JOURNAL OF PROPULSION AND POWER
Vol. 17, No. 6, November–December 2001

Experimentation, Test, and Evaluation Requirements for Future Airbreathing Hypersonic Systems

Dan Marren*
Arnold Engineering Development Center, White Oak, Maryland 20903-1050
Mark Lewis†
University of Maryland, College Park, Maryland 20742-3015
and
Lourdes Q. Maurice‡
U.S. Air Force Research Laboratory, Arlington, Virginia 22203-1977

Experiences gained in recent airbreathing hypersonic vehicle development programs have ascertained that mastering hypersonic flight will depend directly on continued ability to experiment, test, and evaluate. Indeed, many of the hypersonic flight systems being studied will require testing and modeling capabilities that do not currently exist or that may soon be lost if current infrastructures are not maintained. The testing and evaluation of hypersonic systems represents a unique set of challenges. Duplication of the hypersonic flight environment requires extreme temperatures and pressures coupled with complex physical interactions. Ground-test facilities are limited in their ability to duplicate all salient parameters simultaneously. Data from flight experimentation are also limited due to range airspace requirements for long distance flight corridors. These limitations manifest themselves in range safety, data acquisition, and environmental concerns. Computational techniques are a growing supplement to experiment, but are not a replacement. Despite the improvement in both hardware and algorithms, analytical models and computational techniques are extremely time consuming, fall short of adequate fidelity, and require data to anchor and validate them. The conclusion is that only through a unique combination of experiment, flight testing, analysis, and computation, will hypersonic system risks be reduced and the vision of airbreathing hypersonic flight be realized.

Introduction

DEVELOPMENT of airbreathing hypersonic technology has been the subject of renewed interest since the 1980s because of the tremendous military and commercial capabilities that could be enabled by merging the air and space continuum. Many advances are being realized in research programs throughout the world, as evidenced by the wealth of articles on the subject found in this *Journal of Propulsion and Power* special issue on progress in hypersonic science and technology development. To translate these technological achievements into operational hypersonic airbreathing vehicles will require innovation in experimentation, test, and evaluation.

Hypersonic vehicle development is approaching a critical juncture as large-scale hypersonic ground-test facilities are aging, with no major new facilities in sight. Existing facilities with sufficient run time have been unable to match the Reynolds numbers and enthalpies associated with the previous generation of hypersonic flight vehicles, including missiles, rockets, and the space shuttle. As such, these vehicles were designed by collecting data in lower Reynolds number, lower enthalpy facilities, and applying correction factors to predict true transient performance. The corrections have themselves been based on empirically derived formulations, which cannot be validated before flight. To compensate, vehicles have been overdesigned. Both global reach and single-stage-to-orbit airbreathing hypersonic vehicles will operate very close to the limits of performance such that every aspect of the vehicle will have to be optimized for minimal weight and maximum performance. Overdesign due to inadequate data will prevent achieving practical configurations. Empirical corrections to the propulsion, aerodynamic, structure, and control systems must be replaced by an understanding of hypersonic flow physics throughout the entire range of interest that is as complete and physics based as possible. Hence, it is necessary to retain and expand the ability to test and evaluate airbreathing hypersonic vehicles under the most realistic conditions feasible. The present contribution maintains that how that knowledge will be acquired should be a matter of extensive national and international debate.

Background

The conclusions and recommendations of the 1989 Air Force Scientific Advisory Board (SAB)[1] and the 1998 National Research Council (NRC)[2] studies on hypersonic test requirements, indicative of the salient issues, are virtually identical. Both groups observed that the best approach to support hypersonic research and development embodied a combination of modeling and testing (both ground and flight). Both studies identified complete propulsion system ground testing (including forebody compression and aft body expansion effects) as a requirement that could not be met by any existing test facility. The NRC study recommended modifying the Arnold Engineering and Development Center's Aeropropulsion Test Unit to enable testing of full-scale missiles and associated scramjets to Mach 8. A more recent SAB study[3] estimates that a hypersonic vehicle can be acquired in the 2020–2025 time frame and agrees with the facility improvement recommendations listed earlier. All three studies advocated flight experimentation and testing. A reliable prediction of the future of airbreathing hypersonic vehicle development requires an understanding of the technologies that must be demonstrated to make these vehicles a reality.

