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Strategy for Developing Air-Breathing Aerospace Planes

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Hypersonic air-breathing propulsion, utilizing scramjets, can fundamentally change transatmospheric accelerators for transportation to and from low Earth orbits. The value and limitations of ground tests, flight tests, and computations are presented, and scramjet development requirements are discussed. Near-full-scale hypersonic propulsion flight tests are essential for developing a prototype hypersonic propulsion system. To determine how this development should be carried out, some technical and programmatic lessons learned from past programs are presented. A conceptual two-stage-to-orbit prototype/experimental aerospace plane is recommended as a means of providing access-to-space and for developing hypersonic air-breathing propulsion.

Introduction

REVOLUTIONARY rather than evolutionary changes in propulsion methods are most likely to lead to progress in transportation[1]; and propulsion is the most important pacing technology for advancing the maximum speed at which air-breathing piloted flight vehicles can fly. Hypersonic air-breathing propulsion, utilizing scramjets or supersonic combustion ramjets, can fundamentally change transatmospheric accelerators and atmospheric cruisers. A strategy is discussed here for bringing about this change.

As an Earth-to-orbit-and-return transportation system, the multistaged Space Shuttle was successfully developed by using all-rocket propulsion. However, further advancements in all-rocket propulsion will yield only small improvements in performance, since rocket performance has been advanced close to its theoretical limits. Rocket systems require much larger propellant mass fractions, resulting in smaller empty mass and payload mass fractions, and provide smaller weight growth margins for the same percentage increase in dry weight than do systems based on air-breathing propulsion with a rocket assist. Consequently, the former have limited potential for large payload mass fractions. Rocket propulsion can provide boost-glide, but this is unacceptable for hypersonic cruisers. Although air-breathing/rocket systems require about 50% more ideal velocity (energy) to achieve orbit than do all-rocket systems, the factor-of-2 advantage offered by the air-breathing/rocket systems in terms of effective specific impulse more than compensates for their increased drag and gravity losses.[2] Air-breathing propulsion provides for higher overall performance and far greater operability than that possible with rocket propulsion. Air-breathing propulsion with a rocket assist in horizontal takeoff vehicles substantially increases orbital-mission flexibility vis-à-vis that offered by all-rocket propulsion in vertical takeoff vehicles.

Making significant improvements in mass fraction and margin and developing fully reusable vehicles are the primary challenges for the rocket designers; making operational scramjets over the complete air-breathing hypersonic range is the primary challenge for the designers of air-breathing system. The development of both propulsion options should be pursued.

The development of prototype or operational systems requires the effective and efficient use of proved computational tools, as well as appropriate ground and flight tests. Computational tools include simple tools or engineering tools, computational fluid dynamics (CFD) tools, and computational structural dynamics (CSD) tools. In turn, the use of these tools requires models of physical and chemical (natural) phenomena, and models of increments (deltas) when absolute values of pertinent quantities either cannot be predicted or can be predicted only at an impractical cost. Computational models are applicable with a high level of confidence only in the domain in which they are developed and validated.

The development and validation of computational models require test data. These processes are accomplished by research and development (R&D) activities conducted through ground and flight tests. Research tests are well defined and controlled, are generally highly instrumented, are aimed at high-resolution data, are carried out (usually) with small-scale test models, and have short test times. These tests help us understand phenomena related to the development and validation of computational models. Development tests are conducted for parametric tradeoff studies with subscale or near-full-scale subcomponents and components. Research and development tests provide the database for design. Test and evaluation (T&E) or qualification activities with ground tests are used to validate the overall design of a system or of subsystem hardware to assure that it will perform as expected in flight. The qualification is done in terms of performance, operability, and durability near or at flight conditions. Test articles are usually large scale and the test times are relatively long.

Existing ground test facilities and test techniques are inadequate for developing a scramjet R&D database or for qualifying air-breathing propulsion modules utilizing scramjets[3-5]; they are adequate only in a perfect-gas environment. Current vitiated-air facilities that can accommodate relatively large-scale components operate in the Mach number range below 8. Higher Mach number facilities provide only partial flow simulation and either operate for short test times or are too small. Subscale modules and components can be tested to about Mach 12 in arc facilities, to about Mach 15 in shock tunnels, and up to Mach 22+ in impulse facilities. These facilities are suitable for limited research testing. Large-size engine modules can be tested up to a true temperature Mach number of 3.8 in clean (nonvitiated) continuous-flow air for qualification testing and up to about Mach 7 with either vitiated air or nonvitiated

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simulated air in blowdown (shorter duration) facilities for development testing.

With present measurement techniques,[6–8] the level of uncertainty in derived performance measurements generally increases with increasing hypersonic freestream Mach number M_0. The effect of this trend in uncertainty is compounded by the fact that the acceptable level of uncertainty in some measurements decreases with increasing M_0. Consequently, the use of performance measurements in design development processes leads to increasing uncertainty with increasing Mach number. For example, see Ref. 9 for uncertainties in measurements of inlet performance and the sensitivity of the engine specific impulse to these uncertainties (Fig. 1). Moreover, the cost and complexity of tests increase as Mach numbers increase.

New facilities can be built and new or improved test techniques can be developed to overcome some of these current testing deficiencies, but this would require 7–12 years, even given the required new technologies.[3] If the required technologies must be developed, an additional 10 years (estimated) would be required before facility design could begin. Another choice for developing a hypersonic propulsion system is to conduct a flight-test program.

Testing of new concepts, designs, and systems in flight is as fundamental as testing in ground facilities. Neither ground-test data obtained at flight conditions nor computational models based on these data can give all of the answers related to a true flight environment. Flight tests can be used to verify and calibrate or correct ground-test data and computational results, and can be used to validate and develop computational models. Flight testing plays the essential role in ensuring that all of the elements of a vehicle are satisfactorily integrated. Qualification flight testing is done to verify the complete system performance, operability, and durability, and to identify critical problems, to flush out unanticipated unknowns, and to establish the flight envelope.

Although development programs can be conducted in flight, research tests are difficult or impossible to carry out in flight: flight environmental conditions can be neither completely controlled nor defined, and the quality and quantity of data are generally not as good as can be obtained in ground facilities. Moreover, flight tests can be risky and they are expensive.

