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Current State of High Speed Propulsion: Gaps, Obstacles, and Technological Challenges in Hypersonic Applications

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The object of this study is to canvas the literature for the purpose of identifying and compiling a list of Gaps, Obstacles, and Technological Challenges in Hypersonic Applications (GOTCHA). The significance of GOTCHA related deficiencies is discussed along with potential solutions, promising approaches, and feasible remedies that may be considered by engineers in pursuit of next generation hypersonic vehicle designs and optimizations. Based on the synthesis of several modern surveys and public reports, a cohesive list is formed consisting of widely accepted areas needing improvement that fall under several general categories. These include: aerodynamics, propulsion, materials, analytical modeling, CFD modeling, and education in high speed flow physics. New methods and lines of research inquiries are suggested such as the homotopy-based analysis (HAM) for the treatment of strong nonlinearities, the use of improved turbulence models and unstructured grids in numerical simulations, the need for accessible validation data, and the refinement of mission objectives for Hypersonic Air-breathing Propulsion (HAP).

Nomenclature

AHI = Australian Hypersonic Initiative
ASALM = Advanced Strategic Air Launched Missile
ASSET = Aerothermodynamic Elastic Structural Systems Environment Tests
BGRV = Boost-Glide Reentry Vehicle
CFD = Computational Fluid Dynamics
CONUS = Contiguous US
CRV = Crew Return Vehicle
DARPA = Defense Advanced Research Projects Agency
DLR = German Aerospace Center
EHA = European Hypersonic Association
ELV = Expendable Launch Vehicle
FALCON = Forced Application and Launch from CONUS
FIRE = Flight Investigation of Reentry
HCV = Hypersonic Cruise Vehicle
HiSTED = High Speed Turbine Engine Demonstrator

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HRE = Hypersonic Research Engine or Hypersonic Ramjet Experiment
HTV = Hypersonic Technology Vehicle
HyCAUSE = Hypersonic Collaborative Australia/United States Experiment
IRR = Integrated Rocket Ramjet
ISS = International Space Station
L\D = Lift to Drag Ratio
NAI = National Aerospace Initiative
NASP = National Aero-Space Plane
OSC = Orbital Sciences Corporation
OSP = Orbital Space Plane
PRIME = Precision Recovery Including Maneuvering Entry
RATTLRS = Revolutionary Approach To Time-critical Long Range Strike
RBCC = Rocket Based Combined Cycles
RLV = Reusable Launch Vehicle
SHEFEX = Sharp Edge Flight Experiment
SHyFE = Sustained Hypersonic Flight Experiment
SMV = Space and Maneuver Vehicle
SNL = Sandia National Laboratories
SSTO = Single-Stage-to-Orbit
SWERVE = Sandia Winged Energized Reentry Vehicle Experiment
TPS = Thermal Protection Systems
UK = United Kingdom

I. Introduction

VENTURING into the realm of hypersonics can be both exciting and overwhelming. In the past five decades, hypersonic global transport and cost effective access to space have continued to drive this particular area of aeronautical and aerospace research. However, by reviewing the building blocks that constitute a hypersonic flight system, it becomes apparent that the complex tasks associated with the development of high speed vehicle technology are more daunting than first anticipated. Across disciplines, gaps seem to appear between theoretical projections and actual predictions. It is therefore the purpose of this study to locate, compile, and discuss various Gaps, Obstacles, and Technological Challenges in Hypersonic Analysis (GOTCHA) with the hope of identifying and helping to overcome the critical barriers that confront Hypersonic Air-breathing Propulsion (HAP) engineers in both industry and academe.

Given the vast collection of HAP literature, the present survey will not attempt to provide comprehensive coverage of the subject but will rather seek to introduce the reader to some of the critical challenges and opportunities in hypersonics. It thus serves as an evaluation of the current state of knowledge in this field. Several excellent surveys exist, but these are generally focused on either historical perspectives or specific areas of technology. In the spirit of synthesis, the present work will seek to create a cohesive list of commonly encountered GOTCHAs. The effort will build on the work of contributors who have experienced the waxing and waning phases of hypersonic research. These works appear in the form of journal articles, book series, NASA monographs, Air Force reports, textbooks, and periodicals. For example, a limited list of resources examined includes studies attributed to: Hallion,[1-5] Launius,[6-8] Bertin,[9-15] Curran,[16,17] Murthy,[18,19] Jenkins,[20,21] Billig,[22-27] Jacobsen,[28] Walker,[29-33] Lewis,[34-39] Starkey,[40] Blankson,[41-45] Marren,[46,47] Paull,[48,49] Anderson,[50-60] Scheweikart,[61] and many others.

Broadly speaking, several GOTCHA categories may be envisioned that correspond to those that are accepted by the majority of investigators. These include:

1. Aerodynamics.
2. Propulsion.
3. Materials and Structures.
4. Testing.
5. Analytical Modeling.
6. CFD Modeling.
7. Education.
8. Other.

Within these categories, it may be argued that deficiencies in propulsion, configurations, and materials are chiefly responsible for restricting the viability of a full scale hypersonic Single-Stage-to-Orbit (SSTO). As a result of GOTCHAs in propulsion technology, designers are compelled to reduce payloads to a point where new concepts offer no advantages over current or past designs. This challenge seems to be common for several programs including, to a certain extent, the Space Shuttle program, which has only provided a partial solution to the long-standing SSTO objective.[8] In contrast, much has been accomplished in aerodynamics and guidance/control from the lessons learned through such studies as the X-15 and the Space Shuttle programs. The materials and structures sector also requires continual progress to achieve better thermal effectiveness and overall weight reduction. The most pressing need seems to concern the current state of engineering tools for propulsion. It is only through diligence and focused research, the consensus shows,[62] that the most conspicuous GOTCHA issues will be mitigated, one-by-one, to the extent of promoting the development of a true hypersonic workhorse.

In setting the stage for this review, a short summary of GOTCHA categories will be given along with a brief description that relies on information available in the public domain. Some of the issues remain as relevant today as they were nearly five decades ago, and so an effort is exerted to present the material cohesively such that the key connections and common overlap areas among various categories are illuminated.

A. Aerodynamics

Although much has been accomplished to date, the complexity of HAP vehicles continues to push the boundaries of aerodynamic theory. The need to operate in several flight regimes can lead to unforeseen aerodynamic conditions, especially in air-breathing propulsion systems. While a certain shape or lift-to-drag (L/D) configuration may be efficient at low hypersonic Mach numbers (say 4-8), it may exhibit a severe degradation in aerodynamic performance outside this envelope. This would be the case, for example, during the takeoff and landing phases of a space plane. The solution lies, perhaps, in the use of a booster that is capable of accelerating the hypersonic vehicle to the proper conditions at which the air-breathing portion may be effectively engaged. Mission requirements add yet another element of complexity that must be accounted for. In this category, a number of parameters must be studied due to their impact on aerodynamic performance. These include, but are not limited to:

- Variability of lift-to-drag ratios (L/D):
    - Low - blunt bodies, ballistics.

    - High - gliders, lifting bodies, waveriders.
- Shape/geometrical variations used in different components:
    - Conical.
    - 2-D/rectangular.
    - Elliptical.
    - Axisymmetric.
    - Semi-axisymmetric.
- Flowpath geometry heavily based on aerodynamic shape:
    - Inlet.
    - Isolator.
    - Combustor.
    - Nozzle.
- Mission requirements:
    - Hypersonic missile.
    - Hypersonic bomber.
    - Hypersonic transport.
    - Hypersonic space access.
- Volumetric efficiency.
- Aerodynamic loads.
- Propulsion system integration.
- Airframe integration.
- Structural and thermal loads.
- Vibrations/Flutter.

