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
21 November, 2014

Dr. Kevin G. Bowcutt
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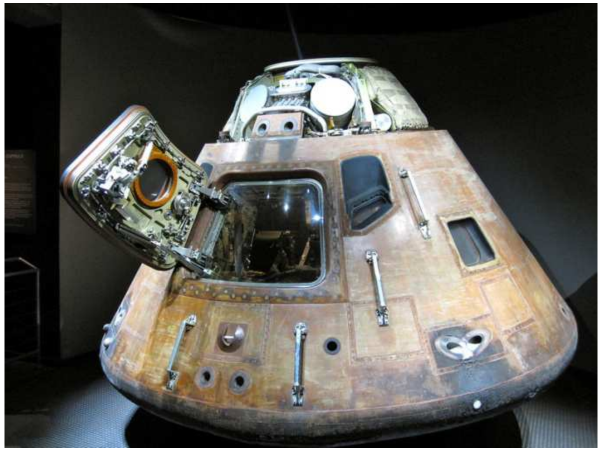
Chief Scientist of Hypersonics
The Boeing Company

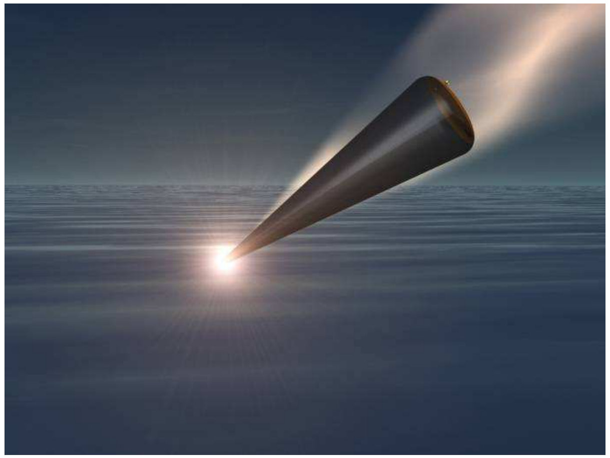
Past Hypersonics – Rocket-Boosted Gliders

X-15 Rocket Plane

Space Shuttle Orbiter

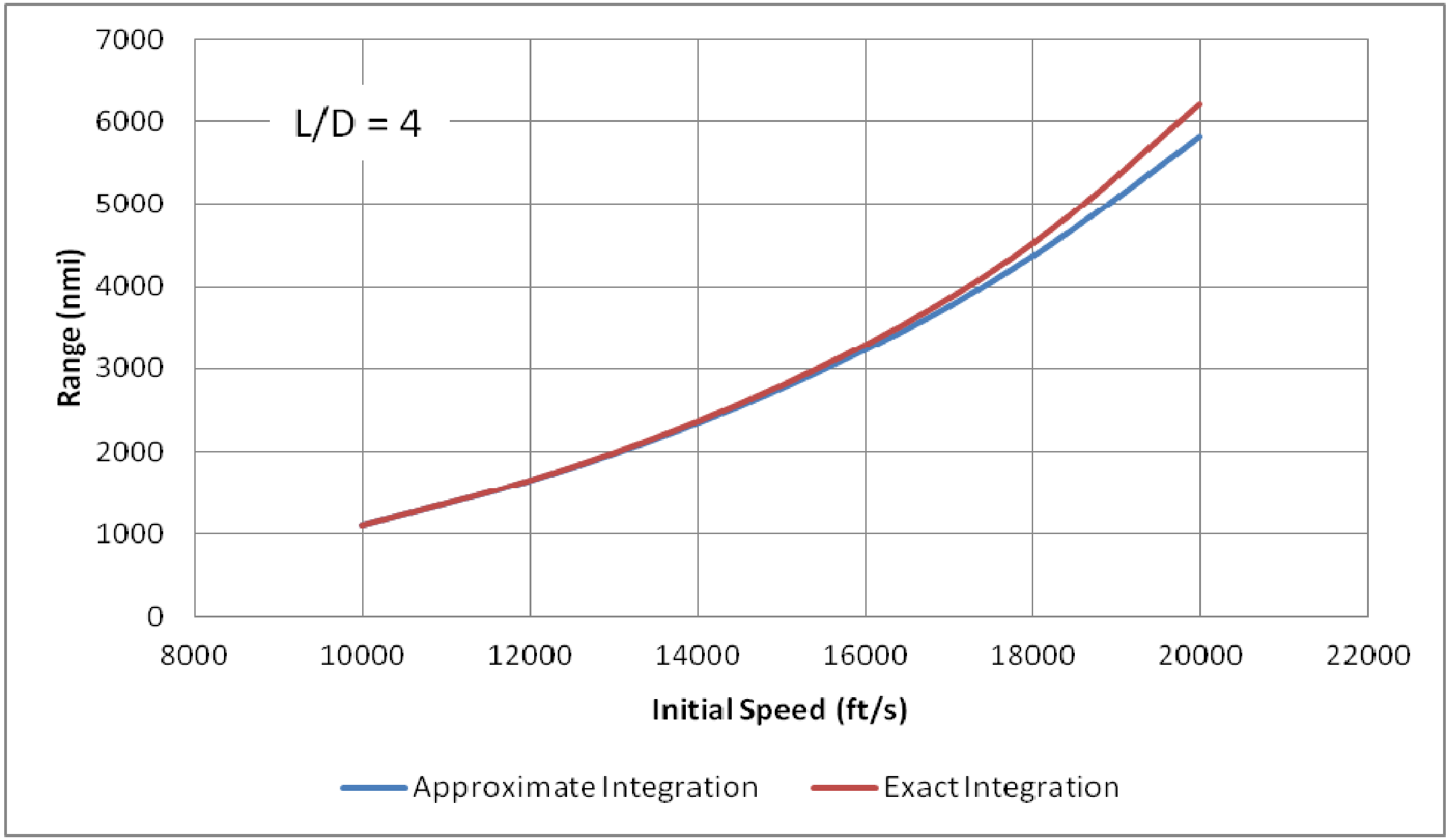


Space Capsules



Ballistic Reentry Vehicles

Extremely High Boost Speed Required to Glide Across Continents or Oceans



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

High Speed Missiles

Mach 5-7 Cruise

Mach 10-20 Glide

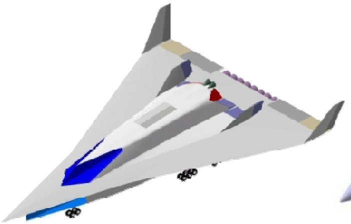
- Hundreds of miles in minutes/global range in under an hour
- High kinetic energy
- Increased survivability
- Throttling provides flexible operation

High Speed A/C

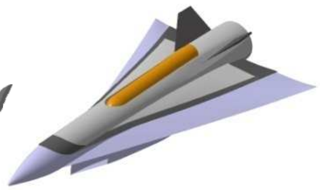
Mach 6-7 Cruise

- Global range in ~ 2 hours
- High utilization rate

Affordable Space Access



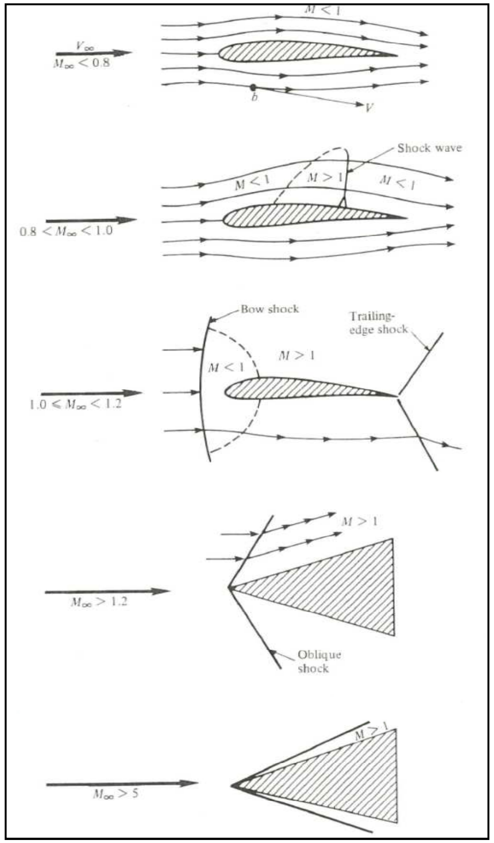
Large (10-20 klb) Payload

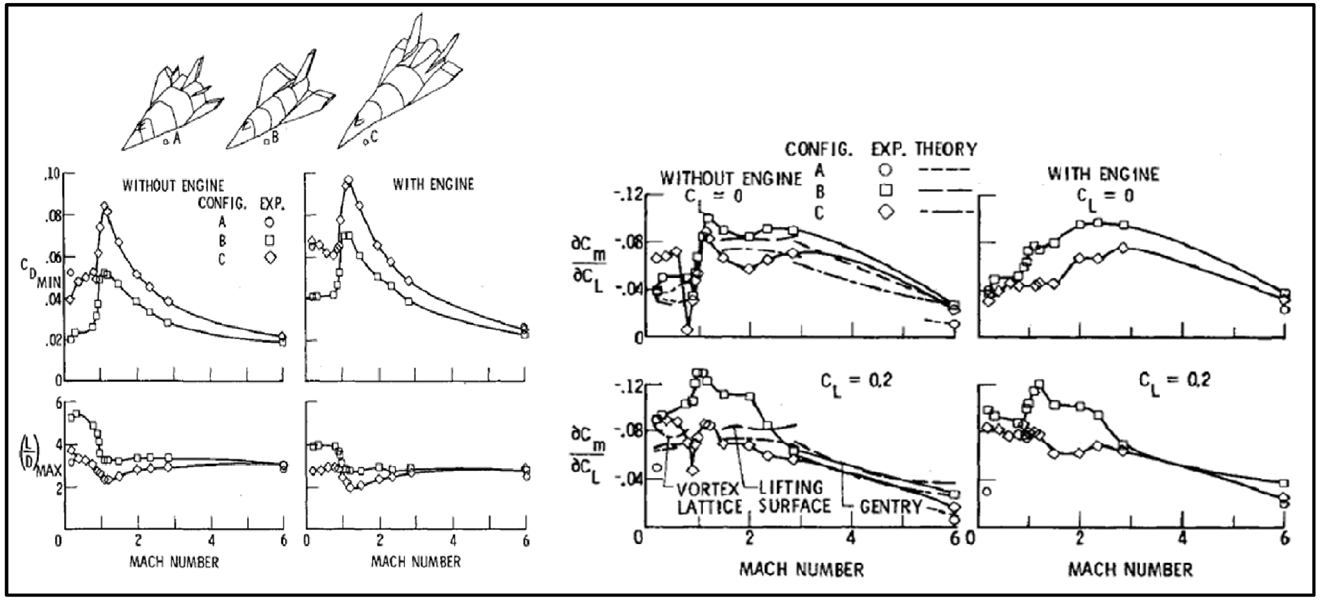


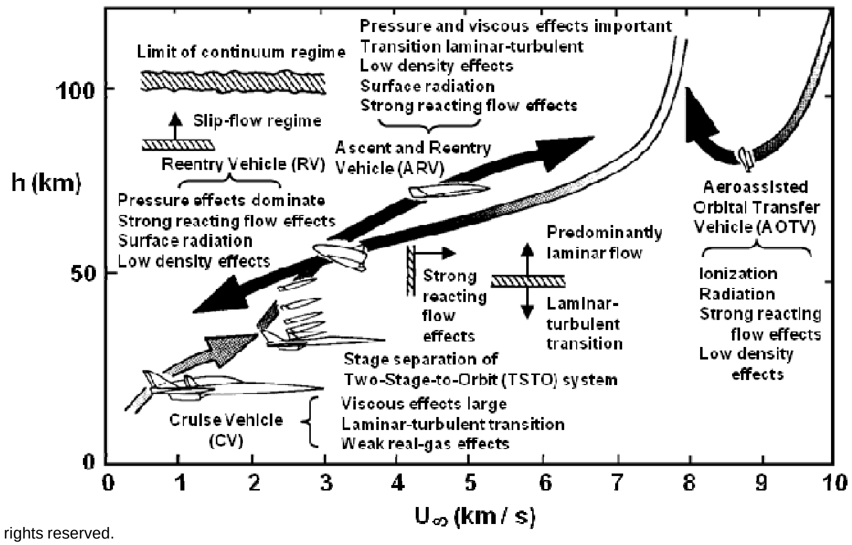
Small (100-500 lb) Payload

- Routine and affordable space launch
- Lighter weight permits horizontal takeoff
- Aircraft-like operations and maintenance
- Operational flexibility and safety

