Tackling the Extreme Challenges of Air-Breathing Hypersonic Vehicle Design, Technology, and Flight

Mathematics, Computing & Design Symposium
Honoring Antony Jameson’s 80th Birthday
Stanford University, CA
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Senior Technical Fellow
Chief Scientist of Hypersonics
The Boeing Company
Past Hypersonics – Rocket-Boosted Gliders

X-15 Rocket Plane

Space Shuttle Orbiter

Space Capsules

Ballistic Reentry Vehicles
Extremely High Boost Speed Required to Glide Across Continents or Oceans

Initial Speed (ft/s)

Range (nmi)

L/D = 4

Approximate Integration
Exact Integration
Present and Future Hypersonics – The Development and Application of Hypersonic Air-Breathing Propulsion

Engineering, Operations & Technology | Boeing Research & Technology
Platform Performance Technology

High Speed Missiles
- Mach 5-7 Cruise
- Mach 10-20 Glide
- Hundreds of miles in minutes/global range in under an hour
- High kinetic energy
- Increased survivability
- Throttling provides flexible operation

High Speed A/C
- Mach 6-7 Cruise
- Global range in ~ 2 hours
- High utilization rate

Affordable Space Access
- Large (10-20 klb) Payload
- Small (100-500 lb) Payload
- Routine and affordable space launch
- Lighter weight permits horizontal takeoff
- Aircraft-like operations and maintenance
- Operational flexibility and safety

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Dramatically Changing Flow Physics With Mach Number Makes Hypersonic Vehicle Design Challenging

Limit of continuum regime
Slip-flow regime
Ascent and Reentry Vehicle (ARV)
Reentry Vehicle (RV)
Aerocardi Orbital Transfer Vehicle (AOTV)
Stage separation of Turbo-Engine-Antenna (TSTA)
Vortex effects large
Laminar-turbulent transition
Weak real-gas effects
Laminar flow
Prandtl-Meyer flow
Transition laminar-bulbent
Surface radiation
Pressure effects dominate
Strong reacting flow effects
Low density effects
Pressure and viscous effects important
Surface radiation
Strong reacting flow effects
Low density effects
Surface radiation
Arrows indicate flow directions.

Mach Number

h (km)

U∞ (km/s)
Extreme Aero Heating Adds to the Hypersonic Vehicle Design Challenge

• Aerodynamic heating increases in proportion to
  – Cube of air speed at constant density (i.e., altitude)
  – Air speed at constant dynamic pressure

![Radiation Equilibrium Temperature: 5-deg Wedge with 0.2 in Leading Edge Radius, 40 in from leading edge, Q = 1 atm](image.png)
Technology Demands Also Challenge Hypersonic Vehicle Design

- Large scramjet engines
  - Ground test limitations: High flow energy limits test engine size and test time
  - Must develop via flight test and computer simulation
- Integrating low- and high-speed propulsion systems
  - Turbine engines, ramjets, scramjets, rockets, combined cycles
- Durable high-temperature materials
  - Durability and maintainability similar to metals but capable of 2500 – 5000 °F operation
- Designing highly integrated (blended) vehicles
Supersonic Combustion Ramjets (Scramjets) the Key to Efficient Air-Breathing Hypersonic Flight

- Shock waves must efficiently compress, heat and slow air
- Turbulence must mix and burn air to near completion in ~1 msec

Performance levels verified in flight by X-43A and X-51A
Low-Speed Engines Required to Accelerate Vehicles to Scramjet Starting Speed of About Mach 4
Ceramic Composites Required to Accommodate High Temperatures – Leading Edges

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- State of the art
  - Space shuttle orbiter RCC
  - X-43A single use

- Requirement
  - Multi-use
  - Light weight
  - High heat flux/temperature
  - Sharp

- Technical challenges
  - Durability
  - Life
  - Manufacturing

- Current advanced material capability
  - DARPA HTV-2 3600°F
Ceramic Composites Required to Accommodate High Temperatures – Surface Panels & Components

Mechanically Attached CMC Panels

- N610/AS Oxide-Oxide CMC
  - N610 alumina fabric-reinforced aluminosilicate matrix
  - Density similar to aluminum
  - Layup and cure similar to polymer based composites

