X-43A: The First Flight of a Scramjet Powered Airplane

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Outline

• Scramjets
• Overview of X-43A
• What Happened the 1st Time
• Return to Flight
• What Happened the 2nd Time
Scramjet Features

Important Scramjet Terms/Concepts

- Inlet starting
- Ignition/Flameout/Flameholding
- Inlet transition
- Combustor/isolator interaction
- Fuel equivalence ratio
- Scramjet-Vehicle Interaction
Airbreathers = Higher Efficiency

\[ I_{sp} = \text{Thrust/Pound per second of propellant (fuel) flow rate} \]
X-43A Role In Hypersonics

Demonstrate & Validate Design Methodology

- X-43A is the first ever flight demonstration of an airframe-integrated, scramjet powered, hypersonic vehicle
- Flight data will be used to validate the tools, test and analysis techniques, and methodology for designing scramjet powered, hypersonic vehicles
- Verify predicted scramjet performance
- Collect propulsion, aerodynamic, thermal, and structural data for future hypersonic vehicle design
X-43A Overview

- A three-flight project
  - Fly three scramjet powered vehicles at Mach 7 & 10
  - **Accelerate the vehicles**

- A 12' long vehicle boosted to test conditions by a modified Pegasus booster
  - Hydrogen fueled scramjet engine
  - Scaled version of a "cruise" configuration
  - It is not flight weight at 3000 lbs

- The booster (HXLV) and experimental vehicle (HXRV) is air launched from NASA's B-52
Flight Phases

- **Captive Carry**
- **Separation**
- **BOOST**
- **Free Flight**
Mission Profile

Mission Profile Diagram:

- **Power-On Test**
- **Mach 7 6,913 fps 1,000 psf**
- **Push-Over -0.7 g's**
- **Fuel Off**
- **Fuel On**
- **Decel - Descent Initial 1g to 10° AOA**
- **Parameter ID Maneuvers to Desired Impact Area**
- **Terminal Glide**
- **Mission Complete**

**Altitude (kft):**
- B-52B Carriage
  - Mach 0.80
  - 40,000 ft
  - q=189 psf
  - Drop Weight: ~37,500 lbs
- Booster Ignition
  - Mach 0.81
  - 39,600 ft

**Timeline:**
- 0 sec
- 5 sec
- ~95 sec
- ~105 sec
- ~115 sec
- ~700 sec
- ~400 NM

**Speeds and G's:**
- 0 sec
- 0 NM
- 0.6 NM
- ~55 NM
- ~65 NM
- ~80 NM
Nominal Mission Time Line

- Ground ops – Days
- Captive carry - 1 hour
- Drop - 5 sec
- Boost - 88 sec
- Separation Event - 2.5 sec
- Cowl open
- Pre-experiment tare - 5 sec
- Ignition w/ H2/silane - 3.5 sec
- **H2 fuel burn - 7.5 sec**
- Post-experiment tare - 4 sec
The X-43A Research Vehicle

Weight: 3000 Pounds

148”

26”

30”

143”

60”

19”
• Fuel: Hydrogen at 8500 psi
• Igniter: Silane at 4500 psi
• Purge: Nitrogen at 8500 psi
• Engine Coolant: Glycol/Water

Pressures 173
Strain Gages 14
Temperatures 111
Misc. Analog 13
1553 Bus 352
Total 663
The Challenge of Size
A Bad Day

• No matter how often you've done something...

• No matter how experienced you are...

