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ABSTRACT

Significant advancements in hypersonic airbreathing vehicle technology have been made in the country's research centers and industry over the past 40 years. Some of that technology is being validated with the X-43 flight tests. This paper presents an overview of hypersonic airbreathing technology status within the US, and a hypersonic technology development plan. This plan builds on the nation's large investment in hypersonics. This affordable, incremental plan focuses technology development on hypersonic systems, which could be operating by the 2020's.

INTRODUCTION

Man's search for higher speeds, as for flight itself, is limited by the propulsion system required for the task. The hypersonic (Mach number greater than 5, or 3,400 miles per hour) rocket powered X-15 aircraft demonstrated flight up to Mach 6.7 (6.7 times the speed of sound, or about 4600 miles/hr.) in the 1960's. The fastest aircraft propelled by an air breathing engine, the SR-71 Blackbird, only reaches speeds slightly over Mach 3 using a turbojet engine. Ramjets have been utilized for missile propulsion at speeds up to about Mach 5. Winged rocket powered vehicles, such as the Orbital Sciences Corporation Pegasus, have been utilized for hypersonic flight within the atmosphere to improve launch efficiency. Not unlike the challenge facing Orville and Wilbur, dramatically improved engine performance is required for hypersonic flight. In fact, efficient hypersonic flight within the earth's atmosphere requires a different engine, one that uses the oxygen within the air for combustion of the fuel. Hypersonic airbreathing propulsion also provides the option to "fly" to orbit. This air breathing engine option has been considered and studied for over 40 years, but not realized because of low technology maturity as compared to the rocket. Recently, as hypersonic airbreathing technology matured, and space access requirements continued to grow, the world started seriously considering airbreathing propelled vehicles for space access.

NASA, DOD, the U.S. industry and global community have studied scramjet-powered hypersonic vehicles for over 40 years. Within the U.S. alone, NASA, DOD (DARPA, U.S. Navy and USAF), and industry have participated in hypersonic technology development. Over this time NASA Langley Research Center continuously studied hypersonic system design, aerothermodynamics, propulsion, high temperature materials and structural architectures, and associated facilities, instrumentation and test methods. These modestly funded programs were substantially augmented during the National Aero-Space Plane (X-30) Program, which spent more than $3B between 1984 and 1995, and brought the DOD and other NASA Centers, universities and industry back into hypersonics. In addition, significant progress was achieved in all technologies required for hypersonic flight, and much of that technology was transferred into other programs, such as X-33, X-37, X-43, etc. In addition, technology transfer impacted numerous other industries, including automotive, medical, sports and aerospace.

Recently, NASA initiated several hypersonic technology programs: the LaRC/DFRC Hypersonic X-Plane Program, Hyper-X, in 1996; the GRC Trailblazer in 1997; and the MSFC Advanced Reusable Transportation ART technology program in 1997, Bantam in 1997, Spaceliner-D and finally, just "Spaceliner" in 1999. Of these programs only Hyper-X and ART build on the technology gains of the X-30 program. The Hyper-X Program focus is to extend scramjet powered vehicle technology to flight, elevating as much technology as possible, and validating, in flight, the design systems, computational fluid dynamics (CFD), analytical and experimental methods required for this complex multidisciplinary problem. The smaller ART program focus is on RBCC wind tunnel testing of alternate airframe integrated scramjet flowpath concepts.

Likewise, within the DOD several hypersonic programs are emerging. The USAF AFRL Hypersonic Technology (HyTech) program, the Defense Advanced Research Projects Agency (DARPA) Affordable Rapid Response Missile Demonstrator (ARRMD) Program, The USN Rapid Response Missile Program and the Army Scramjet Technology Development Program. In addition, the USAF Aeronautical Systems Center, in collaboration with the Air Combat Command, is conducting a Future Strike study, which focuses on hypersonic aircraft.

With this renewed interest in hypersonic vehicles, requirements are being developed which can only be met with hypersonics systems. These include the USAF CONUS-based Expeditionary Aerospace Force concepts, and reduced cost to orbit.

This paper discusses the potential of hypersonic airbreathing technology for endo- or exo-atmospheric vehicles (airplanes and space planes). The status of hypersonic technology, the significance of the X-43 flights to technology advancements, and a method of filtering vehicle proponents' claims are also discussed. Finally, a plan to efficiently demonstrate hypersonic technology is presented.

HYPERSONIC TECHNOLOGY STATUS

This section discusses the status of hypersonic technology—with the goal of showing significant advancement; thus, justification for continuing to push hypersonic technology development to flight.

System Analysis and Conceptual Designs

The key to any hypersonic vehicle development or technology program is a credible preliminary system analysis to identify the technical requirements and guide technology development. The X-30 program provided an excellent training ground for system design, analysis and development of hypersonic technology. The complexity of the hypersonic airbreathing system and the small thrust margin dictate that a thorough system analysis be performed before any focused technology development is started. Over the past 40 years, many bright individuals and companies brought forward vehicle, engine or structural concepts, which at first blush appeared to be an excellent solution. However, due to the highly integrated nature of this class of vehicles, an excellent component solution is not always beneficial to the overall system. The impact on the overall system is the only adequate measure of goodness. An example of this is the development of a combustor performance index, namely thrust potential (ref. 1). This parameter was developed during the 1990's, as scramjet engine designers realized that combustion efficiency was not an adequate measure of the combustor design. A method of quantifying the combustor impact on overall engine performance was required, and exergy, as applied in the literature, did not provide an optimum design.

Formal system analysis procedures are required for vehicle design and performance analysis. The LaRC design process is illustrated in figure 1. Engine and aerodynamic performance, structural requirements, weights, and flight vehicle performance (mission or trajectory) are evaluated, always "closing" on take off gross weight for the specified mission. This design process can be executed using four basic levels of analysis.

The lowest level, designated "0" in Table 1, does not require a physical geometry. The level zero analysis utilizes ideal engine cycle performance, historical L/D and Cd values for aerodynamic performance, design tables (or weight fractions) for structure and components weight, "rocket equation" for flight trajectory, and estimates for packaging. This analysis does not require a specified vehicle, engine flowpath or systems definition. All higher levels of analysis require a vehicle, engine flowpath shape and operating modes, system definition, etc.

The next level of system analysis, referred to herein as Level 1, utilizes uncertified cycle performance and/or CFD, impact theory, unit or uncertified finite element model (FEM) weights, single equation packaging relations, and energy state vehicle performance. (Certification is discussed in the next paragraph). This level of analysis does not capture operability limits, and thus has large uncertainties.

Level 2 analysis utilizes "certified," methods; i.e., the user has sufficient relevant experience. This level uses the same methods for propulsion, aerodynamics, structure and weights (but certified), trimmed 3-DOF (degree of freedom) vehicle performance analysis and multiple equation, linear or non-linear packaging relations. Certification is only achieved by demonstration that the methods used work on the class of problems simulated (this relates to the method, as well as the operator applying that method). For example, at level 2 analytical models utilize corrections for known errors, such as inlet mass spillage, relevant empirical fuel mixing models (ref. 2), shear and heat flux models (ref. 3), etc. This empirical approach is based on experimental (wind tunnel tests, structural component tests, etc) data. Higher level methods (CFD, FEM) are used to refine the vehicle closure.

The highest design level (level 3) is achieved only by having a significantly large fraction of the actual vehicle manufactured and tested. Wind tunnel and other ground testing provide less verification than flight tests. Although numerous components have been built and ground tested, flight data is required for the highest level of design. This has not yet been done for a hypersonic airbreathing vehicle.

Whatever the level of system analysis, closure is achieved by sizing the vehicle so that the propellant fraction required (for the mission) is equal to the propellant fraction available (packaged within the sized vehicle). However, the reported closure weight is only as good as the lowest level of analysis used in the “closure.”

Quantifying the uncertainty associated with the “level” of closure is difficult. Clearly the higher-level design methods have less uncertainty—level 3+ would be near zero. On the other extreme, level “0” analysis includes so much uncertainty as to be non-quantifiable. Level 0 analysis simply indicates that the objectives can be achieved, but does not indicate how. Any configuration shown with this level of analysis is meaningless.

Level 1 analysis is the first step toward a real vehicle definition. However, the methods used are not validated, so the uncertainty in each discipline is large, and the closed TOGW uncertainty is huge. The potential for over predicting the TOGW is negligible. However, because of the small thrust margins associated with hypersonic airbreathing systems, and potential operability limitations, the potential for under prediction by a factor of 10 is not unusual.

Level 2 design methods retain significant uncertainty—again because of the overall level of this technology development and small thrust margin. Therefore, it is prudent to carry 15% dry weight margin, 5 to 10% thrust or ISP margin and +/-10 to 15% on the predicted aerodynamic forces. The resulting impact on TOGW is significant, but quantifiable. Estimates of +20 / -5% on TOGW uncertainty are considered reasonable.