There are numerous examples of flight data being at variance with ground-test data and with computed results. Neither flight tests, ground tests, or computations, taken alone, are adequate for developing new concepts or new prototypes. The aerospace vehicle development quartet: 1) design, 2) computations, 3) ground tests, and 4) flight tests, is required (Fig. 2).

Hypersonic–propulsion flight tests are essential to the realization of the propulsion revolution offered by the scramjet cycle. The objectives of flight tests are to assemble databases for developing prototype or operational propulsion systems and to gather data for developing computational-design technology and for corroborating ground-test data. But how should flight tests be conducted for developing air-breathing aerospace planes? In the sections that follow, an attempt is made to answer this question, the requirements for developing this propulsive cycle are discussed, relevant lessons are drawn from past hypersonic and nonhypersonic programs, and a strategy is proposed for achieving this revolution in propulsion leading to progress in transatmospheric and atmospheric transportation.

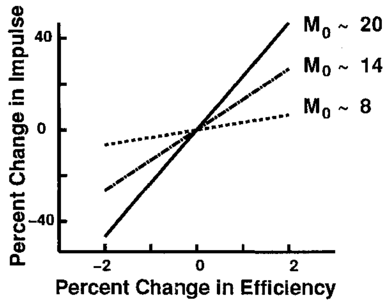

Fig. 1 Estimated sensitivity of engine specific impulse to uncertainty in inlet efficiency at three Mach numbers (based on Ref. 9).[10]

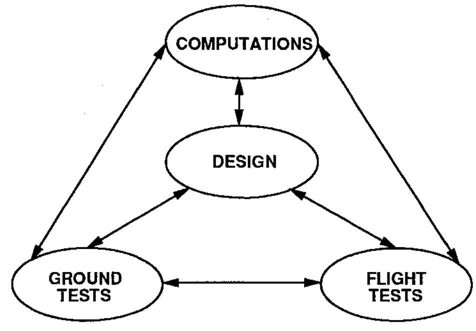

Fig. 2 Aerospace vehicle development quartet.

Requirements for Developing Hypersonic Air-Breathing Propulsion

The propulsion system of a single-stage-to-orbit (SSTO) transatmospheric accelerator consists of 1) a low-speed propulsion system for acceleration from takeoff to a freestream speed of about Mach 3; 2) a combined-cycle or a dual-mode engine that operates in a ramjet mode from $M_0 = 3$ to about $M_0 = 6$ and in a scramjet mode from $M_0 = 6+$ to $23+$; and 3) a rocket system to assist the low-speed system, to achieve orbit, and to maneuver on-orbit/de-orbit. (Note that whether these three systems are integrated into one combined-cycle system is immaterial as far as the central theme of this article is concerned.) At freestream speeds above Mach 3, the entire underbody of a lifting-body or wing-body vehicle, excluding wings and control surfaces, but including the engine, is the propulsion system. The forebody underneath the vehicle is used to compress, decelerate, and direct the required airflow into the engine, which consists of an air inlet, an air duct (isolator), fuel injectors, burners, and an exit nozzle. Inside the engine, the air is further compressed, is subsequently mixed with fuel, and is ignited and burned. The combustion products exit the engine and expand along the underneath afterbody to provide thrust.

A strong coupling or integration between the propulsive and aerodynamic flowfields and between different components of the propulsive system leads to a sensitivity-intensive vehicle, with the level of integration and the level of sensitivity increasing as Mach number increases along the air-breathing corridor. For example, the expected performance of the scramjet at moderate and high M_0 may require control of the angles of attack or sideslips within 0.1 deg. (Low-, moderate-, and high-hypersonic freestream Mach number ranges are defined, respectively, as $M_0 = 5+$ to 10, $M_0 = 10+$ to 18, and $M_0 = 18+$ to 24.) The development of such a propulsion system is a strongly integrated multidisciplinary and multitechnology process.

The feasibility and operability of the air-breathing hypersonic propulsion system are key developments required for building transatmospheric accelerators. The entire propulsion system must be carefully designed to achieve the desired propulsive performance under all expected flight conditions. There are at least the following five formidable design challenges:

1) Optimum performance is a design goal for each type of propulsion system over its operational Mach number range.

2) Smooth transition is required from the low-speed system to the ramjet-propulsion cycle, from the ramjet cycle to the scramjet-propulsion cycle, and from the scramjet cycle to the rocket system.

3) Efficient and reliable control of the thermal environment is necessary, with active fuel cooling of the propulsion system during the ramjet/scramjet operation.

4) The different propulsive systems must be integrated in a way that does not degrade their individual performances when they are active and that keeps their individual weights and complexities acceptable.

5) Some common components among different propulsion systems and some components of the same system need to be in-flight variable for efficient use at each flight condition.

On one hand, it is propulsion system performance at moderate and high Mach numbers that will ultimately determine the success or failure of the transatmospheric accelerator. On the other hand, the compromises made to ensure the proper propulsion system performance at moderate and high Mach numbers must also permit adequate propulsion system performance below Mach 6. The propulsion system for the cruiser is a fallout of the development of the propulsion system for the accelerator; but the converse is not true.

There are three essential issues related to the ramjet–scramjet propulsion system. The first is whether the engine will perform as expected when integrated with the forebody and the afterbody, that is, with the airframe. Only when the engine is integrated with the airframe does engine performance have a useful meaning. The second issue is whether the inlet, isolator duct, burner, and nozzle will perform as their individual tests indicate they will, after they are integrated into an engine. The third issue is the effect of one engine module or flow path on another engine module, that is, the effect of module-to-module interaction on the operability and reliability of the engine, caused by forebody and afterbody flow distortions or by unstart of one of the engine modules. Related to this third issue is the issue of vehicle controllability. These issues may not be answered fully without flight tests, because neither the full-scale vehicle nor the full-scale engine—nor its most crucial and least understood component, the burner—can be tested in existing ground-test facilities or credibly analyzed with computational tools at crucial flight conditions.

