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

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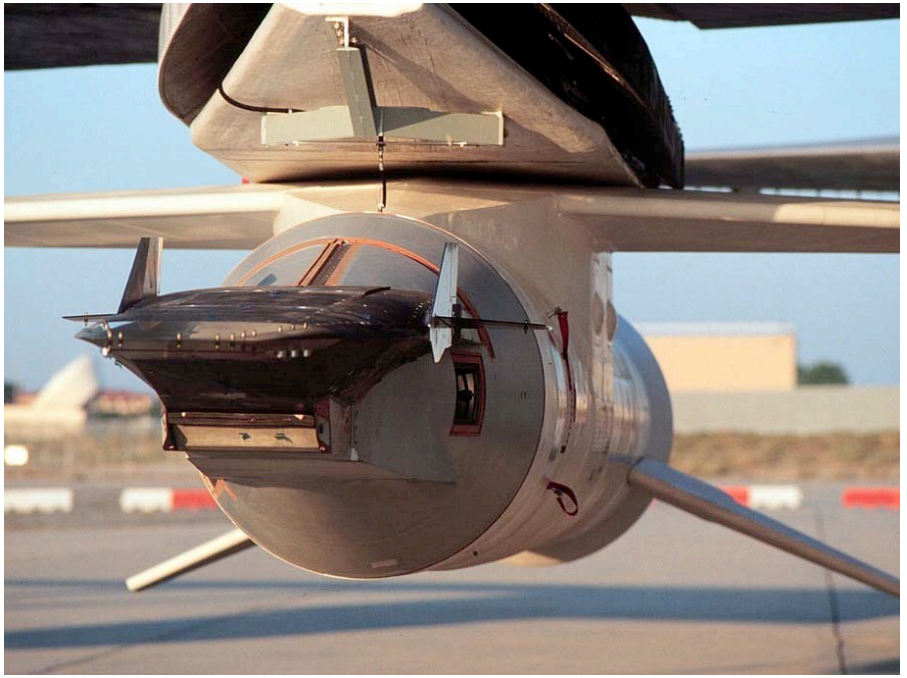
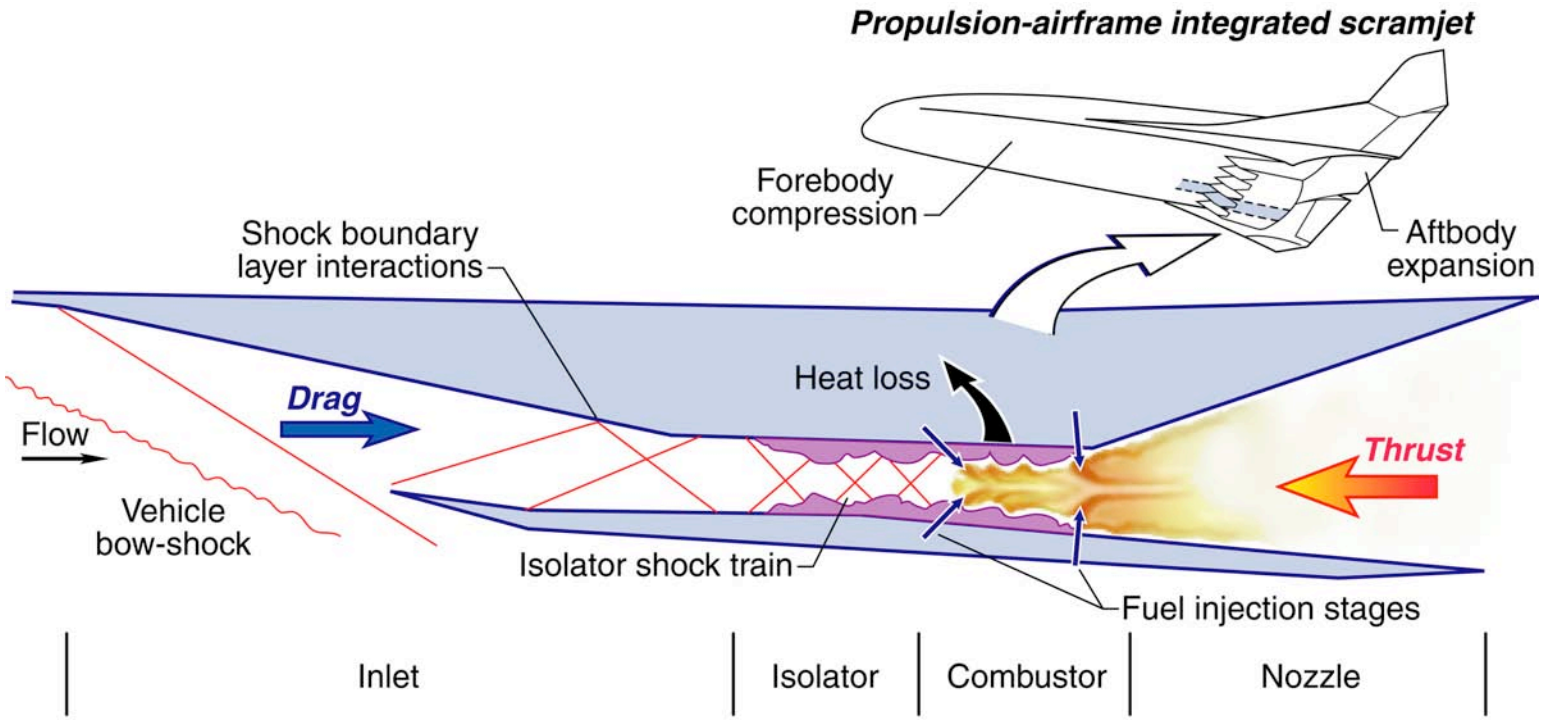
Outline

