

Hyper-X Mach 7 Scramjet Design, Ground Test and Flight Results

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The successful Mach 7 flight test of the Hyper-X (X-43) research vehicle has provided the major, essential demonstration of the capability of the airframe integrated scramjet engine. This flight was a crucial first step toward realizing the potential for airbreathing hypersonic propulsion for application to space launch vehicles. However, it is not sufficient to have just achieved a successful flight. The more useful knowledge gained from the flight is how well the prediction methods matched the actual test results in order to have confidence that these methods can be applied to the design of other scramjet engines and powered vehicles. The propulsion predictions for the Mach 7 flight test were calculated using the computer code, SRGULL, with input from computational fluid dynamics (CFD) and wind tunnel tests. This paper will discuss the evolution of the Mach 7 Hyper-X engine, ground wind tunnel experiments, propulsion prediction methodology, flight results and validation of design methods.

Nomenclature

AHSTF	=	Arc-Heated Scramjet Test Facility
AOA	=	angle of attack
Beta	=	angle of sideslip
CFD	=	computation fluid dynamics
DFRC	=	Dryden Research Center
HSM	=	HYPULSE Scramjet Model
8-ft HTT	=	8-foot High Temperature Tunnel
HXEM	=	Hyper-X Engine Model
HXFE	=	Hyper-X Flight Engine
HYPULSE	=	Hypersonic Pulse Facility
LaRC	=	Langley Research Center
Psf	=	pounds per square foot
Qbar	=	dynamic pressure
X-43	=	vehicle NASA experimental designation for Hyper-X

I. Introduction

Man has long strived to go faster and farther. The NASA LaRC-DFRC led Hyper-X program was designed to advance technologies for vehicles utilizing hypersonic airbreathing propulsion - taking it from the laboratory to flight environment. The X-43 flight vehicle brings together many coupled hypersonic technologies for the first time - technologies that do not have to be integrated for most wind tunnel tests. The overarching objective was to achieve confidence in the highly integrated set of hypersonic technologies to allow development of

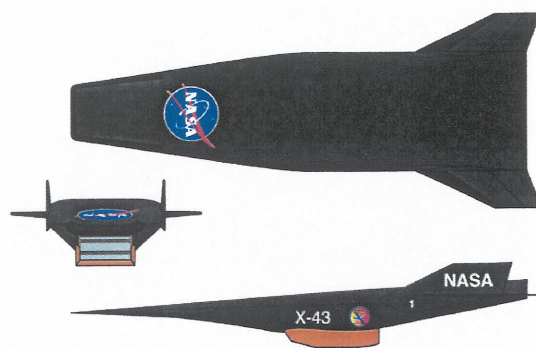


Figure 1. X-43 Vehicle Configuration.

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§ Hyper-X Propulsion Lead Flights 1 and 3.

partially airbreathing hypersonic vehicles to allow safer, more reliable, affordable, responsive and operationally flexible space launch. The Hyper-X team designed and developed the X-43 as a small-scale, hydrogen-fueled research vehicle based on the Dual-Fuel, Global-Reach long-range strike vehicle¹. Three tests were planned: two at Mach 7 (because of program risk) and one at Mach 10. The final design and fabrication of these vehicles were performed by a contractor team led by MicroCraft that includes The Boeing Company and GASL, Inc. Figure 1 shows the X-43 sharp-nose lifting body research vehicle configuration with an airframe-integrated scramjet engine.

The program started in 1996, the first vehicle was delivered to DFRC in 1998, and the first flight was attempted in 2001. The first attempted flight was unsuccessful due to a booster anomaly². The second flight of the X-43 was successfully completed in March 2004. As shown in the nominal flight envelope, Figure 2, the X-43 is dropped from the NASA DFRC B52 and boosted to the test altitude using the first stage of a Pegasus rocket. After the X-43 separated from the booster, the cowl door opened, and after a few seconds of tare (unfueled), the fuel was turned on and the scramjet powered experiment began. After the engine test concluded, the cowl was closed and the aerodynamic experiment was performed during the 15 min. of descent. All phases of the flight were performed as planned². This paper concentrates on the engine development, and validation of the analytical and experimental procedures used to design and develop the Mach 7 airframe-integrated scramjet engine.