During ramjet operation and during scramjet operation at low- and moderate-hypersonic freestream speeds, combustion takes place at subsonic speeds and supersonic speeds, respectively. When speeds approach Mach 18, hypersonic combustion takes place. In the latter case, the burner entrance flow is at a hypersonic Mach number (Mach > 5) and the burner bulk flow remains hypersonic throughout the fuel injection, mixing, ignition, and burning process.

In the burner there is a strong interaction and synergism between the fuel, fuel injectors, and the burner configuration, with a number of issues related to each one of them. Temperature, kinetics, mixing, and ignition are issues associated with the fuel. The injection scheme, mixing enhancement and control, axial momentum, and thermal protection are problems related to fuel injectors. Entrance flow conditions; area ratio and distribution; length; wall friction, heat transfer, and reactivity; mixing; turbulence; chemistry; finite strength shock waves; and flow separation are concerns regarding burner configurations. The issues of turbulence, mixing, and combustion at moderate and high Mach numbers are significant and currently confound theoretical understanding. Flows with hypersonic combustion differ from those with supersonic combustion in that the effects of heat release through combustion are smaller. It is also known that turbulence can create random shock waves and intermittent zones of chemical reaction.

Burners are designed to attain the highest performance, lightest weight, lowest cost, and most durability and reliability. Different priorities are placed on each of these design requirements for different applications. From the point of view of performance, burner designs differ at low-, moderate-, and high-hypersonic flight Mach numbers. For example, to enhance fuel penetration, the fuel injection angle can be normal to the airflow at $M_0 < 10$; but this angle needs to approach the flow direction as the high Mach range is approached, because the axial momentum of the fuel is a major contributor to engine thrust.[11]

The scramjet propulsion or mode is not terminated at the instant when the rocket propulsion or mode is turned on to achieve orbit; there is a Mach number range over which both modes are operational. Although the rocket propulsion increasingly contributes to the net thrust at speeds approaching the orbital speed, the scramjet system is expected to contribute until possibly just before this speed is achieved. That is, the operation of the latter system ought to assist rather than hamper the contribution of the former. This requirement makes the understanding of hypersonic combustion phenomena as significant as that of supersonic combustion.

Hypersonic propulsion testing requires test conditions for proper chemical reactions, mixing, boundary layers, shock-wave patterns, and near-full-size hardware. It is necessary to duplicate the primitive variables that are likely to occur in flight at the burner entrance, including gas composition, and at the sides of the burner, so that the combustion chemistry is correctly reproduced. This is explained as follows.[12] Damköhler's first number is proportional to a product of Reynolds number and is a function of temperature and velocity. This relation requires matching of Mach number (the ratio of kinetic energy to thermal energy), Reynolds number (the ratio of inertial forces to viscous forces), and Damköhler's numbers (the rato of flow transit time through the burner to chemical reaction time and the ratio of heat added by reaction to the stagnation enthalpy of the inviscid flow). Hence, the burner length is determined by chemical kinetics, and it is nonscalable. If the needed burning length is shortened, performance results for subscale models of engines are subject to large errors.

There are three approaches to conducting tests.

1) There is a duplication of the flight values of certain well-known dimensionless groups, namely, simulation parameters leading to the testing of subscale models.

2) The propulsion system is decomposed into testable units using control volumes and reference planes (cf. Ref. 13). This approach requires the matching and simulation of at least the upstream and lateral boundary conditions at these interfaces of testable units or components.

3) Ground tests are used to define incremental effects to a well-established baseline.[8]

However, these three approaches are of limited use for developmental testing of the moderate- and high-speed hypersonic air-breathing propulsion system because of the current limitations of ground testing.

Scaling issues and interface simulation issues for flight tests are no different from those for ground tests. As the scale of the system is reduced, the quality and quantity of useful test data gathered are less, and more of the phenomena observed in the near-full-scale propulsive system are less observable in the subscale systems (cf. Ref. 14).

There are two principal scaling issues (Fig. 3). First, the performance and operability of the subscale design may differ from those of the full scale. These differences may lead to the

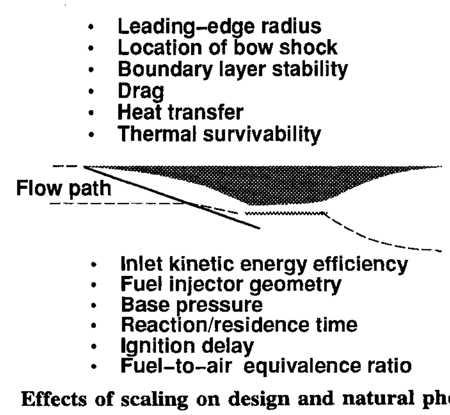

Fig. 3 Effects of scaling on design and natural phenomena.

development of inappropriate computational models for full-scale applications. Photographic scaling of a full-scale propulsion system or of a component can result in a system or a component that does not function. The photographically scaled test article is invariably modified because of some of the following reasons: manufacturability, functionality, performance, preservation of full-scale natural phenomena and of nearly the same flow conditions, instrumentation, cost, and timeliness. For example, manufacturability of leading edges and fuel injectors limits the smallness of these devices. The changing of fuel temperature affects fuel–air mixing, ignition and reaction rates, fuel thrust, and the fuel-to-air equivalence ratio (the ratio of the actual fuel-to-air-flow ratio to the stoichiometric fuel-to-air ratio, the latter being the fuel flow required to burn all of the oxygen present in the air).

The second principal scaling issue is the traceability of natural phenomena and representative flow conditions in subscale articles to those likely to occur in full-scale articles. A functional subscale article may either manifest phenomena other than those likely to occur in the full-scale article or manifest the same phenomena, but produce flow conditions vastly different from those in the full-scale article. Along the propulsive flow path, scaling can, for example, affect phenomena related to the transition from laminar to turbulent flow; entropy layer; viscous layer; shock-wave and boundary-layer interaction; shock–shock interaction; low-density effects; chemical kinetics; mixing; ignition; interactions between chemical reactions and turbulence; surface conditions in terms of materials, temperature, and roughness; and transition from turbulent to laminar flow. A lack of traceability also affects the development of appropriate computational models.

