NASA Technical Memorandum 108857

Air-Breathing Aerospace Plane Development Essential: Hypersonic Propulsion Flight Tests

Unmeel B. Mehta

November 1994

National Aeronautics and
Space Administration

NASA Technical Memorandum 108857

Air-Breathing Aerospace Plane Development Essential: Hypersonic Propulsion Flight Tests

Unmeel B. Mehta, Ames Research Center, Moffett Field, California

November 1994

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

AIR-BREATHING AEROSPACE PLANE DEVELOPMENT ESSENTIAL: HYPERSONIC PROPULSION FLIGHT TESTS

Unmeel B. Mehta
NASA Ames Research Center, Moffett Field, California

ABSTRACT

Hypersonic air-breathing propulsion utilizing scramjets can fundamentally change transatmospheric accelerators for low Earth-to-orbit and return transportation. The value and limitations of ground tests, of flight tests, and of computations are presented, and scramjet development requirements are discussed. It is proposed that near full-scale hypersonic propulsion flight tests are essential for developing a prototype hypersonic propulsion system and for developing computational-design technology so that it can be used for designing this system. In order to determine how these objectives should be achieved, some lessons learned from past programs are presented. A conceptual two-stage-to-orbit (TSTO) prototype/experimental aerospace plane is recommended as a means of providing access-to-space and for conducting flight tests. A road map for achieving these objectives is also presented.

1. INTRODUCTION

Revolutionary rather than evolutionary changes in propulsion methods are most likely to lead to progress in transportation (Ref. 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 revolution.

As an Earth-to-orbit and return transportation system, the multi-staged space shuttle was successfully developed by using all-rocket propulsion. However, further advancements in this type of propulsion will yield only small improvements in performance, since rocket performance has been advanced close to theoretical limits. Air-breathing propulsion with a rocket assist significantly reduces gross takeoff weight for a given payload and substantially increases mission flexibility vis-á-vis those offered by all-rocket propulsion in vertical takeoff vehicles. Rocket systems require much larger propellant mass fractions, resulting in smaller empty mass and payload mass, and provide smaller weight growth margins for the same percentage increase in dry weight than do air-breathing/rocket systems. 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 (Ref. 2). Air-breathing propulsion provides for higher over all performance and far greater operability than that possible with all-rocket propulsion.

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

The development of prototype/operational systems requires the effective and efficient use of proven 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, these tools need 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.

These models are validated by research and development (R&D) activities conducted with 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 trade-off studies with subscale or near full-scale subcomponents and components. Research and development tests thus 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 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 and for qualifying air-breathing propulsion modules utilizing scramjets (Refs. 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 roughly 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 (non-vitiated) continuous-flow air for qualification testing and up to about Mach 8 with vitiated air in blowdown (shorter duration) facilities for development testing. With present measurement techniques (Refs. 6-8), the level of uncertainty in performance measurements generally increases with increasing hypersonic free-stream Mach number, M_0, making their use in design development processes increasingly uncertain. For example, see Ref. 9 for uncertainties in measurements of inlet performance and the sensitivity of the engine specific impulse to these uncertainties. 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 that would require 7-12 years, even given existing new technologies (Ref. 3). If the needed technologies must be developed, an additional 10 years (estimated) would be required before facility design could begin. Another choice for developing 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 the answers related to a true flight environment. Flight tests can be used to verify and calibrate/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 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. Either flight tests, or ground tests, or computations, taken alone, are inadequate for developing new concepts or new prototypes. The aerospace vehicle development quartet – design, computations, ground tests, and flight tests – is required (Fig. 1).

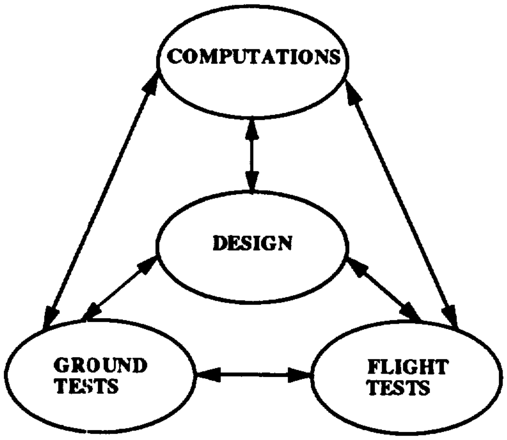

Figure 1. The aerospace vehicle development quartet.

