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Hypersonic Airbreathing Propulsion — An Aerodynamics, Aerothermodynamics, and Acoustics Competency White Paper

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Abstract

This White Paper examines the current state of Hypersonic Airbreathing Propulsion at the NASA Langley Research Center and the factors influencing this area of work and its personnel. Using this knowledge, the paper explores beyond the present day and suggests future directions and strategies for the field. Broad views are first taken regarding potential missions and applications of hypersonic propulsion. Then, candidate propulsion systems that may be applicable to these missions are suggested and discussed. Design tools and experimental techniques are then described, and approaches for applying them in the design process are considered. In each case, current strategies are reviewed and future approaches that may improve the techniques are considered. Finally, the paper addresses needs in each of these areas to take advantage of the opportunities that lay ahead for both the NASA Langley Research Center and the Aerodynamic, Aerothermodynamic, and Aeroacoustics Competency.

Contents

1 Introduction

Hypersonic vehicles with airbreathing propulsion systems provide an efficient means for access to space because the oxidizer required by the propulsion system can be supplied by the earth's atmosphere for much of the flight trajectory. For this reason, hybrid systems that employ turbojet or rocket propulsion to achieve flight speeds for utilization of a ramjet cycle, and rocket propulsion for orbital insertion following utilization of a scramjet cycle, offer an attractive alternative to rocket propulsion alone. Hypersonic flight is of interest to both NASA and the Department of Defense. NASA's interests concentrate on access to space vehicles whereas the interests of the Department of Defense extend into other areas including cruise vehicles and airbreathing missiles. To advance the state-of-the-art in hypersonics and support the associated programs, NASA must continue to extend the required technology areas and conduct flight programs where these technologies can be implemented. The NASA Langley Research Center maintains a core competency in hypersonic propulsion for the agency, and has an obligation to the country to provide the technology base for advancing hypersonic propulsion research and hypersonic flight.

This white paper addresses the current state of hypersonic airbreathing propulsion at the NASA Langley Research Center and the ability of Langley to meet the nation's needs. Using this assessment as a basis, the paper explores beyond the present day and suggests directions and strategies that will provide future benefit to the agency and the country.

Historically, hypersonic airbreathing propulsion flowpath research conducted at NASA Langley and elsewhere has been focused primarily on the development of point-designed, that is, designed for a single Mach number, engine flowpaths. This focus has resulted in the development of a technology base well positioned for the next step in the revolution which hypersonic airbreathing propulsion can bring to manned and unmanned air and space flight. The next step must be the synthesis of these point designs into an engine technology capable of driving a vehicle from zero velocity at takeoff to some mission-dependent upper limit, possibly Mach 10 to 15 or higher. In addition to this synthesis effort, the time has come to make a concerted effort to explore the range of opportunities associated with nonsteady-flow propulsion cycles.

The development of point-design engine flowpaths has been aided by the use of a set of design methods, varying in complexity from rules of thumb, to correlations, to engineering design and analysis codes, to full three-dimensional computational fluid dynamic (CFD) analyses. The field of multidisciplinary design optimization (MDO) has developed methodologies for incorporating these types of methods into an overall design process, a process whereby it might be possible, for example, to design a propulsion system flowpath of minimum complexity or variability which, when flown along an optimal trajectory, would be capable of performing a takeoff-accelerate-cruise-return mission. The need to incorporate thinking from other fields such as MDO is apparent; the current level of point-designed hypersonic propulsion flowpaths makes possible the radical advances which could result from such synthesis.

The current state of prediction methods is far from adequate, for example, for optimizing the distribution of fuel injection over a range of conditions, or locating with precision the areas of extreme heat transfer which must be adequately cooled to prevent structural failure; or determining ignition and flameholding limits. Work must be augmented in the area of advanced prediction capability, including the collection of spatially precise data required for the verification of those predictions.

The new designs must be tested in modern facilities, where the flow is well characterized and repeatable from test to test. As all hypersonic flow facilities generate flow which is contaminated (by the heating process) to some extent, it is critical to know how to extend the data acquired on the ground to what could be achieved in flight. This extension of data will begin when flight data are returned from the Hyper-X program, but for some of the critical parameters, detailed wall and in-stream measurements will need to be made in flight as well as on the ground. This will require advanced instrumentation for both flight and ground tests. Some flight tests will have to be conducted to find the limits of operability of an engine flowpath. Finding these limits will require pushing an engine past them, with the associated chance of vehicle loss. Such high-risk flight tests must be done to ensure a reliable flight-worthy system will be developed.

In summary, substantial progress in hypersonic airbreathing propulsion flowpath development has put us on the verge of developing a new class of aerospace vehicle. What needs to be done to make that leap is to embark on a bold program designed to rejuvinate and upgrade our stagnated infrastructure, so that we can begin to synthesize the current single-point knowledge base into a viable, complete system capable of driving a real vehicle on a real mission, while at the same time evaluating technologies which may offer further performance benefits over the steady flow cycles being considered today.

2 Status of Existing Activities

Presently, several U.S. government sponsored hypersonic programs exist. The significant efforts are a mixture of research-oriented technology-development efforts and flight-type efforts, focused primarily on air-augmented, ramjet and scramjet engine modes of propulsion operation, in conjunction with associated vehicle integration activities. Furthermore, all of the programs, to varying degrees, are conducting ground-based testing of prototypical hardware, and supplemental analysis activities. Specifically, NASA has three programs: (1) the Marshall Space Flight Center (MSFC) led ASTP, the Advanced Space Transportation Program, to develop airbreathing hydrogen or hydrocarbon fueled propulsion systems for access to space; (2) the Langley Research Center (LaRC) led Hyper-X program to develop and fly a scramjet propelled subscale hypersonic vehicle at Mach 7 and 10; and (3) the Glenn Research Center (GRC) led GTX program, the Glenn Trailblazer Program, consisting of a rocket-based combined cycle propulsion system employed on a vertical takeoff, horizontal landing vehicle. Additionally, the Army sponsors an airbreathing scramjet propulsion effort led by Redstone Arsenal personnel; the Air Force (through the Air Force Research Laboratory (AFRL)) sponsors the HYTECH program, a hydrocarbon missile technology activity; the Navy, via the Office of Naval Research (ONR), sponsors a Johns Hopkins University-Applied Physics Laboratory (JHU-APL) effort to address hydrocarbon missile technology; and DARPA sponsors (in conjunction with AFRL) ARRM, the Affordable Rapid Response Missile Program, a hydrocarbon missile flight activity focused on military mission scenarios. In the aggregate, these efforts constitute the majority of ongoing U.S. funded programs; however, recently NASA has initiated a significant twenty-year third-generation space access program with the goal of vastly reducing cost, and simultaneously increasing reliability and safety. This program is led by MSFC personnel, and in proposed funding represents the bulk of expected out-year budgets in airbreathing propulsion for NASA.

Internationally, both the English (mostly using DERA personnel) and the French (using government and industry consortiums) are, to modest levels, designing and testing hypersonic propulsion systems. The latter group is primarily focused on the near-term deployment of a missile system, and to this end is aggressively pursuing ground-based testing (inclusive of facility upgrades), with the expectation of flight tests to follow. However, the group most focused on addressing space access appears to be Japan, as witnessed by their large effort in ground-facility enhancements, with particular emphasis on scramjet simulations. Lastly, the Germans appear to be interested in space access systems, and have invested heavily in ground-based testing facilities; an example being the HEG hypervelocity facility. The Australians have also invested in ground based testing facilities. In short, no well coordinated foreign government-to-government effort is presently functioning; however, the academic, industry and government efforts, taken in total, are a non-trivial intellectual effort, and are rapidly approaching the U.S. state-of-the expertise and capabilities.

2.1 Activities at Langley Research Center

From a technical standpoint, NASA Langley is currently the leader in the U.S., and probably the world, in dual-mode scramjet flowpath technology and overall vehicle systems analysis. This is made possible by exceptional expertise in scramjet flowpath design, test, and analysis capability; good (but not excellent) propulsion facilities with speed and scale range; excellent (but few in number) CFD capabilities in both reacting internal flows and external aerodynamics; good (but declining) diagnostics capabilities; excellent (but awaiting direction) propulsion/airframe integration capabilities; and good experience in systems analysis.

However, NASA's position for continuing effective hypersonic airbreathing propulsion research is definitely not in a good posture in early 2000. All of the dollars for this area are lumped under Space Transportation and that money, and therefore the power in this discipline, passes through NASA MSFC for the Spaceliner Program. The only exception to this is the Hyper-X Program, which is led jointly by NASA Langley and NASA Dryden. However, upon completion of the Hyper-X Program, NASA will be left only with the Spaceliner Program. Spaceliner propulsion dollars will be split primarily between MSFC and GRC with Langley basically getting small change. This situation looks as if it cannot be altered through logical technical arguments and, therefore, is destined to remain in effect unless there is major intervention from senior management at Langley or NASA Headquarters. The irony of the current reality is that NASA Langley, primarily through the Hypersonic Airbreathing Propulsion Branch (and, more recently through the former Hypersonic Vehicles Office and now the Hyper-X Program Office), is clearly the leader within NASA in dual-mode scramjet flowpath technology. This is demonstrated through the HAPB's record of more than 4000 scramjet flowpath tests since 1976; the Branch persistence during the low cycle of hypersonic activity from 1975 to 1985, which was a significant factor in the birth of the National Aero-Space Plane Program (which educated a new national cadre of scramjet engineers); and the Branch involvement and leadership in the Hyper-X Program.

3 Future Directions and Strategies

Current activities in hypersonic propulsion primarily involve the development of a 12 foot long research vehicle (Hyper-X) utilizing hydrogen fueled scramjet propulsion to achieve Mach 7 and 10 cruise for a short period following release from a B-52 and rocket boost to near cruise Mach numbers. The purpose of the current program is to develop scramjet technology and provide a database for design tool development.

The current state of the art in hypersonic propulsion includes the ability to design scramjet engine flowpaths primarily by the iteration of cycle codes and facility testing. This design strategy is augmented by more detailed calculations using advanced cycle codes (e.g. distortion theory) and by parabolized Navier-Stokes (PNS) and full Navier Stokes (FNS) codes [1]. The Navier-Stokes codes are limited by longer run times that prohibit their use in rapid design cycle studies.

Measurement techniques actively used in facilities are currently limited to classical techniques, including wall pressures, temperatures, and heat transfer measurements, and in-stream probes, i.e. interference techniques. Development of nonintrusive laser diagnostics has been carried out and recent promising refinements were underway, but laser diagnostics have not been systematically employed in facility engine testing due to some difficult application environments.

In the next 10 years, NASA Langley should continue the development of hydrogen-fueled scramjet technology and flight vehicles to test scramjet propulsion systems. In addition, both new and also older, but undeveloped hypersonic propulsion strategies should be studied and promising concepts should be researched and developed. Concepts should include higher Mach number (hypervelocity) systems such as shock-initiated-combustion scramjets, pulsed or stable detonation engines, MHD devices, and other advanced concepts. The development of current small scale flight vehicles should be extended to include larger scale vehicles and ultimately, full scale flight vehicles. In addition to the current vehicle concepts, attention should also be given to military systems including defensive air-to-air missiles and cruise missiles, high-speed remotely piloted vehicles, reconnaissance aircraft, and other advanced military systems. Military systems will require consideration of hydrocarbon fuels that are safer, more easily handled and stored, and routinely used by the services.

Because older ground based facilities will remain the mainstay for propulsion system design in the next 10 years, instrumentation used in those facilities should be significantly enhanced. Flight instrumentation is also critically important to measure certain essential parameters when engines are tested in flight. In addition, computational tools should be advanced to where they play a more significant role in the final engine design. Emphasis should be placed on the advancement of computer systems that will provide significantly more rapid turn-around of code runs, and optimization of those codes to run on new computer systems. If run efficiency can be achieved in this manner, PNS and FNS codes will contribute significantly in the engine design cycle. Gains in efficiency are more likely to occur through advancements in computer technology than code algorithm development.

Nonintrusive diagnostics should continually move from the laboratory into ground based test facilities and later into flight vehicles themselves. The development of improved diagnostic techniques to measure all critical flow field parameters required in a design effort should be emphasized for the payoff can be considerable. In addition, methods to “harden” the diagnostic techniques should also be developed to allow their use in facilities with hot flow and severe vibration.

Each of these issues will be addressed in more detail in the following sections.

