Hyper-X: Flight Validation of Hypersonic Airbreathing Technology

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Abstract

This paper provides an overview of NASA's focused hypersonic technology program, i.e. the Hyper-X program. This program is designed to move hypersonic, air breathing vehicle technology from the laboratory environment to the flight environment, the last stage preceding prototype development. This paper presents some history leading to the flight test program, research objectives, approach, schedule and status. Substantial experimental data base and concept validation have been completed. The program is concentrating on Mach 7 vehicle development, verification and validation in preparation for wind tunnel testing in 1998 and flight testing in 1999. It is also concentrating on finalization of the Mach 5 and 10 vehicle designs. Detailed evaluation of the Mach 7 vehicle at the flight conditions is nearing completion, and will provide a data base for validation of design methods once flight test data are available.

Introduction

Airbreathing propulsion offers substantial advantages for hypersonic flight as illustrated in figure 1. It is an essential ingredient for sustained endoatmospheric hypersonic cruise applications such as "global reach" vehicles, and can significantly improve the performance of space launch vehicles. Airbreathing ramjet/scramjet (supersonic combustion ramjet) engines could improve mission effectiveness by reducing on-board propellant load in favor of payload and by increasing operational flexibility.

The fastest airbreathing engine-powered airplane, the SR-71, can cruise just above Mach 3, about 60% of the Mach 5 transition to the hypersonic regime. Ramjet powered vehicles have flirted with the hypersonic threshold. History's only hypersonic airplane, the Mach 6.7 X-15 of the 1960s, used only rockets—as have all space flight launch vehicles to date, the expendable ones and the reusable Shuttle alike. A rocket-powered vehicle's operational penalties (such as large infrastructure requirements), and its need to transport its own oxidant for combustion exacts large payload penalties. Current efforts (e.g., X-33, X-34) to achieve more aircraft-like, affordable access to space continue to rely solely on rocketry.

The pacing airbreathing hypersonic technology is certainly the scramjet engine. Hypersonic airbreathing propulsion has been studied by NASA for nearly 60 years. Numerous scramjet tests have been performed in a host of ground facilities (ref. 1-5). Significant improvements in design methods, experimental data bases, experimental facilities and testing methods, as well as demonstrated engine performance, have been made over the years. However, these tests have limitations. For example, all ground test facilities have some sort of contamination, vis-à-vis flight conditions. This contamination affects combustion (ignition, flameholding and combustion contribution to engine thrust), boundary layer formation and possibly fuel mixing characteristics. In addition, facility size generally limits the experiment scale, resulting in subscale or partial simulation of the scramjet flowpath. For example, no test has been performed on a complete airframe integrated scramjet. Another limitation is in data measured. Scramjet tests to date focus on engine thrust, component efficiencies, and combustion efficiency. Little if any effort is expended, for example, on quantification of lift and/or pitching moments. These measurements, and validation of the prediction of these will be important for any flight application of scramjet propulsion.

To enhance hypersonic airbreathing propulsion technology for application in the longer term, NASA has initiated the Hyper-X program (ref. 6). Four autonomous research flights at speeds up to Mach 10 will demonstrate, validate, and extend scramjet technology readiness for stepping into the hypersonic century. Each of the 12-foot-long, 5-foot-wingspan hypersonic aircraft, illustrated in figure 2, will have a single airframe-integrated scramjet. These vehicles will be boosted to flight test conditions using a modified Pegasus booster, air launched from the NASA DFRC B-52. The airframe design and flight test techniques are expected to prove readily adaptable for other advanced-propulsion-technology studies. This flight test of a scramjet-powered vehicle will focus technology on key propulsion-airframe integration issues, provide data to validate hypersonic vehicle design tools and ground based wind tunnel results, including identifying the impact of laboratory facility contamination effects on scramjet performance.

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The Hyper-X program is the product of an integrated government-industry effort. This paper presents highlights of the Hyper-X program and summarizes work performed over the past few years by both the Government and industry partners.

Program Goals and Approach

The goal of the Hyper-X program is to demonstrate and validate the technology, the experimental techniques, and computational methods and tools for design and performance predictions of hypersonic aircraft with an airframe-integrated dual-mode scramjet propulsion system. Accomplishing this goal requires flight demonstration of a hydrogen-fueled dual-mode scramjet powered hypersonic aircraft.