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/operational propulsion systems and to gather data for developing computational-design technology and for corroborating ground test data. But how should these tests be conducted? 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 non-hypersonic programs, a strategy is proposed for achieving this revolution, and a conceptual flight-test vehicle is recommended. The requirements for developing computational-design technology and a road map for achieving this development are presented.

2. SCRAMJET DEVELOPMENT REQUIREMENTS

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 free-stream speed of about Mach (M_0) 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 $M_0 = 23+$, and (3) a rocket system to assist the low-speed system, to achieve orbit, and to maneuver on-orbit/de-orbit. At free-stream speeds above Mach 3, the entire vehicle underbody, 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/integration between the propulsive flow field and the aerodynamic flow field and between different components of the propulsive system leads to a sensitivity-intensive vehicle, with the level of integration and of the sensitivity increasing as M_0 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 0.1^0. (Low, moderate, and high hypersonic free-stream Mach numbers ranges are defined, respectively, as $M_0 = 5+$ to $M_0 = 10$; $M_0 = 10+$ to $M_0 = 18$; and $M_0 = 18+$ to $M_0 = 24$.) Development of such a propulsion system is a strongly integrated multidisciplinary/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 a number of formidable design challenges. First, an optimum performance is a design goal for each type of propulsion system in its operational Mach number range. Second, smooth transition is required from the low-speed system to the ramjet propulsion cycle or from the ramjet cycle to the scramjet propulsion cycle or from the scramjet cycle to the rocket system. Third, the efficient and reliable control of the thermal environment is necessary, with active fuel cooling of the propulsion system during the ramjet/scramjet operation. Fourth, the different propulsive systems need to 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. Fifth, 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/high M_0 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/high M_0 must also permit adequate propulsion system performance below Mach 6. The propulsion system for the cruiser is a fall-out 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, the isolator duct, the burner, and the nozzle will perform as their individual tests indicate 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 module-to-module interaction on the operability and the 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 at crucial flight conditions and credibly analyzed with computational tools.

During ramjet operation and during scramjet operation at low- and moderate-hypersonic free-stream 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; 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 performing, lightest weight, lowest cost, and most durable and reliable burner. Different priorities are placed on each of these design requirements for different applications. Just from the point of view of performance, burner designs differ at low-, moderate-, and high-hypersonic flight Mach numbers. For example, in order to enhance fuel penetration, the fuel injection angle can be normal to the airflow at $M_0 < 10$; but this angle need 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 (Ref. 10).

Although the rocket propulsion increasingly contributes to the net thrust at speeds approaching the orbital speed, the scramjet system is operational until just before this speed is achieved. 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, including gas composition, at the burner entrance and at the sides of the burner that are likely to occur in flight, so that the combustion chemistry is correctly reproduced. This is explained as follows. 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 ratio 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) (Ref. 11). Hence, the burner length is determined by chemical kinetics, and it is non-scalable. 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. In the first method, there is a duplication of the flight values of certain well-known dimensionless groups, namely, simulation parameters leading to the testing of subscale models. In the second method, the propulsion system is decomposed into testable units using control volumes and reference planes (cf. Ref. 12). This approach requires the matching and simulation of at least the upstream and lateral boundary conditions at these interfaces of testable units or components. In the third method, ground tests are used to define incremental effects to a well-established baseline (Ref. 8). However, these three approaches are of limited use for developmental testing of the moderate- and high-speed, hypersonic air-breathing propulsion system.

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. 13).

There are two principal scaling issues (Fig. 2). First, performance and operability of the subscale design are different from those of the full-scale. These differences may lead to the 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 – the fuel flow required to burn all the oxygen present in the air – fuel-to-air ratio).

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.

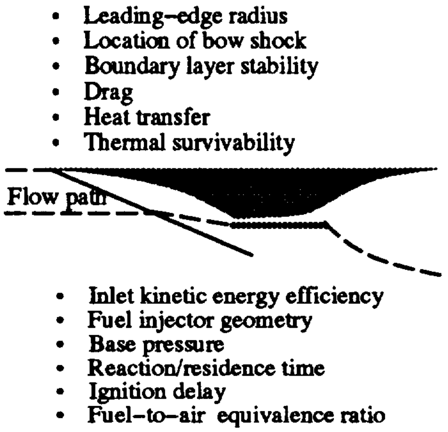

Figure 2. Some effects of scaling on design and natural phenomena.

The reference-plane approach is difficult to use for the complete development of individual components. Unprecedented attention is required to 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 M_0, 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 (Ref. 9). Net thrust is a small difference between a large gross thrust and a large gross drag. Even errors of the order of 1% to 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 for developing the burner, particularly, at moderate- and high-hypersonic Mach numbers requires new ground facilities and the development of enhanced, that is, having smaller uncertainties, nonintrusive flow-diagnostic techniques.