II. Mach 7 Engine Design

A. Design Approach

The X-43 vehicle was derived from the dual-fuel Global-Reach Mach 10 cruise vehicle³. Clearly the X-43 vehicle cannot be photographically scaled from the 200-foot long vision vehicle. A complex design process was followed which incorporated analytical, numerical and experimental tools⁴. First, the minimum acceptable engine length was determined using an analytical three-stream finite rate chemical kinetics code (SCRAM3L)⁵. That code determined the reaction efficiency for progressively smaller engines using a "full" hydrogen-air finite rate chemical kinetics mechanism coupled with approximated mixing limited flow. These solutions showed that the full-scale engine could be photographically scaled to less than 12 feet, only losing about 5% in combustion efficiency. However, going to a smaller scale became problematic, so the 12-foot length was selected. The next task was to refine the engine flowpath at the 12-foot length to gain back losses due to the viscous-dominated flow: i.e. high shear forces at low unit Reynolds number and over contraction caused by increased relative boundary layer displacement thickness. These design investigations were performed with the SRGULL⁶ hybrid analytical-numerical computer program. Next, parallel efforts with computational fluid dynamics (CFD) and experimental tests were performed to provide additional information to the SRGULL code, and check the scramjet operability. CFD was included to assess three-dimensional mass spillage in the inlet and nozzle, and some preliminary estimates of fuel mixing efficiency. Experimental tests of the engine module were performed to verify/quantify combustion efficiency and engine operability. These tests were performed in multiple facilities^{4,8} to assure that the information was not misleading due to contaminant or other test facility related effects.

B. SRGULL Propulsion Code

The Mach 7 engine conceptual design, ground test data analysis, flight predictions, and flight data analysis were performed using an integrated engine performance analysis code called SRGULL. The SRGULL program was developed at the NASA LaRC to provide an accurate and consistent engineering simulation of the complex airframe integrated scramjet engine loads and performance. Compared to other engine cycle codes which require operator estimates of numerous physical phenomena, the SRGULL code utilizes a family of codes to predict most flow phenomena, such as inlet mass capture, boundary layer (shear, heat flux and boundary layer transition), inlet kinetic energy efficiency, isolator performance, combustor distortion, nozzle expansion and divergence losses. The code

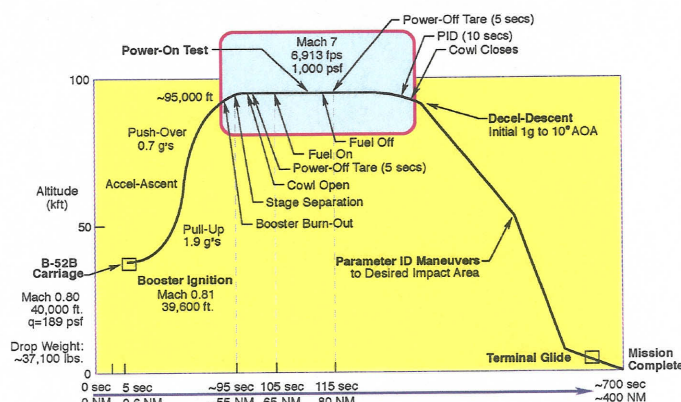


Figure 2. Nominal Mach 7 Flight Profile.

uses a 2-D Euler calculation on the forebody and inlet, coupled with an integral boundary layer solution, to predict the forebody/inlet drag and the flow properties entering the engine. The ramjet/scramjet solution continues with a 1-D multiple step, equilibrium chemistry cycle analysis through the isolator and combustor. Finally, the nozzle forces are resolved using the 2-D Euler and boundary layer codes with a frozen ratio of specific heats. Finite rate chemistry, mixing, and 3-D effects are modeled through parameters calibrated to CFD solutions and ground test data⁷. The primary input for the SRGULL code are engine geometry, boundary and initial conditions and some empirical parameters used to correct known limitations in the analysis. The SRGULL code allows an accurate assessment of performance for any ramjet, scramjet, rocket based combined cycle, or ducted rocket. The code works over the (Mach 2 to 25) speed range, and can generate solutions in a few minutes on a Personal Computer, compared to a few weeks to months with classical CFD codes. In addition, the code accurately predicts inlet unstart (operability), propulsion lift and pitching moments, thermal and pressure loads, and fuel temperature for regeneratively cooled engines. SRGULL was used in the design of the flight engine, analysis of the ground tunnel data, prediction of flight performance, and analysis of flight data.

