrate flowpath performance and operability and to verify flowpath design methods.[11] During the 1980's, the 8-Ft. HTT underwent modifications to install a liquid oxygen (LOX) injection system to replenish the oxygen consumed by the methane-air combustion process.[12] These modifications enabled testing of large-scale hypersonic airbreathing propulsion systems at flight enthalpies from Mach 4 to 7. Comparisons of the SXPE and CDE test data also provided insight into ground test simulation concerns, such as facility test gas composition, dynamic pressure and geometric scale effects.

NASA initiated the Hyper-X (X-43) flight research project in 1995 to demonstrate the in-flight performance of a hydrogen-fueled, airframe-integrated scramjet at flight Mach numbers of 5, 7, and 10.[13] The flight engine design was based on a Mach 10, dual-fuel, global-reach reference vehicle.[14] The project was subsequently redirected to focus on Mach 7 and 10 flight tests, with ground engine research continuing at Mach 5.[15] As part of the Mach 7 flight engine and vehicle development, extensive ground freejet engine and aerothermodynamic testing was conducted to demonstrate performance and operability and to develop the engine and vehicle control laws.[16,17] Figure 4 illustrates the X-43 ground engine test flow logic. The dual-fuel experimental (DFX) engine was tested in the Langley AHSTF to characterize combustor and flowpath performance. A hypersonic scramjet model (HSM) was tested in the NASA HYPULSE tunnel (reflected shock tunnel mode) to examine the effects of pressure and facility test gas vitiation. The Hyper-X Engine Model (HXEM), a full-length, partial-width engine with truncated aftbody, was tested in the AHSTF and the 8-Ft. HTT. This comparison also provided data on facility test gas

Figure 3. NASP Concept Demonstrator Engine.

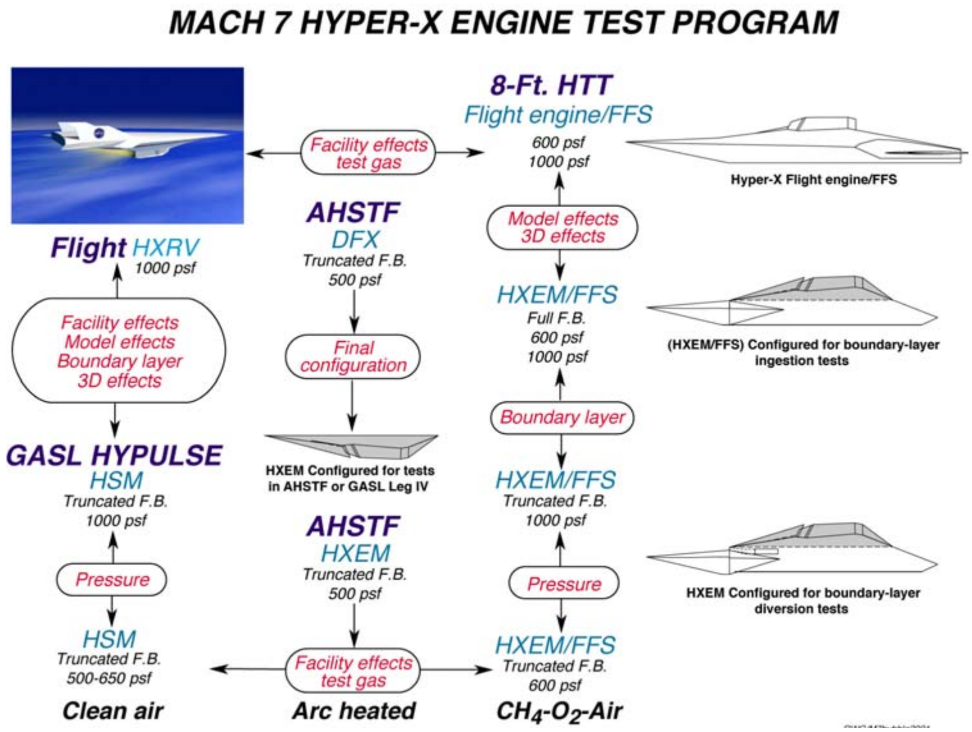

Figure 4. X-43 (Hyper-X) Ground Test Program Flow.

and dynamic pressure effects. The Hyper-X Flight Engine (HXFE), a full-scale duplicate flight engine, was tested extensively in the 8-Ft. HTT to verify flight performance and control laws.[18] The HXFE is shown in figure 5 during a run in the 8-Ft. HTT. The first flight attempt of the Mach 7 X-43 in June 2000 resulted in a failure of the booster rocket prior to reaching research vehicle separation and the scramjet test point. A second Mach 7 flight attempt is planned in 2003.

Airbreathing launch vehicle and other concept studies continue to mature potential concepts for future flight demonstration and candidate architectures for future operational systems.[19] These concept systems analyses are used to determine appropriate technology investments and mature performance evaluations of potential vehicles. Studies have identified RBCC and TBCC propulsion concepts as potential candidates for SSTO systems. The TBCC concept integrates a high-speed turbojet and a scramjet in an "over/under" dual-flowpath configuration, depicted in figure 6.[20]

Figure 5. Hyper-X Flight Engine (HXFE) in the Langley 8-Ft. High Temperature Tunnel (HTT).

Current Research Efforts

NASA's Advanced Space Transportation Program (ASTP) seeks to mature technologies to enable third-generation RLV systems.[21] This program encompasses three aspects of hypersonics technology development: flight demonstration, ground demonstration and foundation technology investments. Program implementation occurs at several NASA centers, including Marshall Space Flight Center, Langley Research Center, Glenn Research Center and Dryden Flight Research Center.