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

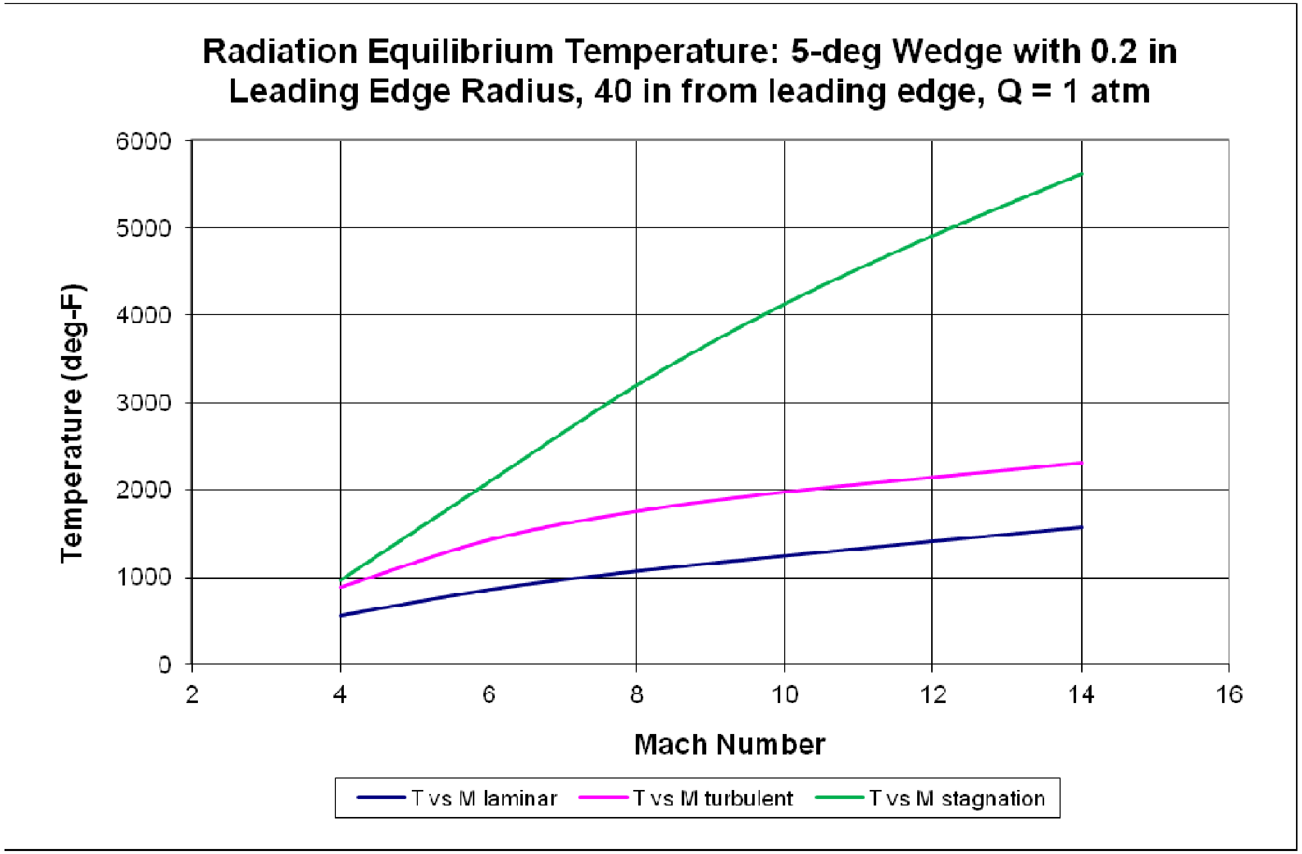






Extreme Aero Heating Adds to the Hypersonic Vehicle Design Challenge

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

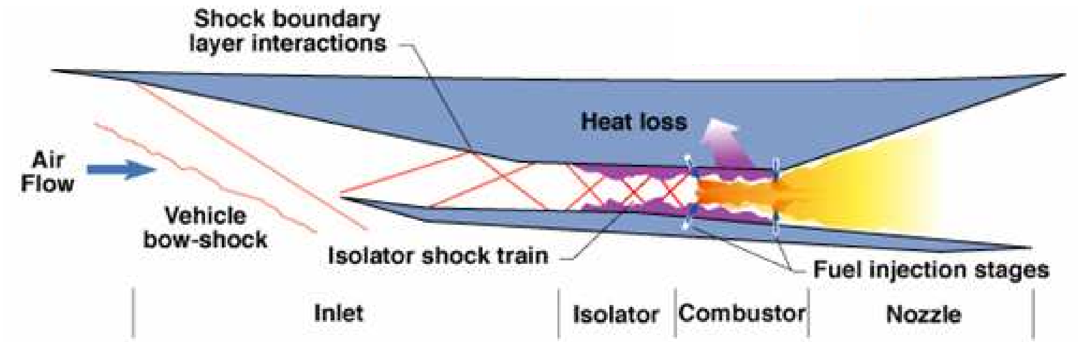


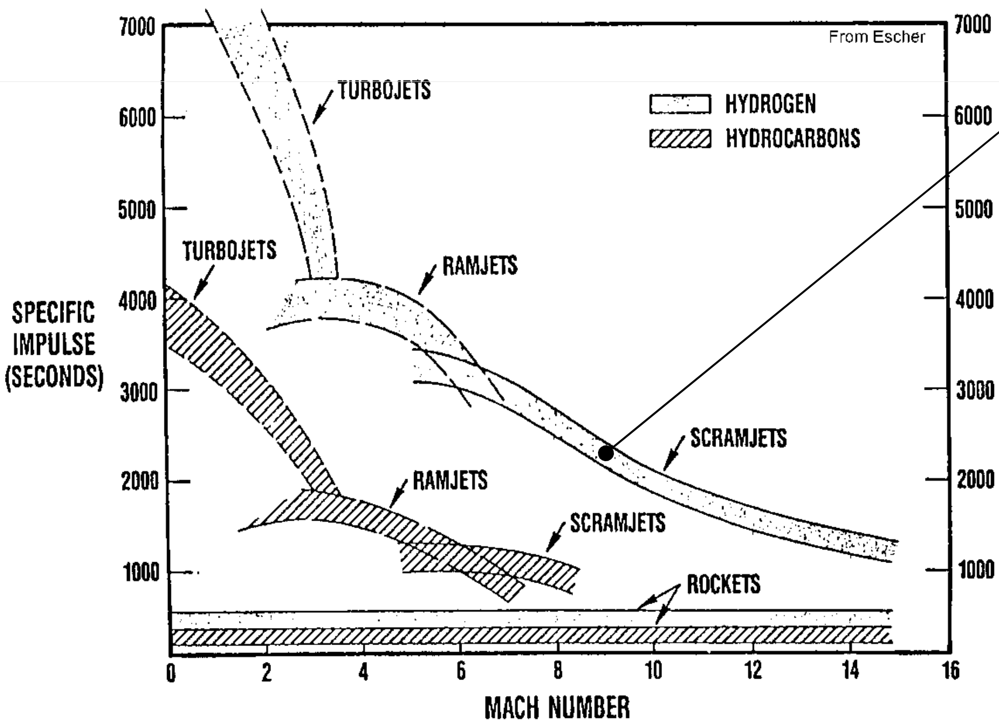
Technology Demands Also Challenge Hypersonic Vehicle Design

- **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

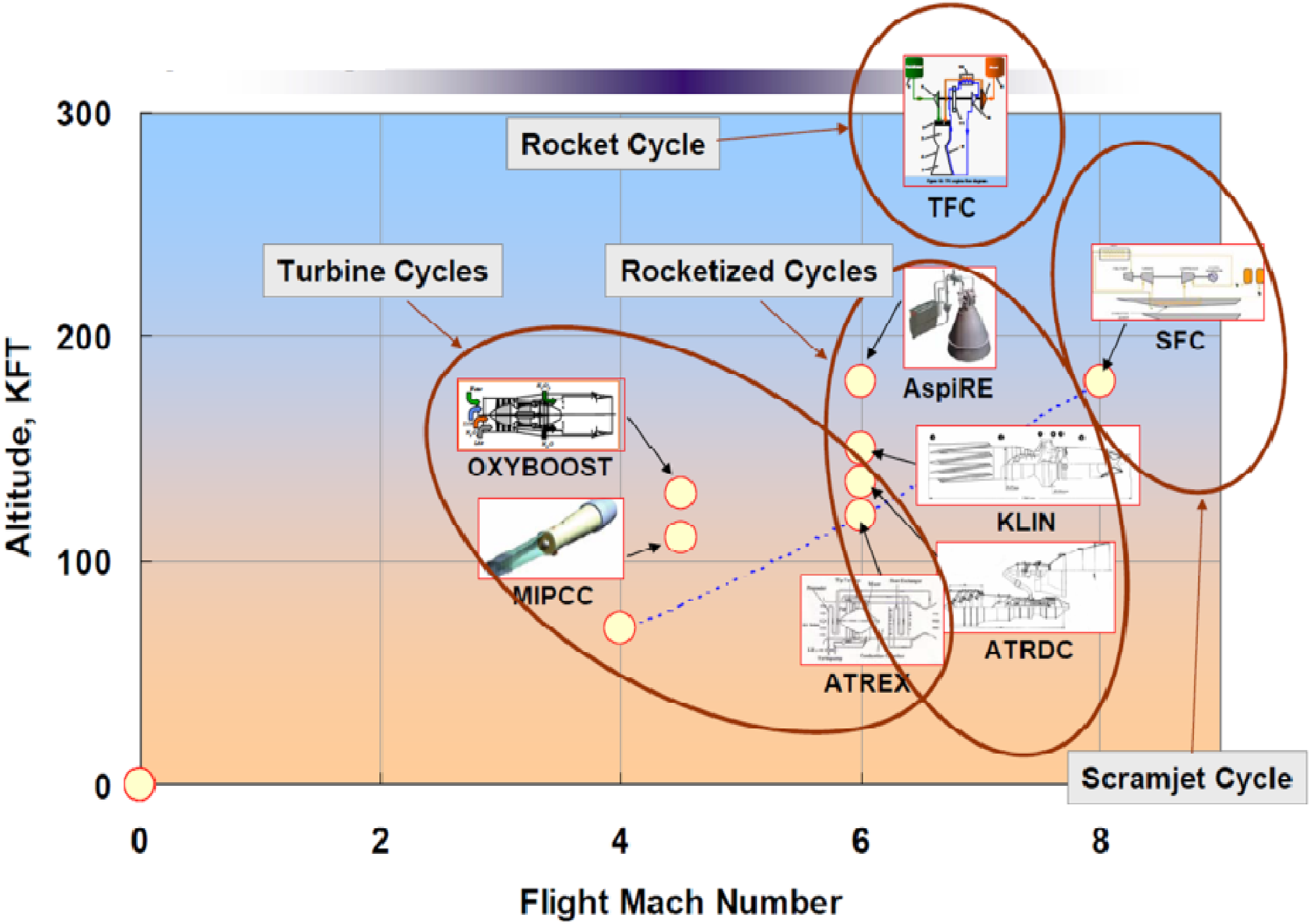
- **Shock waves must efficiently compress, heat and slow air**
- **Turbulence must mix and burn air to near completion in ~ 1 msec**





