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Airbreathing Hypersonic Systems Focus at NASA Langley Research Center

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by
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ABSTRACT

This paper presents the status of the airbreathing hypersonic airplane and space-access vehicle design matrix, reflects on the synergies and issues, and indicates the thrust of the effort to resolve the design matrix and to focus/advance systems technology maturation. Priority is given to the design of the vision operational vehicles followed by flow-down requirements to flight demonstrator vehicles and their design for eventual consideration in the Future-X Program.

INTRODUCTION

Airbreathing hypersonic vehicles encompass cruise airplanes with speeds from Mach 5 to 12, and space access vehicles that accelerate from takeoff to orbital speeds. (Missiles are a part of the matrix but will not be included in this paper.) The cruiser designs reflect high lift-to-drag whereas the accelerators reflect low drag per unit inlet capture; thus, these engine/airframe integrated designs that are prescribed for acceleration missions attribute a much larger percentage of their fuselage cross section to the propulsion flowpath.

One of the more design influencing items is fuel. The hydrogen-fueled vehicles must be very volumetrically efficient to contain the low density fuel and thus tend to be a bit bulgy (more conducive to lifting bodies or wing bodies) whereas with hydrocarbon-fueled vehicles, the concern is loading because of the high density fuel; thus, they may tend more towards waveriders which are not usually as volumetrically efficient. On the other hand, hydrocarbon fuels (endothermic) are limited in engine cooling capacity to below about Mach 8, depending on contraction ratio and dynamic pressure (ref. 1).

The airbreathing hypersonic horizontal-takeoff, horizontal-landing (HTHL) vehicles matrix being explored in Langley's Systems Analysis Office/Hyper-X Program Office/Aerospace Transportation Technology Office (SAO/ HXPO/ATTO) is presented in figure 1 along with the airbreathing corridor in which these vehicles operate. It includes endothermically-fueled theater defense and transport aircraft below Mach 8; above Mach 8, the focus is on dual-fuel and/or hydrogen-fueled airplanes for long range cruise, first or second stage launch platforms and/or single-stage-to-orbit vehicles.

The space-access portion of the matrix has been expanded and now includes pop-up and launch from hypersonic cruise platforms as well as vertical-takeoff, horizontal-landing launch vehicles. Also, activities at the NASA centers are becoming integrated. For instance, LaRC, LeRC and MSFC are now participating in an advanced launch vehicle study of airbreathing systems for single-stage-to-orbit (SSTO).

The cruise aircraft portion of the matrix has been focused on Mach 10 global reach designs for the past several years; this design activity led to the scramjet integrated Hyper-X configuration (ref. 2) of which a 12 foot research vehicle is scheduled for flight tests at Mach 7 in 2000 (two) and Mach 10 in 2001. The emphasis now is on resolving Mach 7 operational vision airplane designs and a requirements/technology flowdown to a Hypersonic Systems Integration Demonstrator (HySID, ref. 3).

The purpose of this paper is to present the status of the airbreathing hypersonic airplane and space-access vehicle design matrix, reflect on the synergies and issues, and indicate the thrust of the effort to resolve the design matrix and to focus/advance systems technology maturation.

IMPETUS FOR DIRECTION/THRUST

NASA's mission includes developing technology in support of endoatmospheric and exoatmospheric vehicle systems for both future military and civilian needs. Airbreathing hypersonics certainly fits within this mission perspectus and is a major part of NASA's Aeronautics and Space Transportation Technology Enterprise.
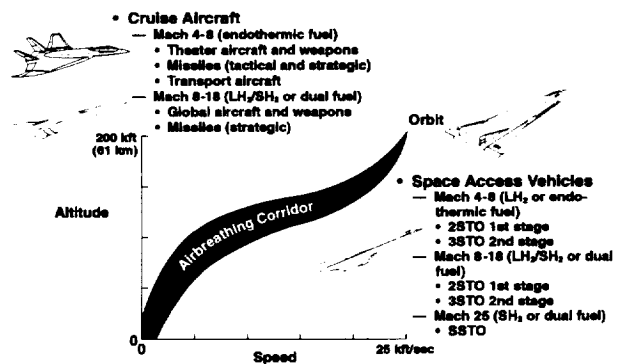

Figure 1. Potential airbreathing hypersonic vehicle applications.

Advancing technology from the laboratory environment to the flight environment is being emphasized throughout the agency; hypersonic systems technology is at a readiness level that accommodates such endeavors as reflected by the Hyper-X Program to flight test an airframe integrated scramjet research vehicle at Mach 7 and 10 (ref. 3).

The recent cruise airplane and space-access airbreathing hypersonic systems studies matrix is presented in figure 2. The Hyper-X configuration evolved from the cruise airplane side of the matrix, namely, the Mach 10 lifting body study in which a dual-fuel, global reach, reconnaissance (Recce)/strike/suppression of enemy air defenses (SEAD) vehicle was designed. However, as indicated in figure 2, there are considerable synergies between the two classes in terms of configurations, propulsion systems, engine integration concepts, thermal management approaches, fuels and subsystems, and thus the Hyper-X research vehicle drew from and supports the technology advancement of the entire matrix to some degree.

Looking beyond Hyper-X, the Future-X Program (fig. 2) being established by NASA to promote flight demonstrations offers a substantial opportunity to continue to advance both hypersonic technologies and the vision vehicles these technologies support. The Future-X Program is to supposedly consider proposals for flight demonstrators and/or demonstrations in the trailblazer and/or pathfinder classes during the third quarter of the millennium (2000).

On the airplane side of the matrix (fig. 2), a hypersonic systems integration demonstrator (HySID) concept (ref. 3) which would demonstrate the technologies critical to Mach 7 aircraft from horizontal takeoff and thus compliment the Hyper-X flight demonstrations at Mach 7 and 10 could be an excellent candidate for consideration in the Future-X Program. The results of a HySID conceptual design activity will be discussed later in this paper including constraints which provide traceability to the Mach 10 global reach design (ref. 3) and Hyper-X (ref. 2). However, the missing link in this support rationale is the design of an endothermically fueled Mach 7 vision operational vehicle as indicated by the dashed stem lines to the Mach 7 lifting-body in figure 2. With this Mach 7 design in hand, a HySID concept could be evolved/refined with flowdown requirements/ constraints from both a Mach 10 Dual-Fueled vision operational design and a Mach 7 Endothermically-Fueled vision operational design. Thus, the Mach 7 design activity is currently one of the

FLIGHT DEMONSTRATION

Figure 2. Hypersonic airbreathing system studies matrix.

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higher priorities for initiation. Results from the earlier HySID design activities indicate that considerable synergy will exist between the two vision vehicles in terms of configuration and engine integration, and thus a Mach 7 vision vehicle design could possibly reinforce the current HySID concept to be discussed later.

On the space-access side of the matrix (fig. 2), there is a strong possibility that an excellent candidate will emerge from the Advanced Reusable Technologies (ART) Project within the Advanced Space Transportation Program (ASTP) where the focus is on Rocket Based Combined Cycle (RBCC) propulsion systems and the space access configurations/vehicles they engender. As part of this program, NASA's LaRC, LeRC and MSFC have joined in an Airbreathing Launch Vehicle (ABLV) study to investigate the airbreathing systems in the operational vision vehicle matrix and hopefully resolve the more viable SSTO configurations for both horizontal and vertical takeoff/horizontal landing systems. From this refined vehicle matrix and the technologies that sustain it, demonstrator vehicle designs would be evolved for consideration as candidates for the Future-X Program also.

AIRPLANES

For hypersonic airplanes, range for a given payload at a given cruise Mach number is a good figure of merit (ref. 1). This figure of merit is impacted by the fuel selection. Calculations indicate that Mach 8 is approximately the cruise speed limit to which a dual-mode ramjet/scramjet can be cooled with state-of-the-art endothermic fuels/cooling-techniques (depending on flight dynamic pressure and inlet contraction ratio, ref. 1). On the other hand, liquid hydrogen has much more cooling capacity and provides considerably more range than hydrocarbons for the same Mach number as indicated in figure 3. The range of hydrogen fueled vehi-

Figure 3. Range potential for hypersonic airplanes.

cles maximizes at about Mach 10, beyond the cooling limits of the endothermic hydrocarbons. The takeoff gross weight (TOGW) of the hydrocarbon-fueled airplane is much greater for the same cruise Mach number than that for hydrogen-fueled airplane; the dry weight (DW) is slightly higher (ref. 1).

The shape of the vehicle and the systems that constitute it will be different for hydrocarbon-fueled airplanes than for the hydrogen fueled ones because of the fuel density and resultant planform to accommodate loading. Therefore, the discussion will be broken along these lines with the assumption that the speed breakpoint is Mach 8 even though hydrogen-fuel systems could be designed for lower cruise Mach number. The hybrid approach, dual-fuel, will be considered as a subset of hydrogen-fueled systems.

All hypersonic airplanes considered are under-slung-nacelle/engine-airframe integrated configurations in that the forebody serves as an external precompression surface for the engine inlet and the aftbody as a high expansion ratio nozzle. The differences are in whether the engine integration embodies a single duct or a two-duct approach, or something in between.

Design Architectures

The status matrix for hypersonic airplane designs is presented in references 4, 5 and 6. It consists of a Mach 5, endothermically fueled, waverider configuration design (fig. 4, ref. 4) and a Mach 10, dual and/or hydrogen fueled, lifting body configuration design (fig. 5, refs. 5, 6). Both were designed for Recce/Strike/SEADS missions and included 10 klb. payloads in 2,000 ft^3 payload bays.

