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HYPER-X ENGINE TESTING IN THE NASA LANGLEY 8-FOOT HIGH TEMPERATURE TUNNEL

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ABSTRACT

Airframe-integrated scramjet engine tests have been completed at Mach 7 in the NASA Langley 8-Foot High Temperature Tunnel under the Hyper-X program. These tests provided critical engine data as well as design and database verification for the Mach 7 flight tests of the Hyper-X research vehicle (X-43), which will provide the first-ever airframe-integrated scramjet flight data. The first model tested was the Hyper-X Engine Model (HXEM), and the second was the Hyper-X Flight Engine (HXFE). The HXEM, a partial-width, full-height engine that is mounted on an airframe structure to simulate the forebody features of the X-43, was tested to provide data linking flowpath development databases to the complete airframe-integrated three-dimensional flight configuration and to isolate effects of ground testing conditions and techniques. The HXFE, an exact geometric representation of the X-43 scramjet engine mounted on an airframe structure that duplicates the entire three-dimensional propulsion flowpath from the vehicle leading edge to the vehicle base, was tested to verify the complete design as it will be flight tested. This paper presents an overview of these two tests, their importance to the Hyper-X program, and the significance of their contribution to scramjet database development.

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NOMENCLATURE

8-Ft. HTT	Langley 8-Ft. High Temperature Tunnel
AETB	Alumina-Enhanced Thermal Barrier
AHSTF	Langley Arc-Heated Scramjet Test Facility
AOA, α	angle of attack (deg)
C_D	Drag coefficient
C_L	Lift coefficient
C_M	Pitching moment coefficient
CFD	Computational Fluid Dynamics
EDM	Electro-Discharge Machining
ESPTM	Electronically-Scanned Pressures
FFS	Full Flowpath Simulator (used with HXEM)
FMS	Force Measurement System
H	enthalpy (BTU/lbm)
H_2	gaseous hydrogen
HSM	HYPULSE Scramjet Model
HXEM	Hyper-X Engine Model
HXFE	Hyper-X Flight Engine
HYPULSE	NASA Langley Hypersonic Pulse Facility at GASL, Inc., Ronkonkoma, NY
LO_2	liquid oxygen
M	Mach number
N_2	gaseous nitrogen
NASA	National Aeronautics and Space Administration
PSC	Propulsion Subsystem Control
PLC	Programmable Logic Controller
p	pressure (psi)
q	dynamic pressure (psf)
SERN	single expansion-ramp nozzle
SiH_4	gaseous silane
T	temperature ($^{\circ}R$)
TPS	thermal protection system
VFS	Vehicle Flowpath Simulator (used with HXFE)
X-43	experimental flight vehicle designation for the Hyper-X flight research vehicles
ϕ	fuel equivalence ratio

Subscripts

comb	facility combustor condition
t	total condition
∞	freestream condition

INTRODUCTION

NASA's Hyper-X Program will move hypersonic air-breathing vehicle technology from the laboratory to the flight environment by obtaining data on a hydrogen-fueled, airframe-integrated, dual-mode, supersonic combustion ramjet (scramjet) propulsion system in flight.¹ These data will provide the first flight validation of analytical and computational methods and wind tunnel test techniques used to design this class of vehicles. The Hyper-X Program is jointly performed by NASA Langley Research Center and NASA Dryden Flight Research Center. The flight-test project phase of this program involves the fabrication and flight testing of three unpiloted, autonomous Hyper-X research vehicles, designated X-43. The first two flight tests will be conducted at Mach 7, and the third flight will be tested at Mach 10. These vehicles are fabricated by a contractor team led by MicroCraft and including Boeing and GASL, Inc.²

The development of the Mach 7 X-43 engine flowpath and its integration with an airframe are described in References 3 and 4. A roadmap of the Mach 7 flowpath verification test program is presented in Figure 1 and involves three engine models in three facilities from NASA Langley's Scramjet Test Complex.⁵ The facilities used are the Hypersonic Pulse Facility (HYPULSE), the Arc-Heated Scramjet Test Facility (AHSTF), and the 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 engine operability and performance caused by geometric-scale, dynamic-pressure, and test-gas differences between tests. These differences, encircled in Fig. 1, exist due to test-technique and facility limitations. The effects of these differences must be properly accounted for in the design and analysis methodologies when using wind tunnel test results as an integral part of vehicle/engine design.

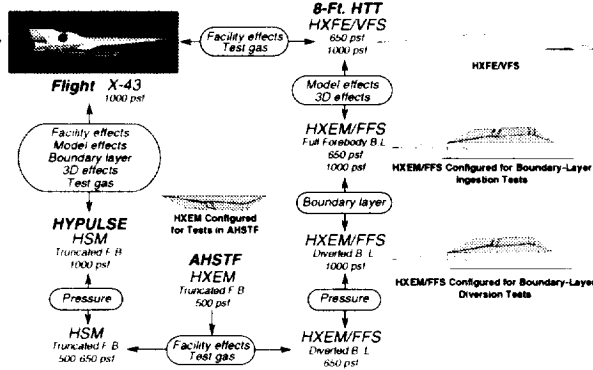


Figure 1. Hyper-X Mach 7 flowpath verification roadmap.

The tests of the final Mach 7 flowpath in the 8-Ft. HTT are part of an overall effort to understand the major differences between the preliminary flowpath development database and the X-43 flight database. Following the flowpath development tests, verification testing of the engine in the context of a complete flight-like vehicle flowpath was initiated. Two engine models and their supporting airframe keel-line simulators were designed and fabricated for testing in the 8-Ft. HTT at Mach 7 conditions. The first engine is the HXEM, a partial-width, full-height representation of the X-43 Mach 7 engine. The airframe structure to which the HXEM is mounted is the Full Flowpath Simulator (FFS), which consists of a full-length forebody and a truncated single expansion-ramp nozzle (SERN) aftbody. The HXEM/FFS was tested from February 1999 to June 1999. The second engine, HXFE, is a spare X-43 Mach 7 flight engine currently dedicated to ground testing. The HXFE is the only full-width Hyper-X scramjet engine that will be tested in a ground facility prior to the X-43 flights. The airframe structure to which the HXFE is mounted is the Vehicle Flowpath Simulator (VFS) and represents a three-dimensional, geometrically accurate forebody and aftbody of the X-43. The entire 12-foot-long X-43 propulsion flowpath (i.e., the entire undersurface of the X-43) is tested in the 8-Ft. HTT with the HXFE/VFS. This is the first-ever wind tunnel test of a full-scale, airframe-integrated, scramjet-powered, flight-vehicle, engine flowpath at representative flight conditions. The HXFE/VFS was tested from August 1999 until June 2000.