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 hypersonic Mach number range, verification and validation 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, 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.***

Until more becomes known, these requirements can be only partially met with a subscale propulsion system. For fulfilling all of these requirements, either near-full-scale systems or at least two and (preferably three) appreciably different size subscale systems should be tested so that extrapolation to near-full scale can be done with a high level of confidence.

3. LESSONS DRAWN FROM PAST PROGRAMS

In the United States, the X-series of vehicles have been tested in flight mainly in order to understand and demonstrate new design concepts and to explore new flight regimes (Ref. 14). In the past, such activities led to two major contributions: development of supersonic flight technology and 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 either aerodynamics, or 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. This plane was boosted to ramjet ignition speed before the reusable ramjet engine was started. A large ramjet database with three different size, pod-mounted engines was collected. This database is still the foundation of related ramjet investigations and developments. The X-7 program demonstrated that a series of flight tests with reusable flight vehicles and testbeds provides the most productive experimental flight program.

The reusable, piloted, rocket-powered X-15 plane, 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 to 6 range, and 1 hour 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 minutes. From the X-15 program we learned (1) that what may be minor and unimportant aspects of a subsonic or supersonic plane can be major design problems in a hypersonic plane (Ref. 15); (2) that robustness/margins are necessary for hypersonic experimental planes (Ref. 14); and (3) that a test program in which numerous flight tests are conducted in a 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 aerospace X-plane program, Dyna-Soar (X-20), was started in October 1957 with an objective of developing in three steps a piloted vehicle for orbital military uses. This program was twice redirected before being finally redirected in December 1961. The final objectives were the development in one step of an orbital experimental glider for piloted maneuverable entry from orbit, extensive exploration of the hypersonic flight regime to solve design problems associated with controlled entry, and horizontal landing at a designated location (Ref. 16). Apparently, there was a bureaucratic failure to provide an understanding of the possible space missions and economical advantages of Dyna-Soar vis-á-vis other options. In December 1963, this program was cancelled. At the time of cancellation, $410 million had been spent; 7,670 people were involved; 14,000 hr of wind-tunnel tests had been conducted; 11 million man-hours out of a total of 16 million man-hours had been spent in engineering; and the first flight was an estimated $373 million away (Ref. 16). The lessons to be drawn from this program are the following: (1) a lack of a clear program definition and of the ultimate purpose of the program is detrimental to its health and survival; and (2) when a choice is made between economics and technology demonstration, the former wins. 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 aerospace X-plane program, the National Aerospace Plane (NASP) (X-30), was begun in February 1986. The objectives of this program were 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 after approximately $2.4 billion had been spent by the U.S. government and NASP contractors.

The NASP program is replaced by the Hypersonic System Technology Program (HySTP) for ground-test and flight-test activities to demonstrate scramjet performance and validate computer codes for computing this performance. Apparently, this program is constrained with a design-to-cost requirement leading to a single-point-design testbed. Very few flight tests at speeds of about Mach 15 are being contemplated for testing roughly one-eighth scale scramjets mounted on surplus missile boosters. It should be observed that the success or failure of this program cannot establish the feasibility and the operability of a near-full-scale hypersonic air-breathing propulsion system for an aerospace plane.

A postmortem examination of the NASP program would reveal many lessons, among which two are of paramount importance. The first is that depending in a major way on a single unproven 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, in 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. Over about 70% of the X-30 flight envelope this dependence on CFD was necessary.

Computations are based on models for natural phenomena and for increments. Validation of these models requires test data. Obviously, computed results obtained with unvalidated models introduce uncertainties, risks, and conservatism which may be unacceptable. In the absence of test data, the level of credibility of CFD results can be established by the use of uncertainty analysis (Ref. 17). This approach is taken, for example, in the nuclear field (Ref. 18). This utility of uncertainty analysis in the aerospace field is yet to be developed. Thus, the credibility of a design is no better than the credibility of the tools used in the design; and computation-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. Please note that (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; and (3) the design of the X-30 was not able to achieve orbit (Ref. 19). This lesson is a direct consequence of a premature program requirement, namely, the SSTO capability.