Presently, the flight demonstration aspect of

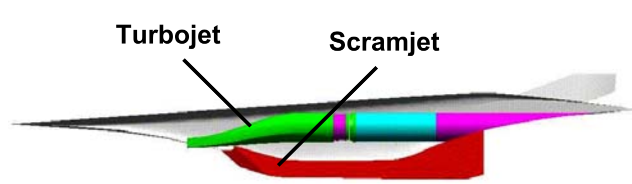

Figure 6. Over/Under Combination Cycle Concept.

ASTP consists of the X-43A (Hyper-X) and X-43C projects. The X-43C project is a joint NASA-Air Force project to achieve a flight demonstration of the USAF HyTech engine, a hydrocarbon-fueled dual-mode scramjet (DMSJ).[22] Similar to the X-43A, this mission is accomplished by boosting the research vehicle to the flight test altitude and condition via a solid-rocket booster which is air-launched from a B-52 aircraft. Whereas the X-43A is designed to achieve only a few seconds of powered flight at a single point design condition with heat-sink hardware, the X-43C vehicle is designed to fly an accelerating trajectory from Mach 5 to 7, demonstrating ramjet-scramjet mode transition. Additionally, the X-43C engine utilizes active regenerative fuel cooling, which will provide a validation of the heat exchanger design and the endothermic cooling capacity of liquid JP-7 fuel.

The two ground-based demonstration projects are formulated to enable development of hydrocarbon-fueled combined-cycle propulsion technology up to Mach 7 conditions. The RBCC project, led by NASA-Marshall Space Flight Center (MSFC), seeks to develop and ground test a Mach 7 capable RBCC engine system.[23-24] The proposed RBCC flowpath utilizes an ejector rocket system for approximately Mach 0-3 operation, transitioning to ramjet mode at approximately Mach 3 and finally transitioning to scramjet mode for operation up to Mach 7. The current RBCC ground demonstration activity builds upon earlier efforts to develop hydrogen-fueled RBCC technology under the Advanced Reusable Technologies (ART) program.[25] The primary objective of the TBCC project, led by NASA-Glenn Research Center (GRC), is to develop, and demonstrate through ground testing, high-speed turbojet engines capable of operation up to Mach 4 conditions. DMSJ performance and integration with a high-speed turbojet is also being studied at the conceptual level. A proposed X-43B sub-scale hydrocarbon-fueled reusable flight demonstrator vehicle is envisioned that would utilize either RBCC or TBCC propulsion for Mach 0.7 to 7 flight. This project would extend the flight performance database to low-speed systems, demonstrate mode transitions and address various operational aspects of reusable flight vehicle technology.

These ground and flight demonstration projects support several DMSJ technology development areas. The X-43C project will mature regeneratively-cooled hydrocarbon-fueled scramjets. The RBCC project will examine rocket integration, mode transition, fueling strategies and engine controls. Inlet operability and fuel injector designs have been examined in recently-conducted component-level tests. The TBCC project will examine over/under system integration and conceptual design of a DMSJ engine to function over a Mach 4-7 flight trajectory.

The remaining foundation technology aspects of the program are addressed in airframe and propulsion technology projects within ASTP. The airframe project includes maturation of aerothermodynamics technologies as well as propulsion-airframe integration and Mach 3-15 integrated flowpath performance. Efforts in the propulsion research project related to DMSJ development include combustion flow physics and tool development as well as high-temperature lightweight materials and seals. This paper describes current efforts and long-term research objectives in these foundation research and technology areas, including combustor technology, hypervelocity scramjet development, DMSJ and continuous performance and operability, propulsion-airframe integration and tool development.

Technology Development Roadmap

Technology development goals are driven by the requirement for efficient DMSJ propulsion systems for Mach 3-8 (near-term) and Mach 3-15 (far-term) operation to support future flight demonstration projects and operational space-access system development. Figure 7 shows a summary of current efforts as well as near-term and far-term technology goals in each area.

Mid-Speed (Mach 3-8) Combustor Technology

The mid-speed flight regime generally refers to the range from subsonic combustion operation to the transition to supersonic operation. Generally, the term is used to refer to the Mach 3-8 flight range. The combustor is characterized by highly distorted flow with regions of mixed subsonic and supersonic flow. In this context, the term “dual-mode” refers to the region where mixed subsonic and supersonic flow is present in the combustor. The upstream pressure rise caused by heat release in the combustor extends forward into the isolator section, which is characterized by an oblique shock train. A primary purpose of combustor component research is to study the basic physical processes of fuel injection and mixing as well operability of the isolator and the combustor. Emphasis is placed on a better understanding of low-speed (Mach 3-5) performance. In subsonic combustion mode, fuel injection and combustion primarily occur downstream in the diverging section of the combustor and the heat release due to combustion

Current Efforts	Near-Term Foci	Far-Term Goals
Hypervelocity (Mach 10-15) Scramjet Engine Development		
• Flow Physics and Test Technques	• Hypervelocity Scramjet/RBCC Ground Demonstration	• LOx-augmented Ejector-Scramjet Demonstration
Mid-Speed (Mach 3-8) Combustor Technology		
• Flow Physics and Modeling	• Parametric Combustor Test Rig • M 3-15 multi-speed optimization	• Flight-weight H2-Fueled Combustor Validation.
Mach 3-8 DMSJ/Combined-Cycle Performance and Operability		
• Mach 3-6 Performance Data • Engine Control Algorithms	• Variable-Geometry Performance Demonstration	• H2-Fueled Flight-like, Fuel-Cooled Engine Demonstration
Propulsion-Airframe Integration		
• Powered Transonic Aero • Sub-scale Simulation	• Multi-speed Aero-Propulsive Performance Methods	• Aero-Propulsive Trajectory Simulation Capability
Analysis Tools and Diagnostics Development		
• Code Development & Validation • Combustor Flowfield Temperature Measurements	• Physical and Algorithmic enhancements and validation • Temperature, species and velocity measurements.	• Rapid nose-to-tail design tools • Routine measurements of complete combustor flowfield properties