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



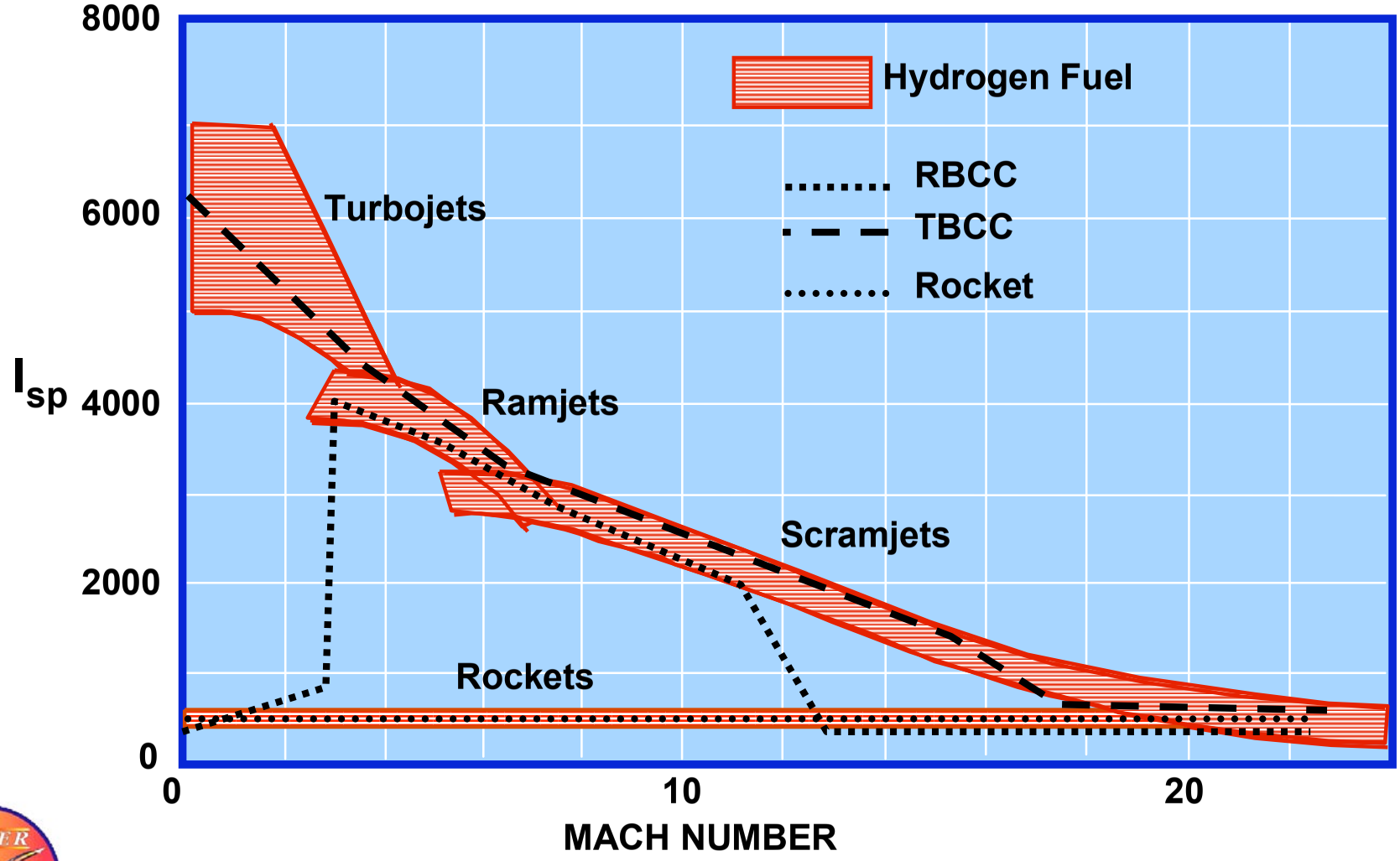
Scramjet Features



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} = *Thrust/Pound per second of propellant (fuel) flow rate*

X-43A Role In Hypersonics

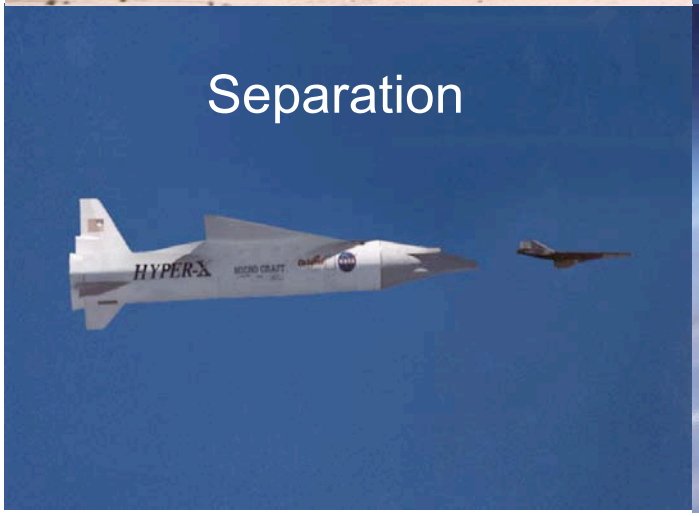
Demonstrate & Validate Design Methodology

