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A Survey of Gaps, Obstacles, and Technical Challenges for Hypersonic Applications

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A Survey of Gaps, Obstacles, and Technical Challenges for Hypersonic Applications

A Thesis Presented for

The Master of Science

Degree

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Timothy Andrew Barber

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Dedication

I dedicate the toils of my labor to my exceptional parents, Jerry Dean Barber and Linda Ann Barber, and my gracious wife, Katherine Ann Barber. This is also dedicated to those who have fostered and those who are currently bolstering the advancement of science, technology, engineering, and mathematics.

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"the reward of understanding the universe may be a glimpse of 'the mind of God."' -Stephen Hawking

"If we knew what it was we were doing, it would not be called research, would it?" - Albert Einstein

"If I have seen further it is by standing on the shoulders of giants." - Isaac Newton, letter to Robert Hooke, 1676

"When I get a little money I buy books; and if any is left, I buy food and clothes." - Desiderius Erasmus

"No man is an island,
Entire of itself.
Each is a piece of the continent,
A part of the main.
.... Therefore, send not to know
For whom the bell tolls,
It tolls for thee." - For Whom the Bell Tolls by John Donne

Nullius in verba (Take nobody's word for it) - Motto of the Royal Society of London

Per aspera ad astra (Through hardships to the stars) - The University of Tennessee Space Institute's Motto

"I want to help turn the wheel of progress." - young Wernher von Braun

“Scientists discover the world that exists; engineers create the world that never was...” -Theodore Von Karman

“A book is a gift you can open again and again.” - Garrison Keillor

“Knowledge is of no value unless you put it into practice.” - Anton Chekhov

“The only source of knowledge is experience.” - Albert Einstein

“Real knowledge is to know the extent of one’s ignorance.” - Confucius

“To know that we know what we know, and that we do not know what we do not know, that is true knowledge.” - Henry David Thoreau

“There comes a time when the mind takes a higher plane of knowledge but can never prove how it got there.” - Albert Einstein

“Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world.” - Albert Einstein

“Beware of false knowledge; it is more dangerous than ignorance.” - George Bernard Shaw

“Knowing others is wisdom, knowing yourself is enlightenment.” - Lao Tzu

“Knowledge is a process of piling up facts; wisdom lies in their simplification.” - Martin H. Fischer

“A doctor can bury his mistakes but an architect can only advise his clients to plant vines.” - Frank Lloyd Wright

“Make everything as simple as possible, but not simpler.” - Albert Einstein

“Learning LaTex is like learning to ride a bike. Once you do it, you look down upon those who haven’t learned it yet and run them over.” - Unknown

‘In three words I can sum up everything I’ve learned about life: it goes on.” - Robert Frost

‘Two roads diverged in a wood, and I–
I took the one less traveled by,
And that has made all the difference.”
- Robert Frost, The Road Not Taken

Abstract

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 and falling 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 (HABP).

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Nomenclature

$2-\mathrm{D}$	Two-Dimensional
A	Area
I_{sp}	Specific Impulse
L/D	Lift-to-Drag Ratio
M	Mach Number
ω	Vorticity
ψ	Stream function
ρ	Density
p	Pressure
T	Temperature
u	Velocity in the x-direction
U_w	Injection velocity at the wall
v	Velocity in the y-direction
ABP	Air-Breathing Propulsion
ADTHEORET	Advanced Theoretical Research Team

AEDC	Arnold Engineering Development Center
AFRL	Air Force Research Laboratory
AHI	Australian Hypersonic Initiative
AIAA	American Institute of Aeronautics and Astronautics
ASALM	Advanced Strategic Air Launched Missile
ASSET	Aerothermodynamic/Elastic Structural Systems Environment Tests
ATK-GASL	Alliant Techsystems, Inc.'s General Applied Science Laboratory
BGRV	Boost-Glide Reentry Vehicle
BWT	Blast Wave Theory
CCE	Combined Cycle Engine
CFD	Computational Fluid Dynamics
CIAM	Central Institute of Aviation Motors
CONUS	Continental US
CUBRC	Calspan-University of Buffalo Research Center
DARPA	Defense Advanced Research Projects Agency
DCR	Dual-Combustion Ramjet or Dual Combustor Ramjet
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt (German Aerospace Center)
DMRJ	Dual-Mode Ramjet
DMSJ	Dual-Mode Scramjet

DOD	Department of Defense
DR	Ducted Rocket
DSTO	Defence Science and Technology Organization
EHA	European Hypersonics Association
ELV	Expendable Launch Vehicle
FAAMT	Fisk Altitude Achievement Missile Team
FALCON	Forced Application and Launch from CONUS
FASST	Freeflight Atmospheric Scramjet Test Technique or Flexible Aerospace Solution for Transformation
FIRE	Flight Investigation of Reentry
GOTCHA	Gaps, Obstacles, and Technological Challenges in Hypersonic Applications
GOTChA	Gaps, Objectives, and Technical Challenges and Approaches
HAB	Hypersonic Air-Breather or Hypersonic Air-Breathing
HABP	Hypersonic Air-Breathing Propulsion
HABV	Hypersonic Air-Breathing Vehicle
HAM	Homotopy Analysis Method
HCV	Hypersonic Cruise Vehicle
Hf	Hafnium
HFL	Hypersonic Flying Laboratory
HIFiRE	Hypersonic International Flight Research and Experimentation

HPM	Homotopy Perturbation Method
HRE	Hypersonic Research Engine or Hypersonic Research Experiment
HSDT	Hypersonic Small Disturbance Theory
HT	Hypersonic Technology
HTV	Hypersonic Technology Vehicle
HUNCH	High Schools United with NASA to Create Hardware
HV	Hypersonic Vehicle
HVT	Hypersonic Vehicle Technology
HyCAUSE	Hypersonic Collaborative Australia/United States Experiment
HyPS	Hypersonic Propulsion System
HyTech	Hypersonic Technology Program
JAXA	Japan Aerospace Exploration Agency
JPC	Joint Propulsion Conference
LES	Large Eddy Simulation
MAE	Matched Asymptotic Expansion
MCE	Multi-Cycle Engines
MSFC	Marshall Spaceflight Center
MVIM	Modified Variational Iteration Method
NAI	National Aerospace Initiative
NASA	National Aeronautics and Space Administration

NASP	National Aerospace Plane
NT	Newtonian theory
PAI	Propulsion-Airframe Integration
RBCC	Rocket-Based Combined-Cycle
RLV	Reusable Launch Vehicle
SFR	Solid Fueled Rocket
SFS	Solid Fuel Scramjet
SHARP	Slender Hypersonic Aerothermodynamic Research Program
SHEFEX	Sharp Edge Flight Experiment
SHyFE	Sustained Hypersonic Flight Experiment
SSTO	Single-Stage-to-Orbit
STEM	Science, Technology, Engineering and Math
STS	Space Transportation Systems
SWBLI	Shock Wave/Boundary Layer Interaction
SWERVE	Sandia Winged Energized Reentry Vehicle Experiment
SWTBLI	Shock Wave/Turbluent Boundary Layer Interaction
TAV	Trans-Atmospheric Vehicle
TBCC	Turbine-Based Combined-Cycle
TDA	Technology Development Approach
TPS	Thermal Protection System

TSTO	Two-Stage-to-Orbit
UK	United Kingdom
USAF	US Air Force
UTSI	University of Tennessee Space Institute
WR	Waverider
Zr	Zirconium

Chapter 1

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), a play on the National Aerospace Initiative (NAI) Technology Development Approach (TDA) GOTChA (Goals, Objectives, Technical Challenges, and Approaches; Richman et al. 2005), with the hope of identifying and helping to overcome the critical barriers that confront engineers in both industry and academe in the field of hypersonic technology (HT) . Given the vast collection of HT 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.

Generally, the Mach number range of five and above describes the hypersonic regime. However, some extreme phenomena can begin to appear at lower Mach numbers of three and four. Thus, an excellent definition for hypersonic flows illustrates the emergence and dominance of certain physical characteristics which do not appear or are not as relevant at lower speeds. The hypersonic regime introduces a number of flow attributes such as: **extremely high turbulence, pressure, temperature, density, vorticity, and energy**, **thin shock layers**, **viscous interactions**, **entropy layers**, **changes in vehicle stability and control**; and **physical-chemical gas changes** such as **ionization, dissociation, equilibrium effects, and other molecular phenomena**. In addition, the hypersonic designer must remain **aware of the other flow regimes** since a hypersonic vehicle will have to **transition from rest to the designed hypersonic flight Mach number** and **transition throughout the various characteristics of the atmosphere**.

The large driving force behind hypersonic research emerges from the need to reduce cost to space and faster global transportation for both military and civilian purposes. Introducing an air-breathing propulsion stage to space transportation is hoped to eventually reduce launch costs while reducing, from a military standpoint, global strike and surveillance times.

Today the hypersonic sector has reached a new age. Figure 1.1 shows how the area of hypersonics has blended space and air studies that Hallion (2005) calls "*genuine aerospace*." This is an excellent portrait of how the hypersonic programs, research, and goals have varied (from space ballistics to hypersonic planes) while remaining intimately connected. In this diagram, various programs are displayed according to their design realm with pure rocket, aeronautic, and hypersonic projects. Hallion gives

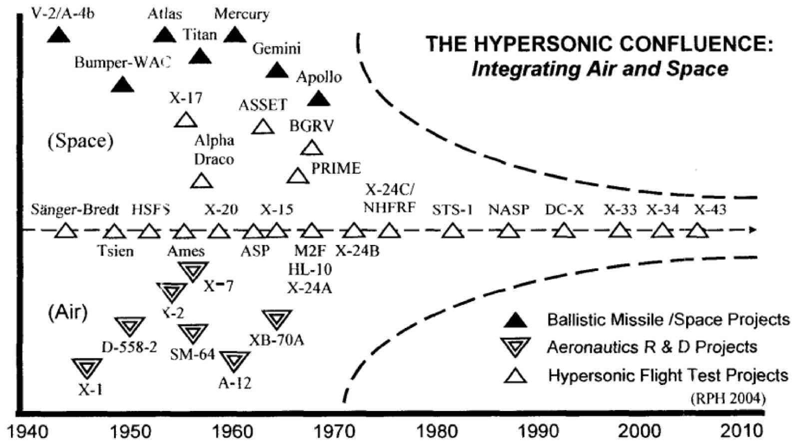

Figure 1.1: The hypersonic confluence (Hallion 2005).

a good description of how the hypersonic flight realm traverses a complex environment as,

> "*ranging from high in the stratosphere to operations into and cross the demarcation of spaceflight, where the laws of aerodynamics cease to apply and the laws of ballistic, Keplerian trajectories, and Hohmann transfers take over.*"

This next sentence by Hallion beautifully describes the hypersonic research area,

> "*Hypersonics thus blends the twin stream of space and aeronautics research into a **confluence, the hypersonic revolution*** [emphasis added]."

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 and Modeling.
   (a) Flight Testing.
   (b) Ground Testing.
   (c) Computational Testing & Numerical Modeling.
   (d) Analytical Modeling.
5. Education.

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 some extent, the Space Shuttle program, which has only provided a partial solution to the long-standing SSTO objective (Ferri 1973; Freeman Jr. et al. 1995; Whitmore and Dunbar 2003; Hallion 2005). 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 (Tang and Chase 2005), that the most conspicuous GOTCHA issues will be mitigated, one-by-one, to the extent of promoting the development of a true hypersonic workhorse. Some of the issues remain as relevant today as they were nearly five decades ago, and so an effort is exerted here to present the material cohesively to the extent that the key connections and common overlap areas among various categories are illuminated.

Chapter 2

Aerodynamics

Although much has been accomplished to date, the complexity of hypersonic vehicles (HV) 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 taken into account. In this category, a number of parameters or hypersonic technological areas (HypTAs) must be studied due to their impact on aerodynamic performance. These include, but are not limited to those shown in the following list.

Aerodynamic GOTCHAs & HypTAs

- Fluid mechanics/dynamics
  - Inviscid effects
  - Viscous effects
    - Boundary layers
    - Laminar/Transition/Turbulence
  - Flow regimes
    - Subsonic/Transonic
    - Supersonic/Hypersonic
  - Compressibility effects
  - Heat transfer effects
    - Conduction/Convection
    - Radiation
  - Thermodynamics
    - Low density
    - Non-equilibrium
    - Combustion and reactions (Chemistry)
- Lift to drag ratios (L/D)
  - Low - blunt bodies/ballistics
  - High - gliders/lifting bodies/waveriders
- Shape/geometry of the vehicle
  - Conical
  - Two-dimensional (2-D)/rectangular
  - Ellipitcal
  - Axisymmetric/Semi-axisymmetric
- Propulsion system integration

Continued on the next page...

Aerodynamic GOTCHAs & HypTAs (continued)

Aerodynamic loads
Volumetric efficiency
Airframe integration
Structural and thermal loads
Vibrations/Flutter

Materials
  Lighter, stronger, cheaper
  Thermal protection

Flowpath geometry heavily based on aerodynamic shape
  Inlet/Intake
  Isolator
  Ellipitcal
  Combustor
  Nozzle

Mission requirements
  Hypersonic missile
  Hypersonic bomber
  Hypersonic transport
  Hypersonic space access

Flight trajectories   Ballistic
  Boost glide
  Skip
  Orbital insertion

SSTOs vs TSTOs (Two-Stage-to-Orbit)
Reusable Launch Vehicle (RLVs) vs Expendable Launch Vehicles (ELVs)

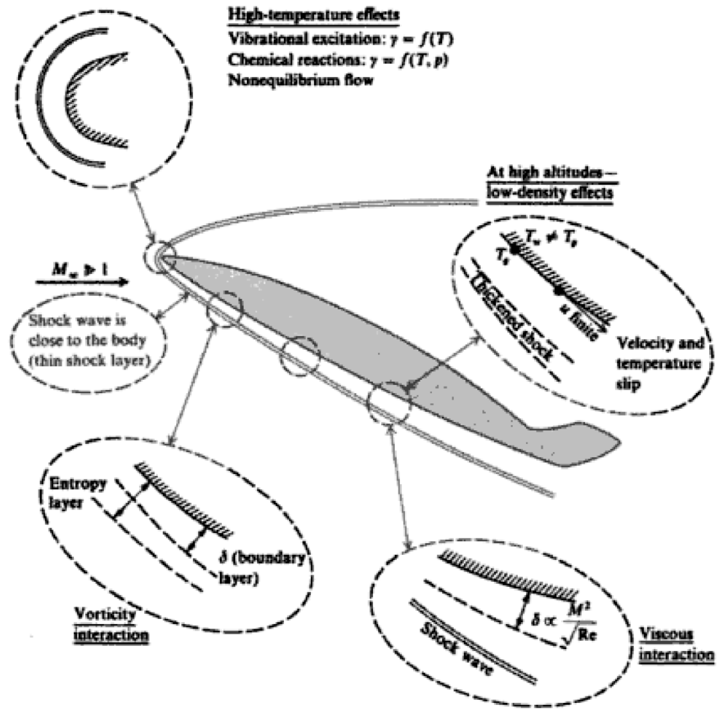

Figure 2.1: Hypersonic aerodynamic effects on the HV (Anderson 2000, 2006).