B. Propulsion

Propulsion driven challenges are similar to those affecting aerodynamic performance, thus tying the two areas closely together. Despite the effort poured into rocket and ramjet technologies, the disparities among HAP flight regimes have no easy propulsion solutions. What has been deemed suitable for one flight speed corridor has not been for others. At the outset, a combination of propulsion systems has been suggested to facilitate engine operation at various flight speeds using different modes of propulsion. For example, the turbine based combined cycle (TBCC) unites the turbine and ramjet/scramjet propulsion systems. In this context, the turbine portion of the engine is used to power the vehicle at flight speeds leading up to ideal ramjet operation. However, combined cycle engines incur additional difficulties in implementation such as the effective integration and transition through the multiple propulsion cycles. Since the development of air-breathing engines (ramjets/scramjets) continues to lag behind rocketry, advancements in both areas are needed because of their interlocking uses and similarities. Desirable areas of investigation include:

- Engine components:
    - Bearings.
    - Seals.
    - Turbomachinery.
- Compressor and turbine blades.
- Air-breathing engines:
    - Dual-mode ramjet/scramjets.

  - High speed turbines.
  - No operational hypersonic vehicle even with much work done on ramjets/scramjets.
  - Lags the success of rocket based hypersonic flight; has limited success with ramjet propelled missiles at subsonic to supersonic speeds.
  - Encouraged by the success of NASA's X-43 and by current programs such as X-51, Falcon, HyCAUSE, and others.
  - Specifically for transatmospheric vehicles (TAV).
- Rocket propulsion:
  - Improvements to solids, liquids, and hybrids used in RBCC or booster stages
    - Internal flowfield modeling.
    - Combustion instability.
    - Components such as nozzles and turbomachinery.
  - Booster stages - make more efficient and cost effective
    - TSTO system.
    - Flight testing.
- Combined cycles:
  - Turbine based combined cycles (TBCC)
    - Mode transitioning and integration.
    - Variable geometry.
    - High speed turbines/turbojets.
    - Thermal management.
    - Materials.
    - Engine components.
  - Rocket based combined cycles (RBCC)
    - Linear aerospike rockets and nozzles.
    - Rocket-scramjet integration.
- Fuels and combustion:
  - Hydrogen.
  - Hydrocarbons.
  - Alternate fuels.
  - Mixed fuels.
  - Environmentally friendly exhaust products.
  - Radical farming.
  - Injector type and configuration.
  - Shock wave interactions.
- Plasma research to recoup energy/power in flight from ionization and dissociation outside of the vehicle.
- Vehicle and engine heat/thermal management.
- Engine performance.
- Flowpaths:
  - Inlet.
  - Isolator.
  - Combustor.
  - Nozzle.
  - Acoustics.

    - Structure.
    - Drag/Viscous effects.

C. Materials and Structures

The need for strong, light-weight, heat resistant, and cost effective materials has long been considered one of the most critical in high speed propulsion applications. If such materials could be developed, then many hypersonic vehicle problems could be solved. In this vein, a judicious balance between weight and strength poses a unique problem. In order to compensate for payload weight, lighter materials are desirable, but these may not be strong enough to withstand the operational thrust, moments, and pressure loads. Thermal protection adds another complication as hypersonic vehicles often require special materials, such as heat resistant paints, to assist with thermal shielding. These inevitably result in increased vehicle weight. Striking the right balance between strength, weight, and thermal protection must be carefully achieved. Based on the current state of knowledge in this field, there seems to be a need for

- Lighter and stronger materials and structures.
- Improved thermal protection systems (TPS).
- More cost effective manufacturability and availability.
- Synthetic – lab-grown.
- Environmentally friendly.
- Bioengineered to withstand heat and self-repair.
- Morphing shapes to accommodate aerodynamic performance and variable inlet geometries.
- More streamlined manufacturing technologies for hypersonic vehicle parts and components.

D. Testing

In order to confirm engineering theories and concepts, the ability to test labscale models remains a high priority for HAP vehicle technology. Flight testing, ground testing, and numerical/CFD ‘experiments’ comprise the three widely accepted areas of testing. Many difficulties linger today despite the visible progress that has been made in this area. Actual flight tests continue to require the most effort due to complexity and expense but prove to be the most rewarding and validating. Ground facilities bear limitations in flow conditions, scaling, and test durations but allow verifications in the absence of full scale vehicles. CFD experiments produce quicker results, but the simulation time can rapidly increase with the complexity at hand. Some CFD programs allow users to run problems using a desktop computer, but users need to be aware of the attendant limitations. These codes may be used synchronously and, preferably, in conjunction with analytical modeling. The characteristic features of testing may be reported under:

- Flight testing:
    - Reducing the cost of flight testing appears to be one of the most significant hurdles to overcome. This can be accomplished through
        - Smaller test articles for validation.
        - Faster turnaround times.
    - Streamlining the process can help to reduce the support staff required.

    - Encouraging private enterprises and academic pursuits can aid at promoting the needed expertise.
    - Developing more sensitive and robust instrumentation can help in capturing the rapidly evolving phenomena during hypersonic flight (e.g., in tracking boundary layer transition). It would also help to reduce the amount of onboard instrumentation through the use of wireless technology and advanced materials.
- Ground testing:
    - Facilities are limited in the ability to reproduce needed flow conditions for the pressure, enthalpy, air purity, temperature, flight speed, etc.
    - Facilities are limited in their ability to cover a wide range of scaling sizes.
    - Shock tunnels can reach improved flow conditions albeit with smaller test durations.
    - Small scale hypersonic technologies need to be verified before committing to flight tests.
    - Measuring devices have inherent limitations that would be helpful to reduce.
- CFD:
    - Improved models are needed to allow for wider ranges of parametric trade studies.
    - Improved re-meshing tools are needed to permit quick geometric changes.
    - The use of unstructured grids in HAP codes will help in shock capturing.
    - Reduced run times can be sufficient in the initial design stages.
    - Parallel processing can substantially expedite the solution of large problems.
    - Increased exposure and accessibility to CFD codes is quintessential at the college level.
    - Improved analytical models are needed to identify the key characteristic parameters in a problem and provide benchmarks and guidance to CFD models.
    - Improved models are needed for high speed fluid phenomena involving
        - Turbulence.
        - Boundary layer transition.
        - Heat transfer.
        - Chemical processes – plasma and combustion.
        - Acoustics.
        - Low density - rarefied gas dynamics.
        - Droplet dispersion.
    - Improved solid models are needed to capture
        - Structures.
        - Mechanical-thermal loads.
        - Vibrations.
        - Flutter.
        - Aeroelasticity.
        - Fluid-solid interaction.

E. Modeling

Modeling is closely coupled with testing. Interpreting data from experiments or numerical solutions is difficult without an analytical framework. An understanding of the fundamental physics of a process is vital in the design of experiments for ground and flight tests. Likewise, formulating useful analytical models without accurate test data is troublesome. Analytical and computational methods complement each other, providing validation and verifications for comparison. Models continuously progress as improved analytical and computational techniques are mastered and applied to existing implementations.

