X-43A Final Flight Observations

Laurie Grindle
NASA Dryden Flight Research Center

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Outline

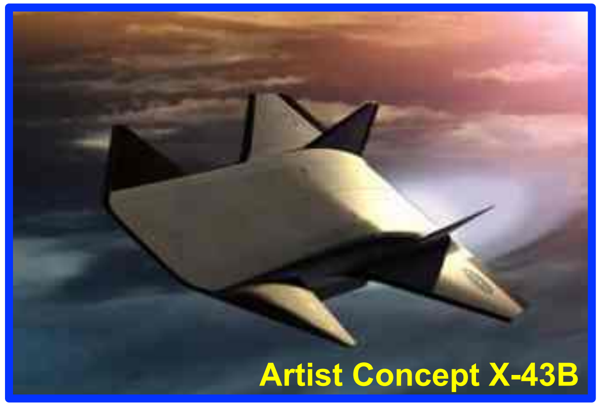
- X-43 Program Overview
- X-43A Project Overview
- Mission Details
- Mission Objectives
- X-43A Vehicle Description
- Approach & Philosophy for Mach 10 Flight
- X-43A Hardware and Software Modifications
- Flight Preparation Challenges
- Flight Results Summary
- Concluding Remarks

X-43 Program Overview

- X-43A
  - First flight demonstrator of X-43 Program flew at single test conditions.
- X-43C
  - Planned flight demonstrator provides testing over a range of Mach numbers in a single flight
  - Accelerates from Mach 5 to Mach 7 under it's own power.

Artist Concept X-43C

- X-43B
  - Planned reusable vehicle would fly from subsonic to hypersonic speeds in single tests.
  - Accelerates from Mach 0.7 to Mach 7.



Artist Concept X-43B

- X-43D
  - Post X-43A conceptual design and feasibility study
  - Conceived to test in the Mach 12 to Mach 15 range at single flight test conditions much like X-43A.

Hyper - X

X-43A (Hyper-X) Project Overview

Project Start 1995 — Flt 1 6/2001 — Flt 2 3/2004 — Flt 3 11/2004 — Proj. End 12/2004

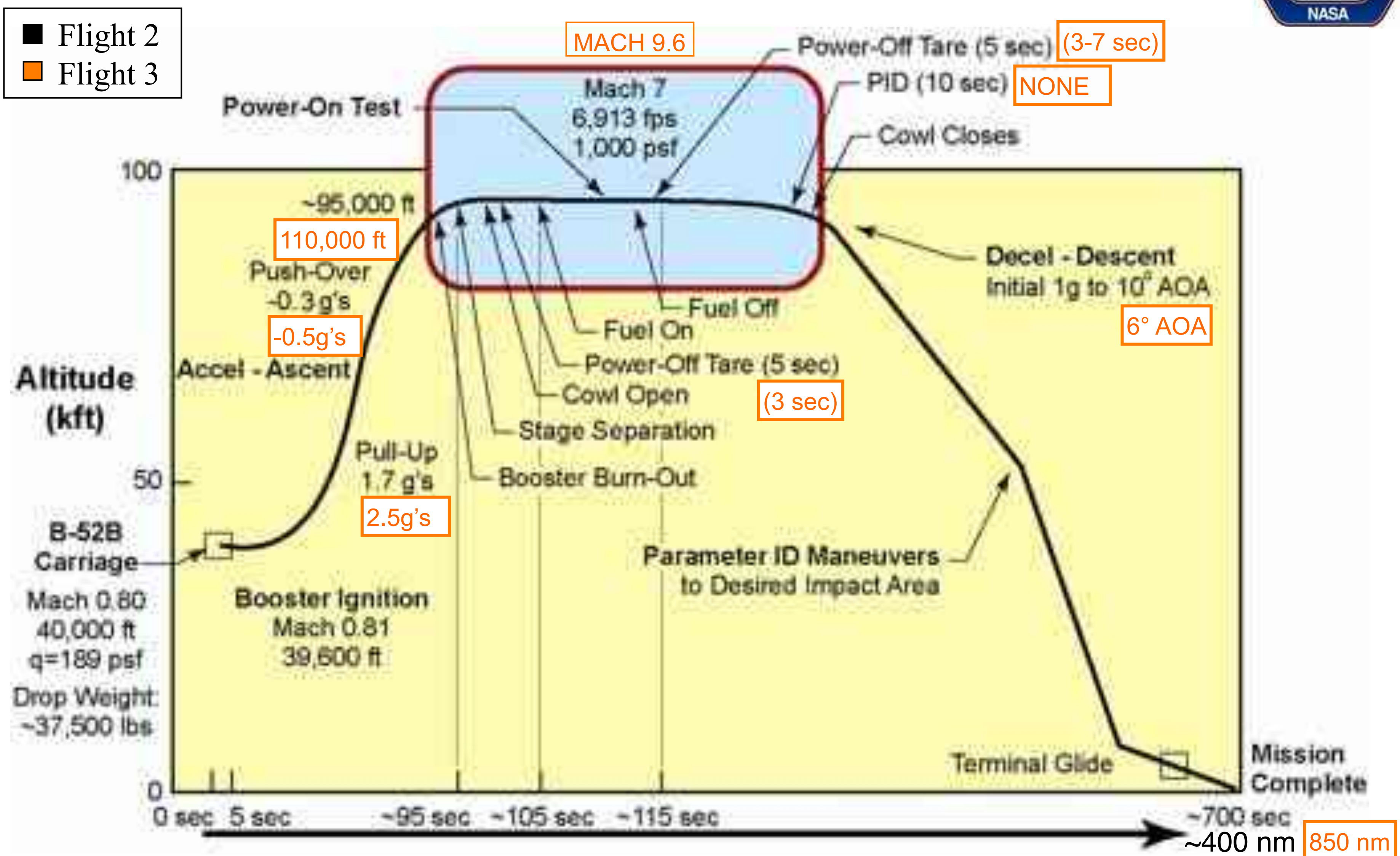
- First ever flight demonstration of an airframe-integrated scramjet powered hypersonic vehicle
- Primary objective was to validate the tools, test and analysis techniques, & design methods of scramjet powered, hypersonic vehicles
- Three flight project
  - Two flights at Mach 7
  - One flight at Mach 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

