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NASA's Hyper-X Program

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ABSTRACT

This paper provides an overview of the objectives and status of the Hyper-X program which is tailored to move hypersonic, airbreathing vehicle technology from the laboratory environment to the flight environment, the last stage preceding prototype development. The first Hyper-X research vehicle (HXRV), designated X-43, is being prepared at the Dryden Flight Research Center for flight at Mach 7 in the near future. In addition, the associated booster and vehicle-to-booster adapter are being prepared for flight and flight test preparations are well underway. Extensive risk reduction activities for the first flight and non-recurring design for the Mach 10 X-43 (3rd flight) are nearing completion. The Mach 7 flight of the X-43 will be the first flight of an airframe-integrated scramjet-powered vehicle.

ACRONYMS

AEDC	Air Force Arnold Engineering and Development Center
AETB	Alumina-enhanced thermal barrier tiles
AHSTF	LaRC Electric Arc Heated Scramjet Test Facility
AOA	Angle-of-attack
CDR	Critical design review
CFD	Computation fluid dynamics
DFRC	NASA Dryden Flight Research Center
DFX	Dual-fuel experimental engine (full-scale, partial-width/length engine)
GNC	Guidance, navigation and control
HSM	HYPULSE scramjet model (full-scale, partial-width/length engine)
8' HTT	LaRC 8' high temperature wind tunnel
HXEM	Hyper-X engine model (full-scale, partial-width/length engine)
HXFE	Hyper-X flight engine (full-scale, dedicated to ground testing)
HXLV	Hyper-X launch vehicle
HXRV	Hyper-X research vehicle (X-43)

HYPULSE	LaRC HYpersonic PULSE Facility
LaRC	NASA Langley Research Center
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane
TBCC	Turbine-Based Combination Cycle
X-43	Hyper-X research vehicle

INTRODUCTION

NASA initiated the joint LaRC and DFRC Hyper-X Program in 1996 to advance hypersonic airbreathing propulsion and related technologies from the laboratory to the flight environment (ref. 1, 2). The program goal is to verify and demonstrate the experimental techniques, computational methods and analytical design tools for hypersonic, hydrogen-fueled, scramjet-powered aircraft. Accomplishing this goal requires flight data from a scramjet-powered vehicle (fig. 1). Because of the highly integrated nature of scramjet-powered vehicles, the complete vehicle must be developed and tested, as propulsion verification cannot be separated from other hypersonic technologies.

This technology is required for any efficient hypersonic cruise vehicle, and has the potential to significantly reduce the cost and increase the mission flexibility of future U.S. single/two-stage-to-orbit access-to-space systems.

The X-43 is small to minimize development cost and the cost of boosting it to the test condition. In addition, to reduce design time and cost, the vehicle is based on an existing Mach 10 cruise, global-reach mission configuration (ref. 3), and the extensive NASP database. Figure 2 depicts the 12-foot long X-43 mounted on the Pegasus-based Hyper-X launch vehicle (HXLV), which is carried to the launch point by the DFRC B-52.

The X-43 will be boosted to approximately 95,000 feet for the two Mach 7 tests and 110,000 feet for the Mach 10 test. The fully autonomous X-43 vehicles will fly preprogrammed 700 to 1000-mile, due-West routes in the Western Test Range off the California coast (figure 3). Test data will be transmitted to aircraft and ground stations. The X-43, the vehicle-to-booster adapter, and the HXLV are in final check-out at DFRC. The first X-43 flight is scheduled for late 2000/early 2001.

The following sections present a brief overview of the design phase, vehicle development, vehicle ground tests, and Hyper-X technology. Tests at true flight pressure and enthalpy of the full-scale, powered X-43 model in a Mach 7 wind tunnel at LaRC are described. Finally, the connection between the flight tests and technology development for future hypersonic air-breathing engine-powered vehicles is examined.

CONCEPTUAL/PRELIMINARY DESIGN

The conceptual design for the Hyper-X was completed in May 1995 (ref. 3) and the preliminary design was completed in October 1996 (ref. 1, 3). The HXLV contract was awarded to Orbital Sciences Corporation in February 1997 and the HXRV contract to Micro Craft, Inc. (with Boeing, GASL and Accurate Automation Corp. as team members) in March 1997. The Hyper-X Program operates as a closely allied government-industry team. Integrated product teams for vehicle development and technology and/or discipline teams for technology and flight test activities perform day-to-day program activities.

The X-43 was scaled photographically from the Mach 10 cruise global-reach concept (ref. 3). Scaling the configuration external lines, with the exception of details such as leading edges, enabled the utilization of existing databases, as well as rapid convergence to a controllable flight research vehicle with low trim drag penalty. The scramjet flowpath was re-optimized to ensure engine operability and vehicle acceleration. For the single-Mach operating flight condition, the Hyper-X engine geometry is fixed, except for the inlet cowl, which is closed to protect the engine during boost and descent. Although there are differences between the reference Mach 10 vehicle and Hyper-X scramjet engine flowpaths, demonstration of the Hyper-X predicted performance will be validation of the design process (ref. 4).