The technology portion of the program concentrates on three main goals:
1) risk reduction - i.e., preflight analytical and experimental verification of the predicted performance and operability of the Hyper-X flight vehicle,
2) flight validation of design predictions, and
3) continued development of the advanced tools required to improve scramjet powered vehicle designs.

This activity includes analytical and numerical methods applied to design the scramjet engine, wind tunnel verification of the engine, vehicle aerodynamic and thermal data base development, thermal-structural design, boundary layer analysis and control, flight control law development and flight simulation models.

The flight test part of the Hyper-X program focuses directly on the advancement of key technology readiness levels, elevating them from the laboratory level to the flight environment level required before proceeding with a larger, crewed X-plane or prototype program. In addition, the flight test portion must advance many flight test techniques.

Rather than starting the flight vehicle design on a clean sheet of paper, the program used the extensive National Aero-Space Plane (NASP) data base, and follow-on hypersonic mission study programs (ref. 7). Also, to meet budget and schedule, the flight research vehicle is based on existing design data bases, and off-the-shelf materials and components wherever possible. For example, the copper alloy engine materials and fabrication methods are similar to those used for many experimental wind-tunnel programs, rather than the flight weight actively-cooled material systems that will be required for operational hypersonic aircraft. So in summary, the Hyper-X program is aimed directly at demonstrating and flight-validating airframe-integrated scramjet-powered vehicle performance while concur-

rently continuing the development of design methods and experimental tools for future vehicle development.

Vehicle Design and Data Bases

Preliminary studies were performed by NASA to determine the minimum size flight research vehicle, as size is a major cost driver, and to develop a flight test approach. These studies indicated that a 10-12 foot vehicle could be "smart scaled" from a 200-foot operational concept and still demonstrate scramjet powered acceleration. In addition, evaluation of operability limits indicates that the scramjet will be operating far enough from flameholding and ignition limits so that hydrogen-fueled operation can be achieved. The 12-foot size was ultimately selected over a 10 foot vehicle because of small performance gains with minimal effect on overall program cost as it did not affect booster selection.

The conceptual design for the Hyper-X was performed between Feb. and May, 1995, by McDonnell Douglas Aerospace (MDA) under contract to NASA (ref. 8). Preliminary design of the vehicle (called the government candidate design) was completed between March and October, 1996 under contract to MDA, utilizing Phase III of the Dual-Fuel Airbreathing Hypersonic Vehicle Design Study. The Hyper-X research vehicle is essentially photographically scaled from previous study concepts. This allowed utilization of existing data bases, as well as rapidly converging to a controllable flight test vehicle with low trim drag penalty. The scramjet flowpath, on the other hand, was re-optimized for engine operability and vehicle acceleration, accounting for scale, wall temperature effects, etc. For example, the inlet contraction, fuel injector details and combustor length have been modified, rather than simply photographically scaled. Validation of the Hyper-X predicted performance will be considered as validation of the design process, and designs generated using these methods. Figure 3 illustrates results from the highest level tools used for design. This Reynolds Average Navier Stokes solution, produced using the GASP code, provides a complete solution of the flowfield of the flight vehicle at the powered test condition, and was used to verify the performance predicted using normal design tools (ref. 9).

Wind tunnel testing commenced in early 1996 to verify the engine design, develop/demonstrate flight test engine controls, develop experimental aero-dynamic data bases for control law and trajectory development and support the flight research activities. Mach 7 engine performance and operability was verified in reduced dynamic pressure tests of the "DFX" (dual-fuel experimental) engine in the NASA Langley Arc Heated Scramjet Test Facility (ref. 1). Figure 4 illustrates the extent of the full-scale, partial-width flowpath simulat-

ed in those tests. The shaded region represents the DFX engine. Preliminary experimental results for the Mach 5 and 10 scramjet combustor design have been obtained using the direct connect combustor module rig (DCM) and HYPULSE facility in the reflected shock mode (ref. 10). Additional tests will be performed at Mach 7, 5 and 10 using a partial width, full scale engine segment, which incorporates all variable geometry and cooling features of the Hyper-X flight engine. These tests will include full dynamic pressure and enthalpy, and flight controls and/or flight control simulation.