- Improved analytical models for hypersonic fluid phenomena encompass:
    - New approaches to nonlinear modeling such as the Homotopy Analysis Method (HAM).
    - Application of advanced perturbation tools such as the Successive Complementary Expansions Method (SCEM).
    - Improved phenomenological models for turbulence.
    - Boundary layer and stability models using generalized techniques.
    - Heat transfer.
    - Chemical processes – plasma.
    - Acoustic wave modeling and instability assessment.
    - Low density - rarefied gas dynamics.
    - Shock interactions and compressibility effects.
- Solid modeling:
    - Structural models.
    - Mechanical-thermal loads.
    - Vibrations.
    - Flutter.
    - Aeroelasticity.
- Fluid-solid interaction.
- Optimization models and codes.
- Trajectory models.

Note that some of these issues are common to more than one GOTCHA category.

F. Education

Proper education is quintessential to the advancement of HAP research. A great source of concern today is the attrition in the workforce in addition to the waning interest in aerospace engineering at the college level. Due to the pressing competition to produce more engineers in less time, the number of credit hours required to obtain a degree is constantly reduced at various institutions. Many valuable courses are no longer offered in a standard academic curriculum. This includes electives in propulsion and hypersonics, which are often dropped in favor of more traditional core courses. Consequently, numerous graduates are finding themselves ill-prepared to confront the challenges of HAP research. This issue is further exacerbated by the lack of adequate STEM preparation during secondary education. The problem affecting the aerospace industry is quite serious because (a) fewer students are graduating in this field and (b) even those graduating do not seem to be adequately prepared. The need to revitalize interest in propulsion at the high school and college levels cannot be overstated; in fact, it may be one of the most effective endeavors that our national agencies can recognize and support. Recommended actions include:

- Bolster aerospace industry by investing in advanced technologies.

- Continue and create interest in space and science.
- Keep pace with other countries.
- Prepare students with superior educational curricula.
- Continue investments in programs such as HyCAUSE.
- Understand past mistakes and successes - disseminate history with theory.

G. Other

Other secondary challenges remain that require further investigations of:

- Environmental impacts such as noise and high altitude pollution.
- Hypersonic vehicle interactions (as in the case of fleet formations).
- Controls and guidance.
- Tracking and detection.
- Hypersonic infrastructure.
- Academic and private funding resources.

II. Gaps and Challenges

A. Propulsion Systems

Designing a hypersonic vehicle may be viewed as a daunting endeavor, especially when considering the numerous attempts in the past which have led to a number of successes and failures but only a few operational vehicles. Two compounding hurdles that plague HAP technology are the extreme hypersonic flight conditions and the strict mission objectives. Mission objectives can include space access and global transportation which demand

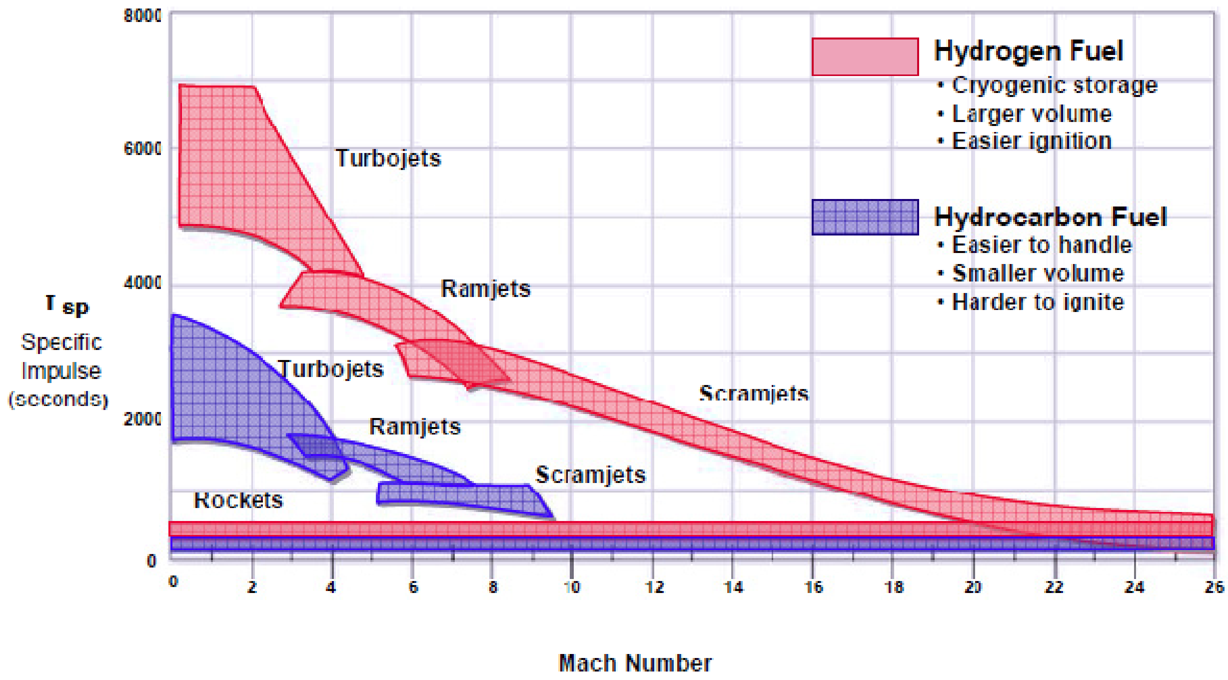


Figure 1. Air-breathing and rocket engines performance over flight speed for two fuels.[62]

Figure 2. X-15 landing and Gemini/Mercury capsules.[21]

superlatively high vehicle velocities. Achieving the necessary speeds and altitudes gives rise to harsh and unforgiving environmental conditions which, in turn, demand complex vehicle systems. Solid, liquid, and hybrid rockets, in conjunction with turbine, ramjet, and scramjet engines, embody some of the available propulsion concepts that are capable of hypersonic flight. Two branches emerge as the dominant hypersonic engine mechanisms, the rocket motor and the air-breather. Figure 1 compares the performance of air-breathing and rocket engines per Mach number for hydrocarbon and hydrogen fuels. This graph illustrates the wide range of choices and performance characteristics of each. Since the WWII era, much progress has been made in both of these areas. While the turbine engine has brought the world closer together with jet airliners, the ramjet has allowed high powered weapons and aircraft to be developed, and the rocket has sent men, scientific equipment, and satellites into space. The rocket stands out as the most successful at propelling test articles and vehicles to hypersonic speeds. The X-15, Mercury, Gemini, Apollo, and Space Shuttle round out some of the well known hypersonic vehicles (see Fig. 2). However, despite the milestones achieved thus far, the dream of a pure hypersonic craft still eludes researchers, engineers, and designers alike. Today, emphasis is placed on systems that are reusable, reliable, affordable, and efficient. Although the Apollo program worked well for its objectives and the Space Shuttle experienced a remarkable run, several issues, which designers of the next generation HAP vehicles are hoping to avoid, still plague these systems. Some of these issues will be recapitulated in the context of scramjets, TBCC, and RBCC engines.

Scramjets:

Since the fifties, researchers have been seeking to develop improved models of a high Mach number engine that runs more efficiently than ramjets. To overcome the deterioration in ramjet efficiency with subsonic combustion, scramjets have been devised for the purpose of promoting supersonic inlet conditions. Today, some of their deficiencies and hurdles include:[17]

- Energy limitations of fuels.
- Low component efficiencies.
- Understanding the scramjet process.
- Inconsistent funding.
- Improbability of use in orbital maneuvering where air is limited.

a)

b)

Figure 3. a) X-43A,[62] and b) HyShot 2 launch.[63]

Note that since 2001, there have only been two additional scramjet flight tests, the HyShot and X-43A in 2002 and 2004, respectively (see Fig. 3).[62] While some of the obstacles have been removed, much work lies ahead. Other challenges include those connected with:

- Investigating axisymmetric flowpaths instead of traditional 2-D designs.
- Providing sufficient flight tests and flight test data.
- Improving ground testing facilities.
- Improving CFD and analytical modeling capabilities.
- Making effective use of materials for strength, weight reduction, and thermal management throughout the engine.