C/SiC Body Flaps

*CMC’s are the material system that will provide the required strength at elevated temperature*
• Tanks must be lightweight, robust and long-life
• Joint design critical to non-round tanks
Air-Breathing Propulsion Integration Critical to Efficient Hypersonic Flight

Body-Integrated Scramjets

- Outward Turning Inlets
- Inward Turning Inlets

Pod-Mounted Scramjets

- Engine flowpath topology options
- Low drag integration
- Large inlet and engine for high thrust/drag
- Optimal propulsion contribution to vehicle lift and trim
High Thrust-to-Drag Ratio a Critical Requirement for Air-Breathing Accelerators

[Graph showing the relationship between Thrust-to-Drag Ratio and Propellant Fraction Required for Hydrocarbon PFR to M7 and Hydrogen PFR to M14]
Highly integrated nature of hypersonic vehicles makes them difficult to design

- Highly integrated = all vehicle parts and functions interact
  - Aero, propulsion, control, structure, tank, thermal protection, etc.
  - A flying engine:
    - Most of the aircraft is part of the engine inlet or nozzle
    - Engine produces lift and rotational torque as well as thrust
  - A flying fuel tank: most of internal volume filled with fuel
  - High temperature insulated structure or thermal protection shell that limits heat penetration inside vehicle
New Design Approach Essential for Highly Integrated Systems Such as Hypersonic Vehicles

Conventional Design

- Conventional airplane design approach cannot be used for highly integrated hypersonic vehicles

Highly Integrated Design

- New design approach requires integrated computer design tools and mathematical optimization
  - Multidisciplinary Design Optimization (MDO)
Numerical Example Illustrates Integrated Vehicle Design Challenge

• Design Challenge: “Needle in a haystack problem”
  • Large number of variables (V)
  • Several permutations (P) of each variable required to capture interactions
  • Number of possible designs, \( N_D = P^V \)

<table>
<thead>
<tr>
<th>V</th>
<th>P</th>
<th>( \times 10^3 )</th>
<th>( \times 10^6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
<td>243</td>
<td>1024</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>59,049</td>
<td>1.05 x 10^6</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>1.43 x 10^6</td>
<td>1.07 x 10^9</td>
</tr>
</tbody>
</table>

• Optimization algorithms permit efficient design space searches
Feasible/Superior Hypersonic Vehicle Design Enabled by Multidisciplinary Design Analysis & Optimization

1. Develop Parametric Vehicle Model & Select Parameters (Variables) for Optimization
2. Construct Design of Experiments – Defines Vehicle Set for Analysis
3. Perform Multidisciplinary Analysis of Vehicle Set
4. Create Mathematical Model of Analysis Output
5. Analyze Model Quality (Analysis of Variance)
6. Run Optimizer to Find Best Design
7. Add Configuration Design Details
8. Refine Optimization
Phoenix Integration’s ModelCenter® Used to Integrate Hypersonic Vehicle Analysis Tools Into an MDA System

- Geometry
- Propulsion
- Aerodynamics
- Mass Properties
- Performance
- Aerothermal
- Mass Properties
- Performance
- Tabulate Metrics

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GEODUCK Provides MDAO-Friendly Parametric Analysis-Ready Geometries

- MDAO-friendly parameterization
  - Robust for large parametric variations
  - Continuous geometry in design space
- Allows coding of physics and engineering rules into geometry construction (Example: Waverider)
- Directly feeds analysis codes
  - CFD-ready outer mold line
  - Inputs for mass properties analysis
  - Pseudo streamlines for aerothermal analysis
- Can run multiple instances in batch mode on computer cluster
- Easy to program Jython environment
MDAO Demonstrated on 2\textsuperscript{nd} Stage of a Two-Stage-To-Orbit Reusable Launch Vehicle

\begin{itemize}
  \item ~50 design parameters used to define 2nd-stage geometry model
  \item 12 design parameters selected for MDO
    \begin{itemize}
      \item 6 propulsion
      \item 6 body
    \end{itemize}
\end{itemize}