3.1 Missions and Applications

There are a number of future potential missions and applications for hypersonic vehicles propelled by high-speed propulsion systems. High-speed propulsion systems include the more conventional ramjet and scramjet propulsion systems as well as less developed concepts such as shock-initiated combustion and detonation devices and even more revolutionary engine cycles.

Candidates for future research and development include the following concepts.

- Hypervelocity flight propulsion systems
  - Hypervelocity scramjet development
  - Shock-initiated combustion engine concepts utilizing strong shocks for ignition and flameholding
  - Pulsed detonation engines
  - Oblique detonation engines
  - Other unsteady engine flow cycles
  - Air-augmented rockets
- Revolutionary engine cycles
  - MHD energy extraction and addition to scramjet cycle

- Ground-based injected energy sources
- Matter-antimatter energy sources
- Micro-fusion/fission engines that use anti-matter and deuterium or hydrogen to achieve high specific impulse
- Plasma enhanced scramjet cycles

There are a number of potential missions to which conventional or advanced propulsion systems can be applied. Earlier efforts as well as current activities have concentrated on the evolution of hypersonic cruise vehicles utilizing scramjet propulsion systems. These vehicles have served mainly as testbeds for the development of the propulsion system. Future work should continue to evolve improved scramjet systems, but more effort should be expended on vehicle classes that will perform well and capture the interest of potential users. The Department of Defense is an excellent candidate for hypersonic vehicles that could result from these efforts.

High speed vehicles that should interest Department of Defense users include the following:

- Hypersonic cruise missiles
- Hypersonic reconnaissance vehicles
- Ground-to-air-defensive systems
- Mach 6 to 8 vehicles with excursive ability to go suborbital and return (in case of attack.) Tow attached rocket propelled vehicles would allow boost outside of the atmosphere. These rockets could serve as false targets on return.
- A scramjet as a specific impulse enhancer. Rockets would be packaged with the scramjet allowing the package to operate in the intermediate range of Mach 6 to 10.

By broadening the research and development base of Langley's scramjet program, future opportunities would be created for work and support from other organizations. With the declining funding base from NASA in hypersonics, we must seek these opportunities. In addition, by extending the class of vehicles that are considered to utilize ramjet/scramjet/detonation propulsion systems, vehicle designs would become simpler and less expensive to build and test, and the vehicle being tested would more likely be the actual vehicle of interest. This direct approach to a final design may be more attractive to customers in the competitive NASA environment in hypersonics.

3.2 Propulsion Systems

There are many opportunities available to advance the current state-of-the-art in high-speed propulsion systems. In addition, there are propulsion cycles, yet undeveloped, that should be seriously explored and seriously developed. These concepts are considered in this section.

3.2.1 Dual-Mode Scramjet

The NASP dual-mode scramjet design was intended for operation from Mach 3 to 16. It included variable geometry for control of contraction ratio and combustor area-length ($\delta A/\delta L$). The NASP concept projected poor performance (low combustion efficiency) in the Mach 3-5 speed range, which has been experimentally investigated by early Hyper-X tests in DCM at Mach 5 enthalpy.

Hyper-X is based on a similar variable geometry scramjet flowpath, which only operates as a dual-mode scramjet (DMSJ) over the Mach 4.5 to 10 range. The higher scramjet "takeover" is based on a non-existent turbojet for the low speed system. Tests have been conducted on the Hyper-X flowpath down to Mach 4.5. Again, these tests showed a need for better performance.

Hyper-next, the X-43B, a 30-foot proposed phase 1a scramjet demonstrator vehicle utilizes a dual mode scramjet over the Mach 3 - 7 range. Mach 3 takeover is currently predicated on the lack of a Mach 5 turbojet, and the desire to start combination engine flight demonstrators on a turbojet-scramjet combination engine rather than a rocket-based combined-cycle engine. This is planned using existing or slightly modified turbojet engines. Significant challenges remain to assure that adequate performance (combustion) is achieved at low speed.

Future flight vehicles will require improved performance in the Mach 3 to 5 range. A robust dual-mode scramjet can likely be developed that will provide the needed performance. Initial investigation of Mach 3 to 5 operation could begin at GASL utilizing the existing direct connect model (DCM) rig to provide more efficient fueling (mixing, flameholding, and combustion). The resulting scramjet could then be tested on a Pathfinder class vehicle in the FY00 to 04 time frame.

3.2.2 Dual-Mode Scramjet Variable Geometry Structural Concept

As noted above, current dual-mode scramjet concepts utilize variable geometry, but have never been tested as such. French/German variable geometry combustor hardware (the Wide Range Ramjet) has been completed, and is in storage because of a change in direction in the French program. However, this combustor may be available for testing. The hardware includes remotely actuated, articulating top wall, fixed cowl, replaceable/parametric seals.

Future flight vehicles will require some variable geometry. This requires sliding seals, actuation and engine controls. Therefore, it is important that seals, actuation, etc. be demonstrated for real engines. The existing cooled, variable geometry French scramjet combustor should logically be tested in French facilities, if possible, to develop a database of combustion efficiency and mixing efficiency for combustor area distribution. The design-of-experiments procedure employed in current scramjet designs at Langley should be utilized. Bringing the hardware to the United States for more specific tests is also desirable. Finally, a plan should be developed for the flight weight engine. Tests must include cycle life determination for the cooled panels. This could be a contracted effort which builds on ARRMD/HyTech programs.

3.2.3 Hydrocarbon Scramjet Technology

The U.S. Air Force HyTech program and the DARPA ARRMD Program have made significant headway in the hydrocarbon scramjet technology area. Most of the expertise resides with the prime contractor, Pratt and Whitney. However, some expertise has been developed at Wright Patterson Air Force Base and the Johns Hopkins Applied Physics Laboratory. Most of the focus has been on Mach 5-8, and problems with flameholding have been observed at lower Mach numbers. Hydrocarbon scramjet combustion is a requirement for affordable demonstration of storable scramjet systems. Spaceliner Generation 3 programs intend to fund trailblazer ($100-200M) and pathfinder ($0.5-1B) class flight vehicles over the next 20 years.

Therefore, Langley should partner with the Air Force Research Laboratory at Wright Patterson to perform required hydrocarbon combustor tests for low speed operation, down to Mach 3. GASL or Langley should be utilized to develop a piloted ignition system which can be utilized on demand.

3.2.4 Revolutionary MHD Ramjet

Magnetohydrodynamic (MHD) energy extraction with later addition to supersonic flow offers possible benefits in the area of propulsion flowpath flow control that are not available in conventional supersonic reacting flow, where high pressures and temperatures are continually present. MHD flow control can in principle be used to minimize flow losses and increase engine efficiency. MHD technology has been developed in a number of fields, but has not yet been applied to scramjet engines.

Current work is underway at NASA Langley, the Johns Hopkins University Applied Physics Laboratory, a number of U. S. universities, and in Russia to explore the uses of MHD flow control for drag reduction and shock attenuation. This work should be extended to include scramjet flowpaths where MHD energy extraction/addition can be studied. The associated plasmas could also be useful for enhancement of fuel-air mixing in scramjets.

3.2.5 Combined Cycle Engine Optimization

NASA Langley and Air Force studies show that scramjets integrated with a high speed turbojet, in an "over-under" configuration, may provide optimum vehicles in terms of take-off gross weight. Turbojets have long been known to have high reliability, vis-a-vis rockets. Integration of the two engine flowpaths is currently in the conceptional stage. Boeing Phantom Works is clearly in the lead. Glenn Research Center has had little or no interest over the past 20 years.

The attempted integration of NASP secondary and primary inlets identified some concerns with the over-under approach. These concerns are reduced at the transition Mach number, where both inlets must function simultaneously. Utilization of a single inlet was proposed, such as the Langley/McDonnell Douglas/Pratt and Whitney Mach 5 Navy aircraft designed by L. Hunt, et al. in the Langley Vehicle Analysis Branch.

The agency is beginning to understand the importance of the turbojet - dual mode scramjet combination engine technology, but it has not "stepped up to the problem." Potentially this configuration may be selected as a near-term flight demonstrator. Langley should initiate studies of alternate integration schemes for turbojet - dual mode scramjet engines. Mach 4 tests should then be performed to verify performance at the transition point. Once accomplished, Langley will be positioned to develop this engine in a future flight demonstrator program.

3.2.6 Hypervelocity Scramjet Development

NASA Langley led the National Aerospace Plane direct connect and semi-direct connect combustor-nozzle tests at: Mach 8 and 10 in the Calspan 96-Inch Reflected Shock Tunnel; Mach 12 and 14 in the NASA Ames Research Center 16-Inch Reflected Shock Tunnel; and Mach 13 to 17 in the GASL HYPULSE expansion tube. These tests were used to quantify uncertainty of predicted mixing, combustion, shear heating and drag, and injector base pressure. This initial work showed rather large uncertainty and future required measurements and analysis procedures.

Hypervelocity scramjet technology will be required for airbreathing space access vehicles, such as those to be addressed by the Spaceliner technology development program being led by the Marshall Space Flight Center. However, there is currently no activity in this area in the Marshall program.

Development in this area should be extended by continually upgrading the HYPULSE facility, performing tests to narrow the uncertainty, expanding databases, and refining the design methods through development and validation. There are also critical nozzle issues that should be considered, including measurement and prediction of chemical recombination, relaminarization in high enthalpy environments, and distortion and expansion losses.

3.2.7 Hypervelocity Air Augmented Rocket Development

NASA Langley performed a hypervelocity air augmented ramjet (AAR or "LOX addition") test series for the NASP program. This was the only known test of its kind. Results from the entry were not encouraging, as the thrust decreased. During these tests, the pulsed, uncooled rocket motor was destroyed.

This technology will be required for airbreathing space access vehicles, such as being addressed by the Spaceliner Technology development program led by Marshall Space Flight Center. Currently, however, there is no indication of this technology being funded by the MSFC. The MSFC program is focused on Mach 0-8, and assumes that the hypervelocity air-augmented rocket can be simulated simply by running the rocket in the duct with low enthalpy, high Mach number secondary air.

Development of the air-augmented rocket should be continued by improving test techniques, rocket integration and heat-sink-copper cooling, and performing tests to narrow the uncertainty, expand databases, and refine design methods. A long-range test plan should be initiated to complete this technology development.

3.2.8 Detonation/Pulse Detonation Engines

An effort should be initiated to establish experimental and computational databases on the operation and performance of innovative hypervelocity, airbreathing, propulsive flowpath designs, in the Mach 10 to 18 flight regime. These databases would enable the design, development, and integration of advanced detonation engine concepts for future vehicles, including military missile concepts. Candidate engine cycles should include oblique detonation engines, pulsed detonation engines, and premixed shock-initiated combustion engines employing strong wave structure below detonation strength.

Achievement of the objective would be multidisciplinary, and would include: the application of CFD to study flow physics and conduct design predictions and flowpath analyses; the replication of flight conditions in ground test facilities; thermo-chemical modeling of test facility flow; the application of state-of-the-art measurement systems and diagnostics; test technique definition and improvement; and the testing and refinement of engine components and engine flowpaths.

3.2.9 Non-steady Flow Cycles

It is considered advantageous to learn how to harness the potential of unsteady flow cycles in applications to high speed airbreathing propulsion. Examples include pulsed detonation wave engines, and the use of nonsteady fuel injection to improve both low-speed entrainment and high-speed mixing.

Pulsed-detonation-wave engine technology has the potential to enable the design and use of highly efficient, lightweight engines for hypersonic flight. This and other non-steady cycle concepts have been investigated from both a theoretical and experimental standpoint, but the field is still in its infancy. Further work is required to provide the basic information necessary to evaluate the ultimate utility of these concepts.

A small experimental effort is currently underway at NASA Langley to investigate the systematic generation of large-scale unsteady flow phenomena, and the potential benefits of such phenomena to the problems of hypersonic airbreathing propulsion. This effort involves the design and fabrication of a pulsed fuel injector/shock generator. The very high speed flow through a hypersonic engine requires that tailored-fuel pulsation be accomplished at frequencies of 10 to 100 kHz to achieve the desired unsteadiness, rather than generating simple sequences of interrupted steady flows. Generation of such high frequencies is currently beyond the state of the art, but the current work shows much promise.