Critical Hypersonic Technologies

Several hypersonic technologies are generally identified as critical to the success of future hypersonic weapon and space access concepts. The needs for validation in each of these areas will in turn drive the requirements for hypersonic experimentation, test, and evaluation integrated capabilities. These areas include

Received 27 August 2001; revision received 27 August 2001; accepted for publication 30 August 2001.

*Hypersonic Test and Evaluation Plans and Programs Lead; dan.marren@arnold.af.mil.

†Professor, Department of Aerospace Engineering; lewis@eng.umd.edu.

‡Principal General Engineer, Air Force Office of Scientific Research, 801 N. Randolph Street, Suite 732; Drs.Maurice@worldnet.att.net.

the following categories, which are then summarized: propulsion and propulsion/airframe integration, thermal management, aerodynamics, materials and structures, guidance navigation and control, weapon-related technologies, and revolutionary hypersonic technologies.

Propulsion and Propulsion/Airframe Integration

The combined test requirements for propulsion and propulsion integration highlight the most pressing test deficiencies. Overcoming these deficiencies will be critical to the success of hypersonic system development. Flight experimentation arguably will play an essential role in the demonstration of propulsion techniques; however, ground demonstration is needed to reduce risk to acceptable levels before flight. Testing hypersonic propulsion systems requires adequate simulation of the flight conditions, representative engine scale (for combustion, mixing, heating, and viscous losses), and sufficient test duration. Because there is no capability to safely flight test actual flight weight systems for true mission duration, a balance must be achieved between test conditions, engine scale, and test duration. Test duration is defined by whether tests are for performance (milliseconds), operability (tens of seconds), or durability (minutes to hours). The size of the engine is directly related to the mixing and combustion processes. By definition, the flow of air inside a scramjet engine is supersonic, so that the corresponding residence time of air and fuel molecules is measured in milliseconds. The scramjet's combustion chamber must be long enough to allow the fuel and the air to mix and burn effectively. If the fuel releases its energy after exiting the back of the vehicle, the scramjet would not produce sufficient thrust to maintain flight. Attempts at scaling combustion processes are seriously compromised by the nonlinearity of chemical reaction times and dissipative processes. Therefore, it is critical that supersonic combustor testing be accomplished at or near full scale. Testing of components in a direct connect mode (where inlets are omitted and the facility flow exits into the combustor) can allow full-scale hardware to be developed in smaller facilities before freejet testing. However, true performance will involve integration with an inlet and nozzle, which would most likely require flight testing.

Thermal Management

The thermal loads on airbreathing hypersonic vehicles are high, growing with (roughly) the cube of the speed. High temperatures on large portions of the airframe structure due to aerodynamic heating and high combustor temperatures are beyond the current capability of high-temperature materials. Therefore, active cooling of many structural components, most likely using the fuel to recuperate heat into the engine, is essential for hypersonic flight. A ground-test facility capable of preconditioning the fuel to the appropriate composition, temperature, and pressure would require roughly 2 MW of power per kilogram of feed fuel.[4]

Aerodynamics

Several hypersonic aerodynamic test facilities exist in the United States and abroad. Complimentary computational techniques benefiting from validated data sets from these facilities have matured to the point where test matrices can be significantly minimized in some instances. However, some regimes stretch the limits of our established data or our capability to obtain new data. Several examples of aerodynamic and aerothermal related challenges are summarized as follows: the influence of propulsion system on aerodynamics, high-speed weapons eject and store separation, integration of seekers and antennas to vehicle aerodynamic designs, highly accurate static stability data, quantification of the effects of reaction control systems, telemetry and communication through ionized shock layers, and plasma effects on drag and flow structure.