Figure 7. Hydrogen-Fueled DMSJ Technology Roadmap

creates a thermal throat. The primary challenge in combustor design is determining appropriate fueling strategies and injector designs to improve performance in and through this rapid expansion region. Parametric combustor design databases are needed in this speed regime to characterize performance and improve multi-speed combustor optimization.

An understanding of combustor operation and the design application to future hypersonic flight demonstrators and operational vision vehicles is further complicated by fuel selection. Hydrogen fuel is the preferred option for single-stage-to-orbit airbreathing launch vehicles with scramjet cycles to Mach 15 or greater. However, liquid hydrocarbon fuels have beneficial applications because of their greater fuel densities and endothermic cooling capabilities. There is a generally accepted upper limit of approximately Mach 8 for storable JP-type hydrocarbon fuels.[26,27] An advantage of liquid hydrocarbon fuels for the proposed combined-cycle flight demonstrators is smaller vehicle designs and therefore, potential cost savings. Also, the use of hydrocarbon fuels also extends the applicability of technology development to hypersonic cruise missions. In addition to the hydrocarbon-fueled combustor development in the ground and flight demonstration projects previously discussed, there is a need for fundamental supersonic combustion studies for hydrogen-fueled engines, including an understanding of performance relationships and scaling parameters between hydrogen and hydrocarbon-fueled combustor designs.

The Langley Direct-Connect Supersonic Combustion Test Facility (DCSCTF), depicted in figure 8, is devoted to DMSJ combustor testing and development.[10] This facility utilizes hydrogen-air combustion to achieve a test gas that duplicates the stagnation enthalpies of flight Mach numbers from 4.0 to 7.5. Oxygen replenishment is used to achieve a test gas with the same oxygen mole fraction as atmospheric air (0.2095). Gaseous hydrogen is the principal fuel used in combustor models tested in the DCSCTF, although other gas mixtures, such as ethylene, have been used to simulate cracked hydrocarbon fuels. Modifications are in progress to accommodate testing with heated liquid hydrocarbon fuels. Near-term efforts will consist of parametric direct-connect combustor testing with both gaseous and liquid fuels. A parametric combustor test article is proposed which will allow for the investigation of combustor design parameters, injector configurations, fueling strategies, ignition and flameholding characteristics. These efforts will provide risk reduction for future flight demonstrator engine development, specifically the RBCC and TBCC engine concepts and will generate a parametric design database for multi-speed combustor optimization. These efforts are coupled with investigations of combustion flow physics,

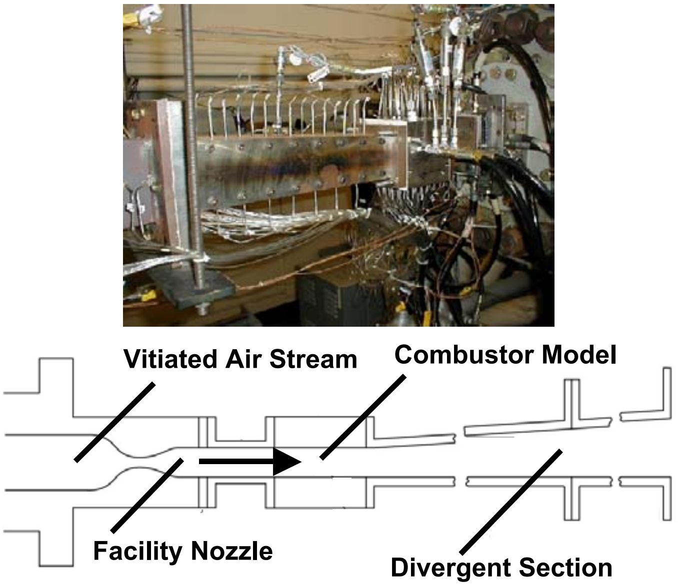

Figure 8. Langley Direct-Connect Supersonic Combustion Test Facility (DCSCTF).

computational modeling and associated diagnostic tool development (described in the next section). Far-term goals are to design and demonstrate a flight-weight, regeneratively-cooled, hydrogen-fueled combustor for future Mach 0-15 flight demonstration and vision vehicle development.

Analysis Tool and Diagnostic Development

Computational Fluid Dynamics (CFD) modeling of scramjet combustors is complicated by various physical processes, including large regions of subsonic flow, separated flow regions, complex mixing phenomena, non-equilibrium transfer of turbulence energy, and interactions between turbulence and chemical kinetics that may impact both the chemical reactions and turbulence field.[26] Limitations in physical modeling capabilities as well as computational overhead costs limit the practical use of three-dimensional CFD tools in design and development of scramjet combustors. Several efforts are underway to incorporate advanced physical models and algorithmic enhancements in CFD tools and to acquire high-fidelity data sets for code calibration.