The foremost objective of the NASP program was the SSTO capability. The initial selection of and the subsequent adherence to this objective were apparently ill-advised. This objective could have been dropped following the 1989 Space Council's directive or by heeding a prudent rule such as that established for the Skunk Works by Clarence L. "Kelly" Johnson, namely, that the outfit's "reputation for integrity would gain more business than [the outfit] would ever lose by turning away questionable ventures" (Ref. 20). In 1984, the U.S. Air Force Space Command had determined that in the mid-1990s the projected technology required for a SSTO vehicle would not be available, but that required for developing a two-stage-to-orbit (TSTO) vehicle would be available (Ref. 21). A RAND report has argued that there are no clearly compelling mission-related reasons for developing operational SSTO aerospace planes (Ref. 22). In December 1992, the U.S. General Accounting Office recommended a re-examination of the worth of pursuing SSTO on its own merit (Ref. 19). Regarding the X-30 program, Ben Rich wrote the following: "But long before the 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" (Ref. 20).

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 in the technical and political communities beyond those directly involved with the program. Before and continuously after the initiation of the NASP program there were serious doubts about the program's technical feasibility and cost estimates among people with no direct interest in the program.

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 (Ref. 23). This program was done on time and within budget. In contrast, significant cuts were made in the budget for the shuttle program in order to get it started. These cuts affected its design and its operational costs. A lesson that can be noted is that the design-to-cost philosophy keeps a program alive but ends up costing more in the long run.

The Apollo program had considered three principal methods of a piloted lunar landing: 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% to 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 (Ref. 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 (Ref. 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. The WW II Manhattan Project is a relevant example. Several alternatives were pursued simultaneously, and this "approach, as much as anything, that enabled the United States to produce a nuclear weapon before Germany did" (Ref. 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" (Ref. 26), because correcting failures eventually costs even more.

4. A 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. 3). *The air-breathing SSTO capability should be developed after developing the air-breathing TSTO capability* (Ref. 27). The air-breathing TSTO plane significantly reduces risk, increases margin, and maintains the air-breathing SSTO option.

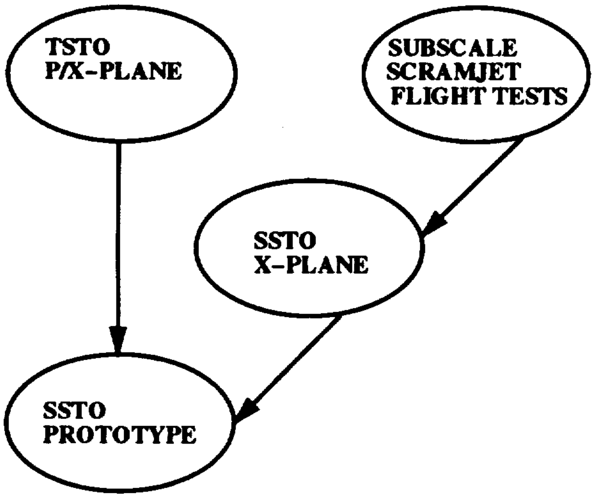

Figure 3. Two options exist for developing a prototype air-breathing SSTO: (1) safe and (2) risky.

Staging has the potential to increase performance for a given technology or to deliver equal performance and lower risk with less advanced technology, as observed in Ref. 28. For example, TSTO rocket vehicles have the following advantages over SSTO rocket vehicles: (1) SSTO vehicles are characterized as small-payload launchers that cannot compete with the payload capability of TSTO vehicles; and (2) SSTOs are more sensitive than two-stage vehicles to weight growth.

A NASA access-to-space study has defined the following desired payload launching requirements of a new piloted operational system with initial operational capability (IOC) circa 2008: carry a 20,000 to 25,000 pound-mass payload to a low-Earth-orbit (LEO), namely, a 220 nautical mile circular orbit inclined at 51.6^0. 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 with a design-to-launch-cost philosophy; 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 by a factor of 2 without adversely affecting other attributes.

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 (rocket SSTO, air-breathing SSTO, and air-breathing + rocket TSTO) considered under Option 3 of the NASA access-to-space study are similar to 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 (Ref. 28). 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 (Ref. 22). Moreover, reducing launch costs from say \$3,000 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 (Ref. 29). In the final analysis, it is the total cost of space operations that must be reduced rather than only the launch or life-cycle costs.

A prototype/experimental (P/X) TSTO aerospace plane (Table 1) is proposed as a means of providing access-to-space and for developing the hypersonic air-breathing propulsion system. This plane consists of a first-stage plane, the carrier, and a second-stage plane, the orbiter. Three orbiters are developed. The carrier and the orbiters are full-scale, are fully reusable, are piloted, and takeoff 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 $M_0 = 10$. The upper Mach limit of 10 for the carrier is chosen considering the overall simulation limits of current ground-test facilities.