The color codes presented on table 1 will be used herein to identify the quality of vehicle closure when discussing current configurations.

Vision Vehicles—

Based on over 30 years of detailed hypersonic system analysis at NASA Langley Research Center and the Boeing Phantom works a clear trend in vehicle configurations emerged (ref. 4). These trends are consistent with trends noted by the X-30 contractor team. Hypersonic aircraft configurations have converged to either lifting body or wave rider configurations, as illustrated in figure 2. Lower speed, Mach 5 cruise vehicles tend to favor the wave-rider configuration, whereas higher speed cruise configurations favor the lifting body. This is partially due to fuel selection and operation range. The lower speed vehicle operates with hydrocarbon fuel, resulting in higher wing loading, favoring the wave rider configuration.

Numerous classes of vehicles have been evaluated for horizontal take-off and landing, single or two-stage access to space (ATS) missions. These include cone, wing-body, high-fineness, lifting body and other “novel” concepts, such as inward turning (“funnel”) inlet designs. The lifting body configuration is the clear choice for these missions (see figure 3). These vehicles are somewhat different from hypersonic cruise configurations; mostly in the relative size of the engine package. Vehicles designed for accelerating ATS missions require as much air capture as possible.

“An early lesson of high speed flight was that proper aerodynamic integration of the ramjet or scramjet with the remainder of the vehicle is critical to success…” (ref. 5). This comment is generally associated with podded engines. However, it applies equally to engine integration which ties the scramjet engine mass capture to wing area, such as the X-30 “Government Baseline” wing-body configuration, or to fully wrapped configurations which utilize ineffective conical compression surfaces (providing high surface area/unit capture, and excessive engine weight. The two-dimensional high-fineness ratio lifting body configurations provide one-sided compression, which efficiently pre-compress the inlet air. Top and side panels add little to the profile drag, and low local surface pressure results in relatively low heating and shear drag. This approach has been successful for a wide range of vehicle applications (figures 2 and 3).

Engine selection for air breathing hypersonic vehicles is another mission dependent design parameter. If the vehicle is truly hypersonic, a scramjet is required (except for a Mach 5 vehicle, which can operate with a classical ramjet and possibly with a Revolutionary Turbine Based Engine (RTBE, see below). For this discussion, the term scramjet refers to a dual-mode scramjet, or a scramjet that can operate in supersonic, subsonic and mixed supersonic/subsonic combustion modes, without the use of a second minimum, or nozzle throat. This is the type of scramjet which has been studied for 40 years in the U.S., and is traditionally referred to simply as a scramjet (SJ).

For single stage to orbit (SSTO) access to space (ATS) missions, a rocket is required for the final stage of boost, orbital insertion, orbital maneuvering and deorbit. SSTO is highlighted because of the perceived reduction in complexity and operating cost vis-à-vis a two or more stage system.

Several options are available for low-speed propulsion, and are defined by the following notation in ref. 6:

- Air-augmented rocket (AAR),
- Rocket ejector with ramjet after burning (ERJ), for configurations with a second minimum (nozzle throat).
- Rocket ejector scramjet (ESJ), for configurations without a second minimum.
- Pure airbreathing, such as
  - Turbojet (TJ)
  - Turbofan (TF)
  - Turboramjet (TRJ) which is a combined cycle in its own right. It includes turbofan engines operating with “wind milling” compressors at high speed.
- Air-turborocket (ATR), where a compressor or fan is driven by a rocket or monopropellant-decomposition.

The propulsion system required for SSTO operation can then be defined as either a combined cycle engine or combination engine. Combined cycle engines are single flowpath, integrated engines capable of operation in two or more modes, such as:

- Low speed: ejector-ramjet/mid speed: ramjet/high speed: rocket. This is referred to as an ERJ/RJ/R combined cycle engine (popularly called a RBCC).
- Low speed: ejector—scramjet/mid speed: scramjet/high speed: rocket. This is an ESJ/SJ/R combined cycle engine (popularly called a RBCC).
- Low speed: air augmented rocket/mid speed: scramjet/high speed: air augmented rocket/orbital: rocket. This is referred to as a AAR/SJ/R (popularly called a RBCC).

Combination engines can also be used for SSTO, such as:

- Low speed: turboramjet/mid speed: scramjet/high speed: stand alone (tail) rocket. This is referred to as TRJ, SJ, R combination engine (popularly, but incorrectly called a TBCC—the TRJ is in fact a TBCC).
- Low speed: ESJ/mid speed: scramjet. This is referred to as an ESJ/SJ combined cycle engine. When used with a high-speed external (tail mounted) rocket, the total package is referred to as a ESJ/SJ, R combination engine or propulsive system.

The effect of low-speed engine selection on TOGW is illustrated for the SSTO and TSTO configurations in figure 3. For the SSTO heavy lift (25,000 pounds to space station) mission, the TRJ, SJ, R combination engine system provides a substantial benefit over the ESJ/SJ, R combined cycle engine system. It is interesting to note that lightly loaded two-stage to orbit (TSTO) vehicles are not as sensitive to low speed engine selection.

For airplane configurations, which are required to operate over a large speed range within the atmosphere, the low speed system requirement dictates utilization of an efficient airbreathing engine. Therefore, based on today’s technology, a turbine-based engine is mandatory.

Structural concepts for the vision vehicles also converged as the analysis fidelity improved. Current concepts include cold integral graphite/epoxy LH2 tanks (developed under X-30 and used in the X-33) with a carbon/silicon-carbide “insulated multi-wall insulation” (IMI) thermal protection system (TPS) on the windward side, and tailored advanced blanket insulation (TABI) on the lee side. This provides a light weight TPS with durable external skin. Wing and tail structure is titanium metal matrix composite, developed for the X-30.

The engine primary structure is graphite-polyimide (being demonstrated on the X-37). Regeneratively cooled copper, aluminum, and high temperature superalloy panels are utilized in the engine, and the engine and vehicle sharp leading edges are cooled by the impingement process developed and verified for the X-30.

SSTO vision vehicle capabilities are summarized in figure 4. This figure illustrates the TOGW for several vehicles, for either “LEO” or Space Station Freedom. The small (2000 lb.) payload X-30 vehicle which started as the 50,000 lb. TOGW “Government Baseline” is shown as the red symbol. The X-30 program started with a vehicle analyzed with a combination of level 0 and 1 methods. After 8 years and $3+B of technology development and configuration refinement the final X-30 configuration TOGW was about 500Klbs, determined with a predominately level 2 analysis. The final X-30 vehicle is shown as light green because of one non-verified critical structural element. The other SSTO vehicles from figure 2 are also shown on figure 4. The vehicles with liquid oxygen are heavier than current runway limits.

Hypersonic Propulsion

Hypersonic propulsion has been studied continuously at NASA Langley Research Center for the past 40 years. Technology development has focused on design methods, experimental methods, experimental databases, air vehicle configuration and flowpath designs. Although engine study emphasis was on the scramjet flowpath, it also included structural concepts, designs and tests.

Design methods range from cycle analysis (ref. 7) to complex 3-D Navier Stokes analysis (ref. 8). This work included development of full and reduced finite rate chemistry models for scramjet operating conditions (for both combustor and nozzle flow), evaluation and selection of turbulence models (ref. 9), and other CFD methods required to accurately model the flow.

Scramjet test capability also has been continually improved at LaRC over the past 40 years. Combustion, arc and shock heated facilities (figure 5) were developed for testing components or engines from Mach 1 to about Mach 20, over the scramjet operating flight trajectory. Both component (inlet, combustor and nozzle) and integrated flowpath tests have been performed. Facility, instrumentation and test techniques were tailored to scramjet testing requirements, and understanding the scramjet flow physics (ref. 10), including airframe integration effects. Between 1975 and 1999, tests were performed on 21 scramjet engine flowpath models. More than 3500 tests were performed, providing about 30 hours of testing, equivalent to about 4 trips around the world at Mach 5. Results from these tests verified scramjet powered vehicle performance and were instrumental in the 1984 initiation of the X-30 Program. A summary of some of the work leading up to the X-30 program is included in ref. 10.

The NASA Langley Research Center played a key role in the generation of the large X-30 database for dual mode, hydrogen-fueled scramjet operation from Mach 3 to 16 and low speed engine operation from Mach 0 to 3. Component investigations included dual-mode scramjet combustor tests from Mach 3 – 20, ducted rocket tests at Mach 15, inlet tests from Mach 1.5 to 18, and nozzle afterbody tests from Mach 0 to 14. This large database was used to verify and improve both analytical and CFD based design methods.