Performance estimates for the Mach 5 waverider design indicate a 6,000 nm tanker-to-tanker range with a refueled gross weight of 550 klbs.; TOGW was 400 klbs. with a DW of 141 klbs., and a vehicle length of 113 ft.

The mission radius of the Mach 10 dual fuel design would be about 8500 nm in a 200 ft. long vehicle with a TOGW of 500 klbs. The mission would consist of take-off in a balanced field length of under 15,000 ft., acceleration and climb to hypersonic cruising altitude and Mach number, Mach 10 cruise, completion of a 2.5g turn at the target, and an unpowered, maximum L/D descent to a subsonic rendezvous with tankers for a multiple endothermically refueled subsonic cruise return to base (fig. 6). The airplane would accelerate to Mach 4.0 on endothermically-fueled air core enhanced turboramjets (AceTRs) and transition to the hydrogen-fueled, dual-mode scramjet for continuation of the mission; the subsonic return segment is on the endothermically fueled AceTRs.
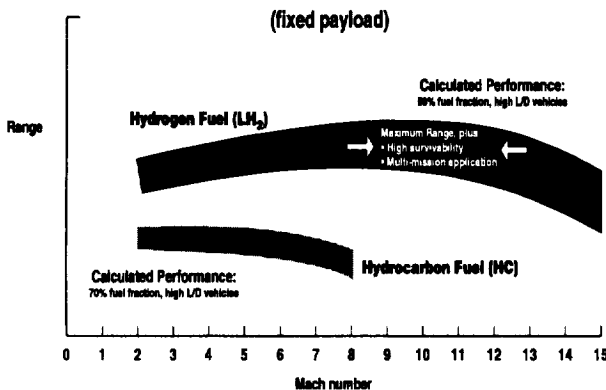
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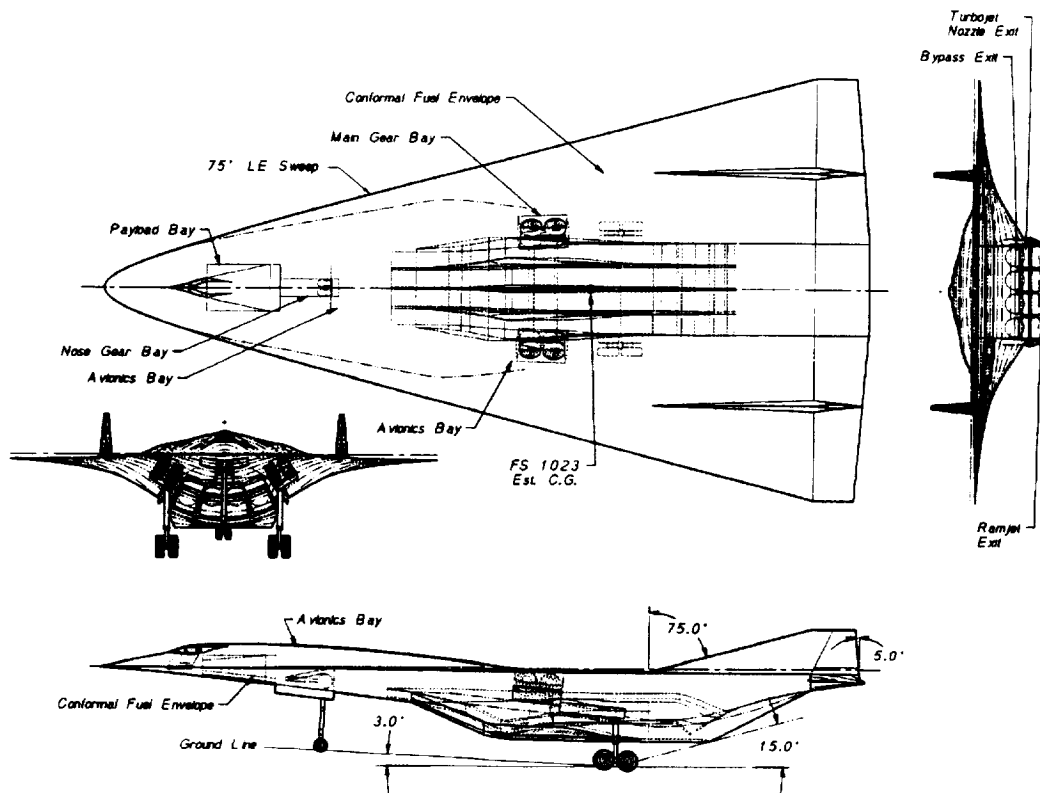
Figure 4. Aircraft three-view.

Labels in Figure 4:
- Conformal Fuel Envelope
- Main Gear Bay
- 75° LE Sweep
- Payload Bay
- Nose Gear Bay
- Avionics Bay
- Avionics Bay
- FS 1023 Est. C.G.
- Turbojet Nozzle Exit
- Bypass Exit
- Ramjet Exit
- Avionics Bay
- Conformal Fuel Envelope
- Ground Line
- 75.0°
- 5.0°
- 3.0°
- 15.0°
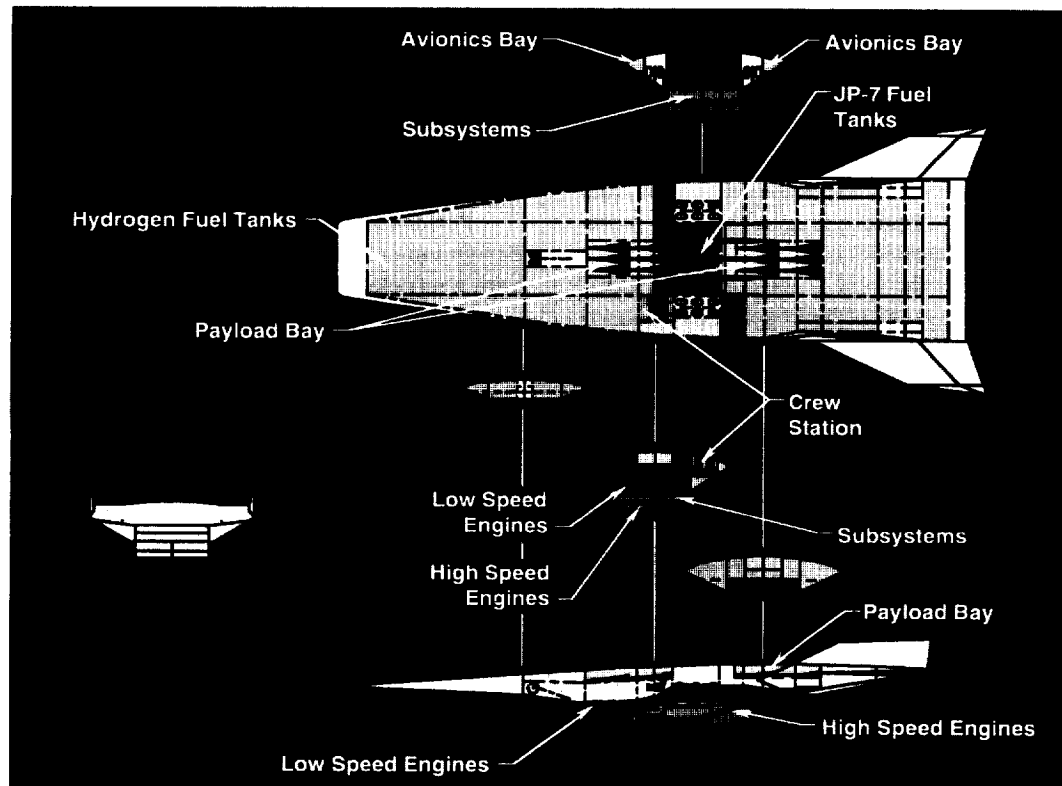
Figure 5. Dual-fuel lifting-body cruiser design.

Labels in Figure 5:
- Avionics Bay
- Avionics Bay
- Subsystems
- JP-7 Fuel Tanks
- Hydrogen Fuel Tanks
- Payload Bay
- Crew Station
- Low Speed Engines
- Subsystems
- High Speed Engines
- Payload Bay
- Low Speed Engines
- High Speed Engines

4
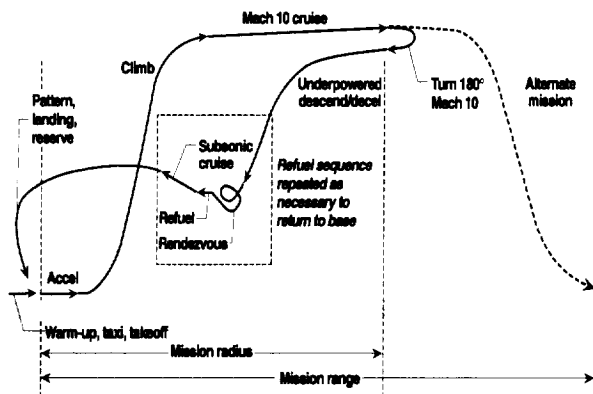
Figure 6. *Candidate hypersonic cruise mission scenarios.*

The Mach 5 waverider has a single inlet with a variable geometry, internal flow diverter for the over/under ducting downstream of the throat; whereas, the Mach 10 over/under engine integration has separate split inlets (ref. 3); the two-inlet approach provides the shortest inlet/diffuser system. The Mach 5 vehicle has a single thermal management system employing endothermic fuel for active cooling of the critical systems and engine. The Mach 10 vehicle has two active cooling systems although integrated; the endothermic system is similar to that for the Mach 5 vehicle, but at Mach 4 to 4.5 the cooling load is switched to a separate but interwoven hydrogen circuit (ref. 3).

