Comparison of HYPER-X Mach 10 Scramjet Preflight Predictions and Flight Data

Paul G. Ferlemann*
Swales Aerospace, Inc.
NASA Langley Research Center, Hampton, VA, 23681

The third X-43 vehicle in the HYPER-X program targeted flight at Mach 10. The successful flight test was an important demonstration of many hypersonic technologies. The performance of the scramjet engine is a primary example. In order to maintain control of the vehicle, the axial and normal forces and pitching moment induced by the propulsion system had to be predicted accurately. The computational fluid dynamic codes used in this process will be described. These codes were used to build a database around the intended flight conditions. The same codes were also used in a consistent approach to wind tunnel test data analysis. The engine performance deduced from wind tunnel testing of the X-43 Mach 10 engine will be discussed. Comparisons with flight data will be used to illustrate the accuracy of preflight predictions.

I. Introduction

NASA developed the concept for the HYPER-X program based on recommendations that flight demonstrations of airframe-integrated scramjet propulsion systems be the next major step in hypersonic research. In order to reduce cost, an existing configuration based on a Dual-Fuel Global Reach vehicle was selected.[1] This vehicle was designed to cruise over 8,000 nautical miles at Mach 10, using a scramjet from Mach 4 to 10. It was a hypersonic cruise lifting-body configuration. As a result, it used a relatively small percentage of the cross section for the propulsion system, in comparison with an accelerator where the dominant design characteristic is low drag per unit inlet capture. Program requirements specified that the vehicle would resemble the Global Reach vehicle, be controllable through powered and unpowered flight, have positive acceleration at Mach 7, and demonstrate cruise at Mach 10. However, since the HYPER-X program would use a subscale vehicle, the engine was redesigned rather than photographically scaled.

The final vehicle in the HYPER-X flight test program flew at record breaking speed on November 16, 2004. The flight met all mission objectives; remaining very well controlled and achieving powered scramjet operation at Mach 9.6. The cowl door was open for over 19 seconds and the fueling sequence required just over 11 seconds. During this time (or 14.5 miles fuel off and 20 miles fuel on) an enormous amount of information was acquired. The mechanical cowl door actuation, ignitor, and hydrogen fuel systems performed as expected. Vehicle surface pressure measurements, axial and normal acceleration, and wing trim positions have been compared with preflight expectations. This paper will summarize the engine design process, engine testing, data analysis of wind tunnel tests, creation of the flight vehicle propulsion database, and comparison with flight data.

II. Initial X-43 Mach 10 Engine Design Process

Designing an engine which could produce enough thrust to equal airframe drag on a subscale version of a Mach 10 cruise vision vehicle was very challenging due to many features which can not be scaled photographically. In addition, a large number of constraints were imposed on the engine since the vehicle was already defined. However, since an experimental aerodynamic database existed, designs could be evaluated based on trimmed net axial force. Since there were a large number of design variables, a two stage analytical approach was used to define the initial flowpath and fuel injection system. The first stage was accomplished with SRGULL.[2] SRGULL is the tip-to-tail cycle analysis tool used in the HYPER-X program. The fidelity of these cycle analysis solutions was increased by using information from other analysis tools and experiments. These inputs included: three dimensional spillage, kinetic energy efficiency penalty, combustion efficiency, and base pressure. In order to understand sensitivities to flight condition, the flight Mach number, angle of attack, and dynamic pressure were included along with five

* Research Engineer.

Copyright © 2005 by the American Institute of Aeronautics and Astronautics, Inc.
The U.S. Government has a royalty-free license to exercise all rights under the copyright claimed herein for Governmental purposes.
All other rights are reserved by the copyright owner.

geometry variables. Following construction of the database, additional constraints were imposed such as; combustor entrance pressure, angle of attack based on forebody shock positions, combustor geometry, and similarity with the HYPER-X Mach 7 engine. The result was an understanding of vehicle level sensitivities to major design variables and a preliminary engine flowpath. The engine flowpath includes the vehicle external lower surface, and body and cowl internal surfaces. The second stage in the initial design effort focused on fuel injector and combustor design variables. GASP[3] was used to model the forebody and inlet and SHIP[4] was used to model the fuel injectors, combustor, and nozzle. Propulsion forces and moment were again combined with the vehicle aerodynamic database so that design decisions could be based on trimmed vehicle net axial force rather than a component performance metric such as fuel mixing efficiency. Thermal analysis was performed on the thrust optimized design to verify that it could survive several seconds of exposure to Mach 10 enthalpy flow with and without hydrogen fuel. The result was a completely defined engine flowpath and fuel injection system which could be built and experimentally tested.