III. Wind Tunnel Testing

A roadmap of the Mach 7 experimental test program is presented in Figure 3, and involves three engine models in three facilities from NASA LaRC's Scramjet Test Complex⁸. The facilities used are the shock heated Hypersonic Pulse Facility (HYPULSE), the Arc-Heated Scramjet Test Facility (AHSTF), and the combustion heated 8-Foot High Temperature Tunnel (8-ft HTT). The engines tested are the HYPULSE Scramjet Model (HSM), the Hyper-X Engine Model (HXEM), and the Hyper-X Flight Engine (HXFE). These facilities and engines allow an integrated test program to isolate and measure the effects on the engine operability and performance caused by geometric-scale, dynamic-pressure, and test-gas differences between tests. These differences, encircled in Figure 3 exist due to test technique and facility limitations. The effects of these differences were accounted for in the design and analysis methodologies as an integral part of vehicle/engine design and selection of flight test condition and fuel/igniter schedules. Representative test results were evaluated using SRGULL to determine combustion efficiency, and to quantify test methodology impact on combustor performance.

A total of 710 engine tests were performed to support the X-43 Mach 7 flight test. All of the tests were full scale in flow path height between the internal body and cowl surfaces. The HXFE was a full-scale in length, height and width, but the HSM and the HXEM were partial length and width. Since the X-43 configuration is a quasi-two-dimensional configuration, partial width was considered to be a good representation of the full engine. Of course, differences due to corner effects are more dominant for partial width engines. Partial length is the normal approach to testing scramjet engines - vis-à-vis a module with a simulated forebody inflow boundary layer. Early tests of the X-43 engine were done in the AHSTF because of its low cost operation. Minor design changes were made as a result of these early tests. The final design was then tested in electric arc-heated, combustion heated and shock heated flows to identify any facility effects on performance and/or operability. The final configuration was also tested at full scale, including width and length using a spare flight engine mounted on a full representation of the vehicle underside. Figure 4 shows a representation of the final engines that were tested in each facility.

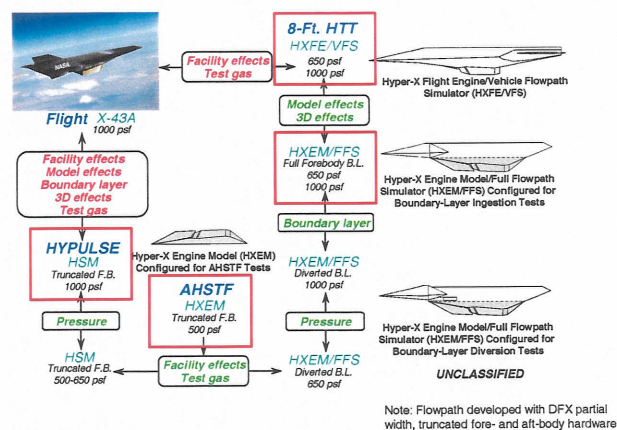


Figure 3. Hyper-X Mach 7 Ground Test Program.

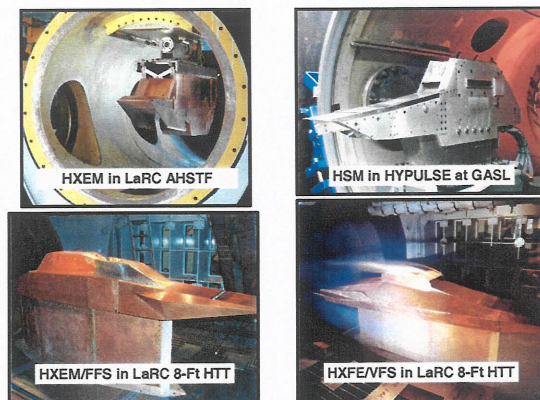


Figure 4. Hyper-X Ground Test Engines.