Designing a HV often appears daunting and difficult. Numerous attempts have been made in the past with many successes and failures. Only a few programs ever became operational vehicles. Two hurdles which essentially link into a co-hurdle are the extreme hypersonic flight conditions and hypersonic mission objectives. For example, mission objectives include space access and global transportation. Space access not only requires the attainment of very high vehicle velocities but also must traverse the varying atmospheric layers to reach an orbital path. Global access missions also benefit from hypersonic speeds but do not require the large orbital altitudes. Therefore, HV systems provide the desired speeds but demand complexity. Figure 2.1 demonstrates possible aerodynamic effects in hypersonic flight as previously mentioned.

Figure 2.2 from Bowcutt (2003) and Bertin and Cummings (2003; 2003) illustrates the complexity when dealing with HV aerodynamics. A conglomeration of figures and tables appear in Figure 2.2 delineating the types of HV at mission specific altitudes

Speed Regimes	Flow Properties
Subsonic ($M < 0.8$)	Ideal Gas
Transonic ($0.8 < M < 1.2$)	Weak Shock Waves Ideal Gas
Supersonic ($1.2 < M < 5.0$)	Shock Waves Calorically Imperfect Gas
Hypersonic ($M > 5.0$)	Thin, Hot Shock Layers Thermally Imperfect Gas Chemically Reacting Flow

Flow Regimes (Knudsen Number, K_n)

- Continuum Flow ($\sqrt{Re}/M>100$ and $K_n<0.01$)
- Slip Flow ($1<\sqrt{Re}/M<100$ and $0.01<K_n<0.1$)
- Transitional Flow ($0.1<\sqrt{Re}/M<1$ and $1<K_n<10$)
- Free Molecular Flow ($\sqrt{Re}/M<0.1$ and $K_n>10$)

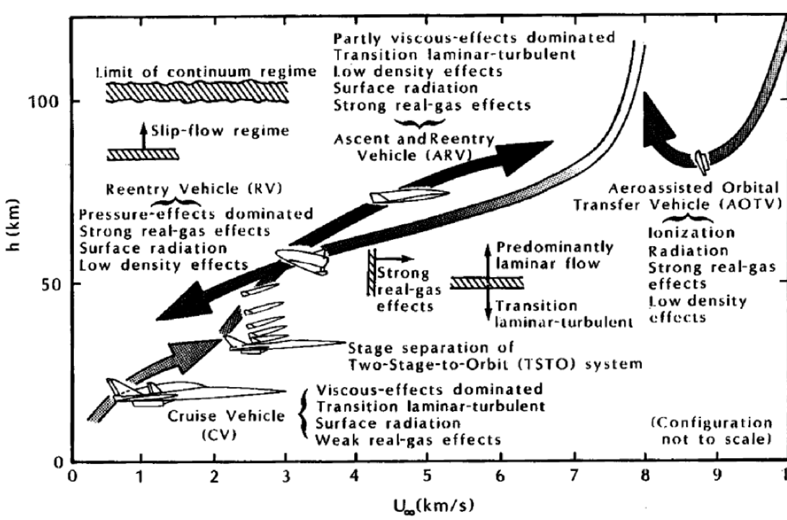

Figure 2.2: Complexity of the aerodynamics associated with the HV (Bertin and Cummings 2003; Bowcutt 2003).

and speeds and the various aerodynamic phenomena that occur at the corresponding altitude and flight speeds. Figure 2.2 also displays the various flight speed regimes and some analogous flow phenomenon that occur in these regimes. Finally, the flow regimes involving the range of Knudsen numbers shows how molecular effects emerge in aerodynamic phenomena.

Much work has been accomplished in hypersonic aerodynamics. A large body of test data has been collected and compiled by successful programs such as the X-15 and Space Shuttle as mentioned by Launius (2003a). Due to the increasing flight speeds created by missiles and spacecraft, the fifties and sixties saw a large research effort directed to hypersonic aerodynamics (Clarke 1991); Louie and Ockendon (1991) even call this era the golden age of theoretical hypersonic flow research. With the hypersonic flight regime as a new area of aerodynamic research, scientists turned their attention to the additional complexities of the flow through the use of fundamental physic principles such as the "*kinetic theory of gases, thermodynamics and statistical thermodynamics of gas mixtures, radiation, and the kinetics of chemical and internal-molecular energy change* (Clarke 1991)." After this boom in hypersonic research a lull dominated until a rekindling of interest in the eighties and nineties due to projects such as the National Aerospace Plane (NASP), which once again needed to identify and conquer hypersonic flow/flight problems (Cheng 1993). Thus, even though much has been accomplished in previous projects and programs, the hypersonic aerodynamics area still has posed a problem due to the complexity of HVs. Ferri (1959) compares the hypersonic aerodynamics to the classical chicken and egg problem. He says,

> "*The field of hypersonic aerodynamics is dominated by two conflicting characteristics: The phenomena to be investigated are much more complex and less amenable to simplified schemes of analysis and to experimental investigation than other fields of fluid dynamics while at the same time*

much more precise detailed knowledge of the flow field is required in order to obtain the information necessary for practical applications."

Bletzinger et al (Bletzinger et al. 2005) describe hypersonic flight as being substantially difficult. Scaling laws related to required energy and thermal loading present hardship since nonlinearities appear in consensus with the Mach number. For example, the aerodynamic drag correlates with the increase of ρM^2 and aerodynamic heating with ρM^3. Bletzinger et al (Bletzinger et al. 2005) also note that the speed of sound remains closely the same until the edge of space. For every 50 km in altitude, the density decreases on an order of 10^3. Thus, the Mach number range for atmospheric flight remains around a Mach number of 10. Higher Mach numbers require vehicles to fly at higher altitudes. When considering the range and limits of hypersonic flight the space access corridor graph demonstrates possible HV trajectories as shown in Figure 2.3. The area marked with hatch designates the limit of aerodynamic lift. The lower limits determine the equilibrium skin temperature and maximum possible loading of the HV.

Much of the data on hypersonic aerodynamics may be derived from keystone projects such as the X-15, the Space Shuttle program (Launius 2003a) and even the man-in-the-can Apollo-Gemini-Mercury programs. Furthermore, beginning in the eighties, several studies on waverider (WR) research have been conducted by the University of Maryland group including Capriotti et al. (1987), Corda and Anderson (1988), Anderson et al. (1991a), Anderson et al. (1991b), O'Neill and Lewis (1992), Anderson and Lewis (1993), Burnett and Lewis (1993), Lewis and Gupta (1995), Gillum and Lewis (1996), McRonald et al. (1999), Lewis et al. (1998), Santos and Lewis (2002), Lewis (2003), and Chauffour and Lewis (2004), to name a few. 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.

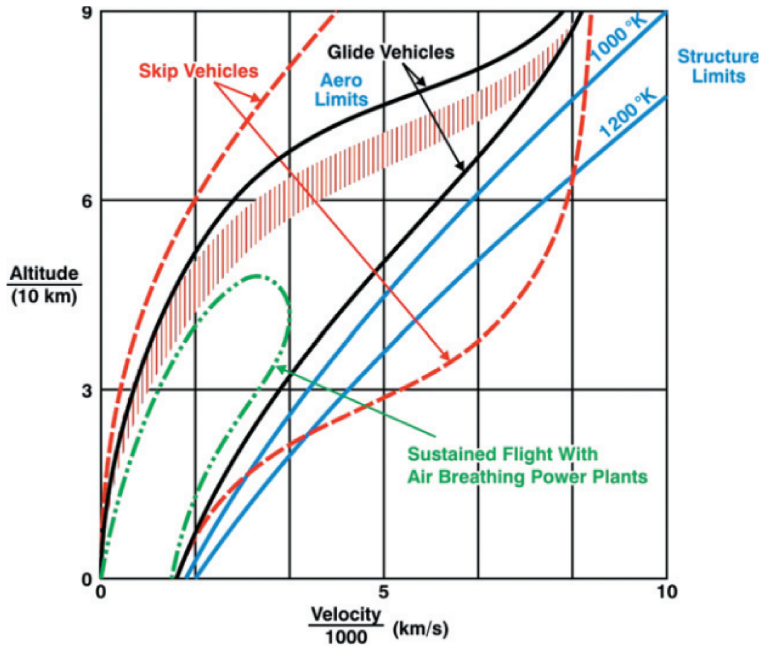

Figure 2.3: Space access and flight trajectories for HVs (Bletzinger et al. 2005).

- The limited aerothermodynamic flight test database.
- The stringent access restrictions to existing databases.
- The limited verification efforts of computational fluid dynamics (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 the collection of usable flight data from a controllable reentry vehicle as seen in Figure 2.4. The second of the SHEFEX experiments plans to examine key technologies such as a facetted ceramic thermal protection system, ceramic based aerodynamic control elements (canards), mechanical actuators and an automatic flight control unit. Some secondary experiments include an actively cooled thermal protection element, advanced sensor equipment for temperature, heat flux and pressure, and high temperature antenna inserts.

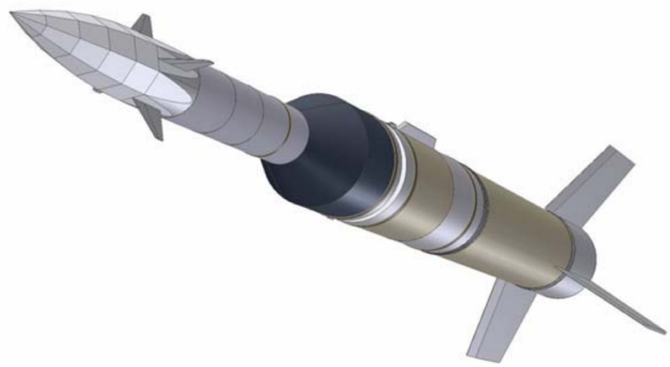

Figure 2.4: SHEFEX II staged flight experiment concept (Weihs et al. 2008).

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 (2007; 2008) have reported on boundary layer transitioning experiments that have been conducted under the auspices of such programs as the Slender Hypersonic Aerothermodynamic Research Program (SHARP) (Hallion 2005). 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.

Figure 2.5: The SHARP-B2 flight experiment (Kuntz and Potter 2008).

- 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 (2007; 2008) for a excellent report on the SHARP-B2 flight experiment illustrated in Figure 2.5. 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, elevons, tailerons, flaperons, etc. The technological factors associated with these control surfaces include:

- 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).

Chapter 3

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 HV 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 those in the following list.

Propulsion GOTCHAs & HypTAs

- Materials
  - Lighter
  - Stronger
  - Cheaper
  - Thermal protection
- Engine components
  - Bearings
  - Seals
  - Turbomachinery - compressor and turbine blades
- Air-breathing engines (ABE)
  - Dual-mode ramjet/scramjets
  - High speed turbines
  - No operational HV (except missiles) despite the appreciaple work done on ramjets/scramjets
  - Encouraged by success of NASA's X-43 and encouraged by current programs such as X-51, FALCON, HyCAUSE, and many others
  - Transatmospheric vehicles (TAV)
  - Internal flowfield modeling
- Rocket propulsion
  - Improvements to solids, liquids, hybrids used in RBCC or booster stages
    - Internal flowfield modeling
    - Combustion instability
  - Booster stages - make more efficient and cost effective
    - TSTO system
    - Flight testing

Continued on the next page. . .

Propulsion GOTCHAs & HypTAs (continued)

Combined cycles
Turbine based combined cycles (TBCC)
Transitioning and integration
Variable geometry
High speed turbines/turbojets
Thermal management
Materials
Improve engine components
Rocket based combined cycles (RBCC)
Linear aerospike rockets and nozzles
Rocket-scramjet integration
Fuels and combustion
Hydrogen
Hydrocarbon
Alternate fuels
Mixed fuels
Environmentally friendly - exhaust and noise
Plasma research to recoup energy/power in flight from ionization and dissociation in internal flowfield through flowpath
Radical farming
Shock wave interactions
Airframe-propulsion integration
Engine Performance
Engine flowpaths
Inlet/Intake
Isolator

Continued on the next page...

Propulsion GOTCHAs & HypTAs (continued)

Various geometrical shapes
Combustor
Nozzle
Acoustics
Structure
Drag/Viscous effects
Heat/thermal management
Mission requirements
Hypersonic missile
Hypersonic bomber
Hypersonic transport
Hypersonic space access
Flight trajectories
Ballistic
Boost glide
Skip
Orbital insertion
SSTO vs TSTO

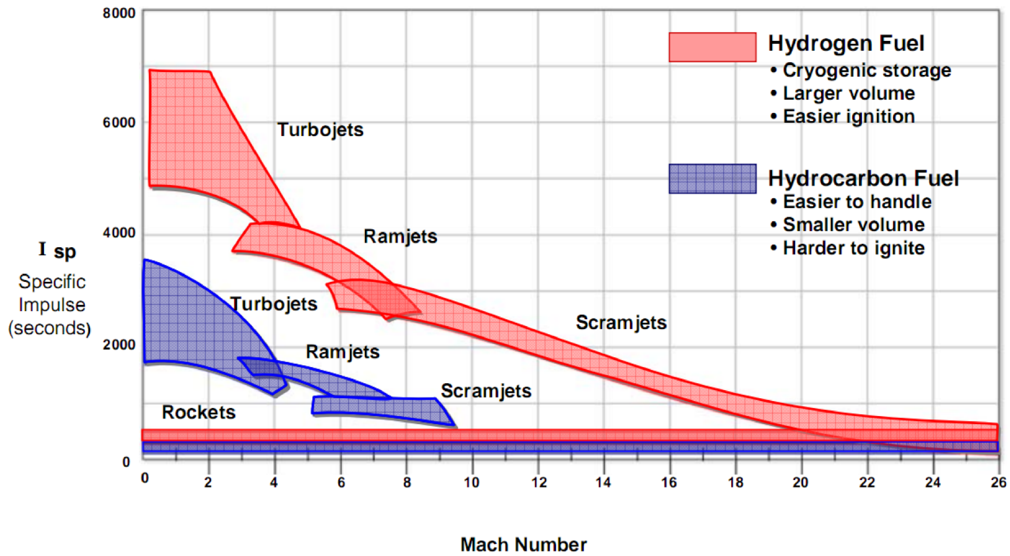

Figure 3.1: Comparison of engine and fuel performance for HypPS (Tang and Chase 2008). Also see (Kors 1988; Cheng 1989; Townend 1991; Bertin 1994; Blankson 1994; Orton et al. 1997; Carter II et al. 1998a,b; Daines and Segal 1998; Anderson et al. 2000; Cockrell Jr. et al. 2002; Bertin and Cummings 2003; Fry 2004; Heppenheimer 2006).