Vehicle	Mach Range	Propulsion Cycle
Carrier	0 to 10	Low–Speed Ram–Scram Rocket
Orbiter–A	8 to Orbit	Scramjet Assisted by Rocket
Orbiter–E	8 to Orbit	Rocket Assisted by Scramjet
Orbiter–R	6 to Orbit	Rocket

Table 1. The characteristics of TSTO P/X-plane.

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 NASA access-to-space performance requirements and to do so with appropriate margins. 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, thus requiring a stronger landing system on the carrier. These are just a couple of design issues.

This proposal breaks up the hypersonic Mach number range from $M_0 = 5$ to $M_0 = 24$ into three ranges (as previously defined), low-, moderate-, and high-Mach number ranges. This breakup facilitates the testing of the scramjet operation at 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 flight-testing risks. Moreover, operations of the low-speed system, of the ramjet system, and of 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 hypersonic flight test and access-to-space launch 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 the "X-15" of this proposal.

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 orbiter.

The TSTO concept does not take the low-speed system to orbit as does the air-breathing/rocket SSTO concept; and the TSTO concept takes much smaller dry weight to orbit than either air-breathing/rocket or all-rocket SSTO. These advantages reduce launch costs of the TSTO concept. In optimized TSTO vehicles, orbiter-A needs a lower propellant fraction than that required by orbiter-R. An optimum M_{st} reduces life-cyle costs. Orbiter-A would be more reusable than orbiter-R (Ref. 30), which also would reduce life-cycle costs. The development of prototype TSTO aerospace plane (the carrier and orbiter-R) would evolve into an fleet of operational vehicles earning revenue. This revenue in part would pay for the flight tests of orbiter-E and the development of orbiter-A. An operational fleet of TSTO vehicles does not need to have the same number of carriers and orbiters. This flexibility also reduces life-cycle costs. Moreover, 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. This commonality in technologies and designs also helps to reduce the life-cycle costs.

For the reasons set forth below, the carrier and orbiter-R can be developed with a high level of confidence by about 2005: the technologies developed under the NASP program; the large database available from low-speed systems, ramjet systems, the space shuttle orbiter and other reentry vehicles; the possible further development of some relevant technologies; the aerospace vehicle development quartet; the available ground-test facilities; and the previously presented three approaches to conducting tests. 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. Primarily, the ramjet-scramjet transition, vehicle performance at low hypersonic Mach numbers, and full reusability of the orbiter-R are the 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, 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 design 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 would result in a high level of confidence in the design of orbiter-A.

5. COMPUTATIONAL-DESIGN TECHNOLOGY

Computational models are the backbones of the computational-design technology. It is essential to define conceptual designs before assessing the utility of available models and developing new models, because models are applicable with a high level of confidence only in the domain in which they are developed and validated. The desired designs, in terms of performances and specifications, of flight vehicles and the natural phenomena they are likely to encounter, identify the possible domains in which models are needed. Ground tests are also conducted in these domains. The computational-design technology development efforts are guided by the goal of minimizing technical uncertainties in the design for the purpose of reducing risks.

The principal challenge of aerospace vehicle design is to provide credible design computations to work from, to assess the risk associated with the use of those computations, and to develop design tools (Ref. 31). The level of credibility required is determined by the degree to which system specifications, such as takeoff gross weight (TOGW), are sensitive to performance quantities, such as the engine specific impulse, and in turn the degree to which performance quantities are sensitive to design parameters and to computational uncertainties (Ref. 32).

Among computational-design tools, computational fluid dynamics (CFD) is an awesome tool in the hands of knowledgeable designers. It may, for example, be used in the design process in understanding natural phenomena, in making trade-off studies, in determining design sensitivities, in optimizing designs, in making design evaluations, in developing the design database, in computing increments, in building absolute performance estimates, and in developing and calibrating simplified tools. With CFD the designers can often address problems for which no design experience, test-data base, or test techniques exist. Computational fluid dynamics has the potential of representing and computing the phenomena associated with hypersonic, free-flight conditions more accurately than can be done and measured in ground-test facilities.

Computational fluid dynamics plays the following multifaceted role in R&D tests and qualification tests: pre-fabrication (that is, before a test model is fabricated) and preflight computations assess the feasibility of the proposed test program. Computational fluid dynamics provides an understanding of phenomena; assists in improving flow through existing test facilities; supports design activities of new facilities; predicts flow around and through test models for the purpose of instrumentation design, precision, and location; helps determine the type, quality, and quantity of test data necessary; interpolates and extrapolates test data to fill gaps in the test database; assists in the design of model support and other test devices and assesses their interference effects; and helps in formulating the relevant test matrix. Thus, CFD collaborations enhance the credibility and usefulness of ground and flight tests, reduce costs of conducting these tests, and enhance confidence levels for safely expanding flight envelopes.