The reference-plane approach is difficult to use for the complete development of individual components. Unprecedented attention is required for details of the various phenomena that are likely to occur along the propulsion flow path and to the integration of these phenomena between components. Only a small number of high-level decisions can be made concerning the overall design philosophy. Once these decisions are made, the design of components evolves to support the initial decisions.

There are two main challenges involved in the reference-plane approach for component qualification testing. First, interface boundary conditions must be simulated with a high level of fidelity; otherwise, this approach introduces uncertainties that may cast serious doubts on the outcome of testing. When such an accurate simulation is not feasible or practical, which is almost always the case, different sets of interface boundary conditions encompassing the required set of conditions need to be simulated, and the sensitivity of these simulated sets to the performance of the testable unit is determined. At moderate and high Mach numbers, the burner or the nozzle entrance conditions are extremely difficult, if not impossible, to completely simulate and test in present ground-test facilities. Simulations of these conditions without other relevant components in flight tests are either even more difficult or impossible.

Second, net propulsive thrust cannot be measured in ground tests. In principle, a force-accounting procedure can first assess the performance of each testable unit and then determine the performance of the complete propulsion system. The measurement of component performance is not a trivial task.[9] Net thrust is a small difference between a large gross thrust and a large gross drag. Even errors of 1–2% can introduce significant uncertainty in determining net thrust. Further, energy requirements will preclude building a facility large enough to test the complete propulsion system. Consequently, net thrust can be measured only in flight.

The incremental approach provides increments that account for the various modeling shortcomings that preclude a test at flight conditions. These increments are added to a properly characterized baseline flow. This approach to developing the burner, particularly, at moderate- and high-hypersonic Mach numbers requires new ground facilities and the development of enhanced nonintrusive flow-diagnostic techniques, that is, techniques producing smaller uncertainties in measurands and derived quantities.

The principal scramjet developmental challenge is in the Mach number range from Mach 10 to 23+. The development of a prototype transatmospheric accelerator leading to a fleet of operational vehicles requires a demonstration of net scramjet thrust across the complete air-breathing hypersonic Mach number range, validation of computational models and verification of computational-design tools, and verification in an actual vehicle of the technologies and systems needed for such vehicles. The latter requirement includes items such as those related to vehicle controllability and operability, structural and subsystem weights, integrity, and survival, and thermal-environment controllability. These requirements go far beyond research inquiry concerning hypersonic air-breathing propulsion and technology demonstrations in individual propulsive components.

These requirements can be only partially met with a subscale propulsion system. At least two and (preferably three) appreciably different size subscale systems must be tested so that extrapolation to near-full scale can be done with a high level of confidence. Until more becomes known, all of these requirements can be fully met only with near-full-scale systems. The testing of these systems would lead to an even higher level of confidence in the development of a prototype system.

Lessons Drawn from Past Programs

In the U.S., the X-series of vehicles have been tested in flight mainly to understand and demonstrate new design concepts and to explore new flight regimes.[15] In the past, such activities led to two major contributions: 1) the development of supersonic flight technology and 2) an understanding of the problems of flight out of the atmosphere and of lifting entry into the atmosphere from orbit. Many minor contributions have also resulted from the flight tests of these vehicles. Note that the designs and operations of these vehicles required relatively minimal integration of propulsion and aerodynamics. A lesson deduced from flight-test programs is that flight testing is done with limited objectives over a relatively narrow spectrum of unknown natural phenomena primarily related to aerodynamics, aerothermodynamics, or propulsion.

The reusable, unpiloted X-7 plane (which set a speed record of Mach 4.31), was designed to serve as a ramjet engine testbed (Fig. 4). This plane was boosted to ramjet ignition speed before the reusable ramjet engine was started. A large ramjet database for three different size, pod-mounted engines was collected. This database is still the foundation of related ramjet investigations and developments.[16] The X-7 program demonstrated that a series of flight tests with reusable flight vehicles

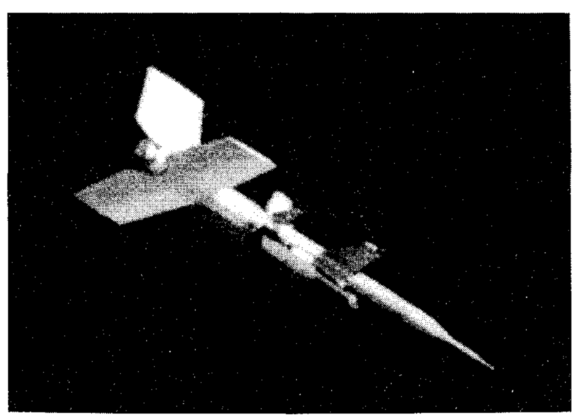

Fig. 4 X-7A testbed with a ramjet engine just after launch from a B-29 (courtesy of *Lockheed Martin Skunk Works*).

and testbeds provides the most productive experimental flight program.

The reusable, piloted, rocket-powered X-15 plane (Fig. 5), which was launched from a B-52 bomber, was the most successful of all the X-planes. One hundred and ninety-nine flights were conducted with three planes. A majority of the X-15 flights were in the Mach 5–6 range, and 1 h of flying time was accumulated at speeds above Mach 5; on four occasions the vehicle speed exceeded Mach 6, but over a total of only 6 min.[16] From the X-15 program we learned the following:

1) What may be minor and unimportant aspects of a subsonic or supersonic plane can be major design problems in a hypersonic plane.[17]

2) Robustness or margins are necessary for hypersonic experimental planes (cf. Ref. 15).

3) A test program in which numerous flight tests are conducted in an unknown region with reusable, modifiable, and piloted flight vehicles can provide a wealth of new information that can be used in developing new technologies and concepts.