As mentioned before, designing a HV may be viewed as a daunting endeavor, especially when considering the numerous attempts in the past that have led to a number of successes and failures but only a few operational vehicles. Similar to hypersonic aerodynamics, two compounding hurdles that plague HV technology (HVT) are the extreme hypersonic flight conditions and the strict mission objectives. Mission objectives can include space access and global transportation that demand 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 3.1 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. 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 HVs are hoping to avoid, still plague these systems. Some of these issues will be recapitulated in the context of scramjets, TBCC, and RBCC engines.

3.1 Scramjets

Since the fifties and sixties and even back to the late forties (Anderson et al. 2000) researchers have been trying to create an engine that runs efficiently for larger Mach numbers than ramjet engines. Ramjets become less efficient at higher Mach numbers due to the ramjet's subsonic combustion. In fact, the natural progression forces the switch from subsonic to supersonic combustion due to the increase in flight speed and in turn the increase in stagnation pressure and temperature within the engine for reasonable mass (Townend 1999). Thus, combustion transitions take place in supersonic flowfields which are known as scramjet engines. Scramjets potentially hold the capability to realize the objective of a long range airliner at hypersonic speeds and, as is discussed later, complement the traditional rocket in space launchers. Waltrup et al (1996; 2002) contend that supersonic combustion ramjets operate in the Mach 4+ range and cannot operate at subsonic speeds. In fact, higher speeds on orbital levels

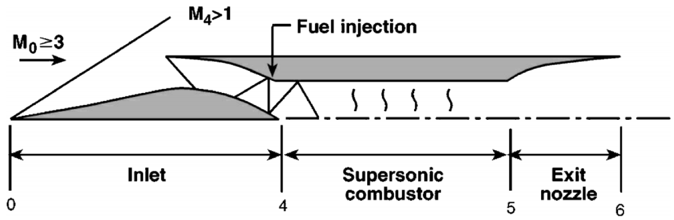

Figure 3.2: Scramjet illustration (Fry 2004).

(Mach 26) theoretically prove possible. However, Waltrup et al provide an upper limit for practical purposes of around Mach 20. Using hydrogen fuel and variable geometry, the scramjet potentially operates from $M_0 = 4$ to $M_0 = 15+$.

Waltrup et al (1996; 2002) describe the process for the scramjet as beginning with supersonic or hypersonic free stream air entering the inlet. In the inlet, the air flow diffuses to lower speeds yet remains supersonic. Liquid or gaseous fuel enters from the wall through holes, slots, pylons, or by other means and/or by injectors located within the flowpath through struts, tubs, pylons, or other alternative means. The addition of heat, a diverging combustor, and no nozzle throat creates a shock train from the combustor entrance back into the inlet unlike the terminal normal shocks in ramjets. The strength of the shock train ranges between a normal shock and no shock and relies on flight conditions, the inlet compression or exit Mach number, M_4, overall engine fuel-air ratios, ER_0, and combustor area ratios, A_5/A_4.

Before the X-43, the SR-71 held the record for fastest air-breathing propulsion (ABP) at just above Mach 3, and the X-15 carried the title for fastest aircraft type flight at just under Mach 7. Other tests where the engine was simply mounted to the nose or forefront of the boosting system (instead of being integrated into the aerodynamic body) include Russia's Central Institute Aviation Motors (CIAM) scramjet tested on the Kholod Hypersonic Flying Laboratory (HFL) (Voland et al. 1999; Fry 2004) and the Freeflight Atmospheric Scramjet Test Technique (FASST, not to be confused with another program with the same acronym known as the Flexible Aerospace Solution for Transformation; Blocker et al. 2003). Stalker et al (2005) discuss how five to six decades ago AB hypersonic flight seemed to be on the edge of everyday reality. Supersonic missiles with ramjet propulsion became utilized during the fifties and sixties, and the next logical step was for supersonic combustion to propel missiles to hypersonic speeds. The trends would then continue in which the hypersonic missiles provides hypersonic data, produces piloted HVs, and then provides propulsion for the eventual air-breathing orbital spaceplane. Stalker et al (2005) additionally points out that researchers were not overly excited as this was just the expected turn of events. However, many stumbling blocks have held back progress to reach HAB spaceplanes as researchers and designers are still struggling to obtain hypersonic data. The steps may still pan out in the same predicted way but at a much longer timescale. The hypersonic ABP (HABP) evolution may be disappointing even to those unfamiliar with the subject. The HABP evolution reminds us of the adage, "Where's my flying car?"

Heitmeir et al (1996) also state that ABP was deemed favorable at the beginning of spaceflight exploration. Combined with reusable vehicles, the economic and operational pros make ABP auspicious. However, Heitmeir et al also highlight that a primary agent for unsuccessful endeavors is due to lacking technology. Even at the time, 1996, Heitmeir et al conclude that many technologies are still insufficient. At that time and even today in 2012, space transportation systems (STSs) rely on ELVs or partially RLVs. Rocket systems provide all thrust to propel the vehicle. The cost to operate current systems causes the search for reducing cost in STSs which point to SSTO or TSTO AB vehicles.

Townend (1991) points out how ABP spans the myriad of flight regimes usually operating at non-optimized conditions. A HABV travels through a large range of speeds which makes engine efficiency difficult much like the variable nozzle efficiency in rocket systems over a range of atmospheric pressures.

An excellent graph depicting the viable range of flight parameters for AB engines shows the Mach number vs. altitude for constant lines of pressure, temperature, and dynamic pressure as illustrated in Figure 3.3. Fry continues by observing that the higher the speed, the more AB engines require special attention in design since flight

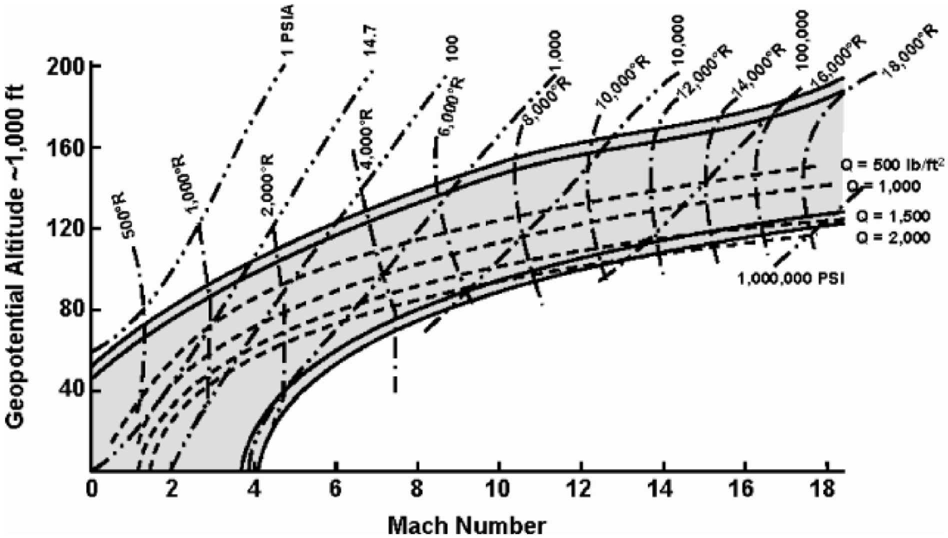

Figure 3.3: AB flight corridor (Fry 2004).

characteristics such as internal duct pressure, skin temperature, and dynamic pressure loading become increasingly complex. The extreme boundaries limit the vehicles in the AB corridor and delineates perimeters for operation at ram compression; this solicits higher dynamic pressure than a rocket engine for adequate chamber pressures (1/2+ atm) to ensure efficient combustion and thrust. The AB corridor encompasses an upper limit due to inefficient combustion and strict fuel/air ratio ranges. A lower limit provides the severe spectrum of high skin temperature and pressure loading where materials begin to fail. For high Mach numbers, intense dissociation results in NE flow and causes sever effects on the compression ramp flow, enormous LE heating rate, alterations to the inlet flow, an impact on fuel injection and fuel-air mixing, effects on combustion chemistry, changes within the nozzle flow, and an influencing factor on performance. Finally, in the low Mach number regime the compression ratios decrease where compression increases occur mechanically and the ramjet no longer sustains enough pressure to function efficiently.

Moses et al (1999) explain that a large focus of hypersonic technology research lies in airbreathing engines. In their views, the focus lies in ramjets and, especially, scramjets. However, improving turbine and/or turbojet engines will be beneficial to the hypersonic propulsion community due to the use of the turbojet in the combined cycle engine. Bushnell (2002) projects that one of the advantages of AB engines will be to double the in-atmospheric cruise range for an air-launched device. A major HypTA focus area that Bushnell foresees involves ABP systems. AB systems used for space access allow for space war battles between forces enabling vehicles to cruise at hypersonic speeds, to utilize large cross range maneuvers, provide many options for launch, orbital inclination change, and the capability to orbit, deorbit, and reorbit. Olds (1994) states that airbreathing SSTOs contain advantages such as incorporating low overall gross weights, high average I_{sp}, several abort options, mission flexibility including cruise, and aircraft-like characteristics. Fry (2004) adds to the list of pros for using AB engines in lieu of rockets, factors such as not needing to carry oxidizers, high engine efficiencies, thrust throttling for better cruise and acceleration, better control over flight path changes, and reusability. Fry also notes more efficient mission times (turnaround times for space access) and cost savings between 10 to 100 times per pound of payload.

Next, we overview the aerothermodynamic issues connected with AB engines (scramjets) as noted by Park (1990). These may be summarized in:

- Problems surrounding inlet fluid dynamics and thermodynamics such as how molecular excitation and dissociation affects the airflow.
- Boundary layer displacement thickness effects and inlet performance caused by thermochemical phenomena occurring inside the BL.
- The thermodynamic state of the gas in the nozzle.

Additionally, one may enumerate several deficiencies and hurdles of the scramjet engine according to Curran (2001); these are:

- Energy limitations of fuels.
- Inefficient propulsion for orbital speeds.

- Low component efficiencies.
- Understanding the scramjet process.
- Inconsistent funding.

Although Curran's paper was written in 2001 there have been a few additional scramjet flight test, the X-43A (Tang and Chase 2008), HyShot (Smart et al. 2006; Steelant et al. 2006), the Hypersonic Collaborative Australia/United States Experiment (HyCAUSE) (Walker et al. 2008a), and the X-51A (X-5 2010; Lewis 2010; Sec 2011). While researchers continue to overcome obstacles, much work lies ahead. These and additional scramjet technologies need to mature before deployment in HVs. Other noteworthy challenges include:

- Axisymmetric flowpaths instead of traditional 2-D designs.
- Flight test and flight test data.
- Adequate ground test facilities.
- CFD and analytical modeling.
- Effective use of materials for strength, weight reduction, and thermal management throughout the engine.

In the ramjet survey by Fry (2004) the top ten influential advances in ramjet technology areas are reproduced in the following list.

Top 10 advances in ramjet propulsion technology

1) High speed aerodynamics analysis CFD code analysis and validation methodologies (external and internal flow) Improved design tools and techniques
2) Air induction system technology Fixed and variable geometry Subsonic, internally/externally ducted supersonic and dual-flowpath designs Mixed cycle flowpath development Improved design tools/integration with the airframe Improved materials, especially in the cowl region
3) Combustor technology Improved design tools and techniques, such as mapping fuel and heat-transfer distributions Improved insulators (ablative, nonablative) Advanced structural materials Combustion ignition, piloting and flameholding, and mixing
4) Ramjet/scramjet fuels Higher-energy liquid and solid fuels Low-temperature liquid fuels Endothermic fuels
5) Fuel management systems Liquid fuel injection and mixing Improved injectors; wider range of operation, tailoring of atomization, and spray distribution Solid ramjet and ducted rocket fuel grain design Solid ducted rocket fuel value design **Continued on the next page**...

Top 10 advances in ramjet propulsion technology (continued)

Variable-geometry injection systems, especially for the ducted rocket (DR)
Improved feed systems, including turbopumps
Improved feedback control systems
6) Propulsion/airframe integration, materials, and thermal management
CFD code analysis and validation methodologies
High-temperature metals and alloys
High-temperature structures
Passive and active cooling
Carbon-carbon and ceramic metal matrix composites
7) Solid propellant booster technology
Tandem boosters
Integral rocket-ramjet boosters
Self-boosted ramjet (mixed cycle RBCC, TBCC, etc.)
8) Ejectable and nonejectable component technology
Inlet and port covers
Fixed- and variable-geometry nozzle technology
9) Thermochemical modeling and simulation development
Thermochemical tables
Ramjet cycle analysis and performance modeling
10) Ground-test methodologies
Direct-connect
Semifreejet and freejet
Airflow quality improvements
Instrumentation advances
Computational tools and flight-test correlation

Efforts to promote scramjet research in Australia have been ongoing since the nineties (Paull 1993; Stalker et al. 1994; Paull et al. 1995; Paull and Stalker 1998; Paull 1999). This program later on developed into the HyCAUSE project where much work is being done on scramjet engines between the US and Australia (Stewart et al. 2005; Walker et al. 2005, 2008a).

Other programs advancing scramjet technology are the X-51A (Hank et al. 2008), the Forced Application and Launch from CONUS (Continental US) or FALCON program (Walker and Rodgers 2005; Walker et al. 2008b,c), the Hy-V (pronounced "high five") (Goyne et al. 2006; Craig 2007; Goyne and Cresci 2008; Goyne et al. 2009), the Hypersonic International Flight Research Experimentation (HIFiRE) (Kimmel et al. 2007; Dolvin 2008; Kimmel 2008; Adamczak et al. 2009; Jackson et al. 2009; Smart and Suraweera 2009), and the HyShot (Hass et al. 2005; Smart et al. 2006). The X-51A program is part of a smaller step approach to developing scramjet technology. The scramjet engine under research is a derivative of the Hypersonic Technology (HyTech) program, a 2-D design. Plans of the X-51A successes are to one day power a cruise missile (small missile) to hypersonic speeds. Further development from the X-51A has the potential to easily scale to medium applications such as large missiles, reconnaissance or strike aircraft, and small launch systems. The FALCON program uses a different approach for a different mission. A TBCC propulsion system uses a combination of turbojets, ramjets, and scramjets to one day propel a global reach vehicle. Research efforts from the HyCAUSE program directly benefit the FALCON program due to the use of similar scramjet flowpath and engine technology. The Hy-V program focuses on developing and flight testing a dual-mode scramjet (DMSJ) which is also called a dual-mode ramjet (DMRJ) and a Dual Combustor Ramjet (DCR). Instead of pursuing a technology demonstration like the X-51, the Hy-V team aims to collect data from the three testing areas of CFD, ground, and flight for the purpose of validation/verification and to advance predictive methods.