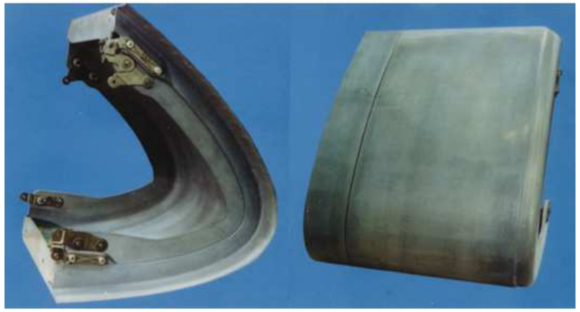
Performance levels verified in flight by X-43A and X-51A

Low-Speed Engines Required to Accelerate Vehicles to Scramjet Starting Speed of About Mach 4

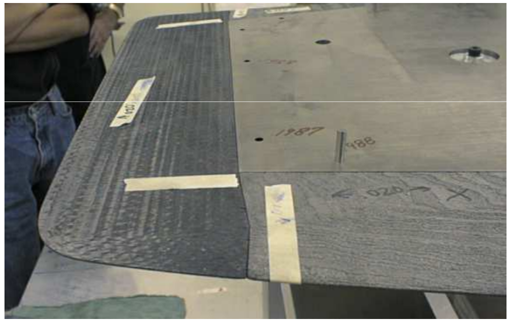


Ceramic Composites Required to Accommodate High Temperatures – Leading Edges

- **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**



Space shuttle Orbiter Leading Edge

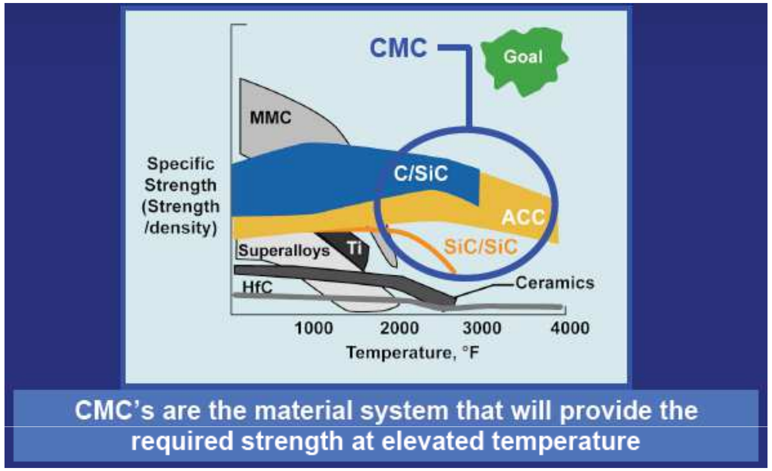


X-43A Leading Edge

Ultra-High Temp Ceramic Test Article

Ceramic Composites Required to Accommodate High Temperatures – Surface Panels & Components

C/SiC Body Flaps



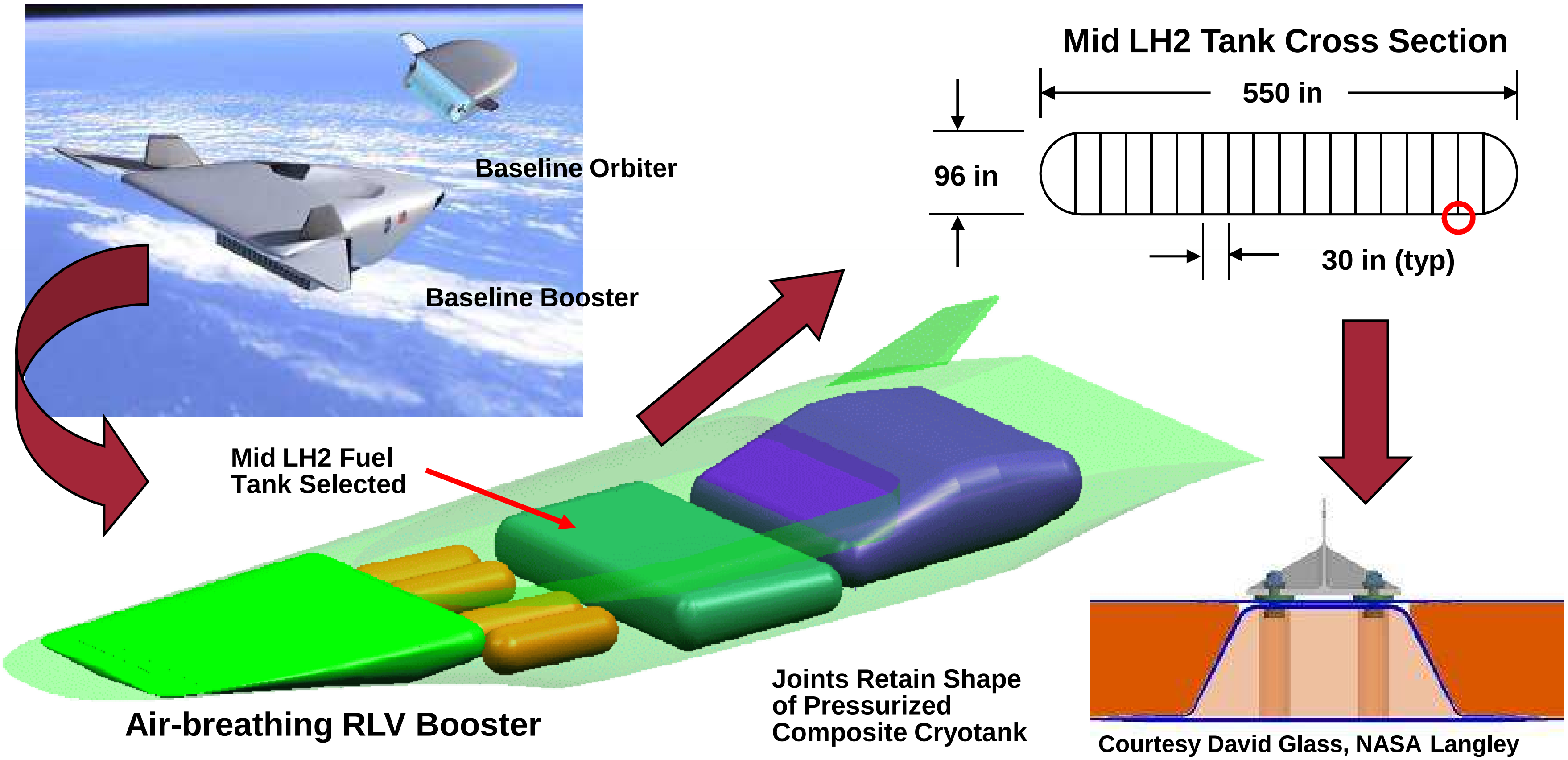
Mechanically Attached CMC Panels

N610/AS Oxide-Oxide CMC

- **N610 alumina fabric-reinforced aluminosilicate matrix**
- **Density similar to aluminum**
- **Layup and cure similar to polymer based composites**

Hypersonic Vehicle Shapes Require Use of Conformal Tanks to Achieve High Propellant Mass Fraction

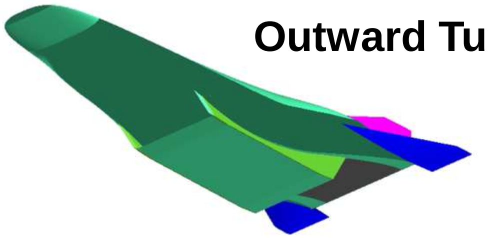
- **Tanks must be lightweight, robust and long-life**
- **Joint design critical to non-round tanks**