The first orbital–aerospace X-plane program was the redirected Dyna-Soar program, which was started in October 1957 with the objective of developing in three steps a piloted vehicle for orbital military uses. This program was redirected three times, the final redirection occurring in December 1961. The final objectives were the development in one step of an orbital experimental glider launched from a Titan IIIC booster for piloted maneuverable entry from orbit, extensive exploration of the hypersonic flight regime to solve design problems associated with controlled entry, horizontal landing at a designated location, and exploration of man's military functions in space.[18] The program retained the name Dyna-Soar and in June 1962 it got the designation X-20 (Fig. 6). About three years before the first flight, Secretary of Defense Robert McNamara requested information on the necessity of manned military space systems. Apparently, the response was not satisfactory to provide an understanding of the ultimate purpose of the program or of possible space missions and economical advantages of Dyna-Soar-derived vehicles vis-á-vis other options; and in December 1963, this program was cancelled. The relevant lessons to be drawn from this program are the following:

1) The lack of a clear definition of a program and of its ultimate purpose is detrimental to the program's health and survival.

2) A program is selected on the basis of the return it promises on investment. A corollary is that a major program should offer short-term benefits.

The second orbital–aerospace X-plane (X-30) program, the National Aerospace Plane (NASP) program, was begun in February 1986. The X-30 (Fig. 7) was to have the capabilities of single-stage-to-orbit (SSTO), air-breathing propulsion at hypersonic speeds, hypersonic cruise, horizontal takeoff and landing from conventional length runways, powered approach to landing and go-around, and aircraft-like operability. The NASP program was redirected by the Space Council directive in June 1989 to develop and demonstrate hypersonic technologies with an ultimate goal of SSTO, with the performance of the X-30 constrained to the minimum necessary to meet the highest priority research, as opposed to operational objectives, and with the program conducted in such a way to minimize technical and cost uncertainties. This program was terminated in October 1994.

The NASP program was followed by the Hypersonic System Technology Program (HySTP) for ground- and flight-test activities; HySTP was to demonstrate scramjet performance and validate computer codes for computing this performance. In January 1995, the U.S. Air Force pulled out of this joint DOD/NASA program, effectively terminating it, because there was no compelling requirement-driven reason to fund it.[19] The compelling requirement-driven reason or the foremost customer's need is an affordable and reliable access-to-space system. A lesson to be learned is that a major demonstration and validation activity or a major experimental activity itself can be conducted only if it directly meets or is formulated to meet the goal. The pursuit of a major activity on the promise that it would eventually lead to the goal may not be done.

The HySTP was constrained with a design-to-cost requirement leading to a single-point-design testbed. Very few flight tests at speeds of about Mach 15 were contemplated for testing smaller than one-fourth scale scramjets (required for prototype or operational vehicles) mounted on surplus missile boosters. Although this program would have been highly educational, its success would not have established or its failure would not have ruled out the feasibility and the operability of a near-full-

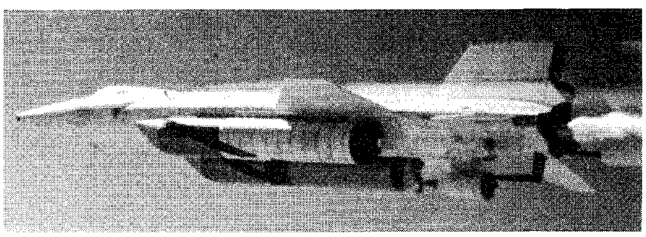

Fig. 5 X-15A-2 with full ablative coating and a dummy ramjet, just after launch from a B-52.

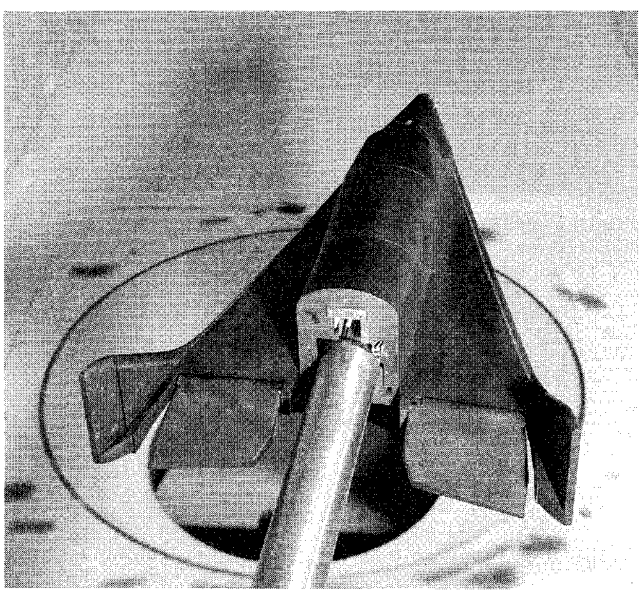

Fig. 6 Three-fourths rear top-view of the X-20 glider in the 9 by 7 ft supersonic wind tunnel at NASA Ames Research Center, November 1962.

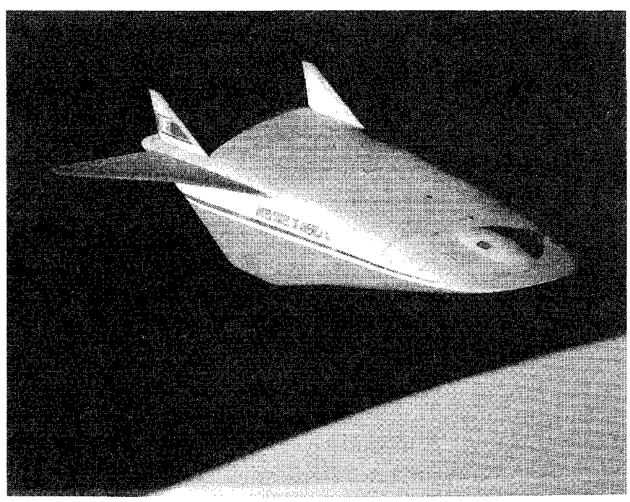

Fig. 7 Artist's view of the X-30 in an Earth orbit.

scale hypersonic air-breathing propulsion system for an aerospace plane.

A postmortem examination of the NASP program would reveal many lessons, two of which are of paramount importance. The first is that depending in a major way on a single unproved technology for designing a vehicle over a significant portion of its flight envelope is indeed an adventuresome design philosophy. In the mid-1980s, advances in propulsion, material and thermal management, and in CFD and the necessity of flight tests to demonstrate structural and thermal designs with full-size articles and to solve problems associated with such designs were used to technically justify the initiation of the X-30 program. Whenever ground-test data were not available at flight conditions, CFD was assumed to be the principal means of assessing the X-30's performance and for understanding various phenomena. Apparently, this assumption was a mistake. Computational-design technology is not complete enough in itself to be used as a design tool.