This paper presents an overview of the two Hyper-X engine flowpath tests performed in the 8-Ft. HTT in support of Mach 7 Hyper-X engine operability and performance verification.

8-FOOT HIGH TEMPERATURE TUNNEL

The NASA Langley 8-Ft. HTT⁶ was designed in the late 1950's and placed into service in the mid-1960's as a facility to conduct aerothermal loads, aerothermo-structures, and high-enthalpy aerodynamic research. The high-enthalpy flow is produced by burning methane in air at high pressure in the facility combustor, then expanding the flow through an eight-foot exit-diameter hypersonic nozzle into the open-jet test section. The high-enthalpy combustion products contain very little available oxygen; so during the late 1980's and early 1990's, the tunnel was modified with a liquid oxygen (LO₂) injection system to replenish the oxygen consumed by the methane-air combustion process to provide an oxygen molar concentration in the test gas equal to that of air. This oxygen replenishment system, which became fully operational in 1993, enables the testing of large hypersonic airbreathing propulsion

systems at flight enthalpies from Mach 4 to Mach 7.⁷ The H₂ and SiH₄/H₂ fuel/ignition systems utilized during airbreathing propulsion testing were also installed and became operational in 1993.⁸ A schematic drawing of the facility for hypersonic airbreathing propulsion testing is shown in Figure 2.

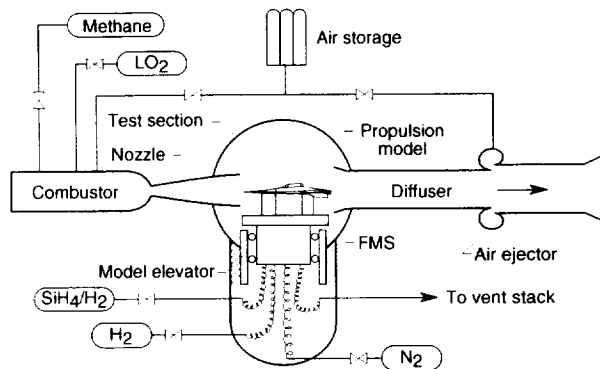


Figure 2. 8-Ft. HTT schematic for airbreathing engine testing.

Facility Test Conditions

Testing of the engines occurred at two nominal conditions corresponding to a low dynamic pressure (for AHSTF data comparisons) and the X-43 flight dynamic pressure. The tunnel combustor conditions and resulting flow parameters are shown in Table 1. The data in the table are calculated based on forebody rake data that was used to back out the appropriate freestream conditions in air to provide a comparison to flight parameters. The results indicate that the Mach number, static pressure, and static temperature at flight simulation conditions are within four percent of those expected for the X-43 flight condition. Exact duplication of these properties at the same dynamic pressure and total enthalpy as the actual flight is impossible because the vitiated air in the 8-Ft. HTT contains approximately 18% water vapor and 9% carbon dioxide by mole fraction. Furthermore, the actual test

Table 1: Summary of Simulated Freestream Conditions for 8-Ft. HTT Hyper-X Engine Tests and Comparison to Flight

Simulation	Low q_∞	Flight Simulation	Actual Flight
P_{comb} (psig)	1000	1585	n/a
T_t ($^{\circ}R$)	3550	3550	n/a
M_∞	6.84	6.92	7.00
P_∞ (psia)	0.140	0.211	0.204
q_∞ (psf)	647	1000	1000
T_∞ ($^{\circ}R$)	434	423	408
H_t (BTU/lb _m)	1064	1052	1052
α	2 $^{\circ}$	0 $^{\circ}$, 2 $^{\circ}$, 4 $^{\circ}$	2 $^{\circ}$

conditions achieved in the tunnel during any given run vary slightly (within 3%) from the nominal test conditions both for similar tunnel setpoint conditions and as a function of time within the same run.

Facility-to-Model Interfaces

For these engine tests, a significant number of subsystems are required. Major subsystem interfaces with the facility are shown in Figure 3. Certain features in the model are controlled by the tunnel Programmable Logic Controller (PLC) system and others are controlled by the Propulsion Subsystem Control (PSC) computer, which has a wind-tunnel specific version of the flight PSC control software. To the extent practical in the 8-Ft. HTT, subsystems for the two engines replicate those of the X-43. The similarities and differences of these subsystems are discussed in this section. Specifics of each subsystem are subsequently discussed.

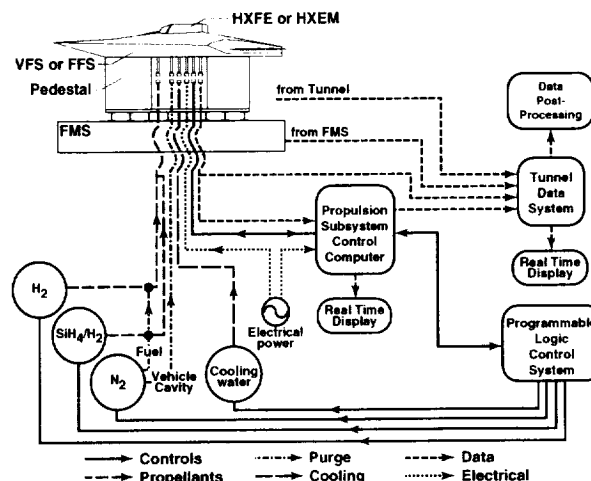


Figure 3. Hyper-X engine interfaces with the 8-Ft. HTT.

Fluid Subsystems

In general, the low pressure components of the X-43 fluid systems were simulated, but facility supply systems were utilized in place of the flight high-pressure ignitor, fuel, coolant, and nitrogen subsystems (consisting of high-pressure storage tanks, heat exchangers, and regulator valves in the X-43). The addition of fuel, ignitor, and purge lines to the test section was included during the facility upgrades for propulsion testing that were discussed earlier. Currently, all fluid penetrations into the test section are connected to steel-braided flex lines that are of sufficient length to allow for full injection and retraction of the model into the test section. These fluid delivery subsystems are located primarily in the model pedestal to simulate flight systems. This also provides a simpler design and fast response required by the PSC.

The ignitor and hydrogen fuel systems comprise the propellant delivery system. Flow control is provided by

ground test units of the Hyper-X pintel-type motorized control valves. Removable valve pintels and venturi flow meters are utilized to provide precise flow control to both the partial-width HXEM and the full-width HXFE. Each engine utilized separate pintels to maintain high fuel system mass-flow-rate control/fidelity and possess about the same dynamic characteristics between the two engine tests. The plumbing configuration, ignitor/fuel mixing manifold, and pressure instrumentation replicate the X-43 systems. The ignitor system uses a 20%/80% silane/hydrogen mixture by volume for igniting the engine fuel. The ignitor gas is delivered to the fuel control system from outside the test pod via double-walled, vacuum-jacketed, steel-braided flex lines at 1,200 psia, which is approximately the same as the pressure downstream of the X-43 ignitor high-pressure regulator. Gaseous hydrogen fuel is delivered from outside the test pod via double-walled, vacuum-jacketed, steel-braided flex lines at 1,150 psia, which also is approximately the pressure downstream of the X-43 fuel high-pressure regulator.