By definition a simulation, either with computations or in ground-test facilities, is not the reality of flight.

A simulation is acceptable if it reproduces the reality to the level required for a specific utilization of the simulation. The departure of the simulation from the reality is an error in the simulation. An *estimate* of this error is the uncertainty in this simulation. Sources of uncertainties unique to computations are a lack of equivalence between theoretical and computational problems, unsatisfactory computational accuracy, and improper modeling of phenomena, whereas sources of uncertainties unique to tests are the insufficiency of measurements and unsatisfactory measurement accuracy. Computations and tests also have common sources of uncertainties, which are owing to isolation of phenomena, extraneous phenomena, and those attributable to the human element. A crucial uncertainty introduced by the latter source is caused by the phenomenon of creative overbelief. The uncertainties of natural phenomena are owing to the departure of the modeled phenomena from reality. Sometimes a phenomenon that ought to be there is not modeled, causing isolation uncertainty. And sometimes a phenomenon that does not occur in the real situation is modeled, causing extraneous uncertainty. Humans tend to believe that what they have done is right. This belief creates uncertainties. Reference 17 provides examples of various kinds of uncertainties.

Two kinds of benchmark computations are conducted. The first is for assessing whether the problem is solved correctly, that is, by verifying computations. The second is for determining whether the right problem is solved, that is, for validating computational models. There is always some uncertainty, even if one uses validated models and verified computed results, and the value of this uncertainty is important in the design process. Validation and verification/demonstration processes are combined into one word, "certification," for establishing the level of credibility of the results, that is, for determining the degree to which the right problem is solved correctly. To certify is to inform with certainty or to attest as meeting a standard. Certification is defined as follows: the process of evaluating a computer code in terms of its logic, numerics, natural phenomena, and the results to ensure compliance with specific requirements. These requirements are specified by the utility of the code. A road map for establishing credibility is discussed below.

The following are the guidelines for tests. First, the sensitivity of critical measurands and derived quantities to test parameters, test instruments, etc. are determined and various sources of uncertainties are identified. Second, computational tools are used to design and formulate the test to meet the objectives of this test. Third, a provision is made for having redundancy of data to cross-check and to verify consistency. Fourth, relevant quantities at boundaries are measured to facilitate computations. Fifth, performance quantities are obtained when design-like articles are tested. Sixth, *the uncertainties in measurands and derived quantities are determined.* Seventh, an independent evaluation of the data is done. Eighth, some tests are repeated in the same facility and in two other test facilities. Ninth, a documentation of all test-related activities is prepared.

The guidelines for establishing the accuracy of discrete computations are the following. The number of grid-points is doubled twice in each direction and key results are processed using the Richardson extrapolation, under the following conditions: (1) one- and two-dimensional problems; and (2) one of the space direction is the marching direction in three-dimensional problems. This extrapolation is done at at least three values of a parameter that is to be varied in the application of a code, two extreme values and a nominal value. When none of the space directions is a marching direction in three-dimensional problems, the sensitivity of the relevant computed results to the grid size in each direction is provided. This is an interim guideline, because of the current limits of computing power. Moreover, computations of propulsive flow path ought to provide the levels of error in conserved variables. Performance quantities can be significantly sensitive to conservation errors.

Sensitivity analysis is generally defined as the procedure for determining the sensitivities of output parameters to input parameters. This analysis is a necessary step in the uncertainty analysis, and the results of this analysis highlight which measurand and derived quantities in tests and which computed quantities and integrated quantities in computations need to be determined accurately and which quantities do not require such attention. The analysis begins by identifying output parameters. The sensitivity of each of these parameters to each of the input parameters is determined by computing the influence coefficient of each parameter, while neglecting the influence of the other parameters. These coefficients are obtained by perturbing the input parameters and obtaining the response in the output parameter.

The uncertainty analysis is generally defined as the analysis of the effect of the uncertainties involved in all stages of a process on the final responses. This process may be a test process or a computational process with the responses being test data or computed results, respectively. Uncertainty analysis is a powerful tool for locating the source of trouble in a malfunctioning test or computation. There are two approaches for conducting the uncertainty analysis: experimental and computational. These approaches are briefly presented in Ref. 17.