The HXFE test was also designed to provide flight engine control development and demonstration. Many tests were performed on the HXFE: including engine unstart, engine fueling profile, angle of attack and sideslip. Figure 5 shows the centerline pressure distribution from an HXFE tunnel test along with the resulting SRGULL analysis of the data. This SRGULL analysis was used to identify test combustion efficiency and validate the SRGULL isolator model. Similar analyses of data from the HXEM and HSM provided alternate estimates of combustion efficiency. Facility to facility variation were on the order of 10%. This uncertainty was carried to flight in the scramjet performance database.

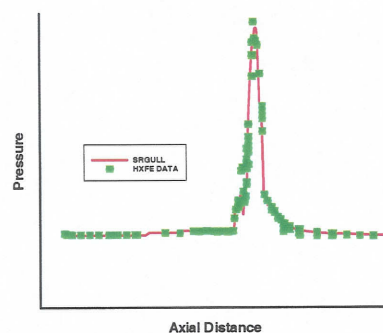


Figure 5. SRGULL Analysis vs. HXFE

A. CFD Analysis

Three-dimensional (3-D) CFD was used throughout the design process⁹. Solutions were obtained using both GASP¹⁰ and Vulcan¹¹. Some of these were performed in Euler mode, but most also modeled viscous effects. Multiple 3-D forebody solutions, and a few complete "tip-to-tail" solutions were acquired around the Mach 7 flight condition, and at wind tunnel test conditions. The forebody solutions were used to quantify inlet mass capture and inlet efficiency at various vehicle flight conditions (AOA, Beta, Mach, Qbar) to improve the predictions made by 2-D SRGULL code and wind tunnel test measurements. These improvements are input as corrections to the SRGULL inlet solutions. Figure 6 shows the 3D view of the powered tip-to-tail solution with axial planes of Mach number contours and the surface shaded by heat transfer (1-12 BTU/ft² range.) CFD was also used to model the nozzle flow field, and provide 3-D and finite rate chemical kinetics corrections to the SRGULL 2-D/frozen chemistry nozzle prediction. CFD investigations showed pressurized combustion products spilling over the nozzle chine. As it turned out, this divergence loss matched the chemistry gain from continued reaction and chemical recombination. Therefore, the nozzle forces and moments predicted by SRGULL were not corrected.

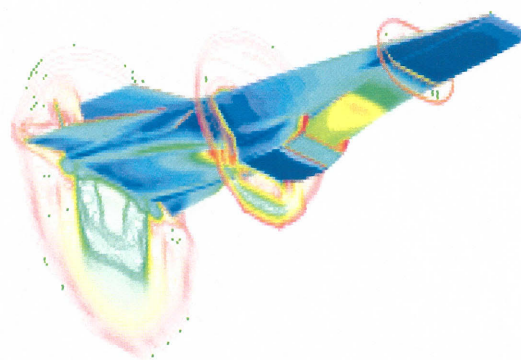


Figure 6. X-43 Pre-flight Vehicle 3-D CFD.

IV. Flight Engine Predictions

A database to model the expected engine performance during flight was developed using the SRGULL code with corrections/adjustments developed by CFD and experimental results. This database evolved with time due to the execution of the ground test program and the CFD analysis efforts. The final pre-test version of the database derived its combustion efficiency from the HXFE ground tests but was also decremented to account for the expected reduced efficiency in flight for "clean" air. Three flight Mach numbers, three angles of attack, four dynamic pressures, and six fuel equivalence ratios were included in the database and supplied to the X-43 Simulation Team. The Simulation team used the propulsion database and also an aerodynamic database to construct the control laws and fly simulated trajectories.