It may be refreshing to note that scramjet engine technology is gaining ground with some recent programs such as those ongoing in Australia since the late nineties (e.g., the HyShot program since 1997).[37,48] These efforts have spurred on the highly successful Hypersonic Collaborative Australia/United States Experiment (HyCAUSE) carried out jointly between the U.S. and Australia.[29,31,64] The HyCAUSE team has been exploring alternate scramjet flowpaths and injection designs by leveraging academic resources. Additional areas of research include CFD modeling, shock tunnel ground testing, and fuel/combustion research (such as radical farming).

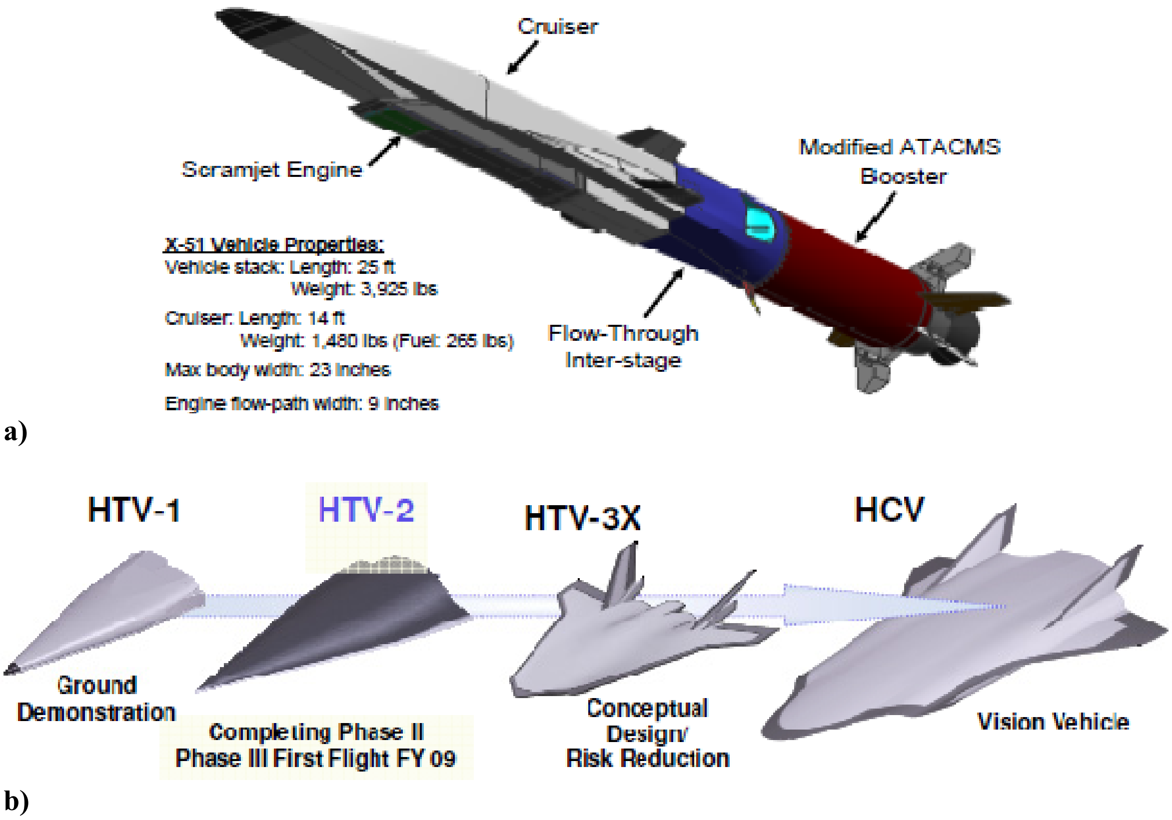


Figure 4. a) X-51A,[65] and b) FALCON HTV's and HCV.[32]

The HyCAUSE team takes advantage of CFD, ground, and flight testing to ameliorate and validate their concepts and designs.

Other U.S. programs that have been devoted to the advancement of scramjet technology consist of the X-51A and FALCON (Forced Application and Launch from Contiguous US).[30,32,33,65] The X-51A WaveRider program is a consortium of the USAF, DARPA, NASA, Boeing, and Pratt & Whitney Rocketdyne. The scramjet engine under consideration uses a 2-D design with the potential of propelling a missile to hypersonic speeds (Fig. 4a). The FALCON program is different in that it aims partly at developing a reusable rapid-strike Hypersonic Cruise Vehicle (HCV), and partly at producing a launch system that is capable of accelerating a Hypersonic Technology Vehicle (HTV) to cruise speeds, as well as launching small satellites into earth orbit. The FALCON is based on a TBCC system that employs a combination of turbojets, ramjets, and scramjets (Fig. 4b). Research results obtained from the HyCAUSE endeavor directly benefit the FALCON program due to their common scramjet flowpath and engine technology.

TBCC:

Innovative yet complex, the Turbine Based Combined Cycle (TBCC) takes advantage of a multi-engine cycle in order to transition from an airplane-like take off to high altitude. Currently, the joint DARPA/USAF initiative aims at implementing a TBCC propulsion system for Task 2 of the FALCON program.[30] The FALCON's Task 2 involves the HTV which has the goal of overcoming hypersonic technology issues. The program is intended to reach an eventual target of a reusable HCV designed by Lockheed Martin Advanced Development Projects. To

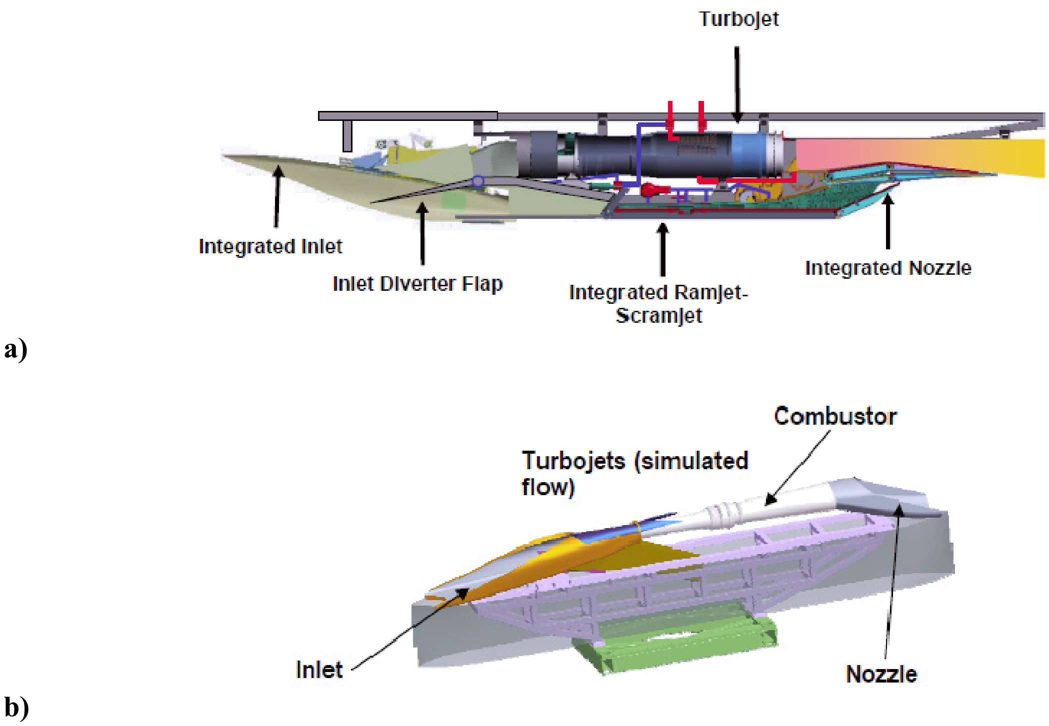


Figure 5. a) FALCON TBCC concept[62] and b) FALCON TBCC ground test article flowpath.[33]