III. Mach 10 Engine Wind Tunnel Testing

A. Initial Engine Testing

The engine was tested in the HyPulse reflected shock tunnel in three test entries from the middle of 1999 through late 2000.[5-7] Separate tests were conducted with a silane-hydrogen mixture, to simulate piloted operation, and pure hydrogen. For all test conditions the silane fuel mixture provided more robust operation. Test information from the LENS reflected shock tunnel also showed a sensitivity to fuel composition. Although an ignition sequence would eventually be incorporated for the flight test (which could not be wind tunnel tested) the program desired that hydrogen-only ignition be as robust as possible, and this was included in the overall design approach. As a result, the design was modified to improve hydrogen-only ignition based on engineering experience. This became the final design for the X-43 Mach 10 flight vehicle. Therefore, design of the engine flowpath used a great deal of scramjet design experience and a very complimentary computational and experimental effort.

B. Final Engine Testing

The final design of the X-43 Mach 10 engine was tested in the HyPulse and LENS reflected shock tunnels. The HyPulse scramjet model was a full-scale height, partial width engine model with truncated forebody and aftbody sections.[8] It was tested in a semi-direct-connect arrangement at 8 test conditions. These tests included Mach 9 total enthalpy conditions, Mach 10 total enthalpy conditions at 6 different model mounting angles and cowl leading edge positions to vary the combustor entrance properties, and tests with slightly greater than Mach 10 total enthalpy. A total of 55 runs were completed where 9 were without fuel injection, 20 with hydrogen only, 24 with 2% silane by volume, 1 with 1% silane, and 1 with 20% silane at low fuel equivalence ratio to model the flight fuel sequence prior to starting the hydrogen.

The LENS scramjet model was a full-scale height, width, and length replica of the X-43 Mach 10 flight engine. It was tested in a free-jet configuration with the facility nozzle producing Mach 10 flight freestream conditions. These tests included a range of dynamic pressure at 1° angle of attack and an angle of attack of 2° at the nominal dynamic pressure. A total of 20 runs were completed where 3 were without fuel injection, 2 mixing (hydrogen into nitrogen test gas), 5 with cold hydrogen, 3 with heated hydrogen, 5 with 2% silane, and 2 with 5% silane.

C. Wind Tunnel Test Data Analysis

A consistent computational data analysis methodology was applied to every experimental test. GASP was used to model the forebody and inlet sections. Two dimensional solutions were possible since the tests used a modified forebody to minimize three dimensional effects. Blunt leading edge effects were included and an elliptic solution approach was used for the inlet to capture any shock-induced boundary layer separation. SHIP was used to model the flow from the combustor entrance to the end of the model. SHIP calculates the fuel mixing process and mixing efficiency (η_m). However, the amount of reaction is controlled by a reaction efficiency (η_r) profile, or variation with combustor length. Combustion efficiency (η_c) is then defined as: $\eta_c=\eta_m \bullet \eta_r$. Therefore, with the combustion efficiency for each test based on the test conditions and pressure rise, and the computationally predicted mixing efficiency, a reaction efficiency model was developed based on experimental results. This solution approach was fast, robust, and the thermodynamic properties of the fuel and combustion products were easily modified; thereby greatly simplifying combustor analysis with silane. The discrete comparison with pressure levels in the combustor was used to determine the reaction efficiency profile while the reaction efficiency at the combustor exit was determined by matching the integrated internal nozzle pressure force.

The analysis of wind tunnel engine test data indicated a reaction efficiency sensitivity to combustor entrance pressure and velocity. Therefore, a functional model was created to define combustor reaction efficiency over the desired flight vehicle propulsion database design space. The range of this database (intended to be greater than boost trajectory uncertainty) and the resulting range in combustor entrance pressure and velocity is shown as the large box in Figure 1. The black circles indicate the various conditions achieved in the wind tunnel test program. The color shading indicates the model developed from the wind tunnel test data analysis. Although no wind tunnel test data was collected toward the high velocity edge of the design space, results with the available data suggested a fairly significant decline in performance at high inflow velocity and low pressure. This was not unexpected considering the small scale of the X-43 vehicle and the ranges of the design space. The range of expected combustor entrance properties based on the final trajectory uncertainty is shown as a dashed red box. The combustor entrance pressure and velocity condition achieved in the flight test is shown as a yellow diamond just inside the low velocity edge of the design space where good reaction efficiency was expected.