A. Engine Uncertainties

One thing that was learned through the execution of the Hyper-X flight program was the importance of uncertainties. As mentioned above, a database of calculated performance was supplied. Also provided was a range, i.e. a maximum and minimum, for each flight condition. Performance included axial force, normal force and pitching moment. These uncertainties were necessary so that a Monte Carlo analysis could be run varying the forces

and moments to assess potential flight test results, and “stress” the flight and engine controls laws for the experiment. Unlike a ground test, this airplane and engine had to be autonomously controlled at all times during the flight. The uncertainties were chosen to try to capture the extremes of possible engine performance. The goal was to complete the test without losing the vehicle due to unexpected engine performance.

V. Flight Experiment Results

A. Flight Test

The X-43 Mach 7 flight was successfully conducted on March 27, 2004. The test conditions and vehicle attitude are well characterized. The preliminary assessment is that the data meets Hyper-X Program objectives: validation of design methods, which include experimental, analysis and computational methods.

X-43 primary instrumentation included a highly accurate 3-component accelerometer, over 200 surface pressures, over 100 surface temperatures, strain gages, and fluid systems monitors. X-43 instrumentation density is illustrated in Figure 7 by external wall pressure and temperature. Internal engine instrumentation within the cowl is denser to aid in understanding engine performance. Accuracy of the flight conditions benefited from day-of-flight atmospheric measurements by weather balloons. These measurements provide a 1-2% change in flight Mach and dynamic pressure relative to initial estimates based on standard atmospheres. The trajectory reconstruction is discussed in reference¹².

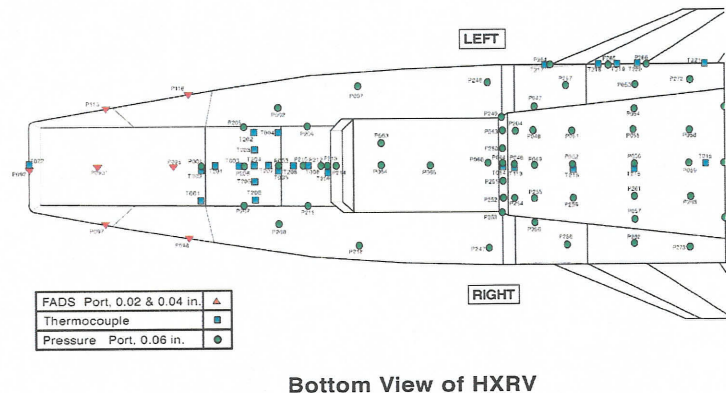


Figure 7. X-43 Mach 7 Flight Pressure Gages.

The X-43 was commanded to fly at 2.5 degrees AOA during the cowl-open portion of the flight. The vehicle was well controlled even during events which caused large changes in pitching moment or “upsets”. Figure 8 shows the angle-of-attack during the cowl-open portion of the test. The green band represents the many Monte Carlo simulation runs down on the trajectory. The thin green line denotes the nominal pre-test trajectory and the heavy red line shows the actual flight results. The arrows point out events that potentially upset the vehicle: cowl open; fuel turned on; and fuel turned off. The vehicle controls were developed knowing when these upsets are going to occur and starts correcting for them before they begin (feed forward control) to minimize the impact. The resulting axial acceleration from the cowl-open portion of the test is presented by the heavy blue line shown in Figure 9. The green band shows the previously mentioned Monte Carlo pretest runs using the engine and aerodynamic uncertainties in conjunction with boost and stage separation uncertainties.