The Hyper-X scramjet engine is currently being tested in all the engine test facilities shown in figure 5 to provide pre-flight scramjet performance data for flight test risk reduction, and to provide data for comparison to flight data and for validation of wind-tunnel test methods. Continuous improvements in scramjet engine flowpath designs are demonstrated by these tests; the X-43 engine has the highest performance and operability, and shortest length (weight) of all dual mode scramjet flowpaths tested to date. The largest uncertainties following these tests are hypervelocity scramjet performance, flight vs. wind tunnel performance and operability, integration effects and geometric scaling.

NASA LaRC also tested a first generation, “flight-weight” liquid-hydrogen cooled engine (ref. 11) and performed detailed structural design of two second-generation regeneratively cooled concepts (the three-strut engine, ref. 12, and the CIAM-NASA axisymmetric scramjet (ref. 13) which was wind tunnel and flight tested by CIAM). In addition, NASA LaRC was involved in third generation engine design activities, with the X-30, including design and tests of advanced regeneratively cooled, film cooled, and transpiration cooled panels and leading edge cooling concepts to Mach 15 flight heat loads (refs. 14 and 15).

Hypersonic Aerothermodynamics

Hypersonic aerodynamics and aero heating has been studied at NASA Langley Research Center for over 40 years. Technology development focused on design methods, experimental methods, and experimental databases (ref. 16). Design methods range from simple analytical to complex 3-D analysis. This work included: development of full and partial finite rate chemistry models, for operation in continuum and non-continuum flows; evaluation and selection of turbulence models and other CFD solution requirements to accurately model the heat transfer; and, development of CFD and analytical models for complex flowfield issues such as shock-shock interaction heating, wing gaps, etc.

Construction of the hypersonic facility complex at LaRC was started in the late 1940s. These facilities (figure 6) supported numerous programs. Some of these include the X-15, the Space Shuttle, X-30, Pegasus, X-33, X-34, X-38, X-43 and the X-37, starting this year. These facilities (figure 6) span the Reynolds number range required for Space Shuttle, X-38, and X-43 vehicles from Mach 6 to 20. Much of the work performed in these facilities, and the aerodynamic databases developed, were validated with traditional blunt lifting body flight data. The upcoming X-43 flight will provide the first flight validation of these facilities for sharp, high-fineness hypersonic lifting body configurations.

LaRC led the X-30 aerodynamic program which provided extensive databases for numerous hypersonic configurations including the final X-30 configuration. Unpowered models of the X-30 final configuration were tested over the Mach range of 0.25 to 17. Aerothermal models were tested at Mach 3.5, 6, 10, 10-17, and 18. Powered models were tested over the Mach 3.5 to 10 range at NASA LaRC in the Unitary Plan Wind Tunnel, 20" Mach 6 and 31" Mach 10 tunnels. Following the X-30 program, the largest aerodynamic uncertainties are boundary layer transition, powered effects and external burning. The Hyper-X program is resolving powered effects and providing additional information on natural and forced boundary layer transition. The Program is also evaluating the possibility of generating base burning data, with the X-43 low-pressure remnant hydrogen.

Materials and Structural Architecture

Many hypersonic structural concepts and materials were developed and/or tested at NASA Langley Research Center (see figure 7) over the past 30 years.

Primary airframe structures for advanced space transportation vehicles, such as, X-33, X-34, and X-37 are being constructed of graphite composite materials. Graphite epoxy is currently being used; however, higher temperature bismaleimides and polyimides are being considered for other vehicles. These are “cool” structures, which must be protected with a thermal protection system (TPS). Large airframe structural sections fabricated and tested for the X-30 were used to anchor the FEM models (Ref. 17) which are used to design the vision vehicles illustrated in figures 2 and 3.

Thermal protection systems (TPS) must be used to keep the airframe structure within allowable temperature limits. Tailored advanced blanket insulation (TABI) is being used for the lower temperature leeward side of the airframe; alumina enhanced thermal barrier (AETB) is being used on the higher temperature windward side. Metallic TPS is being developed at Langley Research Center where it has been tested to high temperatures and Mach 7 flow in the 8-ft High Temperature Tunnel. (ref. 14)

A carbon-carbon wing elevon was developed under the X-30 program (ref. 17). This control surface was designed to operate in a 3000°F environment. Ceramic matrix composites are being used for the wing ailerons and rudders on the X-37 vehicle. Improved coatings are also being studied by the Hyper-X Program for Mach 10 application to sharp leading edges. Heat pipe concepts and designs were developed and tested for the X-30 program, undergoing stagnation point heating to conditions in excess of Mach 10.

Graphite composites are being used for the liquid H2 cryogenic tanks on the X-33 and fuel tanks on the X-34 and X-37 (ref. 17). Foam has been added to the tank for cryogenic insulation.

Analysis methods are an integral part of structural development. Methods developed for hypersonic vehicles include detailed thermal structural coupled flow-structural analysis, 3-D solution methods for shock-shock impingement heating, thermal modeling for active/regeneratively cooled engines, etc. These methods have been verified by experimental tests and hardware fabrication.

Hyper-X

The primary goals of the Hyper-X Program (ref. 18) are to validate the airframe integrated, dual-mode scramjet powered vehicle in flight and provide databases for validation of design methods and tools. This will be accomplished using data from the X-43 vehicle (figure 8) under powered conditions at Mach 7 and 10, and unpowered conditions down to subsonic flight. In preparation for these X-43 flights, refinement of the vehicle design using optimization methods was required to assure that the small, compact X-43 vehicle accelerates. In addition, every detail of the hypersonic system was evaluated, including the high Mach number, high dynamic pressure stage separation. The most extensive hypersonic aerodynamic, propulsion and thermal database ever generated for this class of vehicle is being used to develop autonomous flight controls, size TPS and reduce risk for this first ever scramjet-powered hypersonic flight. This flight will usher in the hypersonic century.

TECHNOLOGY DEVELOPMENT PLANS

The Hyper-X Program Office (HXPO), under the direction of NASA Code R, is developing a plan to continue the farther advancement of hypersonic vehicle technology after the X-43 flights. This plan focuses on elevating the Technology Readiness Level (TRL) of all airbreathing hypersonic vehicle related technology to TRL 6 (system demonstration in flight environment) as fast and efficiently as practical. The technology to be addressed is applicable to both endo- and exo-atmospheric missions (represented by the configurations that are shown in figure 2 and 3).

For this technology development plan, the HXPO established the following guidelines: 1) expedite technology development; 2) leverage existing technology; 3) provide incremental approaches/options; and 4) provide “test beds” for other hypersonic technology and programs. Expediting technology development is necessary due to limited R&D resources. As mentioned previously, scramjet and other related hypersonic technologies have been extensively studied; the time is right for moving to flight.

Leveraging from existing technology is critical to expedite development and reduce cost. This plan leverages from the X-43 flight research vehicle, which in turn leveraged from the X-30 and NASA’s 40 years of basic research in hypersonic propulsion. In addition, the plan leverages from the ongoing USAF, DARPA, and U.S. Army Hypersonic Technology Programs. The USAF and DARPA programs are maturing hydrocarbon scramjet technology, which is essential in reducing the cost of demonstrating hypersonic systems in flight. The U.S. Army program is addressing Mach 8-14 scramjet technology including full pressure and enthalpy tests of the Mach 10 X-43 full forebody and engine configuration.

This technology plan provides an incremental approach to reduce risk, provide budget options, and allow for early flight tests/technology demonstration. Some of the incremental steps can be skipped, without adding undue risk.

The proposed hypersonic development plan is illustrated in Figure 9. The plan builds on three ongoing hypersonic technology programs: Hyper-X Phase 1, HyTech (USAF AFRL), and ARRMD (DARPA). Hyper-X provides wind tunnel, analysis and flight databases, systems, and flight controls for a hydrogen-fueled, scramjet-powered, hypersonic vehicle. This includes an extensive wind tunnel database from Mach 4.5 to 10 for the engine and Mach 0.6 to 10 for the vehicle aerodynamics. HyTech will provide hydrocarbon scramjet flowpath and engine designs and design methods, and a wind tunnel database for the hydrocarbon-fueled engine, flight-weight engine structures, and hydrocarbon fuel control systems. The DARPA program will provide low-cost flight hardware, manufacturing techniques, and flight validation of the hydrocarbon fuel cooled engine and fuel control system.

HyFLITE Subsonic Remotely-Piloted Vehicle (RPV)

One additional on-going “hypersonic vehicle” activity is the Accurate Automation Corporation (AAC) HyFLITE remotely piloted vehicle (RPV) program. The subsonic RPV (figure 9) is a 12' long, density scaled replica of the dual-fuel, global-reach Mach 10 cruise vision vehicle (ref. 19). The vehicle is powered by two 35 lbf thrust micro turbojet engines. This vehicle was fabricated during Hyper-X Phase 1 by the McDonnell Douglas Aerospace Corporation, and later donated to Accurate Automation Corporation. Flight tests have been funded by the USAF and NASA ARC. These tests are to investigate flight characteristics and control during low speed takeoff and landing operations. This vehicle is sharing aerodynamic data with the Hyper-X Phase 1 Program: using low speed wind tunnel data from the X-43, and will provide low speed flight data to the Hyper-X Program.