The structural architecture is totally different for the two airplane designs. The Mach 5 design would consist of a hot structure with integral tanks lined with insulation and containing flexible fuel cells (ref. 4). Honeycomb sandwich panels of a monolithic titanium alloy were selected for airframe skins. Wing and tail leading edges were designed with a titanium matrix composite (TMC).

The airframe for the Mach 10 cruise airplane would be a cold structure with integral slush-hydrogen (SH2) tanks (fig. 5, ref. 7). A conformal graphite-epoxy (Gr/Ep) tank design would be used since the maximum pressure differential for the slush hydrogen tank is only 5 psi. Graphite composite would constitute the remainder of the fuselage structure. The all-moveable wings would be hot structure (TMC). The thermal protection system would consist of Internal Multiscreen Insulation (IMI) covered with a heat shield of carbon/silicon-carbon (C/SiC) panels on the windward surface and a Tailorable Advanced Blanket Insulation (TABI) on the lee surface.

Design/Technology Challenges

The technology challenges for the Mach 5, endothermically fueled, waverider airplane and the Mach 10, dual-fuel and/or hydrogen fuel, lifting-body airplane are similar with considerable commonality

(ref. 7). Both require the development of turbojet and/or turboramjet and ramjet and/or dual-mode scramjet power plants, and integration in a viable over/under arrangement that will accommodate an efficient inlet system and allow a smooth transition from the turbojet and/or turboramjet in the upper position to the ramjet and/or dual-mode scramjet in the under position. These engine systems must be integrated together in both a viable vehicle flowpath configuration and a viable mechanical design with actuation/seal systems that allow variable geometry operation over a broad Mach range with engine mode transition. Given the sensitivity of inlet bleed on range and complexity, designing high performance inlet systems with minimum or no bleed is also a challenge worthy of pursuit.

Due to the relatively long cruises at high speed , the thermal protection systems (TPS) and the thermal management system (TMS) designs must be analyzed as an integrated system and optimized interactively. The TMS must provide adequate cooling for the dual-mode combined-engine structure/subsystems, the airframe leading edges, crew station, avionics, radar, hydraulics, and electrical power; a reasonable weight, direct-cooling non-integral heat exchanger for the ramjet/dual-mode scramjet that allows high fuel injection temperatures without surface oxidation is a technology readiness concern. One of the biggest challenges for the TMS is cooling of the aircraft(s) during high-speed deceleration when fuel flow requirements for combustion are low.

For the Mach 10 vehicle, the challenge is to develop conformal, integral, graphite-epoxy, slush-hydrogen tankage; graphite composite fuselage-structure and IMI /heat-shield TPS with integrated purge. Also, the wing box and airframe interface for the rotating TMC wings require some development. Perhaps the biggest challenge is to overcome negative paradigms with respect to the use of SH2 and to establish the infrastructure required for its use. Conversely, designer/specialty fuels are being examined with the possibility of reducing the need for slush hydrogen.

In the controls area, neural networks (ref. 8) appear to offer a significant advancement for both the airframe and engines controls and the coupling between the two. Accurate Automation Corporation is currently in the process of demonstrating a neural network for the rudder control of the Mach 5 waverider configuration at subsonic speeds in their LoFLYTE™ flight test vehicle (8 ft. long); they will flight test the inner-loop within the next six months in a new Phase I SBIR activity.

Emphasis For Future Airplane Design Activities

In the Mach 10, Dual-Fuel airplane design study, osculating-cone waverider (ref. 9) and lifting-body config-

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urations were examined. The aerodynamic efficiency (L/D) build-up for these configuration classes is given in figure 7, ref. 10. The inviscid L/D favors the waverider, but the trimmed L/D at Mach 10 was the same. The lifting-body configuration was selected in the Mach 10 "Dual-Fuel" study because it is closer to a Sears-Haack area distribution, had higher fineness ratios and thus lower drag in general and lower transonic drag in particular. The latter is very important since it sizes the low speed engines (in the over position) which are coupled in mechanical integration to the sizing of the high-speed engines (in the under positions). The high speed engines were sized for acceleration from Mach 4.5 to 10 and to accommodate an appropriate lower throttle position at Mach 10 cruise to maximize the product of L/D and specific impulse (Isp).

The above perspective suggests that perhaps the use of the classic waverider configuration below Mach 8 (fig. 4) as an optimum approach should be reexamined. This may be correct, but it should be kept in mind that at Mach 10 and above, the lifting-body is a quasi-waverider itself. Below Mach 8 with the exclusive use of hydrocarbon/ endothermic fuels, the higher density of the fuel would place more emphasis on loading and lifting capability, which is an attribute of the waverider. Also, subsequent analysis has shown that a relaxation in the planar shock width constraint of the osculating-cone waverider can reduce the width and associated trim drag of the configuration (ref. 9). Nevertheless, the results of the HySID study presented in the next section suggest that a lifting-body-derivative configuration should be given serious consideration in an endother-mically-fueled operational, vision vehicle design study for airplanes with cruise speeds below Mach 8.

Hypersonic Systems Integration Demonstration (HySID) from Mach 0 to 7

The Hyper-X Program will provide flight demonstration at Mach 7 and 10, only. Flight demonstrations for the critical technologies from horizontal take-off to Mach 7 must also be addressed. HySID, an acronym given to a conceptual flight vehicle design study conducted by Boeing, under the sponsorship of NASA LaRC from May to September 1997, would have the objective of demonstrating integrated hypersonic air-breathing system performance from Mach 0 to 7 and the technologies applicable to operational hypersonic Recce/Strike/SEADS airplanes, Uninhabited Combat Air Vehicles (UAV's) and Space Access Vehicles (SAVs).

The critical technology to be demonstrated would be the transition from the turboramjet (over position) to the dual-mode scramjet (under position) near Mach 3. A number of advanced propulsion systems were investigated as potential flight demonstration testbed options; they included the AceTR, ATEGG, RBCC, PDE, etc. In addition, HySID technology demonstrations examined included plasma aerodynamic, magneto-hydrodynamic and virtual inlet/power generation as well as hypersonic airborne laser operations and vehicle-related technology demonstrations such as structures and materials, subsystems and flight controls.

The first question that came to mind when embarking on this study was why not use the Hyper-X configuration. The answer lies in the planform loading for a sub-scale vehicle of this type. If the 12 ft. Hyper-X research vehicle had the density of the Mach 10 dual-fuel global-reach airplane from which it was scaled/modeled, it
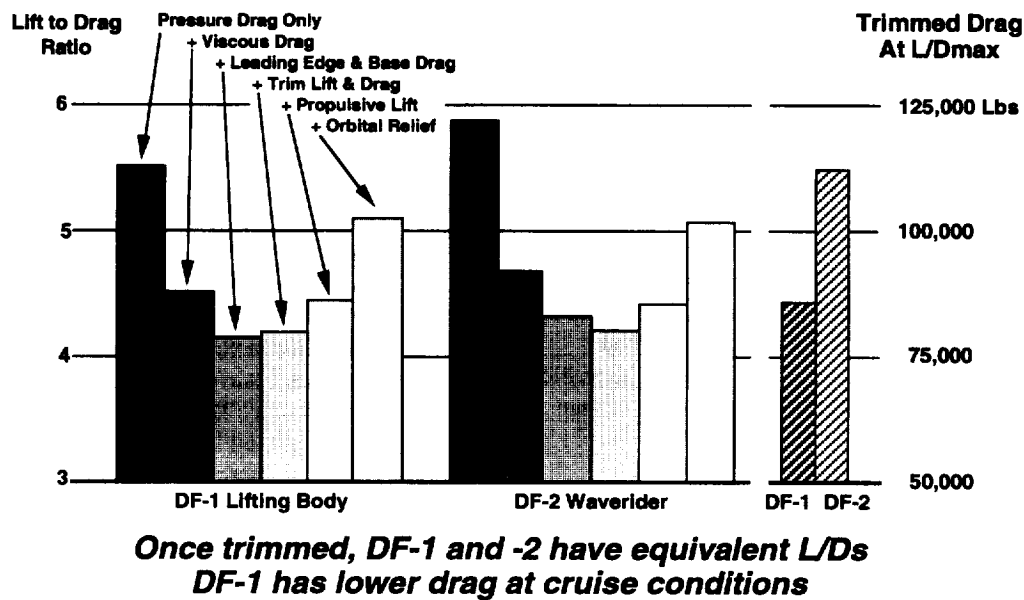

Once trimmed, DF-1 and -2 have equivalent L/Ds
DF-1 has lower drag at cruise conditions

Figure 7. Aerodynamic results: DF-1 & 2.

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would weigh about 250 lbs....it actually will weigh about 2800 lbs. Also given that the primary focus on HySID is hydrocarbon fuels, not lower density dual-fuel or liquid-hydrogen, and that it must takeoff horizontally, a new configuration is required which will still have traceability to the Hyper-X configuration. The requirements/ constraints for the HySID configuration/ vehicle study are given in figure 8. The key to providing compatibility with Hyper-X was that the HySID configuration would retain a 2-D propulsion flowpath. Starting with Hyper-X, the HySID configuration evolved from rotating horizontal controls to fixed wings with canards for pitch stability/control. Circular cross-section fuel tanks were integrated on each side of the 2-D flowpath and adjustments were made to increase the fineness ratio and tailor the area distribution. The resultant HySID configuration is shown in figure 9 and the structural arrangement (aluminum with TPS) is shown in figure 10.