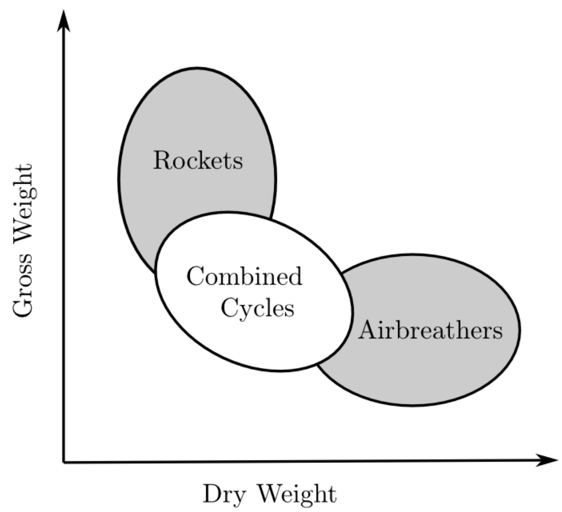

Figure 3.4: Graph illustrating various propulsion systems and weight (Olds 1994).

3.2 Rocket Based Combined Cycle (RBCC)

Combined cycle engines (CCE) or multi-cycle engines (MCE) may be the best of low speed to high speed propulsion systems. CCEs and MCEs also lead the pack for the best viable option for future hypersonic cruise and space access vehicles. As mentioned by Olds (1994) and illuminated by Figure 3.4, multi-cycle and combined-cycle engines provide a combination of advantages from each separate propulsion system. Combined systems meet in the middle of the propulsion spectrum by balancing between low dry and low gross weights.

It may be useful to note that a difference exists between multi-cycle and combined cycle engines. One the one hand, a *multi-cycle* system employs *individual* systems for every operating mode such as a turbojet *and* a rocket engine that can either work in *parallel* or *separately*. One the other hand, a *combined cycle* engine incorporates operation modes into a *single* system so that efficiency is higher and weight is lower. Fry (2004) breaks down engine types in an alternate means. He defines *combined* cycle engines as systems that consist of a *single* flowpath and integrated engines equipped for operating in two or more modes. In constrast, *combination* cycle systems *bifurcate the flowpath* for two or more modus operandi.

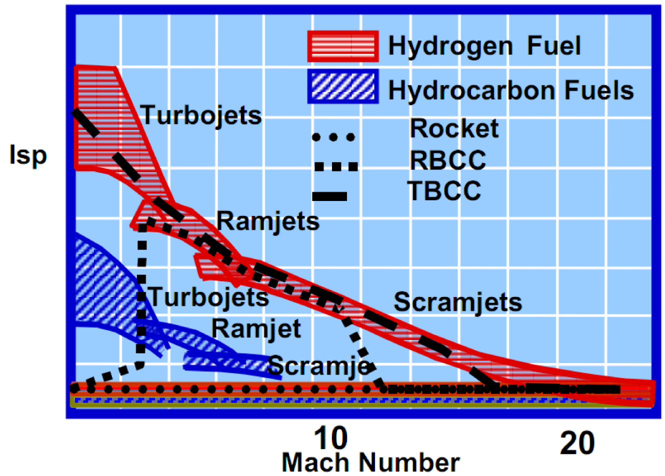

Figure 3.5: Specific impulse and Mach number graph highlighting RBCC and TBCC possible ranges (Cockrell Jr. et al. 2002).

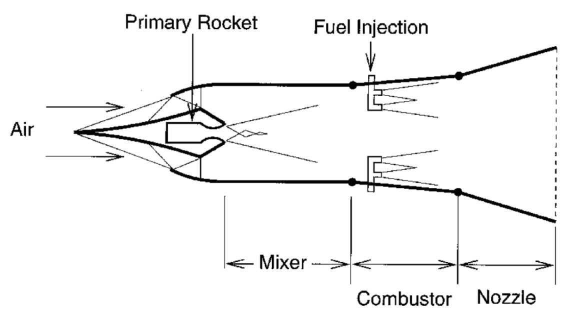

Figure 3.6: Diagram of a type of RBCC (Tang and Chase 2008). Also see (Daines and Segal 1998).

Time and time again, the literature produces the infamous graph depicting specific impulse over Mach number flight speeds and compares different propulsion systems as shown in Figure 3.1. Figure 3.5 essentially depicts the same graph except for ranges of RBCCs and TBBCs that are indicated by dotted and dashed lines to emphasize the importance of combined cycle propulsion.

One type of combined cycle utilizes a rocket-scramjet propulsion system or the RBCC. Typically the design consists of a single flowpath with a rocket built into a DMRJ engine flowpath located at the aft-end of the isolator and the fore-end of the combustor (see Figure 3.6). 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 over each individual mode taken separately (rocket only or scramjet only)
- The capability of the rocket engines to take advantage of the flowpath structure, namely the large scramjet exit nozzle (during an exoatmospheric climb this increases the rocket only mode specific impulse)
- System takes advantage of high impulse AB portion instead of traditional pure multiple stage rocket design

However, many challenges remain and stand in the way of creating an efficient RBCC vehicle. Specifically, for the RBCC propulsion system the hurdles consist of:

- Increased drag with the larger rockets acting as pilot structures within the flowpath.
- Mass fractions/payload issues if AB portion is carried to orbit (solution: lighter materials, reduce complexity, TSTO).
- Optimal Mach number operation modes (i.e. when to fire combined rocket and scramjet mode; also if multiple stages are used then how large should the booster be).
- Reentry heating effects on AB structure (possible solution is to invert on reentry to where the AB portion is on top and not directly exposed to the high heating environment).

Other gaps are the same as the scramjet or HV as a whole:

- Airframe/structure/engine heating involves multiple materials with various thermal expansion rates and also various heating loads; will need to design with space in between joints and structures while minimizing the area where heat leakage can occur (overall will need complex thermal protection system (TPS) or super material)
- Need for individual improved components such as turbomachinery:
    - Need to handle larger range of flowrates, temperatures, and pressures.
    - Long feed lines may produce transient effects between operating modes.
    - High performance bearings and seals.
- Overall thermal management at high Mach number (~ 10).
- Structural issues.
    - Thin walled flowpaths.
    - Inlet types such as the sugar scoop (this type breaks the hoop stress which then may need additional support such as ribs, however, this in turn adds weight); the same applies to the nozzle frame.
- If, for instance, a design with a linear plug nozzle is used at the rear of the scramjet then additional support is needed to compensate for additional thrust vectors.
- Need for possible bleed injection to improve rocket only mode.
- Ground test facilities are limited to smaller scales.

3.3 Turbine Based Combined Cycle (TBCC)

Innovative yet complex, the TBCC takes advantage of a multi-engine cycle in order to transition from an airplane-like take off to high altitude and possibly space. Currently, the joint initiative by the Defense Advanced Research Projects Agency (DARPA) and the United States Air Force (USAF) aims to take advantage of a TBCC propulsion system for the Task 2 of the FALCON program (Walker and Rodgers 2005). The FALCON's Task 2 involves the Hypersonic Technology Vehicle (HTV) which has the goal of overcoming hypersonic technology issues. The program task plans to reach an eventual target of a reusable Hypersonic Cruise Vehicle (HCV) designed by Lockheed Martin Advanced Development Projects. A set of TBCC engines power the vehicle in the conceptual stage. The flowpath constitutes an inward-turning inlet connected to a dual mode ramjet (see Figure 3.7). Using the dual TBCC engines allows designers optimal space for the payload bay, landing gear, and other major subsystems. Another benefit stems from the independent aerodynamic and propulsion optimization. In 2005, propulsion technologies remains on the top of the list for enabling hypersonic technologies for the FALCON HCV. Critical areas of research include:

- Efficient inward turning inlet from takeoff to cruise of Mach 10.
- Transitioning from the turbojet to the ramjet/scramjet.
- Thermal and operating designs of the scramjet engine need work since the overall design is much different than the NASP and NASA's 2-D X-43A engine.

Additional generic hurdles are analogous to those associated with scramjet engines:

- Flight test and flight test data.
- Adequate ground test facilities.
- CFD and analytical modeling.

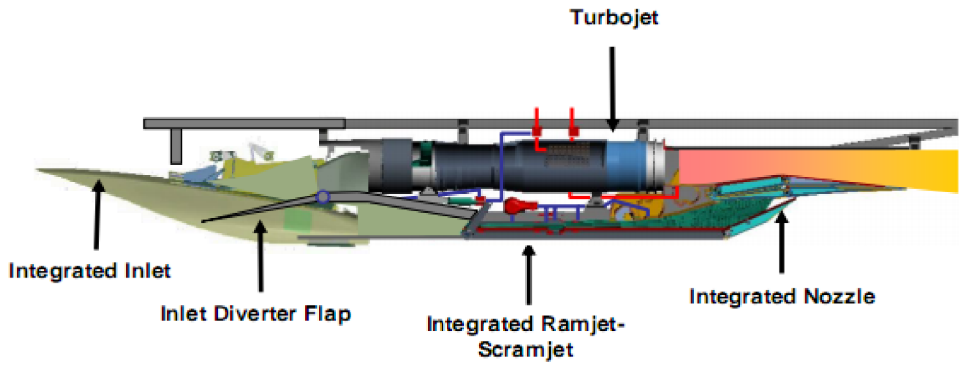

Figure 3.7: The concept of a TBCC from FALCON (Tang and Chase 2008).

- Effective use of materials for strength, weight reduction, and thermal management throughout the engine.

Chapter 4

Materials & 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 is desirable, and this poses a unique problem. Recalling Launius (2003a), in order to compensate for payload weight designers prefer lighter materials, but these may not be strong enough to withstand the operational thrust, moments, and pressure loads. Thermal protection adds another complication as HVs often require special materials, such as heat resistant paints, to assist with thermal shielding. These "add ons" inevitably result in increased vehicle weight. Striking the right balance between strength, weight, and thermal protection must be carefully achieved. The following list summarizes the specific properties and needs associated with materials and structures.

Thornton (1990; 1992) notes that ***severe*** challenges cause difficulties for designers of hypersonic vehicles. Material selection and structure configurations needed to compensate for the aerothermal loads comprise the two leading decisions that designers face. Forces encountered in high speed flight include pressure, skin friction or shearing stresses, and aerodynamic heating. Of course, pressure and skin friction participate in lift and drag coefficients whereas aerodynamic heating influences the

HypTAs and GOTCHAs for materials and structures.

Lighter
Stronger
Thermal protection systems (TPS)
Cheaper - manufacturability, availability
Synthetic - lab grown, lab discoveries
Environmentally friendly
Bioengineering inspired materials that can withstand heat, self-repair, etc.
Morphing shapes to accommodate aerodynamic performance and variable inlet geometries
Manufacturing hypersonic vehicle and parts/components

structure of the craft. Aerothermal heating raises temperatures which in turn affects elastic properties such as decreasing Young's modulus and ultimately reducing the materials capability to handle aerodynamic loads. Additional concerns consist of a decrease in allowable stress and the time-dependent phenomenon creep. Thermal stresses then become prevalent due to local or global expansions or contractions that induce increased deformation, a change in buckling loads, and flutter behavior.

Glass in 2008 discusses the latest material technology and problems and challenges for the hypersonic material community. A key issue for hypersonic materials is the approach or method of thermal management. At this point in time, air-breathing technology needs to be matured, specifically scramjets. Unfortunately, the older thermal systems used for rocket based hypersonic vehicles do not handle certain loads an air-breather would see in flight. Hence, a combination of old and new materials and methods provide the best thermal protection. The main challenges for air-breathing hypersonic vehicles are illustrated in the following list.

As Glass states reviewing the hypersonic vehicle materials in the past leads us to believe that advancing materials will in turn result in the advancement of hypersonic vehicles. Glass advocates the use of ceramic matrix composites for hypersonic vehicle applications due to their combination of high temperature endurance, strength, and

GOTCHAs for HAPV in the materials and structures HypTAs.

Large thermal gradients (cryogenic tanks to high surface temperatures) cause differences in thermal expansions on structures
Thermal-mechanical loads on structures such as sharp leading edges, gaps, and steps
Surface and airframe connection, thermal expansion issues
Cheaper - manufacturability, availability
Affordability of materials for vehicle
Costs involving life cycle and safety such as inspection/maintenance
Damage tolerance
Low speed impact such as tool drops, runway debris
High velocity impacts such as small debris particles
Weather
Reuse potential

density. However, the material in question has some key issues that need to be resolved:

- Manufacturing and processing to include a coating which increases strength and toughness and allows for a graceful failure.
- The coating would also have to prevent oxidation at high temperatures.

Sharp leading edges needed for air-breathing engines pose challenges for proper thermal protection. Other systems, such as the Space Shuttle and the once proposed VentureStar X-33, have blunter leading edges that work well for the application but may complicate manufacture and maintenance (such as replacement of TPS tiles for the Space Shuttle). Over the past several years, one such program, SHEFEX, has played a leading role in collecting essential data on sharp leading edges for hypersonic vehicles along with possible TPS arrangements (Eggers et al. 2005; Weihs et al. 2008). The SHEFEX group favors a sharp-edged configuration to reduce TPS-related expenses (for fabrication, inspection, and repair), and these, in turn, can result in a trickle-down effect on overall developmental costs. In addition, an effective

TPS allows for potential mass payload increases, and the sharp edged configuration tested by the SHEFEX team shows virtually no difference in aerodynamic properties when compared to a contoured vehicle. Glass points out that since air-breathing vehicles experience higher temperatures due to the utilization of sharp leading edges the materials for heat protection use could be:

- Carbides.
- Oxides.
- Diborides of hafnium (Hf) and zirconium (Zr).
- Coatings of iridium (Ir).

Evidently, additional issues and research for material applications remain a current topic in the hypersonic community as shown in the following list.

Recently, Zuchowski et al (2011) haver reviewed some issues concerning hypersonic vehicles and structure, materials, and thermal management. Based on their findings, the most significant areas for improvement appear in the following list.

Additional GOTCHAs for materials and structures.