Hyper-X Phase 1A

Phase 1a is intended to be the worlds first demonstration of a reusable, flight-weight scramjet powered vehicle, and is planned to operate over a larger speed range than possible with the small X-43 vehicle. This vehicle will allow transition from dual-mode scramjet to pure scramjet operation. Conceptual studies indicate that a larger (25 – 30') vehicle is required to achieve this goal of reusability and operation from Mach 4.5 to Mach 7. This vehicle must be boosted to dual-mode scramjet takeover speed (Mach 4.5). It will investigate controllability issues associated with hypersonic operation and scramjet mode transition. Several solid and liquid rocket boost concepts are being studied both in-house, and under a NASA—AFRL Air Vehicles funded study by a Microcraft–Boeing team. The vehicle will likely use a liquid rocket and be air launched (B-52 drop) to minimize the overall size. The vehicle will land with skids and a steerable nose wheel. Because of size limitations, the Phase 1a vehicle uses hydrocarbon fuel for more volumetric efficient fuel packaging required to extend the scramjet test time.

This Phase 1a vehicle will utilize the X-43 and HyFLITE aerodynamic databases, HyTech endothermic fuel-cooled engine structure, and blended X-43/HyTech engine flowpath, flight systems and databases. By maintaining the same basic configuration (after boost), much of the large X-43 aero propulsion database remains applicable.

Hyper-X Phase 1a will be the first recovered/reused hypersonic airbreathing engine propelled vehicle. This program element will elevate the TRL of the scramjet engine over a large operating range. This will add to the airframe integrated scramjet engine flowpath validation achieved in Hyper-X Phase 1. This vehicle will allow durability testing of hypersonic engines not currently possible in hypersonic blowdown wind tunnel facilities. The vehicle will also be designed with a limited test-bed capability. For example, methods of testing alternate TPS, alternate flight controls, and using hydrogen fuel are being evaluated. In addition, the vehicle will be capable of testing other airframe integrated scramjet-based engines, and may be able to test “RBCC” engines over the full range from Mach 0.8 – 7. This vehicle will also be capable of flight above Mach 7 with limited modifications, as performed on the X-43 vehicle. Figure 9 illustrates one possible configuration, using liquid JP-LOX rocket engines with LOX drop tanks. Mach 4 stage separation of the drop tanks will be designed using the stage separation tools developed for the X-43.

Revolutionary Turbine-Based Engine (RTBE) Development

A multi-agency team (NASA GRC, LaRC, DFRC and MSFC plus the U.S. Navy) has been formed, led by the GRC, to identify the requirements and technology status, and develop a Mach 4 to 5 capable turbine based engine for high speed expendable and crewed flight. The requirements provided by the Hyper-X Program are presented in Table 2. These requirements are based on the technology development plan and conceptual studies illustrated in figure 9. Several U.S. turbine engine companies are currently evaluating/defining plans to meet these requirements. In addition, NASA Langley Research Center is evaluating the Japanese deeply cooled, hydrogen-fueled Mach 6 turbo-ramjet (ATREX) in the SSTO access to space vehicle illustrated in figure 3.

There is reason to believe that a RTBE can be developed to meet the requirements in table 2, considering the current status of high speed component and core testing throughout the industry. The requirements for the RTBE program are consistent with a logical engine development process: starting with small scale expendable engines; then small limited life, non-man rated engines; followed by a large prototype; and finally man rated production engines.

Hypersonic Aircraft-Shaped Low-Speed Demonstrator (HLD)

Preliminary assessment of low-speed propulsion-airframe integration (PAI), performance, aerodynamics, stability and control, and handling qualities can be assessed using a relatively inexpensive X-43 shaped vehicle which provides risk reduction before preceding to an expensive hypersonic capable vehicle. A conceptual assessment of this vehicle was recently completed.

Figure 9 shows a 50' long, dynamically scaled, piloted vehicle based on the dual-fueled, global-reach Mach 10 vehicle (ref. 19). The HLD is very similar in physical size and performance to a T-38 Talon high performance training aircraft. The aircraft will have a maximum level flight speed of approximately Mach 0.6.

A piloted Low Speed Demonstrator allows for safe, incremental flight envelope expansion. The inherent ability of the pilot to do real-time test point repetition and problem solving is an asset that cannot be provided by autonomous or remotely piloted aircraft. A pilot-in-the-loop flight control system also reduces development and operational costs. Thus, the presence of a pilot increases system redundancy and mission safety thereby enhancing data return and program accomplishment. In concert with current and planned hypersonic flight testing of autonomous research aircraft, it will lead to the ultimate goal of a piloted hypersonic cruise vehicle which will revolutionize flight as we know it.

Hyper-X Phase 2

The Phase 2 vehicle is currently envisioned as a 45-foot, reusable, Mach 7 vehicle with a revolutionary turbine based engine (RTBE)– dual-mode scramjet combination (TRJ/SJ) engine. The primary objective of this flight test program is elevation of the TRL for the TRJ/SJ engine, not just the flowpaths as done in Hyper-X Phase 1, or the scramjet engine as planned in Phase 1a. This vehicle will be designed for horizontal take-off and landing and acceleration through engine mode transitions (turbine to ramjet, ramjet to scramjet). This vehicle will be used to investigate the controllability issues associated with hypersonic vehicle operation from Mach 0-7, integrated TRJ/SJ performance and operability, engine mode transition, durability testing, powered take-off and landing, 3rd generation scramjet regeneratively cooled concepts, dual-fuel operation, and flight weight hypersonic aircraft structures. Boeing completed a conceptual study of this vehicle, called HySID (ref. 19). Because of the size limitations, the only way to extend the TRJ/SJ test time is by use of volumetrically efficient hydrocarbon fuel. This Phase 2 vehicle will utilize the X-43 aerodynamic database, a blended X-43/HyTech engine flowpath, HyTech-ARRMD derived endothermic fuel-cooled engine structures, the RTBE from the GRC led program discussed above, and X-43 systems and database. Low speed aerodynamics, handling, and scramjet engine and systems will be supplemented by data from Phase 1a, the AAC RPV and the piloted HLD discussed above.

This vehicle will be the first hypersonic airbreathing engine powered vehicle to operate from takeoff to hypersonic speed. It will allow durability testing of hypersonic engines not currently possible in blowdown, hypersonic wind tunnel facilities. This vehicle will be capable of about 5 minutes cruise at Mach 7 with on-board fuel using the baseline TRJ/SJ engine (can not be achieved with the Phase 1a vehicle). The vehicle will also be designed as a test-bed for other engine and hypersonic systems. Hydrogen fuel tanks/systems will be interchangeable with the hydrocarbon system. The vehicle will be capable of testing other airframe integrated scramjet-based engines (RBCC: ERJ/RJ, AAR/SJ, etc.). To allow the same mission range, additional fuel will be required, and could be contained in drop tanks as shown for the Phase 1a vehicle. This vehicle is also large enough, and timing should be right for a complete system demonstration of weakly ionized gas (WIG) effects. This vehicle will also be capable of Mach 10+ flight with limited modifications, as performed on the X-43 vehicle. Figure 9 illustrates the conceptual configuration for this vehicle. The canard is added to the X-43 shape, to meet takeoff and low speed requirements for the higher density of the hydrocarbon fueled system.

The pacing technology for the Phase 2 vehicle is the RTBE. The Phase 2 program can be pursued earlier using existing turbojet engines, with transition to the dual-mode scramjet at Mach 2.5 to 3. This adds some risk, and time to the Phase 2 schedule if Phase 1a is not performed first. The major risks are the increased variable geometry requirements and low-speed operability of the dual-mode scramjet.

Hypervelocity, Structures and Advanced Design Methods

Other technology development is required for SSTO capable vehicles. This includes:

- Mach 10 to 17^+ scramjet;
- Mach 12 to 20 ducted rocket;
- Leading edge design/validation testing; and
- Mach 15-20 capable, regeneratively cooled scramjet hardware.

Other related technology which could affect hypersonic vehicle systems, designs and operation include:

- Hydrogen cooled, variable-geometry scramjet;
- Refined design systems (fully three-dimensional and real-time flight simulation);
- Thermal management for combined/combination engines;
- Pulse detonation (airbreathing and rocket) engines
- Plasma physics such as WIG, energy extraction from hypersonic flows, etc.; and
- Improved facility, instrumentation, and test techniques.

These technology areas are required to push hypersonic airbreathing vehicles beyond Mach 10. Work is underway in most of these areas, and a sound foundation remains from the X-30 program. However, these efforts need to be directed toward a particular application, and eventually flight validation.