Wind tunnel testing commenced in early 1996 to verify the engine design, develop and demonstrate flight engine controls, develop aerodynamic data bases for stage separation, control law and trajectory development and support the flight research activities. Mach 7 engine performance and operability were verified in reduced dynamic pressure tests of the DFX (dual-fuel experimental) engine in the NASA LaRC Arc-Heated Scramjet Test Facility (AHSTF, ref. 5). During this same time, preliminary experimental results for the Mach 5 and 10 scramjet combustor designs were obtained using the direct-connect combustor module rig and an existing semi-direct connect combustor model

in the HYPULSE facility (ref. 6). In addition, tests were performed early in the program to verify inlet starting with the articulating cowl door.

A preliminary aerodynamic database was developed in 1996 from results of quick-look experimental programs. These tests were performed using 8.3% and 3.0% scale models of the X-43 and the HXLV at Mach numbers of 0.8–4.6, 6 and 10. The aerodynamic database includes boost, stage separation, research vehicle powered flight (with propulsion data) and unpowered flight back to subsonic speeds. Figure 4 illustrates the range of tests used to develop the Hyper-X aerodynamic database. The final aerodynamic database uses the results from over 5808 tests in 10 facilities of 16 models ranging from 3.0% to 100% scale (when including powered test data from the 8' HTT).

Other work leading up to the fabrication of the first Hyper-X research vehicle included control law development, evaluation of trajectories, development of aerothermal loads and design of the engine structure.

Measurements and instrumentation for the Hyper-X flight test are selected to:
• Determine overall vehicle performance (attitude, rates and position)
• Monitor vehicle systems for health/safety
• Identify failure modes
• Evaluate local flow phenomena
• Validate design methods (propulsion, aerodynamic, thermal, structures and controls)

The instrumentation approach utilizes a limited quantity of proven reliable measurements (pressure, temperature, and strain gage). Off-the-shelf data system components are utilized to process and telemeter measurements. The primary measurement is vehicle acceleration. Of the 503 measurements, about 200 are Vehicle Management System digital and about 300 are analog parameters (194 pressure, 107 temperature, and 13 strain gauge). About 160 of the surface measurements provide propulsion flowpath-related data and 100 provide aerodynamic data.

Vehicle Development and Flight Tests

The HXLV and HXRV CDR's were held in December 1997 and February 1998, respectively.

Hyper-X Launch Vehicle Development

Orbital Sciences Corporation activities focused on configuration and systems definition, structural stiffness,

control law refinement, trajectory uncertainty analysis, and aerodynamic and thermal assessments for the Hyper-X trajectory which is depressed when compared to a normal Pegasus trajectory. A joint study by the contractors and the government established that the separation condition for the Mach 7 flight should be at dynamic pressure = 1066 psf (+/- 50), Mach = 7.06 (+/- 0.1), and flight path angle = 2.0 (+/- 0.2) degrees. A Monte Carlo analysis (accounting for uncertainty in B-52 drop conditions, atmospheric properties and winds, inertial navigation unit, flight controls, aerodynamic database, rocket motor Isp, propellant load and burn time, and vehicle mass properties) established that these conditions could be achieved. It also revealed that the flight path angle is the most critical of these trajectory aim point parameters.

The first HXLV (fig. 5) has been delivered to DFRC and final preparations for flight are underway. The second HXLV is also at DFRC and is undergoing final preparations prior to its delivery to the government. Orbital is also responsible for vehicle integration and launch support activities. In addition, Orbital performed some structural testing tasks for the HXRV contractor.

Hyper-X Research Vehicle Development (X-43)

The primary Micro Craft activities for the X-43 and vehicle-to-booster adapter included design, materials and systems procurement, fabrication, and testing.

The vehicle structural design and final systems layout are presented in figure 6. The vehicle structure consists of 4140 heat-treated steel keels and side longerons; titanium, or 4130 steel bulkheads; and 4130 steel, 301 stainless or 6061-T6 aluminum skins. Thermal protection consists of alumina-enhanced thermal barrier tiles (AETB-12) and carbon-carbon wing and nose leading edges. The majority of the wings and tails are constructed from high-temperature, Haynes-230 alloy. The nose is tungsten. The first X-43 is undergoing final tests and preparations at DFRC (fig. 7). The second X-43 is undergoing systems tests at Micro Craft in Tullahoma, TN.

Verification of the structural stiffness of the mated HXLV/adapter/X-43 stack necessary for HXLV flight control requirements, required extensive analyses and tests. Modal tests in early 1999 validated the predictions (fig. 8). Additionally, the flight controls team has identified and implemented relatively simple solutions (filters) to reduce the bending modal limit.

The flight engine is a heavy, robust design similar to wind tunnel flowpath models. Most of the engine struc-

ture is copper which is primarily heat-sink cooled for the short-duration scramjet test. Water cooling is included for the cowl and sidewall leading edges. An articulating cowl leading edge section closes the flowpath, protecting the engine internal surfaces during boost and descent after the scramjet test. Figure 9 shows the first engine, a Mach 7 flight spare, which is dedicated to ground testing in the LaRC 8' HTT.

Engine control laws were designed to: determine fuel requirements; provide timing for inlet open/close and fuel and ignitor sequences; actively monitor vehicle acceleration; and provide closed loop monitor/control of inlet-isolator and vehicle acceleration performance. For the first test the powered segment of the flight will be at nearly constant angle-of-attack. The target fuel flow will be established based on estimated air mass capture. The fuel sequence includes ignition using a silane-hydrogen mixture, transition to hydrogen only fueling, and ramp-up to full fuel flow rate. The HXFE engine control laws were verified through an extensive series of 8' HTT tests.