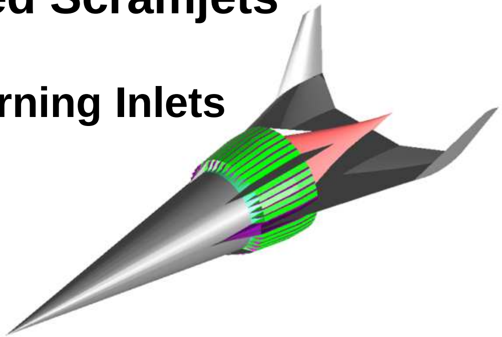


Air-Breathing Propulsion Integration Critical to Efficient Hypersonic Flight

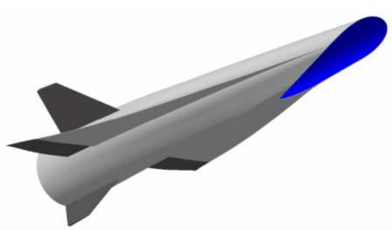
Body-Integrated Scramjets

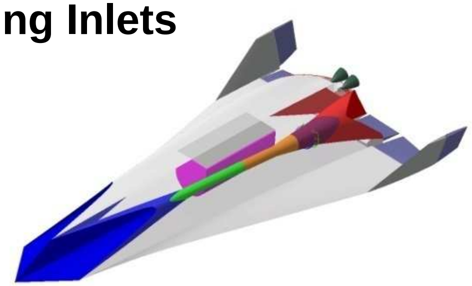
Outward Turning Inlets





Inward Turning Inlets

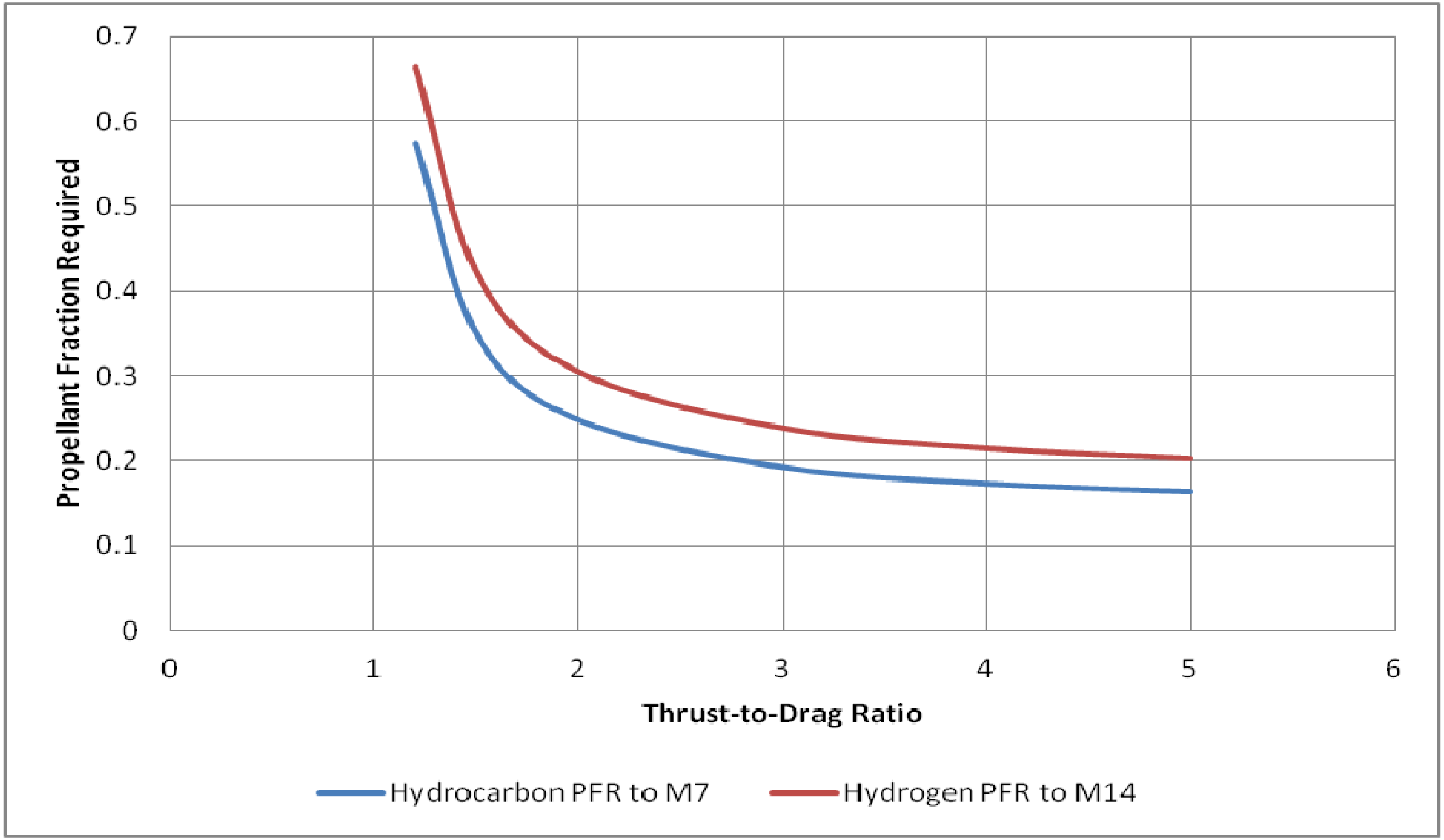




Pod-Mounted Scramjets

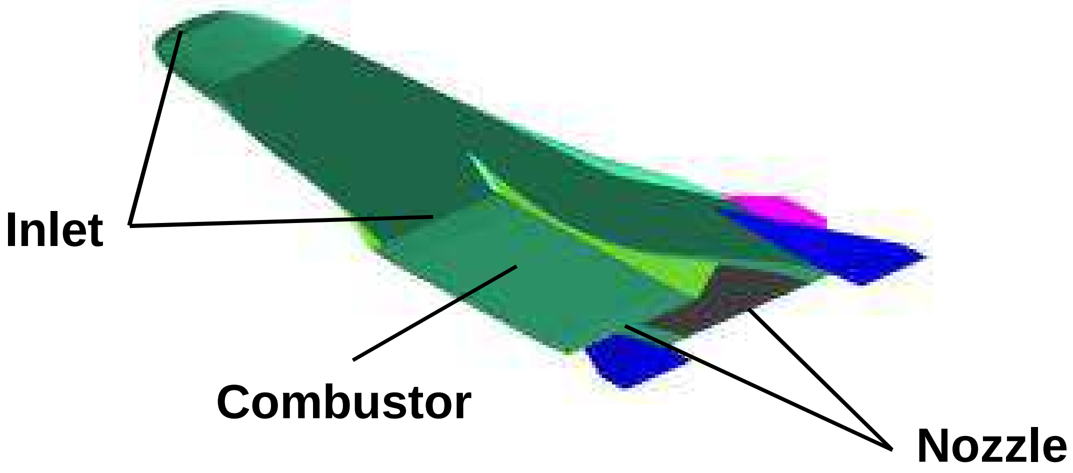
- **Engine flowpath topology options**
- **Low drag integration**
- **Large inlet and engine for high thrust/drag**
- **Optimal propulsion contribution to vehicle lift and trim**

High Thrust-to-Drag Ratio a Critical Requirement for Air-Breathing Accelerators

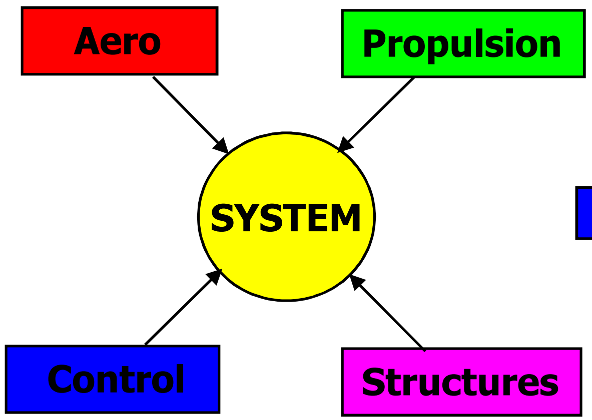


Highly Integrated Nature of Hypersonic Vehicles Makes Them Difficult to Design

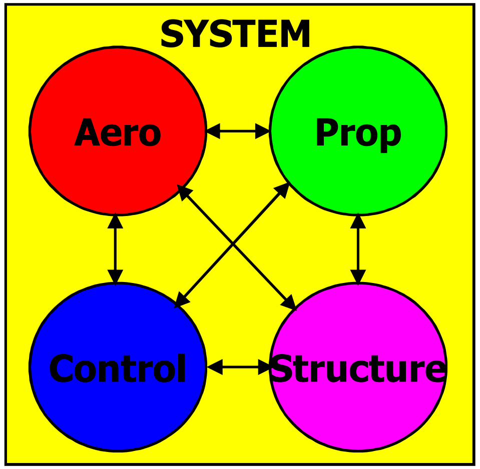
- **Highly integrated = all vehicle parts and functions interact**
  - **Aero, propulsion, control, structure, tank, thermal protection, etc.**
  - **A flying engine:**
    - **Most of the aircraft is part of the engine inlet or nozzle**
    - **Engine produces lift and rotational torque as well as thrust**
  - **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



Highly Integrated Design

- **Conventional airplane design approach cannot be used for highly integrated hypersonic vehicles**
- **New design approach requires integrated computer design tools and mathematical optimization**
  - Multidisciplinary Design Optimization (MDO)

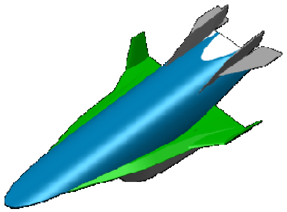
Numerical Example Illustrates Integrated Vehicle Design Challenge

- **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, $N_D = P^V$**

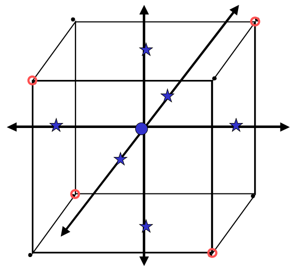
V \ P	3	4
5	243	1024
10	59,049	1.05×10^6
15	1.43×10^6	1.07×10^9

- **Optimization algorithms permit efficient design space searches**

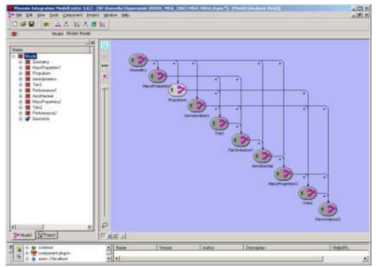
Feasible/Superior Hypersonic Vehicle Design Enabled by Multidisciplinary Design Analysis & Optimization



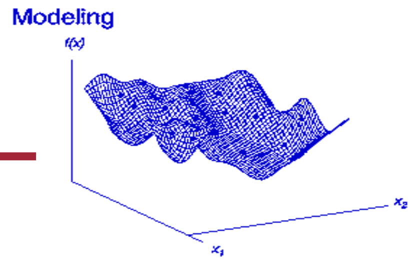
Develop Parametric Vehicle Model & Select Parameters (Variables) for Optimization



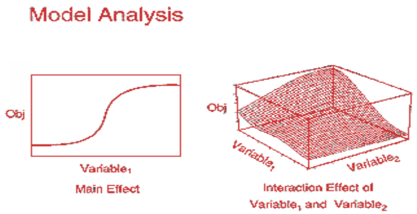
Construct Design of Experiments – Defines Vehicle Set for Analysis



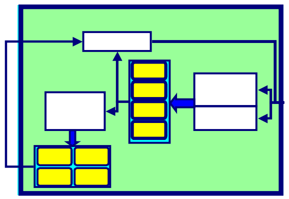
Perform Multidisciplinary Analysis of Vehicle Set



Create Mathematical Model of Analysis Output



Analyze Model Quality (Analysis of Variance)

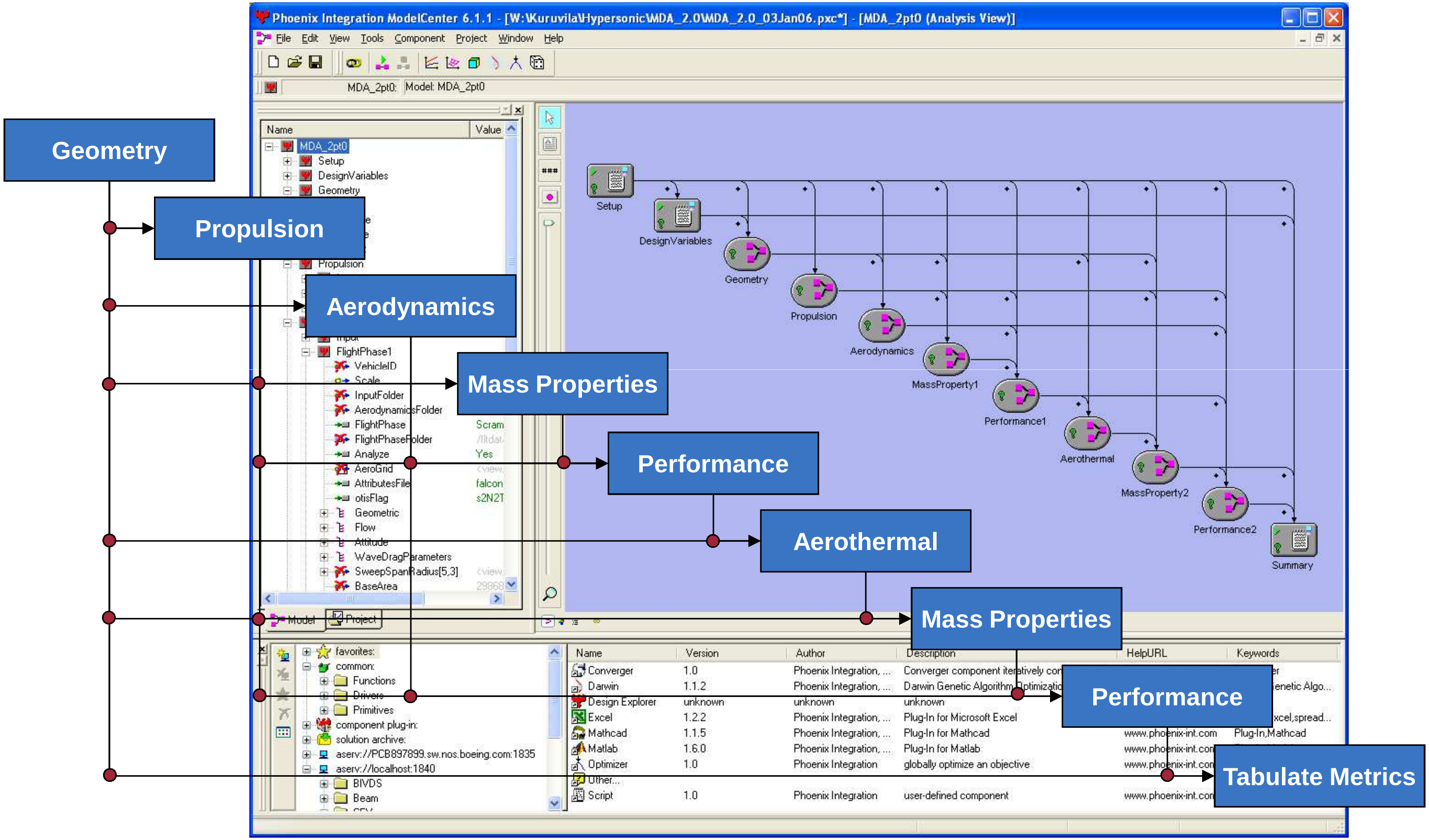


Run Optimizer to Find Best Design

Refine Optimization

Add Configuration Design Details

Phoenix Integration's ModelCenter® Used to Integrate Hypersonic Vehicle Analysis Tools Into an MDA System