- 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

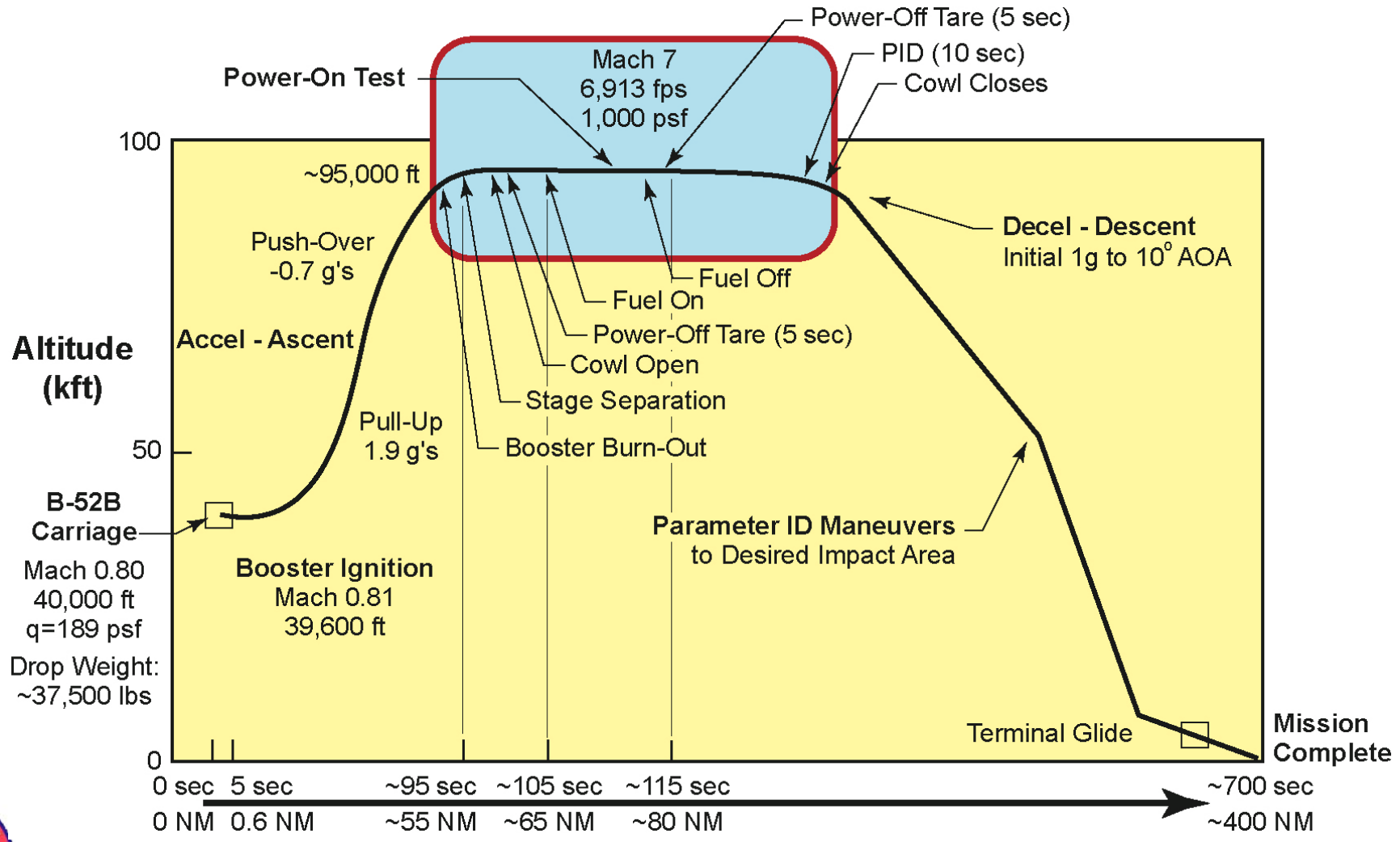
X-43A Overview

- 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

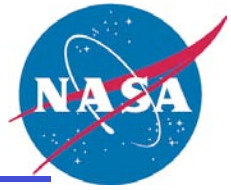
Flight Phases



Mission Profile

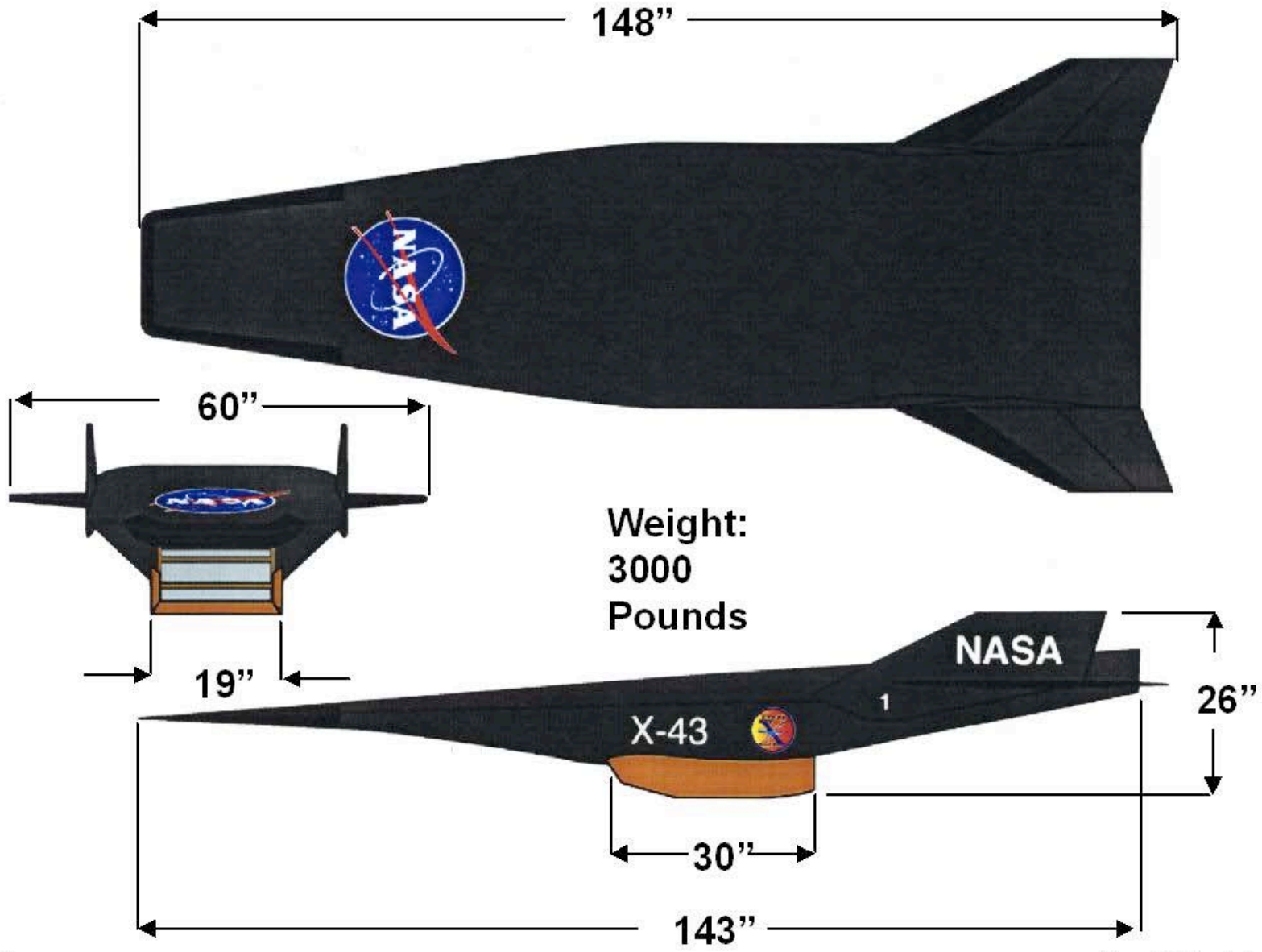