Thermal conductivity and fiber/weave architecture
Thermal-mechanical loads on structures such as sharp leading edges, gaps, and steps
Emissivity of materials
Catalytic efficiency
Oxidation
All composite actively-cooled structures
Optimum through-the-thickness conductivity
Cooling containment
Manifolding
Lifespan
Material compatibility
Transferring the aero-loads and not the thermal loads using a stand-off TPS approach and handling vibrations and acoustic loads
Internal insulation for the stand-off TPS
Load bearing aeroshells (potential to reduce weight) such as the FALCON HTV-2 and the United Kingdom's Sustained Hypersonic Flight Experiment (SHyFE)
Structurally integrated TPS (potential for lower maintenance but should be a low priority approach)

The propulsion-airframe integration (PAI) HypTA fits with both the aerodynamics and propulsion HypTAs. However, with a separate materials and structures HypTA, PAI fits well in consolidating all three aspects, especially since aerodynamics and propulsion are previously covered. Placing PAI into the materials and structures chapter avoids repetition or choosing either aerodynamics or propulsion where one is favored over the other.

Robinson et al (2006) begin their article by noting how new hypersonic cruise and space access vehicles ideally have a light, efficient, and cost effective propulsion system. These researchers point to solutions of superior propulsion for hypersonic cruise and space access missions in the scramjet and ramjet engines. Then given, the degree of difficulty in developing scramjet and ramjet technology they propose that

GOTCHAs for materials and structures by Zuchowski et al.

Predicting aeroelastic characteristics of very thin metallic as well as non-metallic structure at high temperatures for sustained periods of time
Actuator stiffness predictions
Sonic fatigue under elevated temperature and accurate prediction of the acoustic environment
Damage tolerance under elevated temperatures, dynamic pressure levels, and acoustic spectrums
Interaction of fuselage dynamics in flutter analysis and how to model the fuselage, as a flat plate or body of revolution, and do current methods represent fuselage aerodynamics well
Adequately characterizing stiffness of vehicle at hypersonic temperatures, under complexities of stiffened panels and TPS
Hypersonic vehicle airframe analysis needs to be heavily validated with testing and a building block test approach to validate analytical tools is essential
Accurately characterizing the mass, stiffness, and damping of a hot structure and/or thermal protection system

scramjet engines could greatly benefit being tightly fused to the craft. In agreement, Bowcutt (2001) opens his paper stating that designing a hypersonic vehicle requires close connectivity between multiple disciplines especially for large L/D and a scramjet engine due to the highly integrated airframe-propulsion system. O'Neill and Lewis (1992) go as far as stating that in order to achieve a successful air-breathing hypersonic vehicle an emphasis upon PAI is crucial. Figure 4.1 demonstrates a vehicle that utilizes PAI.

Lewis (2003) acknowledges that a looming issue for hypersonic vehicle designers persists as,

> "*A key challenge in hypersonic vehicle design is balancing the integrated requirements for efficient propulsion with highly efficient aerodynamics while providing good volumterics, structural efficiency, controllability, and heating survivability. The degree of coupling, and close integration, raise many questions about practical designs for hypersonic*

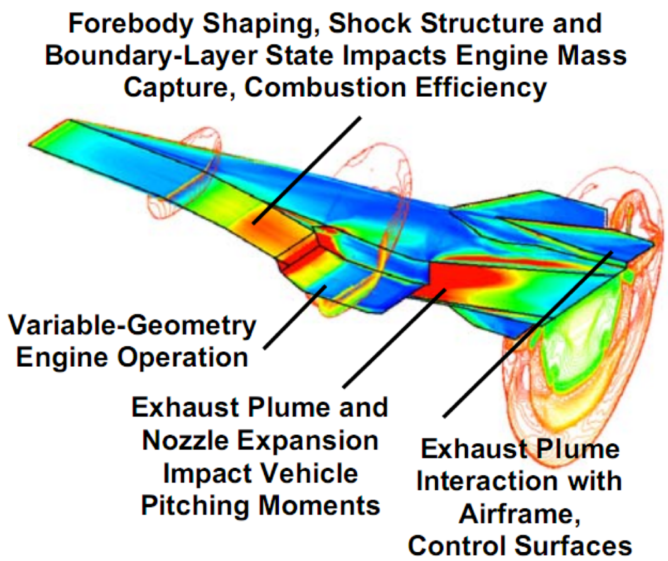

Figure 4.1: Illustration of PAI (Cockrell Jr. et al. 2002).

flight, including some of the most basic issues regarding fuel selection, engine cycle, and off-design performance."

Chapter 5

Education & Research

Proper education is quintessential to the advancement of HT 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 being constantly reduced at various institutions (Musselman 2011). 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 HT research. This issue is further exacerbated by the lack of adequate Science, Technology, Engineering and Math (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.

Not every challenge hindering progress in hypersonic vehicle development is technological in nature. In Hallion's (2005) historical survey, 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 others, including both emerging (China, India, Brazil, Russia, Ukraine) and more established countries (Australia, the European Union, Japan), are investing heavily in advanced technologies and aerospace, the prospect of aerospace domination in the U.S. remains leveraged on previous achievements. Tirres (1999) even goes as far as stating that, "*Aerospace plays a key role in the United States' economy and national security.*" After mentioning the remarkably fast foundation building of ground test facilities during the forties through the seventies and the success of Operation Desert Storm and commercial airline travel, Tirres points out that, "*Aerospace, no doubt, has played a significant role in the United States becoming a 'Super Power.'*" 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. 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 NAI, a 2001 joint effort of the US Department of Defense (DOD) and the National Aeronautics and Space Administration (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 HABP activities the situation may be more dire than it seems (Hallion 2005; Canan 2007).

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). 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 US and Australia, the HyCAUSE program was conceived (Walker et al. 2005; Ho 2006; Walker et al. 2008a). 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. A team of US and Australian academic leaders from universities such as the University of Queensland, the University of New South Wales along with support from the Defense Advanced Research Projects Agency (DARPA) leade the HyCAUSE joint efforts. It is through such collaborations that vibrant activities may be vigorously pursued with graduate students, faculty, and field experts. (Boyce et al. 2003; Hass et al. 2005; Ho and Paull 2006; Neuenhahn et al. 2006; Smart et al. 2006). The names from the US and Australian team members show up frequently in hypersonic research literature (see Table 5.1), and the program consists of several universities, agencies, and companies.

An additional international collaboration, the HIFiRE, combines forces from the Australian Defence Science and Technology Organization, the United States Air Force Research Lab (AFRL), and NASA (Jackson et al. 2009). The purpose of HIFiRE and the difference from other flight testing programs is the focus on the phenomena of combustor mode transition. Additionally, HIFiRE plans

Table 5.1: **HyCAUSE contributors and affiliations.**

Contribuors	**Affiliation**
Allan Paull	Defense Science and Technology Organization (DSTO), Brisbane, Australia University of Queensland
Steven Walker	DARPA, Arlington, Virginia, USA
David M. Van Wie	Johns Hopkins University Applied Physics Laboratory (JHU/APL), Laurel, Maryland, USA
Frederick Rodgers	Centra Technologies Inc., Arlington, Virgina, USA
Russell Boyce	University of New South Wales, Australian Defence Force Academy, Canberra, 2600, Australia
Sook-ying Ho	Defence Science and Technology Organisation, P.O. Box 1500, Edinburgh, SA 5111, Australia
Michael S. Holden	Calspan-University of Buffalo Research Center (CUBRC), Buffalo, NY, 14225
Timothy P. Wadhams Matthew MacLean	CUBRC, Buffalo, NY, 14225

to study stable supersonic combustion of hydrocarbon fuel for free-stream Mach numbers of 7 and greater. Completing the study, an investigation of measurement techniques exploring boundary layer transition and shockwave turbulent/boundary layer interaction (SWTBLI) is planned utilizing both flight test and ground test (Holden et al. 2008).

A good example of government and educational synergy comes from NASA's Bantam-X program (Olds et al. 1999). The purpose of this program identifies GOTCHAs that immensely help to reduce launch costs for the ultra-lite and small payload community. The payload type ranges from 300 to 500 lbs, which usually classifies University Explorer scientific missions. The budgets range from \$1M to \$1.5M for a dedicated flight which remain much lower compared to larger endeavors. The Bantam-X program exposes the need for aggressive new concepts and technologies for the described payload missions. An excellent example of a large governmental based space agency involves scaled aerospace vehicle research. One example of a Bantam-X inspired study involves a team from Georgia Tech's Space Systems

Design Laboratory in collaboration with NASA's Marshall Spaceflight Center (MSFC) technical group in Huntsville, AL who, together, investigated a TSTO RBCC vehicle called *Stargazer*.

More recently, in May of 2008 Japan's law makers have passed a law called the Basic Space Law (Fujii and Ishimoto 2009). Japan had not enacted a law related to space activities since 1970. Japan then in 2009 moved on to establish the so called Basic Plan, a derivative of the Basic Space Law. The Plan foresees the period between 2009 and 2013 to direct the government and country towards space research. Some keystone objectives from the Plan include "Better Quality of Life," "contribution to the international community," and "be fostering Strategic Industries for the 21st Century." It is abundantly clear that Japan considers space exploration as one important industry that is worthy of attention. In fact, Japan's chief research and development focus aims at constructing a future space transportation system. Two systems and their technologies are thus under development by the Japan Aerospace Exploration Agency (JAXA). The first system consists of an ELV while the second system relies on an RLV. Developing these technologies is planned to be completed by 2015 with vehicle operations by 2020-25.

Combining government, industry, and academia, the Hy-V program focuses on the development of a hypersonic database in order to compare ground and flight experiments and thereby improve prediction tools (Craig 2007). Both undergraduate and graduate students are able to participate through faculty groups located at the five Virginia Space Grant Consortium universities, and these include the University of Virginia, Virginia Tech, Old Dominion University, Hampton University, and College of William and Mary (Goyne et al. 2006). NASA Wallops is supporting the project by providing the launch logistics and a Terrier-Improved Orion sounding rocket. Other entities involved with the Hy-V program include Alliant Techsystems, Inc.'s General Applied Science Laboratory (ATK-GASL), Arnold Engineering Development Center (AEDC), and Aerojet (Goyne and Cresci 2008).

Other educational efforts encompass the NASA sponsored University Centers for Hypersonic Research (Lewis and Gupta 1995). Three universities were rewarded the support from proposals, the University of Maryland, Syracuse University, and the University of Texas at Arlington. The research centers focus efforts on a balance between research and teaching activities with insight from industrial partners. A even and wide distribution of research topics are to be developed for the hypersonic the program. Additionally, the development of cruisers and accelerators continue to be pursued from the university side.

Therefore, not all is doom and gloom. Efforts are being made such as the previously mentioned initiatives, and these and other analogous programs provide key opportunities for promoting aerospace and hypersonic education. In fact, the material useful to educators, students, design engineers, and researchers appears to be quite extensive and quite certainly overwhelming to review in its entirety. In academia, much progress has been made in the form of quality textbooks that have been published in the past 10-20 years. Even though large advances have been made in the fifties and sixties, not many books could be found on the subject of hypersonics. Anderson (1984a) notes that only about five major textbooks (Hayes and Probstein 1959; Truitt 1959; Chernyǐ 1961; Dorrance 1962; Cox and Crabtree 1965; Hayes and Probstein 1966) on hypersonic flows existed in the fifties and sixties and this status quo remained the case up until the eighties. Presently, a substaintially larger collection of textbooks and monographs are available for the treatment of hypersonic flows by authors and editors such as Anderson, Bertin, Curran, Murthy, Heiser, Pratt, and others (Bertin et al. 1989; Murthy and Curran 1991; Bertin et al. 1992; Heiser and Pratt 1994; Rasmussen 1994; Murthy and Curran 1996; Curran and Murthy 2000; Hirschel 2005; Hirschel and Weiland 2009; Segal 2009).

Both Dr. John D. Anderson Jr. and AIAA have spearheaded an effort to increase hypersonic educational resources. Anderson, a professor at the University of Maryland, has produced several excellent textbooks on the subject of aeronautics, aerodynamics, and aerospace engineering. His books always include a human and historical perspective which makes his books stand out from the rest. Specifically, his books on compressible flow (Anderson 1990, 2003) and hypersonic gas dynamics (Anderson 1989, 2000, 2006) constitute invaluable resources for the aerospace and hypersonic communities. It should be mentioned that Anderson has published several additional books that provide essential background information and pedagogical tools for studying the subject of aerodynamics (Anderson 1984b, 1997, 1999, 2001, 2007).

Another player, American Institute of Aeronautics and Astronautics (AIAA), works to increase the promotion of hypersonic education for the aerospace community. For one, the AIAA book series on Education and series on Progress in Astronautics and Aeronautics continue to offer each new generation fundamental reviews of contemporary development in the aerospace field. Two, the AIAA regularly host exceptionally annual conferences that are devoted to aerospace and hypersonics, such as the Joint Propulsion Conference (JPC), the International Space Planes and Hypersonic Systems and Technologies, the Aerospace Sciences Meeting, and many more. These technical meetings bring together professionals and enables them collaborate and share research and development ideas. Such gatherings allow for social and work related networking, dissemination, job recruitment, valuable experience for students and workers alike, and a minor boost to the local economy of the hosting city. The AIAA student conferences have been equally instrumental in fostering interest among upcoming generations of engineers. Lastly, AIAA provides a venue through which researchers are able to publish their findings in the form of conference papers and quality journals such as the *AIAA Journal*, the *Journal of Propulsion and Power*, the *Journal of Thermophysics and Heat Transfer*, the *Journal of Rockets and Spacecraft*, and the *Journal of Aircraft*.

It is clear that academia, private industry, and government agencies will have to team up in order to efficiently and successfully advance hypersonic vehicle technology. Using all three venues of research cooperatively allows the pros from party to overcome the cons associated with the group as a whole. For example, in the HyCAUSE program academic researchers can use low cost university resources such as established CFD and ground testing facilities to effectively promote hypersonic research. Meanwhile, government agencies such as DARPA, DOD, etc. can invest their resources such as B-52 planes and naval ships to support the proposed flight test. Moreover, utilizing academic resources can be of benefit to both academia and industry by better preparing and equipping graduate students with the latest technological tools of research. In this manner, graduates become more qualified and confident to enter the workforce whether they choose academia or industry. 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.
- Replicate successful programs such as the SystemsGo High School Rocketry Initiative, NASA's (University).
- Expand the impressive activities of the Student Launch Initiatives, the Fisk Altitude Achievement Missile Team (FAAMT), HUNCH (High Schools United with NASA to Create Hardware), etc.
- Create and mature university-based programs such as Hy-V and the NASA sponsored University Centers for Hypersonic Research.
- Develop more programs such as HyCAUSE and HIFiRE, perhaps through alliances with other nations that are invested in this research.
- Allocate more resources to universities that grant aerospace degrees.
- Get involved!