Unsteady flow may be useful in the low-speed regime as well. The efficiency of an ejector can be enhanced by the use of oscillating or pulsating flow. If a ducted rocket or airbreathing rocket were used as part of an integrated engine system (e.g., rocket based combined cycle), an ejector capable of entraining a large amount of air per unit of rocket exhaust would be required. Based on cold-flow studies of unsteady ejectors, the thrust augmentation of a pulsating or oscillating ducted rocket should be much greater than that of a steady ducted rocket, leading to a smaller rocket and lower fuel consumption.

3.2.10 "Exotic" Engine Cycles

Exotic, nonconventional high-speed propulsion systems have been discussed in the literature. Some of the possible approaches, listed in order of decreasing potential, are given below.

1. "Off-body" energy addition (fixed ground- or space-based lasers or microwaves which heat an onboard propellant and/or captured air; also, on-board fusion reactors to add energy and accomplish the same thing). In both of these areas the idea is to significantly increase T/W and ISP by reducing propulsion system and propellant weight and/or increasing thrust.

2. The various claims associated with weakly ionized gases (drag reduction, fuel-air mixing enhancement, etc.)

3. Other "fringe" ideas such as:

   (a) Zero-point energy extraction (ZPE)

   (b) Anti-gravity

   (c) Anti-inertia

   (d) Matter-antimatter propulsion

   (e) Wormhole travel

3.3 Fuels

In this section, we consider the following candidate fuels: hydrogen, hydrocarbons, pyrophorics, exotic high-energy-density fuels, endangering fuels, and environmentally acceptable fuels. Hydrogen ignition and combustion will occur in moderately-heated air under very lean conditions, and is rapid enough that scramjet combustion is possible over a reasonable length. Furthermore, because H_2 ignition and combustion can be sustained at strain rates 10 to 30 times higher than in flames using gaseous light-hydrocarbons (HCs) at typical temperatures, hydrogen is the necessary/preferred fuel for airbreathing scramjets based on reactivity alone. Also, liquid H_2 is very effective for active cooling of vehicle structures, which is required at high speed. Unfortunately, liquid (or slush) H_2 is difficult to store and handle on a routine basis, and it has three to four times lower energy density than typical storable hydrocarbons.

3.3.1 Hydrocarbon Fuels

Although HCs heated during active cooling will become more reactive, such increases are limited without significant decomposition. So-called storable endothermic fuels may be catalytically hydroformed, dehydrogenated and/or cracked in-situ, so that additional heat is absorbed and resultant fuel fragments (including H_2 and CO) become more reactive. However, such heterogeneous catalytic processes are difficult to accomplish, reproduce, and control without forming significant carbon deposits on catalysts and within fuel passages and injectors.

Pyrophorics (e.g. 20 mole percent silane in H_2) ignite spontaneously and burn when injected into air, and thus make good ignition and piloting aids. However they are not endothermic, and they usually carry molecular weight penalties, are toxic, and produce troublesome condensed phase products (e.g. silica).

Finally, fuel chemists working over the last 40 years have devised a number of so-called exotic high-energy-density fuels (e.g. cubane, various strained-ring compounds, polymeric BxNyHz, and liquid H_2 gelled with light HCs), and/or organic additives (e.g. nitrates, nitrites, nitro compounds, ethers and peroxides) with improved reactivity and energy release. Typical problems with these materials are stability, safe storage and handling under field conditions, toxicity, and increased cost – but, these problems are not necessarily insurmountable.

Where do we need to go in next 10 years? Whereas we need to advance the science of ignition and flameholding (discussed earlier) to improve engine designs based on H_2 and reduce the need for silane as an ignition / piloting aid, we also need to aggressively pursue alternative hydrocarbon fuels for hypersonic airbreathing propulsion applications using recently developed tools. Scaling of existing H_2-fueled designs to HC-based designs is now viewed as critical. For either one-time use (missiles) or resuable launch vehicle applications such as Spaceliner 100, success in the storable high-energy-density hydrocarbon scramjet combustion area would result in increased overall system performance, reduced utilization costs and improved missile applications having important defense capabilities. In recent years new understanding of chemical processes and some very detailed reaction kinetics methodology have emerged that could prove useful in the search for, and application of custom tailored fuels.

Specific recommendations can be summarized as follows. First of all, the AAAC should support in-house efforts to keep abreast of international research developments in the hydrocarbon fuel and combustion areas; total reliance on hydrogen-fueled engine systems is technically unhealthy from the standpoint of discovering new and significantly-improved methodology for high speed flight. Second, we must begin to seriously address the H_2 to HC scaling question in all its ramifications. This is a very difficult problem.

Some degree of meaningful co-participation with other agencies may be possible, and should be sought despite the current narrowness and shallowness of LaRC's and NASA's baseline research efforts in the high-performance storable fuels area. For example, the AAAC might engage jointly with the NASA Marshall Spaceflight Center, and perhaps the Glenn Research Center and the Air Force to revitalize fundamental investigations of fuel decomposition using modern analytical techniques; and to design, refine, and test catalytic test beds for the practical development of safe, storable, and effective high-energy-density endothermic fuel systems.

For the long run, the AAAC should move quickly towards establishing long-term investigations of storable fuels for high-energy combined-cycle airbreathing propulsion systems.

3.3.2 Densified Hydrogen Fuel Research

Hypersonic vehicles require fuels with high heat capacity to absorb excess heat. This may be accomplished with liquid hydrogen or with endothermic hydrocarbon fuels. Hydrogen fuel cooling capacity offers stochiometric operation to flight Mach 10, and endothermic hydrocarbon fuels may allow operation to about Mach 7-8. Fuel selection is based on the operating speed range. Space access vehicles require liquid H_2 fuel, which is volumetrically inefficient. Slush H_2 has been studied extensively by GRC and others, but has proven very difficult, ineffective, and expensive to date. Sandia has performed research on metastable phases of solid hydrogen, but this fuel has not been seriously considered for hypersonic vehicles.

Densified fuel may allow more efficient technology demonstrators for space access vehicles. Effective densified fuel could also enable and pull technology for space access and in-the-atmosphere vehicles. Therefore, Langley should establish a long-range plan to understand, apply, and effect completion of densified fuel technology development.

3.4 Propulsion-Flowpath Design Requirements

3.4.1 Inlet Flowpath Design Requirements

The most significant inlet issues for hypersonic airbreathing propulsion lie in the areas of configuration and inlet unstart. We know how to design inlets, 2-D, axisymetric, and 3-D, for a multitude of applications from auxiliary systems to primary propulsion systems (turbojet, ramjet, scramjet). Usually these designs accept some pre-idea of the capture shape and overall requirements (mass flow, contraction ratio, pressure rise, total pressure recovery, etc). Computer codes are sometimes used to generate the grids for complex 3-dimensional shapes, although 2-D and sidewall compression configurations do not require this step. Shock diagrams are laid out, followed by boundary layer thickness corrections and then applications of variable geometry to meet the Mach number range.

After completing the preliminary design, the inlet is often evaluated experimentally. Full Navier-Stokes computer codes are then used, first to be validated by comparison with the experimental data and then to evaluate inlet performance and other parameters that are not easily obtained by the experimental program. Often models are not tested (or cannot be) over the Mach number range and data are extrapolated with the aid of analytical tools. Scale is also extrapolated as small models are expanded to flight vehicles.

Knowledge of inlet starting is important for all inlets, but is especially valuable for fixed geometry designs. Usually the surest way of obtaining inlet starting information is through an experimental program. Because inlet contraction ratios are usually increased to the limit to obtain maximum performance, the "startability" of an inlet is typically very hard to predict with accuracy. This is understandable considering the possibility of having two or more real experimental flow solutions. Small "twitches" in the tunnel flow, incoming boundary layer characteristics, and even model wall temperature can affect starting. Inlets can also pulse-start in the wind tunnel, and this must be compensated by providing a method of unstarting and then restarting the inlet during test. Small, relatively inexpensive models are usually used to get this information, but extrapolating the data to larger models and to flight scale is not assuredly accurate. Larger inlet models may be found to start easier in a large test facility, but an even larger flight article may not start again if it has to swallow a thick vehicle boundary layer that was not be simulated in the wind tunnel test.

Given the above issues, research areas to be addressed in the next ten years are now discussed. Few engineers are seriously interested in inlets, believing they are simple in nature (compared to combustors) and that all the problems can be solved by CFD. However, detailed trade-off between fixed geometry, sidewall compression inlets and variable geometry, and 2-D inlets of the NASA and Hyper-X design, are far from complete. Mission is also a problem. For example, SSTO, TSTO, cruise at Mach 6, 8, or 10, HRV, missile, or hypersonic transport requirements make for interesting trades and design differences. Two of the most serious challenges in inlet design are given below.

1. There is no clear-cut advantage between the safe (but extremely heavy and complex) variable geometry 2-D inlets and the more daring (but simple) fixed sidewall compression concepts. It is felt that the only viable airbreathing concepts, for either cruise or insertion into orbit, must be simple with as few moving mechanical parts as possible. However, changing throat heights over the Mach range will never "make the grade." A revisit of thermal compression concepts to attain variable geometry may be in order. (The Pre-Mixed Shock Induced Combustion concept (PMSIC) was introduced some years ago, but this concept offers some very tough challenges and safely issues that may put it beyond

reach.)

2. The design of inlet systems capable of dealing with proposed RBCC and/or TBCC concepts is one of the greatest challenges of current SSTO concepts. Splitting the flow into two flow paths, each with different requirements will not be easy — and this is not a new problem. NASP's low speed inlet concept was a technical disaster. No one could figure out where to locate the low speed inlet; therefore, they never dealt with the vehicle boundary layer. At NASA Langley, John Weidner's dual flow path concept has come the closest to a real concept seen at Langley. Bobby Sanders has requested support to analyze the problem; and Zane Pinckney and Shelly Ferlemann are now planning to place concepts on a TBCC/ABLV configuration.

A shortcoming in inlet work at NASA LaRC is the quick acceptance of a point design inlet configuration without any in-depth study (Hyper-X is an example). The bounds of the inlet's operating range (to obtain margin), with regard to maximum shock strength, effect of wall temperature, and entering boundary layer parameters, have not been determined. CFD alone cannot be depended upon to accurately evaluate inlet starting. Thus, we will never have cutting edge inlet performance information without experimental work, in combination with a CFD analysis, on relatively large scale models of selected configurations. The NASA Glenn Research Center has done much better than we have in testing large scale inlets. Our own HRE program was an excellent example of using inlet models to evaluate inlet performance outside of the engine tests.

Based on this discussion, what do we need to do specifically in NASA, LaRC, and AAAC? We need methodology to optimize inlet shape for a particular mission. This should include structural weight and account for system complexity. Vehicle integration is still key to hypersonic airbreathing propulsion, and we need techniques to maximize the benefits of these concepts. People tend to accept the best nonintegrated performance numbers, and then use them in their analysis. They should, however, use only realistic performance numbers when they assess the benefits of integration.

We should begin looking more closely at two different flow path inlet configurations for some missions. Our TBCC ideas (Weidner, Sanders, etc.) need to be worked, if we are really serious about the turbojet system. For example, methods of dealing with the vehicle boundary layer that would enter the turbojet need to be found. In contrast, there are several RBCC concepts that need to be evaluated in the near future to determine the most optimum design (Aerojet, Rocketdyne, and GTX to name three). They are similar in flow path characteristics but quite different from the TBCC concept, in which they are in direct competition. Besides inlet/engine performance, vehicle integration, weight, and system complexity will be of extreme importance, and may even determine the best concept.

Work that tests the extremes of inlet design and includes vehicle integration parameters (i.e. boundary layers) when they apply, must be done. When a design is selected for a prescribed mission, we should not wait for engine tests, which usually have severe cost and schedule limitations, to determine inlet operational characteristics and margin. The inlet should be tested alone over as much of the Mach range as possible (including unstart tests where applicable), and the results compared with good CFD analysis.