The nitrogen purge subsystem has a nominal supply pressure of 1,200 psia and is used for two primary purposes. First, it serves as a safety feature for supplying an inert purge of the fuel and ignitor lines prior to and immediately following a run. These purges are performed by the use of facility-controlled valves that bypass the two motorized control valves. Second, the nitrogen subsystem is used to purge the internal cavities of each model. The nitrogen is injected through discretely-placed tubes to displace air inside the model cavity and actively cool certain components that are susceptible to additional heating and thermal sensitivity, such as the two motorized fuel control valves, the cowl actuator motor, and the Electronically-Scanned Pressure (ESP™) modules. The nitrogen subsystem also provides pneumatic actuation (regulated to ~750 psig) for all fuel/purge system isolation valves.

Both of the engines have water cooled sidewall- and cowl-leading edge designs identical to the X-43 flight engines. Water at 900 psia is delivered to three open-loop cooling paths which dump the water overboard through small holes on external surfaces to the flowpath at the mass flow rates expected in flight. Figure 4 shows a photograph of the water jets exiting the HXEM during a tunnel run. (A closed-loop water path was also used during HXEM testing; its location and purpose will be described in the HXEM/FFS Model Description part of the paper.) Pressure and flow-rate requirements were established from finite element analysis conducted by GASL, Inc., based on worst-case X-43 heating in flight (a more severe condition than was seen in the tunnel). The water cooling subsystem is active for the time that the model is in the test section (less than 30 seconds)

and includes a controlled shutoff valve, flow meter, and supply pressure transducer that are interlocked to facility controls to assure that proper water flow is maintained. A visual confirmation of water flow via video camera located above the facility diffuser was also required during testing.

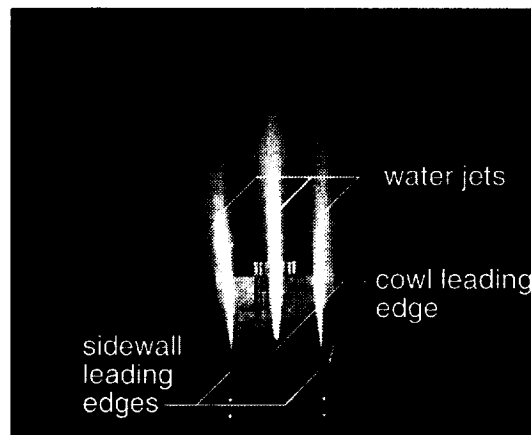


Figure 4. HXEM showing water jets during a run (top front view).

The PSC computer controls the propulsion functions of the X-43 vehicle management system that are needed for 8-Ft. HTT testing. This consists of both hardware and software to perform cowl door actuation and fuel control functions. The fuel control valves are either pre-programmed to perform a timed fuel sequence or operated in an active fuel control mode with closed-loop engine pressure feedback.⁹ The PSC computer has a communication interface with the facility to ensure a proper synchronization of tunnel and engine events, as well as for data synchronization.

Pedestal

The pedestal that supports the model (see upper left of Figure 3) consists of a welded I-beam structural frame, copper side plates (with access panels), and a zirconia-coated leading edge. The aerodynamically-shaped pedestal houses the fuel-control system and model instrumentation and provides model access for internal cavity purging/cooling of the airframe structures and water cooling for the engine leading edges. The pedestal is attached to the 8-Ft. HTT force measurement system with angle-of-attack (AOA) spacers. The AOA spacers are bolted to the FMS. When the model is tested at the nominal 2° angle of attack, the pedestal is installed directly onto the AOA spacers and bolted into place. The HXFE/VFS was also tested at two off-nominal angles of attack (0° and 4°). For these orientations, a set of AOA rails were inserted between the AOA spacers and the pedestal base to provide the correct model attitude and a constant vertical location in the test section during a run for each angle of attack tested.

Force Measurement System

The 8-Ft. HTT's Force Measurement System (FMS) is used to acquire longitudinal aerodynamic loads (axial force, normal force, and pitching moment) on the test articles that are mounted to it. Both the pedestal and the model are metrically attached to the FMS. The FMS is attached to the facility elevator carriage, which injects and retracts the model assembly into the test section (see Figure 2). The FMS was calibrated to provide accurate load-cell output for these three components at expected Hyper-X loads. Incremental check loading of the three components separately or in combination showed that the errors in the three components are less than 0.50% of the full-scale Hyper-X anticipated loads. The primary purpose of the FMS data was to measure the incremental force and moment changes due to cowl door actuation and fuel addition/burning.

Visual Coverage

Visual recordings of the model consisting of video, still photographs, and schlieren images were obtained during testing. Installation and post-run model images were recorded using a digital camera between runs to document hardware condition and any potential anomalies that may occur. Furthermore, a color Hasselblad™ camera was mounted in one of two positions inside the test section to capture run-time photographs of the model. Three test-pod video cameras provided real-time control room display and video recording of the models. A camera mounted above the facility diffuser looking upstream at the engine area was used to document the cowl actuation event and to visually confirm water-cooling flow and engine ignition. A second camera mounted above the facility nozzle provided a downstream view into the diffuser as a backup view of cowl actuation. The last camera provided a view of the model for documentation from injection to retraction. Additional video from outside the test pod included a high-speed video used for overall model surveillance and a black-and-white camera to provide side-view documentation of the runs.

The schlieren system at the 8-Ft. HTT is limited to showing about a two-foot diameter portion of the test section at a given time; therefore, the system was positioned prior to each run to provide flow-structure images in the regions where information was desired for a given run. These locations included side views near the engine leading edges (to document the forebody shock structure and boundary-layer) and near the engine trailing edge (to document the exhaust plume and surrounding shock and expansion structure).

Oil-flow visualization techniques and infrared imaging of the external flowpath surfaces of the model were also employed for a limited number of runs.