• Things can go wrong!!!
A Bad Day: Flight 1 – June 2, 2001

At ~13 seconds after drop booster departed controlled flight

The right fin broke off, followed, within one second, by left fin and rudder

Flight Testing Is An Unforgiving Business
Mishap Investigation – 9 Months

• X-43A Mishap Investigation Board was immediately convened
• Determining the cause of the X-43A mishap was a complex effort requiring a significant commitment of time and resources
  – The team eventually closed 613 fault tree elements
• 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
• Modeling deficiencies caused an over-prediction of autopilot stability margins
  – Aerodynamics
  – Compliance
  – Fin Actuation System
Return To Flight – 2 Years

- Return to Flight (RTF) commenced March 2002 with development of:
  - Corrective Action Plan in response to the MIB findings/recommendations
  - Overall approach and roadmap for Return to Flight
- The project focused on the roots causes
- Applied lessons learned on the launch vehicle to the research vehicle
- Expanded the review process
- Expanded communication processes
**X-43A RTF Actions**

### Launch Vehicle
- Higher fidelity models
  - Aerodynamics
  - Actuators
  - Structures
  - Autopilot
- Actuator upgrade for greater torque capability
- Lower loads trajectory: booster propellant off-load
- Autopilot trades/optimization
- Independent simulation

### Stage Separation
- Higher fidelity models
- Additional separation mechanism testing
- Control law refinements for robustness
- Independent simulation

### Research Vehicle
- Higher fidelity models
- Increased AOA for flameout robustness and greater thrust
- Upgraded engine control logic for unstart robustness
- Adapter fluid systems improvements
- Redesign of wing control horns
- Aircraft-in-the-loop timing tests
- Independent simulation
X-43A Flight Profiles vs. Pegasus

Mach

q (psf)

X-43A Flt. #1

X-43A Flt. #2

6/01 Mishap

Pegasus
40 kft Drop – 20kft Too Much Energy

- Numerous options explored – Final approach go to the source

ATK off loaded ~ 3300 lbs of propellant

Halfway through Machining  Machining Completed
Doubled FAS Torque

Objective: To increase the FAS hinge torque capability from 1850 ft-lbs to 3000+ ft-lbs

Modifications:
- Add second motor in torque summing arrangement
- Fabricate new gears to handle higher loads
- Change housing material from aluminum to stainless steel
- Add two additional batteries
- Redesign the power and pre-driver boards in the ECU
Flight Testing May Be An Unforgiving Business
But It’s Great When It Works
Launch Vehicle Performance

- Boost duration: ~93 seconds
- Separation conditions
  - Altitude: 94 kft
  - Mach: 6.9
  - Dynamic Pres: 1000 lb/ft2
  - Angle of Attack: 0 deg
  - Pitch, roll, & yaw rates: 0 deg/sec

It Was A Great Ride!
Confirmation of Controlled Separation
X-43A Research Vehicle Results

- 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
- X-43 airframe drag (and lift) were higher than expected, but within uncertainty prediction
- Flight controls maintained vehicle angle of attack to 2.5 degrees ± 0.2 during powered flight
X-43A Research Vehicle Results

• Control deflections to trim engine induced moments were close to predictions – minimal trim drag penalty

• Aerodynamic stability and control Mach 7 to Mach 0.9 – as predicted*

• Boundary layer transition, boundary layer trip effectiveness – as predicted*

• Airframe and wing structure, TPS and internal environment – as predicted*

• Data quality excellent

*Preliminary analysis – shows most measurements/phenomena within close (± 1-sigma uncertainty) agreement to pre-test predictions
X-43A Research Vehicle Results

Preflight Monte Carlo Predictions vs Flight Data

X-43 Angle of Attack vs Time

Centerline wall pressure

Positive Acceleration

Flight

Engine cowl open

Acceleration vs. time

Fuel On

Fuel Off

X-43 Angle of Attack vs Time

3

2

X-43 Angle of Attack vs Time

Centerline wall pressure

Flight Data

Pretest Predicted

Pressure

Axial Length

Nose

Tail
Why Did We Succeed

• We were given a second chance and the core team was left intact
• Strong foundation based on Flight 1 experience and MIB findings and recommendations
• Strong technical expertise between NASA, ATK, & Orbital
• Strong teamwork within NASA and between NASA, ATK, and Orbital