3.4.2 Combustor Flowpath Design Requirements

In the past the design of a combustor flowpath has been an experimental procedure consisting mostly of trials and errors. With direct-connect tests, a supersonic nozzle is attached to a facility heater with the nozzle exit flow conditions simulating the combustor entrance conditions for a ramjet or scramjet. A combustor duct, containing fuel injectors, is attached to the supersonic nozzle and the area variation of the combustor flow path is altered (experimentally) to achieve desired pressure and reacted fuel distributions. With freejet engine tests (or, semi-direct-connect tests), a ramjet or scramjet engine, typically with a truncated forebody and a truncated aftbody/nozzle, is placed within a facility test cabin, and tests are then conducted during which the engine geometry is varied such that the desired performance is achieved. More recently engines (or test articles) have been constructed with high contraction ratio inlets which compress the freestream flow to higher levels than have been attempted in the past. Typically these inlets turn the freestream flow ten degrees or greater. The combination of high contraction ratios and large turns will typically separate the forebody boundary layer to some extent. This in turn results in higher pressures and lower throat Mach numbers than would otherwise be expected. The relatively high throat pressure and low Mach number associated with these highly contracted inlets aids in the ignition of fuel within the combustor. Unfortunately, the incoming boundary layer has been stressed to such a large extent that any additional pressure rise due to combustion is sufficient to completely separate the boundary layer and unstart the inlet. As a consequence, an engine is designed and constructed that is only able to burn a relatively small amount of fuel at the front of the combustor. Usually, additional amounts of fuel are injected towards the exit of the combustor so as to reach the design total fuel equivalence ratio. An extreme example of these newer highly contracted engines is the NASA GRC GTX engine. The GTX engine utilizes a moving centerbody to vary the inlet contraction ratio, this allows the inlet to start during tests. The GTX engine was first tested during the summer of 1999 (at GASL). During one of the first tests, the engine's inlet was started by placing the center body forward (reducing the contraction ratio). During the test, the inlet unstarted as the centerbody was being translated to the rear (increasing the contraction ratio) *b*efore the design contraction ratio was reached and before any fuel was injected into the combustor. Since then, the engine has been re-designed to reduce the amount of flow turning present within the inlet. What seems to be lacking in this example (and others) is relatively simple pre-test calculations. A CFD solution of the inlet would yield the flow properties at the throat. A simple equilibrium quasi- one-dimensional calculation would then indicate how much fuel injection and combustion could be achieved within the combustor before the flow became choked. These relatively simple calculations would alert the researcher of any possible performance problems to be expected before construction or testing of the engine would occur. Issues such as these, engine unstart and inability to burn injected fuel, were encountered during the NASP program. Unfortunately, the current scramjet community appears to be re-learning some of these lessons.

The design of the combustor flowpath must also include choosing the location and type of fuel injectors. Various fuel injection mixing "recipes" are available to help the engineer with this task. The "Langley Mixing Recipe" was developed during the early 70's as a way to correlate perpendicular and parallel fuel injection mixing efficiency with downstream distance for scramjets operating in the mid-speed range of Mach 6 to 8. During the National AeroSpace Plane (NASP) Program, the High Speed Injector Design Team (HSIDT) used the SHIP PNS computer program to calculate the mixing efficiency for a matrix of perpendicular, strut-type, and ramp-type fuel injectors at simulated flight Mach numbers of 10, 14, and 18. The attempt here was to correlate the mixing efficiency of these fuel injectors with geometric parameters. Various researchers have suggested that lift and drag should be proportional to mixing for ramp-type fuel injectors. Other researchers have suggested that mixing is directly proportional to the total pressure loss across the fuel injector indicating that a certain amount of total pressure loss is required to achieve a certain amount of mixing. But, increasing the total pressure loss above a certain amount may not increase mixing further. Therefore, there may be an optimal level of pressure loss that yields adequate mixing while not excessively reducing the total pressure of the flow. For the ramp-like fuel injectors that seem to have performed well in the past, it is believed that the near-field mixing is dominated by inviscid vortices. If this is so, then a quick parametric screening of many different fuel injectors could be accomplished using a three-dimensional inviscid computer code. Parameters to be varied could include ramp angles, fuel injection location, aspect ratios, etc. A similar screening could be accomplished in a "cold" test facility by using different fuel injector models, a thrust measurement system, and a measurement system to quantify the achieved mixing. Correlations could then be developed which would show the mixing achieved as a function of total pressure loss across the fuel injector, drag coefficient, or lift coefficient using the experimental and the CFD data. It is hoped that in the future a more systematic, orderly approach to fuel injector testing and design can be developed, perhaps resulting in a new more modern design recipe that would allow engineers to design a combustor that will perform as expected.

The above discussion assumes that the combustion is mixing controlled and that proper ignition and flameholding are provided. Adequate flameholding is crucial for a high-performance scramjet combustor. It is possible to build a combustor that mixes the fuel well without burning the fuel. It is generally believed that large base areas help flameholding. Combustors with large base areas tend to be of the dump type, meaning that there is a large increase in the flow area of the combustor at the primary (upstream) fuel injection station. Unfortunately, it becomes difficult to pressurize these large base areas as the flight Mach number increases above eight. Without adequate pressurization, these large base areas become large drag or suction areas. Experiments need to be conducted which show whether or not the large base areas associated with dump-type combustors can be adequately pressurerized using fuel combustion or, a combination of fuel combustion and shock waves, at high flight Mach number. Additional information regarding ignition and flameholding is given in a following section.

3.4.3 Engine Performance Analysis

The flowfields generated by functioning ramjet and/or scramjet vehicle-engine systems are highly three dimensional and vary widely throughout the flight trajectory; hence, the task of assessing the integrated performance, inclusive of thrust, pitch and moment forces, combustion efficiency, thermal environment definition, subsytem power balancing and associated fuel requirements, is nontrival. Furthermore, since the generation of mission-specific performance data (primarily relied upon in conceptual studies) demands a quantity of data unobtainable without engineering simplifications, there has been, and continues to be, a reliance on engineering methods to obtain simplier, yet still valid, performance assessments. Thus, interpreting multidimensional fluid-dynamic phenomena within a one-dimensional context is often required to assess integrated engine-vehicle cycle performance [2, 3, 4], and is particularly acute for off-axis propulsion systems. Yet, at present no single methodology is widely applied by the industrial and/or scientific community.

Historically, integral boundary-layer techniques have provided much of the focus for this class of analytic reduction, with the majority of emphasis directed toward the characterization of the mass, momentum, and energy defects with the distorted region of the flowfield (i.e. the boundary layer). Other specialized fluid-dynamic implementations have been explored, with notable successes in the design of supersonic diffusers and ramjet isolators. Most importantly, the application of integral-distortion techniques to engine cycle performance analysis are ultimately required to address the inherent limitations of standard, purely one-dimensional cycle techniques commonly utilized throughout the propulsion community.

Given these facts, it is recommended that a more comprehensive engine performance methodology be adopted (to replace the standard, purely one-dimensional techniques now in vogue). In order to ensure the successful completion of this objective, LaRC hypersonic staff will need to address the added complexities required to utilize distortion-based cycle analysis methods (especially during propulsion testing), as well as advocating the benefits via research documentation and hypersonic propulsion program endeavors.

3.4.4 Propulsion-Airframe Integration

Hypersonic airbreathing configurations are characterized by highly integrated propulsion flowpath and airframe systems. Propulsion/airframe integration research for this class of vehicle is focused on understanding various component interactions and their effects on integrated vehicle aero-propulsive performance. Advanced airframe-integrated concepts seek to exploit these interactions to maximize performance and improve stability and control characteristics. Investigations of these phenomena require a range of analytical, computational and experimental methods. Much of the present capabilities and experience in this area is derived from support of various NASA hypersonic programs, such as the National Aerospace Plane (NASP) and the Hyper-X (X-43A) Program. A survey of work from these programs represents the state of the art in this research area. The development of the X-43A configurations provides an opportunity to evaluate testing and analytical capabilities and highlight some areas of opportunity for improvements in methodology leading to the development of a full-scale scramjet-powered flight vehicle.

Interactions between the scramjet powered exhaust plume and vehicle aftbody and wing surfaces have previously been examined through simulant exhaust gas testing in various facilities, and full flowpath testing in the 8-Ft. HTT. These investigations have been mostly limited to longitudinal effects and additional studies are needed to investigate lateral-directional stability characteristics, yaw effects on engine operability and control surface effectiveness under powered conditions. Additionally, a wider body of data is required to fully investigate the effects of fuel equivalence ratio, combustion efficiency, nozzle pressure ratio and other parameters on exhaust plume characteristics.

Alternative design mechanisms to improve flowpath performance have been examined through analytical and experimental programs. The use of stream-traced forebody and rectangular-to-elliptic transition inlets has been studied. Enhancements to vehicle stability and control through thrust vectoring of the scramjet exhaust flowfield have been explored analytically. Alternative placements of engine nacelles on vehicle airframe may also offer performance benefits. These areas require further research to determine their feasibility and effects on integrated system performance.

Determination of integrated vehicle performance and the generation of aero-propulsive data base predictions is accomplished using a wide range of computational and experimental capabilities. Presently, computational predictions employ a multi-level approach, ranging from advanced engineering analysis codes for combustor and internal flowpath analysis to Navier-Stokes CFD solvers for external airframe and internal flowpath components. Determination of longitudinal and lateral-directional stability characteristics through the use of these tools is computationally expensive and time consuming. Capabilities in this area would be greatly enhanced by incorporating appropriate flow modeling capabilities into a sensitivity analysis code which could generate perturbations from high-fidelity CFD solutions over a limited design space. Advances in parallel computing methods and grid generation techniques should be exploited to provide improvements in tip-to-tail CFD solution capabilities.

Experimental testing of complete scramjet flowpath configurations has been accomplished through simulant exhaust-gas techniques and testing in propulsion facilities such as the 8-Ft. HTT. The use of force and moment data in the latter have been limited to longitudinal increments between mission sequences near the scramjet test point. The effects of testing in a vitiated air stream have not yet been fully characterized. Capabilities for obtaining lateral-directional stability information under powered conditions are severely limited.

In order to maintain world-class leadership in hypersonic airbreathing propulsion, a research program in propulsion/airframe integration for hypersonic vehicles is needed which focuses on several issues: First, the development of advanced airframe and flowpath concepts to maximize aero-propulsive performance benefits; second, the development of advanced computational and experimental capabilities to simulate vehicle and flowpath configurations under a wide range of parametric conditions, and investigate propulsion-airframe component interactions; and third, the development of analysis methods to improve the fidelity of, and reduce the time frames necessary to generate, vehicle aero-propulsive data base predictions.

Over a nominal ten-year time period, the following general technical objectives should guide research programs in the area of hypersonic propulsion/airframe integration.

1. Development of advanced concepts to exploit propulsion-airframe interactions, to achieve performance gains and improve stability and control of airbreathing hypersonic configurations.

2. Development of computational methods capable of obtaining three-dimensional flowpath/vehicle solutions with reacting flow chemistry, in cycle times of days.

3. Development of experimental testing capabilities to fully investigate aero-propulsive performance *as well as* longitudinal and lateral-directional stability characteristics of airframe-integrated scramjet configurations.

4. Development of methods for the rapid and accurate generation of aero-propulsive data base predictions for specific configurations, at engineering accuracy level. This includes parametrics of Mach number, Reynolds Number, angle of attack, sideslip angle, control surface deflection angles and fuel equivalence ratio, as well as geometric parametrics such as length, fineness ratio, wing planform, aspect ratio and control surface parametrics.

5. Understand pertinent ground-to-flight scaling differences and techniques to scale ground test data to appropriate flight conditions.

6. Understand mechanisms for integration of multiple flowpaths and engine types into efficient flight-like propulsion systems, including turbine-based combination cycles (TBCC), rocket-based combined-cycle (RBCC) and other candidate systems.

The following items are recommendations for specific research opportunities that have potential to result in revolutionary advances in airframe-integrated scramjet-powered vehicle development. Research projects in the short term could utilize existing configurations, such as the X-43A, or could focus on developing a vehicle or flowpath design for use in computational, experimental and, eventually, flight research.

1. Develop a national scramjet simulation computing facility capable of implementing advanced algorithmic, physical modeling and hardware capabilities to compute three-dimensional integrated vehicle and flowpath configurations with reacting flow chemistry. This includes CFD code development as well as the implementation of advanced grid generation methodologies and parallel computing strategies which take advantage of high-speed multi-processor systems with advanced data storage capabilities.

2. Develop a national airframe-integrated scramjet test facility by upgrading the capabilities of the 8-Ft. HTT to fully investigate the aero-propulsive performance and stability characteristics over an increased angle of attack range, non-zero sideslip angles and control surface deflection angles. This includes experiments to investigate or improve the flow quality of the vitiated-air test stream.

3. Conduct a series of experiments to investigate yaw performance of integrated flowpath configurations in the 8-Ft. HTT, including plume expansion effects, interaction with control surfaces, lateral-directional stability derivatives, and engine operability.