Three vehicles, two self-propelled and one rocket boosted, were designed and performances examined. Only the smaller self-propelled vehicle will be discussed here. It was 43 ft. long with a TOGW of 30.6 klbs. with a performance capability of 300 nm at Mach 3 when taking-off and landing at the same base. For landing at a second base (no turns), some 700 nm out,

- **Capable Of Mach 7 Flight**
- **Reusable**
- **Affordable**
- **2-D Propulsion Flowpath (compatible with Hyper-X)**
- **Interchangeable Propulsion Systems**
- **Hydrocarbon, Dual Or Liquid Hydrogen Fueled**
- **Operational Vehicle Technology Demos**
- **Capable Of Multiple Launch Modes**
- **Able To Accelerate At All Test Conditions**
- **Autonomously Controlled**
- **Instrumentation To Measure Performance And Vehicle Health**

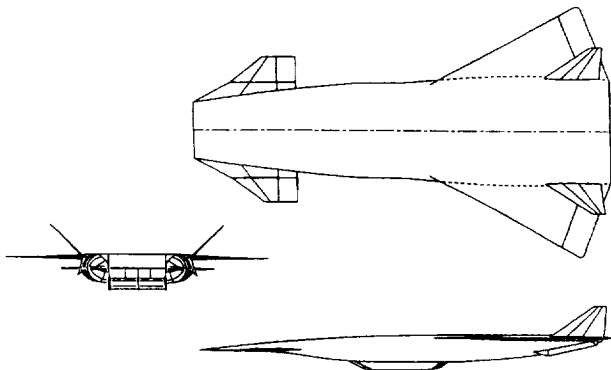**Figure 8.** Test vehicle requirements/constraints.

Figure 9. HySID Canard-Wing Configuration concept.

the vehicle could attain Mach 7. The mission analyses (fig. 11) were calculated assuming AceTR performance to Mach 3 where the transition to an underslung dual-mode ramjet/scramjet occurred. Conventional turbo-ramjets such as the GE J-85 and modified P&W J-60 were examined; they appeared marginally viable.

HySID appears to be an excellent testbed with the potential capability to flight test a myriad of pertinent systems. Also, the HySID configuration class may be attractive for future operational vehicles as suggested earlier. This stems from the fact that it has high lift (required for hydrocarbon fuel loading), low transonic drag for sizing turbojet engine (advantageous area distribution), high aerodynamic efficiency at cruise conditions, effective controls (canards and twin vertical rudders) and efficient packaging.

SWB Inc. has just been awarded a Phase I SBIR contract to establish the feasibility of constructing a 15-ft subsonic flight testbed remotely piloted vehicle (RPV) of the HySID configuration. In the same vain, ERC Inc. has been awarded a Phase I SBIR contract to examine the design, development (including ground testing) and flight demonstration (focus on HySID) of plasma aerodynamic, magneto-gasdynamic, magneto-hydrodynamic and fuel reclamation devices pertinent to the enhanced performance of hypersonic vehicles.
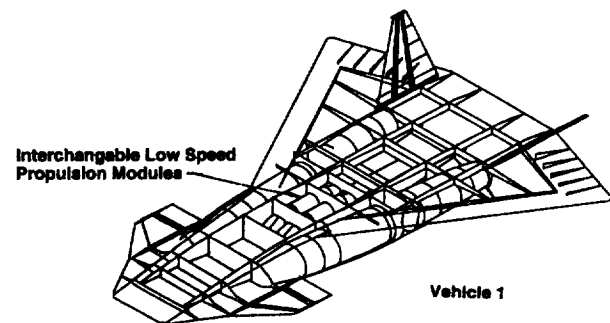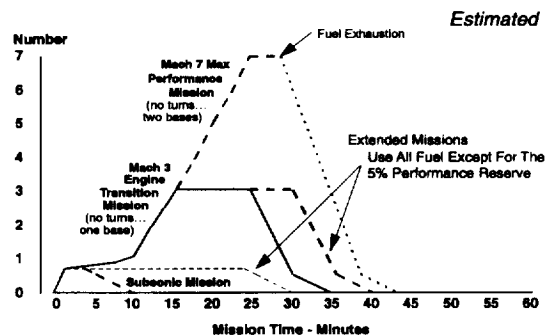

Figure 10. Structural arrangement.

Figure 11. Mission analyses.

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SPACE-ACCESS VEHICLES

Airbreathing space-access vehicles potentially have takeoff gross weight and mission flexibility (launch window, orbital offset, rapid rendezvous, etc.) advantages (fig. 12) over their rocket powered counterparts. The relative disadvantages of present airbreathing designs lie in technology readiness and dry weight (ref. 7), both of which impact initial cost (DDT&E). The goal here is not only to reflect the status of the airbreathing space-access design matrix, but indicate the potential to advance the design matrix toward eliminating the aforementioned relative disadvantages. Of course, operations is a major cost of any reusable launch system; this is yet to be resolved in favor of either the airbreather or rocket propelled systems and will require a more extensive prediction capability/ database than presently exists.

Single-Stage-To-Orbit Vehicles

A design study was performed of an SSTO airbreathing-propelled orbital vehicle with rocket propulsion augmentation in NASA's Access-to-Space study (ref. 11 and
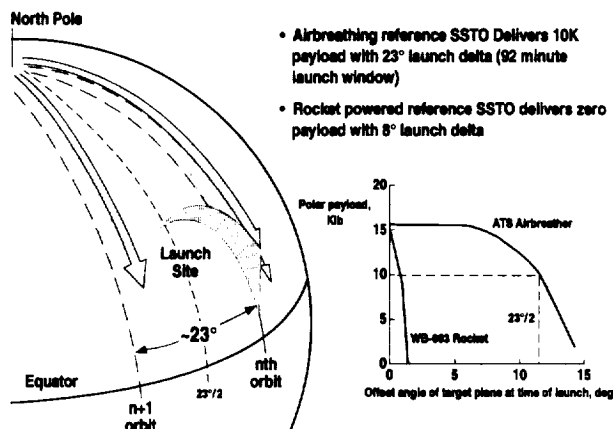
Figure 12. Rapid rescue/rendezvous.

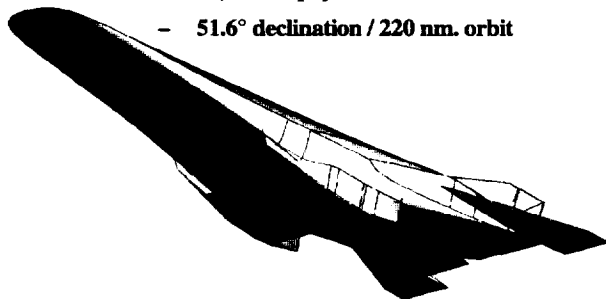- 25,000 lb. payload
- 51.6° declination / 220 nm. orbit

Figure 13. Reference airbreathing SSTO vehicle.

12; Option III Team). This design (fig. 13) provided a reference architecture. It was designed to carry 25,000 lbs. of payload in a 15 ft. x 15 ft. x 30 ft. rectangular payload bay with "shuttle-like doors" to an orbit of 220 nm, 51.6° inclination (reference mission), then dock with a hypothetical space station for delivery of the payload. It had a 15% weight growth margin, a 5-minute launch window, and an ascent delta velocity margin of 1%. The TOGW (sized for the closed mission) was 917,000 lbs., the DW was 239,000 lbs., and the length was 200 ft.

SSTO Vision Architecture

The reference design (fig. 13, ref. 13) consisted of:
- A spatula-shaped forebody planform, lifting-body configuration with all moving horizontal tails, twin vertical tails, and trailing edge body flaps.
- Underslung, 2-D airbreathing engine nacelle; two engine systems with 130 klbs. of thrust each at takeoff.
- Linear, modular, aerospike rocket engine at the trailing edge; two engine systems with 117 klbs. (520 kN) of thrust each at takeoff.
- SH2 and LOX propellant (about a 50/50 split by weight).
- Actively cooled leading edges (fuselage spatula-shaped region and engine cowl); actively cooled, non-integral panels in engine.
- Two 6-wheel main landing gears; one nose gear (two wheels).
- Gr/Ep integral, I-stiffened, conformal SH2 tank; Aluminum/lithium non-integral, multilobe LOX tanks.
- Gr/Ep shell structure fore and aft of integral tank; TMC horizontal and twin vertical controls with C/SiC TPS and carbon-carbon (C/C) leading edges.
- Fibrous Refractory Composite Insulation (FRCI-12) TPS windward surface and Tailorable Advanced Blanket (TABI) over Rohacell insulation on leeward surface.

Trajectory/Engine Modes

The airbreathing corridor to Mach 25 and the engine mode changes experienced in this acceleration process also characterize this aerospace plane. A representative ascent trajectory (ref. 13) for the SSTO vehicle is presented in figure 14 including indicators for propulsion mode events. Most of the airbreathing propelled ascent is along a high dynamic pressure isobar (2150 psf).