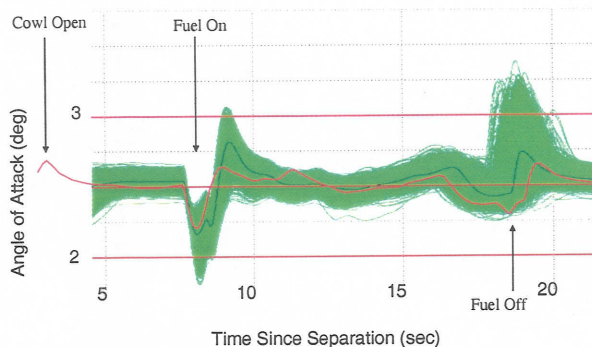


Figure 8. X-43 Mach 7 Flight AOA

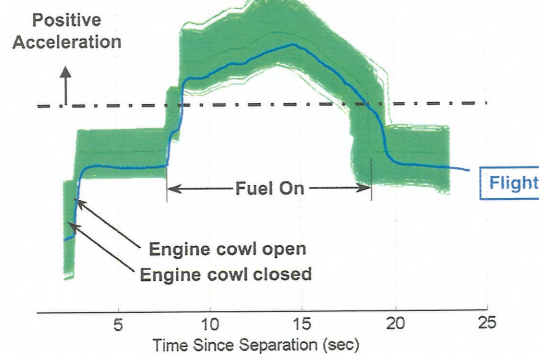


Figure 9. X-43 Mach 7 Axial Acceleration

Under scramjet power the vehicle acceleration was positive, and varied with throttle position. The increment in acceleration is about as predicted which helps confirm that the engine performed as expected. The major contributor to the difference between demonstrated and the nominal predicted acceleration is the flight trajectory, which was low in Mach and dynamic pressure, and high in flight path angle. This scramjet performance is also confirmed by comparing the pretest predicted pressure distribution through the engine with the actual flight data, which is shown in Figure 10. Agreement is excellent, but more importantly, the difference in predicted and measured force, or delta force (fuel on minus fuel off) is small.

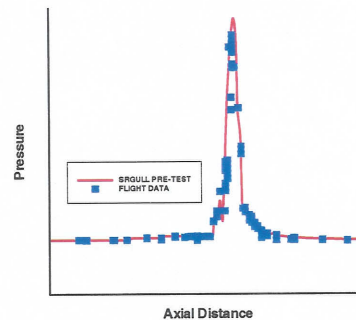


Figure 10. SRGULL Pre-Flight Test vs. Flight.

The flight data was compared directly with wind tunnel measured performance and operability, to provide some credibility to the test procedures. Comparison with wall pressure through the engine was accomplished by selecting the closest wind tunnel conditions (dynamic pressure, angle of attack, and fuel equivalence ratio) and air capture scaling the wind tunnel pressures to flight conditions. Figures 11-14 show direct comparisons between the scaled wind tunnel data and flight data for the four tests mentioned previously. Note that the lines connecting the points are not data fairings. These comparisons are presented for internal body side and cowl side pressures.

Flight pressures generally mimic the results from the AHSTF truncated fore body, partial width tests of the HXEM as shown in Figure 11. However, the combustor pressure is generally higher for the flight data, indicating slightly increased performance in flight. It is clear from this and the following comparison that the instrumentation density in flight is less than the number of gages in each wind tunnel test.

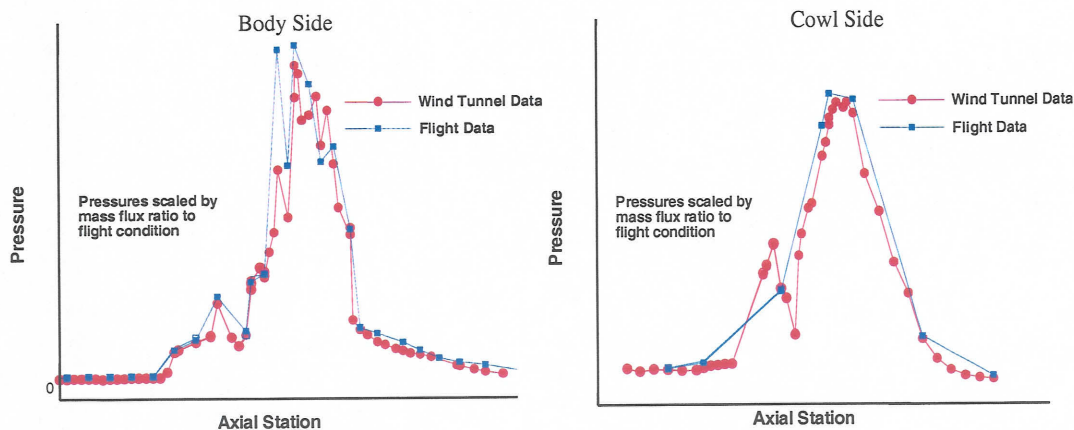


Figure 11. Hyper-X Mach 7 Flight and HXEM in AHSTF Pressures.