A preliminary aerodynamic data base was developed from results of fifteen experimental programs on 11 separate wind tunnel models utilizing over 1,000 wind tunnel runs. These tests were performed using 8.33% and 3.0% scale model tests of the Hyper-X research vehicle (HXRV) and the Hyper-X launch vehicle (HXLV) booster stack models respectively at Mach numbers of 0.8-4.6, 6 and 10. The aerodynamic data base includes boost, stage separation, research vehicle powered flight and unpowered flight back to subsonic speeds. The aerodynamic and propulsion data base is being filled in with additional wind tunnel tests. Figures 5 and 6 illustrate an 8.33% scale Hyper-X research vehicle model and a 3% booster stack model respectively, both in the NASA LaRC 20 inch Mach 6 tunnel at Langley.

Other work leading up to Hyper-X vehicle development contract award included control law development, preliminary trajectory evaluations (including some Monte Carlo uncertainty analysis, using the methods demonstrated in ref. 11) and aerothermal loads for the boost, separation, and flight test portion of the flight. Preliminary control laws (ref. 12) were developed for feasibility studies. For the powered part of the trajectory, longitudinal and lateral control laws were developed for angle-of-attack (AOA) and side-slip control. These include angle-of-attack and side-slip estimators which utilize motion data, aerodynamic data and atmospheric and flight condition data. Preliminary assessments of flight trajectories and stability margins for the longitudinal control laws, using conservative structural bending mode filters, demonstrate that the vehicle meets the flight test requirements. For example, figure 7 presents elevator position and angle-of-attack as a function of time, from stage separation through cowl closure. Initially the elevator controls are locked, and the vehicle is assumed to be at the launch vehicle stage separation condition of zero degrees AOA. Aerodynamic and separation forces drive the vehicle nose down initially, toward negative AOA. When active control is established the control system pulls the elevator (wing) up to regain zero degrees AOA. At 0.5 seconds from separa-

tion the flight controls switch to the powered flight attitude, which is 2 degrees AOA. For this simulation the cowl door opens between 2-2.5 seconds. Tare, no fuel operation, is maintained for 5 seconds. At 8 seconds after separation, ignitor (silane) and fuel flow are initiated. The ignitor is turned off at about 9.5 seconds, as the fuel is ramped up to full power. Full power, design fuel flow rate, is maintained from about 11 to 14 seconds in this simulation. The fuel ramp down and blowout is complete at 14.5 and 14 seconds respectively. Five seconds of engine tare data, and 15 seconds of performance identification maneuvers (PIDs) are performed before the cowl flap is closed 35 seconds after stage separation. During this process the elevator excursions are within reasonable limits, and vehicle response is adequate for the flight test. Preliminary analysis indicate that stability margins for the research are within acceptable margins.

The vehicle structural design and preliminary systems layout are presented in figure 8. Vehicle structure utilizes metallic (largely aluminum) keels, bulkheads and skins, all sized to meet vehicle stiffness requirements. Thermal protection consists of alumina-enhanced thermal barrier (AETB) tiles, which have been fully characterized for the space shuttle, carbon-carbon wing, tail and forebody nose leading edges. The majority of the wings and tails are high temperature steel. High pressure gaseous hydrogen (fuel), silane (scramjet ignition) and helium (fuel system and internal cavity purge) are contained in off-the-shelf fiber wound aluminum tanks. Instrumentation, flight and engine cowl control actuators and controllers, and the flight control computer are all either off-the-shelf or derivatives of existing units. A high pressure water system is included for engine cowl cooling for the Mach 7 and 10 flights.

Measurements and instrumentation for the Hyper-X flight test vehicle were established by a team composed of hypersonic technology "customers" and flight test personnel. The former are primarily interested in determination of propulsion and vehicle performance and obtaining local measurements for validation of design methods (propulsion, aerodynamic, thermal, structures and controls), whereas the latter are more concerned with monitoring vehicle systems for safety and understanding how the vehicle performs, or identifying failure modes. The program intentionally utilizes proven, reliable instrumentation methods, and a relatively small number of simple (pressure, temperature and strain gage) measurements to assure program schedule and cost goals. Off-the-shelf data system components are utilized to process and telemeter measurements. A schematic of the data system is presented in figure 9. Location/function of

the measurements can be summarized as follows:

Airframe — surface	64
Engine surface	63
Airframe structure	55
Fuel system	32
Control surfaces	10
Coolant/purge	17
O2/fire detection	24
Inertial and time	17
Attitude	8
Voltage/current	8
Miscellaneous	65

Of the 371 measurements, 115 are pressure, 96 are temperatures and 37 are strain gauge. The program is also carrying 40% spares for growth potential.