this end, a set of TBCC engines will power the vehicle in the conceptual stage (Fig. 5a). The flowpath comprises an inward-turning inlet connected to a dual mode ramjet (Fig. 5b). The use of dual TBCC engines grants designers optimal space for the payload bay, landing gear, and other major subsystems. Another advantage is derived from the independent aerodynamic and propulsion optimization. In addition to the hurdles shared with scramjet engines, the principal enabling technologies for the HCV include:

- Efficient inward turning inlet from takeoff to a cruise Mach number of 10.
- Transitioning from the turbojet to the ramjet/scramjet.
- Thermal and operating designs of the scramjet engine (which need work) since the overall design is quite dissimilar from the NASP and NASA's 2-D X-43A engine.

RBCC:

The alternative combined cycle utilizes a rocket-scramjet propulsion system called a Rocket Based Combined Cycle (RBCC). Typically the design consists of a single flowpath with a rocket built into a dual-mode ramjet (DMRJ) engine flowpath located at the aft-end of the isolator and the fore-end of the combustor. Component operation entails a rocket only mode for initial acceleration, then a combined ramjet/scramjet-rocket mode, followed by a final rocket boost into space. Evidently, this sequence depends on the configuration and mission goals. For example, if a first stage is available to boost the vehicle, the cycle can begin with a combined ramjet/scramjet-rocket firing and end with a rocket only firing. Some benefits of this design include:

- Good throttling capabilities in the lower Mach number range.

- A good piloting structure due to the rocket placement in the flowpath.
- Higher thrust levels for the combined rocket and scramjet mode versus rocket only or scramjet only.
- The capability of the rocket engine to take advantage of the flowpath structure, namely the large scramjet exit nozzle. During an exoatmospheric climb, this feature enhances the rocket only mode specific impulse.
- The ability of the system to take advantage of the high impulse air-breathing portion instead of the traditional pure multiple stage rocket configuration.

As usual, particular challenges arise in the development of an efficient RBCC vehicle. Some of these consist of:

- Increased drag with the larger rockets acting as pilot structures within the flowpath.
- Increased mass fractions/payload issues when the air-breathing portion is carried into orbit (solution: use lighter materials and reduce complexity).
- Difficulties in achieving optimal Mach number operation.
- Reentry heating effects on air-breathing structures. A possible solution consists of inverting/toppling the vehicle on reentry to the extent of placing the air-breathing portion on the top side, thus protecting it from the intense heating environment.

Other GOTCHAs that are partly shared with scramjets include:

- Challenges caused by airframe/structure/engine heating protection that entails multiple materials with dissimilar thermal expansion rates and heating loads. This warrants the use of complex TPS or super materials.
- Increased component stresses due to
  - The need to handle a wider range of flowrates, temperatures, and pressures.
  - Long feed lines that induce transient phenomena between operating modes.
  - The requirement for high performance bearings and seals.
  - The use of thin walled flowpaths.
  - Inlet types: specifically, a sugar scoop design will require additional support (in the form of riblets) to sustain the increased hoop stresses. These in turn add weight to the vehicle.
- If a design with a linear plug nozzle is used at the aft-end of the scramjet, then additional support is needed to compensate for thrust vectoring.
- The need for possible bleed injection to improve the performance of the rocket only mode.
- The need for better ground facilities which are suitable for RBCC testing.

B. Materials

A combination of both new and well-established methods may provide the best approach to thermal management.[66] Challenges for HAP vehicles include:

- Large thermal gradients (e.g., between cryogenic tanks and surface temperatures) that cause differences in the thermal expansions of metals and structures.

- Thermal-mechanical loads that can be induced on structures such as sharp leading edges, gaps, and steps.
- Surface and airframe connections that can be subject to appreciable thermal expansions.
- The compounding initial and inspection/maintenance costs.
- Damage tolerance in view of either low or high speed impacts.
- Resistance to weathering.
- Reusability limitations.

Ceramic matrix composites are often used due to their unique properties that offer a combination of high temperature endurance, strength, and density.[66] These, however, require special manufacturing and processing to apply an anti-oxidation coating that increases strength and toughness while allowing for graceful failure. In this vein, the development of coatings that remain effective at very high temperatures appears to be critically important. Additional topics that bear on material research and development include:

- Thermal conductivity of fiber/weave architecture.
- Emissivity of materials.
- Catalytic efficiency.
- Oxidation.
- For all composite actively-cooled structures:
    - Optimum through-the-thickness conductivity.
    - Cooling containment.
    - Manifolding.
    - Lifespan.
    - Material compatibility.
- Transferring the aero-loads using a stand-off TPS approach.
- Handling vibrations and acoustic loads.
- Providing internal insulation for the stand-off TPS.
- Using load bearing aeroshells (to reduce weight) as in the FALCON HTV-2 and the UK's Sustained Hypersonic Flight Experiment (SHyFE).
- Using structurally integrated TPS.

C. Testing

The extreme and wide-ranging conditions that hypersonic transatmospheric flight experiences causes difficulty in testing and thus proof of concept. A three-pronged process exists for validating HAP concepts that consists of three testing platforms that can be used in concert: Flight testing, ground testing, and CFD. Note that other computer aided design tools such as mechanical system and optimization techniques are lumped herein with CFD.

1. Flight Testing

Flight testing represents the ideal mechanism for verifying models under real life conditions, although it remains the most costly and complex among testing alternatives. Setting up the experimental plan alone can be quite time consuming and laborious, especially when it involves coordination among several agencies and specialists. For example, in the X-51 flight testing program, additional complexities had to be overcome. A flight path had to be cleared with flight agencies, and instrumentation had to be configured to communicate flight data back to naval ships, chase planes, and the support crew.[65] Nonetheless, it is through such tests that important strides have been made. One exemplary flight program is the X-15 experimental plane which played a key role in validating fundamental hypersonic theories.[6,67,68] Over 700 technical reports resulted from this program and these provided valuable data on:

- Hypersonic/high altitude controls and stability.
- Hypersonic aircraft performance.
- High temperature effects.
- Thermal protection.
- Shock interactions.
- Turbulent boundary layer effects.
- Skin friction.
- Aerodynamic heating.
- Heat transfer.
- Reaction control jets.
- High temperature and ablative materials.
- Combined heat and structural loads.
- Propulsive performance.
- Avionics.
- Biomedical effects on pilots at high altitudes and speeds.
- Designing and constructing high speed craft.
- Confirmation of wind tunnel data.
- Energy management.
- Unpowered glide descent and landing process.
- Throttling and reigniting rocket engines.