The combination of these test requirements will arguably drive aerodynamic test facilities to high-quality, calibrated test environments, better simulation of hypersonic flow physics, and the ability to integrate aerodynamic testing with other subsystem tests.

Materials and Structures

Regardless of the hypersonic system application, concepts will require new materials for thermal protection and airframe/engine development. As an example, the stagnation temperatures of the oncoming airflow approach 2600 K at Mach 8, and the temperatures after combustion inside the engine are more than 3200 K. Internal engine material and structural components will create testing challenges. Material samples will need to be elevated to these high temperatures for a long duration (minutes). Heat soak into structural components must also be measured. Internal cooling schemes such as endothermic fuels could be used to enhance material survivability and durability in this exacting environment. A facility must be able to test for minutes at Mach 8 and a stagnation temperature of 2600 K with preconditioned fuel to provide validation of these components and subsystems.

The materials covering the vehicle and exposed to the hypersonic flowfield (especially on engine cowls, leading edges, and windows/antennas) will need to be validated in these environments. As the integration of engines with airframes progresses, facilities will need to provide some capability for long duration testing at realistic temperatures with increasing scale test articles before flight testing.

Guidance Navigation and Control

The unavoidable challenge of providing guidance, navigation, and control accompany hypersonic flight speeds. Increased reaction time and communication through hypersonic flowfields for target set identification create a unique challenge for the vehicle designers and ultimately the testers.

Guidance and navigation may rely on incoming signal through global positioning system antennas, or active onboard seekers. Obtaining target updates, position, or health monitoring of the vehicle will require communication through a hypersonic flowfield which may be highly turbulent and electrically charged at speeds above Mach 8. To further complicate matters, the antennas and windows must be designed to survive this stressing environment. Testing of these systems will require adequate duplication of flow physics driving the problem, whether on the ground or in flight.

Control of a hypersonic vehicle will require multiple complex aerodynamic control surfaces possibly combined with reaction control or advanced physics, that is, plasma generation, for increased maneuverability or high-altitude maneuver/control. Because of the magnitude of aerodynamic forces and the drag penalties for control surface deflection, control issues will have to be thoroughly understood across the flight spectrum. This will drive the requirement for adequate duplication of flow physics and maintain the need for production data capability. Testing will be driven to larger scales, higher quality data, and improved duplication of certain flow physics.

Weapon-Related Technologies

Delivering a weapon payload at hypersonic speeds presents special challenges. To deliver ordnance adequately at an effective speed would require an endgame maneuver to bring the vehicle into a steep dive and eject the warhead at about Mach 5 to achieve an impact velocity greater than 1200 m/s. This velocity would subject the warhead to a high thermal environment during flight and very high shock loads on impact. Capabilities to validate adequately the weapons eject at high speed and the penetration effectiveness need improvement. For weapons eject, the current capability used for supersonic aircraft, which is a close coupled computational and ground testing capability validated through actual drop tests, should be applied at higher speeds. Several warhead concepts exist. Warheads can be kinetic, using the energy released on impact to damage a target or explosive by detonating energetic material on or after impact or by releasing submunitions to handle multiple targets. Kinetic warheads can be tested in subscale facilities such as ballistic ranges, but difficulties arise with larger scale units. The closest applicable test facilities are supersonic rocket sled tracks. Even these sled tracks are limited, however, by throw weight and energetic explosive limits, as well as the presentation of realistic targets with the proper fidelity to ascertain effectiveness against all target sets and obtain real world authenticity. Currently rocket sleds are also limited to sea-level conditions.

Revolutionary Hypersonic Technologies

The near- and mid-term hypersonic technologies just discussed entail tremendous technical challenges. However, there are far-term hypersonic technologies under consideration that might have even more profound effects on required test infrastructure.