Vehicle Development

An industry team led by Micro Craft, Inc., of Tullahoma, TN, won the recently awarded $33.4 million cost-plus-incentive-fee contract. Micro Craft will build the vehicles and provide overall program management. GASL Inc. of Ronkonkoma, NY, is the scramjet and fuel system detail designer and builder. Boeing North American of Seal Beach, CA, is providing vehicle aero/thermal/structural design and analysis, TPS design and fabrication, and guidance, navigation, and control software and simulations. Accurate Automation Corp. of Chattanooga, TN, is responsible for instrumentation. On a separate contract, the Chandler, AZ, Launch Systems Group of Orbital Sciences Corporation will build the Hyper-X launch vehicles—a first stage derivative of their Pegasus launch system—that will boost the Hyper-X vehicles to the test conditions. In addition, Orbital has major responsibilities for integration with the flight test vehicle and flight test support.

Both contractors have completed Manufacturing Readiness Reviews and are in the process of purchasing material and components, and starting manufacturing. A program schedule, presented as figure 10, shows that the Mach 7 vehicle will be delivered in March, 1998. Subsequent vehicles will be delivered in yearly cycles. The first flight test is scheduled for July, 1999.

Ground Tests of Vehicle

After delivery, each vehicle will undergo extensive testing. In addition to normal validation and verification testing before flight, and integration and stage separation tests, the Mach 7 and 5 vehicles will be tested at flight conditions (Mach, pressure and enthalpy) in the Langley Research Center 8-Foot High-Temperature Wind Tunnel (8' HTT, see figure 11). The objective of these tests is to provide propulsive system verification, validate structural integrity, and verify operation of various components. This test provides flight test risk reduction and will allow comparison of the wind tunnel methods and results with flight performance. The resulting data will be directly compared with the in-flight measurements, but more important, with prediction for the wind tunnel and flight environments.

Each vehicle is being designed for insertion into the tunnel flow for a 30-second period, during which its scramjet can be operated. For safety, the gaseous hydrogen fuel will be supplied from outside the tunnel rather than from the vehicle's on-board fuel system. In addition, data will be transferred using an umbilical hook-up rather than telemetry. In all other respects the tested systems will be operated as they would be operated in flight. Specifications call for each vehicle to be capable of withstanding at least ten thermal cycles in the tunnel. This test also constitutes part of the preflight verification and validation testing checkout.

Each vehicle, in the interim between the 8' HTT tunnel tests and flight test, will undergo a variety of component and system preflight tests; first without the HXLV (6 months), then with the HXLV (1-month), and finally mated to the B-52 (2 months). These tests include aircraft-in-the-loop (AIL) vehicle integration, on/off conditions, and integrated engine system tests, HXRV-HXLV integration, electromagnetic interference (EMI) and combined systems tests. Following B-52 mating, additional tests will include ground vibration tests (GVT), EMI, combined systems (CST) and taxi tests.

Flight Tests

For the flight itself, the NASA Dryden B-52 will carry the HXLV-mounted research vehicle to launch altitude (see figure 12). The desired test condition for the Hyper-X in free flight is a dynamic pressure of 1000 pounds per square foot. For the Mach 10 tests, launch from the B-52 will take place at 40,000 feet. For the lower-speed tests, however, booster launch at lower altitudes will restrain the HXLV from over-accelerating the Hyper-X. For this same reason, in fact, the booster assembly will also incorporate up to 5 tons of ballast. For the Mach 5 test, the HXLV may even fly with a reduced propellant load. The research vehicle will be boosted to approximately 85,000 feet for Mach 5, 100,000 feet for Mach 7, and 110,000 feet for Mach 10.

Nominal flight sequence for the Mach 7 flight test is illustrated in figure 13. Following drop from the B-52 and boost to a predetermined stage separation point, the research vehicle will be ejected from the booster-stack and start the programmed flight test. Once separated from the booster, the research vehicle will establish unpowered controlled flight. The flight controller will

also determine the true flight conditions, which are required to correctly program the fuel system. Following the powered engine test and 15 seconds of aerodynamic parameter identification maneuvers (ref. 13 and 14) the cowl door will be closed. The vehicle will then fly a controlled deceleration trajectory to low subsonic speed. During descent, the vehicle control system will initiate S-turn maneuvers to dissipate vehicle energy. In the process, short-duration programmed test inputs will be superimposed on the control surface motions to aid in the identification of aerodynamic parameters.