TEST OBJECTIVES

Ground tests of the HXEM and HXFE are a vital part of NASA's overall Hyper-X scramjet engine ground test program⁴. The objectives of these tests are to directly support the flight tests and to provide data for design methods verification, for ground-to-flight and facility-to-facility comparisons, and to further develop ground test techniques. Once completed, the ground test program and flight test will have provided data to link scramjet performance in flight with performance in smaller-scale engine development facilities. This link will be established by conducting tests with multiple engine models in multiple ground test facilities in a manner which isolates differences between tests in a quantifiable manner. To accomplish this, the HXEM was designed to be tested in both the 8-Ft. HTT and the AHSTF (see Figure 1). This was done by reducing the width of the Hyper-X flowpath to a width suitable for testing in the AHSTF and by providing the capability to test with the full Hyper-X forebody or a truncated forebody suitable for testing in the AHSTF. Furthermore, the truncated SERN provides a simplified geometry in which to carry out engine analysis. These tests, in conjunction with the HXFE tests and the HSM tests, will provide information on the effect of partial width, forebody truncation, freestream dynamic pressure, and test-media composition on engine performance.

The other main objective of the HXEM test was to provide pretest support for the HXFE test that succeeded the HXEM test in the 8-Ft. HTT. The majority of model-to-facility installation issues were resolved during the HXEM test. A cowl hardware actuation problem was also identified and resolved during HXEM testing which directly caused changes to the HXFE and the actual X-43 flight engine design. Furthermore, the propulsion subsystem control hardware and software used to actuate the cowl door and schedule fueling for the HXFE was exercised during HXEM testing. This provided an opportunity to verify and/or modify these systems in terms of both hardware (cowl actuation equipment, fuel control valves, and associated plumbing and instrumentation) and the software (cowl actuation commands and fuel control logic).

The objectives of the HXFE test were three-fold. First, the results will be a major part of the Mach 7 propulsion database for Hyper-X. This test included inlet and engine operation with a fully integrated forebody and aftbody flowpath with active propulsion subsystem control which includes closed-loop engine feedback. The database will be used to both correlate with the flight data and compare with the partial-width HXEM data. Furthermore, data were obtained for two

segments of the flight profile that have not been tested elsewhere due to limitations in aerodynamic wind tunnel testing; namely, the force and moment increments due to opening the full-width cowl and due to fuel addition. This provided data for comparison with previously computed aero-propulsive increments used to define vehicle control laws for the scramjet portion of the flights. Propulsion wind tunnel tests, specifically of the HXFE, provide the best possible verification of engine effects on the X-43 aerodynamics that can be obtained on the ground. Furthermore, the data will also provide insight into the predictive capabilities of available CFD codes and other tools used in the design and analysis of airframe-integrated scramjet flowpaths.

Second, important component and systems verification was obtained during this test, primarily on the engine mechanical and thermal design, the associated fluid systems, and the PSC software. Engine hardware components that were verified include cowl door actuation, cowl and sidewall leading-edge cooling, and the structural integrity of the engine during the critical part of the flight (from post-separation to completion of the fueling sequence). Although much of the fluid systems hardware was not identical to flight vehicle hardware, each system attempted to mimic the flight hardware in the sense of being able to check out the software that will be used to perform the engine functions. This software, developed as a version of the flight software, contained additional interface points specific to the safe testing of hydrogen-fueled engines in the 8-Ft. HTT.⁹ By fulfilling the first two objectives, this test reduced the risk to the X-43 Mach 7 flights.

Third, this test furthered the development of technology capabilities that will be required to perform ground tests of hypersonic airbreathing propulsion systems that are fully integrated with hypersonic vehicles. There are important differences in the testing that has been performed on engine modules, as compared to using an integrated engine and vehicle. Tunnel integration and interfaces are more challenging when the test is thought of as a tip-to-tail flowpath simulation instead of an engine test. The efforts performed on this test will provide valuable skills and techniques that can be employed with the testing of a completely integrated propulsion/airframe system, as well as interpretation and understanding of the data from an airframe-integrated scramjet engine (most notably force and moment increments).

In addition to these objectives, data was also acquired to understand the flow environment at various places, including the wing-root gap, forebody, and external nozzle and aftbody at true Mach 7 flight conditions.

MODEL DESCRIPTIONS

Both models were tested inverted from the flight orientation to facilitate fluid and instrumentation interfaces and to minimize strut interference on the propulsion flowpath caused by mounting the model to the facility. Each airframe structure was capable of scramjet engine installation on the common Hyper-X pedestal that is, in turn, attached to the 8-Ft. HTT force measurement system. They also housed many of the engine subsystems including cowl door actuation and fluid system hardware. The forebody leading edge radius is the same as the X-43, but possesses a larger angle extending toward the lower surface so that the X-43 carbon-carbon leading edge is unnecessary, allowing it to be fabricated from solid copper. The increased thickness in the lower surface also allows for easier integration of the structure, hardware, and instrumentation required for this test. The section of the forebody containing the nose and first ramp surface is common to both the FFS and VFS airframes. The first forebody ramp is a copper plate that includes a channel used to accommodate a set of boundary-layer trips. Differences in the two models are described below.

HXEM/FFS

As indicated previously, the HXEM is a partial-width model of the Mach 7 X-43 engine. The propulsion flowpath has an inlet flowpath width of 6.6 inches compared to the 16.78-inch width of the actual flight engine. The HXEM inlet, isolator, combustor, and internal nozzle are all two-dimensional representations of the Mach 7 flight engine, and the fuel injectors are of identical design.

The HXEM/FFS model is shown installed in the 8-Ft. HTT in Figure 5. The primary feature of the FFS was to provide a geometrically-accurate representation of the Hyper-X forebody.

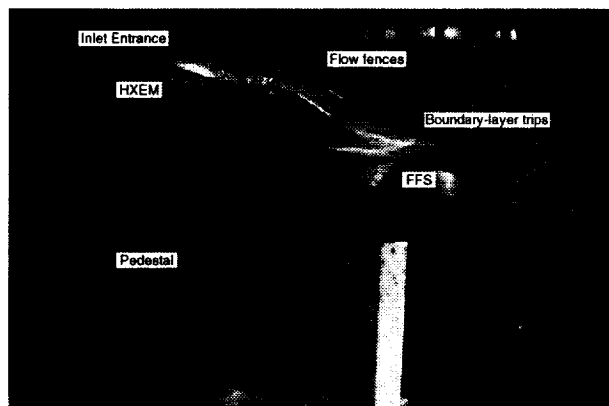


Figure 5. Installation image of HXEM/FFS in the 8-Ft. HTT.