The lessons learned from the X-15 have undoubtedly helped to design the X-20, the Apollo, the Space Shuttle, and many other vehicles. The X-15 also served as a test-bed for carrying science experiments at hypersonic speeds. Other hypersonic flight test programs further contributed to the hypersonic database and understanding. Some of these programs are listed below:[1,67,68]

- A-4.
- Alpha Draco.
- X-1.
- X-2.
- Douglas Skyrocket.
- Lockheed X-7.
- Lockheed X-17.
- Flight Investigation of Reentry (FIRE).
- Sandia Winged Energized Reentry Vehicle Experiment (SWERVE).
- Bumper-WAC.
- Boost-Glide Reentry Vehicle (BGRV).
- Reentry-F.
- Aerothermodynamic Elastic Structural Systems Environment Tests (ASSET).

- Precision Recovery Including Maneuvering Entry (PRIME, X-23).
- HyShot.
- HyCAUSE.
- X-51.

Clearly, flight testing has demonstrated its absolute necessity over the course of history. In fact, the method of flight testing emerged naturally and appeared in the earliest days of the V-2 evolution in Germany where, in the absence of computational platforms, wind tunnels and flight testing were the only available alternatives.[1] Hallion[67] expresses the significance of the X-15 in that, "It demonstrated as well the value, indeed critical importance, of having a research system available for multiple, indeed dozens, of flight test experiences, as opposed to merely one or two 'technology demonstrations.'" Along similar lines, Watillon *et al.*[68] confirm that the first Columbia orbiter flight in 1981 would not have been possible without the previous twenty years of knowledge gained from programs such as the X-15, ASSET, PRIME, and others. As for the actual cost benefit of such a program, it may be best described by historian J. D. Hunley,[6]

> "A final lesson from the X-15 program is that success comes at a cost. Moreover, this may be a cost that researchers cannot usually predict in exploring the unknown regions of aeronautics and space. The original cost estimate for the X-15 program was $10.7 million. Actual costs were still a bargain in comparison to those for Apollo, the space shuttles and the International Space Station, but at $300 million, they were almost 30 times the original estimate. (Admittedly, this compares apples and oranges in some sense, because the actual program lasted longer and included features not originally foreseen.) Because the X-15's costs were not subjected to the same scrutiny from the administration and Congress that today's aerospace projects undergo, the program could continue and yield its many fruits. Perhaps politicians and administrators should learn this particular lesson from an early and highly successful program and be less restrictive in funding new research."

Even though the X-15 is regarded as one of the most successful programs in view of its service life, the program still experienced unforeseen setbacks. For example, in 1967, the X-15 suffered the tremendous loss of life and vehicle when USAF Maj. Michael J. Adams lost control of the aircraft during a high-risk mission.[6,67]

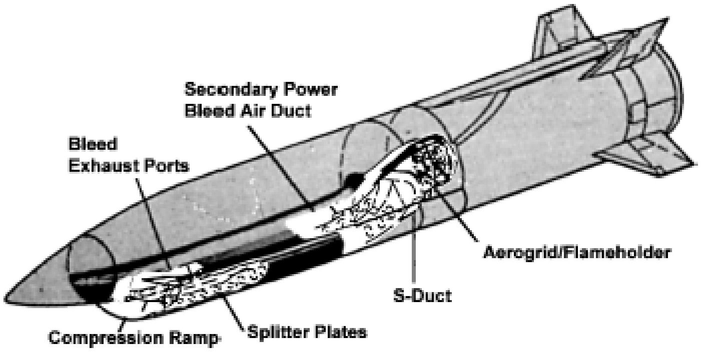


Figure 6. Advanced Strategic Air Launched Missile (ASALM).[69]

It should be noted that flight test experiments are either launched from the ground (X-17) or dropped from an aircraft in flight prior to ignition (X-15). The overwhelming majority of flight tests use rocket propulsion to either boost the test article into altitude or to serve as the main propulsion system for the test article. In contrast, only a few flight tests have been successful using air-breathing propulsion for such a purpose. The Advanced Strategic Air Launched Missile (ASALM) and the X-43A both flew experimentally at hypersonic speeds (although it is debated whether the ASALM achieved true hypersonic speeds).[62,69] The ASALM program unfolded in the mid-to-late seventies and early eighties with several successful missions, although it did not lead to a fully operational missile (Fig. 6).[69,71] The Hypersonic Research Engine/Hypersonic Ramjet Experiment (HRE) also flew as an experimental ramjet/scramjet on the modified X-15, the X-15A-2, but only as a dummy pod that inadvertently damaged the vehicle in flight.[6,67,70,72] Both Figs. 7a and 7b display the various air-breathing programs according to Tang and Chase.[62,70] Note in Fig. 7b the scarcity of experimental programs that have reached the flight testing stage.

Recently, the HyCAUSE program executed a hypersonic flight test on the research group's