HXFE Ground Testing (Ref. 7)

A 10-month test series of the Hyper-X Flight Engine (HXFE) was completed in June 2000, in the LaRC 8-Foot High Temperature Tunnel (fig. 10).

The test objectives were three-fold. First, the results are a major part of the Mach 7 aerodynamic and propulsion database for the X-43. This test series included inlet and engine operation with a fully integrated forebody and aftbody flowpath with active propulsion subsystem control which included closed-loop engine feedback. The data will be used to both correlate with the X-43 flight data and compare with other Hyper-X ground-test data. Furthermore, data were obtained for two segments of the flight profile that have not been acquired elsewhere: the force and moment increments due to opening the cowl door and due to fuel combustion. This provided data for comparison with previously computed aero-propulsive increments used to define vehicle control laws for the scramjet portion of the flights. Furthermore, the data will also provide insight into the predictive capabilities of CFD codes and other tools used in the design and analysis of airframe-integrated scramjet flowpaths.

Second, important component and systems verifications were obtained during this test, primarily on the engine mechanical and thermal design, the associated fluid systems, and the propulsion subsystem control 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-stage separation to completion of the fueling sequence).

Third, this test series 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.

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

Fourteen successful unfueled runs were performed with the HXFE. Six of these runs characterized the inlet flowfield plane via rake survey data for three angles of attack, including 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 simulated flight heat loads.

Forty successful fueled runs were made with the HXFE in which engine performance and operability were of primary interest. Among the details addressed by these runs were the thermal effects on the boundary-layer entering the engine, dynamic-pressure effects, angle-of-attack effects, data repeatability, effects of boundary-layer trips, effects of sideslip, 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. In addition, a post-flight ground test comparison run that will simulate the flight conditions and fueling sequence that existed during the flight as accurately as possible is planned.

A number of significant firsts were accomplished during this test series:

Fuel Delivery Refinement: Fueled tests that were performed late in 1999 indicated that there was a concern about the engine lightoff and the transition from silane-piloted fueling (used to establish a robust flame) to hydrogen-only fueling. In one case, the engine flamed out, and in two other instances, the engine performance data during transition to hydrogen-only fueling indicated that the engine was very close to flaming

out. At this point, minor modifications were made to the lightoff/transition part of the flight fuel sequence that improved lightoff and flameholding.

Attitude Excursions: The nominal test point for the scramjet portion of the X-43 flight is at two-degrees angle of attack and zero-degree sideslip. In order for the flight control computer to be able to correct vehicle attitude when it is not at the nominal angle of attack, estimates of the forces and moments at angles of attack other than two degrees are required. Originally, these increments were obtained using CFD and analytical methods. A series of runs during the HXFE test was used to quantify engine air mass capture and engine performance and operability at off-nominal conditions. Angle-of-attack excursions were performed at zero and four degrees, providing force and moment increment data due to cowl-door opening and due to fueling. Comparisons with the existing database numbers are very good. Sideslip angles of óne and three degrees (the largest known sideslip angle at which a scramjet has ever been tested) were also performed with no significant degradation in engine performance and operability. Data from these tests compared favorably with CFD solutions, confirming predicted powered lateral stability.

Cowl Actuation at Flight-like Heat Loads: The HXFE performed a high-risk engine heat-soak run that simulated the heating that the X-43 scramjet engine will encounter during its ascent on the booster to the test point. The objective of the run was flight risk reduction by determining if that much heat applied to the engine had any adverse effect on cowl door actuation. Based on calculations performed by the engine manufacturer (GASL, Ronkonkoma, NY), subjecting the engine to 25 seconds of Mach 7 enthalpy tunnel flow at a dynamic pressure of 1280 psf equates to about the same amount of heating that it will encounter during the boost to the scramjet test point. During the run, the model was in the flow 26 seconds before the cowl door was commanded open. It opened in less that 0.5 seconds to the full-open position with no problems, as planned.

In addition, two other sets of runs were performed to address post-flight scramjet/vehicle development:

Engine Unstart/Restart Capability: The HXFE successfully demonstrated restart capability of an airframe-integrated scramjet engine. This objective was met by purposely causing the HXFE inlet to unstart (via excess fueling), followed by rapidly throttling-down the fuel, restarting the inlet flow by actuating the cowl door, and re-igniting the engine. The restart process was achieved in 1.76 seconds and the data suggests that it could be achieved significantly faster. In addition to demonstrating engine restart, the analysis of force and moment data will provide valuable insight into vehicle dynamics.

Ablative TPS Effects: The HXFE was also used to verify the use of a new Boeing lightweight ablator thermal protection system (TPS). TPS survivability during the Mach 7 1000-psf dynamic pressure (both extremes for this TPS), 22-second run was very good. The HXFE had a good lightoff and maintained combustion throughout the runs and did not appear to be affected by the ablator. This is the first time this type of ablator material has been tested with an operating engine. The second run was the first time that the TPS was re-tested, providing data to address reusability of the TPS.