A number of the HXEM/FFS model characteristics are identified in Figure 6. The forebody chines were closed out with aerodynamic wedge blocks to eliminate

the large rearward-facing step created by an abrupt termination of the chines. Inlet flow fences prevented forebody flow spillage. The HXEM was tested with two forebody configurations (see the side views of Figure 6). The first configuration placed the HXEM flush with the FFS forebody surface in order to allow a flight-like, fully-developed boundary layer to be ingested into the inlet. The other configuration diverted the forebody boundary layer by lowering the FFS forebody 0.75 inches, thereby exposing a boundary-layer diversion duct to better simulate the boundary-layer characteristics expected when the HXEM is tested in the AHSTF with a truncated forebody. Lowering the forebody created an exposed leading edge at the beginning of the boundary-layer diversion duct, which is exposed to significant heating; therefore, a closed loop water passage was employed to actively cool the leading edge. When the forebody was in the diverted orientation, boundary-layer trips (scaled for the new location and local boundary-layer height) were installed on the HXEM. The HXEM was isolated from the FFS by a metric gap, which was sealed with a fabric material able to withstand the high temperatures that occur during each run. Finally, the HXEM/FFS was tested at the nominal flight angle of attack of two degrees and zero degrees sideslip. The FFS surface panels were easily removed to facilitate servicing by allowing internal access to model mounting areas, structural supports, and instrumentation.

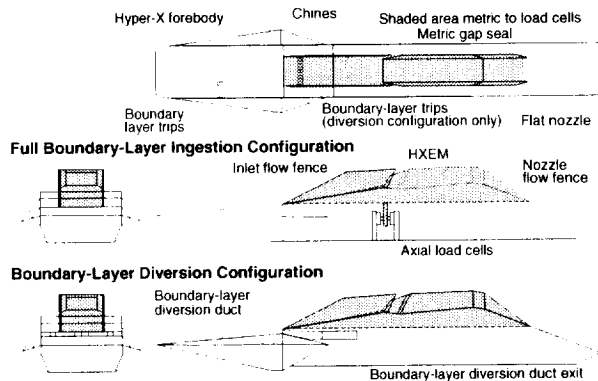


Figure 6. HXEM/FFS configurational details.

The HXEM is a metric engine model, mounted to the FFS by four metal flexures. Independent axial load measurements were obtained for the HXEM-only using two load cells mounted to the FFS as depicted in Figure 6. Confirmation of the accuracy of the FMS axial force component was made by comparing its output with data from the HXEM axial load cells, as well as integration of surface pressure distributions for selected tests. This independent axial force measurement will also be used for comparison with axial force measurements acquired during HXEM tests in the AHSTF.

HXFE/VFS

The HXFE is an exact duplicate of the Mach 7 scramjet engine that will be used on the first and second X-43 flights. It is intended to be a dedicated ground test engine but also serves as a flight spare for the program. The HXFE is rigidly attached to the VFS in a manner similar to installation in the X-43. The larger width compared to the HXEM results in increased mass ingestion, aspect ratio, and tunnel blockage. Many surfaces on the HXFE are zirconia coated.

The inlet/isolator system in the HXFE is fixed once the cowl door is opened and has been designed for sufficient mass capture for the Mach 7 test condition. It also includes pressure measurements used in the closed-loop engine feedback to sense combustor-isolator interaction and prevent inlet unstart. The internal nozzle geometrically transitions the flow from the combustor to the external nozzle with sidewall and cowl geometric expansion near the cowl trailing edge to properly represent the exhaust plume development behind the engine.

A schematic illustration of the HXFE/VFS installation in the 8-Ft. HTT is shown in Figure 7. The entire upper surface of the HXFE/VFS model simulates the lower surface of the X-43, but was fabricated in such a way as to minimize cost and still contain relevant geometric features of the X-43. The model simulates the complete propulsion flowpath, including any geometry which may affect the flow entering the engine inlet or interacting with the nozzle exhaust plume.

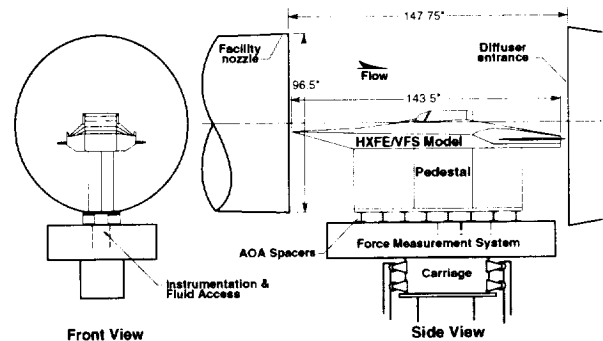


Figure 7. Schematic of HXFE/VFS installation in the 8-Ft. HTT.

A number of unique HXFE/VFS model characteristics are identified in Figure 8. Three inserts for the boundary-layer trip strip were tested, including a blank strip with no trip devices, the preliminary Mach 7 trips, and the final Mach 7 flight trips. The side chines and the external nozzle surface are machined from copper plates. The side chines are sectioned in parts to allow access into the VFS for model attachment points, structural constraints, fluid connections, and instrumentation, as well as to minimize the weight of each section for handling. To address the effect of

boundary-layer heating on engine performance, two configurations for the second and third forebody ramps were tested. Ramps made of the same AETB-12 TPS tile that will be used on the X-43 external surface and copper panels that are more extensively instrumented were used. The cusp between the external nozzle and the aftbody chine is replicated by copper ridge plates. Wing stubs are included to acquire wing-root gap heating data. Finally, the HXFE/VFS was tested at off-nominal angles of attack of zero and four degrees to complement the data taken at the nominal angle of attack of two degrees and to better examine the design space for which the pre-flight performance database was generated. The effects of cowl-door actuation and fueling under a nonzero sideslip condition were of great interest to the program; runs were made at one and three degrees of sideslip.

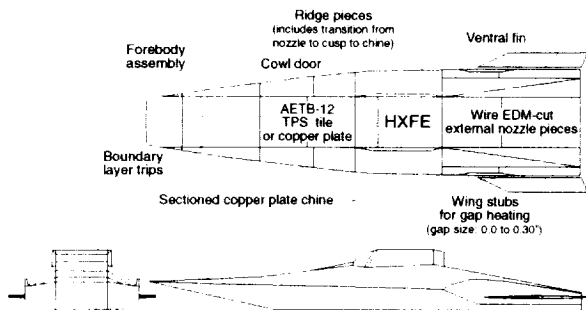


Figure 8. HXFE/VFS configurational details.

Flight and Flight-Like Subsystems

As previously stated, one of the primary objectives of these tests was to reduce risk to flight by exercising hardware and software in the 8-Ft. HTT that is as close to flight-like as reasonably possible. Figure 9 presents the subsystems that were verified, to the extent practical, in these two tests for flight risk reduction.