Nominal Mission Time Line

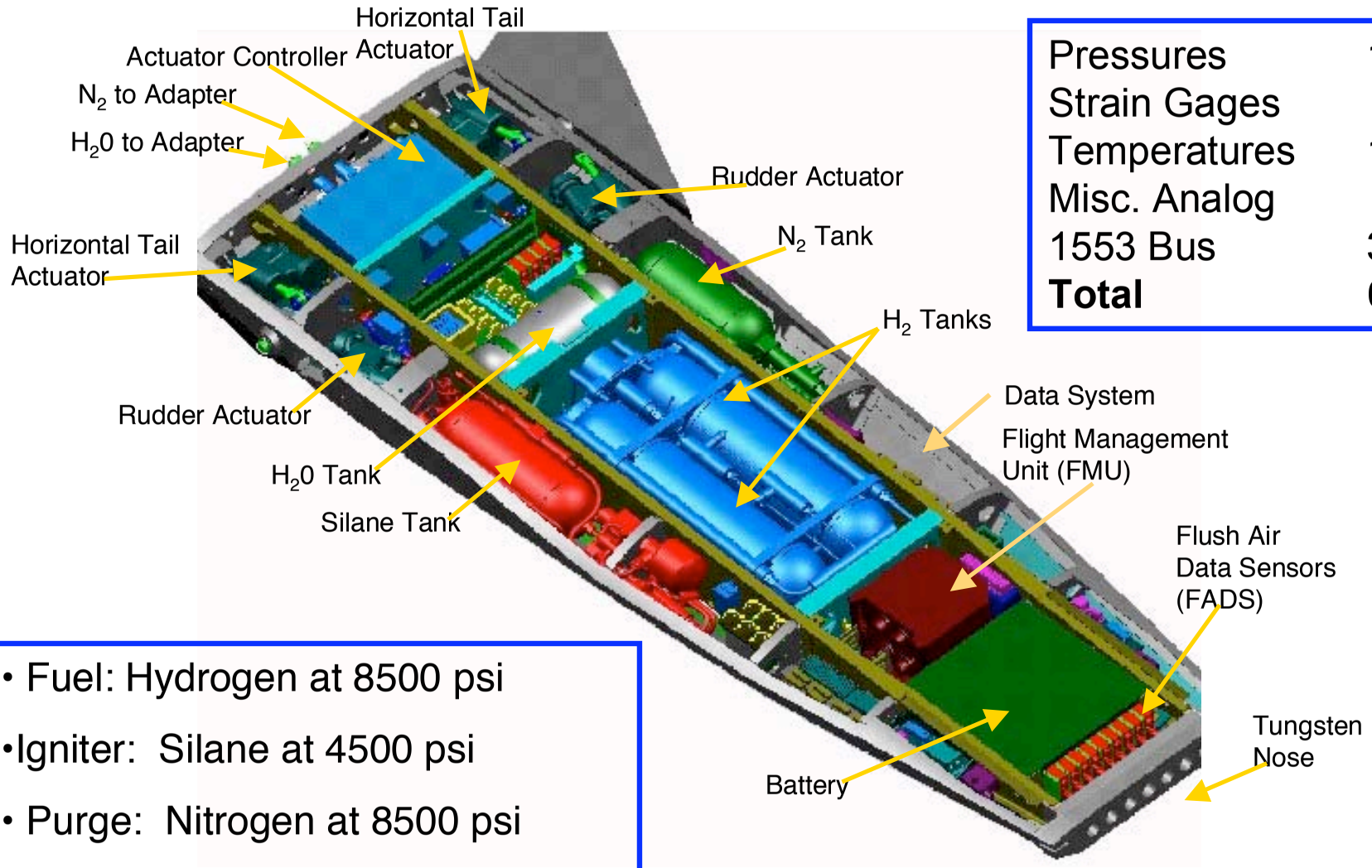


- Ground ops – Days
- Captive carry - 1 hour
- Drop - 5 sec
- Boost - 88 sec
- Separation Event - 2.5 sec
- Cowl open
- Pre-experiment tare - 5 sec
- Ignition w/ H2/silane - 3.5 sec
- **H2 fuel burn - 7.5 sec**
- Post-experiment tare - 4 sec