Validation Tests

A large number of preflight tests are being conducted at DFRC including a full set of subsystem and system validation tests utilizing an aircraft-in-the-loop simulation (fig 7). The X-43 and adapter will then be integrated with the HXLV and a series of integration tests will be performed. In parallel, the B-52, the X-15 pylon, and the HXLV to pylon adapter will be modified for the Hyper-X application and interface testing will be completed. Combined systems tests, performed with all avionics systems, communication systems, telemetry systems, and representative space positioning systems operational will be conducted to ensure there is no significant electromagnetic interference between systems and to verify the transmission and reception of data. Taxi and flight tests of the B-52 with the stack attached will be used to clear the captive carry flight envelope for flutter, exercise the tracking and data reception capabilities of the test range, and provide operational rehearsals.

X-43 Flight Tests

The flight test objectives include:
(1) acquisition of flight data to document the performance and operability of airframe-integrated hydrogen-fueled, dual-mode scramjet-powered research vehicles at Mach 7 and 10;
(2) demonstration of controlled powered and unpowered hypersonic aircraft flight; and
(3 acquisition of flight data to validate/update the computational methods, prediction analyses, and test techniques that comprise a set of methodologies for the design of future hypersonic cruise and space access vehicles.

Specific flight operations objectives are to safely launch the stack from the B-52 (fig. 11), successfully separate the X-43 from the adapter at the appropriate test conditions, and obtain the desired test data in all areas of the flight envelope that are of interest. Flight research objectives include evaluation of a Flush Air Data System and most importantly, development of flight test techniques applicable to highly integrated, airbreathing engine powered hypersonic vehicles.

In addition to the 500 instrumentation parameters on the X-43, 700 parameters are included on the HXLV. The HXLV instrumentation monitors approximately 400 guidance, navigation, and control parameters and 300 acceleration, discrete, and power system information analog sensors, including information on the stage separation sequence. The data will be relayed to the DFRC mission control room and to LaRC for recording and real time display of selected parameters. It will also be recorded at the Navy's Pt. Mugu facility and by two Navy P-3 aircraft. To reduce the risk of loss, scramjet engine data will be rebroadcast at regular intervals.

Real time video from the B-52 will monitor the captive carry portion of the flight as well as the initial drop of the stack. The F-18 photo chase will provide video for the initial drop from the B-52, the rocket ignition sequence, and the first portion of the boost trajectory. In addition, two cameras are mounted in the vehicle-to-booster adapter to record the stage separation. A rawinsonde balloon will be used to measure upper atmospheric pressures, temperatures, and winds near the location and altitude of the scramjet test. These data will be used to correct the X-43 performance calculations to standard day conditions and validate the inertial measurement system information.

Flight test operations will be conducted in accordance with established DFRC practices. The flight approval process will include a Flight Readiness Review and an authorization to proceed from the Airworthiness and Flight Safety Review Board. A large portion of these reviews is allotted to flight safety. In addition, factors affecting mission success will also be considered. Finally, prior to each flight, technical and crew briefings will be conducted.

The first flight is scheduled to occur in late 2000/early 2001 with the following flights scheduled for mid-2001 (Mach 7) and early 2002 (Mach 10). During each of these flight tests, the B-52 will carry the stack to the launch point where it will be dropped, the rocket motor ignited, and a climbing due west boost trajectory flown to the stage separation point. At this point, the HXRV will go through the sequence illustrated in figure 12. The HXRV will not be recovered but telemetered test data will be received almost to splash down in the Pacific Ocean.

Hyper-X Technology

The Hyper-X program technology focus is on four main objectives required for practical hypersonic flight.
* Hyper-X (X-43) vehicle design and flight test risk reduction
* Flight validation of design methods
* Design methods enhancement
* Future vehicle systems development

Design: Recent Hyper-X flight vehicle design activities have focused on the Mach 10 vehicle engine flowpath optimization, loads definition/minimization and vehicle and engine thermal/structural redesign. Assessments of the Mach 7 design at the higher Mach 10 thermal loads concluded that only leading edges, the engine cowl flap, and a few engine parts require modification. Alternate materials and/or limited cooling to ensure thermal survival for the Mach 10 vehicle wing, tail, and body leading edges, and engine parts are being studied.

Flight Test Risk Reduction: Risk reduction includes detailed analysis and testing to assure the flight test is successful. It includes all phases of the flight (fig. 11) and all disciplines. This risk reduction activity also serves to refine and can lead to significant improvements in the design tools. Successful demonstration of the scramjet-powered vehicle's predicted performance will validate the use of these tools in the design process. Experimental propulsion flowpath, aerothermodynamic and propulsion-airframe integration tests play a key role in this activity.

Aerodynamic Facilities, Models and Flight Scaling: The primary aerodynamic wind tunnels and models utilized for the X-43, HXLV, stage separation and FADS database development are listed in table 1. Details of these facilities are presented in references 8 and 9 and use of these facilities in the Hyper-X program is discussed in references 10 and 11. The X-43 models include 12-inch (8.3% of full scale), 18-inch (12.5%) and 30-inch (20.8 % of full scale) steel models of the research vehicle, a 33%-scaled model of the research vehicle forebody, an 80% scaled model of the vehicle nose with a 100% scale FADS system, and the full-scale nose-to-tail flowpath used in the 8' HTT.

