X-43A Project Overview
Adventures in Hypersonics

Based on AIAA Papers:
Chief Engineer's View of the NASA X-43A Scramjet Flight Test (AIAA-2005-3332)
Overview with Results and Lessons Learned of the X-43A Mach 10 Flight (AIAA-2005-3336)
Presentation Topics

- X-43A Program Overview
- Vehicle Description
- Flight 1, MIB & Return to Flight
- Flight 2 and Results
- Flight 3 and Results
- Concluding Remarks
X-43A (Hyper-X) Program Overview

• First ever flight demonstration of an airframe-integrated scramjet powered hypersonic vehicle

• Primary objective was to validate the tools, test and analysis techniques, & design methods of scramjet powered, hypersonic vehicles

• Three flight project
  – Two flights at Mach 7
  – One flight at Mach 10

Hyper-X Research Vehicle (HXRV): ATK-GASL
  – Hydrogen fueled scramjet engine
  – Scaled version of a Mach 10 "cruise" configuration

Hyper-X Launch Vehicle (HXLV) - OSC
  – Air launched from NASA’s B-52
  – Boosts HXRV to test condition
  – Modified 1st Stage Pegasus booster
Scramjets

- **Inlet**: slows the flow efficiently
- **Isolator**: contains the precombustion shock system
- **Combustor**: injects, mixes, flameholds, and burns with minimal losses
- **Nozzle**: expands the gases without quenching the reactions
- All this must be accomplished in as short a distance as possible

- **Allows for air-breathing flight at Mach 5+**
- **Forces and moments balanced to minimize trim drag and maximize thrust**
The Challenge

• During the 0.001 sec
  – Inject the H2, mix the fuel and air, and ignite the mixture
  – Combust the H2+O2 to H2O (a min of 7 reactions modeled in CFD codes)
  – Maintain flameholding and don’t unstart (propagation of shock train forward)
  – Expand the gases and extract the energy to produce thrust > drag
• Accomplish at Mach 7 speed and dynamic pressure of 1000 lb/ft2

“Likened to keeping a candle lit in a hurricane”

Mach 7
~7,000 ft/sec

Approx 3 feet
~3,000 ft/sec
O2 residence time ~ 0.001 sec
X-43A Flight Phases

Captive Carry to Launch Condition

Boost to 100,000 feet

MACH 7/10 Separation

Free Flight & Scramjet Operation
X-43A Mach 7 and Mach 10 Mission Profiles

Mach 7 Mission
Mach 10 Mission

Mach 7 Mission:
- Booster Ignition: Mach 0.81, 39,600 ft
- Drop Weight: ~37,500 lbs
- Mach 0.80, 40,000 ft, q=189 psf

Mach 10 Mission:
- Booster Ignition: Mach 0.7, 39,600 ft
- Drop Weight: ~37,500 lbs
- Mach 0.80, 40,000 ft, q=189 psf

Profiles:
- Power-On Test
- Cowl Closes
- PID (10 sec)
- Power-Off Tare (5 sec)
- Mach 9.7
- Mach 7, 6,913 fps, 1,000 psf
- Push-Over -0.5g's
- Staging Open
- Stage Separation
- Booster Burn Out
- Fuel Off
- Fuel On
- Pull-Up 1.7g's
- Decel - Descent Initial 1g to 10° AOA
- Parameter ID Maneuvers to Desired Impact Area
- Terminal Glide
- Mission Complete

Times:
- ~95 sec
- ~105 sec
- ~115 sec
- ~700 sec
## Nominal Timeline

<table>
<thead>
<tr>
<th>Event</th>
<th>Flight 2</th>
<th>Flight 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground ops</td>
<td>days</td>
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<tr>
<td>Captive carry</td>
<td>1 hour</td>
<td>1 hour</td>
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<tr>
<td>Drop</td>
<td>5 sec</td>
<td>5 sec</td>
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<tr>
<td>Boost</td>
<td>93 sec</td>
<td>88 sec</td>
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<tr>
<td>Separation Event</td>
<td>2.5 sec</td>
<td>2.5 sec</td>
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<tr>
<td>Cowl open</td>
<td>Cowl open</td>
<td>Cowl open</td>
</tr>
<tr>
<td>Pre-experiment tare</td>
<td>5 sec</td>
<td>3 sec</td>
</tr>
<tr>
<td>Ignition w/ H2/silane</td>
<td>3.5 sec</td>
<td>4.5 sec</td>
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<tr>
<td>H2 fuel burn</td>
<td>7.5 sec</td>
<td>4.5 sec</td>
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<tr>
<td>Post-experiment tare</td>
<td>4 sec</td>
<td>6 sec</td>
</tr>
<tr>
<td>Cowl open PID</td>
<td>17 sec</td>
<td>None</td>
</tr>
<tr>
<td>Cowl closed</td>
<td>Cowl closed</td>
<td>Cowl closed</td>
</tr>
<tr>
<td>Cowl closed PID's</td>
<td>Performed at every Mach no. from Mach 5 to 2</td>
<td>Performed at every Mach no. from Mach 8 to 2</td>
</tr>
<tr>
<td>Splash</td>
<td>10 minutes after Sep.</td>
<td>12 minutes after Sep.</td>
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</tbody>
</table>
X-43A External Vehicle Configuration