The X-43A Research Vehicle



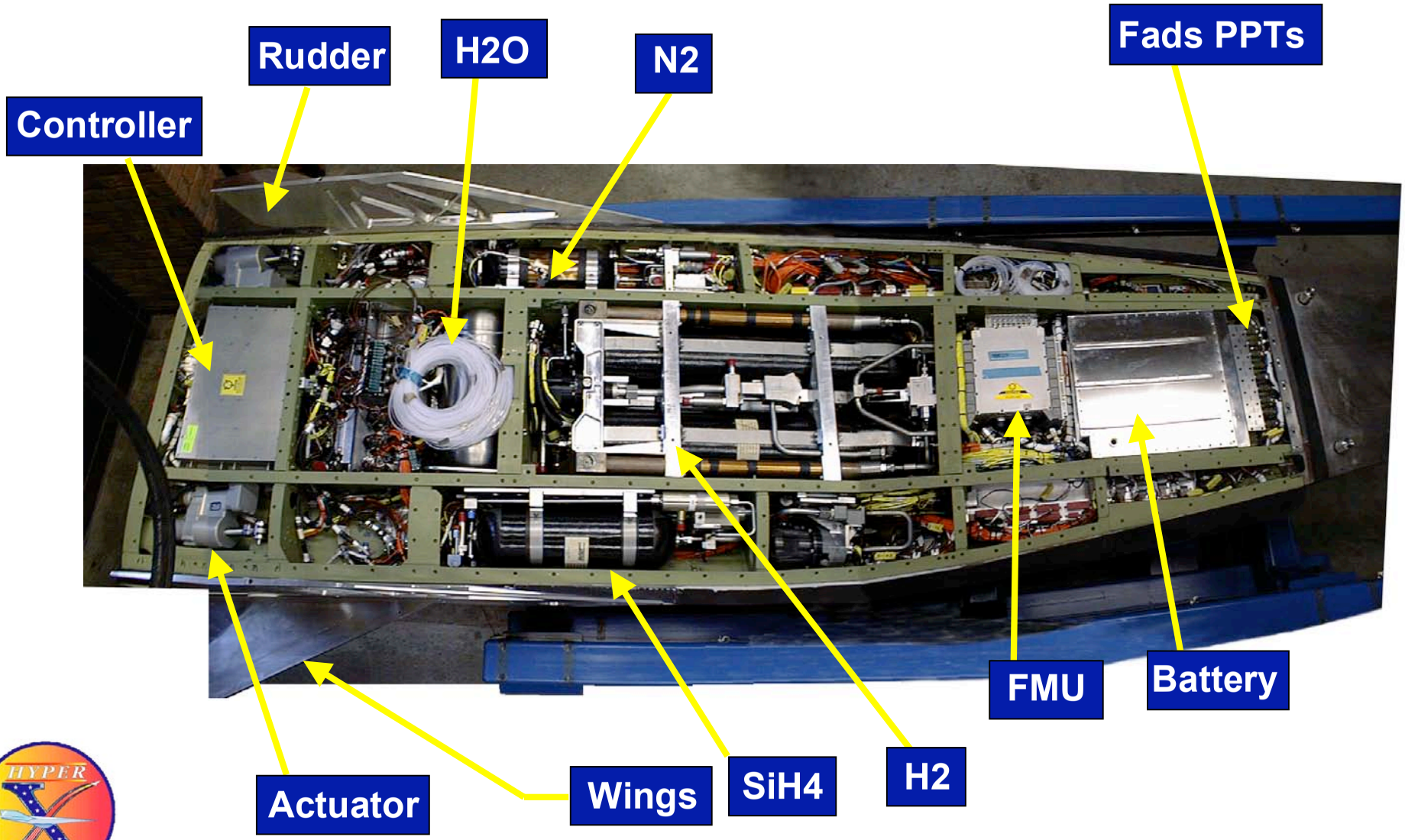
X-43A Vehicle



Pressures	173
Strain Gages	14
Temperatures	111
Misc. Analog	13
1553 Bus	352
Total	**663**