Design/Technology Challenges

The system challenges for the reference SSTO extend from the actively-cooled airframe and engine cowl leading edges to the linear aerospike rocket engine at the airframe trailing edge. Some of the most critical items that

are essentially the same as for the Mach 10 cruise base-line example are: the graphite/epoxy integral fuel (SH2) tank and TPS system, the ramjet/scramjet engine with mechanisms for mode transition; and the actively-cooled engine non-integral heat exchangers that allow fuel injection temperatures of 2,000°R. An 8,000 psia central-ized hydraulic system is also required, as is a health monitoring/management system for the entire vehicle. The biggest challenge at present is establishing the opti-mum configuration as discussed in the following section.

Emphasis For Future SSTO Design Activities

The reference lifting-body SSTO design was reex-amined in the past year within SAO. The original TPS of FRCI-12/ TABI was replaced with purged IMI/ TABI, and a parametric study was performed by Den-nis Petley to determine the impact on TPS weight of TPS retrofitting, of dynamic pressure in the airbreath-ing segment of the trajectory and of pull-up Mach num-ber in transitioning to rocket propulsion. The results are given in figure 15. For the baseline trajectory (fig. 14, q=2150 psf, pull-up Mach = 16.5), the IMI/TABI retrofitted TPS saved 4593 lbs. (16%) and included a purge system which with an umbilical would allow an indefinite hold time at takeoff assuming that the SH2 tank is topped-off. The impact of airbreathing trajectory segments at lower dynamic pressure and earlier pull-up Mach number on reducing TPS weight was essentially

insignificant. Lower dynamic pressure results in slower acceleration and longer ascent times so that there is very little change in total heat load. For the earlier pull-up Mach number, the heat load was somewhat balanced by the required higher angle-of-attack.

The design was also modified for Mach 12 shock-on-lip instead of the original Mach 15 by Zane Pinckney and Lawrence Taylor; substantial performance and trim benefits were realized. However, an omission was found in the original drag accounting that resulted in a higher closure weight (TOGW≈1,000 klbs., DW≈250 klbs.). The Vehicle Analysis Branch at LaRC projects that for the same technology levels (SH2, etc.), vertical takeoff, horizontal landing rocket propelled SSTO designs would have a dry weight near 190 klbs. Thus, in order to drive the dry weight of the airbreathing SSTO below the reference lifting-body design (fig. 13) and toward that projected for SSTO rocket vehicles, different con-figurations and subsystems need to be explored.

Configurations. The generic HTHL SSTO configuration matrix of current interest in SAO is shown in figure 16. Recent examination of an inverted lifting body (fig. 16) was disappointing; it performed well subsonically, but lacked sufficient lift at the required low angles-of-attack during supersonic/hypersonic acceleration, except near shock-on-lip conditions.

The problem with the underslung engine, lifting-body configuration with rotating horizontal controls
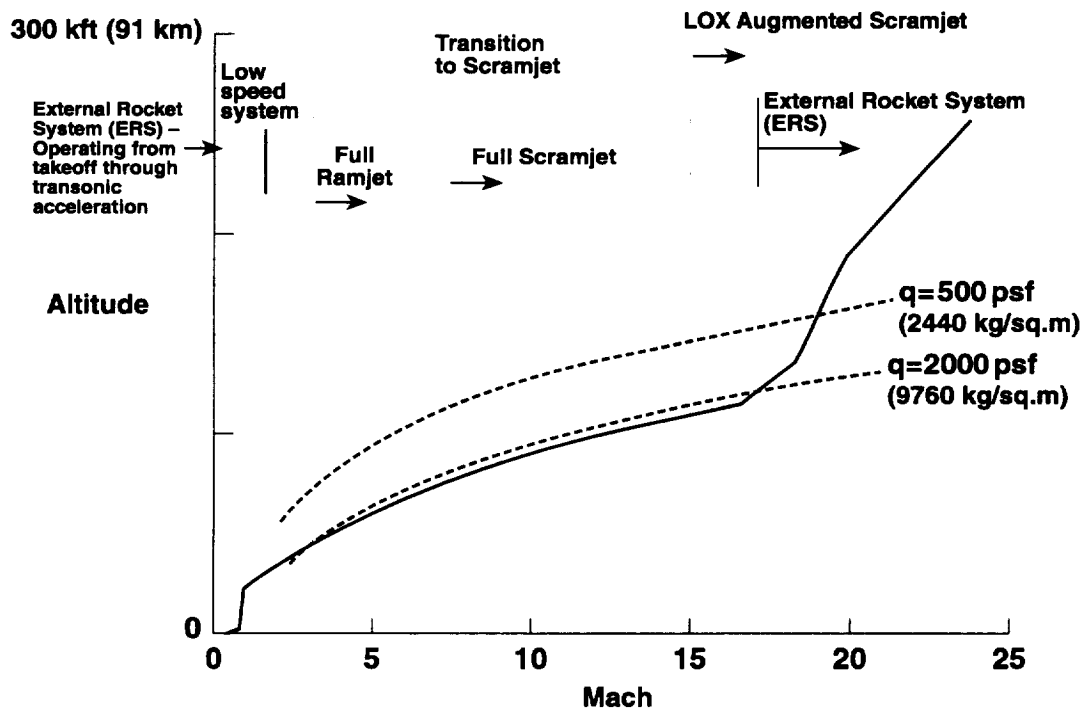

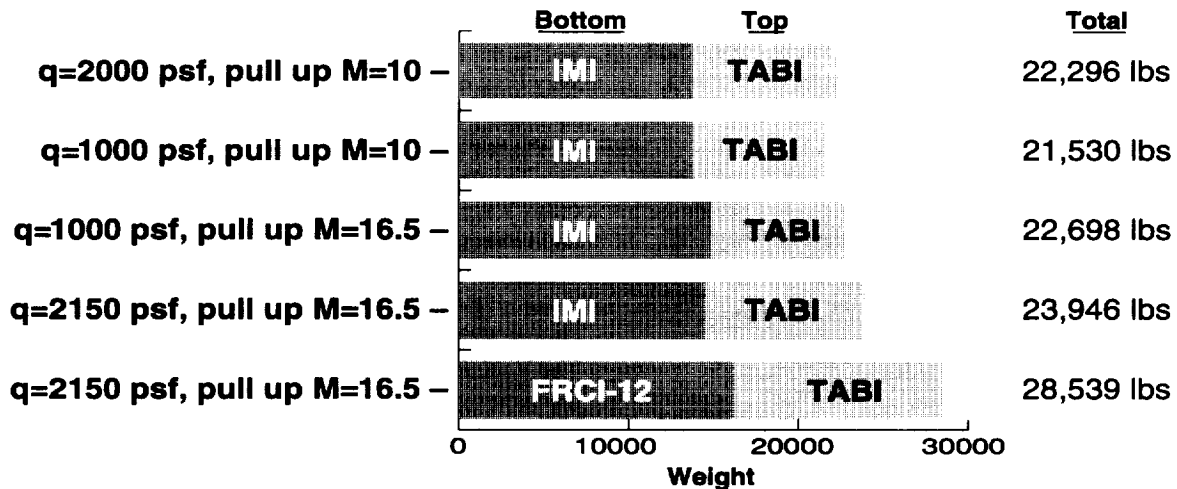Figure 14. Representative ascent trajectory.

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	Bottom	Top	Total
q=2000 psf, pull up M=10	IMI	TABI	22,296 lbs
q=1000 psf, pull up M=10	IMI	TABI	21,530 lbs
q=1000 psf, pull up M=16.5	IMI	TABI	22,698 lbs
q=2150 psf, pull up M=16.5	IMI	TABI	23,946 lbs
q=2150 psf, pull up M=16.5	FRCI-12	TABI	28,539 lbs

Weight: 0   10000   20000   30000

Figure 15. TPS weight for airbreathing Access-to-Space vehicle.

(reference vehicle) is that in order to keep the takeoff speeds below 300 knots, the fineness ratio was forced below 6 whereas a fineness ratio near 7 would be more optimum for this configuration at hypersonic speeds. Therefore, larger drag losses accrued across the Mach range because of takeoff constraints. In order to reduce drag losses during ascent, a high fineness ratio (~9) wing body is being examined. These higher fineness ratio, fixed-wing configurations have lower drag per unit volume relative to the lifting body and thus require less engine size but more wing; therein lies the trade. Also, the fixed wing approach may allow the use of a localized hydraulic system rather than the centralized approach of the reference SSTO (fig. 13).

The high fineness ratio vehicle designs can only approach the levels of effective specific impulse of the lifting body, i.e., the propellant fraction required; it is on the propellant fraction achievable (design/packaging) that it must exceed the capability of the lifting body to provide a more viable approach.

A very promising hypersonic air-breathing configuration in terms of propulsion flowpath is the inward turning configuration (ref. 14). Ideally, the funnel-like inlet configuration offers more air capture and more efficient compression to the inlet throat for less wetted area, with an accompanying more efficient expansion through the radial nozzle than does its two-dimensional or conical counterparts. These characteristics would result in potentially higher net thrust and specific impulse.

An inward-turning inlet concept was suggested for use with missile designs by Jim Keirsey of APL/JHU in the 1960's (ref. 15). During the NASP years, an inward-turning propulsion flowpath approach was suggested for use with SSTO systems by Bob Jackson of LaRC (ref. 16); packaging and off-design performance were concerns (ref. 17). LaRC and MSFC have recently been

pursuing the inward-turning concept for SSTO vehicle designs with Astrox Corporation; an innovation suggested by Astrox/Pyrodyne to remedy earlier concerns is being examined.