Length: 12'4"
Width: 5'0"
Height: 2'2"
Weight: 3000 lb max
X-43A Material Layout

- Green: Tungsten
- Yellow: TUFI/AETB
- Blue: Haynes Alloy
- Red: Carbon-Carbon
- Orange: Copper Alloy

TUF1 = Toughened Uni-piece Fibrous Insulation
AETB = Alumina Enhanced Thermal Barrier
The Hyper-X Partnership

Drawing on Expertise from Coast-to-Coast

‘It takes a village’
Highly Integrated Effort Required

Propulsion
- Fuel system
- Scramjet engine
- Propulsion control laws
- Environmental system

LV, Sep, & RV Sims
- GNC & PSC design & testing
- Monte-Carlo analyses
- Vehicle performance
- S/W & H/W testing
- HIL/AIL testing
- Mission control room training

Stage Separation
- Never been done
- High q, asymmetric bodies

Systems
- Flight computers
- Actuators
- Power
- Software
- V & V testing

GNC
- LV, Sep, & RV control laws

Structures
- Aero & thermal loads
- FEM modeling
- Structural analysis & design

Launch Vehicle
- The ride to Mach 7 and 10
- Modified Pegasus booster

Flight Operations
- Puts it all together
- Vehicle integration, fueling, flight, ground, & control room ops

Aerodynamics
- Outer mold line design
- Aero data base – testing & CFD

Hypermach Hyper-X
Flight 1 - June 2, 2001

Flight Testing IS Risky Business

- Approximately 13 seconds after launch, booster departed from controlled flight.
- The right fin broke off, followed within one second by left fin and rudder.

- HXLV FTS was initiated 48 seconds after launch and caused the uncommanded “separation” of the X-43A.

- The X-43A continued to transmit data until 77 seconds after launch, which is consistent with the time splash occurred.
Mishap Investigation & Return to Flight Effort

- X-43A Mishap Investigation Board (MIB) was immediately convened following the accident on June 5, 2001 and ended 9 months later.
- “The X-43A HXLV failed because the vehicle control system design was deficient for the trajectory flown due to inaccurate analytical models which overestimated the system margins” -- Root Cause MIB Report dated 5/8/2003
  - Modeling deficiencies caused an over-prediction of autopilot stability margins: Aerodynamics, Compliance, and Fin Actuation System
- Return to Flight (RTF) commenced March 2002 (lasted 2 years)
  - Developed a Corrective Action Plan in response to the MIB findings/recommendations
  - Developed an overall approach and roadmap for Return to Flight
  - Focused on the root causes and applied lessons learned on the HXLV to the HXRV
Flight 2 – March 27, 2004

The fastest air-breathing aircraft is NASA’s X-43A, which achieved Mach 6.8316 on 27 March 2004 in a flight lasting 11 seconds over the Pacific Ocean.
Preflight Nominal & Monte Carlo Predictions vs Flight Data

Positive Acceleration

Fuel On

Engine cowl open
Engine cowl closed

Time Since Separation (sec)

Note: Unclassified “Approximate” Monte Carlo Simulation and relative flight “Trends,” NOT Data

Centerline wall pressure

Pressure

Axial Length

Flight Data
Pretest Predicted

Nose
Tail
Why Did Flight 2 Succeed

• We were given a second chance and the core team was left intact

• Strong foundation based on Flight 1 experience, MIB findings and recommendations, and RTF Approach

• Strong technical expertise between NASA, ATK, & Orbital

• Strong teamwork within NASA and between NASA, ATK, and Orbital
Flight 2 Results Summary

Stage Separation:
- All launch vehicle separation conditions were essentially nominal and within the specified tolerance.
- The X-43A successfully separated from the launch vehicle and achieved stable free flight throughout the engine test.