The results from these aerodynamic wind-tunnel tests form the basis of the design aerodynamic database utilized in the determination of scramjet thrust requirements, and for flight simulation. In addition, the final aerodynamic database model is verified by comparison with CFD predictions for the flight conditions (such as fig. 13). This process decreases the design aerodynamic database uncertainty. The extensive aerodynamic database also provides background for quick validation of design methods, and identification of error sources if the flight data does not agree with the design database.

Additionally, a large risk reduction activity including wind tunnel and mechanical tests, CFD analysis, aerodynamic database development, 6+6+3 degree-of-freedom simulation, and Monte Carlo uncertainty analyses was pursued for the research vehicle stage separation (fig. 14).

Scramjet Testing Facilities, Models, and Flight Scaling: Facilities and models utilized by the Hyper-X Program for scramjet engine flowpath and propulsion-airframe integration development and flight test risk reduction are summarized in Table 2. Details of these facilities and use in wind tunnel tests are discussed in references 5, 6, 10, 12, and 13. Unlike aerodynamic tests, scramjet tests require high-temperature (enthalpy) and high-pressure air or "test gas". In these facilities, the test gas is heated by several means: electric arc, combustion, or reflected shock. For each of these facilities the test gas contains some contamination relative to the flight environment. The impact of the contamination on performance adds some uncertainty to the predicted flight performance and engine operability (ignition, flameholding, inlet starting and inlet isolator effectiveness). In addition, some of these facilities do not fully simulate the flight dynamic pressure (listed in table 3). A shock tunnel (HYPULSE facility, ref. 6) is also utilized for Hyper-X Mach 7 engine tests, providing clean-air test gas at dynamic pressures in excess of 1000 psf for Mach 7 full scale flight simulation, albeit with short test times. Testing the engine at Mach 7 in HYPULSE also provides a close comparison with long duration tests to verify the HYPULSE reflected shock tunnel testing methods before the facility is used to determine the Mach 10 scramjet engine performance.

Flight scaling of performance and operability from wind tunnel data is accomplished using a slightly different approach than used for aerodynamic database development. Design methods, including analytical and CFD-based methods (see ref. 4) can model, to some degree, both the wind tunnel test gas and the flight environments. These prediction methods are verified by comparison with multiple ground tests of the X-43 engines. Flight scaling is accomplished by using these methods to predict the flight performance for the expected flight conditions (ref. 11).

Flight Validation of Design Methods

A primary Hyper-X program goal is flight verification of design methods for scramjet propulsion, hypersonic

aerodynamics and propulsion-airframe integration. This is required to develop confidence in predicted capabilities of future hypersonic vehicle systems.

Propulsion-airframe integration design methods, unlike aerodynamic and propulsion methods, have not been adequately ground-test verified due to the limited nature of appropriate data. This limitation was addressed by the wind tunnel test program using the Hyper-X flight engine (fig. 10) and the complete X-43 flowpath in the 8' HTT (table 2). The next step is to validate the design methods with the X-43 flight data. Some issues expected in flight (vis-à-vis wind tunnel) validation include:
- Low free stream turbulence effects on fuel mixing, shock-induced boundary layer separation, and boundary layer transition control;
- Full total enthalpy effects on slender-body, hypersonic, wind-tunnel based aerodynamic performance;
- Clean-air test gas effects on ignition, flameholding and flame propagation;
- Unknowns in propulsion-airframe integration.

Method Enhancements

Scramjet engine and scramjet-powered vehicle design require a matrix of highly integrated design tools encompassing engineering and higher order CFD based analysis methods (ref. 4) and specialized experimental facilities and measurement systems (ref. 14). Successful development of hypersonic airbreathing engine-powered vehicles requires continued refinement of these design tools. Part of the current program focus on parametric tests and analysis around the Mach 5, 7 and 10 conditions is to develop these design systems for the X-43 configuration. These design systems will soon be completed and in place to characterize and optimize the X-43 class engine for the Mach 4 to 10 dual mode scramjet required for future vehicle development.

Hyper-X Phase II and Beyond (Future Vehicle Design)

This technology area represents the long-term look at future systems. The Hyper-X program, as discussed in detail in reference 15, is planned as a two-phase program. Phase 1 emphasis is on the Mach 5 – 10, dual-mode scramjet operating speed range. Phase II is not funded, but studies leading to a Phase II are progressing. Phase II is intended to provide flight validation of critical technologies for hypersonic aircraft or access-to-space vehicles by focusing on operation from takeoff into the scramjet operating speed range (Mach 0 – 7). This includes operation on and transition from the low speed engine to the dual-mode scramjet. Phase II is currently

envisioned to include a reusable flight research vehicle. An air-launched configuration is currently being studied by Boeing under a joint NASA LaRC, Marshall Space Flight Center, and Glenn Research Center study (fig 15).

Other long-term technology development is being directed toward the following:
- Alternate engine cycles (ref. 16-17);
- Plasma aero, magneto-hydrodynamics, virtual inlet power generation (ref. 18);
- System studies to refine existing or to identify new concepts and missions for hypersonic airbreathing reusable vehicles;
- Hypervelocity scramjet engine technology: Mach numbers of 14 - 20 (ref. 19).

SUMMARY

This paper provided an overview of the Hyper-X program. The program is poised to move hypersonic airbreathing technology to the level required for serious consideration for future systems. The Hyper-X flight test program is making the final preparations for the first Mach 7, X-43 flight in late 2000/early 2001. Extensive risk reduction activities for the first flight are complete, and non-recurring design for the Mach 10 vehicle and pre-flight test preparation are nearly complete. This paper also has addressed how the flight test integrates with the overall technology development effort and future development plans.