INSTRUMENTATION

Both the HXEM/FFS and the HXFE/VFS were heavily instrumented with surface pressures and temperatures to better understand the flow physics of airframe-integrated scramjet operation and to provide sufficient data to compare with analytical/computational solutions and other experimental test and flight data. A schematic layout of surface instrumentation on the VFS flowpath surface and HXFE bodyside surface is depicted in Figure 10. It is worth noting that all surface instrumentation locations on the X-43 flight vehicles are

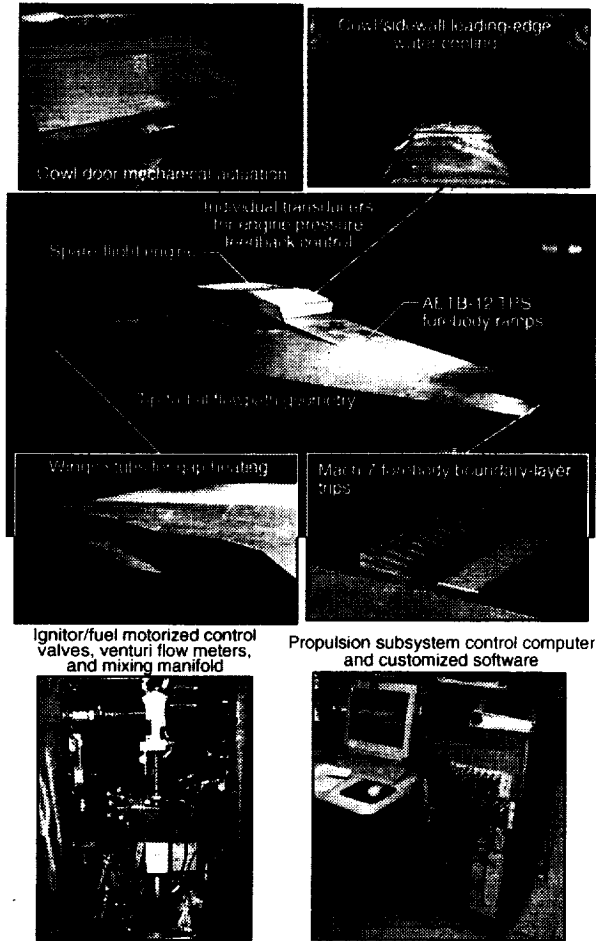


Figure 9. Flight or flight-like subsystems incorporated in 8-Ft. HTT Hyper-X engine testing.

represented in the HXFE/VFS. Most of the pressures were measured using ESPTM transducer modules; however, some of the internal engine pressures were measured by discrete transducers identical to those on the X-43 and monitored by the PSC computer for engine control. The surface instrumentation breakdown for both models is shown in Table 2.

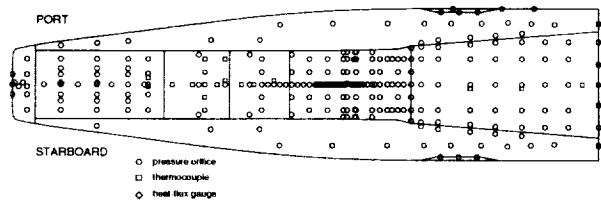


Figure 10. HXFE/VFS bodyside flowpath instrumentation layout.

Table 2: Surface Instrumentation Breakdown for 8-Ft. HTT Hyper-X Engines

	Pressure	Temperature	Heat Flux
HXEM/FFS			
Forebody	86	8	4
Engine Bodyside	114	5	5
Internal Cowl	77	1	
Aftbody	51	1	
Total	328	15	9
HXFE/VFS			
Forebody	67	14	2
Engine Bodyside	97	12	
Internal Cowl	48	2	
External Cowl	4		
Aftbody	80	35*	
Total	296	63	2

* 28 of these temperature measurements were used for wing-gap heating

A set of unfueled runs was performed with both models to quantify the engine mass capture and inflow conditions as accurately as possible. In order to accomplish this, a series of rakes were placed in front of the cowl leading edge that included 66 pitot pressures, 13 static pressures, and 13 total temperature probes for the HXEM rakes and 68 pitot pressures and 18 total temperature probes for the HXFE rakes. Figure 11 shows the HXFE rakes as installed on the model.

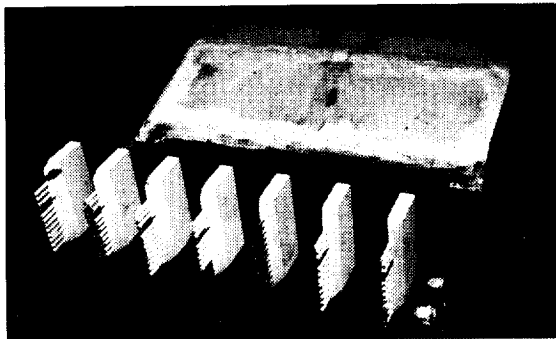


Figure 11. HXFE/VFS cowl leading-edge-plane survey rakes.

TEST SUMMARIES

Typical Model Sequence

A typical fueled-model, run-sequence timeline is shown in Figure 12. The sequence is initiated when the model reaches the test height in the test stream and final fuel system purges are complete. At this point, the PSC is activated. The cowl door is in the closed position during model injection into the test section. Following the acquisition of cowl-closed tare data, the cowl is commanded open and cowl-open tare data is acquired. The cowl door is actuated from a nearly full-closed state (0.1-in. open) to a fully open state (an angular movement of approximately 13 degrees) in less than 0.5

seconds as required for flight. The cowl speed was adjusted faster and slower to characterize the flowfield and to study the effects of cowl door speed on inlet starting characteristics. Various fuel sequences were employed that contained a number of features, some of which are shown in the figure, aimed at meeting the test objectives. The ignitor gas is introduced just prior to fuel delivery, then the fuel flow rate is incrementally increased, with flow-rate plateaus that permit the acquisition of steady engine data for accurate post-run data analysis. If an inlet unstart condition occurs, a signal is sent from the model PSC to the facility PLC to initiate a tunnel Normal Stop to safely bring the tunnel to a wind-off condition. In addition to baseline flight and research fuel sequence runs established with pre-planned flow rates, engine control-law development runs incorporating closed-loop feedback in the PSC were performed such that the fuel delivery schedule was altered by real-time sensing of engine pressure data. The cowl door is either closed or left open prior to model retraction. The arrows above the fuel schedule in Figure 12 represent typical points selected for data analysis.

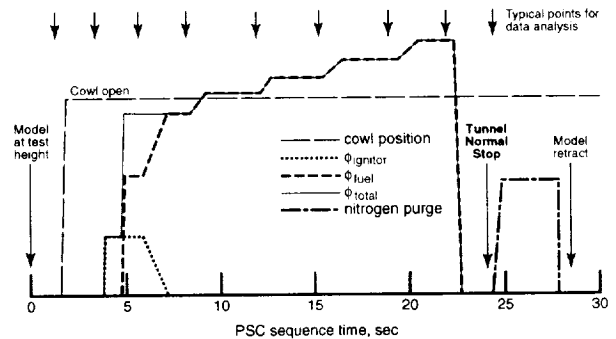


Figure 12. Typical engine run sequence timeline.