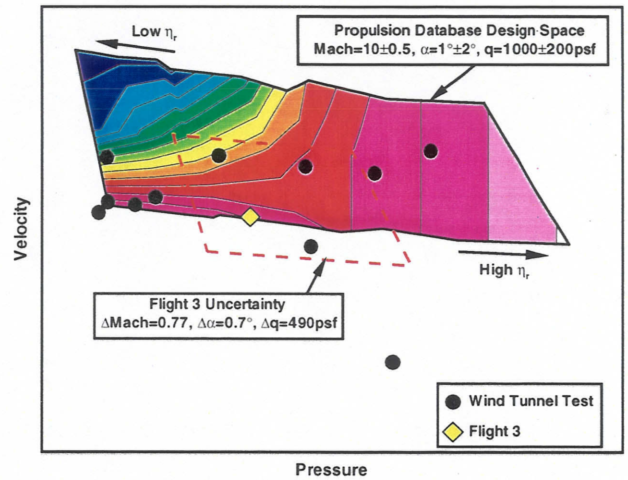

Figure 1. Combustor performance model development.

IV. Flight Vehicle Propulsion Database Development

A. Objective

The purpose of the flight vehicle propulsion database was to provide engine mass capture, propulsion surface forces (axial and normal), and propulsion surface moment over a design space of Mach 9.5 to 10.5, angle of attack -1° to 3°, and dynamic pressure 800 to 1200 psf for both unfueled and fueled conditions. This information was used for flight vehicle simulation and control law development. As shown in Figure 2, the propulsion surfaces include the internal flowpath and the external nozzle when the cowl door is open.

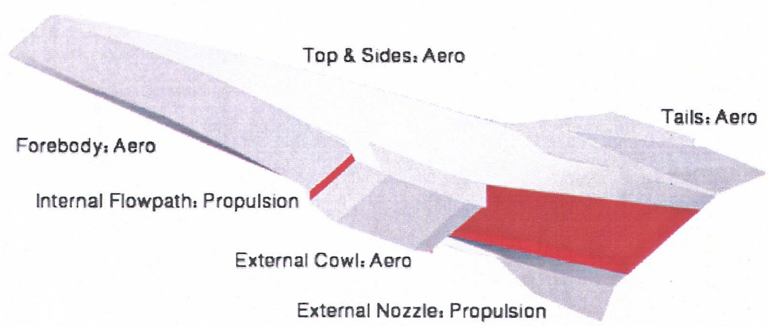

Figure 2. HYPER-X cowl open force accounting.

B. Preflight Propulsion Database Construction

The flight vehicle propulsion database was created with the same computational techniques (GASP and SHIP) as the wind tunnel test engine data analysis. It included two dimensional forebody and inlet solutions and a narrow three dimensional slice through the center of the combustor and nozzle. The effect of three dimensional spillage was imposed at the combustor entrance by decreasing the flow rate of mass, momentum, and energy. In order to capture the possible flight test conditions and different fueling levels the preflight propulsion database variables were: flight Mach number, angle of attack, dynamic pressure, fuel equivalence ratio, and combustor performance. Although analysis of wind tunnel test engine data produced a reaction efficiency model, including an independent combustor performance variable in the propulsion database was valuable for several reasons. First, it allowed the construction of the flight database to be done in parallel with wind tunnel engine testing, before all of the analysis was even complete. Second, sensitivities of all desired output variables could be quantified and assessed relative to the other independent variables. Finally, it allowed the flight combustor performance to be calculated from the change in axial force produced by the flight test scramjet engine and compared with the combustor performance model (i.e., wind tunnel test combustor performance).

C. Database Characteristics

The matrix of CFD solutions used to create the flight vehicle propulsion database provided a large amount of information. In addition to the forces and moment on the propulsion surfaces, functions were created for: boundary layer properties at various locations, cowl leading edge properties, combustor entrance properties, forces and hinge torque on the cowl door, forebody shock positions, and surface pressure at every centerline pressure gauge location on the flight vehicle. Since the functions for the majority of these quantities were a very good fit to the computational database points, they could be used to make predictions throughout the database design space with confidence.