The second principal lesson to be learned from the NASP program is that a vehicle that departs radically from all its predecessors, by exhibiting a wide range of known and unknown phenomena, by presenting unprecedented obstacles in the integration of aerodynamics and propulsion, by allowing little margin of error, and by lacking necessary circumstantial evidence for validating its design before flight tests, is exceedingly hard to design. If a vehicle of a highly questionable design is built, the flight testing of it over a large Mach number range is an extremely difficult, risky, and even foolhardy task. It is prudent to assume that the design of such a vehicle, specifically of its propulsion system, will change significantly more than once during the flight-test program, and such changes are very costly. Note the following:

1) There is a substantial difference between all-rocket propulsion and air-breathing propulsion in terms of the natural phenomena likely to be encountered on the way to orbit and in terms of design.

2) The modifications that the X-7 and X-15 planes went through were relatively minor.

3) As designed, the X-30 was not able to theoretically achieve orbit.[20]

This lesson is a direct consequence of a premature program requirement, namely, the SSTO capability, the foremost objective of the NASP program. The initial selection of and the subsequent adherence to this objective were apparently ill-advised. In the late 1950s and early 1960s, the Recoverable Orbital Launch System (Aerospace Plane) program had selected two-stage-to-orbit (TSTO) concepts as first-generation options after reviewing many vehicle configurations, including SSTO concepts. "Even today, it is difficult to fault this choice."[21] A RAND study argued that there are no clearly compelling mission-related reasons for developing operational SSTO aerospace planes; and RAND proposed a TSTO approach as an alternative option.[21] The U.S. General Accounting Office (GAO) recommended a re-examination of the worth of pursuing SSTO on its own merit.[20] Regarding the X-30 program, Ben Rich wrote the following[22]: "But long before the first serious dollar is plonked down, someone in charge had better realize that Reagan's 'Orient Express' is really two separate concepts—one a rocketship and the other an airplane. Most likely, that particular twain shall never meet successfully."

The Dyna-Soar program and the NASP program provide a reaffirmation of Apollo-era NASA Administrator James Webb's requirement, that of developing a working consensus. There must be a consensus among members of the relevant technical and political communities other than those members directly involved with the program. Continuously, after the initiation of the NASP program, there were serious doubts about the program's technical feasibility and cost estimates.

The Apollo program, landing men on the Moon, was estimated to cost $13 billion. However, James Webb inflated this figure and presented to the U.S. Congress a figure of $20 billion.[23] This program was done on time and within budget. In contrast, significant cuts were made in the budget for the Shuttle program to get it started. These cuts affected its design and its operational costs. Note that the design-to-cost philosophy keeps a program alive, but ends up costing more in the long run.

In the Apollo program, three principal methods of accomplishing a piloted lunar landing were considered: the direct ascent, the Earth-orbital rendezvous, and the lunar-orbital rendezvous. The latter was chosen and was a great success, but it also ensured that the program would be a dead end. It was estimated that the lunar-orbital rendezvous method would cost between 10–20% less than the other methods and that the landing could be accomplished a year to a year and a half earlier than with other techniques.[24] If the Earth-rendezvous technique had been chosen instead, the work on deploying a space station could have begun at least 10 years earlier.[25] A lesson to be learned is that it is necessary to ask about what follow-on programs or growth potential are planned before discarding options and before freezing technology prematurely.

Within the WW II Manhattan Project, several alternatives were pursued simultaneously. It was this "approach, as much as anything, that enabled the United States to produce a nuclear weapon before Germany did."[25]

A lesson offered by a number of space-related failures, such as the Space Shuttle Challenger disintegration right after launch, is that "reliability should have top priority in the design of new systems, even at the expense of greater up-front costs and lower performance,"[26] because correcting failures eventually costs even more.

Prototype/Experimental Plane and Flight Tests

To cut the Gordian knot of developing hypersonic air-breathing propulsion to achieve orbit, the SSTO requirement must be put aside for a while (Fig. 8). The air-breathing SSTO capability should be developed after developing the air-breathing TSTO capability. The air-breathing TSTO plane significantly reduces risk, increases margin, and maintains the air-breathing SSTO option.

Staging has the potential to increase performance for a given technology or to deliver equal performance and lower risk with less advanced technology. For example, TSTO all-rocket vehicles have the following advantages over SSTO all-rocket vehicles (cf. Ref. 27):

1) SSTO vehicles are characterized as small payload launchers that cannot compete with the payload capability of TSTO vehicles.

2) SSTOs are more sensitive than two-stage vehicles to weight growth.

Likewise, TSTO air-breathing/rocket vehicles have the following benefits over SSTO air-breathing/rocket vehicles:

1) The useful air-breathing corridor for TSTO vehicles is larger than that for SSTO vehicles.[28]

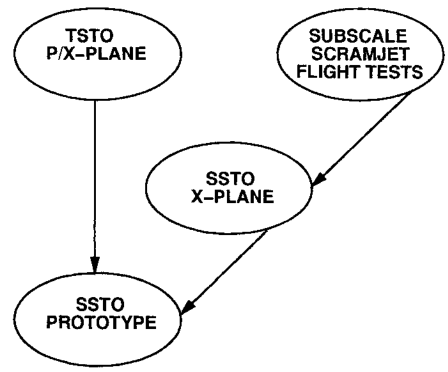

Fig. 8 Two options exist for developing a prototype air-breathing/rocket SSTO: safe and risky.

2) SSTO vehicles require larger propellant mass fractions than TSTO vehicles.

3) TSTO vehicles have higher payload potential and offer greater margin than SSTO vehicles.

4) TSTO vehicles have potential for greater atmospheric-cruise capability than SSTO vehicles.

Note the following:

1) These advantages of TSTOs over SSTOs are unaffected by the advances in technology.

2) SSTO vehicles require additional vehicles, which are launched from the payload bay after achieving LEO, for reaching high-energy orbits [such as geosynchronous transfer orbit (GTO), geosynchronous Earth orbit (GEO), and sun-synchronous orbit (SSO)].