The computational-design technology development is done as follows. First, a systematic determination of the computational accuracy of performance quantities is carried out. Second, whether the computed phenomena are qualitatively satisfactory is determined. Third, the modeling of a part of the phenomena is validated by measurements, and the corresponding modeling uncertainties are determined. Fourth, computations that are likely to be unreliable are identified, and a sensitivity-uncertainty analysis is performed. Fifth, the complete phenomenological model is evaluated and the computational uncertainties are quantified. The computational-design technology for a class of aerospace planes can be considered developed and ready for use as a tool only after the computed results are compared with flight data, and the strengths, the weaknesses, and the domain of applicability of computational-design procedures are established.

6. CONCLUDING REMARKS

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 scramjet development requirements dictate flight tests of near-full-scale vehicles, corresponding to the desired prototype/operational aerospace planes.

3. The lessons drawn from the past program highly recommend flight tests with reusable, modifiable, piloted vehicles over a small Mach number range (a narrow unknown region) and strongly suggest a program formulation that would provide short-term economical benefits, that would have growth potential, and that should be doable.

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

5. The proposed carrier of the TSTO P/X-plane assists the development of hypersonic air-breathing propulsion with orbiter-E and meets the NASA access-to-space requirements near-term with orbiter-R. The development of the air-breathing propulsion system leads to the development of orbiter-A.

6. This proposal 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 definitely doable. This proposal is a sound strategy, a necessary condition for developing a working consensus among relevant technical and nontechnical communities.

7. The sensitivity-uncertainty analysis is the key to successful application of the aerospace vehicle development quartet – design, ground tests, computations, and flight tests.

8. Computational models cannot be validated with measurements, unless uncertainties in the measurands and in the quantities derived from these measurands are known.

9. The principal challenge for hypersonic propulsion flight tests for developing air-breathing aerospace planes is to provide for highly instrumented testbeds.

REFERENCES

1. Allen, H. J., "Hypersonic Flight and Reentry Problem," The Twenty-First Wright Brothers Lecture, Journal of Aerospace Sciences, Vol. 25, No. 4, Apr. 1958.

2. Chase, R. L., "A Comparison of Single-Stage-to-Orbit Launch Vehicle Candidates," AIAA Paper 92-3141, 1992. (See also AIAA Paper 94-3368, 1994.)

3. Laster M. L., and Bushnell, D. M., "A National Study for Hypersonic Facility Development," AIAA Paper 94-2473, 1994.

4. Heiser, W. H., and Pratt, D. T., with Daly, D. H., and Mehta, U. B., Hypersonic Airbreathing Propulsion, AIAA Education Series, 1994.

5. Wettlaufer, B., "Aeropropulsion Facilities," in Methodology of Hypersonic Testing, von Karman Institute for Fluid Dynamics, Lecture Series 1993-03

6. Matthews, R. K., "Hypersonic Flow-Field Measurements, Intrusive," in Methodology of Hypersonic Testing, von Karman Institute for Fluid Dynamics, Lecture Series 1993-03.

7. William, W. D., "Hypersonic Flow-Field Measurements, Nonintrusive," in Methodology of Hypersonic Testing, von Karman Institute for Fluid Dynamics, Lecture Series 1993-03.

8. Kraft, E., and Chapman, G., "A Critical Review of Integration of Computations, Ground Tests, and Flight Test for the Development of Hypersonic Vehicles," AIAA Paper 93-5101, 1993.

9. Van Wie, D. M., "Techniques for the Measurement of Scramjet Inlet Performance at Hypersonic Speeds," AIAA Paper 92-5104, 1992.

10. Billig, F. "Research on Supersonic Combustion," Journal of Propulsion and Power, Vol. 9, No. 4, July-Aug. 1993.

11. Anderson, G. Y., "Hypersonic Combustion Status and Directions," The Second ICASE/LaRC Combustion Workshop, 12-14 Oct. 1992.

12. Boudreau, A., Smith, III, V. K., and Daniel, D. C., "Developmental Testing of Ramjet/Scramjet Propulsion Systems," AIAA Paper 93-5121, 1993.

13. Wierzbanowski, T., and Kasten, T., "Manned Versus Unmanned: The Implications to NASP," AIAA Paper 90-5265, 1990.

14. Hallion, R. P., On the Frontier, Flight Research at Dryden, 1946-1981, NASA SP 4303, 1984.

15. Becker, J., "The X-15 Program in Retrospect," Raumfahrtforschung, Mar.-Apr. 1969.

16. Geiger, C. J., "Strangled Infant: The Boeing X-20A Dyna-Soar," in The Hypersonic Revolution, Vol. I, ed. R. P. Hallion, Aeronautical Systems Division, Wright-Patterson AFB, Ohio, 1987.