Finally, it may be useful to remark that the society-aerospace coalitions can significantly affect the aerospace industry. If the public sees hypersonics positively, then funding aerospace projects and programs with taxpayer money may not be viewed as a concern. In addition, encouraging interest in younger and older generations alike can be helpful in planting the necessary seeds to keep dreams alive. If aerospace engineering involvement is reinforced or perceived as a positive experience, then younger people may be encouraged to pursue aerospace careers that, in turn, will help to bolster the dwindling workforce and sagging economy. In work by, Hallion (2005) hypersonics and space vehicles are viewed as being influencial on the current culture and vice versa. In this vein, Hallion depicts the team of Wernher von Braun, Willey Ley, and Chesley Bonestell as holding substantial influence on engineers, younger generations, and the public in general. Walt Disney and von Braun also teamed up to create films illustrating space travel thus increasing public interest in aerospace technology. Along similar lines, Launius (2003a) also believes that public curiosity will most likely fund the first few hypersonic space access vehicle ventures. Accordingly, such motivation may be generated from the desire to acquire the title of having flown at hypersonic speeds, experiencing space and weightlessness, and gaining the ability of traveling halfway around Earth in a few hours.

Launius (2003b) also suggests that the public perception of aerospace is no longer what it seemed to be. Specifically, he debunks the myth that NASA enjoyed much more public support during the Apollo program than any other time. In fact after studying poll data from the 60's through the 90's, Launius concludes that the public has been extremely pleased with NASA and space exploration throughout the years, despite the unfamiliarity of the public in with what exactly NASA does. Polls demonstrate that the public was not as enthused about lunar exploration as stereotypically thought. The only high points came in 1969 and quickly dissipated with time. Launius compares the end of the program to a marathon runner gasping for air and limping over the finish line. However, the public continues to perceive the Apollo program along with the Saturn V rocket system and Space Shuttle program and vehicle among the greatest American icons. The success of these machines and human efforts allowed the nation to gain immense pride and international recognition. Evidence of cultures influencing aerospace and vice versa transpires through a poll that asked whether NASA should conduct more robotic missions or more manned missions. Surprisingly, the poll logged people in favor of more robotic missions from 1989 up until the summer of 1995, when a blockbuster movie, *Apollo 13*, hit the theaters. Other influential movies Launius mentions are *Armageddon*, *Deep Impact*, *Contact*, and *Space Cowboys*. Undoubtly, the public opinion and the aerospace community are more intertwined than it seems, and the aerospace and cultural/entertainment industries benefit from one another by generating interest and excitement in science and technology.

Chapter 6

Hypersonic Testing & Modeling

In order to confirm engineering theories and concepts, the ability to test labscale models remains a high priority for HVT, especially hypersonic air-breathing or HAB vehicles (HABV). 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 extreme and wide-ranging conditions that hypersonic transatmospheric flight experiences cause difficulty in testing and thus proof of concept. A three-pronged process exists for validating HT concepts that consists of three testing platforms that can be used in concert: Flight testing, ground testing, and CFD (see Figure 6.1). Note

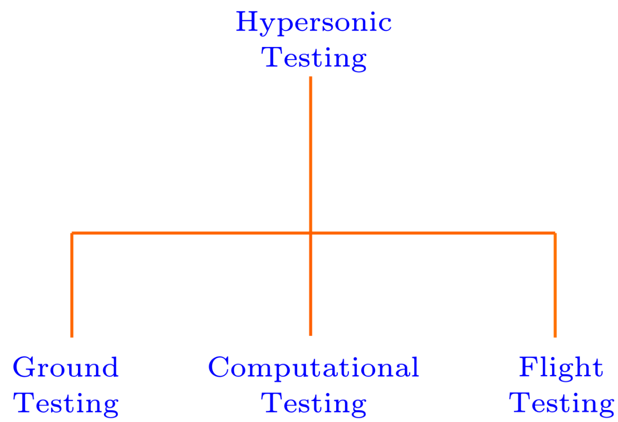

Figure 6.1: The testing prong with three testing forks.

that other computer aided design tools such as mechanical system and optimization techniques are lumped herein with CFD.

Several leaders in hypersonic testing state the importance of testing. When referring to the success of the complex engineering programs of Apollo and the X-15, Leslie and Marren (2009) emphasize that,

> "*One common principle underscoring each of these successful eras is that system development was preceded by rigorous testing and careful evaluation of results. In a synergistic way, tests improved the development of the system, and the system itself required a higher level of test and evaluation. This pushed engineers to develop ever improved test methods and capabilities.*"

An additional quotation supporting and stating the obvious importance and necessary triune of numerical, ground, and flight tests from Lu and Marren reads,

> "*A successful research and development program in hypersonic flight technologies requires wind tunnel testing, numerical simulation and, ultimately, prototype flight testing, resulting in a validated integrated test and evaluation methodology.*"

However, even with numerous research efforts, Weihs et al (Weihs et al. 2008) point out some general lingering issues within the aerodynamic research area which involves all three testing HypTAs. These are:

- Limited ground testing capabilities simulating hypersonic flow
- Hypersonic aerothermodynamic flight tests database is limited and restricted access
- CFD aerothermodynamic codes are inadequately verified with ground test

While testing comprises a three-pronged process, testing and modeling emerges as a cycle or circle of methods as was before mentioned. CFD uses data gathered from ground and flight testing to modify CFD models, and CFD can be used to verify or disprove an incremental change in the attendant theoretical model, this can then be implemented in the wind tunnel model without having to change and use the physical model multiple times, a process that cam become both expensive and time consuming. Also, flight data can be used to find trends in parameters, characteristics, and/or data to assist future ground tests and vice-versa. Applying the three test forms in the proper way and using them as a tightly correlated process along with numerical and analytical modeling will produce a very effective result in advancing hypersonic technology.

A great example of utilizing the triad of testing and modeling (see Figure 6.2) stems from the HyCAUSE program (Walker et al. 2005, 2008a). According to Walker, Rodgers, and Esposita in 2005,

> "*The program takes advantage of low-cost, university-based test facilities in both the U.S. and Australia to characterize flow and aggressively pursue development of novel scramjet technologies. This effort is guided by and augmented with computational fluid dynamic (CFD) analytical modeling.*"

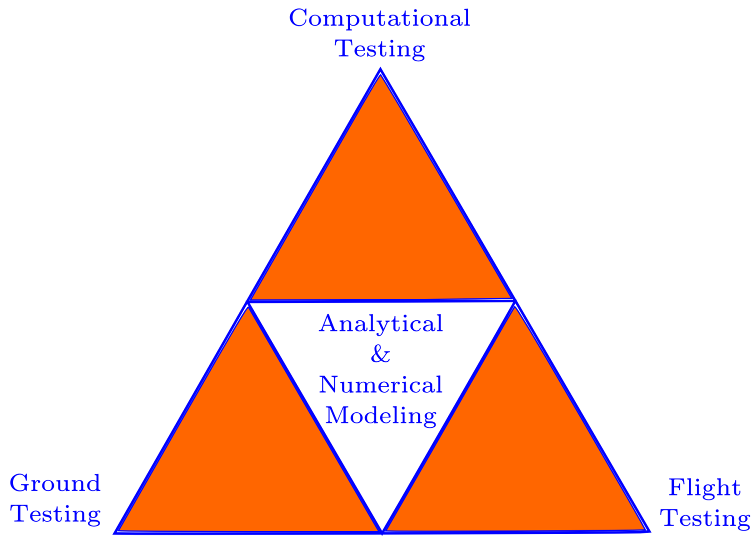

Figure 6.2: The testing and modeling triad.

Another recent program seeking to utilize the three testing aspects is the Hy-V program based in Virginia. The Hy-V team seeks to provide a database of both ground and flight testing of a DMSJ in order to improve CFD analysis and identify database gaps (Goyne et al. 2006). Goyne et al point out that ground testing introduces unnatural effects such as vitiation, flow quality, and inadequate boundary conditions while flight test can only provided a limited database due to the complexity and resource intensiveness. In order to reduce database limitations, Goyne et al offer the following solution,

> "*Therefore, ground and flight databases must both be used in the development of predictive tools, and combined, the inadequacies of each can be identified such that their contribution to predictive tool uncertainties is limited. Further, the cost effectiveness of this approach can be preserved by targeting investment at comprehensive ground based experiments and at a limited number of complementary flight experiments.*"

6.1 Flight Testing

Flight testing is probably the best way to verify models but remains the most costly and complex. According to Walberg (1991),

> "*The **ultimate validation** of hypersonic design techniques, be they theoretical or based on wind tunnel tests, **must come from hypersonic flight data*** [emphasis added]."

Flight testing represents the ideal mechanism for verifying models under real life conditions. 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 (Hank et al. 2008). Nonetheless, it is through such tests that important strides have been made. The X-15 experimental plane which played a key role in validating fundamental hypersonic theories (Launius 2003a; Watillon et al. 2003; Hallion 2005). Over 700 technical reports resulted from this program and these provided valuable data as shown in the following list.

HypTAs helped and investigated by the X-15 program.

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
Propulsion
Avionics
Biomedical effects of pilots at high altitudes and speeds
Designing and constructing high speed craft
Verified and confirmed wind tunnel data
Energy management
Unpowered glide descent and landing
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 or are in the process of contributing to the hypersonic database and understanding (Cain and Walton 2003; Launius 2003a; Watillon et al. 2003; Hallion 2005; Goyne et al. 2006; Goyne and Cresci 2008; Hank et al. 2008; Walker et al. 2008a). Some of these programs are listed next.

Hypersonic flight programs and tests benefiting HypTAs.

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
FASTT
Hypersonic Flight Demonstrator (HyFly)
CIAM
HyCAUSE
X-51
SHEFEX
SHyFE
Hy-V

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 (Hallion 1998). Hallion (2005) 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 (2003) confirmed 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 programs, it may be best described by historian J. D. Hunley (Launius 2003a),

> "*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 (see Figure 6.3) 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 (Launius 2003a; Hallion 2005).

It should be noted that hypersonic 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

Figure 6.3: The X-15 (Jenkins 2000).

X-43A both flew experimentally at hypersonic speeds (although it is debated whether the ASALM achieved true hypersonic speeds) (Fry 2004; Tang and Chase 2008). 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 (Webster 1982; Fry 2004). 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 (Heiser and Pratt 1994; Launius 2003a; Hallion 2005; Tang and Chase 2008). Both Figures 6.4 and 6.5 display the various air-breathing programs according to Tang and Chase (2005; 2008). Note in Figure 6.5 the scarcity of experimental programs that have reached the flight testing stage.

Recently, the HyCAUSE program executed a hypersonic flight test (see Figure 6.7) on the research group's INTINSE scramjet flowpath depicted in Figure 6.6 (Walker et al. 2008a). 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

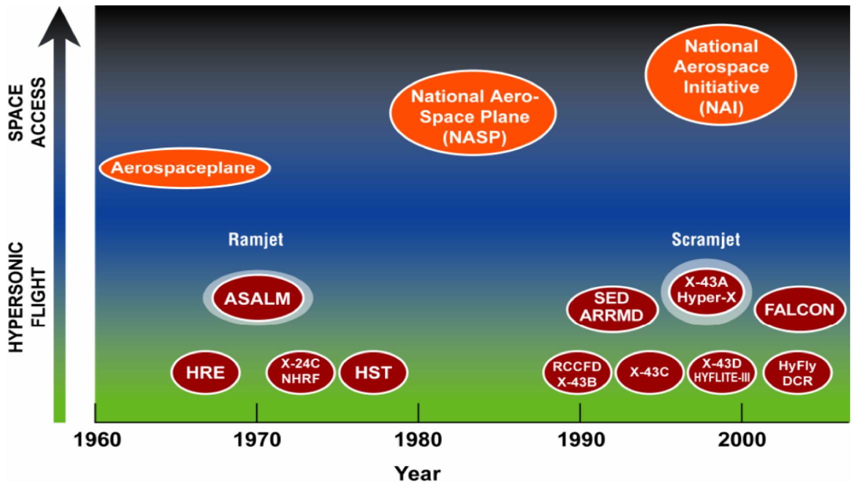

Figure 6.4: A timeline of two hypersonic mission areas, hypersonic flight and space access for ramjet and scramjet programs (Tang and Chase 2005).

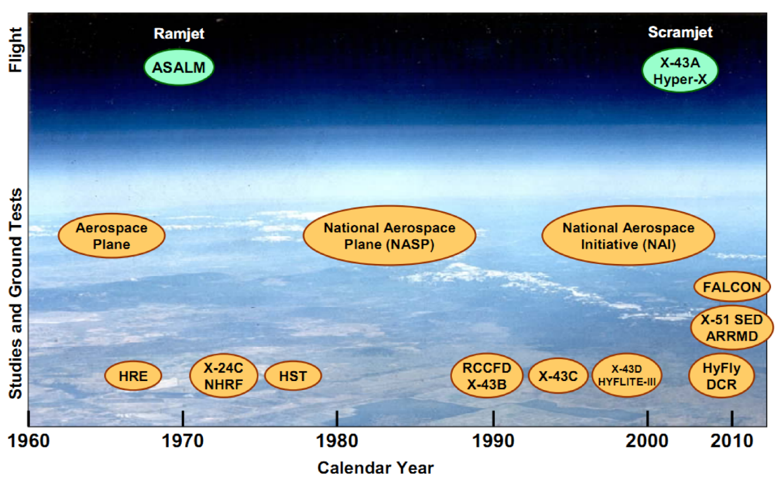

Figure 6.5: Ground and flight test studies (Tang and Chase 2008).

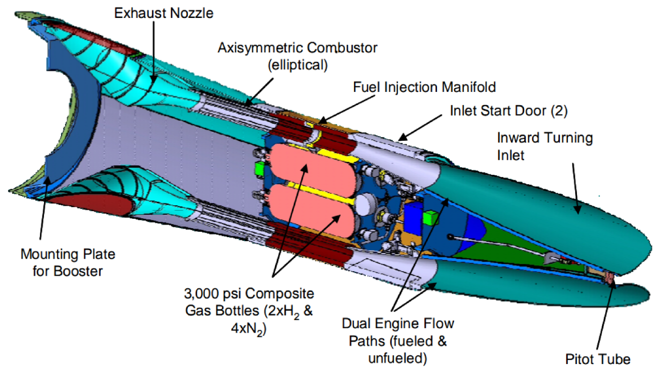

Figure 6.6: A preliminary schematic of the HyCAUSE flight test article (Walker et al. 2008a).

hypersonic technology can continue to move forward in its evolution toward full scale systems.