4. Develop a hypersonic airbreathing sensitivity analysis code with appropriate flow physics to generate multiple parametrics of performance quantities within a defined design space based on high-fidelity CFD solutions. Implement a computational and, perhaps, corresponding experimental program to validate the methodology for complex configurations under unpowered and powered conditions.

5. Conduct a study to investigate full flowpath designs which utilize stream-traced forebody shapes and rectangular-to-elliptical transition inlets. This includes analytical and computational studies to investigate: Combustor designs; internal and external nozzle shapes; transition mechanisms from elliptical combustor cross sections to contoured nozzle shapes; methods for efficient integration with airframe and control surfaces; and the effects of multiple module interactions.

6. Implement an experimental and analytical program to investigate alternative mechanisms, such as thrust vectoring, to improve the controllability of scramjet-powered vehicles while minimizing trim drag and associated performance penalties.

7. Conduct analytical and computational studies to investigate issues associated with the integration of multiple-flowpath engine systems, such as RBCC and TBCC designs. This should include component interaction effects between systems, placement of flowpaths and engine nacelles, interaction of multiple plumes and unsteady effects of mode transitions. Advanced concepts, such as the use of rocket modules for scramjet fuel injection or enhanced controllability by tailoring fuel delivery, may also be examined.

8. A computational and experimental program to investigate Reynolds number scaling issues from ground test to flight conditions, and geometric scales, including the effects of boundary layer transition on flowpath and integrated vehicle performance.

9. An experimental and computational program to investigate the effects of inlet unstart on vehicle performance, stability and control.

10. A computational and experimental study to investigate alternative nacelle placements on vehicle performance.

3.4.5 Ignition and Flameholding

Ignition and flameholding devices in hypersonic airbreathing engines have a 1960's "subsonic pedigree," but largely result from trial and error engineering design processes – despite the fact that recent detailed chemical kinetics, numerical simulations of nonpremixed combustion, and several nonintrusive combustion diagnostic tools are available to transform this activity into systematic scientific study. Blunt-body fuel injector arrays and backward-facing-step fuel-injection configurations are typically analyzed using "calibrated" turbulent mixing codes, and highly simplified chemistry inadequate for the description of "ignition turning points." Designs are refined by trial and error to maximize mixing with minimal losses, and (hopefully) retain flameholding over a required range of conditions. The empirical design goal is to provide just enough reactivity/residence time for combustion initiation, propagation and radical mass transport through injection-stagnation and recirculation flows, while minimizing shocks and flow stagnations, and resultant drag, surface heating and thrust penalties. Thus, although ignition and flameholding are highly critical, they stem from empirical trial-and-error processes which may be far from optimum.

Where do we need to go in next 10 years? We need to apply (and refine) recent comprehensive and reduced kinetic schemes, in combination with nonpremixed numerical simulation tools and diagnostic techniques, to attack these problems more scientifically – e.g., as very recently done in some highly detailed computational/experimental studies that explain the lifting-stabilization-mechanism of jet diffusion flames. Needs include: detailed calculations and characterizations of free-radical initiation/production rates in reaction kernals (without and with air contaminants); residence-time distributions; localized shock and convective heating effects; cavity resonance frequencies; transport rates of free radicals to the primary supersonic flow; detailed sensitivities (partial derivatives) of ignition delays to imposed pressure/temperature fields and injector/flameholder geometric variables; and analyses to unravel complex diffusive/convective stabilization mechanisms that can maintain efficient unsteady combustion without flameout.

The AAAC should focus on long-term development and support of fundamental computational and experimental efforts as described above, with the goals of developing new mapping and optimization strategies for ignition and flameholding. Most importantly, this and similar high-risk and long-term research activities need to be conducted independently of project funding (e.g. Hyper-X or Future-X, etc) while maintaining adequate mechanisms for significant interchange of technical information.

The most significant engineering problem associated with ignition and flameholding in our present scramjet design methods is that we lack engineering prediction tools and methodology for accurately predicting engine light-off and blowout limits in clean air or in vitiated air. While some very old emipirical correlations exist [5, 6] to define these limits for subsonic flows using certain specific geometries (steps, wall jets, etc) the local flow residence time, pressure, temperature and flow composition must be known or estimated in order to use these correlations. In the complex flowfields or flameholding regions of "real" scramjet combustors these quantities are quite uncertain. Present codes which have some ability to predict light-off and flame-out behavior are either too time consuming for use in engineering design, or require specification of uncertain parameters, as in the empirical methods. Presently these limits are found through extensive tests of complex engine models, and are dependent on model scale, facility, and test conditions in many cases which results in highly uncertain "scalability" of results. The lack of a tool and/or methodology to predict light-off and flame-out results in conservative combustor and flameholder designs and is a significant liability in future test and analysis programs which seek to obtain "scalability".

If effective prediction tools and methodology could be developed to predict scramjet engine light-off and flame-out, designers could reduce engine length, drag (reduced flameholders), engine heat load, and increase engine operating margins, and thrust/weight ratios.

Therefore, engineering methods should be developed that are capable of predicting and measuring the required flow parameters in the flameholding region, with and without combustion, for complex "real" scramjet flowfields — so that existing experimental results for engines can be better correlated and "scaled". Ultimately, a unified predictive engineering code must be developed that will adequately predict light-off and flame-out limits for real engines as a function of flow composition, scale and combustor inflow conditions.

3.5 Testing Requirements and Facilities

During the NASP program a renewed interest in hypersonic flow phenomena led to the reactivation and upgrade of some older hypersonic test facilities and the building of new ones for the study of high enthalpy fluid dynamics, and specifically airbreathing propulsion flowpaths. These facilities, generally of the pulse type in which test gas is heated by the passage of a strong shock wave, can deliver a test gas flow at stagnation enthalpy equal to the energy of an aerospace vehicle in atmospheric flight up to orbital speeds. Pulse facilities can operate as either a reflected-shock tunnel (RST) or a shock-expansion tunnel (SET). For airbreathing propulsion testing, RST's are generally best between Mach 7 to 12 flight enthalpy duplication, with the upper limit based on avoidance of excessive dissociation of O_2 in the stagnated air test gas in the nozzle plenum. The SET's are more appropriate at flight Mach numbers above 10, because the test gas energy is achieved by acceleration through an unsteady expansion and is not exposed to stagnation temperature or pressure. The NASA HyPulse shock tunnel is capable of operating in both modes to cover the entire hypersonic flow regime. At flight speeds above about Mach 10, the kinetic energy of the vehicle is the dominant component over the thermal energy of combustion, and the term hypervelocity flow is used to describe the regime.

Although pulse facilities received attention during the NASP program for hypervelocity testing, the need for propulsion flowpath test technology development was felt across the speed regime. As a consequence, combustion and arc heated blow-down facilities, conventionally used to study scramjets with flight duplication up to Mach 8, also experienced growth in number and expansion of operational envelopes. After the NASP program ended, other programs and projects, including Hyper-X, ART, Trailblazer, the overall ASTP, and now the Spaceliner, have continued the expansion of propulsion flowpath test capabilities. Except for the 8-Ft. HTT at Langley, all expansions of the hypersonic airbreathing propulsion flowpath (HAPF) test facilities, including pulse flow and blowdown types, have occurred at contractor sites at government expense.

Although Langley Scramjet Test Complex (LSTC) facilities [7] were used extensively throughout the NASP program to evaluate contractor scramjet engine configurations, most efforts to expand test capability during and post NASP were more expediently done at contractor's sites, using research dollars. (Also see the related discussion concerning this decision in Section 2.2). The projected long lead times for funding and modification of LaRC test facilities precluded their availability for timely testing. The result of these program-driven actions over the past 12 years has been to reduce the LSTC to a second tier level, relative to government-owned test capabilities "built up" at contractor sites, specifically GASL, Inc. in Ronkonkoma, NY [8]. A historical review of the experimental scramjet combustion research at LaRC provides a detailed perspective of the engine test and facility capability [9]. GASL currently operates the NASA HyPulse shock tunnel facility (formerly the LaRC Expansion Tube located in Bldg. 1200), which was upgraded to allow semi-freejet tests of scramjet engines on a comparable scale with blowdown facilities, at Mach 7 and 10. Currently this facility is providing all of the Mach 10 Hyper-X engine flowpath development data.

For LaRC to keep and maintain a strong competency and functional capability in HAPF research, test facilities capable of duplicating flight enthalpy over the airbreathing speed range are critical. However, of equal importance is the need for a skilled and experienced research staff who know the facilities, the test techniques, and how to apply appropriate data analysis and processing tools to extract meaningful information from the test results.

The pressure of program goals will continue to demand critically needed test capability in the hypervelocity (nominally flight Mach 10 to 18 range) regime at GASL. In the next ten years the NASA HyPulse facility needs to be upgraded, to enable engine testing at full flight dynamic pressure in the Mach 7 to 16 range through installation of higher pressure facility hardware. NASA must insure that this unique-in-the-world test capability be maintained with knowledgeable oversight. Other government owned facilities at GASL, for testing current propulsion concepts (e.g. RBCC), also need to be preserved. These facilities have been constructed, upgraded, and operated by LaRC research dollars, and have reached the point of providing critical functional capability to NASA as a whole. (Much of the recent funding has come from NASA Glenn and Marshall programs). NASA (whether LaRC or MSFC) needs to consider ways of preserving this capability outside of the continuing use of research dollars.

Based on the preceding discussion the following recommendations are made:

1. Procure existing RHYFL shock tunnel hardware, and fund its installation to enhance the test operability of HyPulse at GASL. This upgrade will enable both a reflected-shock tunnel, capable of testing near-full-scale airbreathing propulsion flowpath hardware (RBCC,

TBCC, scramjets, etc) at flight conditions in the Mach 5 to 10+ regime, and a shock expansion tunnel of sufficient scale to test airbreathing engines from flight Mach 12 to 18+.

2. Provide means to cover the operation costs of the government-owned test facilities and infrastructure at GASL *without* using PBC task assignment contracts. The most ideal case may be for NASA to buy the GASL complex and covert it to a government-owned, contractor-operated (GOCO) facility, much like Plumbrook is at GRC, or JPL. The advantage here is that research money could be used for research and not for maintaining test equipment. This would enhance the technical oversight of the facility operation.

3. Establish research program(s) to investigate the flow physics and chemistry in a scramjet (or hybrid system) at hypervelocity (say nominally Mach 15). This program could provide the basic database for fuel injection, mixing, ignition, flameholding, and combustion for the high-end speed regime, like the existing Mach 5 to 8 database that has been developed at LaRC over the last 25 years. (The LaRC data served as the basis for launching the NASP program in the late 1980's).

4. Investigate propulsion cycles that are not (or not solely) dependent on chemical energy release. Some alternative means of energizing the captured air mass flow to obtain thrust may be essential to airbreathing engine operation in the hypervelocity regime. Note that the Rule-of-69 is that energy available from burning ideally all the fuel is proportional to 69/M-squared; flight Mach 8 is about the break-even point and at Mach 15, it is about 1/3. Thus, adding kinetic energy to the captured air stream becomes progressively harder at higher flight Mach numbers.

3.6 Scramjet Engine Controls

Fuel controls were developed under the NASP program for the 8-Ft. HTT test of the Concept Demonstration Engine; but due to test cutbacks, only very limited closed loop testing was conducted. Hyper-X has developed closed-loop engine controls for estimating fuel requirements, monitoring for inlet unstart, and assessing vehicle performance. This control will be performed at some point along a specific trajectory.

Improved fuel controls will be required for any scramjet flight application, including startup, acceleration, maneuvering, cruise and decent. These required controls will include integration with the coolant system (thermal management).

Based on these requirements, the following recommendations are offered.

1. Computer models should be developed for engine simulation, including thermal management.

2. Use the HXEM and Hyper-X bench control system, from the 8-Ft. HTT tests, as a test bed for engine controls research in the (AHSTF). These tests should be conducted after the current HXEM and HXFE test plans have been completed. We should consider engine ignition and flameout control, re-ignition, unstart prevention, engine-restart, thrust control, pitch control, engine pressure control, etc. These tests may also prove valuable for Hyper-X Flight 2 engine controls development and verification.

Most of the equipment, software, etc. needed to obtain a good start, is available. New instrumentation, including some additional data acquisition and signal conditioning equipment, will also be needed.

The proposed research should be a good candidate for industry and other government lab partnerships, as well as, alternative funding sources (such as the Director's Discretionary Fund). This approach would be very timely for the AARM Program — several of the AARM participants are very interested. There is also a strong indication of SpaceLiner participation as well.