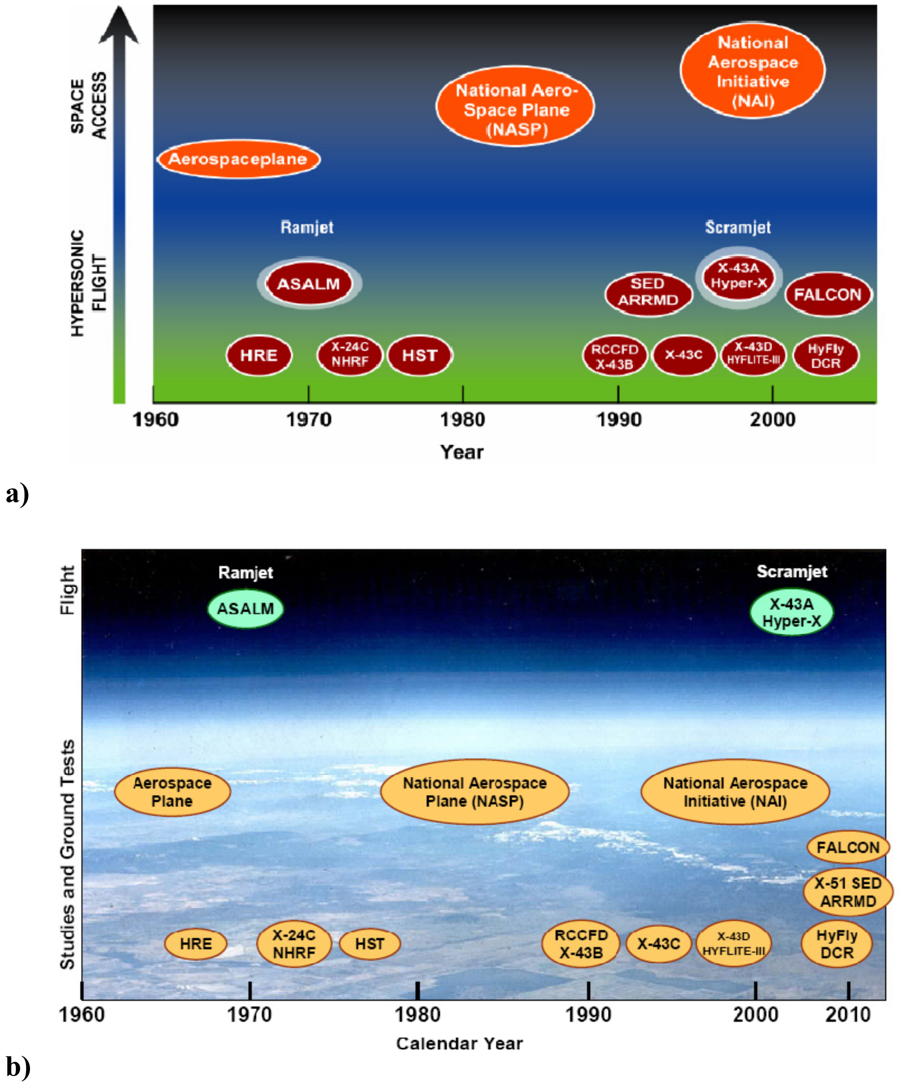
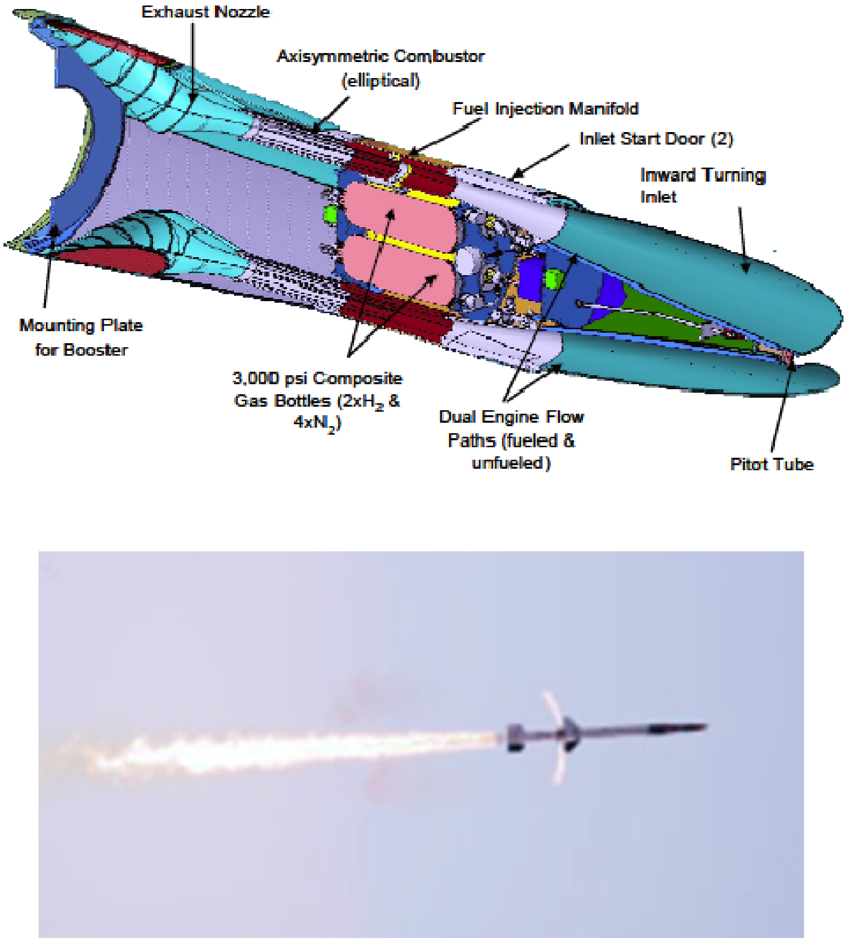


Figure 7. Timelines for a) HAP programs[70] and b) frequency of flight and ground tests.[62]



a)

b)

Figure 8. a) HyCAUSE flight test article with INTINSE flowpath and b) HyCAUSE launch.[31]

INTINSE scramjet flowpath (Fig. 8).[31] Although the test was terminated prematurely due to a sensor mishap that botched the orientation of the vehicle at reentry, it still demonstrated the substantial merit of flight testing at Mach readings that exceeded ground capabilities in both speed and duration. Based on the data collected, the HyCAUSE team identified the need to thoroughly investigate the conditions leading to inlet start and unstart, a condition that affected their vehicle. In addition to these categories of tests, flight experiments need to be gradually initiated at larger scales so that hypersonic technology can continue to move forward in its evolution toward full scale systems.

2. Ground Testing

To most users, ground testing is a surer and more dependable method than CFD due to the realism attached to wind tunnel experiments. As usual, challenges arise in setting up similarity conditions that require proper scaling/sizing and limitations on flow conditions, model construction, instrumentation, and data gathering. Fortunately, most wind tunnel facilities have been extensively used to the extent of streamlining the process that leads to data gathering and interpretation. Nonetheless, ground experiments remain at least one order of magnitude more expensive than CFD. Yet experiments remain indispensable, as a wealth of information can be obtained from lab-scale models that can then be extrapolated to either confirm or repudiate theoretical predictions that apply to larger scales. The HyCAUSE initiative has been proved effective at leveraging ground test measurements, and it is therefore hoped that other programs will soon follow suit.[31]

3. CFD

CFD is advantageous in its ability to permit quick parametric permutations in vehicle dimensions and/or flow conditions. However, this technique requires a well-versed operator who can aptly display proficiency in software use as well as a fundamental understanding of the models that are applied. Expertise and talent hence constitute a requirement for the effective interpretation and communication of CFD findings. Naturally, computers continue to rapidly evolve to the extent of mitigating long simulation run times and both geometric and physical flow complications. When compared to other testing techniques, CFD analysis can be faster depending on the model complexity employed in the simulation. Another element that computers can alleviate is the cost of testing, unless massively large clusters are required. Due to the learning curve that is needed to develop talent in this field, the main challenge remains embodied, perhaps, in the initial effort that is required to train and promote user expertise. Only then will coordination with ground and flight testing be possible.

D. Aerodynamics

As in the case of the propulsion-related GOTCHAs discussed above, much of the data on hypersonic aerodynamics may be derived from keystone projects such as the X-15 and Space Shuttle programs.[6] Furthermore, beginning in the eighties, several studies on WaveRider research have been conducted by the University of Maryland group including Lewis,[34] Corda,[51] Anderson,[52-55] and others.[35,40,41,43,44,74] These studies have uncovered some of the lingering elements that continue to plague vehicle aerodynamics, viz.

- Limited capabilities of ground testing facilities for the simulation of hypersonic flows.
- The limited aerothermodynamic flight test database.
- The stringent access restrictions to the existing databases.
- The limited verification efforts of CFD aerothermodynamic codes against ground test data.

To promote the creation of a European resource, the German Aerospace Center (DLR) has initiated an experiment, the Sharp Edge Flight Experiment II (SHEFEX II), which would permit

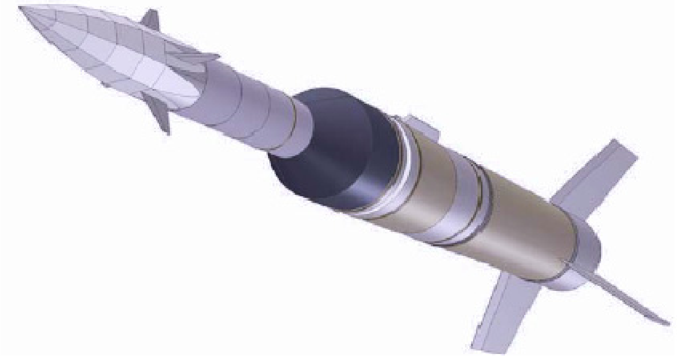


Figure 9. The SHEFEX II flight experiment.[73]

the collection of usable flight data from a controllable reentry vehicle (Fig. 9).