LaRC, LeRC and MSFC are now participating in an Airbreathing Launch Vehicle (ABLV) systems study as a part of the Advanced Reusable Technologies (ART) Project/Advanced Space Transportation program (ASTP). The SSTO configuration matrix being explored encompasses horizontal and vertical takeoff/horizontal landing vehicles using ejector-ramjet/dual-mode scramjet/ejector scramjet/ejector rocket (rocket-based combined cycle, RBCC) propulsion systems; the design matrix for the study is given in figure 17.

Systems. In the initial exploration of the aforementioned configuration matrix, a standard set of systems/subsystems is being used with emphasis on RBCC engines. The

Inverted Lifting Body:
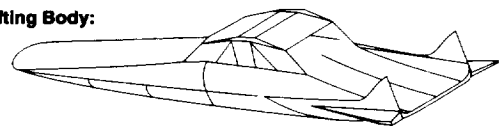
High Fineness Ratio Wing Body:
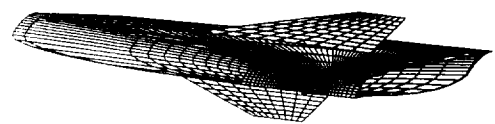
Inward Turning Flowpath (Funnel) Configuration:

Figure 16. Extended/advanced configuration matrix.

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ejector ramjet operates from takeoff to ramjet take over speed (M≈3); the dual-mode ramjet/scramjet operates to Mach 10 or 15, depending on the pull-up Mach number which in turn depends on the installed thrust-to-weight of the engines and the takeoff mode (horizontal or vertical), where the ejector rocket is again ignited to operate simultaneously with the scramjet (ejector scramjet or LOX augmented scramjet) and/or eventually alone as a rocket in a duct (inlet closed off). Thus, a single duct engine that operates over a broad Mach range is possible (ref. 7).

The ejector rocket requires a considerable amount of oxidizer and thus a system that extracts oxygen from the atmosphere could be more optimum. This system which extracts air, condenses it, and uses it in the ejector ramjet is a liquid air cycle engine (LACE, ref. 18). It will be examined as an optimization trade in the design study in conjunction with SH2 fuel. Air collection and enrichment systems (ACES) where liquid oxygen is subsequently separated out and stored is also of interest for SSTO's. MSE Inc. is testing vortex tubes for this separation task including examining their integration with LACE under a contract with NASA.

Pulse detonation engines (PDE), in which detonation waves propagate through a premixed fuel-air mixture to produce large chamber pressures and thereby thrust, are potentially promising for low speed (M=0 to 5) propulsion (ref. 19). Pulse detonation rockets (PDR) could be used for pull-up and exoatmospheric operations. These advanced systems are being examined by Lockheed and Adroit in a space access study sponsored by SAO using the reference lifting body SSTO configuration. They also will be examined in the LaRC, LeRC and MSFC Airbreathing Launch Vehicle (ABLV) systems study (fig. 17).

Two-Stage-To-Orbit (TSTO) Vehicles

The attractiveness of TSTO systems is versatile basing with airplane-like operations, launch offset capability

and nearer-term technology (ref. 7) than SSTO vehicles. For launch systems that stage at Mach 6 or below, the booster could be designed with near-term technology. Boosters that stage above Mach 6 are greater design challenges and would require more advanced technology because of the need for a dual-mode scramjet and more sophisticated/thicker TPS. With their ability to cruise, airbreathing boosters have the potential to return to multiple landing sites, including the launch site, even at the higher staging Mach numbers.

Horizontal takeoff/horizontal landing airbreathing launch configurations with piggy-back, rocket-powered orbiters nested on top have been examined rather extensively in the literature. A reference vehicle of this type (ref. 20) that is configured after the lifting-body of figure 13 is again from NASA's Access-to-Space study (ref. 10). It would stage at Mach 5 and perform the Access-to Space mission with a combined TOGW of 800,000 lbs. and DW of 300,000 lbs. The combined weights continue to decrease with increasing staging Mach number, at least to Mach 12 (ref. 20), but the design/technology challenges increase.

One of the more interesting designs of the piggy-back approach is reported in reference 21 in which an air liquefaction system with a mechanical oxygen/nitrogen separator (Air Collection and Enrichment System, ACES) was integrated into the first stage. Liquid air was collected from Mach 2.5 to 5 with the separated oxygen pumped to the rocket-propelled upper stage which deployed at Mach 5. The advantage over systems without ACES was almost a factor of two less in TOGW for payloads on the order of 30 klbs. (fig. 18).

The focus of the discussion herein (studies conducted or sponsored by LaRC) will be on two stage horizontal take-off and landing systems in which the payload (upper stage) is enclosed within the first stage (launch vehicle).
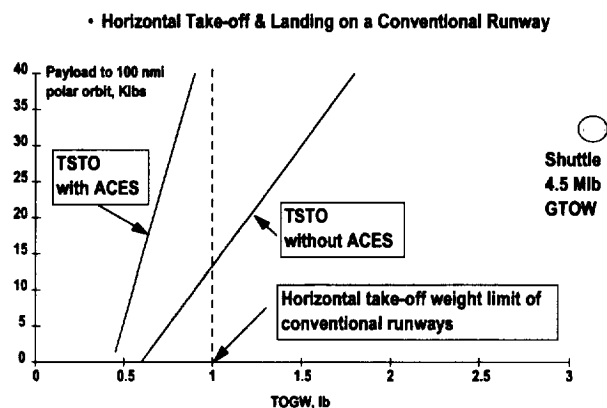

Figure 17. ABLV vision vehicle design matrix.

Figure 18. Impact of ACES on payload delivery of TSTO system (piggy-back...stage at M=5).

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Staging At Mach 8
(2nd Stage Enclosed Within 1st)

An initial design of a second generation TSTO vehicle (ref. 22), with an airbreathing LH2 fueled first stage, capable of delivering 2,000 lbs. payload to orbit is presented in figure 19. Two low-speed propulsion systems were considered for the first stage vehicle for Mach 0 to 3 operation, a LOX ejector ramjet (RBCC) and an air-core enhanced turboramjet engine (AceTR). A dual-mode ramjet was used above Mach 3 for both low-speed systems, but the RBCC allowed the use of a single-duct while the AceTR integration required the use of two ducts (over/under). The airframe structure/TPS design was the same as that for the reference SSTO (fig. 13). Active cooling through aluminum heat exchanger panels was used in the engine.

The second stage was a Centaur-based concept with a LOX/hydrogen powered RL-10 rocket engine. It was sized to deliver a 2000 lb. payload out of a 7 ft. diameter, 10 ft. long bay from a staging Mach number of 8 (near optimal for design/mission) to a 100 nm

polar orbit. Staging dynamic pressure was below 1 psi to accommodate separation and eliminate aerodynamic drag on the second stage. Dry weights ranged from 67 klbs to 69 klbs. and take-off gross weights ranged from 119 klbs to 131 klbs., depending on the low-speed propulsion system (AceTR system was lightest, fig. 20). A three-stage-to-orbit system was also considered with this configuration/ architecture (2nd and 3rd stages) with the first stage being a platform for a Mach 0.8 launch (fig. 20); only a 10 klb. reduction was realized in the TOGW of the combined 2nd and 3rd stages.

Staging At Mach 10
(2nd Stage Enclosed Within 1st)

The study originally scheduled as Phase II of the "Dual-Fuel Airbreathing Hypersonic Vehicle Design Study" (ref. 5) in which the possibility of using a derivative of the Mach 10 global reach vehicle as a launch platform for an enclosed upper stage was recently completed by Boeing (ref. 23). More range potential was obtained with a slightly higher fineness ratio, deep-
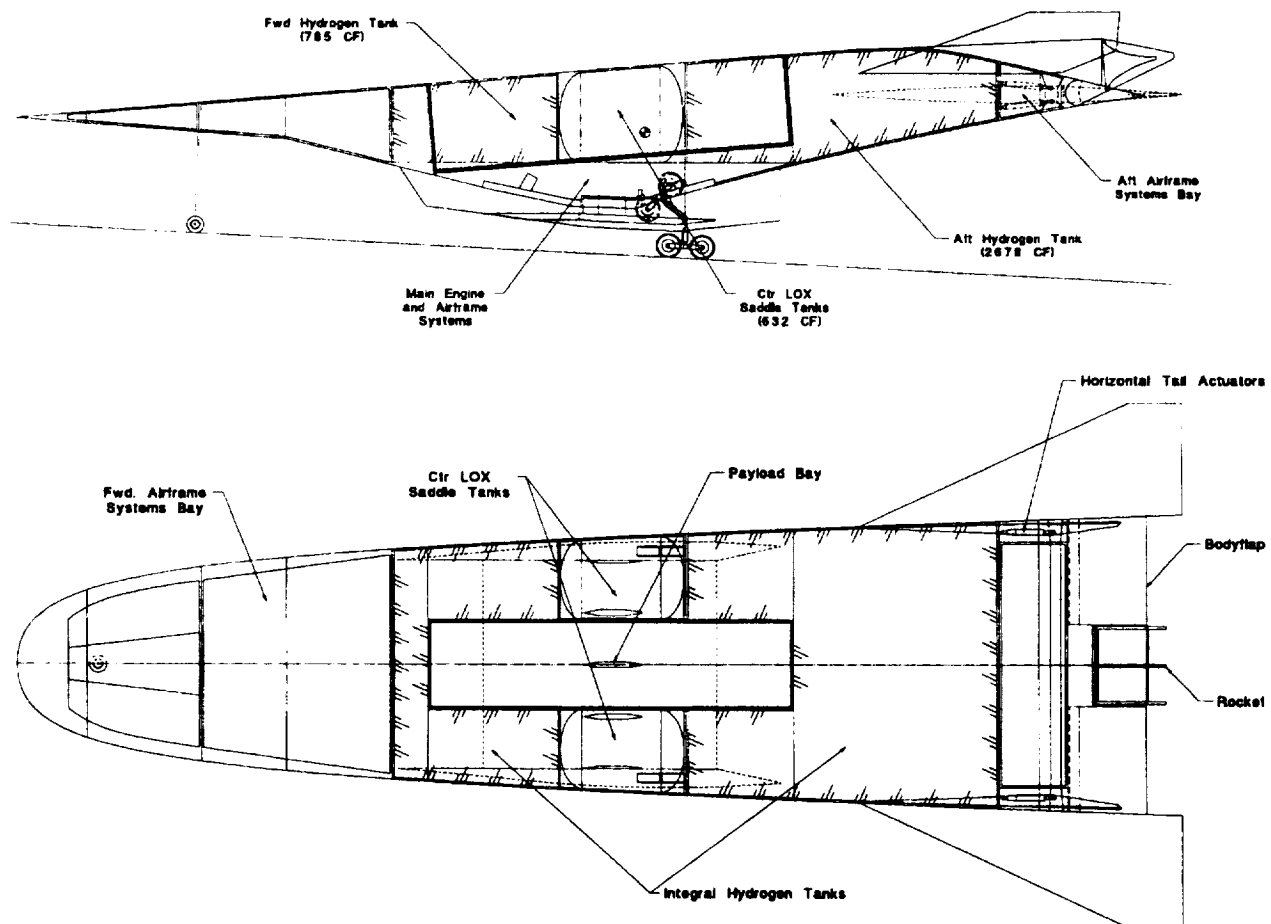