X-43A Flight Phases

X-43A Mission Details

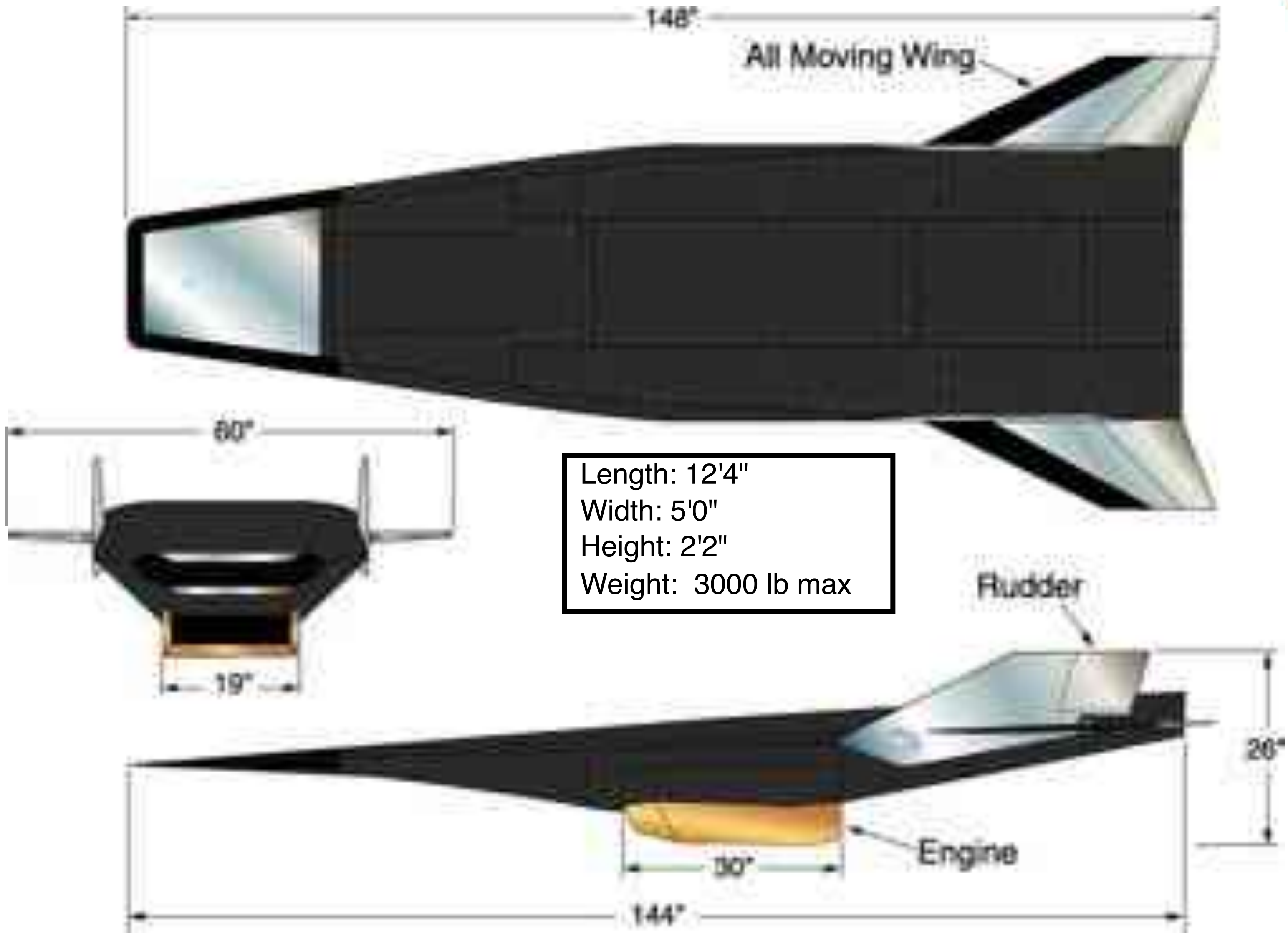


Mission Objectives

- Mission Objectives
  - Safely conduct ground operations, captive carry and flight experiment
  - Successfully launch booster stack and boost to stage separation point
  - Successfully perform stage separation resulting in controlled flight of the X-43A at the scramjet test point
  - Conduct the scramjet propulsion experiment and obtain data