The Coherent anti-Stokes Raman Spectroscopy (CARS) technique has been used recently to acquire flow-field data in the LaRC DCSCTF for this purpose.[28,29] These efforts have succeeded in mapping mean and RMS temperature fluctuations in a supersonic combustor. Figure 9 shows a generic supersonic combustor model with angular fuel injection used for these studies and figure 10 shows mean temperature maps developed using the CARS technique.[28] The experiment was adopted as a test case by the RTO working group on scramjet propulsion (Working Group 10).[29] Near-term objectives of this work include further applications of optical diagnostic techniques to obtain simultaneous temperature and species measurements. The VULCAN CFD code, developed at NASA LaRC, is a Navier-Stokes code used to simulate chemically-reacting flow fields in scramjet combustors and flowpaths.[31] Previously, upgrades to this code, including volume grid capabilities, physical models and convergence acceleration enhancements were incorporated. The combustor data sets described here comprise a partial data base for CFD code validation for this class of flows.

Additional work has included the use of laser-based diagnostics along with flow seeding to obtain fuel plume images and velocity measurements. Reference 31 described the use of this technique to obtain measurements in a Mach 2 hydrogen-air combustor with a 10^{o} unswept ramp fuel injector. The VULCAN CFD code was used to obtain flow field predictions of this flowpath and comparisons with experimental wall pressures and fuel plume images are shown. These comparisons indicate an underprediction in the level of turbulent mixing and heat release due to combustion. This work suggests that improvements in turbulence modeling and turbulent-chemistry interactions are needed to improve supersonic combustor modeling in this speed range.

Future efforts are expected to focus on the development of validated nose-to-tail design and analysis tools. This includes advanced physical modeling capabilities for turbulence, turbulence-chemistry interactions and reduced combustion kinetics models for hydrocarbon and hydrogen combustion. Ultimately, diagnostic tool development will enable routine measurements of all combustor

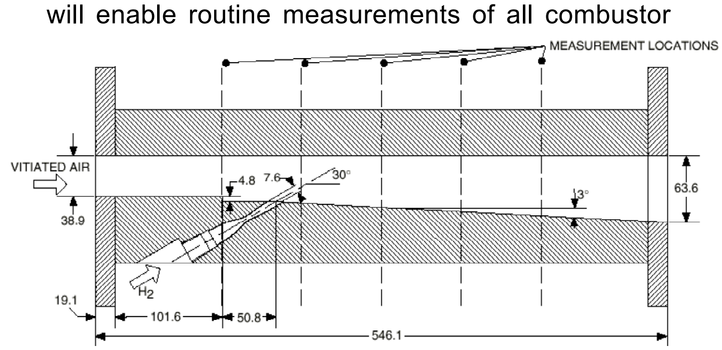

Figure 9. Supersonic Combustor (SCHOLAR) Model.

flow field parameters (temperature, velocity, species

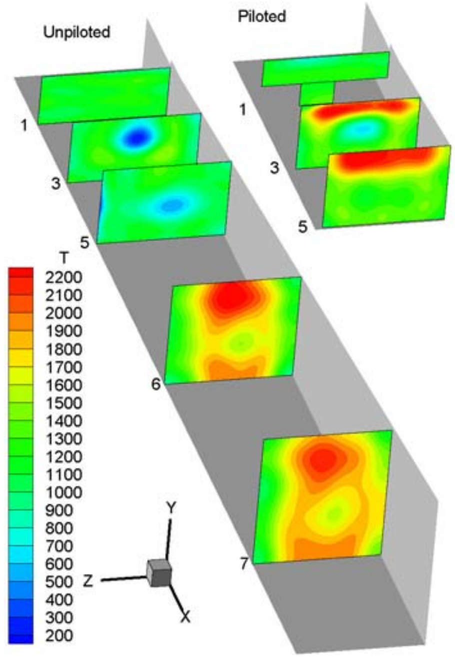

Figure 10. Mean temperature maps obtained in the DCSCTF using CARS (ref. 25).

concentrations) to provide the necessary databases to fully characterize combustor flow fields and to validate CFD methods.

DMSJ/Combined-Cycle Performance and Operability

Dual-mode scramjet engine cycles must function over a wide Mach number range in order to meet mission requirements. Current ground test databases exist only over a limited Mach number range. For candidate X-43B demonstrator configurations, engine performance, operability and system weights must enable accomplishment of the Mach 7 mission objective. Future Mach 15 and SSTO operational concepts require scramjet operation up to Mach 15 before transitioning to a rocket cycle or scramjet ejector cycle for orbital insertion. Therefore, mission specific impulse values must be maximized over the Mach number range in order to provide acceptable performance margin.

Historically, a number of engine test programs at NASA-Langley, discussed previously, have contributed to the performance database for airframe-integrated scramjet flowpaths.[3,4] Depending on the Mach number range and specific mission requirements, efficient inlet operation over the applicable flight regime may necessitate variable contraction ratios. Variable-geometry concepts have been examined to provide this required operability.

Efficient multi-speed engine operation also requires the development of fueling strategies and engine control mechanisms. Engine control algorithms are required to control the engine variable contraction ratio schedule and control fuel flow rates to provide required thrust to meet mission objectives, enable mode transitions and to prevent and recover from engine unstart and flameout. These issues were studied in the Hyper-X program for the Mach 7 and 10 flight experiments and contributed to the development of flight control laws for the X-43A vehicles. This research is being further extended to the Mach 4-7 range and matured for future flight demonstrator vehicle development.