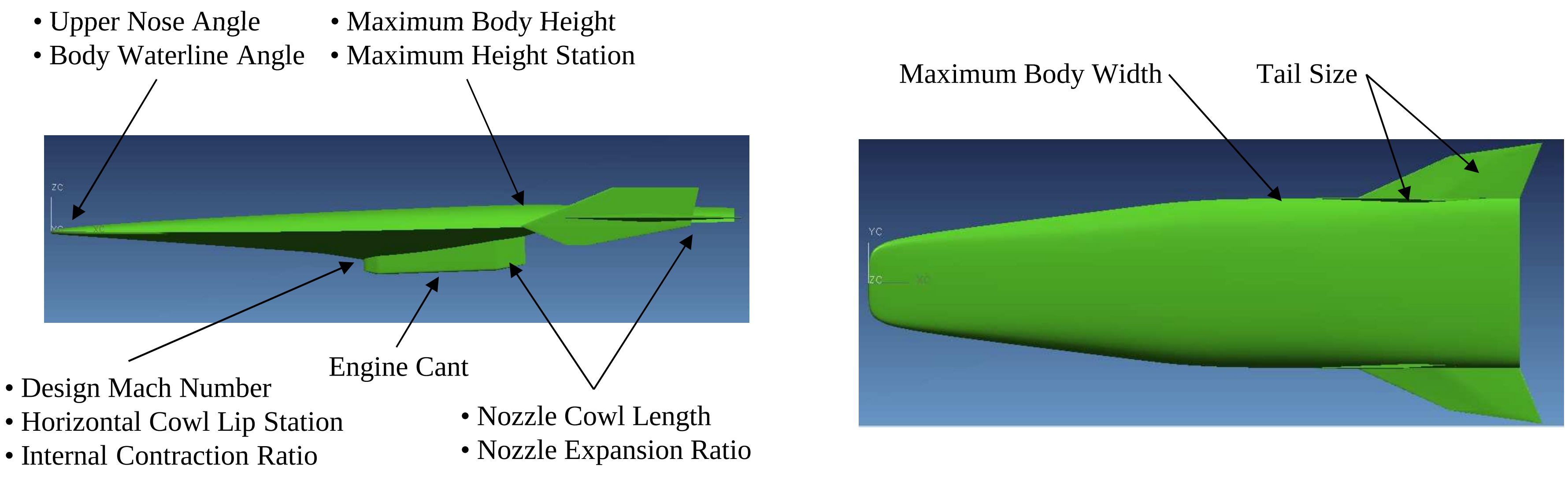


GEODUCK Provides MDAO-Friendly Parametric Analysis-Ready Geometries

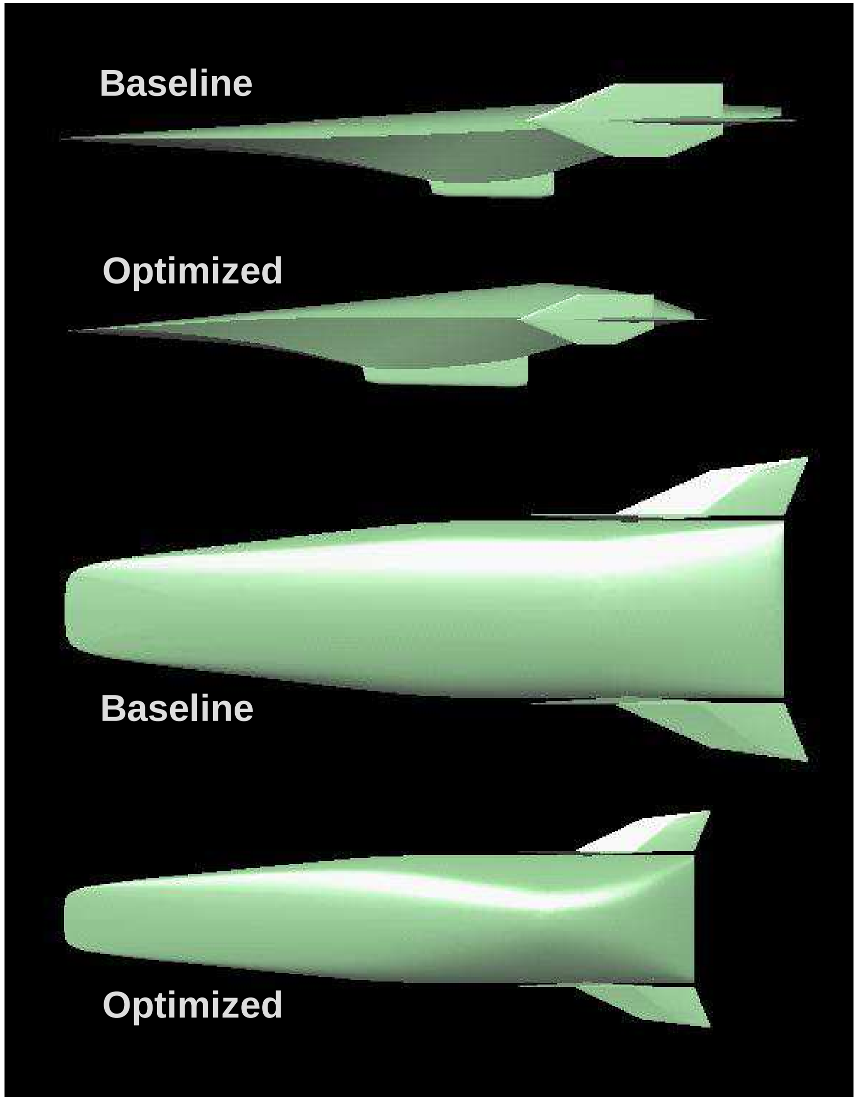
- MDAO-friendly parameterization
  - Robust for large parametric variations
  - Continuous geometry in design space
- Allows coding of physics and engineering rules into geometry construction (Example: Waverider)
- Directly feeds analysis codes
  - CFD-ready outer mold line
  - Inputs for mass properties analysis
  - Pseudo streamlines for aerothermal analysis
- Can run multiple instances in batch mode on computer cluster
- Easy to program Jython environment

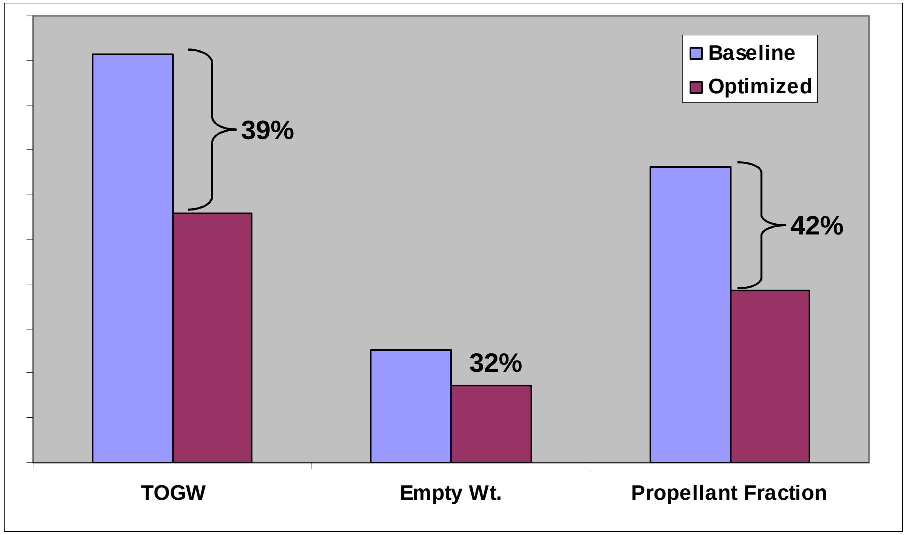
MDAO Demonstrated on 2nd Stage of a Two-Stage-To-Orbit Reusable Launch Vehicle

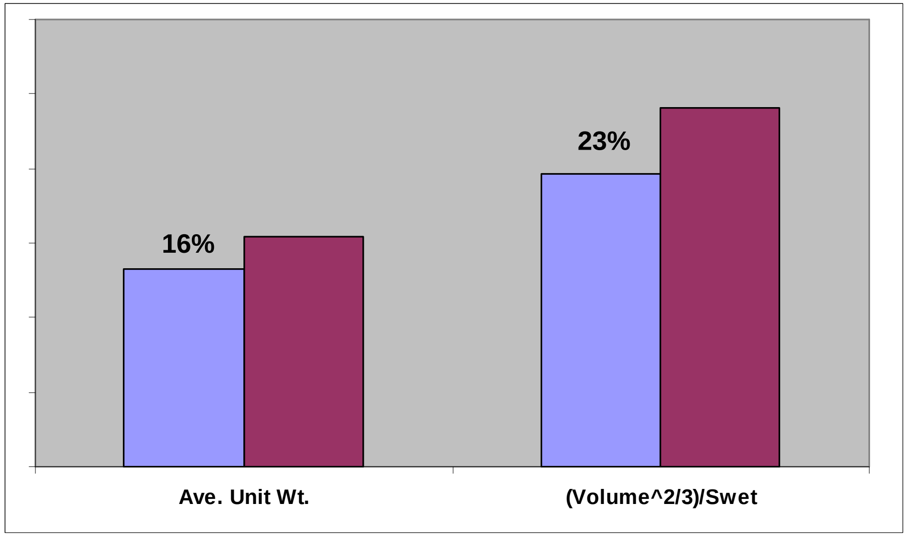
- **~ 50 design parameters used to define 2nd-stage geometry model**
- **12 design parameters selected for MDO**
  - 6 propulsion
  - 6 body