There is an ongoing desire for affordable access to space. Whereas this might be satisfied by relatively conventional scramjets or combined-cycle systems, more radical technologies including pulsed detonation engines, plasma augmented propulsion, and beamed energy may hold the ultimate key. One particularly intriguing concept is the use of available energy within the hypersonic flowfield itself for propulsion. The use of this energy for flow control, drag reduction, offensive energy weapons, or self-protection has been postulated. These and other yet unseen technologies will create further challenges for the test community. Transmission of electrical signals through an electrically charged flowfield, producing stable and repeatable plasmas, and understanding the effects of vehicle-generated energy fields will require updated instrumentation as well as methodologies to understand experimental results.

Discussion

Status of Hypersonic Infrastructure

As already discussed, the need for validated data in the hypersonic regime presents requirements far beyond any experienced in testing to date. These requirements for high-quality data in environments that are difficult to simulate in-ground or in-flight is a fundamental challenge to our hypersonic infrastructure. Vanishing facilities, eroding flight ranges, and skills drain present a challenge. Note that deficiencies in each area are the result of several variables including proper test environment, sufficient test time, or adequate size to permit proper scaling of test data to real systems.

Case for an Integrated Solution

The airbreathing hypersonic system imposes a critical need for the successful integration of modeling and simulation, ground test, and flight test. Moreover, the advancement of these tools to a state where they can be effectively leveraged to provide integrated research, development, test, and evaluation (RDT&E) of hypersonic systems is critical.

According to the recent SAB report on hypersonic technology,[3] "A key factor that has limited the [United States'] ability to sustain development of hypersonics has been the lack of flight test data." To acquire flight-test data requires an integrated, iterative, evolving process of building computational models, ground-test verification, and flight-test validation. Furthermore, integrated RDT&E is a process that continues throughout the system acquisition process, from concept exploration X-planes through developmental test of systems. This concept requires greater use of modeling and simulation (M&S) in test development, leading to more efficient testing and predicting flight results of new concepts. Additional development of computational techniques in conjunction with test technologies needs to be pursued. It bears recognizing, however, that although M&S complements ground and flight testing it is not a replacement.

Modeling and Simulation Option

Accurate modeling of a detailed hypersonic flowfield is complicated by the close coupling between the fluid, chemistry, and structure, as well as some basic unknowns about the governing physics. These unknowns include the structure of shock interactions, boundary-layer transition, chemistry–turbulence coupling, etc. Because these phenomena are poorly understood, in turn limits our ability to model these flowfields computationally. Chemistry and certain unsteady effects can make the governing equations mathematically stiff and, therefore, difficult to solve. Complicating the picture even further, certain fluid structures, including shock waves, are not accurately described by the Navier–Stokes equations. Propulsion efforts are especially hindered by the tremendous challenge of accurately modeling hydrocarbon combustion chemistry in realistic hypersonic flows, which involves independent scalars numbering in the hundreds, in realistic hypersonic flows.

There is general concurrence that hypersonic aerodynamics alone is solvable with a combination of modern computational fluid dynamics (CFD), short runtime duration, high-enthalpy facilities, and limited flight tests. The challenge, however, is in modeling hypersonic propulsion systems and fluid–structure coupling interactions. The short duration runtimes of shock tunnels and impulse facilities cannot be extrapolated to predict actual flight results accurately. The contamination, that is, vitiation, associated with flow facilities obfuscates experimental results and hinders progress in validating CFD results for propulsion systems. Within the experimental community, there is reluctance to believe CFD results validated with data made available before the computational solution is obtained. Nonetheless, recent efforts to compare data-blind CFD results with experiments have been very successful at demonstrating that computational aerodynamic solutions can be accurate and unbiased by the investigator's knowledge of the answer.