CONCLUSIONS AND RECOMMENDATIONS

NASA, DOD and the aerospace industry have invested 40 years, and $3^+B in hypersonic airbreathing vehicle technology development. This includes refined design methods, large wind tunnel and ground test databases, and (with the X-43) flight validation. Additional flight tests are required to elevate the technology to the point that prototype vehicles can be considered. This paper presents a logical, affordable approach to complete the development of this unique technology. Requirements for this technology have been identified. A method of screening hypersonic vehicle configurations proposed to meet these requirements was presented.

Symbols & Acronyms

AAR	Air augmented ramjet combined cycle (RBCC) engine
Ac	Engine frontal area
AEDC	Air Force Arnold Engineering and Development Center
AFRL	Air Force Research Laboratory
ARC	NASA Ames Research Center
ARRMD	Affordable Rapid Response Missile Demonstrator
ART	MSFC Advance Reusable Transportation technology program
ATR	Air turborocket combined cycle (RBCC) engine
ATS	Access to Space vehicle
CFD	Computation Fluid Dynamics
DARPA	Defense Advanced Research Projects Agency
DFRC	NASA Dryden Flight Research Center
DOF	Degree Of Freedom
ERJ	Ejector ramjet combined cycle (RBCC) engine
ESJ	Ejector scramjet combined cycle (RBCC) engine
FEM	Finite Element Model
F_n	Thrust
GRC	NASA John Glenn Research Center
HC or H/C	Hydrocarbon (fuel)
HLD	Hypersonic aircraft shaped low speed demonstrator vehicle
HXLV	Hyper-X Launch Vehicle
HXPO	Hyper-X Program Office
HXRV	Hyper-X Research Vehicle (X-43)
HyFLITE	Hypersonic shaped RPV
HyTech	AFRL hypersonic technology program
H_2	Hydrogen
IMI	Insulated multi-wall Insulation TPS
Isp	Fuel specific impulse, Lbf/Lbm
LaRC	NASA Langley Research Center
LH2	Liquid hydrogen
MSFC	NASA George C. Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane (X-30)
O_2	Oxygen
RBCC	Generic name for Rocket – Airbreathing Combined cycle engine
R	Non-RBCC rocket
RJ	Ramjet engine
RLV	Reusable launch vehicle
RPV	Remotely piloted vehicle
RTBE	Revolutionary Turbine Based Engine
SJ	Supersonic combustion or dual-mode combustion ramjet engine
SSTO	Single stage to orbit
STF	Scramjet test facility

TAC	Engine life
TBCC	Turbine based combined cycle engine
TF	Turbofan (TBCC) engine
TJ	Turbojet engine
TOGW	Take off gross weight, pounds mass
TPS	Thermal protection system
TRJ	Turboramjet combined cycle (TBCC) engine
TSTO	Two stage to orbit
USAF	United States Air Force
USN	United States Navy
Wt	Weight
X-30	National Aerospace Plane (NASP) experimental vehicle
(aaa)/(bbb)	(aaa) – (bbb) combined cycle engine

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Design Maturity	**Color Code**	**Propulsion**	**Aero**	**Structure Weight**	**Vehicle Performance**	**Synthesis & Packaging**
10	**Blue**	Flight Data	Flight Data	Flight Vehicle	Flight Vehicle Performance	Flight Vehicle
8	**Light Blue**	Wind Tunnel Data	Wind Tunnel Data	Components Fab/Test	6-DOF Hardware Simulation	Mock-up, CAD Multi-Eqn. Non-linear
6	**Green**	CFD Certified	CFD Certified	FEM Certified	3-DOF/ 6 DOF Trimmed	CAD Multi-Eqn. Non-linear
5	**Light Green**	Cycle Certified	Engineering Methods Certified	Unit Loads Certified	3-DOF Trimmed	CAD Multi-Eqn Non-Linear
3	**Yellow**	CFD Uncertified	CFD Uncertified	FEM Uncertified	3-DOF untrimmed	Single Eqn., Non-linear
1	**Light Yellow**	Cycle Uncertified	Engineering Methods Uncertified	Unit Loads Uncertified	Energy State	Single Eqn. Linear
0	**Red**	Ideal Cycle	L/D, Cd Estimated	Design Tables	Rocket Equation	Estimated

Table 1. *Vehicle Fidelity Assessment.*

	X-43 Phase 2 HySID	**Duel Fuel Global Reac. Prototype – Production**	**Access To Space Prototype – Production**
Year	**2008**	**2012 – 2020**	**2012 - 2020**
Max. Mach	**4 to 5**	**4.5 to 5**	**4.5 to 5**
Fuel	**JP**	**JP**	**Hydrogen**
Fn/Wt, lb_f/lb_m	**8**	**8 – 16**	**8 – 16 to 20**
Fn/Ac, lfs/in^2	**10**	**15 – 20**	**15 – 20**
Isp @ M=2	**2000**	**2000**	**>4000**
TAC – cycles	**25**	**100 – 1000**	**100 – 1000**
Life – hr.	**25**	**1000 – 5000**	**1000 – 5000**
Thrust, lbs	**~ 6,000**	**18,000**	**50,000**
Diam., in.	**<24**	**<54”**	**<54”**