Tests of this same HXEM in the 8-ft HTT provide results which are in better agreement with flight, as shown in Figure 12. This could be caused by higher dynamic pressure, or errors in scaling since the inlet pressure is slightly high compared to flight. Never the less, again the comparison with flight is good, and possibly better than expected considering the difference in thermal properties (water in 8-ft HTT test gas). Results from the HYPULSE reflected shock tunnel test of the truncated forebody, partial width HSM are compared with the flight data in Figure 13. These results are in excellent agreement with the flight, confirming the HYPULSE shock tunnel test techniques.

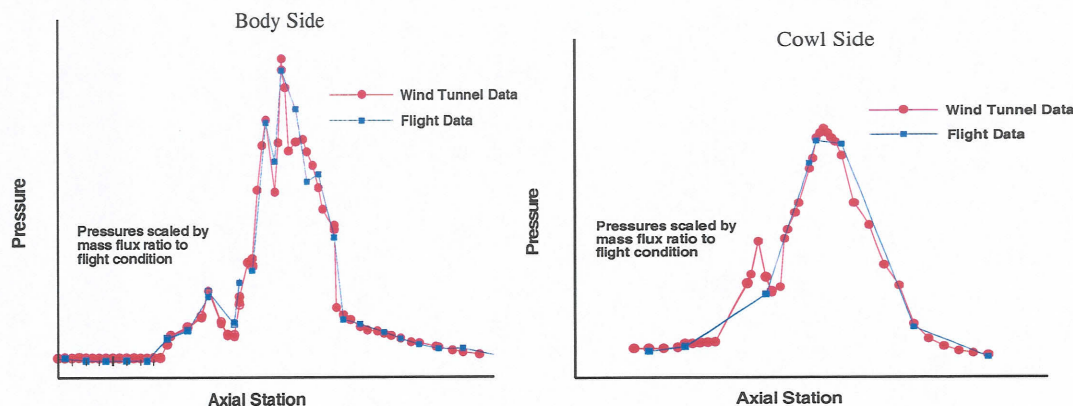


Figure 12. X-43 Mach 7 Flight and HXEM in 8-ft HTT Pressures.

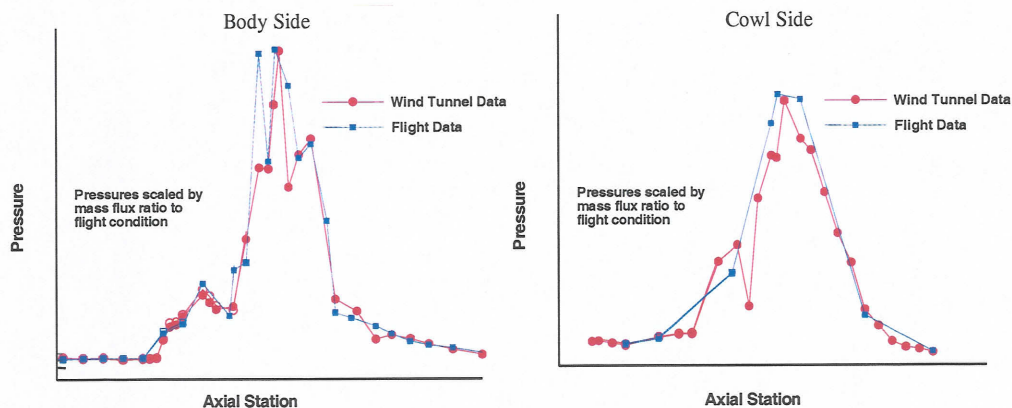


Figure 13. X-43 Mach 7 Flight and HSM Pressures.