Fully autonomously, these vehicles will fly preprogrammed 400-mile due west routes in the Western Test Range (WTR) off the California coast—while telemetering substantial volumes of test data. Following the Mach 7 test, one or more of the vehicles may be used for landing validation studies. These flight(s) would fly from north to south along the coast, within the WTR, and terminate at San Nicholas Island.

Summary
This paper discussed highlights of NASA's hypersonic technology program, Hyper-X, designed to elevate scramjet powered hypersonic flight technology from the wind tunnel to the real flight environment, a mandatory step for preceding to future vehicle applications. Design performance of the Mach 7 Hyper-X research vehicle has been confirmed by results from experimental wind tunnel tests. These experimental wind tunnel tests verified both the performance and operability of the scramjet engine, provided aerodynamic data bases required for the boost, stage separation as well as powered and unpowered flight of the research vehicle. Scaling of these results to flight conditions confirmed that the 12 foot vehicle will accelerate by scramjet power.

Flight test plans call for the first Hyper-X research vehicle to fly at Mach 7 in 1999. These tests are an integral part of, but not the entire program. Experimental results from these flight tests will be used to verify design methods, and provide direct comparisons with ground based wind tunnel tests. In addition, ground based experimental methods and design methods are continuing to be improved, and design studies for follow-on programs are continuing.

Acknowledgments:

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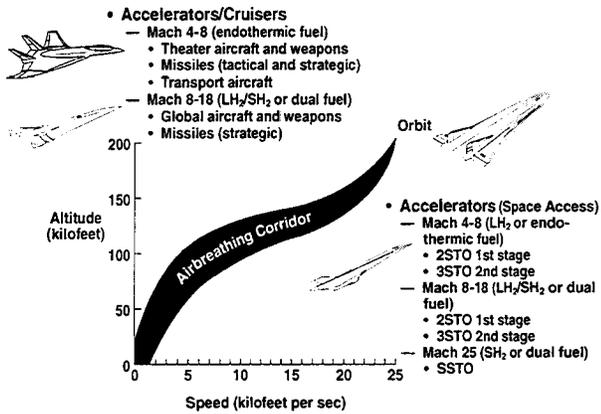
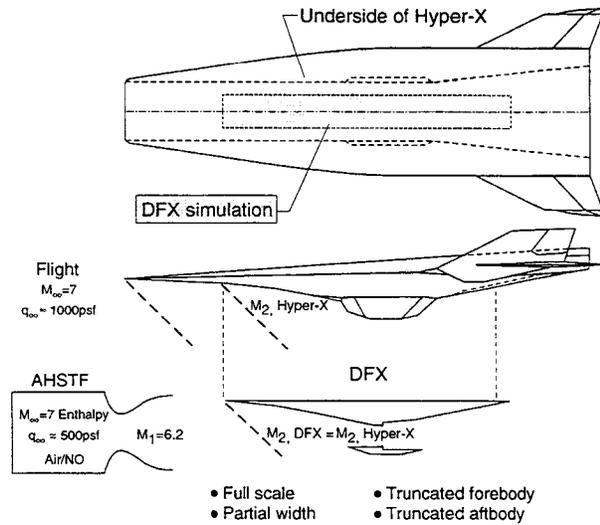**Figure 1.** Potential Airbreathing Hypersonic Vehicle Applications.