V. HYPER-X Mach 10 Flight Propulsion Test

A. Overview

Following the HYPER-X Launch Vehicle boost, the X-43 research vehicle separated from the adaptor. For the next 2.5 seconds the vehicle targeted the desired angle of attack for the engine test with the cowl door still closed. At 2.5 seconds the cowl door opened and the vehicle continued to target the desired engine test conditions for 3 seconds before starting the engine fueling sequence. The angle of attack variation and fuel flow rate sequence are shown in Figure 3. The engine fueling sequence was designed to produce fuel composition and overall fuel levels similar to what had been tested in the engine wind tunnel test program. In order to achieve this with the amount of fuel available, the ignitor gas and hydrogen were brought to high levels quite quickly. A step in the hydrogen flow rate then produced the next level of overall fueling and changed the total fuel composition since the ignitor flow rate did not change. During the relatively gradual transition to hydrogen-only operation the hydrogen flow rate increased to maintain the same overall fuel equivalence ratio. The hydrogen flow rate then decreased to a level where much of the wind tunnel test engine data had been collected for a fairly long steady period. Finally the flow rate decreased as the tanks emptied before the fuel valves closed. The angle of attack variation shows that the vehicle remained very well controlled at all times and recovered from the fuel-off disturbance very quickly. The cowl open duration was approximately 50 times longer than the sum total of all the final engine wind tunnel testing.

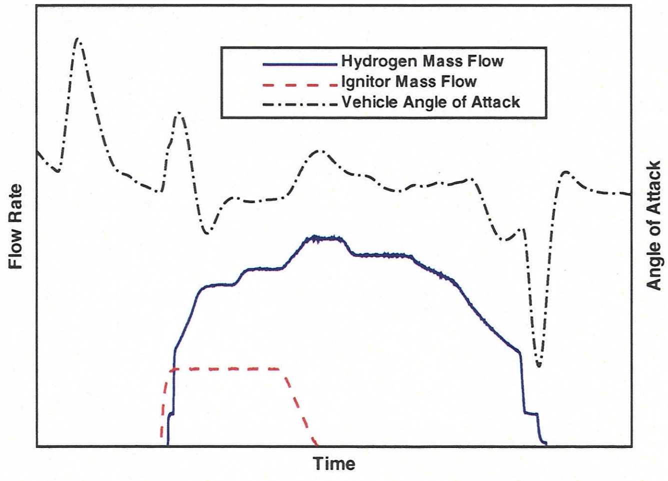

Figure 3. Flight angle of attack and fuel sequence.

B. Measured Surface Pressure

The X-43 flight vehicle had 125 pressure gauges on the lower body surface. These measurements can be triangulated to form shaded contour plots. The triangulation process only interpolates between the available measurement locations so the entire surface can not be shown. The surface pressure measured before starting the fuel sequence is shown in Figure 4. The pressure increases as the flow moves down the forebody and into the inlet. The supersonic flow continues through the engine and expands in the nozzle. Figure 5 shows the fuel-on pressure distribution. In comparison with Figure 4, the pressure is significantly higher in the combustor, internal nozzle, and over the entire aftbody.

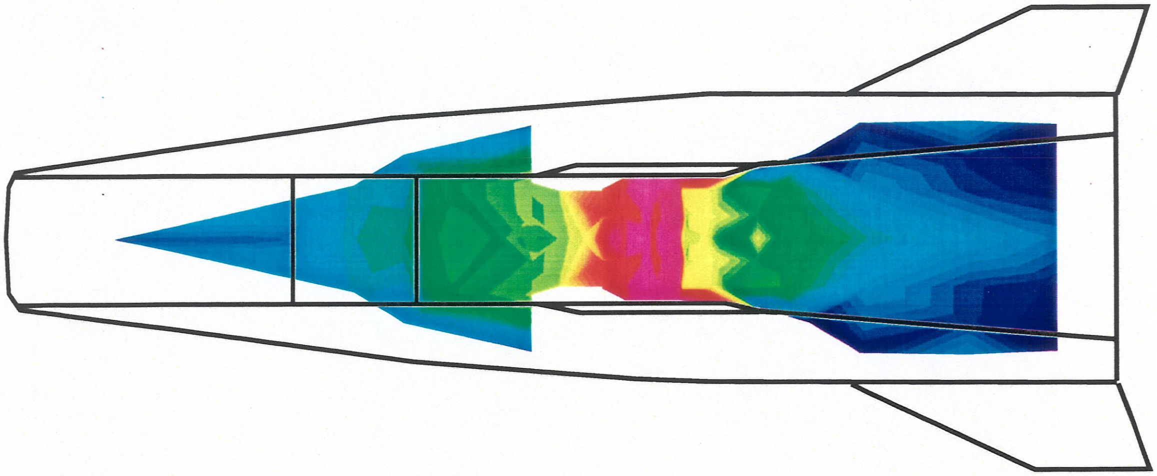

Figure 4. Fuel off flight surface pressure distribution.