3.7 Diagnostics and Instrumentation

Nonintrusive flowfield diagnostics is a term which encompasses a variety of methods applied to a variety of problems to achieve a variety of goals [10, 11, 12, 13, 14, 15]. There are three basic goals which measurement technologies are used to achieve. The first is measurement of performance, i.e. the output of the physical system being studied. For an airbreathing engine, the primary performance measurements of interest are thrust (and other forces, as well as moments), fuel combustion efficiency, pressures and heat fluxes (for thermal and structural loading). The second goal is the verification/validation of design and analysis tools and methods. These tools generally take advantage of simplified models of the complex turbulent, compressible, reacting flows found inside hypersonic airbreathing engines. In order that these tools be applied confidently to the design of engines, measurements need to be made of the flow to verify the accuracy of the models and the design/analysis tools which use them. The third goal is the Missouri goal, or "show me" the flowfield. Qualitative and quantitative flow visualization provide the propulsion engineer with a view of the invisible - what is really happening inside the engine, and what are the physical processes which are controlling the behavior of the engine? The knowledge and physical understanding gained from these applications of measurement technology typically lead the engineer to modify designs in the most productive ways, and can contribute to the "out of the box" thought processes which lead to concepts inconceivable without such a look inside the engine.

Historically, at NASA Langley, there has been a small effort in the areas of development and application of nonintrusive diagnostics to the goals described above. This effort has been hampered by the tendency to fund university and industry research at the expense of in-house efforts, by the lack of commitment to long term efforts, and by the unwillingness to staff the activity at a level consistent with the need. To achieve the goals required from the application of diagnostic methods, the following specific recommendations are made.

For a flight engine, and also ground-test engines, it is highly desirable to have a device which measures combustion efficiency on the fly. This would allow an advanced engine control system to vary parameters such as fuel flow rate, injection location and angle, etc. to maintain peak efficiency during acceleration and cruise operation. This information could also be used in conjunction with a measurement/assessment of engine thrust to calculate and maximize available range, for example, or other parameters of interest. Combustion efficiency may be obtained by measurement of the exiting flux of CO_2 and/or H_2O, and could be accomplished by the integration of fiber-optically coupled mid infrared diode lasers and detectors with rapid data processing algorithms.

Balances and accelerometers are used to determine forces and moments. Some of the newer devices offer much smaller size, allowing placement where more cumbersome older units could not be used. The rate of acquiring data is much improved, as well as the achievement of end-calculated results [16, 17, 18]. This technology seems likely to continue, and should improve through further size reductions (micro- and nanotechnology) and increased speed of data transfer and computations. Artificial intelligence may play a role too, through the use of neural networks. Optical methods, which determine displacement and deformation of the model or vehicle surfaces, have gained some use in recent years to support these measurements (e.g., used to measure strain.) They are likely to gain more widespread use and should be pursued for the advantage of not being inertially dependent.

If engine cycles utilizing nonsteady flow are implemented, engines must be equipped with fast-response instrumentation for on-the-fly evaluation of performance. Optical fiber technology may be suitable for this as well.

The complex internal flowfield generated by the interaction of fuel injection, combustion, shock waves and boundary layers results in surface pressure and heat transfer distributions that are difficult to predict, and may result in a distribution of structural and cooling elements which are not optimal. If pressure- and temperature-sensitive coatings could be developed to withstand the harsh environment inside a hypersonic engine, along with the appropriate viewing methodologies required, it is likely that more efficient physical and thermal protection systems could be implemented, saving weight and increasing vehicle performance.

For improvement of design codes, measurement techniques must be available to provide data with the temporal and spatial scales required to validate these codes. Areas of particular interest include ignition, flameholding, blowoff, and relight phenomena, in addition to long-needed data for steady operation. Techniques which simultaneously provide measurements of multiple parameters are of particular interest, as they may be used to improve the understanding of turbulent interactions which have confounded current models.

The goal of improving the propulsion engineers' physical understanding of the flowfields produced in these engines can only be accomplished with the use of appropriate measurement techniques. Examples of intelligent applications include the use of planar doppler velocimetry (PDV) to quantitatively visualize the velocity field inside a combustor. Such an application would allow the engineer to see the combustion-induced flow separations and subsequent reattachments, shock waves and their interactions with fuel jets and plumes, large and small scale mixing structures, and ignition and flameholding regions — each at a single laser-frozen instant in time. The temporal averaging of many such realizations would, in the same experiment, provide CFD-validation quality data, and the variations of the instantaneous realizations from the mean would aid in the development of physical models to describe the important dynamic phenomena controlling the performance of the engine.

3.8 Computational Methods

Computational fluid dynamics (CFD) has several roles in the design of a hypersonic propulsion system. It primarily serves as an engineering tool for detailed design and analysis. In addition, results from CFD analyses provide input data for cycle decks and performance codes. Finally, CFD has several applications in engine test programs to develop an engine concept. CFD is first used to guide the test setup and to determine the proper location for placement of instrumentation in the engine. It has also proven to be an effective tool for determining the effects of a facility on testing; for example, the effects of contaminants in a combustion heated facility on an engine combustor test. During and following a test, CFD is useful to predict flowfield measurements as a complement to measured data.

The inlet/isolator of a scramjet engine supplies the combustor with a required quantity of air at a specified pressure, velocity, and flow uniformity. The physics of the flow in an inlet are characterized by:

1. Moderate strength shock waves
2. Shock-boundary layer interactions
3. Flow separation in unfavorable pressure gradients
4. Compressibility effects
5. Transition to turbulence
6. High leading edge thermal loads
7. Possible unstart

Computational analyses of inlets typically employ codes that solve the Euler equations, or Euler codes iterated with the boundary layer equations for viscous effects, for initial analyses. More detailed calculations utilize either the parabolized Navier-Stokes equations, or the full Navier-Stokes equations if significant flow separation must be considered. All of the calculations typically solve the steady-state equations so that simulations can be completed in reasonable times. Turbulence is modeled using either algebraic or two-equation turbulence models with empirical compressibility corrections and wall functions. Transition models are not currently being employed. Thermodynamic properties are generally determined by assuming that the inlet flow behaves as a perfect gas or equilibrium air. Calculations are conducted on fixed grids of 100,000 to 2,500,000 points in multizone domains. A limited degree of dynamic grid adaptation is employed when necessary. Typical run times range from a few minutes to 50 hours on a Cray C-90 computer.

Based on the current state of the art for inlet calculations, and future technology demands, the following advancements are needed. More efficient parabolized and full steady-state Navier-Stokes codes are needed with a factor of five increase in run time efficiency. Significant improvements are also required for temporal Navier-Stokes codes for the analysis of unsteady inlet flowfields, including inlet unstart. Improvements should occur with algorithmic advancements, with one promising area being multigrid methods [19]. Continuing advancements in computer architectures will also enhance code speed. Improved methods for dynamic grid adaptation would also enhance the ability of computational algorithms to capture flowfield features.

There is a serious need for the development of advanced transition and turbulence models. This is likely the most limiting area for accurate modeling of inlet flowfields. Promising work is now underway to develop new algebraic Reynolds stress turbulence models with governing equations that can be efficiently solved [20, 21]. For nonequilibrium flows, the differential Reynolds stress equations must be solved, however, and further work is necessary for this to be done more efficiently. Advances in large eddy simulation, with the development of subgrid scale models appropriate to high-speed compressible flow, may also allow this technique to be applied to inlet flows in the future [22]. Finally, work is needed to develop improved transition models for inlet flows, particularly with flows exhibiting adverse pressure gradients.

Experiments must also be conducted to provide code validation data for inlet flowfields. More extensive wall pressure measurements are required, along with detailed wall heat transfer and skin friction data. There should also be an accurate definition of the shock structure present in the inlet flow. Finally, in addition to the wall pressure measurements, in-stream measurements are critical for code validation. Initially, velocity profiles would be very useful for code validation, and pressure and temperature profiles are also needed. Measurements of these quantities in high-speed compressible flow are quite difficult, stretching the state-of-the-art in flow diagnostic techniques. To accurately measure these quantities in inlet flows, significant additional work will also be required to develop nonintrusive diagnostic techniques to collect the required validation data.

The flowfield in the combustor of a scramjet engine is characterized by much of the flow physics of the inlet, but it is further complicated by:

1. A wide range of flow velocities inhomogeneously distributed throughout the combustor
2. Small and large scale vortical flows (for mixing)
3. Separated flows (for flameholding)
4. Complex mixing phenomena
5. Finite rate chemical reaction (that may equilibrate)
6. High temperatures and heat fluxes
7. High degrees of anisotropy and nonequilibrium transfer of turbulence energy

8. Interactions between turbulence and kinetics that affect chemical reactions and the turbulence field.

Computations of combustor flowfields typically employ codes that solve either the parabolized or full Navier-Stokes equations, depending upon the region of the combustor being modeled and the degree of flow separation and adverse pressure gradient being encountered. Steady-state methods are normally used with limited unsteady analyses for mixing studies or the analysis of combustion instabilities. Turbulence is again modeled using algebraic or two-equation models with empirical compressibility corrections and wall functions. There is a limited use of models to account for turbulence-chemistry interactions based on probability density functions. Thermodynamic properties are determined utilizing perfect gas or, in some cases, real gas models. Chemical reaction is modeled with reduced reaction set, finite rate models. For the hydrogen-air reactions occurring in a hydrogen fueled scramjet, a typical reaction mechanism includes nine chemical species and eighteen chemical reactions, although other mechanisms are employed as the case dictates [23]. Hydrocarbon-fueled scramjet concepts are modeled with much more complex mechanisms that must be further reduced to allow practical computations. Calculations in each case are typically conducted on fixed structured grids of 200,000 to 2,500,000 points in multizone domains. Typical run times on a Cray C-90 computer range from 10 to over 300 hours.

Many of the future technology needs for combustor simulations follow from the needs for inlets described earlier, but several of the additional requirements will be more difficult to achieve. For combustor modeling, a factor of ten improvement in the efficiency of steady-state and temporal Navier-Stokes codes will be needed to carry out the required calculations with the necessary accuracy and design turn-around time. Multigrid methods again offer promise for significantly enhancing convergence rates, but the application of multigrid methods to reacting flows also results in additional challenges for success with the method [19]. Current research to apply multigrid methods to high speed reacting flows has resulted in a significant improvement in convergence rates over single grid methods. Dynamic grid adaptation will become even more important for capturing the complex flow structure in combustors, in particular the shock-expansion and vortical structure in the flow. Proper resolution of vortical flow requires very high resolution to conserve angular momentum.

Again, there is a serious need for improved turbulence modeling in high speed reacting flows, both to model the turbulence field and to properly couple the effects of turbulence on chemical reaction and reaction on turbulence. Promising work is again taking place in this area using several approaches. Techniques using velocity-composition probability density functions have been successfully applied to incompressible reacting flows, and this work is now being extended [25] to model compressible reacting flows. Work is also underway to apply large eddy simulation (LES) techniques to compressible reacting flows. Subgrid scale models for the LES of these flows are currently being developed. Recent work utilizing a filtered mass density function for the LES of turbulent reacting flows appears particularly promising for the future [22].

Finally, further work is needed to simplify the modeling of chemical reaction in combustor flowfields. Methods for systematically reducing the number of reactions in a full reaction mechanism are required to reduce the computational work [26]. A number of promising methods, under development, were discussed in a previous section.

As with the modeling of inlet flowfields, experiments are also required to provide data for the validation of combustor codes. In addition to the data required for validating inlet modeling, combustor code validation will require extensive temperature and species concentration measurements, as well as correlations of these quantities with each other and with velocity for validation of advanced turbulence models. Measurements of all the required flow variables are more difficult to obtain in the reacting flow environment of a scramjet combustor. Significant work will also be required to develop nonintrusive diagnostic techniques suitable for making the required measurements.