The pace of progress in computational efforts is governed by the rate at which new breakthroughs occur in the understanding of the relevant chemistry and physics, as well as advancements in the available speed and memory of computers. Though the latter has followed predictable trends, it is difficult to predict the impact of breakthroughs such as quantum computing. Thus, it is a challenge to determine if there will ever exist a truly reliable computational capability that can completely replace experimental efforts in this realm. In the meantime, any breakthroughs in CFD that do occur will require some amount of test data to validate.

If used properly, CFD can be a strong tool in conjunction with experiments. Computational solutions have the great advantage that aspects of the flowfield can be switched on and off to isolate the mechanism of an observed phenomenon. For instance, chemistry may be turned on in a computed flow to determine its influence, boundary layers may be switched from laminar to turbulent, and perturbations can be introduced in upstream calculations to isolate cause and effect. Computational solutions also permit a flowfield to be assessed without intrusion, and numerical measurements can be made to the resolution of the grid. This capability has been used very effectively to identify details of shock–shock interaction, shock–boundary-layer interactions, supersonic shear layers, and combusting systems that could not possibly be measured experimentally. A particularly promising example is the use of CFD investigations of ionized or electrically charged gases to explain reported aerodynamic and propulsion benefits.

Computational solutions also have many of the same limitations as experimental facilities. For instance, wind tunnels have a difficult time producing reliable time-accurate data; this is also a challenge for CFD. Achieving the correct chemistry in a wind tunnel is difficult, especially for propulsion modeling; CFD has difficulty with chemistry because of computational requirements and the stiff nature of the governing equations. Providing the correct conditions for turbulence is also something that is challenging for both CFD and experiment.

A major advantage of CFD is that flowfields can be calculated for a fraction of the cost required for experimental measurement, though computational times for complicated flowfields can still be considerable. Because of its relatively low cost, CFD can be used to augment experimental data sets, exploring more conditions and cases than experimental constraints would allow. Research organizations also find a strong advantage in pursuing CFD approaches, rather than attempting to build or maintain costly experimental facilities.

For the near future, we maintain that CFD will continue to supplement and enhance testing and evaluation. It is difficult to anticipate the total replacement of testing and evaluation with computational capabilities.

Ground-Test Option

Before the final validation of hypersonic vehicle designs through flight test, risks must be reduced sufficiently to safely conduct the flight test and to assure effective flight of the vehicle. The extreme environments and challenges of hypersonic flight dictate that prudent RDT&E should rely on a combination of different types of ground facilities because no one facility can adequately provide duplication of all salient parameters simultaneously. The duplication of environment, scale, and test duration makes it impossible to satisfy all test objectives in one facility. Therefore, it is critical that programs take advantage of the unique benefits of each type of hypersonic facility and concentrate on integration of test results from multiple facilities. Primarily hypersonic facilities can be grouped into two categories: wind tunnels (conventional, arc-jet, combustion heated, and shock heated) and ballistic ranges and sled tracks.

Above Mach 4, current hypersonic ground-test facilities fall far short of duplicating the flight environment of current and future systems. Hypersonic system developments have been very cyclic over the years. In the 1960s, the United States embarked on an ambitious technology program directed toward hypersonic flight in the Earth's atmosphere. The need for empirical data in the hypersonic flight environment stimulated facility planning and research. Large facilities were given priority in the funding cycles, facility design was begun, and prototype facilities were constructed. Then in the late 1960s and early 1970s, few if any of the proposed major test facilities were ever built, and funds to continue hypersonic facility research significantly decreased. New initiatives, that is, the National Aerospace Plane (NASP) and ballistic missile defense, have encountered this test capability deficiency and have attempted to provide primarily single-purpose facilities that could be made ready in a short period of time to support their programs. Many of these assets are hypersonic facilities, which has helped to preclude the total erosion of capability in hypersonic test and evaluation.

Generally, the facilities required by the NASP initiative could not be developed in time to support the program milestones. This has been a common problem in hypersonic system development. Therefore, we must find innovative ways to link hypersonic science and technology to test and evaluation investment strategies.