- Upper Nose Angle
- Body Waterline Angle
- Maximum Body Height
- Maximum Height Station
- Design Mach Number
- Horizontal Cowl Lip Station
- Internal Contraction Ratio
- Engine Cant
- Nozzle Cowl Length
- Nozzle Expansion Ratio
- Maximum Body Width
- Tail Size
Significant Benefits and Tradeoffs Apparent in MDO Results

Baseline

Optimized

Baseline

Optimized

TOGW Empty Wt. Propellant Fraction

Baseline

Optimized

Ave. Unit Wt. (Volume^2/3)/Swet

Baseline

Optimized

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Motivation For Hypersonic Flight Testing

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• Developing a hypersonic vehicle requires an extensive high-fidelity design database
• Database must contain fundamental and system-level performance data that cannot be gathered completely in existing ground test facilities or [currently] by simulation
• **Flight Testing Required!**
  – High flow energy and extreme thermal environment limit ground testing
  – Flight environment difficult to exactly replicate in ground test facilities
X-43A: Scramjet Operation and Performance Proven in Flight

Two flights at Mach numbers of 6.83 and 9.68 achieved in 2004

Technical Objectives:
- Hypersonic vehicle design risk reduction
- Flight validation of design methods
- Design method enhancement
Hypersonic International Flight Research Experimentation (HIFiRE) Program

International collaboration investigating fundamental vehicle and propulsion phenomena and technologies critical to practical and efficient hypersonic flight

- Conduct basic and applied research
- Conduct flight experiments
- Accelerate maturation of key technologies
- Develop analytical methods & data correlations
- Validate design methods
- Enhance hypersonic design database

Program Goal: Flight test in less time and at lower cost than traditionally possible
Nine Flight Experiments Are Investigating Critical Hypersonic Phenomena
HIFiRE Answering Critical Hypersonic Flight Technical Questions

International collaboration investigating fundamental vehicle and propulsion phenomena and technologies critical to practical and efficient hypersonic flight

- Boundary layer transition measured on an axisymmetric cone at Mach 5-7
- Hydrocarbon dual-mode scramjet mode transition from thermally choked ramjet to scramjet (Mach 5.4 - 8+)

N = 14
**X-51A Scramjet Engine Demonstrator (SED)**

**Program Objectives**
- Flight demonstration of an endothermic hydrocarbon–fueled scramjet engine
- Performance Goal: Scramjet acceleration from ~ Mach 4.5 to 6
- Demonstrate scaleable scramjet propulsion, high temperature materials, airframe/engine integration, multidisciplinary design optimization (MDO)
- Purpose: Supports future hypersonic weapons, low cost space access, and global reach

- Four air vehicles designed and fabricated, one flown
- Team: Boeing, Pratt & Whitney Rocketdyne, AFRL, DARPA, NASA, AFFTC, ASC, NAVAIR
### X-51A Vehicle Overview

#### X-51A Mass Properties

<table>
<thead>
<tr>
<th>Description</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruiser Operating Weight</td>
<td>1225 lb</td>
</tr>
<tr>
<td>Booster</td>
<td>2277 lb</td>
</tr>
<tr>
<td>JP-7 Fuel (Useable)</td>
<td>265 lb</td>
</tr>
<tr>
<td>Interstage</td>
<td>160 lb</td>
</tr>
<tr>
<td>Cruiser Launch Weight</td>
<td>1504 lb</td>
</tr>
<tr>
<td>Stack Gross Weight</td>
<td>3942 lb</td>
</tr>
</tbody>
</table>

#### X-51A Dimensions

- **Cruiser length:** 168 inches
- **AVD Stack length:** 301 inches
- **Max body width:** 23 inches
- **Engine flow-path width:** 9 inches
X-51 Subsystems Packaging
Shows Component Locations

Engine Subsystems (Packaged Wet in JP-7)
- Engine Fuel Pump
- Ethylene (Engine Start)
- Nitrogen (Fuel Pressurization)
- Detailed Line Routing

Subsystems Bay
- GCU/IMU/GPS
- FADEC
- Flight Test Instrumentation (FTI)
- Detailed Line Routing

FTS, FTI and Control Systems
- Antennas
- Sensors
- Control Actuators
- Detailed Line Routing