Significant Benefits and Tradeoffs Apparent in MDO Results



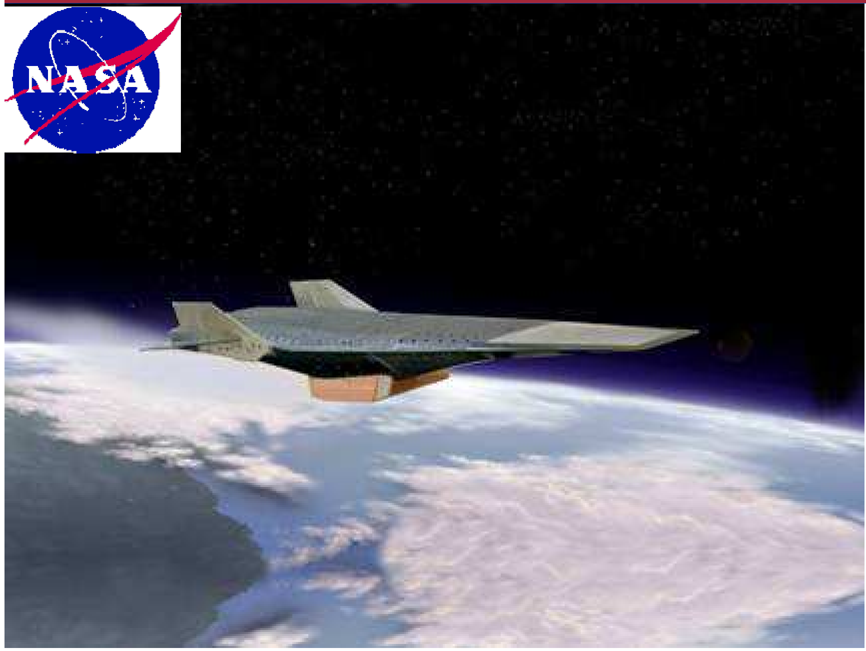




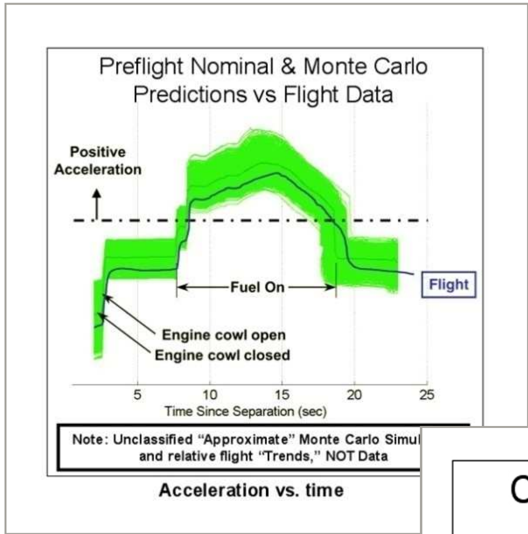
Motivation For Hypersonic Flight Testing

- 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

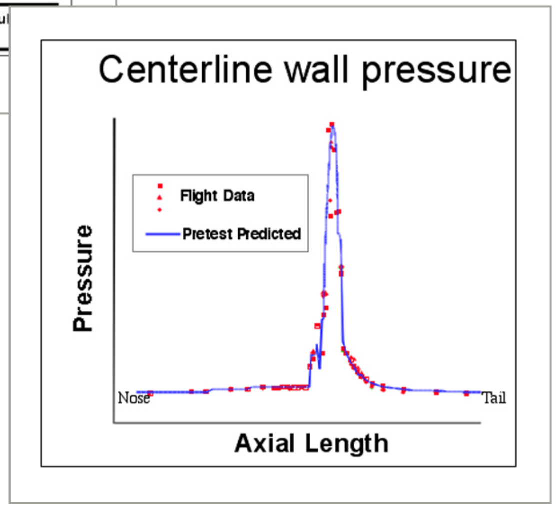
X-43A: Scramjet Operation and Performance Proven in Flight



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



Acceleration vs. time



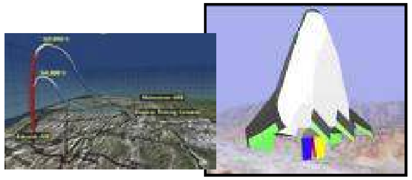
Technical Objectives:

- Hypersonic vehicle design risk reduction
- Flight validation of design methods
- Design method enhancement

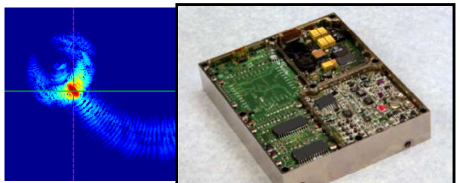
Hypersonic International Flight Research Experimentation (HIFiRE) Program

Australian Government
Department of Defence
Defence Science and Technology Organisation

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

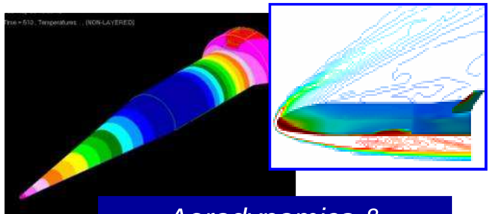


Advanced Flight Control & GNC

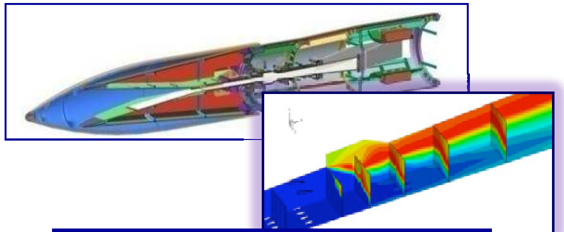


Sensors and Instrumentation

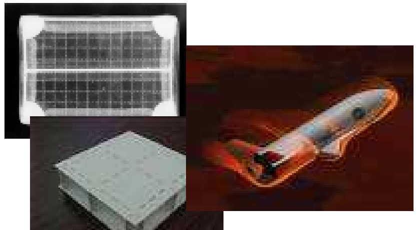
- *Conduct basic and applied research*
- *Conduct flight experiments*
- *Accelerate maturation of key technologies*
- *Develop analytical methods & data correlations*
- *Validate design methods*
- *Enhance hypersonic design database*



Aerodynamics & Aerothermodynamics



Propulsion and Aero-Propulsion Integration



Thermal Protection Systems & Thermal Management

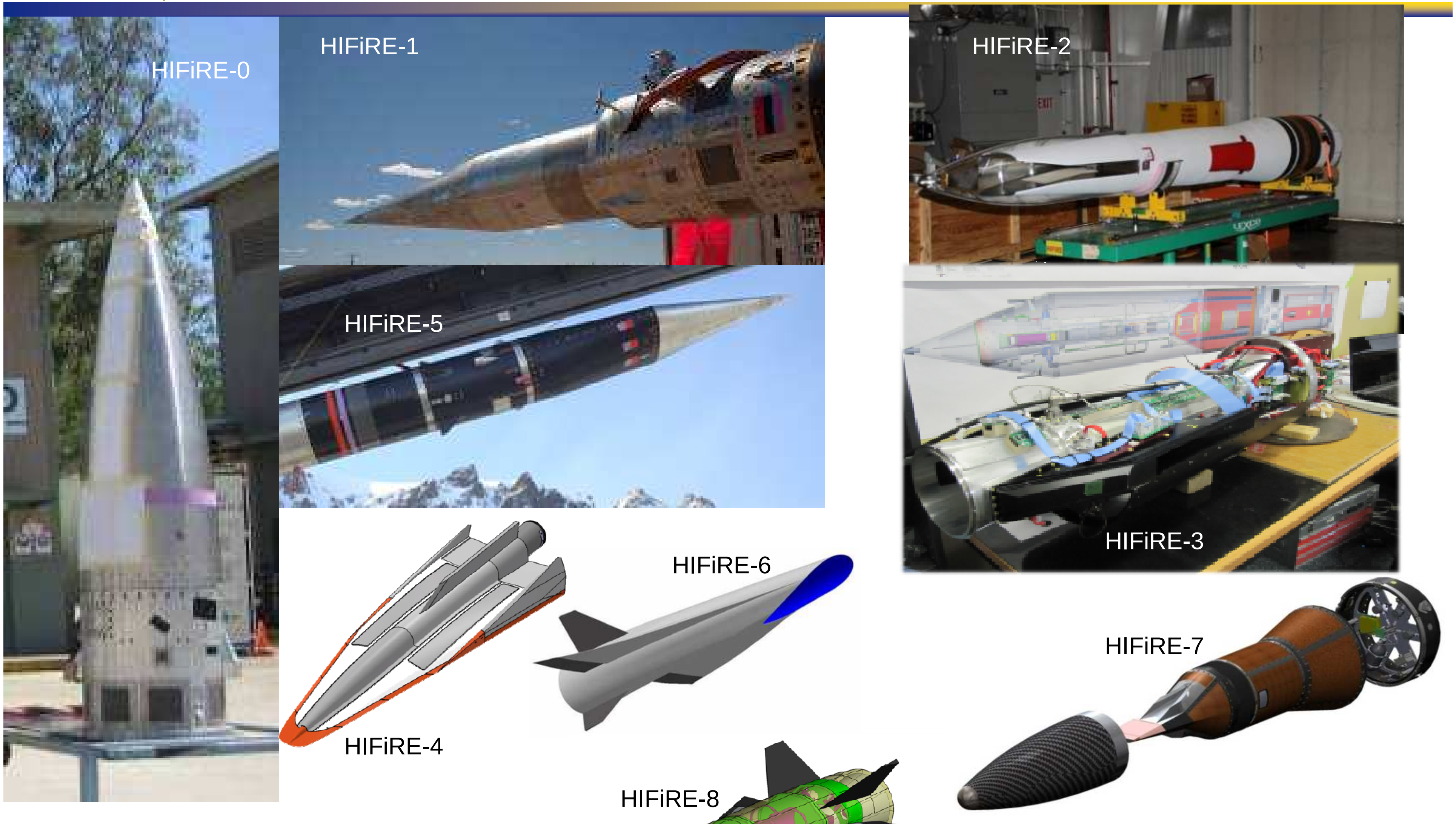
Hot Leading Edges & Structures

Program Goal: Flight test in less time and at lower cost than traditionally possible

BOEING

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

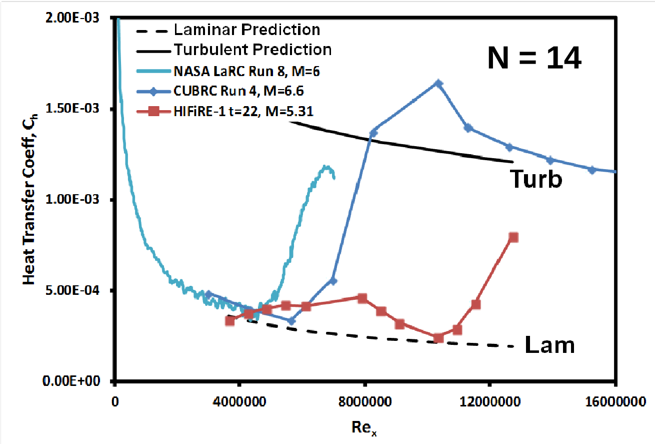
Nine Flight Experiments Are Investigating Critical Hypersonic Phenomena



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+)**

X-51A Scramjet Engine Demonstrator (SED)