The flowfield in the nozzle of a scramjet engine is characterized by much of the flow physics of the inlet and combustor, but additional requirements include the modeling of:

1. Strong aerodynamic and chemical non-uniformities
2. Very high velocities and high initial temperatures
3. Significant divergence and skin friction losses
4. Changing thermochemical state
5. Potential relaminarization of the flow
6. Energy-bound chemical radicals that will not relax in a finite length nozzle
7. Excited vibrational states and their relaxation

Computations of nozzle flowfields are usually conducted with Euler codes, or Euler codes iterated with boundary layer calculations for initial engineering design studies; and with either parabolized or full Navier-Stokes codes for more detailed studies. Steady-state methods are normally employed. Turbulence is modeled by algebraic or two-equation models with empirical compressibility corrections and wall functions. Perfect gas or, when necessary, real gas models are used to determine thermodynamic properties. Chemical reaction is modeled with reduced kinetics models as utilized in the upstream combustor flow. Finite rate analyses are required throughout the nozzle to assess the continuing degree of reaction, and to determine the extent of recombination reactions that add to the available thrust. Calculations for complete nozzles are typically carried out on structured grids of 100,000 to 500,000 nodes grouped in multizone domains. Typical run times range from 1 to 40 hours on a Cray C-90 computer.

Future technology needs for nozzle simulations, even though less demanding, follow very similar lines to the requirements for combustor simulations. A factor of five improvement in the efficiency of steady-state Navier-Stokes codes is needed. Dynamic grid adaptation will be useful for capturing shock structure and resolving possible wall separation due to shock-boundary layer interactions. There is a further need for improved turbulence models. Algebraic Reynolds stress turbulence models offer significant promise for describing these flowfields [20, 21]. The reduced kinetics models currently being applied to nozzle flows appear to be reasonably accurate, although some further work to improve the description of recombination may be warranted. Finally, validation requirements for nozzle codes are similar to those required for combustor codes.

3.9 Special Topics

3.9.1 Nozzle Performance Enhancement with Catalysis

Performance of contemporary Langley nozzle designs for Mach 7 and 10 engines (e.g. Hyper-X-like vehicles) is routinely computed only on the basis of frozen flow at the nozzle throat, although it is sometimes claimed that current nozzles tend to follow earlier more-carefully-studied NASP designs. Neither idealized shifting-equilibrium expansion performance, nor probable finite-kinetics performance have been calculated for any contemporary nozzle configurations to estimate maximum idealized thrust, probable thrust, or the resultant performance loss due to incomplete recombination of H, O, and OH radicals during expansion. Obviously, subsequent iterations on contemporary designs, based on feasible catalysts, have not been part of the design scenario.

Recombination catalysts added to H_2 or hydrocarbon (HC) fuels in relatively small amounts, such as 1 to 4 percent phosphorus (which forms stable high-temperature oxides and acids), have been estimated to greatly enhance H_xO_y radical recombinations and resultant H_2O production and heat release during early stages of high-speed expansions from 3000K (nominal). Other catalyst candidates have also been identified. Because, at relatively high Mach numbers, thrust is typically only slightly larger than drag, and recombination losses are substantial in short nozzles, small improvements in recombination efficiency could significantly improve overall performance.

The main reasons such candidate catalysts have never been tested appear to be "knee-jerk" fears of toxicity and facility contamination (both of which may be minimized by chemical modification and clever chemical engineering – remember silane?); possible environmental effects in the stratosphere (which appear acceptable for typical applications of phosphorus, based on a limited assessment); lack of monetary/test-bed resources and unwillingness to take risk; and sincere beliefs that many other vehicle design problems are more compelling in the short run, and thus deserve the lion's share of attention. The proposed research is clearly risky but it may offer significant payoff, and the outcome cannot be known until tests are conducted – because the essential chemistry is vastly too complex and unknown (in terms of rate coefficients) to compute independently with sufficient certainty.

Where do we need to go in next 10 years? We need to vitalize detailed chemical kinetic and environmental assessments of candidate catalyst systems. Simultaneously, we need to develop a controllable fuel additive system that will facilitate safe catalyst feasibility application tests during high-speed facility simulations and/or free-flight tests – that should distinguish the functionality of candidate catalytic approaches. Overall feasibility of catalyst schemes can be deduced once basic recombination, steam formation, and thrust enhancement data are determined.

The AAAC should promote long-term efforts to assess recombination efficiencies of contemporary hypersonic nozzle designs — a seemingly endless repetition of short-term "critical" needs has eroded our ability to think and act "fundamentally;" define candidate recombination catalysts; and initiate the design and development of a safe, compact and efficient catalyst delivery system that can be used in a facility or in free-flight, e.g. using hot H_2 to vaporize phosphorus-containing molecular species (TBD) during the highest-speed portion of a flight trajectory. Finally, the AAAC should provisionally select a scramjet engine/vehicle test bed, e.g. HyPulse facility or missile-launched flight test hardware, and proceed towards feasibility testing and assessment.

3.9.2 Defensive Military Applications of Scramjets

The military/Department of Defense provides one of the best areas for scramjet applications. A vehicle that could fly at Mach 6 to 8 and 110,000 feet with excursive ability to go suborbital and return (in case of attack) would be desirable. This mission could be accomplished using a vehicle fitted with two attached rocket propelled vehicles to enable boost outside of the atmosphere.

Ordinary hydrocarbon fuels are highly desirable because such fuels are readily available and easy to store and use. It is possible to generate hot hydrogen, CO and hydrocarbons from these fuels, using rich embedded secondary combustion. JP-10 and ethylene are good initial candidates for military application, but hydrogen is not.

The scramjet would function as an overall enhancer of specific impulse. The engine(s) could be mounted on the side of two boost rockets, and used only from Mach 6 to 10 to save fuel. At Mach 10 and 100,000 feet, the engines would be discarded. The scramjet would effectively provide a means of saving fuel and oxidizer, and increasing the payload. Use above Mach 11 is not rewarding or useful. Rocket propulsion is best above Mach 12 and above 130,000 feet.

These concepts must be robust and fully functional. Current designs are neither robust nor fully functional. To make this concept functional, inexpensive scramjets for the Mach 6 to 11 range must be developed that are *attractive* to the potential users.

4 Future Recommendations and Goals

The NASA Langley Research Center has the opportunity to play a significant role in hypersonic airbreathing propulsion in the future. There is no reason why NASA Langley should not be the world leader in all aspects of hypersonic airbreathing propulsion. This includes functional capabilities in scramjet flowpath (and new cycle) technology, propulsion/airframe integration, systems studies, propulsion system controls, propulsion research facilities, computational fluid dynamics for internal reacting flows and whole-aircraft external aerodynamics, and reacting flow diagnostics (both non-intrusive and intrusive). The core personnel are available to accomplish this work, and the Scramjet Test Complex offers the core facilities that are needed.

There are a number of potential missions and applications for hypersonic vehicles utilizing both conventional and nonconventional airbreathing propulsion. Past and current work has included vehicles that have served mainly as testbeds for the development of propulsion systems. Future work should continue to develop and improve propulsion systems, but more effort should be expended on vehicle classes that will capture the interest of potential users. The Department of Defense is an excellent candidate for hypersonic vehicles that could result from these efforts. Vehicles of interest include hypersonic cruise missiles, reconnaissance vehicles, ground-to-air defensive systems, vehicles with excursive ability to go suborbital and return, hybrid rocket-scramjet systems where the scramjet serves as an enhancer of specific impulse, and other systems that will become apparent if we enter this market with a creative approach.

By broadening the research and development base of Langley's scramjet program, future opportunities would be created for work and support from other organizations. With the declining funding base from NASA in hypersonics, we must seek these opportunities. In addition, by extending the class of vehicles that are considered to utilize hypersonic propulsion systems, vehicles would become simpler and less expensive to build and test, and the vehicle being tested would be closer to the actual vehicle of interest. This direct approach to a final design may be more attractive to customers in the competitive NASA environment in hypersonics.

To choose the proper directions, and develop the technologies required to advance vehicle and propulsion system development at Langley, a number of focused programs are required. The Langley technical effort needs to primarily focus on:

1. Scramjet technology (with and without Lox augmentation)
2. Hypervelocity propulsion (including shock initiated combustion, detonation and pulse detonation engines)
3. Hydrogen and hydrocarbon ramjet technology
4. Revolutionary propulsion systems (including MHD, non-steady, and "exotic" engine cycles)
5. Fuels technology
6. Engine/airframe integration (inclusive of PAI)
7. Performance analysis techniques (both cycle and CFD)

8. Engine controls (isolator-combustor-fuel feedback systems)

9. Flowfield diagnostics (with emphasis on *in situ* water vapor measurements)

10. Ground-based propulsion simulation techniques (with emphasis on hypervelocity)

Note that these research activities must be incorporated within an effective organization, that is part of an effective program; otherwise the impact will not be useful for the NASA stated goal of impacting third-generation systems.

This white paper began by stating that substantial progress had been made in hypersonic airbreathing propulsion flowpath development, and that this work had put us on the verge of developing a new class of aerospace vehicle. This paper has shown that to make that leap, we must embark on a bold program designed to synthesize the current single-point knowledge base into a viable, complete system capable of driving a real vehicle on a real mission. At the same time we must look further to the future and evaluate and develop technologies which may offer further performance benefits over the steady flow cycles being considered today. There is a critical need to move ahead in both areas, and the window of opportunity for Langley leaves little time to act. The commitment by our researchers must be made today, and it must be strongly supported by management.

5 Appendix

A Propulsion-Airframe Integration

A.1 Background Material - Current Status and State of the Art

Component Design and Interactions: Due to the highly coupled nature of aerodynamic and propulsive effects for this class of vehicle, substantial improvements in performance may be obtained by investigating various interactions of flowpath and airframe components, and isolating means of potential design enhancements. One area of study is the three-dimensional expansion of the scramjet exhaust plume over the aftbody surface, and its impact on vehicle stability and control. The effects of exhaust gas expansion on wing surfaces has been studied previously on the test technique demonstrator (TTD) configuration with a powered exhaust gas simulation technique. Limited computational and experimental studies have been performed to examine angle of attack effects on longitudinal stability. These experiments were performed on models with metric aftbody components. During the Hyper-X program, a vehicle flowpath simulator (VFS) model was tested in the 8-Ft. High Temperature Tunnel (8-Ft. HTT). This experiment provided measurements showing the effect of plume expansion at the nominal Hyper-X flight test point, and at two additional discrete angles of attack and off-nominal dynamic pressure conditions. The configuration used in this experiment only modeled the flowpath surface of the X-43A, and did not include wing surfaces. Therefore, the issue of control effectiveness under powered conditions was not examined experimentally, and limited analytical methods are available to predict this aspect of vehicle performance.

An area which is lacking in both predictive and testing capabilities is the ability to investigate exhaust plume effects on lateral-directional stability characteristics and engine operability at non-zero sideslip angles. Currently, combustor analyses rely heavily on one-dimensional cycle analyses, so the effect of lateral variations on combustor performance cannot be investigated. Parallel processing and advances in gridding methodologies may be utilized to enable analysis of full-span configurations under powered conditions. Testing in the 8-Ft. HTT may yield information on exhaust plume characteristics at these conditions, including possible interactions with control surfaces. However, more work is needed to make use of force and moment data from such testing. Exhaust plume characteristics will also be affected by fuel equivalence ratio, combustion efficiency, nozzle pressure ratio and other engine performance parameters. The interaction of plumes from multiple engine flowpaths also merits study. A wider body of data is required to fully investigate these effects on vehicle performance.

Effective design and optimization of flowpath components may also result in significant gains in vehicle performance. Various aspects of component design and testing for inlets, combustors and nozzles are addressed elsewhere in this report. Various three-dimensional forebody/inlet designs have been studied which take advantage of streamline tracing techniques and rectangular-to-elliptic transition inlets, to generate configurations which provide adequate compression, mass capture and inlet efficiency while delivering a uniform flowfield to the isolator and combustor. Computational research and some test data have been obtained on various candidate shapes. Additional research is needed to determine effective strategies for integrating these designs into efficient flowpaths and vehicle configurations, including combustor and nozzle design and impacts on integrated vehicle performance.

A characteristic of hypersonic vehicles is that trim drag penalties associated with control surface deflections are significant at high Mach numbers. Therefore, improvements in vehicle performance could be obtained by investigating alternative control mechanisms that minimize associated trim drag penalties. Previous computational and analytical studies have examined the use of a movable cowl trailing edge, which can be extended or deflected to vector the scramjet exhaust flowfield and provide a favorable pitching moment increment for the configuration. More research is needed to determine the feasibility of these concepts and to examine alternative design approaches.

The effects of inlet unstart and other dynamic phenomena on vehicle stability and control is another item for which little data are available. A thorough investigation of the relevant flow physics and the effects on vehicle forces and moments is needed.