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Facility	HXLV	Stage Separation	HXRV	BL Control	FADS Calibration
LaRC 31" Mach 10	3%	8.3%	8.3% 12.5%	33%	
LaRC 20" Mach 6	3%	8.3%	8.3% 12.5%	33%	
AEDC VKF–B Mach 6	8.3%	8.3%	8.3%		80%
Polysonic 0.4<M<4.6	6%		16.7%		80%
BNA Mach 0.2			12.5%		

Preliminary/similar config.   Quick look   Detailed   Benchmarked

Table 1. Aerodynamic Wind Tunnel Tests (model scale in % of full scale).

Table 2. Mach 7 Scramjet Test Matrix.

Facility (contaminants)	Scramjet Model / Width / Length					
	DFX	HXEM		HFE	HSM	HXRV
	Part.	Part.		Full	Part.	Full
	Part.	Part.	Full	Full	Part.	Full
AHSTF (NO⁻)	500	500				
GASL Leg IV (H_2O)		500 1000				
8' HTT (H_2O & CO_2)		600 1000	600 1000	600 1000		1000
HYPULSE (none)					500 1000 2000	
Flight (none)	Notation: Dynamic pressure, psf Partial/full width/length simulation					1000

Table 2. Mach 7 Scramjet Test Matrix.

Facility	Primary use	Flow energizing method (Max $T_{t,\infty}$ (°R))	Simulated flight Mach No.	Nozzle exit Mach No.	Nozzle exit size (in.)	Test section dimensions (ft)	Dynamic Pressure psf
Direct-Connect Module GASL	Combustor tests	H_2/O_2/Air combustion (3800)	4.0 to 7.5	2.2	4.71 x 6.69	----------	>4000 @ M5 & 7
Combustion-Heated Scramjet Test Facility (CHSTF)	Engine tests	H_2/O_2/Air combustion (3000)	3.5 to 5.0 4.7 to 6.0	3.5 4.7	13.26 x 13.26	2.5 W x 3.5 H x 8 L	1500 @ M5
Arc-Heated Scramjet Test Facility (AHSTF)	Engine tests	Linde (N=3) arc heater (5200)	4.7 to 5.5 6.0 to 8.0	4.7 6.0	11.17 x 11.17 10.89 x 10.89	4 dia. x 11 L	800 600
8-ft High Temperature Tunnel (8' HTT)	Engine tests	CH_4/O_2/Air combustion (3560)	4.0 5.0 6.8	4.0 5.0 6.8	96 diameter	8 dia. x 12 L (26 dia. chamber)	1500 @ M7
Hypersonic Pulse Facility (HYPULSE)	Engine and combustor tests	RST (15 550)	7 10	6.5	24 dia.	7 dia.	>2000 @ M7 ~800 @ M10
GASL Leg IV	Engine tests	Pebble-Bed + H_2/O_2/Air combustion (5200)	5 7	4.7 6	13.26 x 13.26	2.5 W x 3.5 H x 8 L	1200 1700

Table 3. Propulsion Test Facility Statistics.

GOALS: Demonstrate and validate the technology, experimental techniques, and computational methods and tools for design and performance predictions of a hypersonic aircraft powered with an airframe-integrated, scramjet engine

OBJECTIVES:

- Free-flight demonstrations
  (Two @ Mach 7, one @ Mach 10)
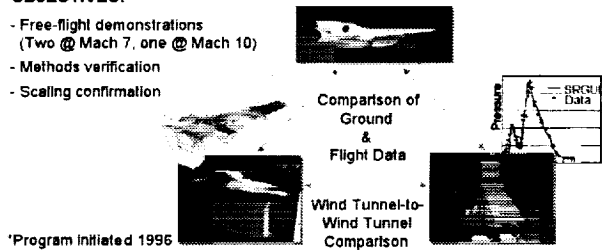- Methods verification
- Scaling confirmation

Comparison of
Ground
&
Flight Data

Wind Tunnel-to-
Wind Tunnel
Comparison

*Program initiated 1996

Figure 1. Goals/Objectives of Hyper-X Program.

Length: 12'4" (3.7 meters)
Width: 5'0" (1.5 meters)
Height: 2'2" (0.6 meters)
Weight: 3000 lb max
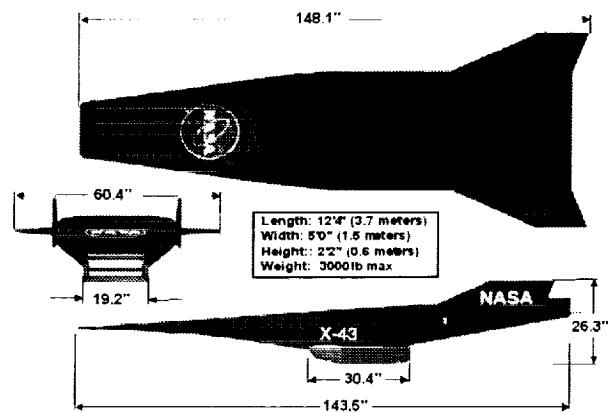
Figure 2. X-43 Vehicle Geometry.