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

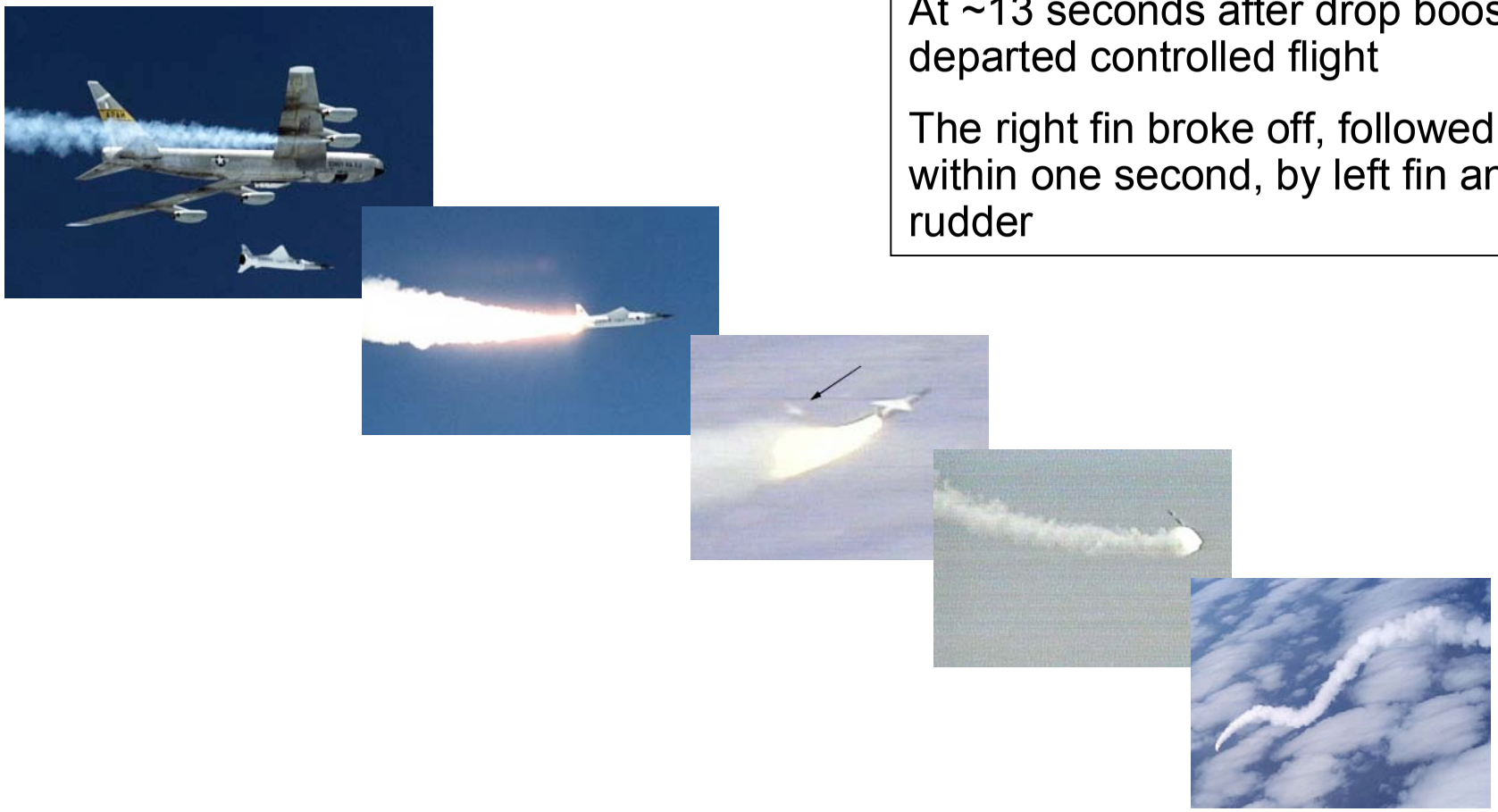
The Challenge of Size



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

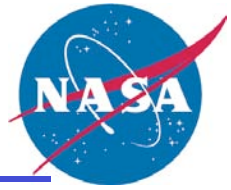


At ~13 seconds after drop booster departed controlled flight

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

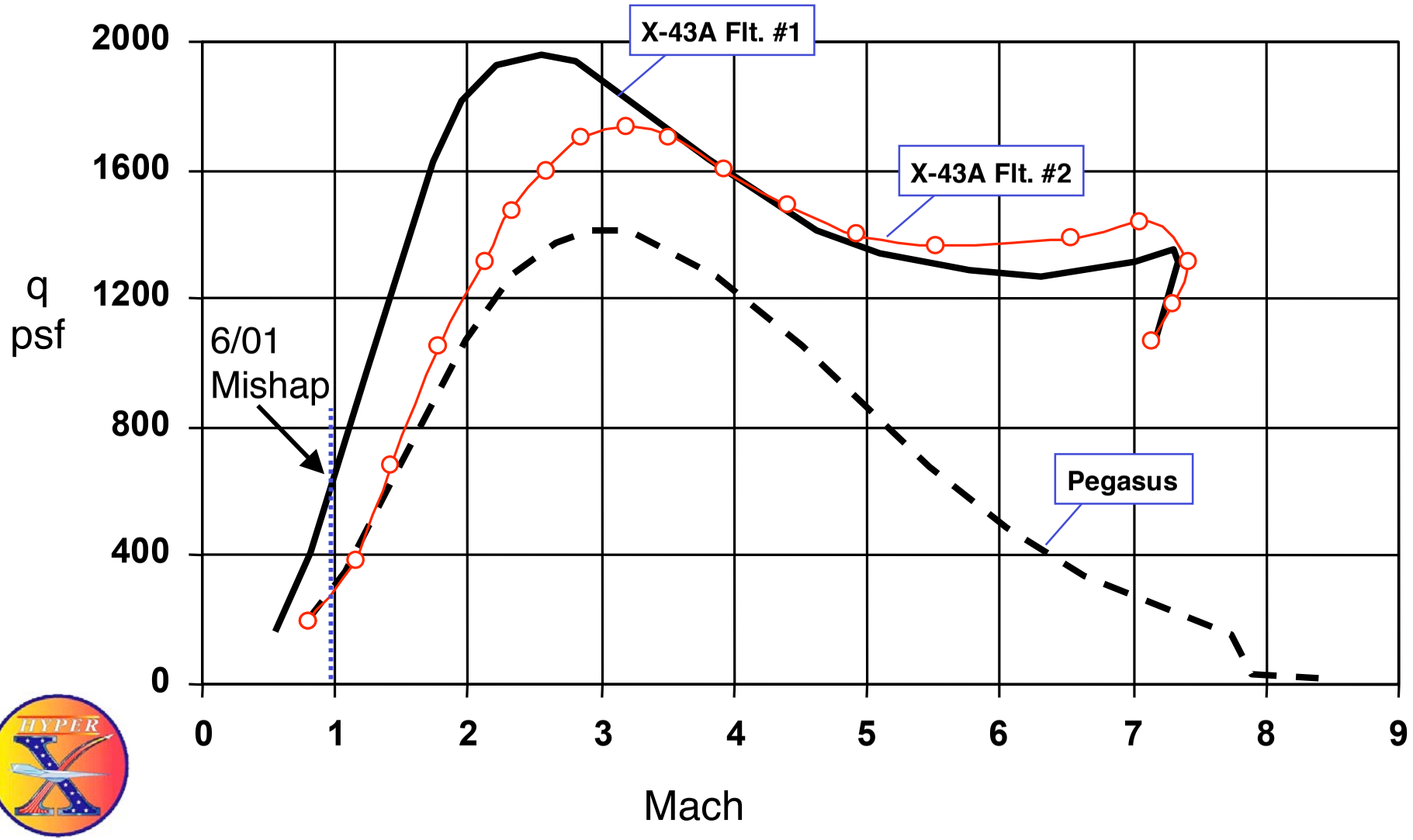
Stage Separation

- 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



40 kft Drop – 20kft Too Much Energy

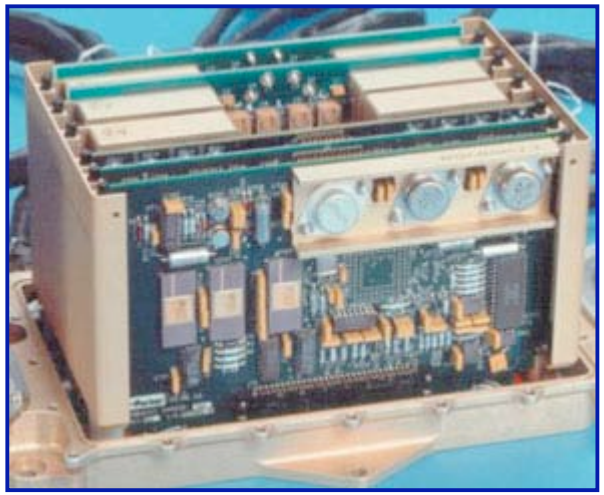
- Numerous options explored – Final approach go to the source

ATK off loaded ~ 3300 lbs of propellant

Halfway through Machining

Machining Completed

Doubled FAS Torque



Electronic Control Unit (ECU)

Actuator

- 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 2 – March 27, 2004

Flight Testing May Be An Unforgiving Business
But It's Great When It Works

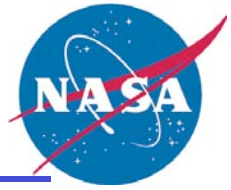
Launch Vehicle Performance

- 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!