Similarly, the X-51A program is built around a flight test to demonstrate advancing scramjet technologies (Hank et al. 2008). Hank et al (2008) simply state that ground test are problematic to test for in-flight simulations for either wind tunnels or CFD. Even with the high power of current computer systems and world class facilities, ground testing runs into issues such as model sizes, length of test times, proper inlet air properties and fixed parameters such as Mach number and dynamic pressure which can lead to data difficult to extrapolate to engine performance. Hank et al (2008) summarize by frankly stating that

> "*Ultimately, the only way to practically and cost effectively validate the rules and tools which will be needed for development of larger hypersonic air breathing vehicles and space access is by flying smaller scaled scramjets, such as the X-51A.*"

6.2 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

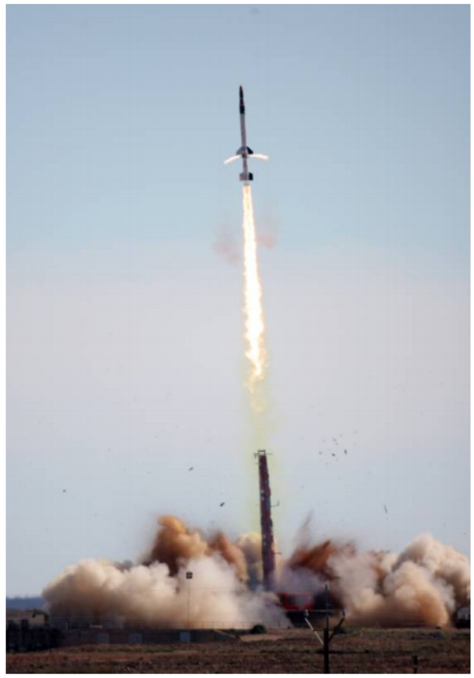

Figure 6.7: The firing of the HyCAUSE test article (Walker et al. 2008a).

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. Heppenheimer (2006) notes that great strides have been made in hypersonic flight due to the success of experiments, specifically wind tunnels and other ground facilities. However, at the same time hypersonic programs suffered due to inadequate ground based facilities. Laster and Bushnell in 1994 identify ground testing problems not only with the NASP but also with the X-15, Gemini, Apollo, Shuttle, and ballistic reentry systems. Problems surfaced especially with aerothermodynamic heating. Laster and Bushnell note that problems become apparent during or after the flight tests due to the poor capability of ground testing systems. In addition, 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 (Walker et al. 2005, 2008a). Hy-V utilizes a myriad of ground test facilities including AEDC APTU, NASA 8' HTT, ATK GASL Leg IV, NASA Langley DCSTF and Aerojet Orange facilities (Goyne and Cresci 2008). It is therefore hoped for the continuation of current programs, and it is desired for future programs to soon follow suit where others have ended.

In Chapter 2 "Principles of Hypersonic Test Facility Development" of the *Advanced Hypersonic Test Facilities* by Lu and Marren (2002a; 2002b), the authors mention that the chance of a ground test capable of meeting all hypersonic requirements is very low. However, in the ground test community/facilities a partial simulation of hypersonic conditions is frequently a goal met. These partial simulations can be separated into three categories: (i) the low hypersonic regime (Mach 5-12), (ii) higher speeds, and (iii) very high altitudes. For the low hypersonic flow regime a perfect gas can be simulated for Mach and Reynolds numbers only. In the hypervelocity range additional simulated components of real gas flow are needed to compensate for chemical reactions, thermal effects, radiation, and ablation. The high altitude range must take into consideration rarefied flow effects. Also, flow characteristics such as laminar-turbulent transition and turbulence must be accounted for in hypersonic flow regimes. These (turbulence and transitions) are still highly not understood and pose a problem that can be a major area of advancement for ground testing. Obviously, many facilities are needed to represent various flows and their features because one facility cannot simply recreate the vast range of gas dynamics. An example of using many resourceful ground tests is the Apollo program which took advantage of at least 25 facilities that tested over the Mach number range of 0-20. Solutions to problems associated with the hypersonic flight of an air-breathing wing-type vehicle require the use of several different experimental facilities since no one facility can handle all of the problems.

An example of the difficulty of the hypersonic realm encases two examples of testing two different areas and their specific, dissimilar needs:

- an air-breathing engine test requiring duplication of the atmospheric conditions for proper test results
- (on the other hand) an aerodynamic body could potentially not require the presence of oxygen in order to record relevant data

An example of flight data and computer capabilities that bolsters ground testing efforts to build suitable facilities is described by Lu and Marren in an attempt demonstrate the importance of coherent experimentation:

> "*The infrastructure, capabilities, and techniques used to obtain knowledge and information to design hypersonic vehicles demand duplication of certain flow physics that have challenged facility designers for years and will continue to do so during the next few decades. Facility designers have relied increasingly on sophisticated tools to aid this process, made possible by more capable computers and data obtained in flight experiments.*"

Generally ground tests are used to assist numerical and flight tests by using subscale modeling as a stepping stone to reach an ultimate goal (full operational flight vehicle); this is known as partial simulation. The definition "*duplication*" is used to describe a test that fully mimics all aspects of actual flight conditions; this is the best test situation often pursued but rarely achieved. A "*replication*" recreates the temperature, pressure, velocity, and chemical composition experimentally of the flight environment. Note that replication is less complex than duplication but still poses challenges with the increase of velocities. Simply, a *simulation* only recreates a few important physical phenomena to obtain data for boosting other experiments and giving confidence to move forward or concern to reconsider the design process. Even though simulation can easily be achieved in ground test, this detracts from other important physical processes that cannot be reached for ground tests. This puts more demand and pressure for numerical and flight simulations to be accurate and able to produce data reasonably, reliably, and timely. Lu and Marren list downfalls of ground testing that tend to deteriorate above Mach 8:

- Test flow uniformity over a wide range of conditions
- Lack of equilibrium because of rapid nozzle expansion of test gas
- Flow containment from facility surfaces because of erosion
- Acoustic and enthalpy fluctuations affecting boundary layer transitioning
- Incorrect surface roughness and catalyticity
- Insufficient test time in impulse facilities
- Motion of the model, especially in impulse facilities
- Interference from model mounts or tunnel walls

6.3 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. CFD sometimes misleads users with its colorful plots and elegant pictures. On the other hand, many prefer to build their own code and numerical models from scratch. Unfortunately, with so many codes and variations, the community has a hard time keeping up with what has been done, what is new, and what is even out there. 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.

The modeling of turbulence emerges as one such area requiring dire improvements. Turbulence eludes scientist trying to model its behavior. Large changes of the characteristics of fluid flow especially from laminar or inviscid flow models occur when turbulence exist. Turbulence appears in the majority of real world physical flows, a fact that demonstrates its importance to fluid dynamicists. Important parameters in aerodynamics such as lift, drag, heat transfer, and control systems change due to turbulence which influences design choices. Thus, understanding turbulence remains essential to aerodynamic designers.

Roy and Blottner (2006) confide that key experimental data needed for confirming turbulence models prevails to be difficult to obtain. Roy and Blottner also disclose that very few flight test data exist and the ones that do usually contain large experimental uncertainties. On the other hand many wind tunnel test do exist with a bountiful amount of data and include much smaller uncertainties. However, high velocities required for hypersonic flows limit ground testing setups because of disagreements in freestream enthalpy levels from actual flight. As a result, verifying turbulence models necessitates extrapolation to in-flight enthalpies. Consequently, the aerospace community depends mainly on present and accessible CFD and included models for turbulence, chemistry, etc.

The review of turbulence models for hypersonic flows by Roy and Blottner (2006) builds off of an earlier paper by Settles and Dodson as an update and extension. However, Roy and Blottner's study limits flows to hypersonic only or for experiments where the freestream flow Mach number is around 5+. Also, Roy and Blottner only consider wall-bounded flows eliminating such flows as mixing layers and jets. Additionally, Roy and Blottner narrow their scope to one- and two equation turbulence models which they state are the most complex even though other, more advanced models, such as Reynolds stress and Large Eddy Simulations (LES) are being developed. Another category of limitations relies on the study of model integration of the governing equations to the wall existence which ceases wall function usefulness. Justification of the non-utilization of wall functions lies in the fact that many hypersonic flows result in shock wave-boundary layer interactions (SWBLIs) that nullify the capability of the wall function. Again, the delimiter of natural transition flows from laminar to turbulent appears as a focus for Roy and Blottner. Roy and Blottner also include the studying of the location of the transition behavior itself, but do not consider the much more difficult task of predicting transition. Lastly, the study by Roy and Blottner neglects the effects of surface roughness, ablation, chemical reactions, real gases, and body rotation as point out that *not much exist* in the experimental database for the listed type of flows.

In the end of the introductory section, Roy and Blottner (2006) discuss another important detail when referring to turbulence models. Generally, developers envisage that the turbulence models the designers built predict correctly a large range of flow types, and not just tailored to a restricted range of only a few flow types. This approach fits more of a model calibration or parameter fitting method and is not a true prediction. Thus, in their study Roy and Blottner want to include the testing of turbulence models for high speed flows which undergo a range of speeds and geometric configurations in order to unearth the turbulent model under scrutiny's weaknesses and strengths. Thus, with that said, Roy and Blottner exclude models which do not have an excellent base of validation history for a vast spectrum of flow types and conditions, especially low-speed flows. Such studies where models have been improved but lack discussion on the effect of the improvements and they relate to the historical development of the original model also do not make the cut for Roy and Blottner's review. Finally, Roy and Blottner give the advice that researchers should test their compressible flow models for incompressible flow standard sets or state why their compressible corrections do not affect the low speed fluid motion regime.

6.4 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. By analytical or theoretical modeling the author means using the mathematical governing equations of a physical system, the methods to solve the mathematical equations, and the capability to produce an answer that satisfies certain constraints imposed upon the system. A favorite quote of the author by Albert Einstein can be used to explain a portion of the analytical process. He quotes,

"*Make everything as simple as possible, but not simpler.*"

In what concerns analytical modeling, the process can be very difficult due to the complexity of the governing equations and the rules of mathematics. Thus, it is sometimes necessary to delegate restrictions in order to reduce the complexity. In most cases the reduced equations do a fair job for engineering calculations. However, other times require more details concerning the actual physics of the system so one may come along and build upon the simple base in order to step up to more defining solutions. For example, the theory of inviscid flow in fluid dynamics assumes that the liquid or gas is frictionless, which considerably decreases the difficulty of the governing equations of motion to be solved. However, inviscid flows never exist except in rare physical systems, such as super cooled helium physics, and the inviscid equations work very well to describe physical motion in a fluid system except near boundaries where viscous effects become important. It can be seen that the more simple inviscid solution provides a stepping stone to the more difficult viscous answer. Adding additional complexity such as compressibility and chemical reactions can then be considered afterwards. The importance of inviscid models is echoed by Louie and Ockedon (1991) namely,

> "*Although inviscid models have limited practical value, it is important to understand them as well as possible if theoretical progress is to be made with more complicated models for real gases.*"

Finally, revisiting Einstein's quote and its connection to analytical modeling, engineers may need a "good enough" approximation while scientists strive for more exact answers.

Anderson (1997; 1999) notes that hypersonic research remained purely two-dimensional, experimental and theoretical, until the advent of computers capability to handle more complex theories. Anderson explains that the numerical methods compliment the others to work in concert as hypersonic research pillars, similar to the hypersonic testing prong in Figure 6.1. Thus, theoretical HypTAs became well used and developed which undertook approximations to simplify the analysis. The theoretical analyses remain valid through modern times and generally illustrate the effects of a myriad of parameters much better than numerical solutions. A quote from Anderson (Anderson 1997, 1999) reiterates the importance of theoretical modeling.

> "*we engineers of know that machine building, through widely extended practical experimenting, has solved problems, with the utmost ease, which baffled scientific investigation for years. But this 'cut and dry method,' as engineers ironically term it, is often extremely costly; and one of the most important questions of all technical activity, that of efficiency, should lead us not to underestimate the results of scientific technical work.*"

In other words, theoretical modeling can guide experimentation without having to blindly test everything, thus reducing cost and time. One example comes to mind from Anderson's quote. The Apollo F-1 underwent extensive test until the problem of stability (the engine exploded) was fixed. Imagine if theoretical models could have supported the test effort and the time and money saved.

Merlen and Andriamanalina (1992) describe the era from 1955 to 1965 as a productive and successful time for analytical theories in hypersonic aerodynamics. However, Merlen and Andriamanalina go on to state that with the computer age analytical methods have fallen by the wayside even though analytical modeling assists with physical understanding and preliminary analysis. The authors then ask some questions regarding the then future of modeling in aerodynamics.

- Do the "classical" methods of theoretical aerodynamics survive in front of the success of computational fluid dynamics?
- Do we definitely have to give up obtaining analytical relations and use the "numerical wind tunnel" without questions?
- What will the cultural background of aerodynamics be made of in the future?

One strong point of Dr. Jospeh Majdalani's Advanced Theoretical Research Team (ADTHEORET) at the University of Tennessee Space Institute (UTSI) pertains to analytical solutions and perturbation theory. Since the author partakes in the team, discussions follow about ADTHEORET's methods and how they could be implemented for hypersonic cases. The first problem involves a study by Maicke and Majdalani (Majdalani 2005, 2007; Maicke and Majdalani 2008) for steady, compressible flow through a rectangular channel with sidewall injection. The dimensions of the channel consist of the height, h, and the length, L_0, in a Cartesian coordinate system, $(\bar{x}, \bar{y})$, where $\bar{x}$ runs along the axis of the channel and $\bar{y}$ runs perpendicular to the axis. The overbar represents dimensional quantities. Axisymmetric conditions allow the chamber to vary from $0 \leq \bar{y} \leq h$ and $0 \leq \bar{x} \leq L_0$. Finally, an injection gas pierces the chamber's sidewall with a uniform velocity of U_w.

Boundary conditions come about from physical assumptions of the flow. First, no gas emanates from the headwall. At the sidewall an injection velocity, U_w, projects perpendicularly into the chamber while an axial velocity does not exist. Finally, no crossflow exists due to the symmetry of the chamber. The Rayleigh-Janzen perturbation technique follows. Perturbations expand the variables into

$$\left.\begin{array}{c} u\,(x,y) = u_0 + M_w^2 u_1 + O\,(M_w^4), \quad \rho\,(x,y) = 1 + M_w^2 \rho_1 + M_w^4 \rho_2 + O\,(M_w^6), \\ v\,(x,y) = v_0 + M_w^2 v_1 + O\,(M_w^4), \quad p\,(x,y) = 1 + M_w^2 p_1 + M_w^4 p_2 + O\,(M_w^6), \\ \psi\,(x,y) = \psi_0 + M_w^2 \psi_1 + O\,(M_w^4), \; T\,(x,y) = 1 + M_w^2 T_1 + M_w^4 T_2 + O\,(M_w^6), \\ \mathbf{\Omega}\,(x,y) = \mathbf{\Omega}_0 + M_w^2 \mathbf{\Omega}_1 + O\,(M_w^4) \end{array}\right\} \tag{6.1}$$

Thus, for hypersonic test cases a small parameter turns out to be $\varepsilon = 1/M_\infty^2$ and needs to be investigated fully. According to the authors, the closed form analytical solutions agrees with computational and experimental data. Similar papers by the ADTHEORET find similar results for various geometries in various coordinate systems for various types of flows such as inviscid, viscous, incompressible, compressible, swirling, and non-swirling types of motion (Majdalani 2005; Maicke and Majdalani 2006; Saad et al. 2006; Batterson et al. 2007; Batterson and Majdalani 2007; Maicke and Majdalani 2007; Majdalani 2007; Majdalani and Rienstra 2007; Majdalani and Saad 2007a,b; Akiki and Majdalani 2009; Barber and Majdalani 2009; Maicke and Majdalani 2009; Saad and Majdalani 2009a,b; Akiki and Majdalani 2010; Batterson and Majdalani 2010; Majdalani and Akiki 2010; Akiki and Majdalani 2011; Saad and Majdalani 2011; Akiki and Majdalani 2012a,b; Maicke and Majdalani 2012a,b). The present author presses for a review to be done for the various ADTHEORET papers and others like it to continue beneficial analytical work in the scientific community which has a high potential to advance HypTAs and solve GOTCHAs. In addition, the Rayleigh-Janzen technique can be chronicled for easy access and through a consolidated source.