Near-term project plans consist of additional freejet testing efforts in the Langley CHSTF and the AHSTF. First, the existing Mach 5 dual-fuel experimental engine (DFX) will be tested in the CHSTF to extend the low-speed (Mach 3-5) hydrogen-fueled engine performance database for DMSJ engines and to further examine facility test-gas vitiation effects. Second, further testing of the HXEM will be conducted in the AHSTF to investigate control laws for scramjet engine operation over the Mach 4-7 range. The HXEM testing will take place following the installation of a new, high-quality flow, Mach 6 facility nozzle in the tunnel circuit. A thorough calibration at three total enthalpy levels will be conducted followed by HXEM performance testing to examine the effects of nozzle exit flow uniformity on engine performance.

A longer-term objective of the program is to conduct a comprehensive test program of a variable-geometry dual-mode scramjet engine configuration over the Mach 3-8 speed range. The goal of this test program will be to investigate parametric performance at fixed contraction ratios, examine contraction ratio changes during runs, examine performance during mode transitions and to verify closed-loop engine control algorithms. Real-time enthalpy and dynamic pressure variation during tests will be accomplished. Variable-geometry demonstration with heat-sink hardware will be followed with flight-like, regeneratively-cooled, hydrogen-fueled engine ground testing.

Hypervelocity Scramjet Development

As indicated in figure 1, the specific impulse of the scramjet cycle decreases as Mach number increases. Heat release due to combustion is inversely proportional to the square of the freestream Mach number. At Mach 15, the combustion energy is approximately less than 25-percent of the free stream kinetic energy, accounting for flow field losses.[9] At these Mach numbers, small changes in effective specific impulse can cause significant changes in vehicle take-off gross weights, thus impacting the ability of the system to meet mission performance requirements.[32] This represents a practical upper limit for efficient scramjet engine operation without LOX-augmentation. A further understanding of the fundamental physical processes that govern engine performance in the hypervelocity speed range is required in order to optimize flowpath lines for efficient operation.

At hypervelocity speeds, scramjet flow physics are characterized by very short residence times. Robust flowpath design is dependent on an understanding of the following flow-field and combustion phenomena: fuel injector geometry, mixing, flameholding, and combustion efficiency as well as thermal balance and protection requirements. The NASA-Langley HYPULSE facility, located at and operated by Allied Aerospace, Inc. (GASL Division) has been used to perform hypervelocity scramjet research in a shock-expansion-tunnel (SET) mode at enthalpy levels duplicating Mach numbers above 10.[33-35] A schematic of the NASA HYPULSE Facility is shown in figure 11. Tests have been conducted most recently on a scramjet flowpath model, representative of the Mach 10 X-43A scramjet flowpath lines, at Mach 15 conditions.[36]

Future test technique development will focus on a definition and calibration of HYPULSE (SET) at baseline test points in the Mach 12-15 range. This includes the design, using CFD, and fabrication of a facility nozzle suitable for scramjet engine tests, and efforts to optimize and calibrate the shock tunnel exit flow conditions for these flight Mach numbers. Various flow diagnostic techniques, including schlieren, fuel-plume (planar) imaging, water temperature and concentration by laser absorption and laser holographic interferometry, will be applied

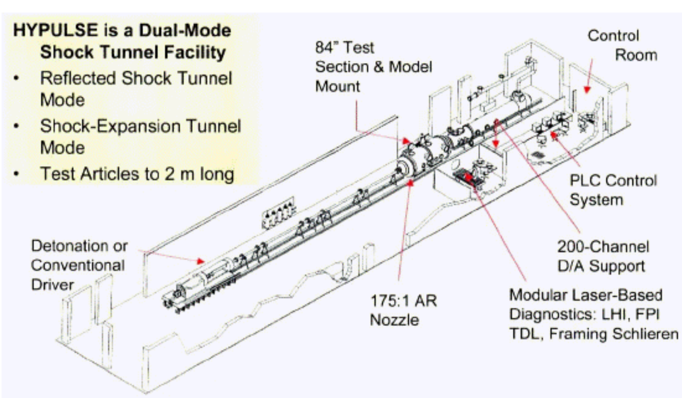

Figure 11. NASA HYPULSE Facility.

to assess facility test conditions.

Near-term efforts also consist of development of a comprehensive Mach 12-15 performance database. This will enable the design of a future flight demonstrator to validate Mach 15 scramjet performance. Long-term goals include demonstrations of a flight-weight combustor at Mach 15 conditions and LOX-augmented ejector-scramjet cycles to enable orbital insertion for SSTO systems. System studies indicate that LOX-augmentation may be required for efficient orbital insertion in SSTO airbreathing launch vehicles.[37]

Propulsion-Airframe Integration (PAI)

Hypersonic airbreathing vehicles are characterized by highly integrated systems with a high degree of interaction between the airframe and propulsion flowpath. Aerothermodynamic performance cannot be decoupled from propulsion performance, due to shared surfaces and flow field interactions, as depicted in figure 12. Therefore, a significant challenge in the design and development of hypersonic airbreathing flight vehicles is the determination of aero-propulsive interactions and installed vehicle performance. Design tools and ground testing techniques are needed to fully characterize these effects across the applicable speed ranges.

During the NASP program, significant work was done to investigate the use of cold-gas mixtures to simulate powered scramjet exhaust products in ground test facilities.[38-40] This technique was investigated in the supersonic and hypersonic speed regimes (Mach 4-10) with powered metric aftbody models to develop the technique and measure external nozzle pressures, exhaust plume impingement on wing surfaces and aftbody forces and moments. Analysis to examine the correlation of cold simulant gases to hot combustion products was initiated, but not completed due to the termination of this program.