Advocates of new large-scale hypersonic system ground-test facilities note ground testing is currently the only means of collecting the quantity and quality of data necessary to achieve this vision (for example, see Ref. 5). They also note the intellectual infrastructure of scientists that understand the requirements to design and construct such large facilities has nearly disappeared and that further delays will mean a new generation of engineers will need to reinvent the wheel. As already stated, for hypersonic propulsion testing, the SAB[1] and NRC[2] observed present ground-test facilities are capable through Mach 7 with a few improvements and recommended addressing facilities for Mach 8 and higher hypersonic systems development.

A new concept ground-test facility has been advocated within the last decade. The facility requires very high-power lasers to heat air compressed to approximately 50,000 atm and provide testing capability at Mach numbers on the order of Mach 16. Many of the facility's enabling technologies have been identified but currently do not exist. Another ground-test major issue is the hydrocarbon fuel system required for a ground-test facility. Note that the amount of heat endothermic fuels absorbs during flight is huge (see Fig. 1[4]). To date, no ground-test facility can condition the fuel to simulate accurately the transient behavior of a hydrocarbon endothermic fuel system throughout the flight envelope. The Air Force designed, built, and tested a relatively modest (0.2 kg/s) endothermic fuel conditioning system to couple with a laboratory-scale scramjet test facility; the equipment lasted through a limited series of tests.[4] Hence, building new large-scale facilities may have unknown challenges from both technical and economical viewpoints.

Flight Test Option

Before the final validation of hypersonic vehicles through flight test, risk must be reduced sufficiently to conduct the flight test safely and to assure that the effectiveness and suitability may be demonstrated in the flight of the vehicle. For hypersonic vehicles, this level of risk reduction will require data unavailable on the ground. Flight experimentation is necessary due to the unavailability of adequate ground-test facilities and computational methods. Hypersonic flight experimentation will serve to obtain these data methodically by isolating variables in the experiment as much as possible. This differs from traditional flight testing where the test article closely resembles the end product, that is, prototype. In flight experiments, the goal is to design an experiment using ground test and modeling that will answer specific questions left open by other methods.

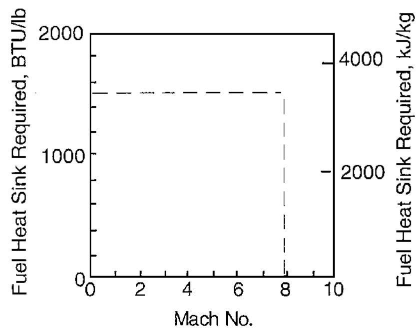

Fig. 1 Heat sink required as a function of Mach number: lower bound, missiles and upper bound, aircraft.

As the hypersonic technologies become progressively more robust, system-level testing will be approached. The final test phase of any new or modified hypersonic vehicle will subject it to rigorous examination of performance and ability to meet the design criteria and successfully accomplish the flight profile (flight test). Test ranges must provide the necessary instrumentation and equipment to verify all of the parameters of the test. Range safety will be a primary concern, especially with flights over inhabited land areas. Environmental impact analysis will need to be extended to cover a larger test range.

For airbreathing hypersonic vehicle demonstrators, some shortfalls exist in the range infrastructure to validate these technologies adequately. Significant questions will have to be addressed concerning many tangible flight-test support issues. Because hypersonic flight-test events will involve extended flight corridors, capabilities for a hypersonic or global test range (permanent data acquisition range) will need to be addressed. Logistical questions such as the storage and production of fuels and availability for adequate hangers will depend on vehicle size and operation of these flight systems. Just as we analyze our ground-test infrastructure, we need to understand the impact of flight ranges. For both mid- and far-term,[3] reusable flight experimentation testbeds are attractive. Returning a hypersonic vehicle safely to a range, recovering the instrumentation, data, and vehicle, and obtaining the necessary approvals and coordination will present challenges.