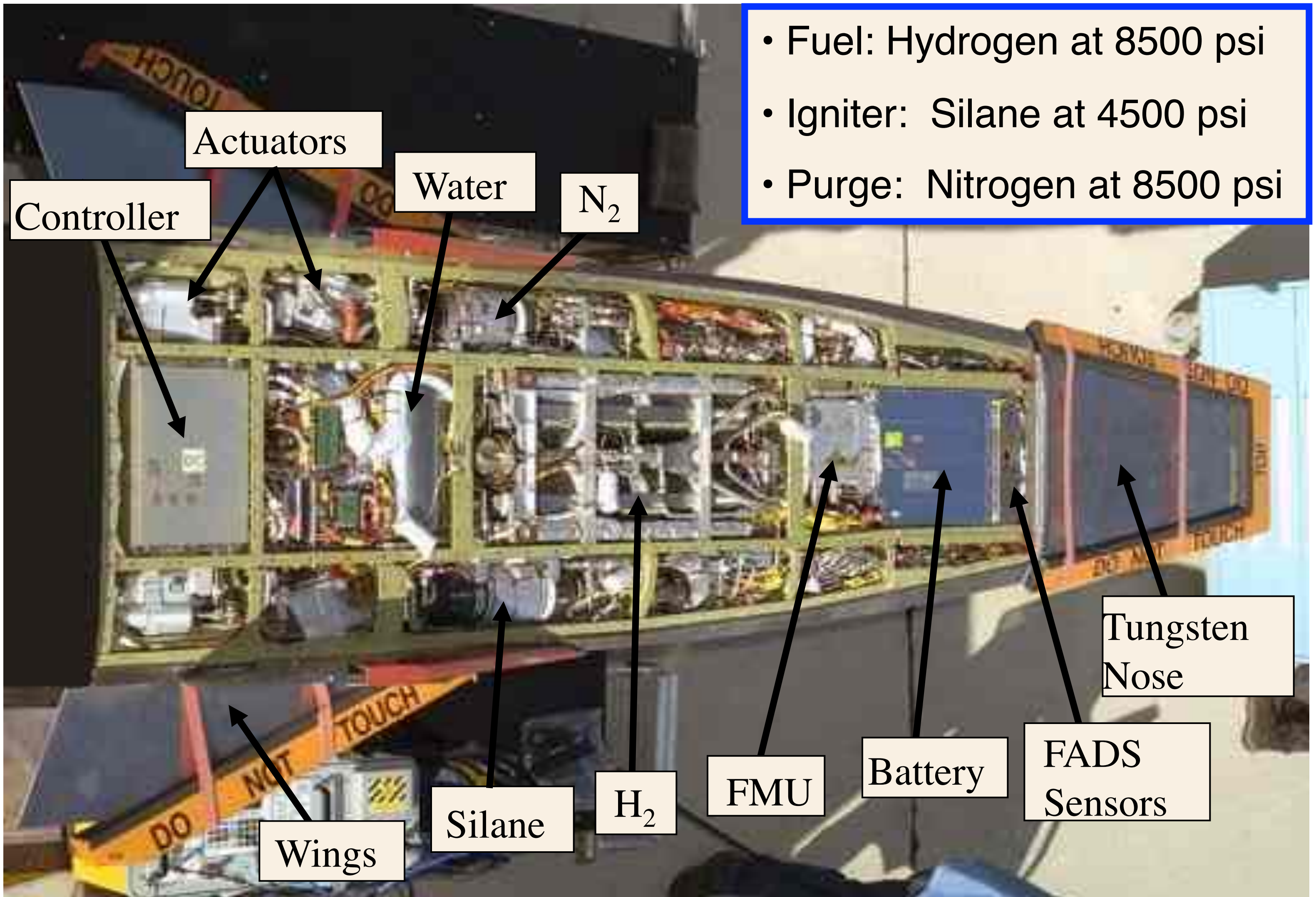
- Additional Research Objectives
  - Vehicle acceleration during the scramjet propulsion experiment
  - Obtain data from all flight phases
    - Captive carry (Launch Vehicle (LV) and Research Vehicle (RV))
    - Boost (LV and RV)
    - Stage separation (LV and RV) - data and video
    - Free flight (RV)
  - Obtain RV aero, structural, GNC, and other data to splash