Table 2. *Hypersonic Program Turbine-Based Engine Requirements.*

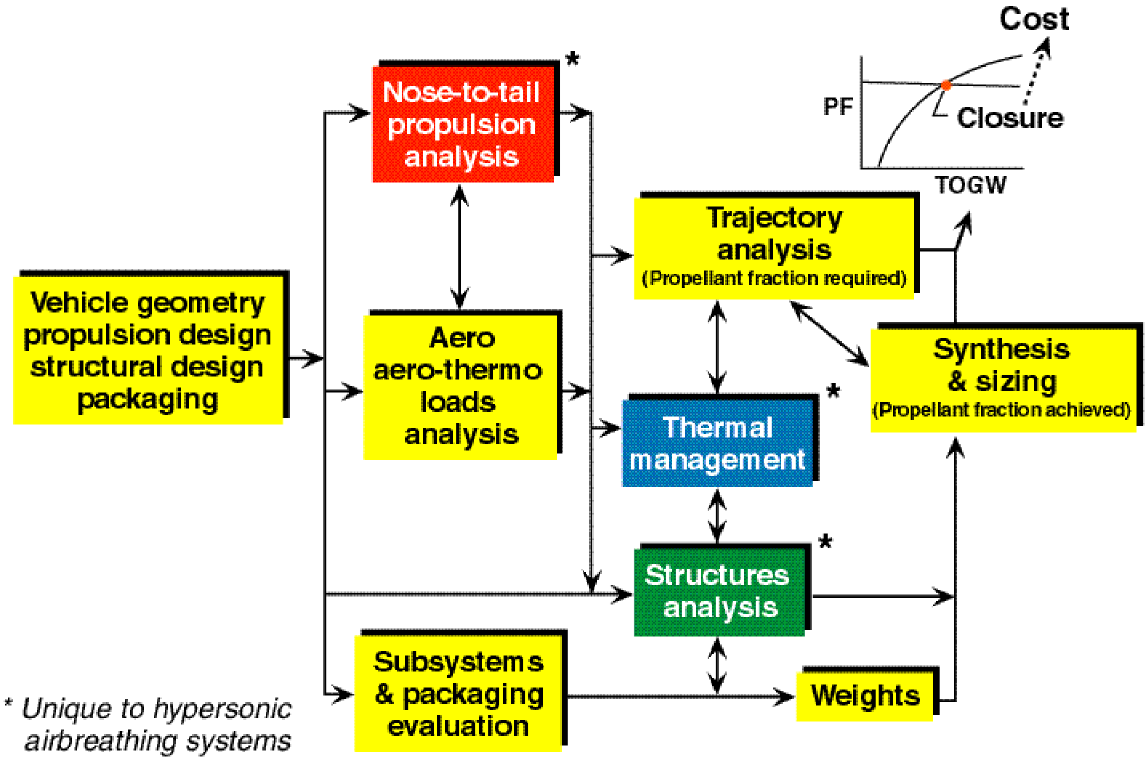


Figure 1. *Design Method for Hypersonic Airbreathing Systems.*

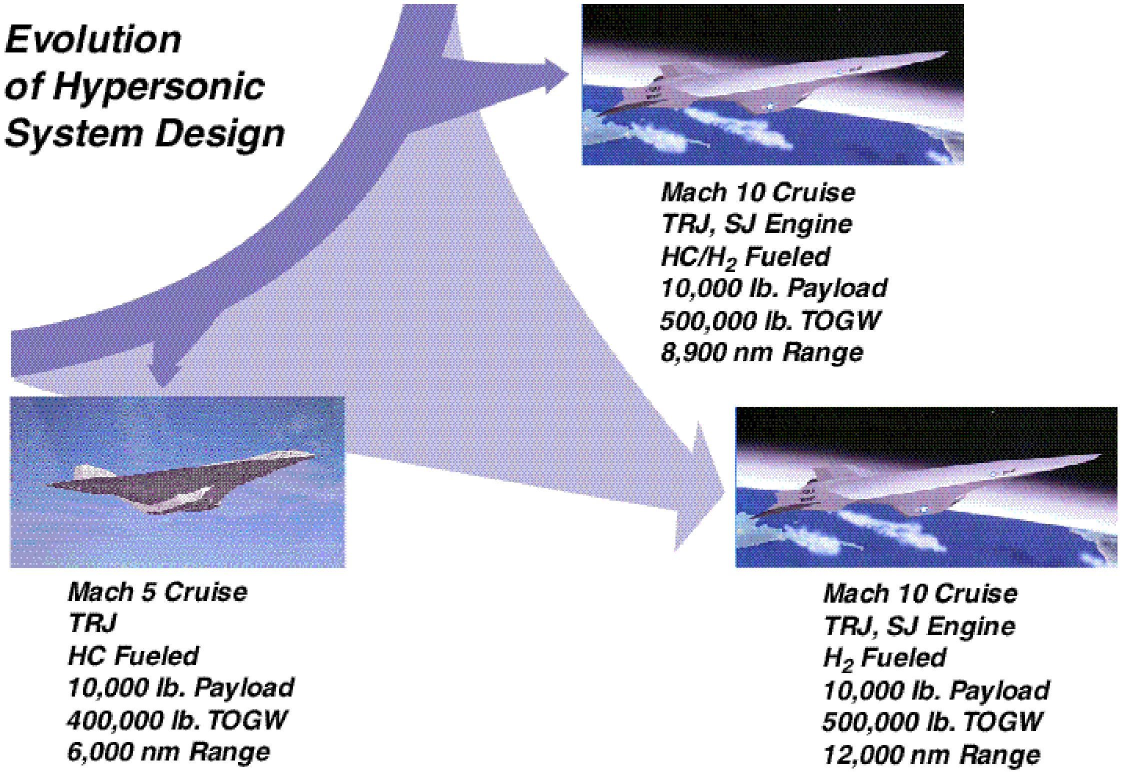