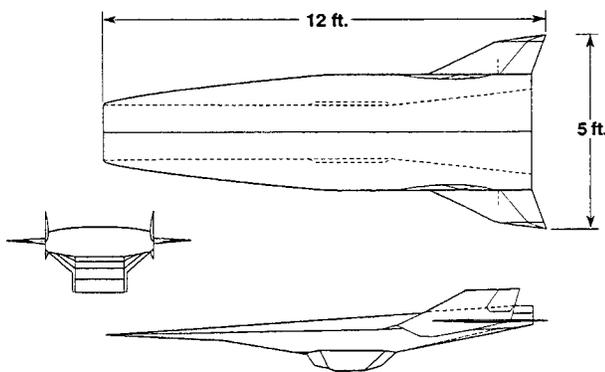**Figure 4.** DFX Simulation Compared to Hyper-X.
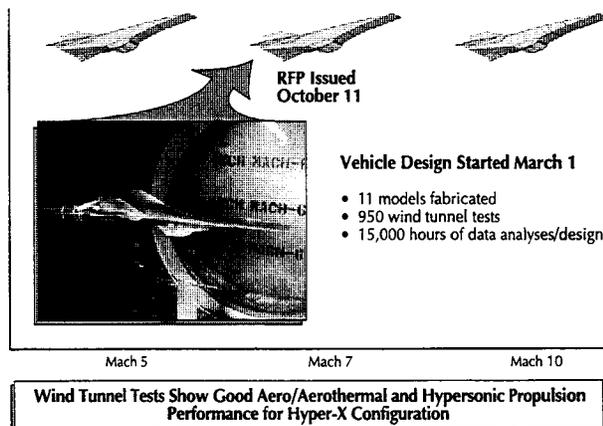

Figure 2. Hyper-X Research Vehicle Configuration.

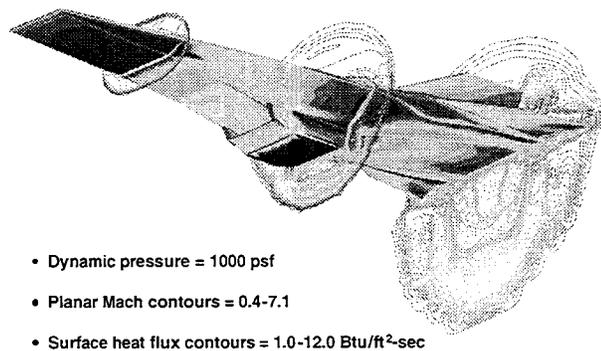**Figure 5.** 8.33% Research Vehicle Model in LaRC 20--inch Mach 6 Tunnel.

- Dynamic pressure = 1000 psf

- Planar Mach contours = 0.4-7.1

- Surface heat flux contours = 1.0-12.0 Btu/ft^2-sec

Figure 3. Hyper-X Mach 7 Powered CFD Solution.
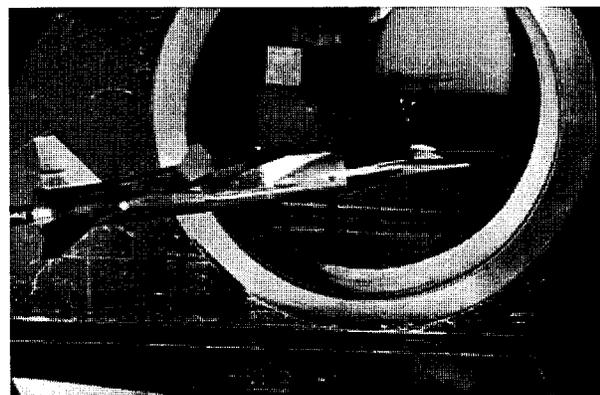
Figure 6. 3% Booster Stack Model in 20-inch Mach 6 Tunnel.