The X-43A flight project undertook a significant ground testing and computational effort to build the pre-flight vehicle database.[41,42] This effort consisted of un-powered aerothermodynamic testing with powered force and moment increments supplied by CFD predictions. These predictions were verified by full-flowpath force and moment data obtained from the HXFE testing in the Langley 8-Ft. HTT.[18]

Future NASA efforts in this area will build on NASP and X-43A research and will focus on test

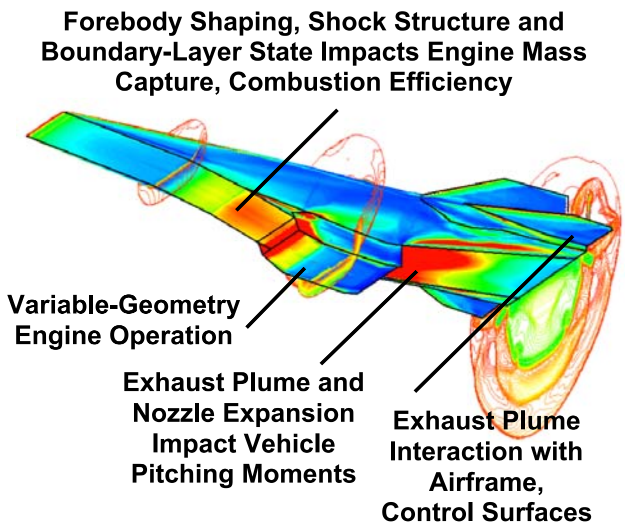

Figure 12. Propulsion-Airframe Integration considerations for hypersonic vehicles.

techniques and analysis methodologies to predict installed vehicle forces and moments through the applicable flight trajectories. In the supersonic/hypersonic speed range, data from sub-scale exhaust simulation methodologies will be compared with data from full-flowpath fueled scramjet test models to further mature this technique and quantify the uncertainty in force and moment measurements.

Vehicle systems studies have identified installed transonic performance predictions as having a high degree of uncertainty. Current analytical methods are not sufficient to fully characterize the integrated powered vehicle performance in this speed range. Recently, a test was conducted in the Langley 16-Foot Transonic Tunnel to measure nozzle/aftbody flow field characteristics and forces and moments on a NASP vehicle model. These data will be used to calibrate existing CFD and other design methodologies for future analyses.

Additionally, maturation of test techniques to measure vehicle forces and moments and propulsion-airframe interactions are required for the hypervelocity (Mach 10-15) speed range. Typically, pulse facilities are used to supply the energy needed for aerothermodynamic and propulsion testing in this speed range. Measurement of powered forces and moments in these environments is a technique not adequately addressed in previous NASA hypersonic programs. The University of Queensland has previously reported efforts to support aerodynamic force and moment measurements in pulse facilities. Reference 43 reports three-component measurements obtained in a reflected shock tunnel and reference 44 describes a 6-component balance design. These devices rely on a stress wave force measurement technique, which measures the propagation of stress waves through test models.

The TBCC over/under configuration requires a high degree of integration to determine the impact on the performance of each flowpath and the transition regime from gas turbine to scramjet. Dual-flowpath inlet and nozzle integration test articles are envisioned to demonstrate the integration and mode transition aspects of this system.

Other aerothermodynamic technologies that impact propulsion system operation are also being addressed in other areas of the ASTP airframe technology project. These include boundary-layer transition studies, evaluation of alternative forced transition mechanisms, shock interaction methods and aeroheating prediction methods. These efforts are fully described in reference 45.

Other Enabling Technologies

In addition to the scramjet combustor and flowpath development efforts described herein, additional key enabling technologies will be required to accomplish operational system goals. These include lightweight high-temperature materials and seals, actuation mechanisms, hot-gas valves and fuel systems. Technology development in these areas is either captured in existing projects or they will be addressed in future focused flight engine development.

Concluding Remarks

The U.S. National Aeronautics and Space Administration (NASA) is developing technologies to enable third-generation reusable launch vehicles (RLV). The focus is on airbreathing and combined-cycle propulsion concepts to take advantage of potential performance gains over conventional rocket propulsion. The dual-mode scramjet (DMSJ) engine cycle, integrated with rocket or turbine-based cycles, is being studied for future RLV vision vehicle concepts. Historically, development of airframe-integrated scramjets has progressed through component testing and sub-scale engine test programs, the National Aerospace Plane (NASP) program and the current X-43A and X-43C flight demonstration projects. Foundation technology investments, supporting propulsion ground demonstration projects, future flight demonstrators and vision vehicle operational system concepts are required to achieve strategic goals. A proposed

NASA technology roadmap has been presented which encompasses mid-speed (Mach 3-8) dual-mode combustion flow physics, hypervelocity (Mach 10-15) scramjet development, multi-speed flowpath operability and performance, propulsion-airframe integration and analysis and diagnostic tool development.