Figure 3. X-43 Range Track.
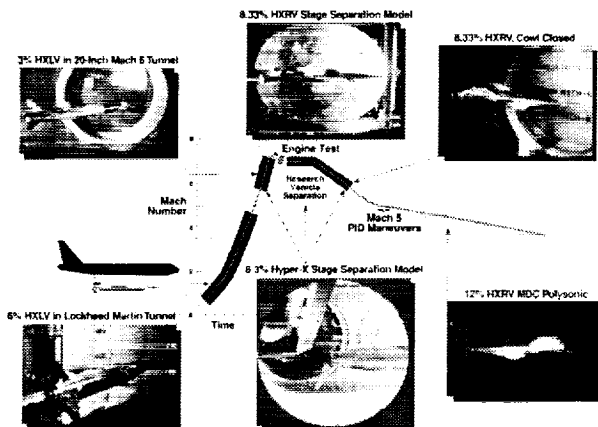
Figure 4. Aerodynamic Test Database.

Figure 5. Booster for X-43.

Actuator Controller
N₂ to Adapter
H₂O to Adapter

Horizontal Tail Actuator

Rudder Actuator

N₂ Tank

H₂ Tanks

Flight Management
Unit (FMU)

H₂O Tank
Silane Tank

Flush Air
Data Sensors
(FADS)
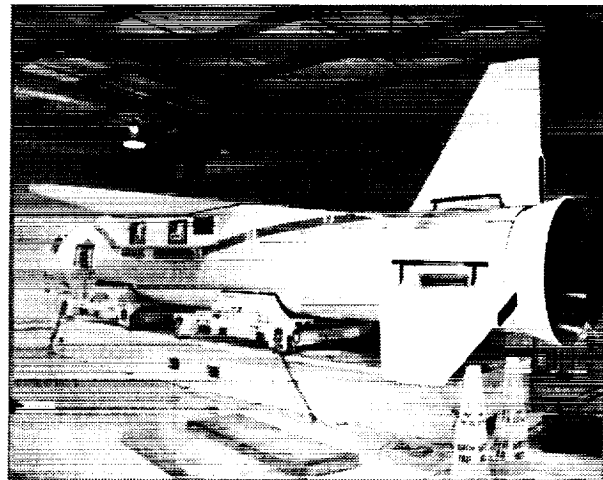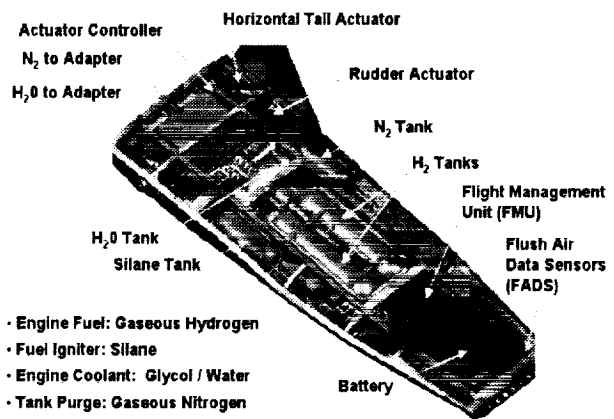
· Engine Fuel: Gaseous Hydrogen
· Fuel Igniter: Silane
· Engine Coolant: Glycol / Water
· Tank Purge: Gaseous Nitrogen
· Control Surface Actuators: Electric

Battery

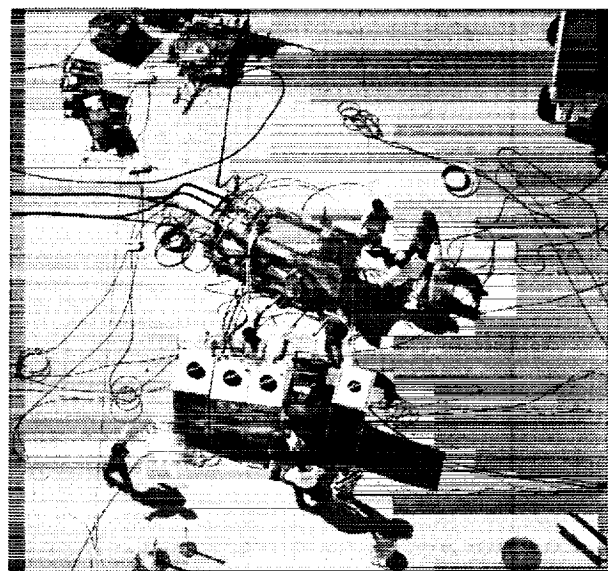**Figure 6.** X-43 Internal Layout.