X-43A External Configuration



Length: 12'4"
Width: 5'0"
Height: 2'2"
Weight: 3000 lb max

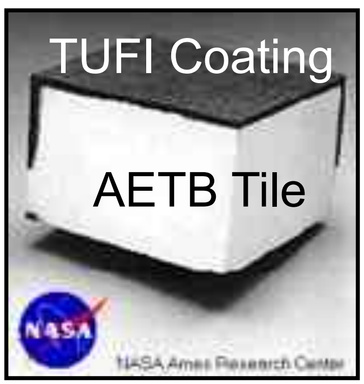
X-43A Systems



- Fuel: Hydrogen at 8500 psi
- Igniter: Silane at 4500 psi
- Purge: Nitrogen at 8500 psi

X-43A Material Layout

- Tungsten
- TUFI/AETB
- Haynes Alloy
- Carbon-Carbon
- Copper Alloy



Carbon-Carbon

Nose Leading Edge

Side Chine

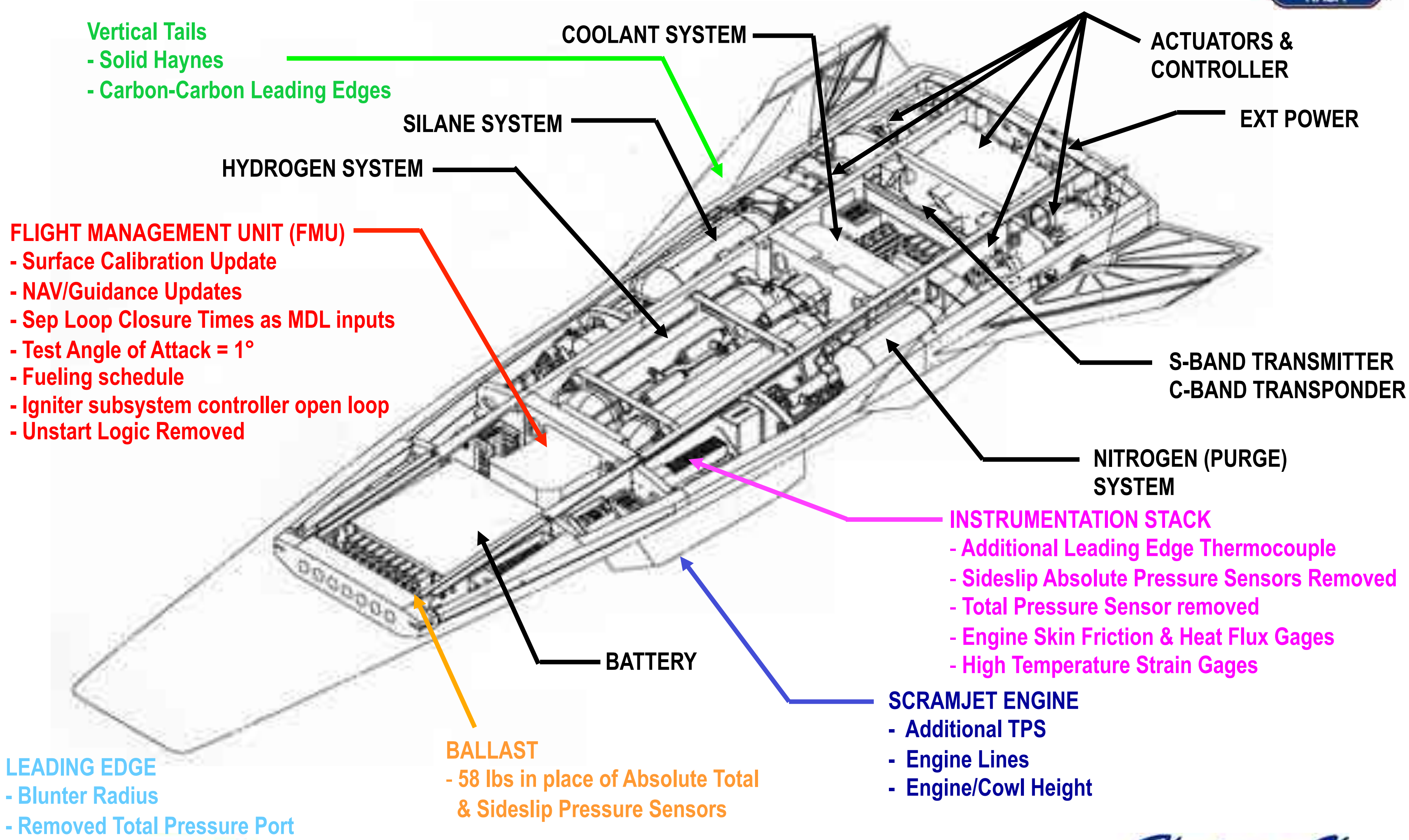
TUFI =Toughened Uni-piece Fibrous Insulation
AETB=Alumina Enhanced Thermal Barrier