References

1. Andrews, Earl A. "Scramjet Development and Testing in the United States," AIAA Paper 2001-1927, Presented at the AIAA/NAL-NASDA-ISAS International Space Planes and Hypersonic Systems and Technologies Conference, April 2001.
2. McClinton, Charles R.; Andrews, Earl A. and Hunt, James L. "Engine development for space access - Past, present and future," ISABE Paper 2001-1074, Presented at the 15th International Symposium on Air Breathing Engines, September 2001.
3. Rogers, R. C.; Capriotti, D.P. and Guy, R. W. "Experimental Supersonic Combustion Research at NASA Langley," AIAA Paper 98-2506, Presented at the AIAA 20th Advanced Measurement and Ground Testing Technology Conference, June 1998.
4. Kumar, Ajay; McClinton, Charles R.; Drummond, J. Phillip and Hunt, James L. "Research in hypersonic airbreathing propulsion at the NASA Langley Research Center," ISABE Paper 2001-1007, Presented at the 15th International Symposium on Air Breathing Engines, September 2001.
5. Andrews, Earl A. and Mackley, Ernest A. "NASA's Hypersonic Research Engine – A Review", AIAA Paper 93-2323, June 1993.
6. Wieting, Alan R. "Aerothermodynamic and Thermal Analysis of Results of Tests of A Hydrogen Cooled Scramjet Engine at Mach 6.3", NASA TM x-2767, May 1973.
7. Andersen, W.L. and Kado, L. "Hypersonic Research Engine (HRE) Project – Phase II, Aerothermodynamic Integration Model (AIM) Test Report", AiResearch Manufacturing Company of California, NASA CR-132655, 1975.
8. Northam, G. Burton and Anderson, Griffin Y. "Supersonic Combustion Ramjet Research at Langley," AIAA Paper 86-0159, AIAA 24th Aerospace Sciences Meeting, January 1986.
9. Anderson, Griffin Y.; McClinton, Charles R. and Weidner, John P. "Scramjet Performance", Scramjet Propulsion, AIAA Progress in Aeronautics and Astronautics, vol. 189, 2000.
10. Guy, R. Wayne; Rogers, R. Clayton; Puster, Richard L.; Rock, Kenneth E. and Diskin, Glen S. "The NASA Langley Scramjet Test Complex," AIAA Paper 96-3243, Presented at the AIAA 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 1996.
11. Voland, Randall and Rock, Kenneth. "NASP Concept Demonstrator Engine and Subscale Parametric Engine Tests," AIAA Paper 95-6055, April 1995.
12. Huebner, Lawrence D.; Rock, Kenneth E. and Wieting, Allan R. "Calibration of the Langley 8-Foot High Temperature Tunnel for Hypersonic Airbreathing Propulsion Testing," AIAA Paper 96-2197, Presented at the 19th AIAA Advanced Measurement and Ground Testing Technology Conference, June 1996.
13. Freeman, Delma C.; Reubush, David E.; McClinton, Charles R.; Rausch, Vincent L. and Crawford, J. Larry. "The NASA Hyper-X Program," Presented at the 48th International Astronautical Conference, October 1997.
14. Scuderi, Lee F.; Orton, George F. and Hunt, James L. "Mach 10 Cruise/Space Access Vehicle Study," AIAA Paper 98-1584, Presented at the 8th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, April 1998.
15. Albertson, Cindy W. and Emami, Saeid. "Alleviation of Facility/Engine Interactions in an Open-Jet Scramjet Test Facility," AIAA Paper 2001-3677, Presented at the 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2001.
16. Voland, R.T.; Rock, K.E.; Huebner, L.D.; Witte, D.W.; Fischer, K.E. and McClinton, C.R. "Hyper-X Engine Design and Ground Test Program," AIAA Paper 98-1532, Presented at the AIAA 8th International Space Planes and Hypersonic Systems and Technologies Conference, April 1998.
17. Holland, Scott D.; Woods, William C. and Engelund, W.C. "Hyper-X Research Vehicle Experimental Aerodynamics Test Program Overview," Journal of Spacecraft and Rockets, vol. 38, no. 6, November-December 2001, pp. 828-835.
18. Huebner, Lawrence D.; Rock, Kenneth E.; Witte, David W.; Ruf, Edward G. and Andrews, Earl H. "Hyper-X Engine Testing in the NASA Langley 8-Foot High Temperature Tunnel," AIAA Paper 2000-3605, Presented at the 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2000.