According to Ben-Arosh et al (1999), one of the biggest driving points to mature HABP systems for HV is to ***reduce cost*** and ***increase reliability and efficiency***

of space access. A good example is the recent attention focused on development of the scramjet engine. Here a solid fuel scramjet (SFS) instead of liquid fuel injection provides benefits in certain HV configurations and mission goals. Similar to rocket systems using solid fuels, the SFS propulsion system becomes simplified due to compact fuel storage and the requirement of no injection configuration. However, setbacks of solid fuel result in no control of burning or injection. After lighting the solid fuel, little to no manipulation exists. In rocket systems solid fuels are used in hybrid rocket configurations where a supply of oxidizer carried on board provides the air flow in the combustion chamber. Instead, the SFS combustion process degrades and gasifies the solid fuel due to a heat feedback mechanism from the injected hot air flow. The solid fuel then retreats due to the consumption of fuel where a diffusion flame forms within the BL of the solid fuel edge. An SFS combustor consists of a channel-type or cylindrical chamber with a portion or all of the sidewall consisting of solid fuel injection as in a solid rocket or hybrid rocket motor. The hybrid engine injects an oxidizer and liquid fuel along part or all of the headwall. However, the combustion chamber resembles a backwards facing step geometry where a central core of injection penetrates into the chamber as seen in Figure 6.8. Another major difference between a solid fueled rocket (SFR) and scramjet combustor is that the injection speed at the headwall is of a Mach number greater than one, $M_{\text{inlet}} > 1$, due to the supersonic combustion requirement, while the SFR usually injects at speeds much lower than the sonic threshold. Ben-Arosh et al note that the exact differences between the SFR and solid fueled scramjet exist between the ramjet and the scramjet. That is, the ramjet featured in chapter 3, operates at supersonic flight speeds but subsonic combustion speeds while the scramjet operates at Mach 5 or above and at a combustion flow above the sonic limit.

In 1999 Ben-Arosh et al undertook a study of modeling the flowfield of a scramjet solid fuel combustor. Computational fluid dynamics was used to solve for the flowfield. The model presented by Ben-Arosh et al is similar in geometry to the ADTHEORET models for rocket chambers. An investigation of high speed flows through scramjet

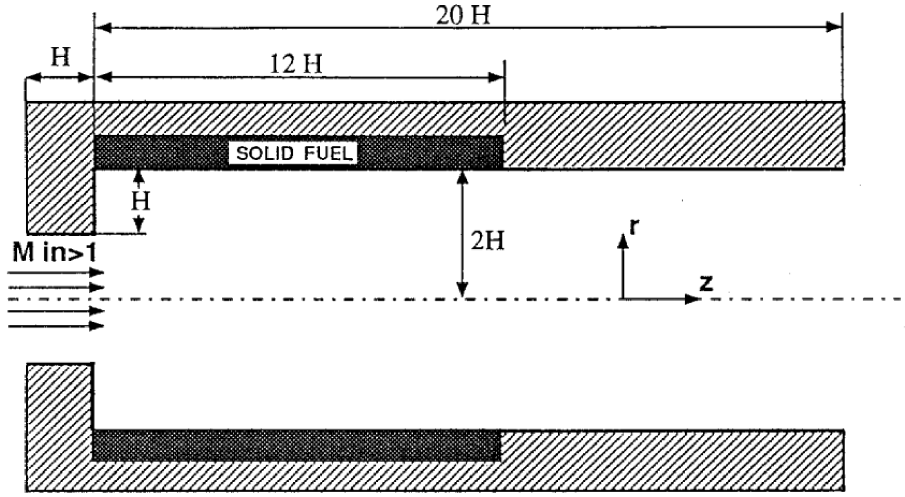

Figure 6.8: A theoretical solid fuel scramjet combustor configuration (Ben-Arosh et al. 1999).

combustors is therefore suggested in order to explore the possibility for new analytical models.

In 1991 Louie and Ockedon undertook a survey of the mathematical aspects of inviscid theory in hypersonic flows. Interestingly, they cited two books from the 1960's, Chernyi's book (1961) translated by Probstein and another written by Hayes and Probstein (1966). They also observed the sparseness of analytical models since the fifties and sixties and the popularity of numerical and computation models. Currently, computational methods are still favored over analytical models due to the ever increasing power of the microchip. However, as stated before, analytical models, once developed, can be much easier to implement for quick calculations. Analytical models also allow researchers to capture certain important parameters. Finally, even though numerical models are treated separate from analytical models, they are, at the same time, one and the same. That is, computationalists and numericalists develop equations analytically, and then use the ability of the computer to calculate quickly and efficiently. Louie and Ockedon review hypersonic inviscid flow theory for several HypTAs.

One area to possibly explore emerges as variational methods. These methods appear in the literature as commonly utilized by Russian researchers. A few papers relate aerodynamic bodies to minimize wave drag in supersonic flows. It may be possible for variational methods to be useful for hypersonic flows, warranting further investigations.

Additional methods to review and methods to further expand include homotopy analysis method (HAM), the modified variational iteration method (MVIM), the artificial small parameter method, the δ-expansion method, the homotopy perturbation method (HPM), Adomian decomposition, matched asymptotic expansion (MAE), Newtonian theory (NT), hypersonic small disturbance theory (HSDT), the blast wave theory (BWT), and the triple deck boundary layer theory to name a few (van Dyke 1953, 1954; Swigart 1960; van Dyke 1963; Mikhailov et al. 1971; Brown et al. 1975; van Dyke 1975; Rizzetta et al. 1978; Brown et al. 1990, 1991; Liao 1995, 1997; He 1999; Liao 1999; Liao and Campo 2002; Liao 2003; He 2007). Important areas of analytical modeling to survey consist of perturbation/analytical methods in all flow regimes and phenomena incorporating hyposonic, subsonic, transonic, supersonic, hypersonic, Stokes or creeping, inviscid, viscous flows, heat transfer, equilibrium, incompressible/compressible, combustion/chemically reactive, laminar/L-T transition/turbulent, swirling/non-swirling, MHD, EM, PD, and continuum/non-continuum flows. In the same vein, perturbation parameters to examine comprise of small or large flow parameters such as the Froude, Strouhal, Lewis, Boussinesq, Dalhmakolar, Prandtl, Nusselt, Knudsen numbers, and many others.

Chapter 7

Final Remarks & Future Recommendations and Work

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 those 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 integration and investigation of these GOTCHA topics that the objective of large scale air-breathing hypersonic propulsion systems can be realized.

Even though this thesis covers many topics and presents a body of evidence for GOTCHAs, only the tip of the iceberg is shown. Much work is not reviewed because of the limited scope of the thesis. The vast material presented and the desire for additional expansion where the material is cut short is a reflection of the high complexity of hypersonics. A future consideration for additional work includes an expansion of the material presented. For example, the WR aerodynamic concept has been known since the fifties/sixties and much work has been accomplished during the eighties and nineties. Obviously, many programs important to hypersonic research were not covered due to time and length restrictions. However, an additional review has the potential to uncover many more GOTCHAs for each HypTA. Much information has been left untouched, uncollected, and undisclosed. Ideally, each section would contain more examples, information, and evidence from related studies that lend support to the GOTCHAs found while catering to the possibility of disclosing new GOTCHAs.

Regardless of the depth of this thesis, a few remarks could be made regarding some of the GOTCHAs identified throughout this survey. In what follows, these are listed in no particular order. The first consists of the ***lack of data, especially flight tests***. Specifically, a strong need exists for ***scramjet flight testing*** to help AB hypersonic systems take off. In this context, the combined cycle propulsion approach seems to offer the highest chance of success for an eventual NASP vehicle, where AB cycles play an essential role in thrust production. This could be temporary until the waning industrial age is overtaken by new technological advances emerging from the rapidly growing IT/bio/nano areas. While flight testing remains the best avenue for acquiring hypersonic data, one must avoid the pitfalls of past programs that have been almost invariably plagued by unforeseen cancelations. The X-20 represents one such example where program termination occurred shortly before flight runs. In this vein, it may be safely stated that past hypersonic flight data has proven instrumental in advancing vehicle technology as experienced by programs such as the X-15, PRIME (X-23), ASSET, the re-entry of space capsules, and the Space Shuttle. Recognizing the importance of test measurements, a key characteristic of new programs has been the building up of databases for various HypTAs. On this note, programs such as HyShot, Hyper-X/X-43, SHEFEX, HyCAUSE, HTV-2, X-51, and HIFiRE must be commended for their diligent efforts and unwavering determination. Similarly, appropriate funding agencies are encouraged to continue supporting these programs in spite of mishaps or failures that may be inevitable in this line of work. One example of a failure-tolerant program that is now considered as one of the premier aerospace achievements is the Apollo program's F-1 engine development and its historical impact on the moon landing mission. The F-1 engine underwent thousands of tests before arriving at a baffle configuration that was capable of suppressing combustion instabilities to manageable levels . However, flight testing alone is not the solution. It would be highly desirable to incorporate in concert with flight testing other methods of data generation from ground testing, numerical simulations, and analytical modeling.

A second major GOTCHA may be connected with the lack of ***consistency*** and, in some instances, ***proper management***. Although hypersonic research is decades old, many ups and downs have been reported throughout its history. This waxing and waning has not been particularly conducive of stability, especially for projects in which a more even keel is necessary. The roller coaster of high excitement followed by a period of disinterest is not only discouraging, it also leads to extended durations of inactivity, lapses in technology, and duplication of effort. Furthermore, it widens the gap between skill already acquired by senior researchers and that of budding engineers who often find themselves having to "reinvent the wheel" by investing precious resources for the purpose of re-discovering what may be perceived as "lost" information. The propulsion community can benefit from leaders and policy makers who can understand this dilemma and take the appropriate action to ensure the much needed continuity in this field.

Within the major HypTAs, numerous sub-categories exist which, when advanced individually, can lead to overall improvements of the main GOTCHAs. With the recent progress made in electronics and miniaturization, fuel cells and regenerative mechanisms, etc., it may be projected that more accurate measurement devices and compact electronic components will be produced and these can lead to substantial savings in weight and heat production while providing higher performance in computational capabilities to sustain the needed modeling efforts. Other examples consist of the latest aeronautical implementations such as composite materials, TPS, heat management, improved turbine engines, etc. Components such as MEMS devices, liquid pump bearings and impellers, nozzle improvements, and so on, will yield individual advancements which, when taken collectively, can have a major impact on the system as a whole through complex integration and consumer/user feedback. Along similar lines, technologies that allow for flawless aerodynamic morphing or that can reduce gravitational effects through magnetohydrodynamics can drastically alter the current state of GOTCHAs.

Examples of effective small step approaches include the HyShot-HyCAUSE-HIFiRE endeavors, the SHEFEX program, and the X-51 project. The long-term connection underlying the HyShot-HyCAUSE-HIFiRE illustrates the benefits of promoting consistent and well-managed programs. By bridging the gaps that separate academic, governmental, and industrial platforms, each of the HyShot-HyCAUSE-HIFiRE programs leverages the strengths stemming from each sector to bolster its overall capabilities. These efforts capitalize on the reduced overhead associated with the use of academic facilities while at the same time exposing the next generation of students and faculty to valuable education in hypersonics that draws from the latest developments in industry. The current derivative, HIFiRE, continues to proceed along this line of constructive outcomes. The SHEFEX also displays consistency with its two launch experiments, SHEFEX I and II, while managing its resources quite effectively by utilizing well-established sounding rocket flight technology. In addition to these efforts, the role of commercial entities must not be under-rated, especially when taking into account the recent shifts that have occurred in the aerospace industry. Private companies such as SpaceX and Virgin Galactic are now able to fund in-house projects that are comparable in size to those that NASA once used to manage. This paradigm shift can promote substantial cost reductions, open technical exchanges, and friendly competition within the commercial sector. However, the recent disinterest in hypersonic and space access programs by NASA is discouraging as their many years of experience in all facets of aerospace research complements the latest private space endeavors.

Finally, in the spirit of effective management of HypTAs and GOTCHAs, it would be helpful to establish a well-organized central database on hypersonics research that may be accessible online. Such a repertoire can be very useful in archiving technical resources, publications, and lessons learned in the variety of subdisciplines that affect hypersonic flight. Along similar lines, a review/progress series may prove beneficial to pursue. Surely, the development of such resources will require maintenance and technical supervision to sift through the wealth of information that is produced on a continual basis. Screening, logging, indexing, and updating this database can be crucially important in helping the world of hypersonics to overcome the various GOTCHAs that still stand in its way.

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Vita

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I was born and raised in Nashville, TN where I lived for approximately 23 years and where my parents still reside. I graduated high school in 2001 from David Lipscomb. I spent my first two years of undergraduate education at Lipscomb University studying Engineering Mechanics. In 2003 I transferred to the Tennessee Technological University in Cookeville, TN (about 80 miles east of Nashville). I graduated from TTU in May of 2006 with a BS in Mechanical Engineering. In the same year, I moved to Huntsville, AL for 6 months and worked at the Redstone Army Base as a Mechanical Trade Helper for Alutiiq, Inc. My duties encompassed assisting technicians who maintained and installed security systems around the base while I finished my last classes for TTU. Since the fall of 2006, I have attended the University of Tennessee Space Institute in Tullahoma, TN, pursuing both an MS and PhD degree in Aerospace Engineering under the supervision of Dr. Majdalani. My work was conducted in collaboration with the Advanced Theoretical Research Team and Labs. My two research foci have been hypersonic vehicle technology and analytical modeling of internal fluid flows. I have jointly published two conference papers with my advisor entitled, *Current State of High Speed Propulsion: Gaps, Obstacles, and Technological Challenges in Hypersonic Applications* and *Exact Eulerian Solution of the Conical Bidirectional Vortex.*