The goal must be an affordable and reliable access-to-space transportation system with future growth potential rather than the SSTO requirement. A NASA access-to-space study has defined the following desired payload launching requirements of a new piloted operational system: carry a 20,000–25,000-lb mass payload to a low-Earth-orbit (LEO), namely, a 220-n mile circular orbit inclined at 51.6 deg. A possible set of the desired attributes of this system are the following: provide mission flexibility; be fully reusable; reduce life-cycle costs, in part by dramatically reducing launch costs; greatly improve the safety of the flight crew; vastly improve operability in terms of reliability, maintainability, and supportability (RMS); and have potential for growth in payload weight and volume by a factor of 2.

Mission flexibility and greatly enhanced operability are achievable if aerospace planes have features that approach those of aircraft. These attributes and full reusability of aerospace planes lead to significantly reduced operational costs, which in turn reduce the life-cycle costs (a sum of development cost, acquisition cost, and operation cost) of a fleet of aerospace planes. The life-cycle costs for each of the three systems [all-rocket SSTO, air-breathing/rocket SSTO, and air-breathing + all-rocket TSTO (Fig. 9)] considered under Option 3 of the NASA access-to-space study are almost the same as those for the other two systems, if the cost-estimating relations are based on previous airplane programs and if these relations are modified, when necessary, to account for the fact that aerospace planes approach rather than actually have aircraft-like operation.[29] However, the cost-estimating relations for new vehicles based on new technologies and new operating procedures are uncertain, producing large error bands in estimated costs.[21] Moreover, reducing launch costs from, say, $3000 to $300 per pound of payload to LEO is estimated to reduce the total cost of procuring and launching a dry spacecraft by less than 2%, because the cost of building a spacecraft is typically much more than the cost of launching it.[30] In the final analysis, it is the total cost of space operations that must be reduced rather than only the development and acquisition or launch or life-cycle costs.

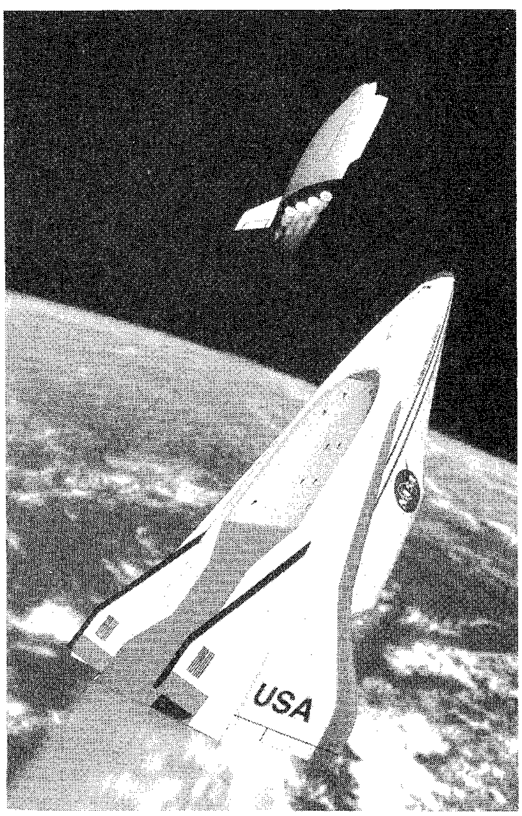

Fig. 9 Conceptual TSTO vehicle.

A prototype/experimental (*P/X*) TSTO aerospace plane (Table 1) is recommended as a means of providing access-to-space, for developing the hypersonic air-breathing propulsion system, and for developing a fully reusable all-rocket propulsion system with substantial improvements in mass fraction and margin. This plane consists of a first-stage plane, which is the carrier, and a second-stage plane, which is the orbiter. Three orbiters are developed. The carrier and the orbiters are full-scale, fully reusable, piloted, and take off and land horizontally. The carrier uses a low-speed system with a rocket assist and a ramjet–scramjet propulsion system; this stage is designed to go up to $M_0 = 10$. The carrier is a prototype vehicle up to $M_0 = 6$, and it is a demonstrator/experimental vehicle from $M_0 = 6+$ to 10. The upper Mach limit of 10 for the carrier is chosen considering the overall simulation limits of current ground-test facilities.

The three orbiters are the following: 1) orbiter-E with a rocket/air-breathing propulsion system, 2) orbiter-R with an all-rocket propulsion cycle, and 3) orbiter-A with an air-breathing/rocket system. Orbiter-E is designed to go from $M_0 = 8+$ to orbit. This orbiter is primarily rocket powered and has only one replaceable air-breathing propulsion flow path, with the engine being the primary replaceable component; it is designed to fly, when required, selected parts of orbiter-A's trajectory to orbit. The airframe of orbiter-E is essentially the same as that of orbiter-A. The development of the propulsion system with orbiter-E is done in two steps, from $M_0 = 8+$ to $M_0 = 18$ and from $M_0 = 18+$ to $M_0 = 24$. Once this system is developed, prototype orbiter-A is built.

Orbiter-R is designed to go from $M_0 = 6+$ to orbit. The start of orbiter-R is chosen at Mach 6+, because the ramjet cycle is relatively well established up to this value. The carrier is used to launch orbiter-R with ramjet operation under the following conditions: 1) before DT&E tests of the carrier are completed for speeds between Mach 7 and 10 and 2) if the scramjet fails to perform as expected. This Mach value is also chosen to build-in payload growth potential up to Mach 10, with the same carrier and with the same size of orbiter-R. Orbiter-R is a prototype vehicle.

Both the carrier and orbiter-R are expected to meet the desired access-to-space performance requirements and to do so with appropriate margins. These prototype vehicles evolve into an operational fleet of TSTO vehicles, while the development of the experimental orbiter, orbiter-E, is ongoing. An operational fleet of TSTO vehicles is strategically the right choice

Table 1 Characteristics of TSTO *P/X*-plane

Vehicle	Mach range	Propulsion cycles	*P* or *X*
Carrier	0–10	Low-speed, ram-scram, and rocket	*P*: $M_0 \leq 6$ *X*: $M_0 > 6$
Orbiter-A	8+ to orbit	Scramjet assisted by rocket	*P*
Orbiter-E	8+ to orbit	Rocket assisted by scramjet	*X*
Orbiter-R	6+ to orbit	Rocket	*P*

for providing an Earth-to-orbit-and-return transportation system that would replace the Space Shuttle, while greatly reducing the cost and substantially improving the reliability for access-to-space and while offering significant future growth potential and multiple avenues.