Figure 2. *Current Revolutionary Vehicle Configurations.*

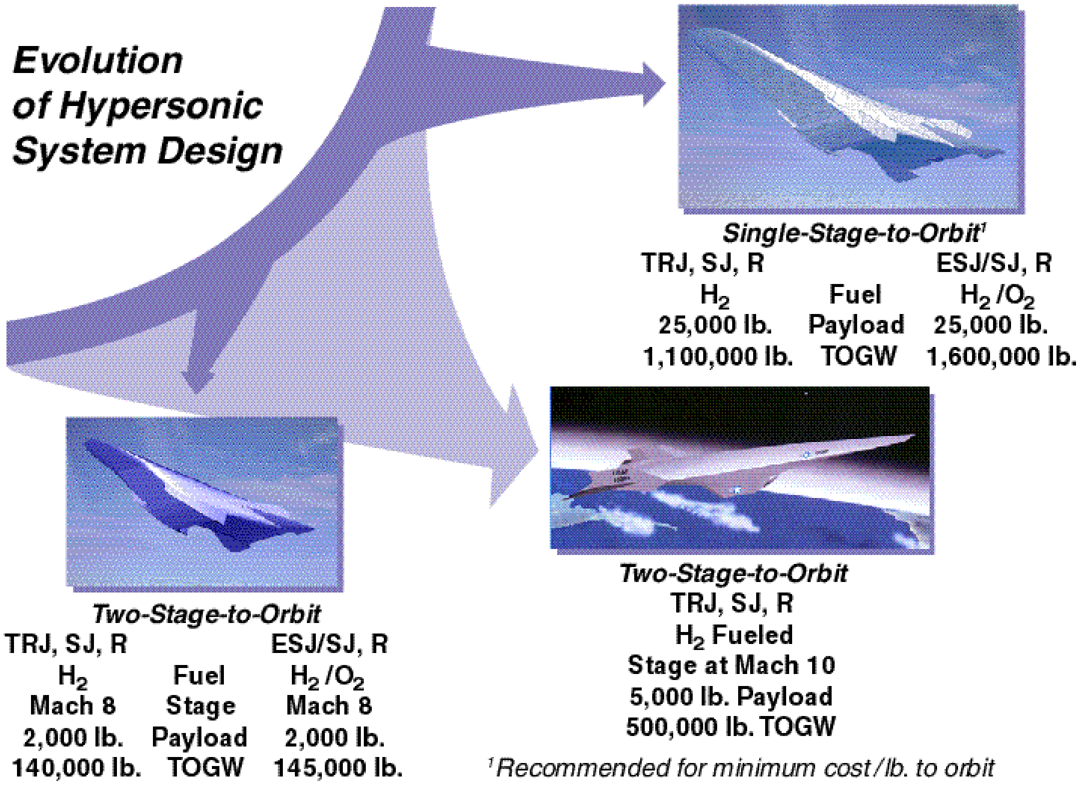


Figure 3. *Current Space Access Configurations.*

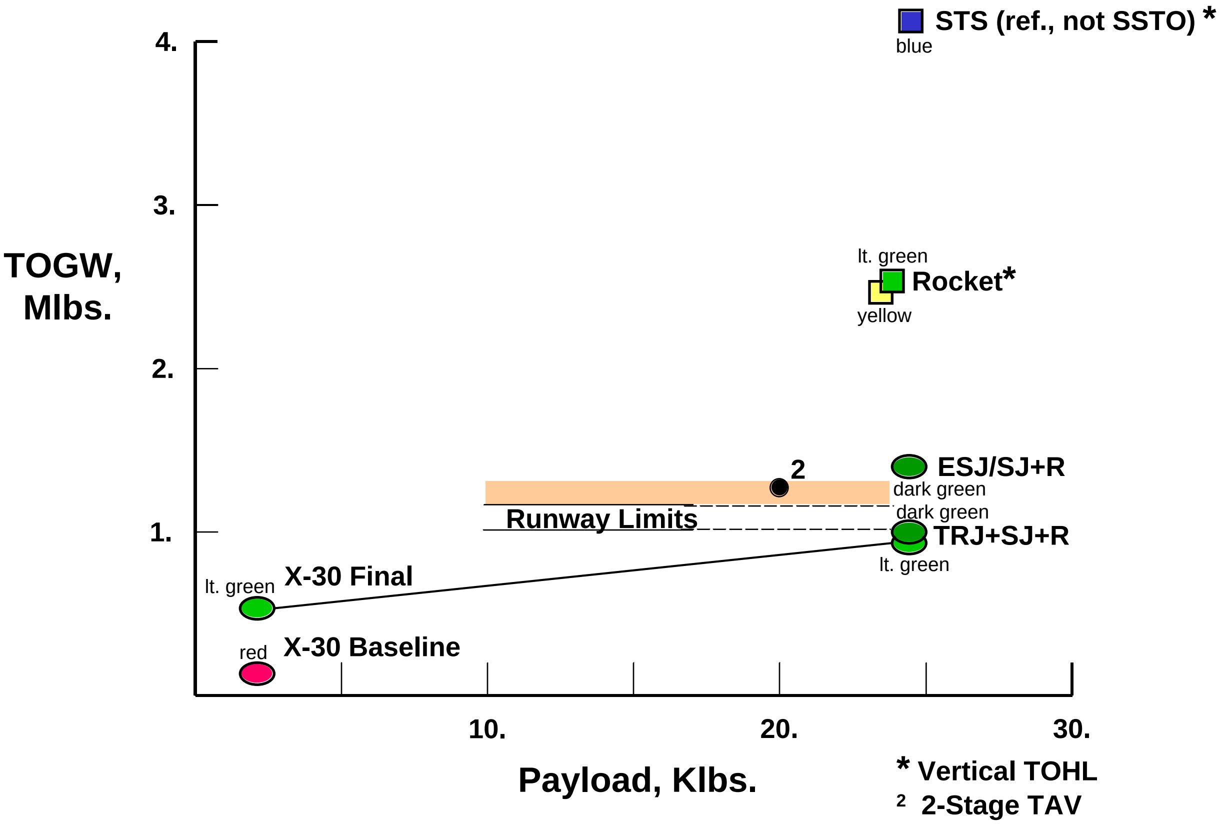
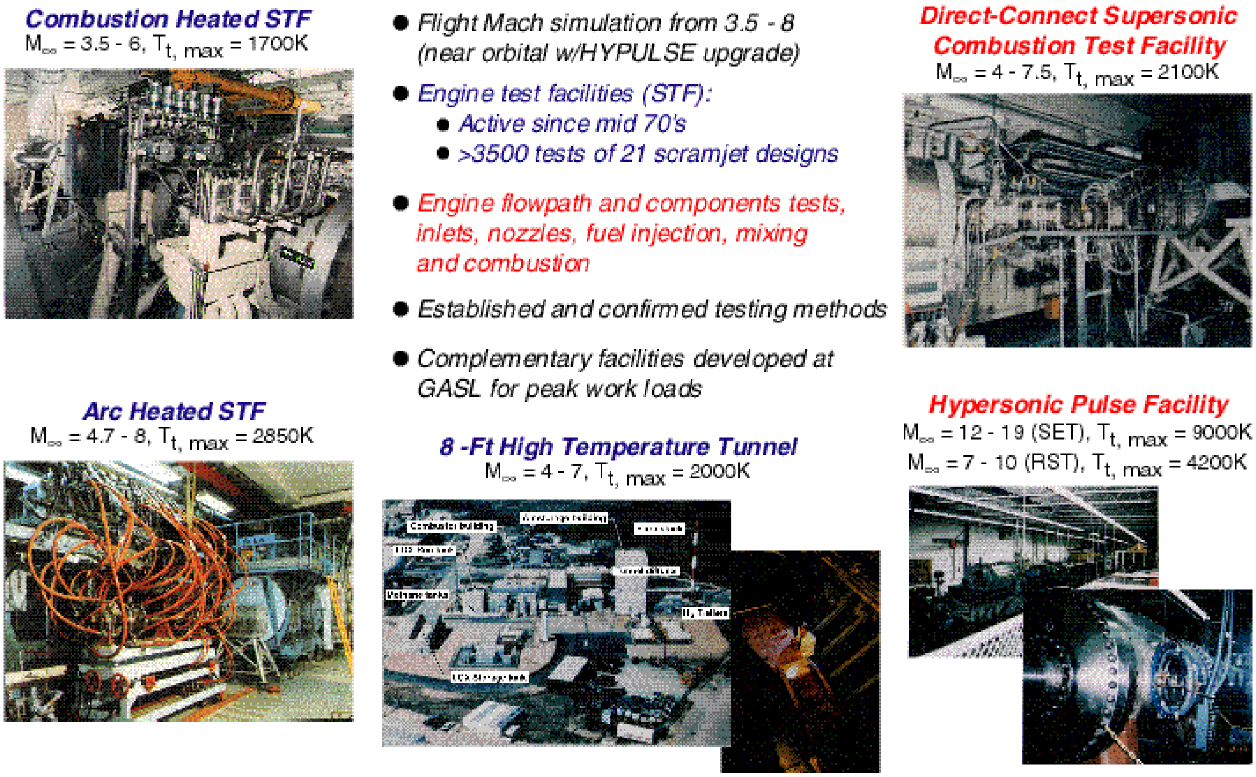