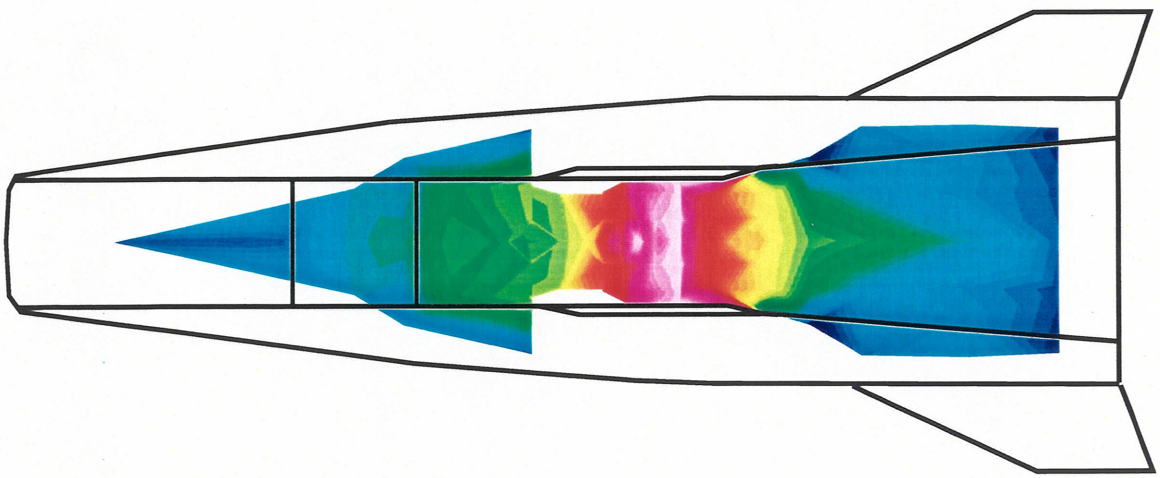

Figure 5. Fuel on flight surface pressure distribution.

C. Comparison With Propulsion Database

1. Discrete Pressure Instrumentation

The CFD solutions used to create the propulsion database were also used to create a database of surface pressure at every centerline pressure gauge location on the flight vehicle. As a result, the pressure distribution could be predicted at any flight condition in the design space using CFD based functions. Most of these functions were a very good fit to the database. However, due to the shock dominated nature of the flow in the engine, the pressure at some locations could not be modeled in functional form with high confidence. The forebody and aftbody functions were also adjusted to account for three dimensional effects. Comparisons with fuel-off and fuel-on data are shown in Figure 6. The fuel-off comparison is an important validation of the numerical models and solution methodology without the complexity of fuel injection and combustion. The fuel-on comparison is an important validation for the numerical models and solution methodology used for wind tunnel engine data analysis and for the testing of scramjet engines in pulse facilities (upon which the flight combustor performance model was based).