Scramjet flowpaths must be integrated with other types of systems to develop efficient flight engines that function from takeoff to hypersonic speeds. Concepts such as rocket-based combined cycle (RBCC) or turbine-based combination cycle (TBCC) engines employ various modes of operation through the various speed regimes. There are numerous issues associated with the integration of multiple flowpaths and the placement of engine nacelles on vehicle aerodynamics and performance. Transition between modes requires an investigation of unsteady flow physics to determine the optimum method and speed range for transition. Rocket-based concepts may also offer the possibility of utilizing internal rocket elements for scramjet fuel injection, or tailoring of fuel delivery to enhance vehicle controllability. None of these issues have been fully examined.

Another element investigated in the Hyper-X program is the integration of the X-43A research vehicle with a launch vehicle configuration designed to boost the research vehicle to the flight test altitude, and the endoatmospheric separation of the research vehicle following the boost phase. The separation mechanism created a separation cavity between the research vehicle and launch vehicle as the configurations separated from one another following booster burnout of the Hyper-X launch vehicle (HXLV). This region is characterized by a highly unsteady, viscous-dominated flow field. In order to investigate the aerodynamic characteristics of the X-43A during the separation sequence, steady-state wind tunnel data obtained for various orientations of the components were used to build a dynamic simulation of the sequence. Data obtained in different facilities showed different trends, and comparisons with CFD predictions were mixed in the level of agreement. In order to more fully understand these types of flow fields, an experimental methodology to examine the unsteady effects is required, along with the capability to perform time-dependent simulations with moving bodies. This type of separation mechanism may be an issue for future two-stage airbreathing launch vehicle concepts.

A.2 Determination of Integrated Vehicle Performance

Predictions and measurements of vehicle force and moment coefficients under powered and unpowered conditions is required in the design and analysis phase of hypersonic airbreathing vehicle development. The prediction of these quantities requires accurate prediction of surface pressure and skin friction distributions, and the need to model the flow physics of the complete engine flowpath as well as external airframe surfaces. Current computing requirements dictate the use of simplified methods to minimize resource use and generate data in reasonable time frames. Testing in aerothermodynamic facilities is generally limited to unpowered configurations or the use of cold-gas powered simulation techniques. Testing of complete scramjet flowpath models under powered conditions in propulsion test facilities has been explored in the Hyper-X program. However, there are a number of issues, such as support system interference and test section flow quality, that may limit the use of force and moment data from these tests. Advances in both areas are required to more fully investigate aero-propulsive performance characteristics of vehicle and flowpath configurations.

A.3 Computational Predictions

The prediction of integrated aero-propulsive vehicle performance for hypersonic airbreathing configurations is accomplished with various tools which range in modeling capabilities and complexity level. A complete nose-to-tail analysis of hypersonic configurations requires a wide range of physical modeling capabilities. These include the ability to model high-temperature gas effects, mixtures of thermally-perfect gases, separated flow regions, shock-boundary layer interaction regions, fuel-air mixing and reacting flow chemistry. In order to minimize cycle times, a multi-level approach is typically used at various points in the design and development phase.

The first level consists of 1-D and 2-D engineering analysis methods, such as the SRGULL flowpath analysis code. SRGULL is comprised of the two-dimensional/ axisymmetric Euler flow solver SEAGULL, which is used to solve forebody, inlet and nozzle flow fields. A one-dimensional chemical equilibrium cycle analysis method, SCRAM, is used to solve the combustor region of the flowpath. An integral boundary layer method is used to provide a viscous increment to forces and moments. SRGULL also includes several scaling factors and a one-dimensional isolator model to predict the onset location of pressure rise ahead of fuel injectors associated with heat addition due to combustion. The scaling factors are based on previous studies and ground test data, to account for mass spillage, inlet kinetic energy efficiency, base pressure, combustion efficiency and three-dimensional expansion in the external nozzle region. This flowpath analysis methodology is typically used to examine parametrics such as Mach number, angle of attack, dynamic pressure and fuel equivalence ratio on engine/flowpath performance.

The supersonic hydrogen injection program (SHIP) is used to solve scramjet flowpaths with flush-wall or intrusive hydrogen fuel injectors. SHIP uses the SIMPLE (semi-implicit method for pressure-linked equations) method to solve the parabolized, mass-averaged equations for conservation of mass, momentum, total energy and turbulence fields in a variable area domain of rectangular cross section.

Three-dimensional inviscid methods can be used to obtain surface pressure predictions for external airframe flow fields. Baseline predictions for total vehicle forces and moments may obtained by solving the three-dimensional external airframe using an Euler solver with one of the above flowpath analysis tools used to obtain engine flowpath performance. Approximate methods are used to obtain viscous force and moment increments on external airframe surfaces. Such an approach neglects any interaction between propulsive and airframe components, such as three-dimensional expansion of the scramjet exhaust plume on aftbody surfaces. The combination of methods also exacerbates uncertainties in integrated force and moment predictions. However, parametric studies of Mach number, angle of attack and sideslip effects may be conducted to examine the basic longitudinal and lateral-directional stability characteristics of configurations to engineering-level accuracy. Comparisons with limited available experimental data and higher-fidelity tip-to-tail calculations at selected points are favorable.

More detailed tip-to-tail calculations may be obtained with a combination of Navier-Stokes calculations and flowpath analysis tools, using a multi-block topology to model the full scramjet flowpath from nose-to-tail and the remainder of the external airframe components. The forebody and external cowl regions are typically solved using the parabolized Navier-Stokes (PNS) equations, with the exception of the blunt nose, blunt cowl leading edge and viscous interaction regions. The internal flowpath is typically modeled with a 3D Navier-Stokes calculation from the cowl leading edge to the inlet throat. The one-dimensional cycle analysis method in SRGULL is used to approximate the combustor flow field. The results of this calculation are used to initialize a 3D internal nozzle computation, including appropriate modeling of the exhaust gas constituents. At the cowl trailing edge, the internal flowpath and external airframe blocks are merged to compute the flowfield in the aftbody region. This approach models several important interaction regions, such as the effect of forebody/inlet performance and boundary layer state on combustor performance and three-dimensional powered expansion effects on the vehicle aftbody. However, these tip-to-tail analyses are computationally expensive and are reserved for selected points where detailed performance and flow field predictions are required.

A goal of CFD analysis for scramjet-powered configurations is the capability of obtaining full 3D tip-to-tail solutions with reacting flow chemistry. Ongoing studies to improve physical modeling capabilities for dual-mode ramjet/scramjet combustors is discussed elsewhere in this report. Improvements in grid generation methods and the use of parallel computing methods to improve cycle times for reacting flow computations are also discussed elsewhere.

CFD predictions of external airframe components generally show good agreement with surface pressure and force and moment measurements from wind tunnel testing. Predictions indicate that force and moment quantities can be sensitive to internal flowpath modeling. Fuel injectors, cowl leading edge geometry, wall temperature boundary conditions, boundary layer state and other factors may influence flow structures and corresponding pressure distributions and integrated force quantities for internal flowpath components.

A.4 Experimental Testing

Testing of configurations with complete scramjet flowpaths in aerothermodynamic facilities is limited due to scale limitations. A significant amount of work using a cold-gas powered exhaust simulation technique has been documented. This technique is useful in simulating characteristics of the scramjet exhaust plume and obtaining force and moment increments and effects due to angle of attack, internal nozzle pressure ratio, Mach number and other parametrics. The need to route a simulant gas on board the model precludes testing the complete flowpath since the forebody flow field may not be ingested into the inlet. Therefore, the contributions of internal flowpath surfaces may not be measured using this technique.

The Hyper-X program conducted the first testing of a complete scramjet flowpath configuration in the 8-Ft. HTT. Tests of the Hyper-X Flight Engine (HXFE)/ Vehicle Flowpath Simulator (VFS) model successfully measured force and moment increments between mission sequences, such as opening of the engine cowl door and the addition of fuel, with good comparisons to CFD and flowpath analysis predictions. The test gas in this facility is a product of methane-air combustion and subsequent oxygen replenishment. The effects of testing in this vitiated-air environment have not yet been fully characterized. Additionally, force and moment measurements are significantly impacted by the model support structure, which implies that only increments between sequences or configurations are meaningful.

The bulk of the data obtained from this testing were at the nominal Hyper-X flight test point. However, additional data were obtained at two off-nominal angles of attack. This testing required significant modifications to the model support mechanism. At the present time, testing at non-zero sideslip angles to investigate engine operability is planned, but the facility force and moment measurement system has only been calibrated for longitudinal components. Therefore, a full investigation of stability characteristics of this configuration is not possible. Future plans in the Hyper-X program call for testing of this model in the arc-heated scramjet test facility (AHSTF) in order to quantify some possible differences due to vitiation effects. However, this facility is limited in dynamic pressure capabilities and is not capable of simulating the Hyper-X flight condition. Another important note is that the configuration tested in the 8-Ft. HTT is only a flowpath model, not the full X-43A vehicle. The model lacks wing and vertical tail surfaces, so control effectiveness under powered conditions cannot be investigated.

The Hyper-X flight tests will generate the first flight data available for an airframe-integrated scramjet configuration at Mach 7 and 10. Analyses of these data will enable correlations with ground test data, and predictions to more fully explore component interaction effects, assess integrated vehicle performance and obtain more information on ground-to-flight correlations. Additional computational studies following the Hyper-X flights, and possible additional experimental testing, will assist in the interpretation of flight data.

A.5 Aero-Propulsive Data Base Generation

Due to limitations in testing complete engine flowpaths at powered conditions, and computational resources required to perform full 3D tip-to-tail calculations, a build-up approach utilizing a combination of tools is typically used. This can generate a data base of predictions that describe the basic longitudinal and lateral-directional aerodynamic characteristics of a specific configuration. The present methodology used in the Hyper-X program is based on the mission profile of the flight experiment, which is characterized by three distinct phases: an unpowered cowl-closed point, representative of the post-separation and descent phases of the mission; an unpowered flow-through engine configuration which follows the opening of the cowl door to establish flow through the engine; and the powered scramjet test point. Baseline force and moment coefficients are obtained for the cowl-closed configuration through extensive wind-tunnel testing, including parametrics of Mach number, Reynolds number, angle of attack, sideslip angle and control surface deflections. Increments for the cowl-opening sequence and fuel-on sequence are computed using a combination of inviscid airframe calculations and flowpath analysis tools, as previously described. Viscous tip-to-tail calculations at unpowered and powered conditions are used to obtain more detailed information and resolve force accounting discrepancies. Comparisons to HXFE/VFS data from the 8-Ft. HTT provide some experimental verification of data base predictions at selected points.

The approach used in the Hyper-X program has numerous shortcomings. First, data obtained on the cowl-closed configuration must be interpolated to the design Mach number as well as to off-design Mach numbers, in a prescribed flight test envelope, because of the limited range of available facilities. Second, an approximate method must be used to account for viscous drag effects. As indicated previously, the approach neglects several important component interaction effects, and uncertainties are difficult to quantify. Even with the use of inviscid flow solvers, this approach is still time consuming and requires careful bookkeeping of the various surfaces. Most importantly, this approach can only be applied to a single-point design where the mission increments are easily defined. No predictive information is available for the dynamic effects of the cowl-opening sequence, or the effects of control surface deflections under powered conditions. For future analyses, it will be necessary to generate predictions for multiple parametrics in reduced cycle times. Sensitivity analysis methods which can compute effects due to small perturbations in flow field variables, based on tip-to-tail CFD calculations, may provide an alternative methodology for data base generation. Existing methods have been calibrated only for simple geometries, and do not contain all of the relevant flow physics necessary to model scramjet flow fields.

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13. ABSTRACT *(Maximum 200 words)*
This White Paper examines the current state of Hypersonic Airbreathing Propulsion at the NASA Langley Research Center and the factors influencing this area of work and its personnel. Using this knowledge, the paper explores beyond the present day and suggests future directions and strategies for the field. Broad views are first taken regarding potential missions and applications of hypersonic propulsion. Then, candidate propulsion systems that may be applicable to these missions are suggested and discussed. Design tools and experimental techniques for developing these propulsion systems are then described, and approaches for applying them in the design process are considered. In each case, current strategies are reviewed and future approaches that may improve the techniques are considered. Finally, the paper concentrates on the needs to be addressed in each of these areas to take advantage of the opportunities that lay ahead for both the NASA Langley Research Center and the Aerodynamic, Aerothermodynamic, and Aeroacoustics Competency. Recommendations are then provided so that the goals set forth in the paper may be achieved.

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