19. Hunt, James L.; Pegg, Robert J. and Petley, Dennis H. “Airbreathing Hypersonic Vision-Operational-Vehicles Design Matrix,” Presented at the 1999 World Aviation Congress and Exposition, San Francisco, California, October 1999.
20. Moses, P.L.; Bouchard, K.A.; Vause, R.F.; Pinckney, S.Z.; Ferlemann, S.M.; Leonard, C.P.; Taylor, L.W.; Robinson, J.S.; Martin, J.G.; Petley, D.H. and Hunt, J.L. “An Airbreathing Launch Vehicle Design with Turbine-Based Low-Speed Propulsion and Dual-Mode Scramjet High-Speed Propulsion,” AIAA 99-4948, Presented at the 9th International Aerospace Planes and Hypersonic Systems and Technologies Conference, November 1999.
21. Hueter, Uwe. “NASA’s Advanced Space Transportation Program,” AIAA 2002-5175, Presented at the 11th AIAA/AAAF International Space Places and Hypersonic Systems and Technologies Conference, October 2002.
22. Mercier, Robert A.; Ronald, T.M.F. “Hypersonic Technology (HyTech) Program Overview,” AIAA Paper 98-1566, Presented at the AIAA International Space Planes and Hypersonic Systems and Technologies Conference, April 1998.
23. Hueter, Uwe. “Rocket-Based Combined Cycle Propulsion Technology for Access-to-Space Applications,” AIAA Paper 99-4925, Presented at the AIAA 9th International Space Places and Hypersonic Systems and Technologies Conference, November 1999.
24. Faulkner, Robert F. Integrated Systems Test of an Airbreathing Rocket (ISTAR). AIAA Paper 2001-1812, Presented at the AIAA Joint Propulsion Conference, June 2001.
25. Turner, James E. and Hueter, Uwe. “A Progress Report on the Advanced Reusable Technologies Project,” Presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 1998.
26. Tishkoff, Julian M.; Drummond, J. Phillip and Edwards, Tim. “Future Directions of Supersonic Combustion Research: Air Force/NASA Workshop on Supersonic Combustion,” AIAA Paper 97-1017, Presented at the 35th AIAA Aerospace Sciences Conference, January 1997.
27. Maurice, Lourdes; Edwards, Tim; Griffiths, John. “Liquid Hydrocarbon Fuels for Hypersonic Propulsion,” Scramjet Propulsion, AIAA Progress in Aeronautics and Astronautics, vol. 189, 2000.
28. Cutler, A.D.; Danehy, P.M.; Springer, R.R.; DeLoach, R. and Capriotti, D.P. “CARS Thermometry in a Supersonic Combustor for CFD Code Validation,” AIAA Paper 2002-0743, Presented at the 40th AIAA Aerospace Sciences Conference, January 2002.
29. Drummond, J. Phillip; Diskin, Glen; Cutler, Andrew and Danehy, Paul. “Fuel-Air Mixing and Combustion in Scramjets,” AIAA 2002-3878, Presented at the 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 2002.
30. White, Jefferey A. and Morrison, J.H. “A Pseudo-Temporal Multi-Grid Relaxation Scheme for the Parabolized Navier-Stokes Equations,” AIAA Paper 99-3360, AIAA 14th Computational Fluid Dynamics Conference, June 1999.
31. Goyne, C.P.; Rodriguez, C.G.; Krauss, R.H.; McDaniel, J.C. and McClinton, C.R. “Experimental and Numerical Study of a Dual-Mode Scramjet Combustor,” AIAA Paper 2002-5216, Presented at the 11th AIAA/AAAF International Space Planes and Hypersonic Systems and Technologies Conference, October 2002.
32. Hunt, James L. “Propulsion Integration Characteristics/Sensitivities for LOx-Augmented Aerospace Planes,” Presented at the NASA-Langley Workshop on Performance Enhancement for Hypervelocity Airbreathing Propulsion, NASA Langley Research Center, July 1991.
33. Bakos, R.J.; Tamagno, J.; Rizkalla, O.; Pulsonetti, M.V.; Chinitz, W. and Erdos, J.I. “Hypersonic Mixing and Combustion Studies in the GASL HYPULSE Facility,” AIAA Paper 90-2095, AIAA/SAE/ASME/ASEE 26th Joint Propulsion Conference, July 1990.
34. Calleja, John and Tamagno, Jose. “Calibration of HYPULSE for Hypervelocity Air Flows Corresponding to Flight Mach Numbers 13.5, 15 and 17,” NASA Contractor Report 191578, December 1993.
35. Foelsche, R.O.; Rogers, R.C.; Tsai, C.Y.; Bakos, R.J. and Shih, A.T. “Hypervelocity Capability of the HYPULSE Sock-Expansion Tube Tunnel for Scramjet Testing,” ISSW23-Paper No. 1047, Presented at the 23rd International Symposium on Shock Waves, July 2001.
36. Rogers, R.C.; Shih, A.T.; Tsai, C.Y. and Foelsche, R.O. “Scramjet Tests in a Shock Tunnel at Flight Mach 7, 10 and 15 Conditions,” AIAA Paper 2001-3241, AIAA 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2001.

37. Hunt, James L. "Airbreathing Rocket/Single-Stage-to-Orbit Design Matrix," AIAA Paper 95-6011, Presented at the 6th International Aerospace Planes and Hypersonics Technologies Conference, April 1995.
38. Huebner, Lawrence D. and Tatum, Kenneth E. "Computational and Experimental Aftbody Flowfields for Hypersonic Airbreathing Configurations with Scramjet Exhaust Flows," AIAA Paper 91-1709, June 1991.
39. Huebner, Lawrence D. and Tatum, Kenneth E. "CFD Code Calibration and Inlet-Fairing Effects on a Three-Dimensional Hypersonic Powered Simulation Model," AIAA Paper 93-3041, July 1993.
40. Tatum, Kenneth E.; Witte, David W.; Monta, William J. and Walters, Robert W. "Analysis of Generic Scramjet External Nozzle Flowfields Employing Simulant Gases," AIAA Paper 90-5242, December 1990.
41. Engelund, Walter C.; Holland, Scott D.; Cockrell, Charles E. Jr. and Bittner, Robert D. "Aerodynamic Database Development for the Hyper-X Airframe-Integrated Scramjet Propulsion Experiments," Journal of Spacecraft and Rockets, Vol. 38, No. 6, 2001, pp.803-810.
42. Cockrell, Charles E. Jr.; Engelund, Walter C.; Bittner, Robert D.; Jentink, Tom N.; Dilley, Arthur D. and Frendi, Abdelkader. "Integrated Aeropropulsive Computational Fluid Dynamics Methodology for the Hyper-X Flight Experiment," Journal of Spacecraft and Rockets, Vol. 38, No. 6, pp. 836-843.
43. Mee, D.J.; Daniel, W.J.T. and Simmons, J.M. "A three-component force balance for flows of a millisecond duration," AIAA Journal, vol. 34, no. 3, pp. 590-595, 1996.
44. Smith, A.L.; Mee, D.J.; Daniel, W.J.T. and Shimoda, T. "Design, modeling and analysis of a six-component force balance for hypervelocity wind tunnel testing," Computers and Stuctures, vol. 79, no. 11, pp. 1077-1088, 2001.
45. Glass, David E. "Airframe Technology Development for Hypersonic Airbreathing Vehicles,", AIAA Paper 2002-5178, Presented at the 11th AIAA/AAAF International Space Planes and Hypersonic Systems and Technologies Conference, October 2002.