Figure 19. Advanced Reusable Small Launch System (ARSLS) airbreathing booster vehicle.

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er body version of the baseline Mach 10 global reach vehicle (fig. 5). This alternate vehicle was modified to include a cylindrical payload bay (10 ft. diameter, 30 ft. long) to contain an upper stage based on an ATLAS IIA design and a 150 klb. thrust linear aerospike rocket in the aft-end for pull-up assist (fig. 21).

The low speed propulsion system (upper position, AceTRs) for the modified Cruiser/Space Launch Vehicle was sized in conjunction with the tail rocket to accelerate through the transonic speed regime and a reaction control system (RCS) to provide stability and control during the high altitude pop-up flight. As a launch system (fig. 22), the TOGW is 532 klbs. Staging occurs at an altitude of 280 kft., a flight path angle of 5.5° and a velocity of

11,120 ft/sec.; a payload of 5 klbs. is delivered to a low-earth easterly orbit by a 30 klb. upper stage. As a cruise system (fig. 22) with a 10 klb. payload, TOGW is 521 klbs.; the mission radius is 7400 nm with refuelings required for the subsonic return. An all-slush hydrogen fuel version had a TOGW of 441 klbs. for the Space Launch Mission and a TOGW of 370 klbs. for the Cruise Mission with a range of 7600 nm (fig. 23).

An RBCC variant was also examined. The two-duct over/under engine integration (fig. 21) was replaced by a single-duct generic RBCC with an installed, take-off thrust-to-weight of 27, the separate tail, linear rocket was removed and the JP-7 fuel tanks were replaced with LOX tanks and another was added. For the space launch
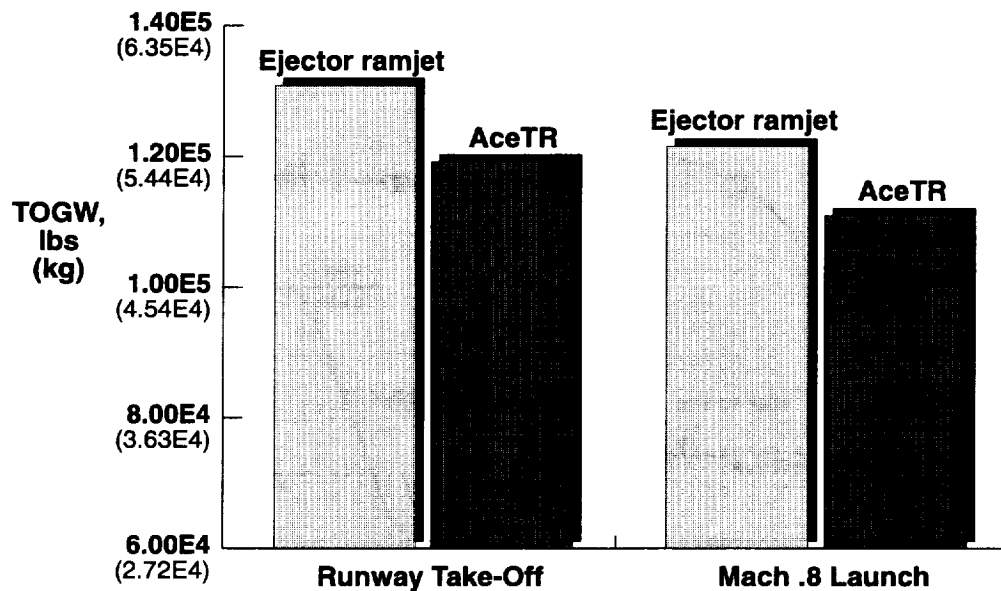
Note: AceTR is Air Core Enhanced Turboramjet

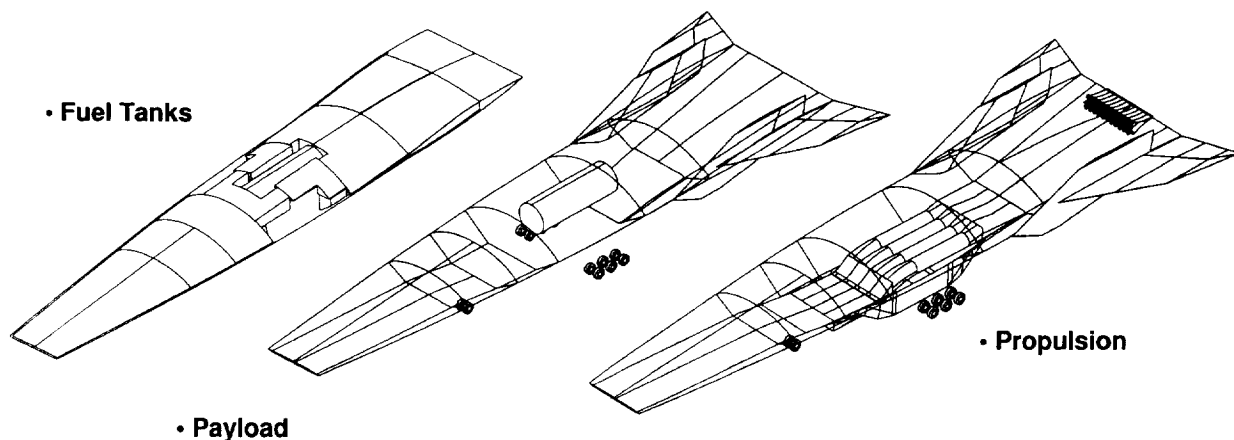**Figure 20. ARSLS design trades.**

Figure 21. Cruiser/Space Launch Vehicle.

mission, the RBCC vehicle's TOGW was 589 klbs. including the 30 klbs. second stage enclosed payload. For cruise, the vehicle's TOGW was only 511 klbs. with a 10 klbs. cruise payload; the vehicle cruised to 9,364 nm, again on a direct route without a turn.

Boost glide capabilities are currently under examination.

SUMMARY

The thrust in airbreathing hypersonic system studies at LaRC is to advance the configuration design matrix for airplanes and space-access vehicles. This operational vision vehicle matrix includes flowdown requirements for flight research vehicles whose flight demonstrations will in turn provide the technology maturation/capabilities leverage that enhances the probability that these vision vehicles will reach fruition (fig. 24).