HXEM/FFS

For the HXEM/FFS test, three successful rake survey runs and thirteen successful fueled runs were completed. Four rake survey runs were planned to acquire inlet flowfield data at the two dynamic pressures of interest and for the two forebody boundary-layer cases (ingested and diverted, see Figure 6). However, the ingested boundary-layer rake survey at flight dynamic pressure was not obtained because the rakes suffered irreparable damage during the diverted boundary-layer run at flight dynamic pressure. The thirteen fueled runs addressed a number of issues including effects of cowl door actuation speed on inlet starting, freestream dynamic pressure effects, forebody length (boundary-layer) effects, effects of silane-piloting levels, engine operability limits, and closed-loop engine feedback control.

HXFE/VFS

Fourteen successful unfueled runs were performed with the HXFE/VFS. Six of these runs characterized the inlet flowfield plane via rake survey data for the three angles of attack, two dynamic pressures at flight angle of attack, and the three boundary-layer trip options at flight dynamic pressure and flight angle of attack. The remaining eight unfueled runs were used to address cowl-door actuation, including effects of cowl door actuation speed, quantification of force and moment increments at different angles of attack and dynamic pressures, and cowl door actuation capability following extended exposure to simulate flight heat loads.

Forty-one successful fueled runs were made with the HXFE/VFS in which engine performance and operability were of primary interest. Among the details addressed by these runs were thermal effects on boundary-layer entering the engine, dynamic-pressure effects, angle-of-attack effects, data repeatability, effects of boundary-layer trips, effects of sideslip (see Figure 13), active fuel-control refinement, improving engine light-off and transition to hydrogen-only fueling, ability to restart the inlet and relight the engine following an engine unstart, and ablative forebody TPS effects on engine performance and operability (see Figure 14). Depending on the date of the actual X-43 first flight and 8-Ft. HTT availability, a post-flight ground test comparison run may be performed, simulating the flight conditions and fueling sequence that existed during the flight as accurately as possible.

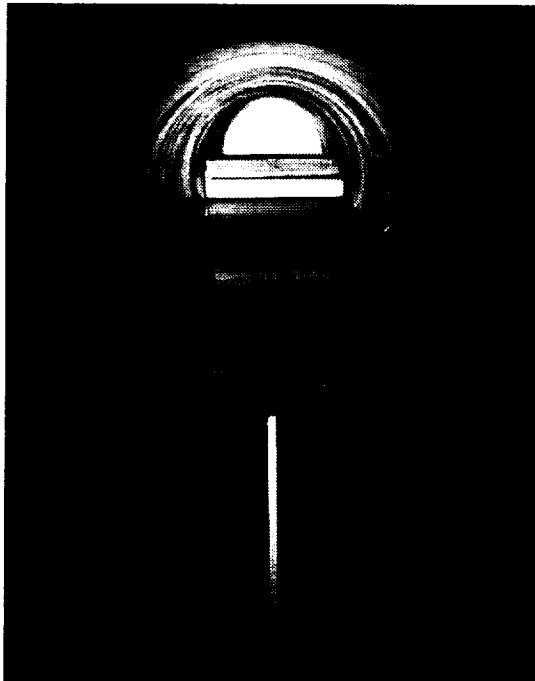
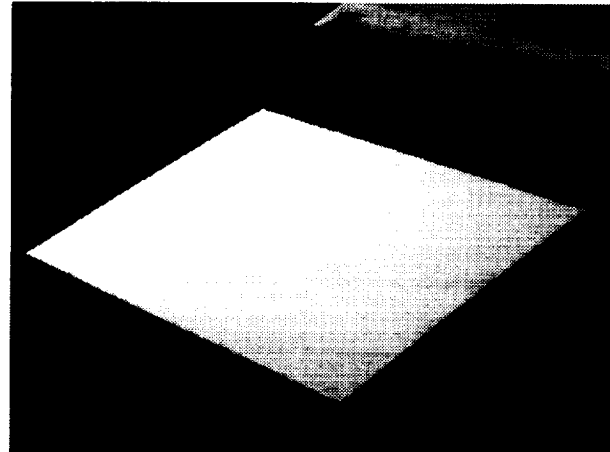
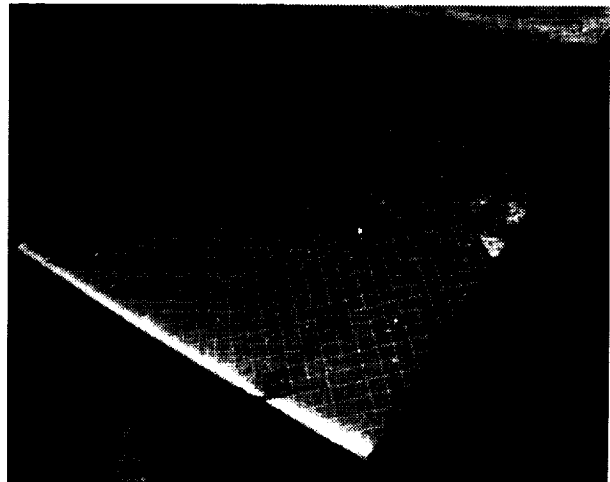


Figure 13. HXFE/VFS at three-degrees sideslip angle.



(a) Pre-run image



(b) Post-run image

Figure 14. Forebody ablator TPS tile visual results.

SAMPLE DATA

The majority of the data from these tests have restricted dissemination, but samples of some of the data obtained are presented herein.

Force and Moment Increment Comparison

Because of the integrated nature of this type of engine, the basic aerodynamic characteristics of this vehicle are strongly coupled with the propulsion system effects. Prior to HXFE/VFS testing, predictions of the longitudinal force and moment data were determined to develop the vehicle performance, stability, and control characteristics for X-43 flight preparation. These predictions were developed from a combination of aerodynamic wind-tunnel testing of the closed-cowl configuration, analytical methods, and computational techniques. The HXFE test allowed the first comparison of the predicted cowl door actuation and powered force and moment increments¹⁰ with actual full-scale flowpath test data; this comparison is presented in

Figure 15. The predictions (with no horizontal tail deflection) are shown by open symbols, and the HXFE/VFS increments are shown with solid symbols with uncertainty bars (corresponding to 3-sigma deviations from the average values shown). The HXFE/VFS increments have been added to the cowl-closed prediction which was derived from aerodynamic wind tunnel test data.

In general, very good agreement is seen between the predicted and measured increments. Where the comparisons differ the most (C_D fueled at $\alpha=4^\circ$), the experimental results actually show improved performance (lower drag, i.e., thrust) over the predictions.