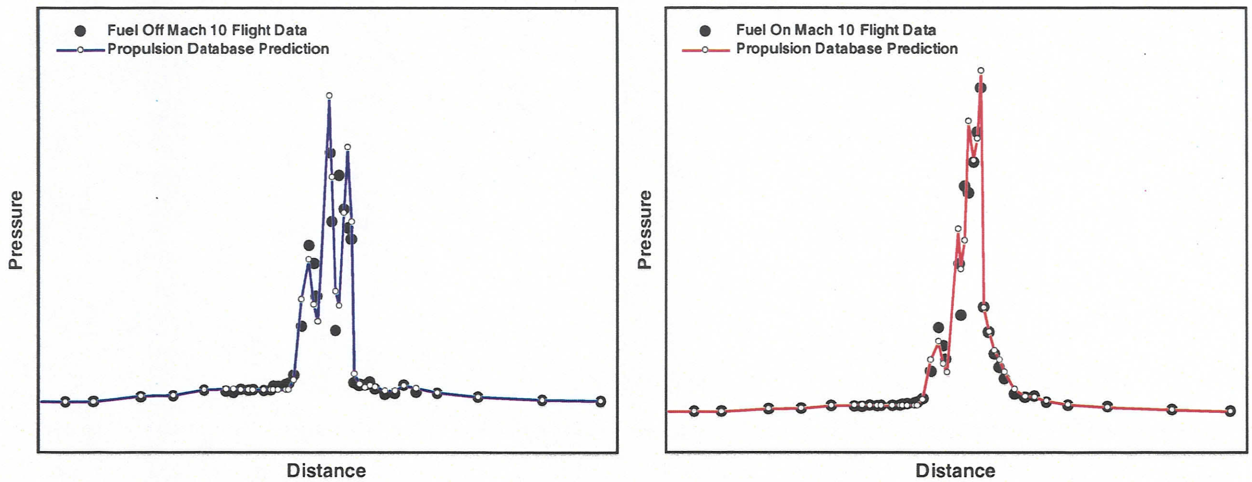

Figure 6. Fuel off and fuel on pressure comparisons (pressure not to scale).

2. *Propulsion Forces and Moment*

The difference between the fuel-on and fuel-off forces and moment can be compared between the flight data and propulsion database functions to determine how well the effect of introducing fuel into the engine was predicted. The net trimmed vehicle axial force followed the trends in the fuel schedule and produced an increase in axial force well within the database uncertainty. The increase in lift was also predicted extremely well. The increment in wing position required to trim the vehicle was less than expected. The difference may have been caused by three dimensional effects not captured in the propulsion database development methodology or in the vehicle force accounting. In addition, there was no preflight experimental pitching moment data at Mach 10 when the cowl was open.

VI. Conclusion

The HYPER-X program's third flight vehicle demonstrated successful air-frame integrated scramjet operation and vehicle control at hypervelocity conditions. Since the scramjet performance showed good agreement to preflight expectations it serves as an important validation of propulsion testing in pulse facilities and in the computational techniques used to understand wind tunnel test data. In addition, since cruise capability has been demonstrated at the design cruise Mach number of a vision vehicle, it shows that a vehicle could be designed to accelerate through Mach 10 using an airbreathing engine.

Acknowledgments

The author would like to thank the entire HYPER-X team for their contributions toward the successful flight and scramjet propulsion demonstration. Special thanks go to Randy Voland and Larry Huebner for leading the HYPER-X propulsion team, Shelly Ferlemann for the SRGULL calculations, Robert Bittner for finite rate kinetics and aerodynamic database analysis, Vince Cuda for fuel injector thermal analysis, Glenn Bobskill for the propulsion database GASP calculations, Tom Jentink and Ben Meyer for many GASP calculations at wind tunnel and flight conditions, and Clay Rogers, Ann Shih, and David Witte for their work on the engine wind tunnel test program. All work performed by the author was supported through contract NAS1-00135 with the HYPER-X Program Office at the NASA Langley Research Center.

References

[1]Hunt, J.L., and Eiswirth, E.A., "NASA's Dual-Fuel Airbreathing Hypersonic Vehicle Study," AIAA Paper 96-4591, 7th International Space Planes and Hypersonics Systems & Technology Conference, Norfolk, VA, 18-22 November 1996.

[2]Pinckney, S.Z., Ferlemann, S.M., Mills, J.C., and Bass, L.S., "Program Manual for SRGULL version 2.0," HYPER-X Program Office Document HX-829.1, December 2004.

[3]McGrory, W.D., Slack, D.C., Applebaum, M.P., and Walters, R.W., GASP Version 2.2, The General Aerodynamic Simulation Program, Aerosoft Inc., 1993.

[4]Kamath, P.S., Mao, M.M., and McClinton, C.R., "Scramjet Combustor Analysis with the SHIP3D PNS Code," AIAA Paper 1991-5090.

[5]Bakos, R.J., Tsai, C-Y., Rogers, R.C., and Shih, A.T., "The Mach 10 Component of NASA's HYPER-X Ground Test Program," ISABE-99-7216, September, 1999.

[6]Bakos, R.J., Tsai, C.-y., Rogers, R.C., and Shih, A.T., "HYPER-X Mach 10 Engine Flowpath Development: Fifth Entry Test Conditions and Methodology," AIAA Paper 2001-1814, 10th International Space Planes and Hypersonic Systems and Technologies Conference, Kyoto, Japan, 24-27 April 2001.

[7]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, 37th Joint Propulsion Conference, Salt Lake City, Utah, 9-11 July 2001.

[8]Rogers, R.C., Shih, A.T., and Hass, N.E., "Scramjet Development Tests Supporting the Mach 10 Flight of the X-43," AIAA Paper 2005-3351.