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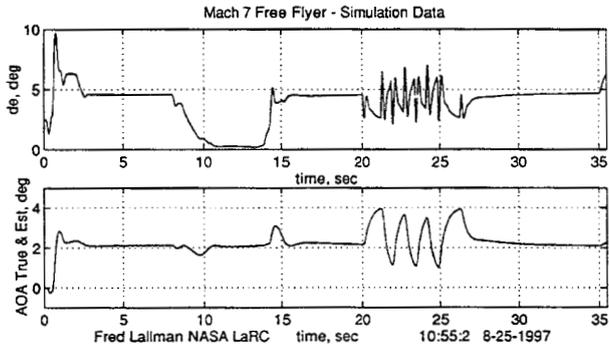
Figure 7. Flight Control Evaluation (rudder and angle-of-attack history).
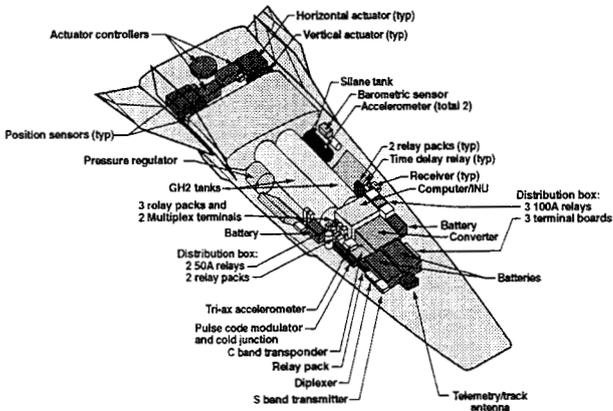
Figure 8. Hyper-X Equipment Layout.
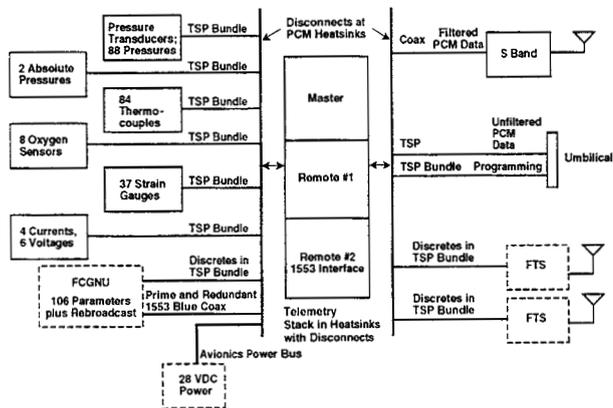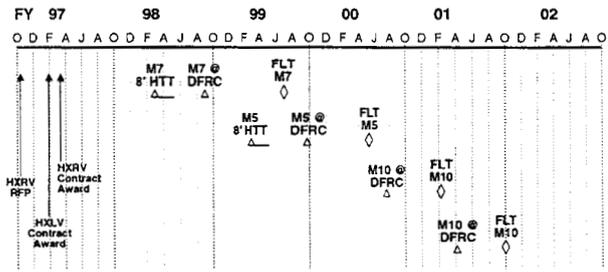

Figure 9. Instrumentation System.
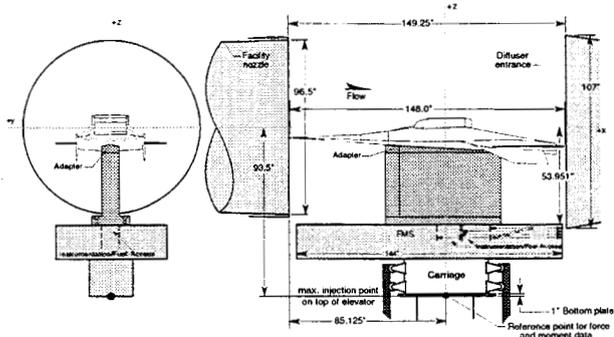

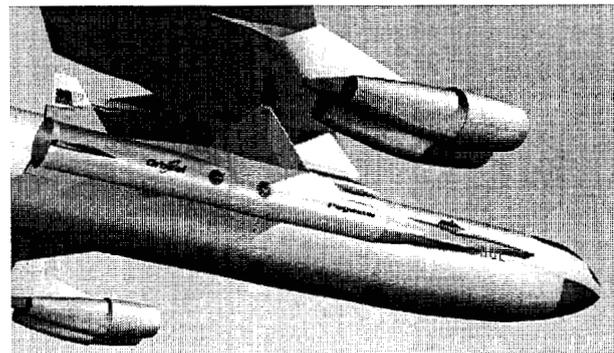**Figure 10.** Hyper-X Schedule.

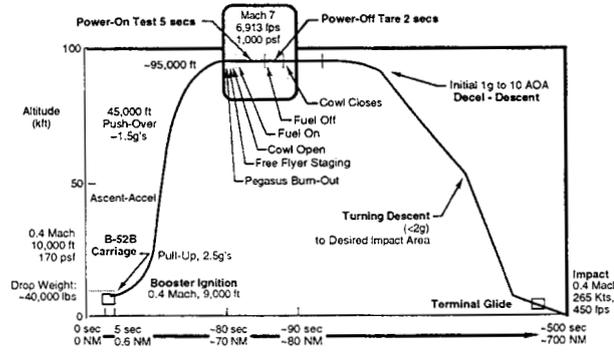**Figure 11.** Vehicle Installation.

Figure 12. HXLV on B-52.

Figure 13. Nominal Hyper-X Flight Trajectory.

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