Since the volume of orbiter-A would be greater than that of orbiter-R for the same payload performance, a design compromise is required in favor of orbiter-A. Orbiter-R would be heavier than orbiter-A, requiring a stronger landing system on the carrier. These are just a couple of design issues.

The Mach number range from $M_0 = 5-24$ is broken up into three ranges (as previously defined), low-, moderate-, and high-Mach number ranges. This breakup facilitates the testing of the scramjet operation over the low-hypersonic Mach range with the carrier and the incremental development of air-breathing propulsion with orbiter-E at moderate- and high-hypersonic Mach numbers. This divide-and-conquer philosophy greatly reduces development and flight-test risks. Moreover, operations of the low-speed system, the ramjet system, and the ramjet–scramjet transition system in the carrier are flight qualified; and the performance of orbiter-R is tested and evaluated.

On one hand, the reusable and operationally flexible carrier provides the vital access-to-space launch and hypersonic flight-test services capability. On the other hand, orbiter-R provides the short-term economical benefits by achieving orbit for space missions, while orbiter-E is used for further scramjet development. This orbiter serves as a testbed for conducting other experiments and developments at high dynamic and heating loads, such as those related to full-scale structural panels and components. Orbiter-E is utilized as the X-7 and X-15 planes were.

Both propulsion options, rocket and air-breathing, are pursued. These propulsion systems and the proposed vehicles open up the following future growth potentials and multiple avenues, any one of which may be pursued with a high level of confidence: 1) staging of orbiter-R between $M_0 = 6$ and $M_0 < 10$; 2) growth of payload as the staging Mach number M_{st} is increased to an optimum value without changing the overall size of the orbiter; 3) improvements in the carrier performance may increase optimal M_{st} beyond 10; 4) replacement of orbiter-R with orbiter-A; 5) development of an air-breathing/rocket SSTO vehicle; 6) development of an all-rocket SSTO vehicle; 7) development of a hypersonic cruiser; 8) development of an unpiloted orbiter; and 9) development of an expendable, unpiloted orbiter for high-energy orbits.

Factors such as the following contribute towards making the life-cycle costs of a TSTO fleet comparable to those for a SSTO fleet:

1) The TSTO concept does not take the low-speed system to orbit as does the air-breathing/rocket SSTO concept.

2) The TSTO concept takes much smaller dry weight to orbit than either air-breathing/rocket or all-rocket SSTO.

3) An operational fleet of TSTO vehicles does not need to have the same number of carriers and orbiters.

4) A number of technologies and design features would be common between those required for the carrier and the different orbiters; for example, the carrier and the orbiters use hydrogen as fuel and use some of the same structures and materials.

For the reasons set forth next, the carrier and orbiter-R can be developed with a high level of confidence: the technologies developed under the NASP program; the large database available from low-speed systems, ramjet systems, the Space Shuttle orbiter, and other re-entry vehicles; and proper use of the aerospace vehicle development quartet (Fig. 2). Because a significant portion of the evidence for establishing the credibility of the design would be direct evidence, the level of confidence in the design of the carrier would be quite high, up to speeds of about $M_0 = 5$. The quantity of this type of evidence would decrease and the level of inferred evidence would increase, as $M_0 = 10$ is approached. Also, the level of confidence in the design of orbiter-R would be high. Primarily, only the ramjet–scramjet transition, vehicle performance at low-hypersonic Mach numbers, and full reusability of the orbiter-R are risk items.

Orbiter-E is not built until the hypersonic propulsion system performs satisfactorily in the carrier and is well understood. While the carrier and orbiter-R are designed, built, tested, and evaluated, phase 1 of a two-phase program for advancing the U.S. hypersonic facility capability is carried out as suggested in Ref. 3 for space launch and rescue and cruise aircraft, and appropriate nonintrusive flow-diagnostic technology applicable to the hypersonic environment is developed. Flight-test data from the carrier flights in the low-hypersonic Mach number range would improve computational-design technology and calibrate ground-test data. These advances and enhancements would help in the design of the full-scale, experimental air-breathing propulsion flow path for orbiter-E, with a high level of confidence in its design. Flight tests of this truly experimental vehicle in the moderate- and high-Mach-number ranges and the implementation of appropriate parts of phase 2 as recommended in Ref. 3 would result in a high level of confidence in the design of orbiter-A.

Conclusions

1) The limitations of ground-test facilities and those of computational-design tools and the highly integrated nature of the hypersonic propulsion system make flight tests essential for developing this system.

2) The requirements for developing hypersonic air-breathing propulsion dictate flight tests of near-full-scale vehicles, corresponding to the desired prototype or operational aerospace planes.

3) Based on lessons drawn from the past programs, it is highly recommended that flight tests be conducted with reusable, modifiable, piloted vehicles over a small range of Mach numbers (a narrow unknown region) and it is strongly suggested that a program be formulated that would provide short-term economical benefits, that would have growth potential, and that would be feasible.

4) The aerospace plane program in the early 1960s and the NASP program 30 years later did not find the SSTO concept viable, given the status of technology readiness. The TSTO concept is the right concept for fulfilling in the near term access-to-space needs.

5) An air-breathing TSTO demonstration is a prudent step before an air-breathing SSTO demonstration is attempted.

6) The carrier of the recommended TSTO P/X-plane assists the development of hypersonic air-breathing propulsion with orbiter-E and meets the desired access-to-space requirements near-term with orbiter-R. The development of the air-breathing propulsion system leads to the development of orbiter-A. This strategy offers a number of advantages. It is technology driven, opens up multiple future avenues, provides short-term benefits, has built-in growth potential, and is feasible. This strategy is sound, a necessary condition for developing a working consensus among relevant technical and nontechnical communities.

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