X-43A Powered Flight (Scramjet Engine Experiment):
- Scramjet engine performance was within 3% of preflight predictions – sufficient to overcome additional airframe drag and produce net positive thrust.
- Scramjet engine test conditions were well within preflight uncertainty levels and requirements.
- The maximum powered Mach number was 6.8.
- During powered flight, the X-43A flight controls maintained the desired vehicle angle-of-attack of 2.5 degrees within an acceptable tolerance.

X-43A Descent:
- Following the scramjet experiment, the vehicle remained controlled during the descent and successfully completed a series of descent maneuvers.

Overall Mission Comments:
- Aerodynamic stability and control Mach 7 to Mach 0.9 – within 1 sigma uncertainty of prediction.
- Boundary layer transition, boundary layer trip effectiveness – within 1 sigma uncertainty of prediction.
- Airframe and wing structure, TPS and internal environment – as predicted w/ exception of rudders.
- All systems on both the launch vehicle and X-43A performed well and extensive research quality data was acquired throughout the boost and descent.
X-43A Flight 3 HW & SW Modification Summary

**Vertical Tails**
- Solid Haynes
- Carbon-Carbon Leading Edges

**FLIGHT MANAGEMENT UNIT (FMU)**
- Surface Calibration Update
- NAV/Guidance Updates
- Sep Loop Closure Times as MDL inputs
- Test Angle of Attack = 1°
- Fueling schedule
- Igniter subsystem controller open loop
- Unstart Logic Removed

**S-BAND TRANSMITTER & C-BAND TRANSPONDER**

**NITROGEN (PURGE) SYSTEM**
- Additional Leading Edge Thermocouple
- Sideslip Absolute Pressure Sensors Removed
- Total Pressure Sensor removed
- Engine Skin Friction & Heat Flux Gages
- High Temperature Strain Gages

**COOLANT SYSTEM**
- Valve upgraded

**HYDROGEN SYSTEM**

**SILANE SYSTEM**
- Valve upgraded

**ACTUATORS & CONTROLLER**

**EXT POWER**

**INSTRUMENTATION STACK**
- Additional Leading Edge Thermocouple
- Sideslip Absolute Pressure Sensors Removed
- Total Pressure Sensor removed
- Engine Skin Friction & Heat Flux Gages
- High Temperature Strain Gages

**BATTERY**

**SCRAMJET ENGINE**
- Additional TPS
- Engine Lines
- Engine/Cowl Height

**BALLAST**
- 58 lbs in place of Absolute Total & Sideslip Pressure Sensors

**LEADING EDGE**
- Blunter Radius
- Removed Total Pressure Port

**BALLAST**
- 58 lbs in place of Absolute Total & Sideslip Pressure Sensors

**HYDROGEN SYSTEM**
- Solid Haynes
- Carbon-Carbon Leading Edges

**SILANE SYSTEM**
- Valve upgraded
Flight 3 – November 16, 2004
Flight 3 Results Summary

Stage Separation:
- All launch vehicle separation conditions were essentially nominal and within the specified tolerance.
- The X-43A successfully separated from the launch vehicle and achieved stable free flight throughout the engine test.

X-43A Powered Flight (Scramjet Engine Experiment):
- The scramjet experiment/fuel on began approximately 5 seconds after separation
- The maximum powered Mach number was 9.6
- During powered flight, the X-43A flight controls maintained the desired vehicle angle-of-attack of 1 degree within an acceptable tolerance.
- The scramjet was fueled for approximately 10 seconds, providing predicted thrust.
- During this time the vehicle achieved cruise condition.
- The data collected during the engine test is by far the largest amount of data acquired for a Mach 10 scramjet. The quantity, quality, and type of the data acquired is well beyond what has been acquired in wind tunnels.

X-43A Descent:
- Following the scramjet experiment, the vehicle remained controlled during the descent and successfully completed a series of descent maneuvers.

Overall Mission Comments:
- All systems on both the launch vehicle and X-43A performed well and extensive research quality data was acquired throughout the boost and descent.
Concluding Remarks

• **Best Possible Outcome: Scramjets Work & Flight Testing Is Necessary**
  – In general results were as expected for scramjet test conditions achieved however, there are some “interesting things” in the data for both flights.

• **Primary Objective Met**
  – Vehicle and engine data substantiates hypersonic vehicle and engine design tools and flight scaling methodologies.
  – The quantity, quality, and type of the data acquired during the Mach 10 engine test is well beyond what has been acquired in wind tunnels.

• **Successful Separation**
  – Confirmed that non-symmetrical high-dynamic pressure stage separation is feasible, leading the way to future safe staged launch systems.

• **Why were we successful?**
  – Rigorous processes for design, development, testing, and validation
  – Strong technical expertise and team work between NASA, ATK GASL, Boeing & Orbital Sciences Corporation