JP-7 Fuel
- Integral Tanks
- 271 lb
- Sealing Concept Defined

Fuel System
- Fuel Pump
- Detailed Line Routing

Batteries
- Engine Systems
- Actuators
- Avionics and FTI
- Flight Termination System
  (Separate)

D875A-08-03.2
Cleared for Public Release
88ABW-2013-3592
Fuel-Cooled Scramjet Overview
Closed Loop Fuel System & Cold Start

Fuel Coolant Collection Manifold
Fuel Coolant Inlets
Body Exit Manifold
Hot coolant fuel out of HEX
Fuel Dist. Valves
Heat Exchanger Panel
Coolant fuel flow through Heat Exchanger (HEX)
Cold coolant fuel into HEX
Hot fuel into flowpath

X-51 utilizes JP-7 Fuel

Engine controlled via F-119 FADEC

Note: FADEC and Fuel Pump not shown

Cleared for Public Release
88ABW-2013-3592
X-51 Flight Test Summary

Four Powered Flights over Three Years (May ‘10 – May ‘13)

First Flight: May 26th, 2010
- 143 seconds of scramjet operation
- Peak Mach of 4.87; 150 nm travelled
- Seal / nozzle breach ended flight early

Second Flight: June 13th, 2011
- Engine “unstarted” nine seconds after scramjet ignition
- Post-flight investigation and ground testing yielded several scramjet operability lessons learned

Third Flight: August 14th, 2012
- Run-away control fin actuator and loss of control prior to engine light

Fourth Flight: May 1st, 2013
- Full duration flight: ~209 seconds of scramjet operation and 361 seconds of controlled flight
- Peak Mach of 5.1; ~240 nm traveled in six minutes
X-51A: Verified Flight-Weight Hydrocarbon Scramjet Operability & Performance

Four Powered Flights over Three Years (May ‘10 – May ‘13)

Fourth Flight: May 1\textsuperscript{st}, 2013

- Full duration flight: \sim 209 seconds of scramjet operation and 361 seconds of controlled flight

- Scramjet acceleration from Mach 4.8 to \sim 5.1; \sim 240 nm traveled in six minutes

- Proved benefits of MDO to integrated engine-airframe performance, trim, and control

- Pre-flight lift, drag, and moment CFD predictions compare to flight data with less than 5% error
Hypersonic Technology Could Change the World

What might the future hold with mature hypersonic technology and proven vehicle design concepts in hand?
We Need A More Affordable Way of Getting to Orbit!

Current launch costs of $5,000 to $10,000 per lb would require tens of $B just to put manned space exploration payloads in low earth orbit

- Reductions limited with expendable systems
A Combination of Reusability, Reliability and Utilization Rate Drive Launch Affordability

Current launch cost $5,000 to $10,000 per lb to LEO

Launch cost < $500 per lb possible with a fully reusable system, high system utility, and sufficient markets

- Hypersonic technology and horizontal launch beneficial to goal
Possible Advantages of Airbreathing Launch Vehicles

- Less propellant required
  - Permits increased dry weight to enhance system robustness/safety/reliability
- Less sensitive to dry weight growth
- Reduced gross weight
  - Airbreathing second stage reduces stage weight – results in smaller first-stage or larger orbital payload
  - Makes horizontal takeoff practical, increasing basing flexibility and reducing base vulnerability to attack
- Horizontal takeoff increases launch window, flight trajectory, and orbit flexibility
- Same technology required for hypersonic ISR aircraft and hypersonic missiles
- Viable growth path for ultimate single-stage-to-orbit
Starting Small to Prove Technology and Vehicle Architecture a Prudent & Feasible Path

• A two-stage air-breathing RLV could dramatically reduce launch cost (> 10X)
• A large payload system would be very expensive to develop and have risks difficult to mitigate before development

• A small system would be much more affordable and much less risky to develop
• Significant interest in, and valuable applications of, small satellites (10 - 500 lb)
Summary

- Hypersonic vehicles will provide valuable new military and commercial aerospace capabilities
- Hypersonic vehicles have demanding design requirements and tough technical challenges that make their development interesting & rewarding
- Hypersonic vehicle enabling technologies and integrated systems are being rapidly matured via ground and flight testing
Happy 80th Antony!

A fond adieu until we all meet again …