Program Objectives

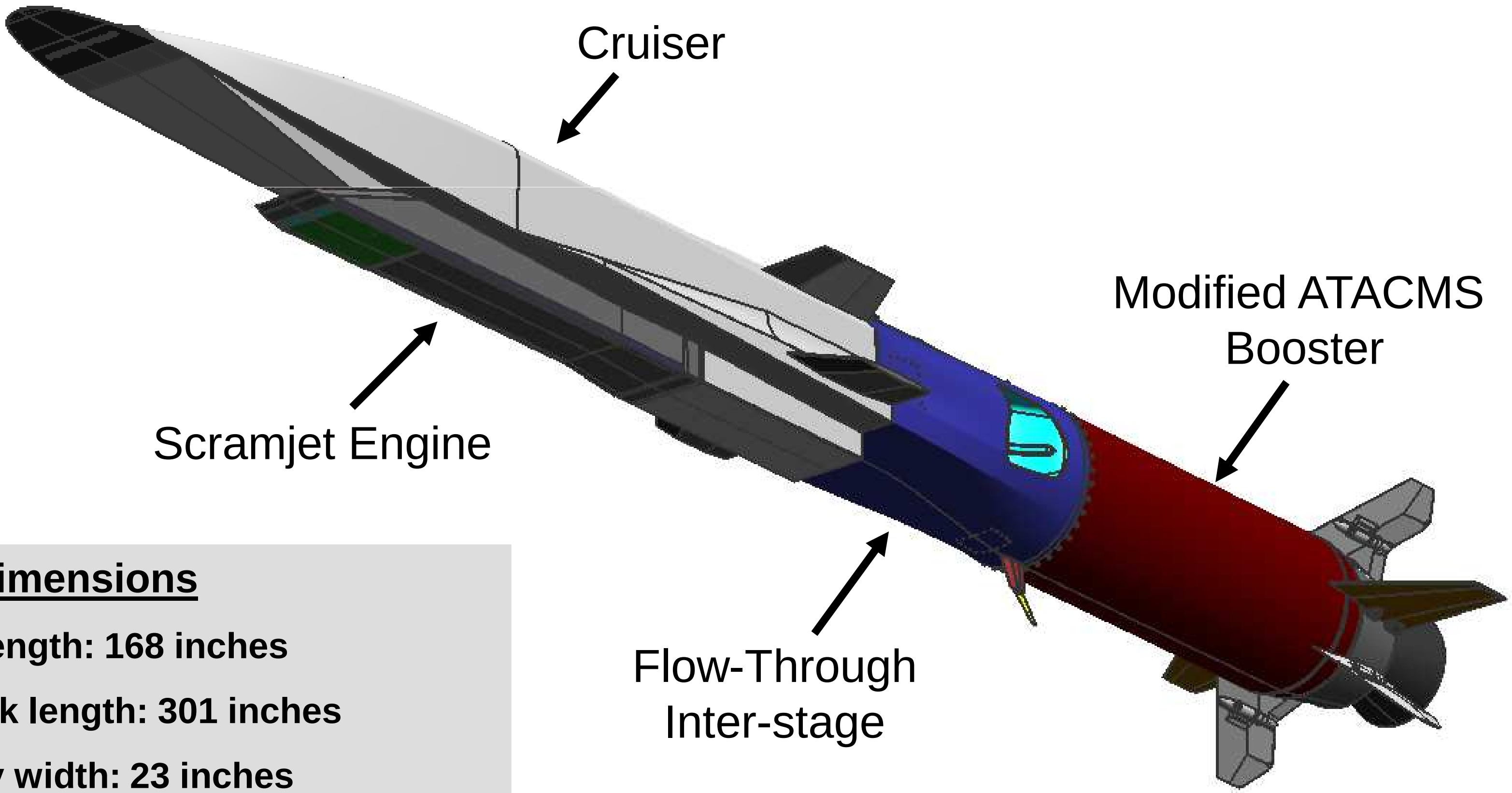
- Flight demonstration of an endothermic hydrocarbon–fueled scramjet engine
- Performance Goal: Scramjet acceleration from ~ Mach 4.5 to 6
- Demonstrate scaleable scramjet propulsion, high temperature materials, airframe/engine integration, multidisciplinary design optimization (MDO)
- Purpose: Supports 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

Cruiser Operating Weight = 1225 lb	**Booster = 2277 lb**
JP-7 Fuel (Useable) = 265 lb	**Interstage = 160 lb**
Cruiser Launch Weight = 1504 lb	**Stack Gross Weight (Captive Carry) = 3942 lb**



X-51A Dimensions

Cruiser length: 168 inches

AVD Stack length: 301 inches

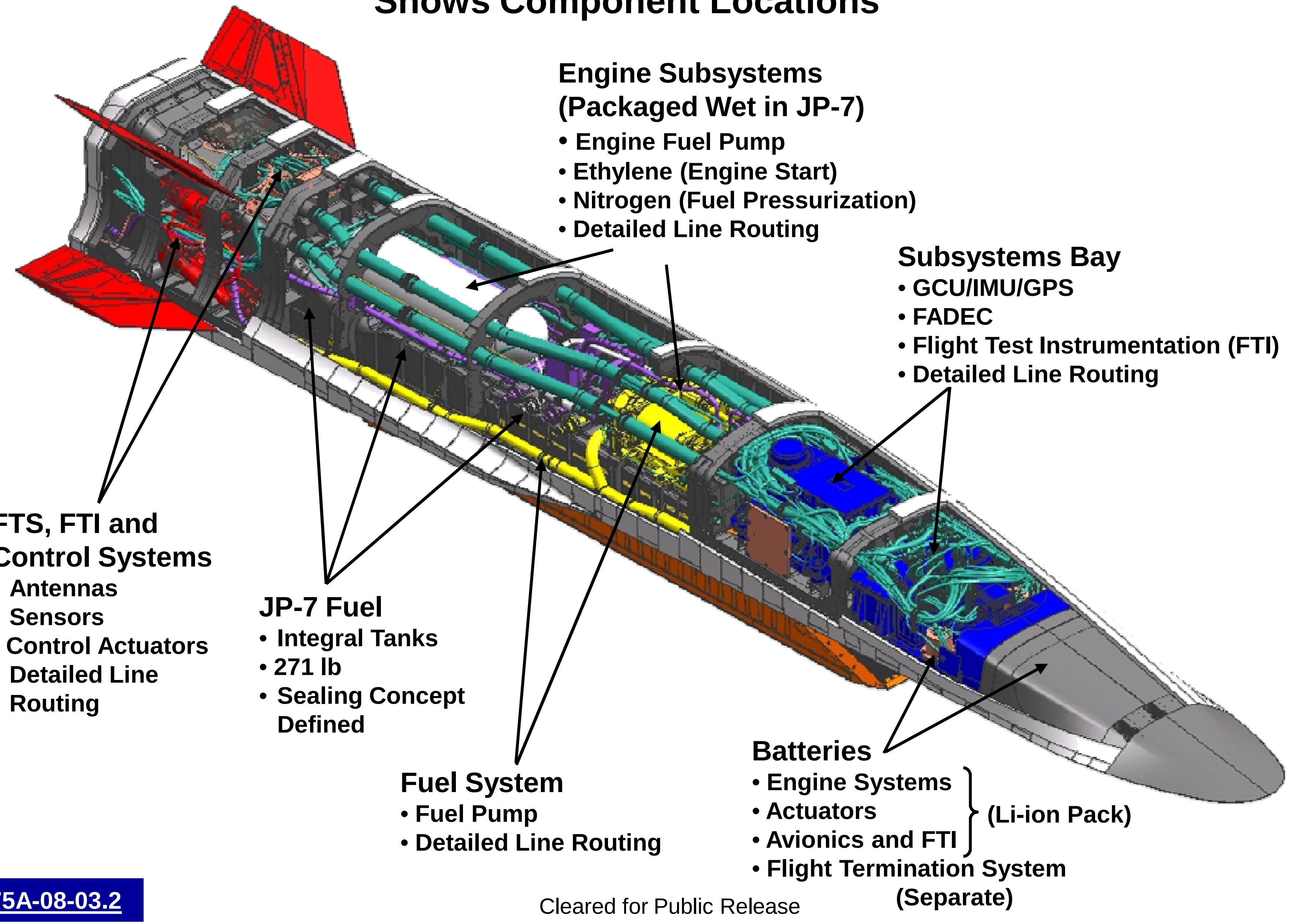
Max body width: 23 inches

Engine flow-path width: 9 inches

Cleared for Public Release
88ABW-2013-3592

X-51 Subsystems Packaging

Shows Component Locations



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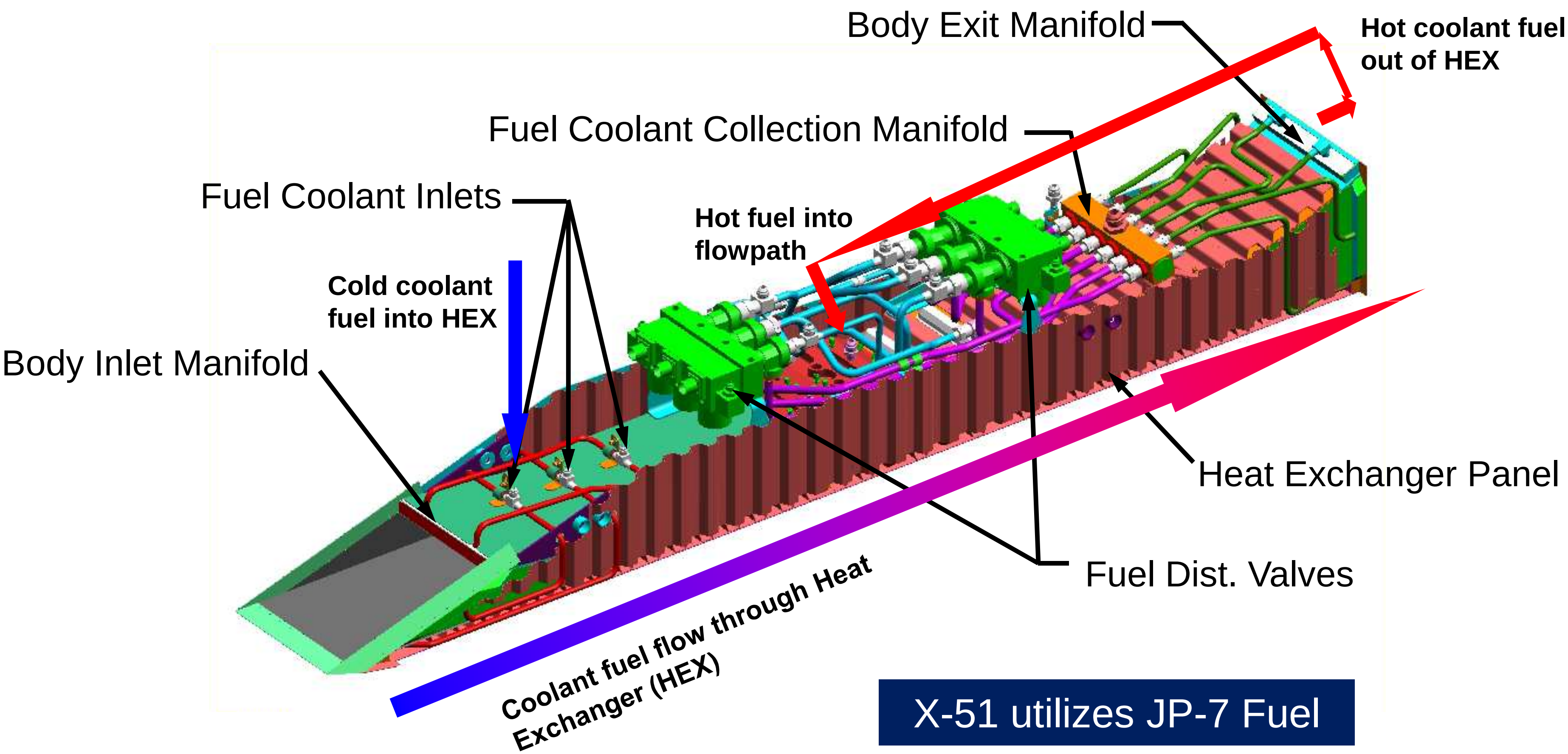
Fuel-Cooled Scramjet Overview