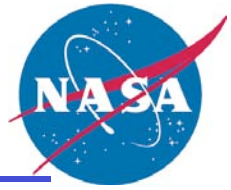
Confirmation of Controlled Separation

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

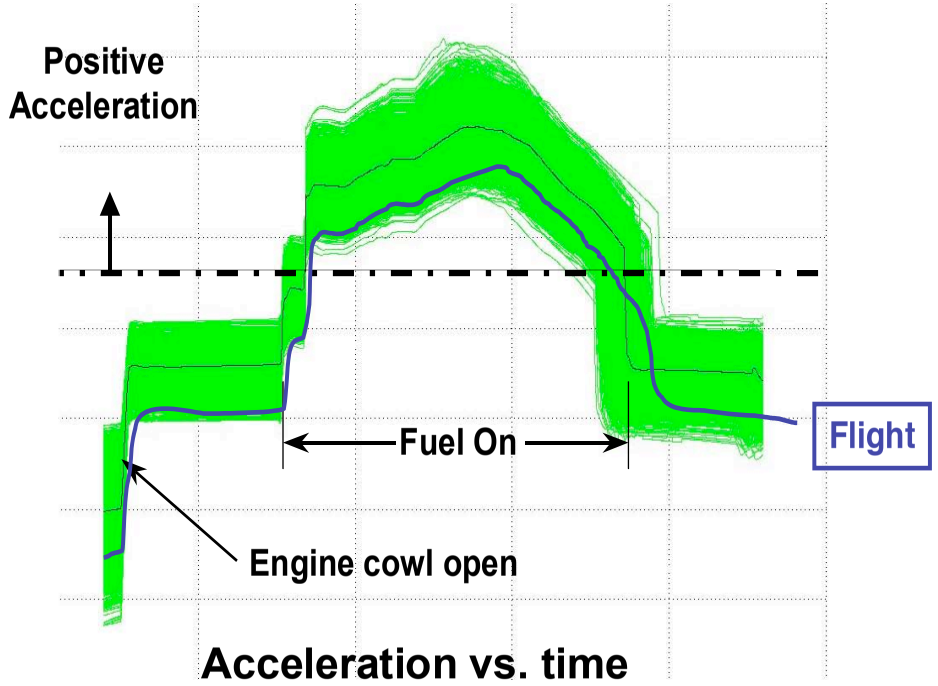


- Control deflections to trim engine induced moments were close to predictions – minimal trim drag penalty
- Aerodynamic stability and control Mach 7 to Mach 0.9 – as predicted*
- Boundary layer transition, boundary layer trip effectiveness – as predicted*
- Airframe and wing structure, TPS and internal environment – as predicted*
- Data quality excellent

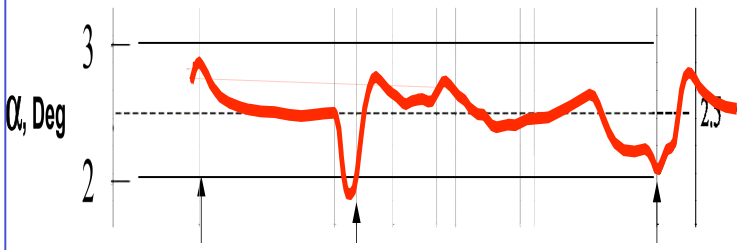
*Preliminary analysis – shows most measurements/phenomena within close (± 1-sigma uncertainty) agreement to pre-test predictions

X-43A Research Vehicle Results

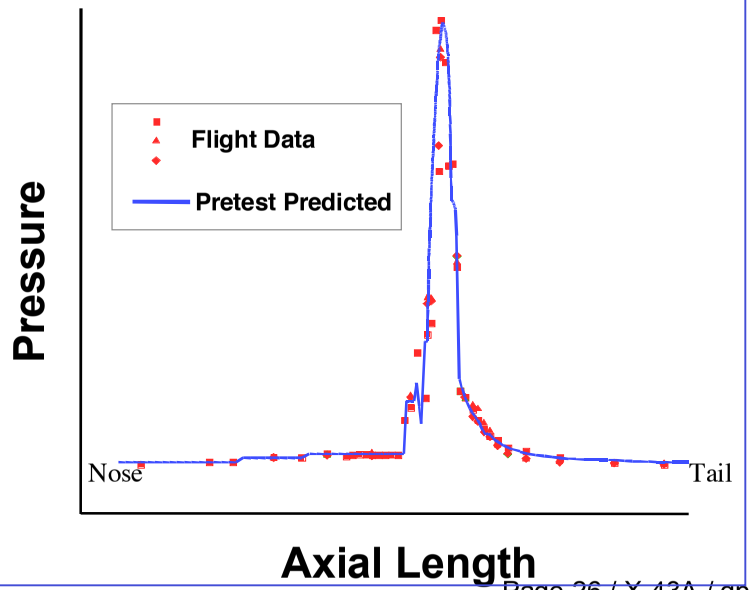
Preflight Monte Carlo Predictions vs Flight Data



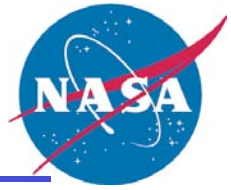
X-43 Angle of Attack vs Time



Centerline wall pressure



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