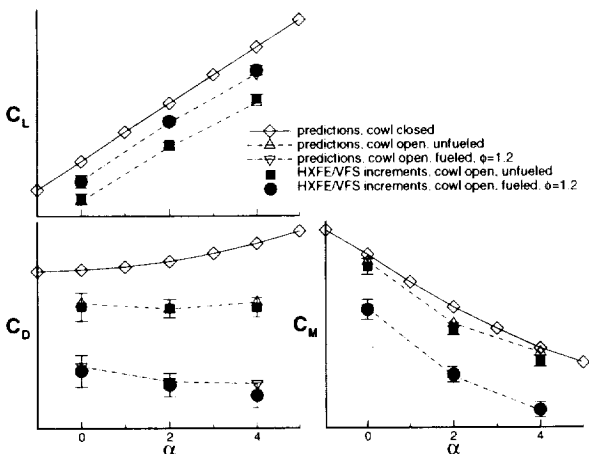
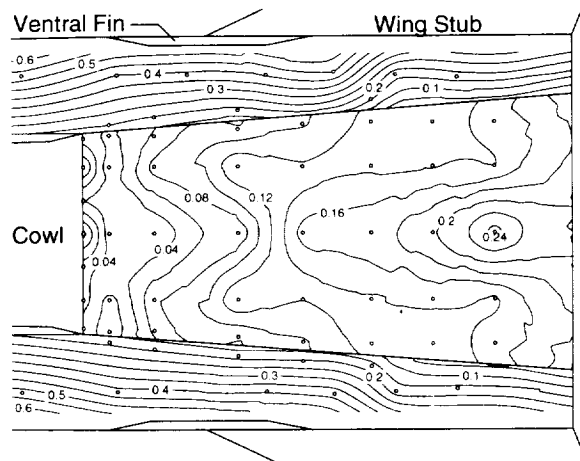


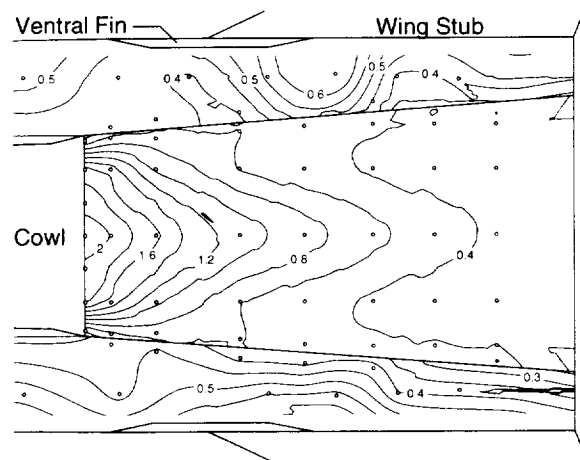
Figure 15. X-43 force and moment incremental data comparison with HXFE/VFS data, $M_\infty=6.92$ and $q_\infty=1000$ psf.

Aftbody Pressure Distributions

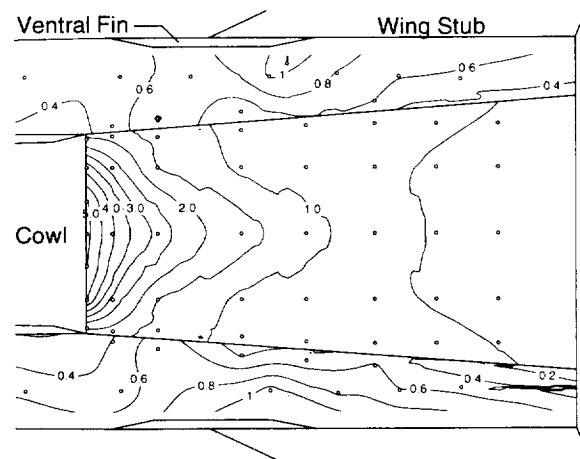
With the number of pressure taps that exist on the aftbody, it is possible to create pressure coefficient contours from the discrete measurements to understand surface effects during various parts of the scramjet sequence. Figure 16 presents the aftbody pressure coefficient contours for the flight test condition with the closed cowl, open cowl (unfueled), and open cowl (fueled). (The pressure coefficient range for each subplot is optimized to the existing pressure levels for each part of the sequence to allow for optimum interpretation of the data.) With the cowl closed, the aftbody is dominated by low pressure caused by massive separation. When the cowl door is open, the aftbody pressures react to the processing of the air through the engine. When the engine is fueled, aftbody pressurization is maintained on the external nozzle surface, and a fairly significant increase in chine pressures is observed, suggesting that measurable spillage is occurring under powered engine conditions. This is consistent with computational fluid dynamic solutions.



a. cowl closed, unfueled



b. cowl open, unfueled



c. cowl open, fueled

Figure 16. HXFE/VFS aftbody pressure coefficient distributions for cowl-closed, cowl-open unfueled, and fueled segments of scramjet operation, $M_\infty=6.92$, $q_\infty=1000$ psf, and $\alpha=2^\circ$.

SUMMARY

This paper presented an overview of two tests of Hyper-X engine models that were performed in the NASA Langley 8-Foot High Temperature Tunnel in support of the Mach 7 flights of the X-43. These tests will help quantify flight scramjet performance to scramjet performance obtained in smaller-scale, engine-development ground facilities. Following a discussion of the role of these two tests in the overall Mach 7 flowpath verification process, a discussion of the facility, test objectives, and model characteristics was presented. A brief description of test summaries and a sampling of data obtained conclude the paper.

These tests provided valuable data in the historical progression of developing a scramjet database insofar as they employed the complete airframe-integrated flowpath approach for the first time. Contributions to the database include the use of forebody boundary-layer trips, engine leading-edge active cooling, inlet mass-flow properties, cowl actuation speed, effects of forebody surface temperature on engine performance, and engine unstart/restart capability. These tests also successfully demonstrated the closed-loop feedback control on engine fueling and provided risk reduction for flight by: determining force and moment increments for two important flight events (cowl door actuation and engine fueling/burning) to improve the fidelity of the pre-flight performance database, improving design of cowl actuation hardware, providing data to best determine the flight fueling schedule, determining feedback input levels to minimize the potential of either engine flame-out or unstart during flight, determining the various geometry and test condition effects, as well as acquiring data on engine performance and operability. These tests provided the best pre-flight ground-test simulation of the actual scramjet portion of the X-43 flight.

ACKNOWLEDGMENTS

The tests described herein required a herculean effort by many individuals other than the authors. We take this opportunity to thank the following groups of dedicated professionals:

- Hyper-X Program Office, for their technical support and encouragement to produce the most meaningful information from these tests,
- GASL, Inc., for designing and building the model hardware, including the engines, flowpath simulators, and pedestal,
- and, especially, the 8-Ft. HTT operations team, whose support, expertise, insight, and performance of duties were invaluable in successfully performing these tests.

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