17. Mehta, U. B., "Some Aspects of Uncertainty in Computational Fluid Dynamics Results," Transactions of the ASME, Journal of Fluids Engineering, Vol. 113, No. 4, Dec. 1991.

18. Ronen, Y., ed., Uncertainty Analysis, CRC Press Inc., Boca Raton, Florida, 1988.

19. "National Aero-Space Plane, Restructuring Future Research and Development Efforts," GAO, NSIAD-93-71, U.S. Government Accounting Office, 1993.

20. Rich, B. R., and Janos, L., Skunk Works: A Personal Memoir of My Years at Lockheed, Little, Brown & Co., 1994.

21. Hallion, R. P., "Yesterday, Today, and Tomorrow: From Shuttle to the National Aero-Space Plane," in The Hypersonic Revolution, Vol. II, ed. R. P. Hallion, Aeronautical Systems Division, Wright Patterson AFB, Ohio, 1987.

22. Augenstein, B. W., Harris, E. D., et al., "The National Aerospace Plane (NASP): Development Issues for the Follow-on Vehicle," Executive Summary, RAND, R3878/1-AF, 1993.

23. Trento, J. J., Prescription for Disaster, Crown Publishers, Inc., New York, 1987.

24. Holman, M. A., The Political Economy of Space Program, Pacific Books, Publishers, Palo Alto, Calif., 1974.

25. Mark, H., and Levine, A., The Management of Research Institutions, NASA SP-481, 1984.

26. From Earth to Orbit, Committee on Earth-to-Orbit Transportation Options, Aeronautics and Space Engineering Board, National Research Council, 1992.

27. Mehta, U., "A Suggestion for Getting 'Phase 3' Go-Ahead - A White Paper," NASP Program, Mar. 1993.

28. Gregory, T., Bowles, J., and Ardema, M., "Two-Stage-To-Orbit Airbreathing and Rocket System for Low Risk, Affordable Access to Space," SAE Paper 94-1168, 1994.

29. "Affordable Spacecraft: Design and Launch Alternatives-Background Paper," OTA-BP-ISC-60, U.S. Congress, Office of Technology Assessment, Government Printing Office, Washington, D.C., 1990.

30. Chase, R., private communication, Oct. 1994.

31. Mehta, U. B., "The Aerospace Plane Design Challenge: Credible Computations," Journal of Aircraft, Vol. 30, No. 4, July-Aug. 1993 (with errata in Vol. 30, No. 6, Nov.-Dec. 1993).

32. Mehta, U. B., "Computational Requirements for Hypersonic Flight Performance Estimation," Journal of Spacecraft and Rockets, Vol. 27, No. 2, Mar.-Apr., 1990.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY ***(Leave blank)***

2. REPORT DATE
November 1994

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Air-Breathing Aerospace Plane Development Essential:
Hypersonic Propulsion Flight Tests

5. FUNDING NUMBERS
505-59-53

6. AUTHOR(S)
Unmeel B. Mehta

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Ames Research Center
Moffett Field, CA 94035-1000

8. PERFORMING ORGANIZATION REPORT NUMBER
A-95017

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-108857

11. SUPPLEMENTARY NOTES
Point of Contact: Unmeel B. Mehta, Ames Research Center, MS T27B-1, Moffett Field, CA 94035-1000; (415) 604-6744
Invited presentation at the Second European Symposium on Aerothermodynamics for Space Vehicles, ESTEC, Noordwijk, The Netherlands, 21–23, November 1994.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category – 01

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Hypersonic air-breathing propulsion utilizing scramjets can fundamentally change transatmospheric accelerators for low Earth-to-orbit and return transportation. The value and limitations of ground tests, of flight tests, and of computations are presented, and scramjet development requirements are discussed. It is proposed that near full-scale hypersonic propulsion flight tests are essential for developing a prototype hypersonic propulsion system and for developing computational-design technology so that it can be used for designing this system. In order to determine how these objectives should be achieved, some lessons learned from past programs are presented. A conceptual two-stage-to-orbit (TSTO) prototype/experimental aerospace plane is recommended as a means of providing access-to-space and for conducting flight tests. A road map for achieving these objectives is also presented.

14. SUBJECT TERMS
Hypersonics, Scramjets, Flight testing, Computational fluid dynamics, Two-stage-to-orbit, Aerospace plane

15. NUMBER OF PAGES
16

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102