Figure 4. *Capability and Fidelity of Some HTHL SSTO Vehicles.*



Combustion Heated STF

M_∞ = 3.5 - 6, $T_{t,\ max}$ = 1700K

Arc Heated STF

M_∞ = 4.7 - 8, $T_{t,\ max}$ = 2850K

- *Flight Mach simulation from 3.5 - 8 (near orbital w/HYPULSE upgrade)*
- *Engine test facilities (STF):*
  - *Active since mid 70's*
  - *>3500 tests of 21 scramjet designs*
- *Engine flowpath and components tests, inlets, nozzles, fuel injection, mixing and combustion*
- *Established and confirmed testing methods*
- *Complementary facilities developed at GASL for peak work loads*

8 -Ft High Temperature Tunnel

M_∞ = 4 - 7, $T_{t,\ max}$ = 2000K

Direct-Connect Supersonic Combustion Test Facility

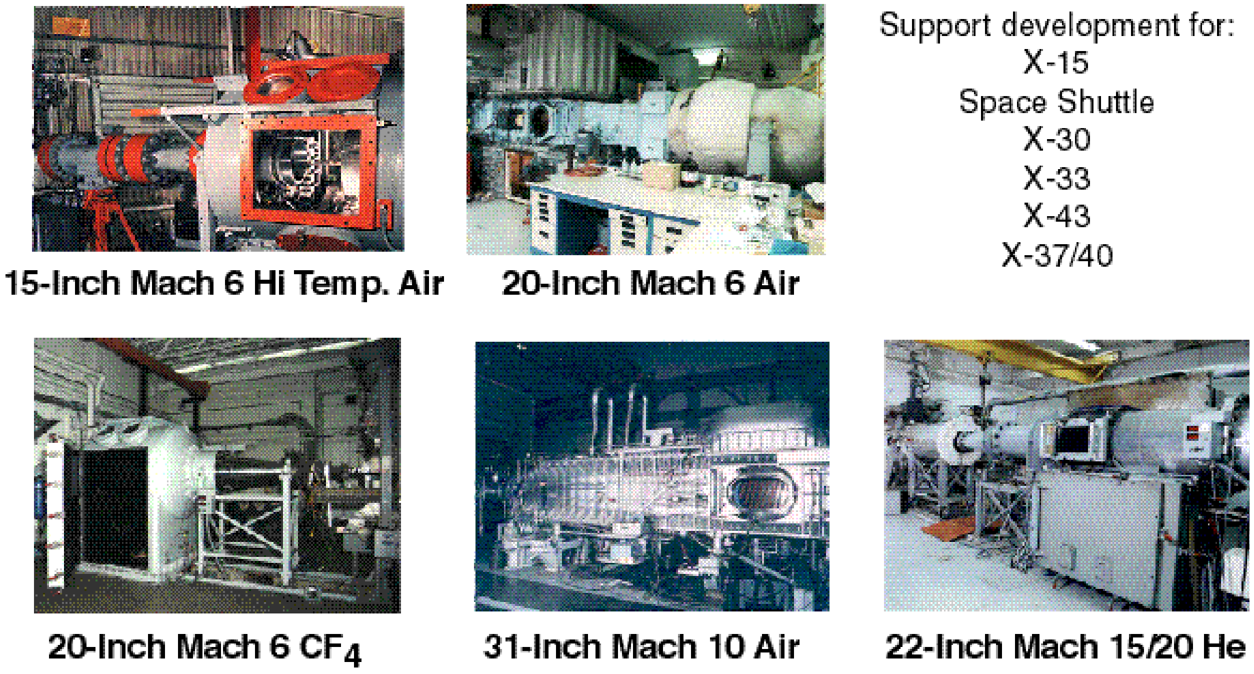
M_∞ = 4 - 7.5, $T_{t,\ max}$ = 2100K

Hypersonic Pulse Facility

M_∞ = 12 - 19 (SET), $T_{t,\ max}$ = 9000K

M_∞ = 7 - 10 (RST), $T_{t,\ max}$ = 4200K

Figure 5. *Hypersonic Propulsion at LaRC.*



15-Inch Mach 6 Hi Temp. Air

20-Inch Mach 6 Air

Support development for:
X-15
Space Shuttle
X-30
X-33
X-43
X-37/40

20-Inch Mach 6 CF_4

31-Inch Mach 10 Air

22-Inch Mach 15/20 He

Figure 6. *Aerothermodynamic Facilities Complex (AFC).*

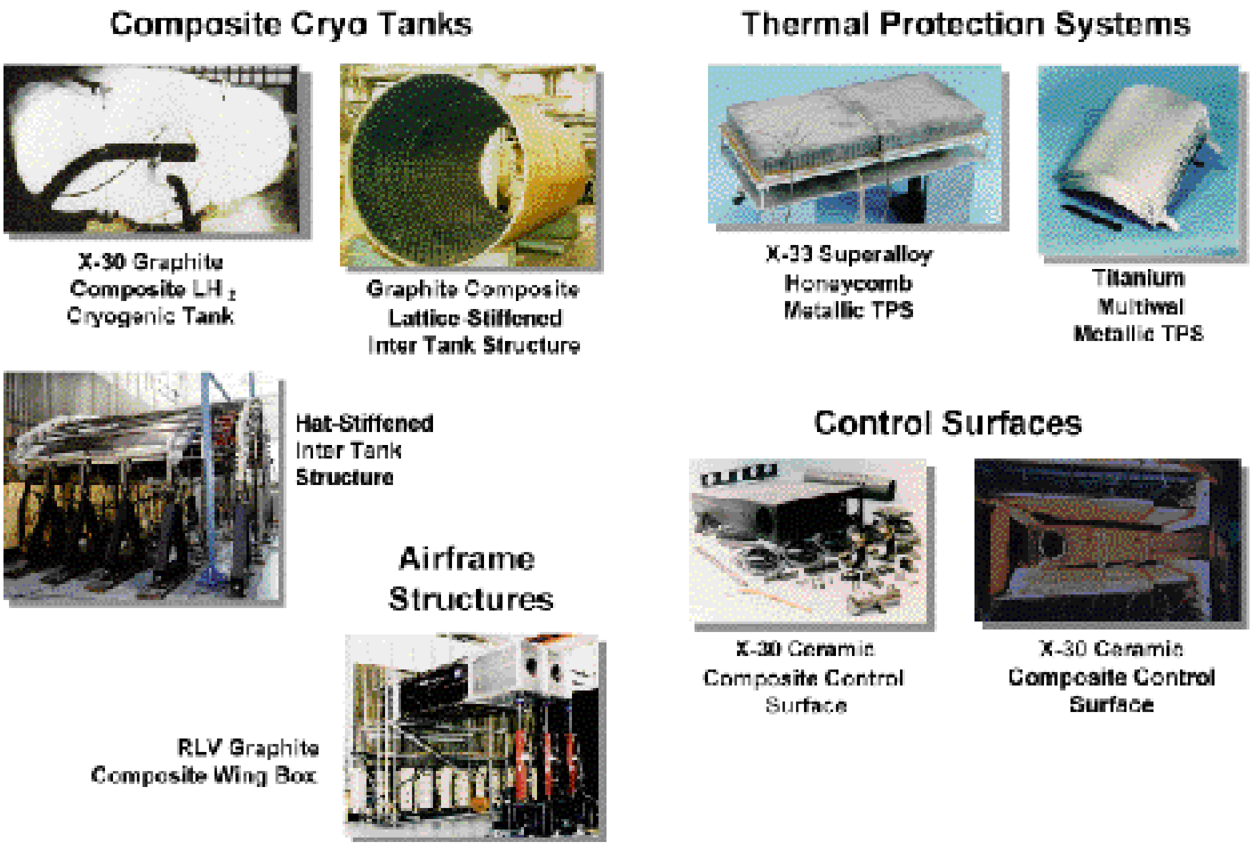


Figure 7. *Hypersonic Structural Developments.*

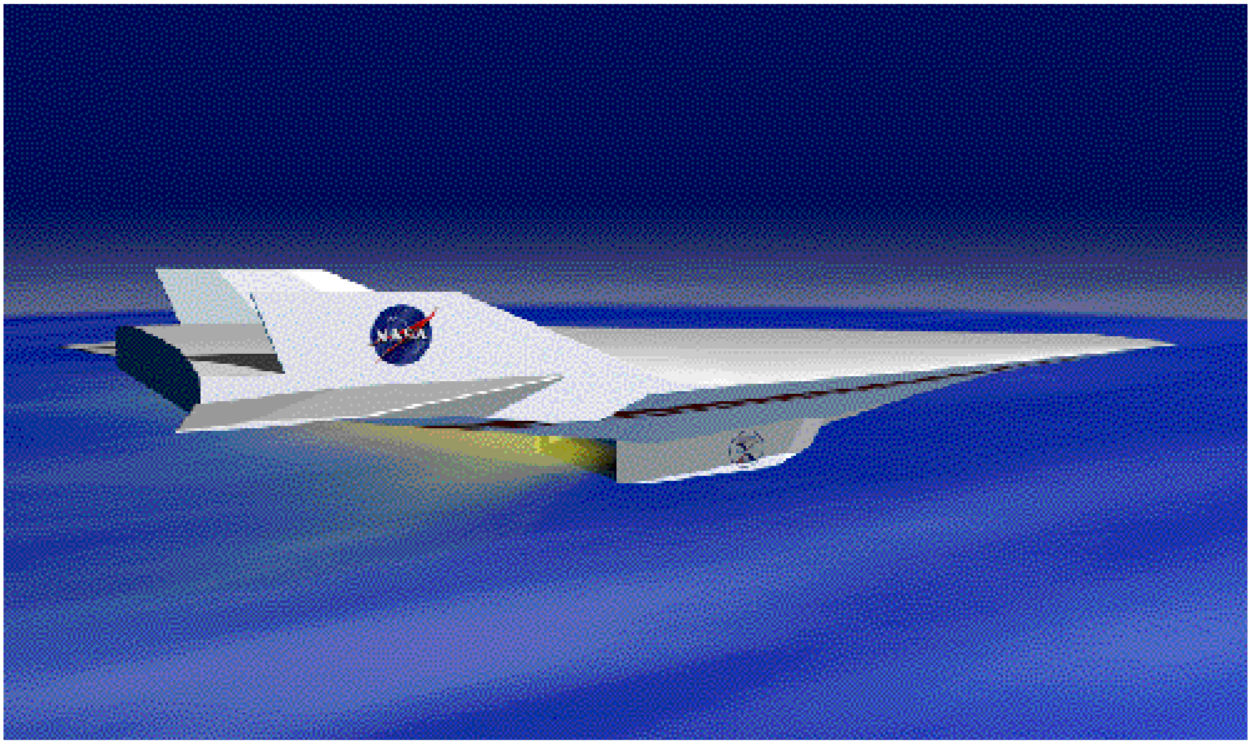


Figure 8. *X-43 Flight Vehicle.*

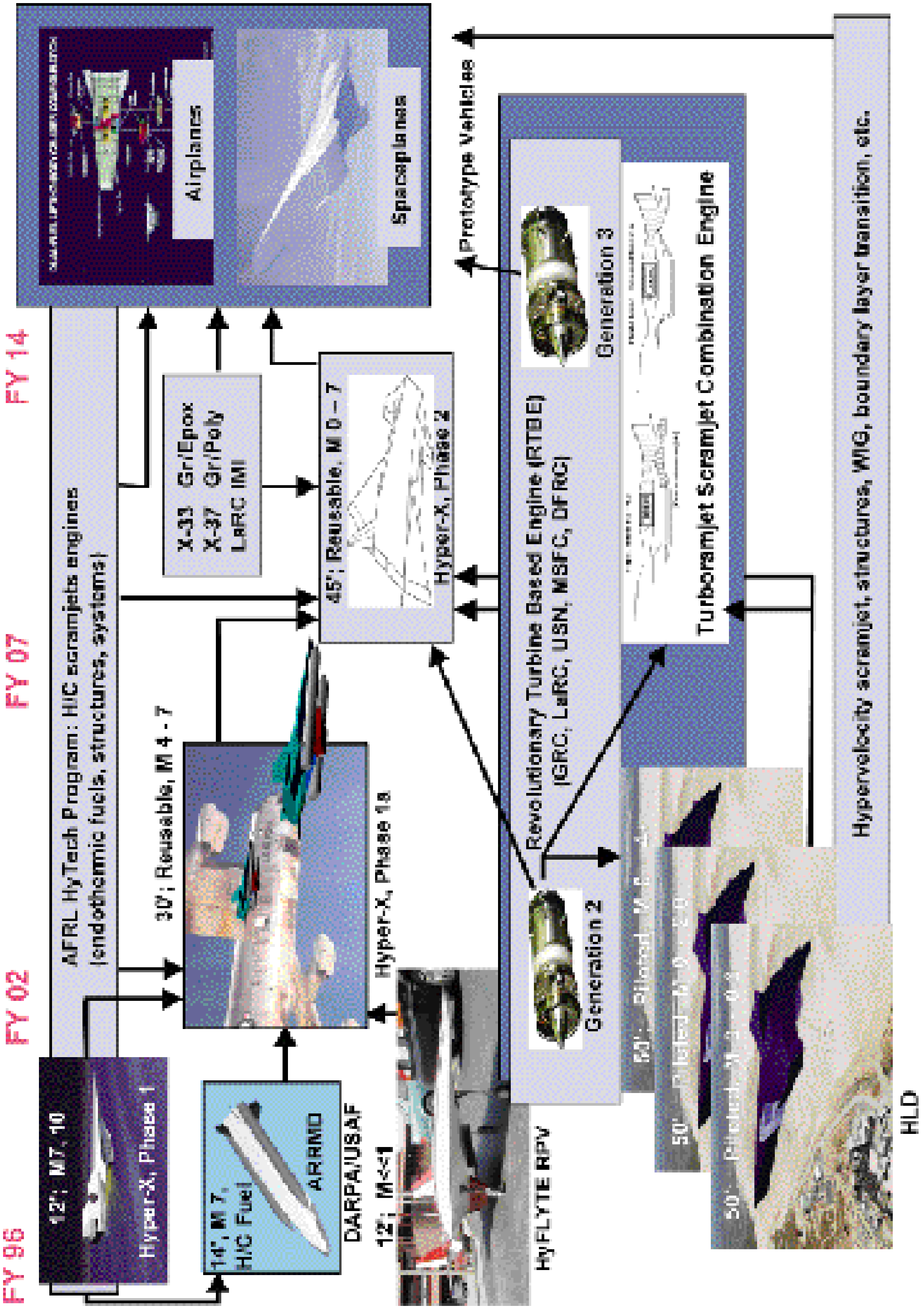


Figure 9. *Hypersonic Technology Development Plan.*