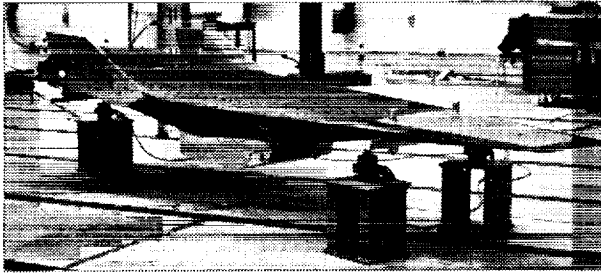**Figure 7.** Test Setup—Inert Blowdown/Mission Simulation.
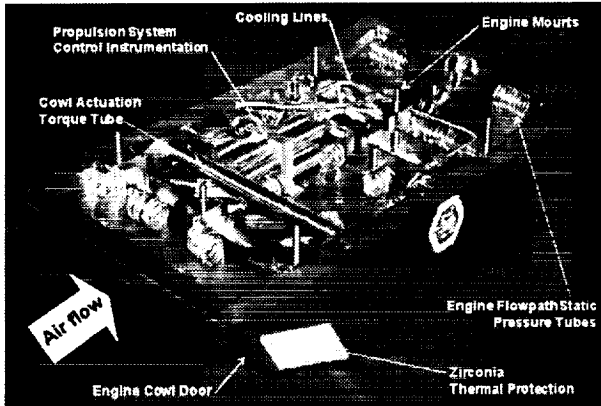
Figure 8. Ground Vibration Test.

Figure 9. Engine Module.

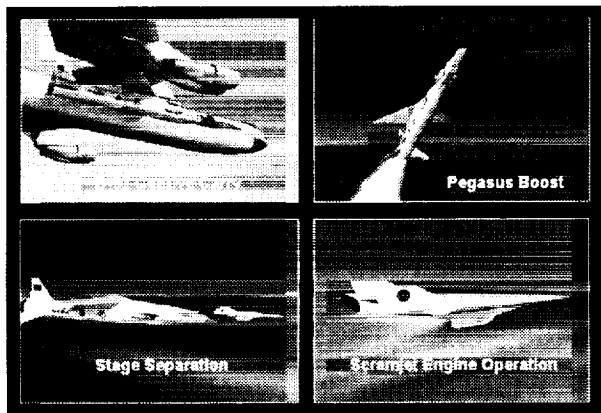Figure 10. X-43 FFS in 8'HTT: Real-Time Data/CFD Comparisons.
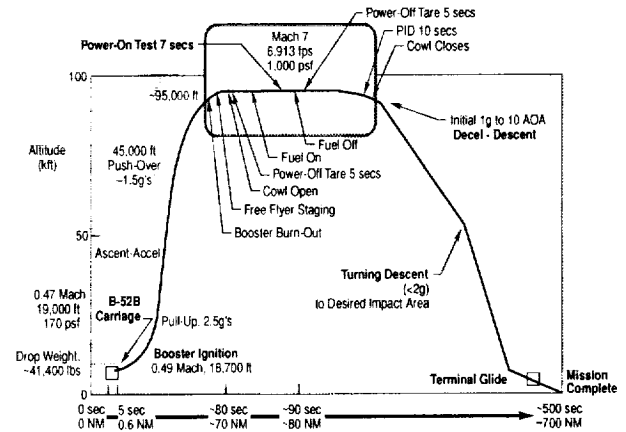
Figure 11. Hyper-X Key Mission Events.
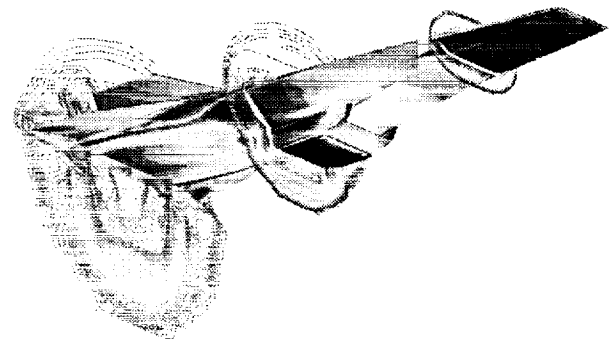
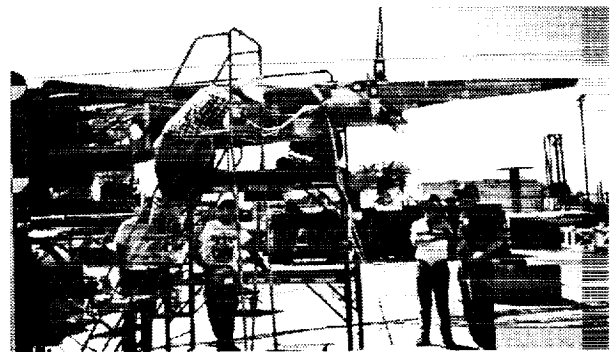Figure 12. X-43 Mach 7 Flight Trajectory.

Figure 13. CFD Solution.

Figure 14. Full-Scale Separation Hardware Test.

X- 43B "TBCC" Powered Vehicle
- 40'
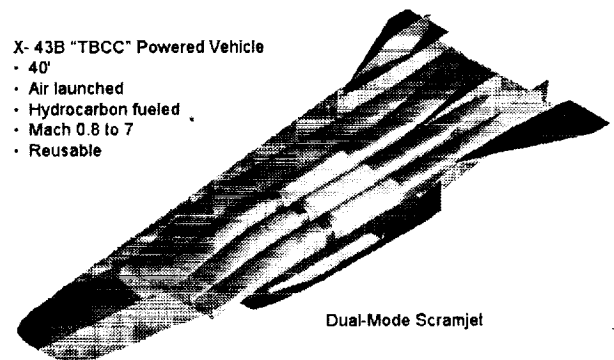- Air launched
- Hydrocarbon fueled
- Mach 0.8 to 7
- Reusable

Dual-Mode Scramjet

Figure 15. X-43B TBCC Conceptual Design.

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