Closed Loop Fuel System & Cold Start

Engine controlled via F-119 FADEC



X-51 utilizes JP-7 Fuel

Cleared for Public Release
88ABW-2013-3592

Note: FADEC and Fuel Pump not shown

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

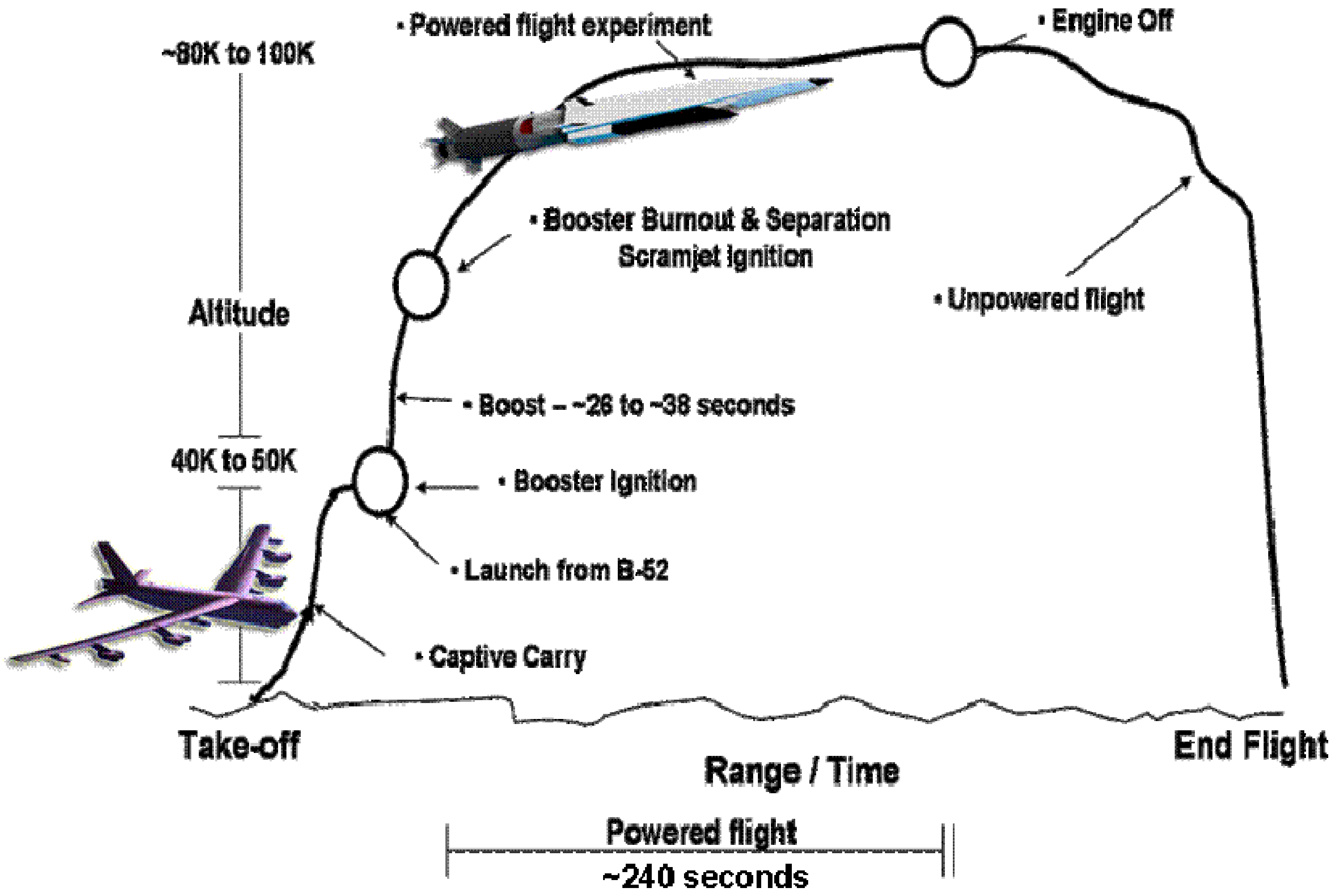
X-51A: Verified Flight-Weight Hydrocarbon Scramjet Operability & Performance

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

Fourth Flight: May 1st, 2013

- Full duration flight: ~ 209 seconds of scramjet operation and 361 seconds of controlled flight
- Scramjet acceleration from Mach 4.8 to 5.1; ~ 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

X-51 Flight Test Profile



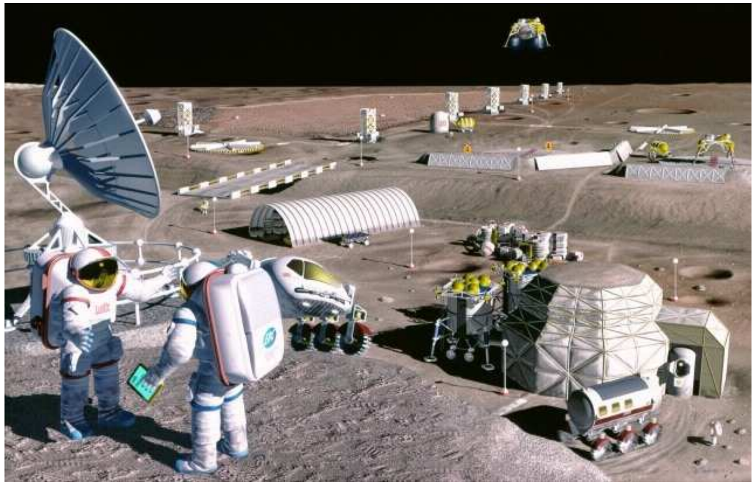
Hypersonic Technology Could Change the World

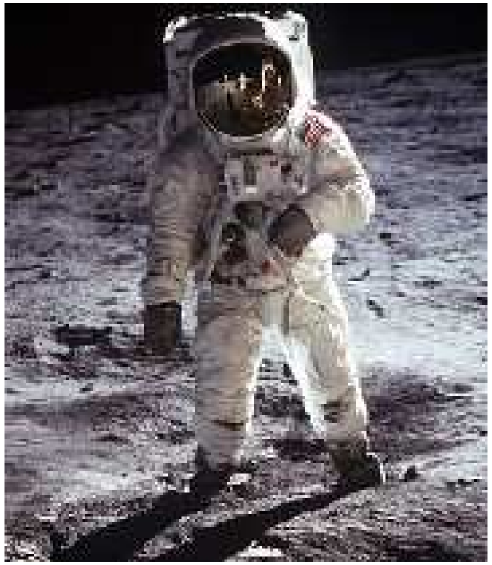
What might the future hold with mature hypersonic technology and proven vehicle design concepts in hand?

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

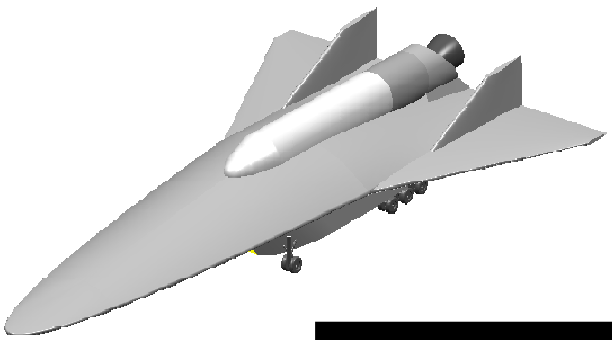
- **Reductions limited with expendable systems**

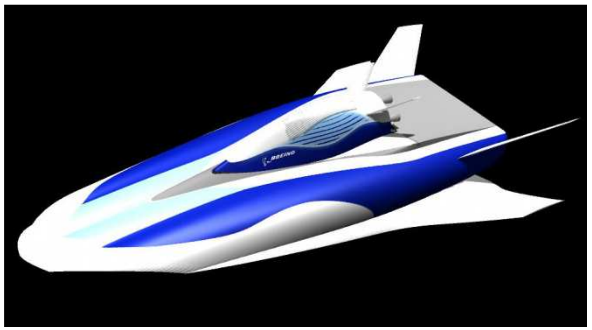


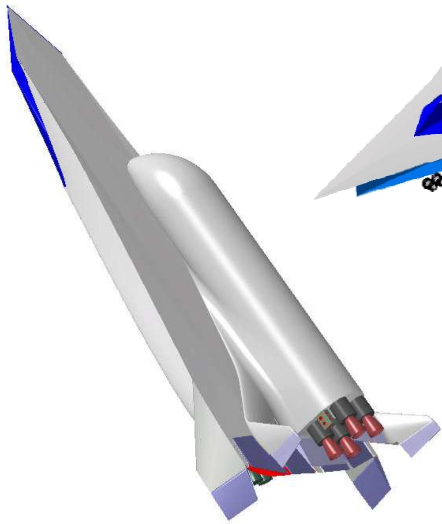


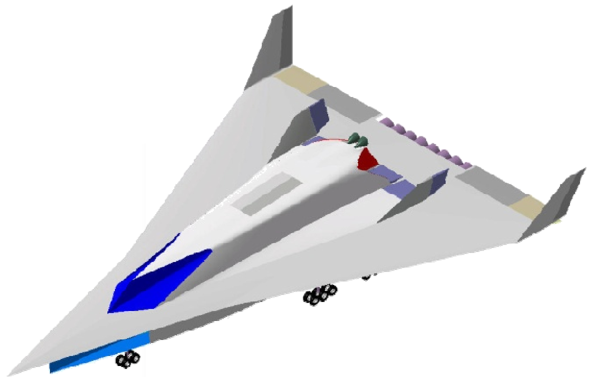
A Combination of Reusability, Reliability and Utilization Rate Drive Launch Affordability

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

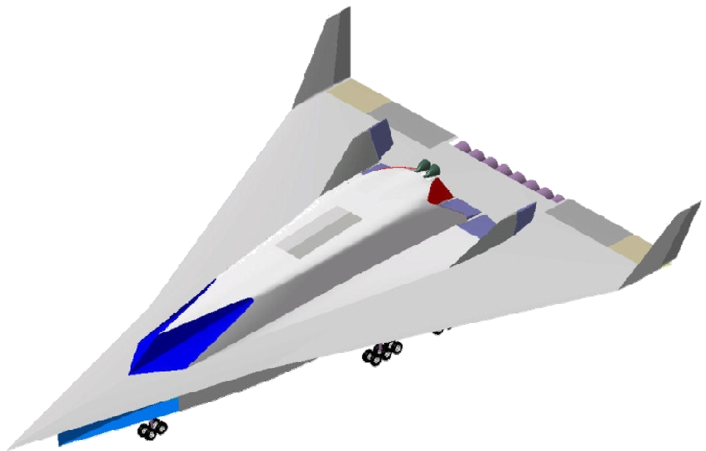
- **Hypersonic technology and horizontal launch beneficial to goal**

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 …