In addition to database creation, fundamental fluid dynamics analysis of hypersonic flow motions constitutes another essential aspect of aerodynamic research. Specific topics include boundary layer transition in hypersonic flight and boundary layer effects around vehicles that directly impact surface heating. Understanding boundary layer transition is vital not only from a theoretical standpoint but also from a practical aspect due to its substantial bearing on design considerations. At Sandia National Laboratories, Kuntz and Potter[75,76] have reported on boundary layer transitioning experiments that have been conducted under the auspices of such programs as SHARP.[67] In connection with the theoretical challenges associated with this problem, another issue that is identified here is the need for multiple, well-calibrated instruments to detect the onset of transition. This in turn requires:

- Global instrumentation:
    - Flight dynamics instrumentation (accelerometers).
    - Base instrumentation (calorimeters and pressure transducers at the base of the test vehicle).
- Local instrumentation:
    - Near-surface thermocouples.
    - Photodiode transition indicators.
    - Boundary layer acoustic monitors.

Note that careful post-processing of acquired data poses a challenge in its own right as the signals obtained from the collection of instruments are often obscure to the extent of requiring separate analysis before interpretation can be made. The reader may consult Kuntz and Potter[76] for a excellent report on the SHARP-B2 flight experiment (Fig. 10). The need for improved, cost effective instrumentation hardware and interpretive techniques seems to be essential for advancing hypersonic flight technology. Furthermore, collaboration through CFD, ground testing, and analytical modeling will greatly assist in data interpretation.

Other relevant areas that fall under this category consist of control surfaces such as fins,

Figure 10. The SHARP-B2 cone.[76]

elevons, tailerons, flaperons, etc. The technological factors associated with these control surfaces include:[66]

- The requirement to employ thin structures that reduce drag.
- The need to overcome the thermal protection barriers imposed by the thin surface requirement.
- The need to design for longer life cycles and mitigate oxidation.
- The need to integrate both hot and cold structures (e.g., in actuators).

E. Education

Not every challenge hindering progress in hypersonic vehicle development is technological in nature. In Hallion's historical survey,[67] some interesting yet concerning issues are brought to light. One of these cannot be over-emphasized as it refers to education and public interest in aerospace engineering as a whole, and hypersonics in particular. The U.S. aerospace community, especially in the field of hypersonics, is shrinking. This is driven on the one hand by retirements from an aging workforce, and on the other by difficulties in encouraging young generations of Americans to pursue aerospace engineering careers. In hindsight, this problem may be traced to the appreciable lack of enthusiasm for and inadequate K-12 preparation in mathematics, science, and technology. Essential knowledge is continually lost as seasoned generations retire and fewer newcomers enter the workforce. This generational gap is causing studies to be repeated and resources, time, and effort to be squandered. While other countries are investing heavily in advanced technologies and aerospace, the prospect of aerospace domination in the U.S. remains leveraged on previous achievements. What we need is to breathe new life into the U.S. aerospace industry through innovative educational, research, and outreach initiatives that can be promoted at the K-12 level and further sustained in college. This particular point is echoed in the report submitted by a Federal commission that reviewed the U.S. aerospace industry in November of 2002.[67] Accordingly,

> "The contributions of aerospace to our global leadership have been so successful that it is assumed U.S. preeminence in aerospace remains assured. Yet the evidence would indicate this to be far from the case. The U.S. aerospace industry has consolidated to a handful of players. . .The U.S. airlines that rely upon aerospace products find their very existence is threatened. . .The industry is confronted with a graying workforce. . .the U.S. K-12 education system [has failed] to properly equip U.S. students with the math, science, and technological skills needed to advance. . . We noted with interest how other countries that aspire for a great global role are directing intense attention and resources to foster an indigenous aerospace industry. This is in contrast to the attitude present here in the United States. *We stand dangerously close to squandering the advantage bequeathed to us, by prior generations of aerospace leaders. We must reverse this trend and march steadily towards rebuilding the industry. The time for action is now.*"

Action has been taken in the form of the National Aerospace Initiative (NAI), a 2001 joint effort of the U.S. Department of Defense and NASA that is intended to sustain the nation's long term aerospace leadership, improve science education, boost the economy, and stabilize the nation's global position. The NAI program seeks to encourage NASA and DOD to continue leading efforts in three critical aerospace areas: high-speed hypersonic flight, space access, and space technology. However, "the program has many technical and financial hurdles," according to a public NAI announcement. "This initiative is certainly worthwhile, but some of the challenges it faces are formidable," said NAI committee chair E. Dunford, "In particular, sharply higher budgets will be required to achieve long-term objectives, which could significantly impact other programs of DOD and NASA." It can thus be seen that with NASA's waning interest in HAP activities,[67,77] the situation may be more dire than it seems.

Outside the U.S., several initiatives have been taken that reflect a growing interest in aerospace education. In September 2001, Russia, France, Germany, and the Netherlands assembled a team of experts to form the European Hypersonics Association. EHA strives to research and encourage hypersonic reentry, ramjet/scramjet, and hypersonic vehicle research. In late 2003, Australia engendered the Australian Hypersonic Initiative (AHI) to promote hypersonic and scramjet technologies. Subsequently, through the spirit of mutual cooperation between the U.S. and Australia, the HyCAUSE program was conceived.[29] These particular efforts were inspired by the widely acclaimed achievements of HyShot, a pioneering hypersonic program that was launched in 1997 at the University of Queensland. The HyCAUSE program fosters a unique environment for research and technical exchange between academe and industry. It is through such collaborations that vibrant activities may be vigorously pursued with graduate students, faculty, and field experts.

In the midst of these developments, the American Institute of Aeronautics and Astronautics (AIAA) has continued to play a central role in promoting technical exchanges, not only through their prestigious journals and educational series, but also through their international conferences and workshops (e.g., Joint Propulsion, Aerospace Sciences, and International Space Planes and Hypersonics Systems Meetings). Hosting these professional conferences has provided an affordable platform for learning, networking, and recruiting participants from all over the globe. The AIAA student conferences have been equally instrumental in fostering interest among upcoming generations of engineers. Thus, given the present relationship between funding prospects and public perceptions, some of the solutions that may be offered include:

- Increase awareness of aerospace activities at K-12 schools and colleges nationwide.
- Replicate K-12 science programs that promote interest in STEM and aerospace activities. Examples include the SystemsGo High School Rocketry Initiative, NASA's (University) Student Launch Initiatives, the Fisk Altitude Achievement Missile Team (FAAMT), HUNCH (High Schools United with NASA to Create Hardware), etc.
- Develop more programs such as HyCAUSE, perhaps through alliances with other nations that are invested in this research, including the United Kingdom, Germany, Israel, and France.
- Allocate more resources to universities that grant aerospace degrees.
- Get involved!

III. Conclusions

While there are still significant challenges ahead, notably in HAP programs, it is important not to lose sight of progress made so far. Many aerodynamic and control issues have been studied and resolved via past programs. It is vital to capitalize on these achievements with sustained research efforts in advanced hypersonic propulsion systems. The GOTCHA lists provide an effective roadmap for existing hypersonic research programs as well as providing fledgling research groups with an introduction to the hypersonic literature. Even programs that do not culminate in full scale flight testing can provide valuable insight and experience to the hypersonic community. To ensure that these future technical challenges are met, it is essential to increase the profile of hypersonic research at the secondary school and college level through STEM outreach and graduate research programs in aerospace and high speed propulsion. It is through the systematic investigation of these GOTCHA topics that the objective of large scale air-breathing hypersonic propulsion systems can be realized.

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