Concerning airplanes, the emphasis is on Mach 5 to 8 endothermically-fueled designs and Mach 8 to 10 slush hydrogen and/or dual-fuel designs. The issue at present is whether a derivative of the lifting body that was used in the Mach 10 dual-fuel and/or hydrogen-fueled designs will replace the classic waverider as a more optimum configuration for the endothermically fueled Mach 5 to 8 designs. This issue is focused around transonic drag which sizes the low-speed engines in over/under integration schemes and does not presently appear to favor the waverider. Of course, the level of trimmed, cruise aerodynamic efficiency is very important in this discrimination, but it was not a factor in the Mach 10 global reach, dual-fuel study (ref. 5, no difference in trimmed L/D). A Mach 7 vision operation vehicle design study is being considered and should help resolve this issue.
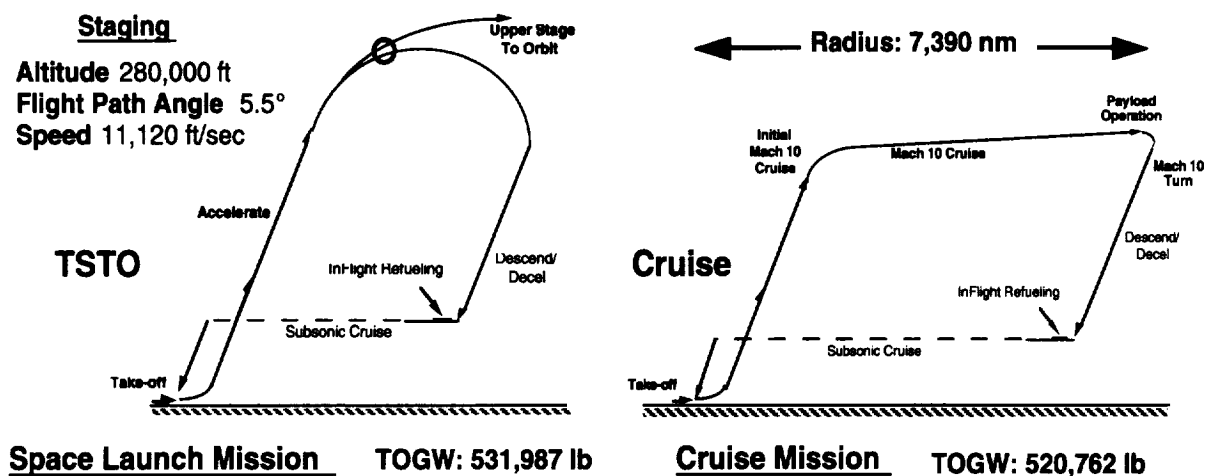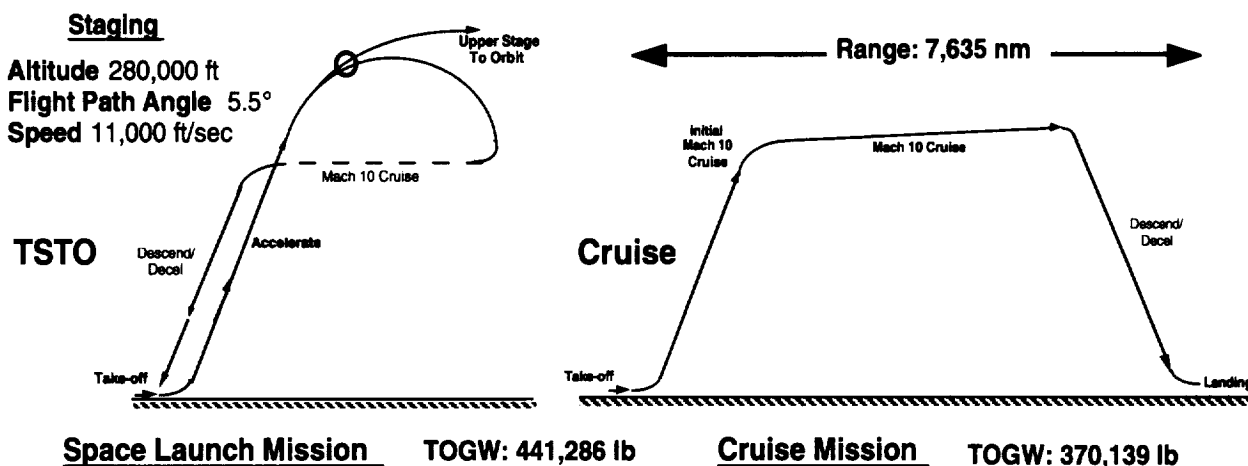

Figure 22. Dual-fuel DF-9 performance.

Figure 23. All-hydrogen DF-9 performance.

Along with the Mach 7 vision operational vehicle, the airplane design focus is on a Hypersonic Systems Integration Demonstrator (HySID); this is an acronym given to a conceptual flight vehicle design study with the objective of providing a flight testbed for demonstrating airbreathing systems from Mach 0 to 7 and the technology applicable to operational hypersonic Recce/Strike/SEADS airplanes, Uninhabited Combat Air Vehicles (UAV's) and Space Access Vehicles(SAV's). This study was constrained to a 2-D propulsion flowpath in order to complement Hyper-X and resulted in a lifting body with fixed-wings and cannards with favorable aerodynamic configuration characteristics. Such a testbed aircraft could be a candidate for the Future-X Program.

For space-access vehicles, the focus is on SSTO and TSTO vehicle systems design. The objective in the HTHL airbreathing SSTO design space is to resolve more optimum configurations than the reference lifting body where drag losses accrued because of the low fineness ratios to accommodate takeoff is a detriment. High fineness ratio and inward-turning propulsion flowpath

configurations are being examined. This is being accomplished in an Airbreathing Launch Vehicle (ABLV) study, jointly supported by LaRC, LeRC, and MSFC in which both HTHL and VTHL systems are being examined. This activity is being conducted under the Advanced Reusable Transportation (ART)/ Advanced Space Transportation Program (ASTP) using RBCC propulsion systems.

As for TSTO systems, a study was just completed to modify the Mach 10, global reach, dual-fuel and/or hydrogen fueled airplane to include a pop-up/launch capability to deliver 5 to 8 klbs to low earth orbit (LEO) through a rocket-powered upper stage. Not only did the payload delivery from a Mach 10 launch platform appear viable, but the linear aerospike rocket installation in the trailing edge of the airplane to allow staging at low dynamic pressures (less than 1 psf) did not appreciably deter its cruise capability. Also, a single-duct, rocket based combined cycle (RBCC) engine trade in place of the over/under (AceTR/dual-mode scramjet) baseline appeared advantageous, assuming an installed RBCC engine thrust-to-weight of 27.
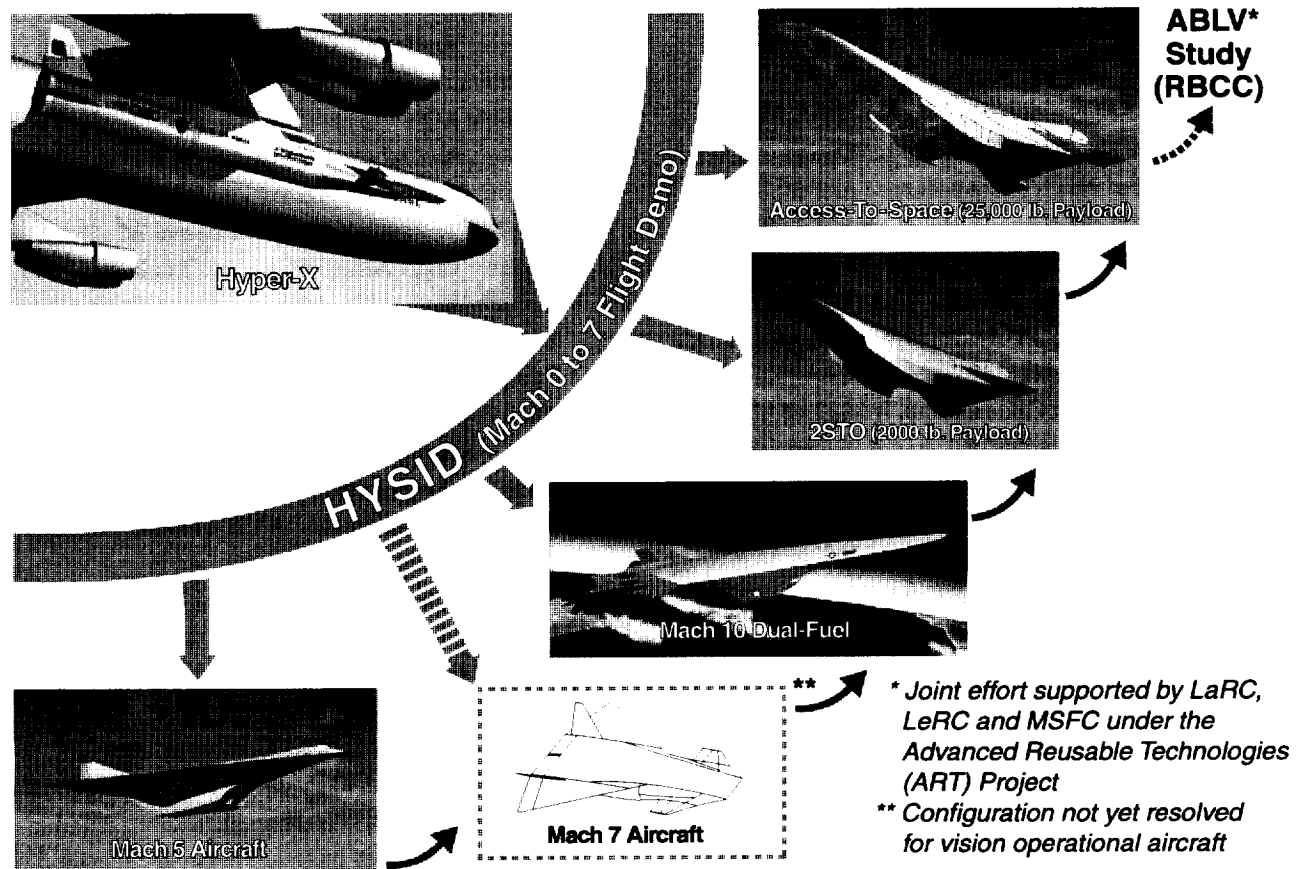

ABLV*
Study
(RBCC)

Hyper-X

HySID (Mach 0 to 7 Flight Demo)

Access-To-Space (25,000 lb Payload)

2STO (2000 lb Payload)

Mach 10 Dual-Fuel

Mach 5 Aircraft

Mach 7 Aircraft

* Joint effort supported by LaRC, LeRC and MSFC under the Advanced Reusable Technologies (ART) Project
** Configuration not yet resolved for vision operational aircraft

Figure 24. Hyper-X legacy...back to the future.

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