Hypersonic vehicles, by their nature, will push the envelope of test range resources. Range instrumentation was originally site based and has recently evolved to systems that are more mobile. However, hypersonic systems may well require a different approach to be examined for vehicles covering long distances at the fringes of the atmosphere. Issues of vehicle control, telemetry, position, and flight termination systems must be addressed. One possibility is the global range concept that envisions relaying range requirements through air- or space-based assets.

Whereas the hypersonics community agrees experimental data are required, there is disagreement as to how much data is required, and whether existing hypersonic facilities coupled with computational predictions and limited flight-test data is sufficient. Arguably, the SAB[1] and NRC[2] studies regarding hypersonic ground-test facilities were fundamentally flawed because they assumed data are required throughout the flight spectrum. This would be the case if flight test alone is to provide validated risk reduction for a hypersonic system. When flight tests are used in conjunction with validated models and carefully chosen ground test points in validated facilities, the flight-test data requirement may be reduced. Data may only be required for a limited number of validation points, and flight experimentation may satisfy this need more inexpensively than ground testing. Unfortunately, we may be currently too adverse to risk supporting an inherently very high-risk flight-test program. Note that the X-7 program (testing the Bomarc Mach 3, 300-mile range ramjet) built some 60 vehicles, and 130 flights were logged from 1951 to 1960.[6]

Near-term needs for experimental data for validating design tools may be met using data from NASA flight tests, such as Hyper-X (X-43) and X-43 follow-on missions, possibly powered by hydrocarbon scramjet engine. Requirements further out can be met in a similar fashion. The Hyper-X programs may be the ideal design process, where significant modeling is coupled with ground testing in existing facilities and empirical corrections that are believed to be very accurate. The risk associated with these programs may be less than that associated with a large hypersonic facility.

Conclusions

Although experts may disagree on the best way to safely and efficiently develop a hypersonic vehicle, it is clear, however, that a truly revolutionary, design optimized vehicle will require significant data to truly understand the physics of hypersonic flight. Today we are at a crossroads where the intellectual corporate memory that built the infrastructure that put the men on the moon and the space shuttle into orbit may all be retired and gone before we have clearly defined a need for a hypersonic vehicle, and we cannot afford to reinvent the wheel. If we are to succeed in the long term, we need to maintain our existing hypersonic infrastructure and to find innovative ways to use this investment in infrastructure to accomplish science and technology goals. This will undoubtedly involve the integration of validated CFD and flight experimentation. Evolutionary vehicles such as NASA's Hyper-X should be developed with a combination of minor facility upgrades, CFD, and flight testing. Ultimately, the best chance to achieve this vision may rely on a basic research breakthrough or a discovery that has yet to be realized.

References

[1] "Requirements for Hypersonic Test Facilities," U.S. Air Force Scientific Advisory Board, Vol. 1, Study Rept., May 1989.

[2] "Review and Evaluation of the Air Force Hypersonic Technology Program," National Research Council's Air Force Science and Technology Board, 1998, URL:http://www.nap.edu/html/hypersonic/.

[3] "Why and Whither Hypersonics Research in the US Air Force," U.S. Air Force Scientific Advisory Board, SAB-TR-00-03, Dec. 2000, URL: http://www.sab.hq.af.mil/Archives/index.htm.

[4] Maurice, L. Q., Edwards, J. T., and Griffiths J. F., "Liquid Hydrocarbon Fuels for Hypersonic Propulsion," *Scramjet Engines*, Progress in Aeronautics and Astronautics, Vol. 189, AIAA, Reston, VA, 2000, pp. 757–822.

[5] Paull, A., and Stalker, R. J., "Scramjet Testing in the T3 and T4 Hypersonic Impulse Facilities" *Scramjet Engines*, Progress in Aeronautics and Astronautics, Vol. 189, AIAA, Reston, VA, 2000, pp. 757–822.

[6] Curran, E. T., "Scramjets Engines: The First Forty Years," *Journal of Propulsion and Power*, Vol. 17, No. 6, 2001, pp. 1138–1148.