The final comparison is for the full length and width HXFE, Figure 14. Both the body side and the cowl side pressure agreement are better than for the previous engine/tunnel comparisons. Both inlet and nozzle pressures are nearly identical. However, the lower peak combustor pressure was not expected, considering test gas (water) effects. Assessment of the difference noted between the wind tunnel tests and the flight test are continuing in order to quantify the effects of test gas contaminants, inflow boundary layer, dynamic pressure, and isolator/combustor interactions.

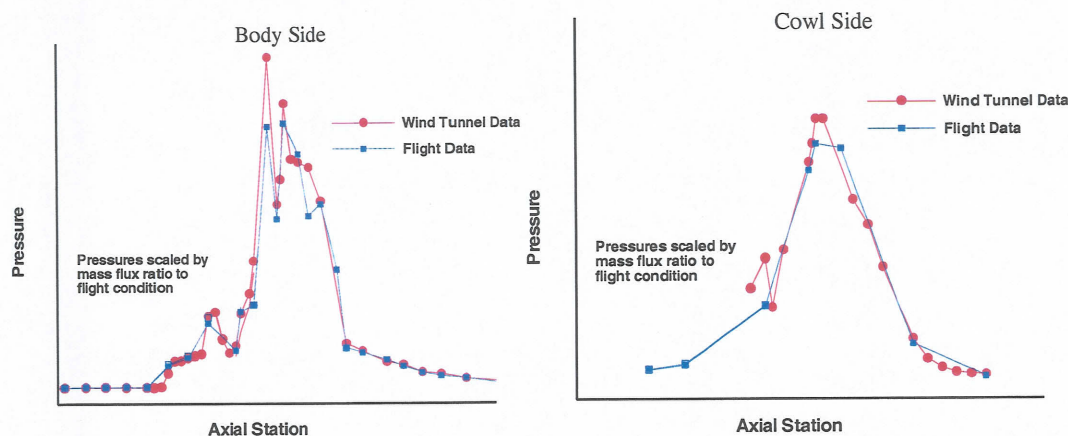


Figure 14. X-43 Mach 7 Flight and HXFE Pressures.

B. Engine Post-Test Analysis

Although the pretest prediction was close, post-test analysis has improved the SRGULL agreement. Post-test analysis used the best estimated trajectory, and did not need to be scaled using simplified methods. A 3-D CFD solution was run at the actual flight conditions and used to update mass capture and the momentum correction in the SRGULL analysis. Using these updates, the combustion efficiency is then varied to match the isolator/combustor pressures and the flight estimated engine thrust in the SRGULL analysis. In the flight test, the peak pressure did not reach those of the HXFE ground test. Figure 15 shows the post-test SRGULL analysis compared with the centerline flight test data (and also plotted for reference is centerline HXFE ground test). The HXFE ground data has been scaled by mass capture since it was run at slightly different flight conditions than those that occurred in flight.

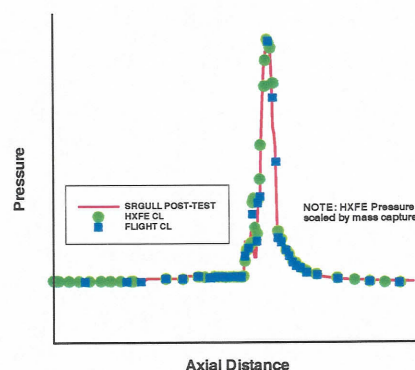


Figure 15. SRGULL Analysis with Flight and HXFE.

VI. Conclusion

The successful Mach 7 Hyper-X (X-43) flight test has proven that integrated scramjet engine can produce predicted vehicle performance and acceleration even at small scale. The two major goals of the program, verifying scramjet performance and verifying scramjet design tools, were accomplished. Scramjet performance was predicted to an acceptable level of uncertainty. The flight data also verified experiment wind tunnel test procedures, such as simulated forebody boundary layer ingestion, and flight scaling methods using delta force and mass flux. Assessment of the differences between the wind tunnel and the flight, and analysis and flight is still continuing to quantify the secondary effects of test gas contaminants, engine module inflow boundary layer, dynamic pressure, test gas turbulence, isolator aspect ratio, and isolator/combustor performance.

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