Hyper-X

Flight 3 Approach and Philosophy

- Quick turnaround, goal for flight was 6 months after initial model release in early April.
  - The Flight 3 hardware was worked in parallel with Flight 2.
  - Final models and analysis were not available until after Flight 2 and initial post-flight analysis was complete.
  - Capitalized on recent Flight 2 experience and Return-to-Flight Approach
  - Work efficiently and quickly without losing attention to detail.
  - Team remained mostly intact
  - Tests and procedures went faster than they did for flight 2.
- Assumptions
  - Do very little independent analysis (i.e. no duplication of effort)
  - Look at Flight 2 data to determine what Flight 3 modifications would be necessary for success.
  - Models would not be updated based on flight data. The flight data would be used for guidance for modifications and for stress cases.
  - Engine test region was primary objective and therefore was the highest priority
- Flight 3 approach was success oriented and assumed no major issues.

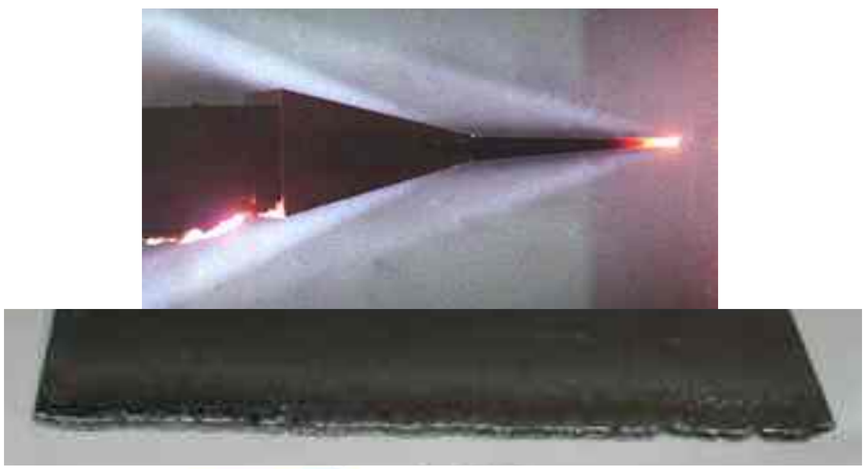
X-43A HW & SW Modification Summary



Hyper-X

Flight Preparation Challenges (1 of 3)

- Limited M10 Propulsion Ground Test Data
  - High energy requirement to simulate the mission flight conditions meant fewer ground test options were available. Shock tunnel testing was the only option.
  - Short test times only allowed single performance points per run, so no fueling or cowl position transitions possible.
  - Propulsion database uncertainties increased.



- Leading Edge Radius Erosion
  - Results of the arc jet tests performed on ship 3 C-C test samples showed ablation of the C-C nose leading edges at heating conditions and durations more severe than final Mach 10 trajectory.
  - Machined a new leading edge incorporating a larger leading edge radius and altering the upper OML of the nose so as to not change the nose planform to reduce the likelihood of material ablation.

Flight Preparation Challenges (2 of 3)

- Carbon-Carbon Chine De-lamination
  - C-C chine de-lamination discovered during a final fit check.
  - The C-C pieces went through several heat treatment cycles during the manufacturing process
  - Replacement chine was fabricated and special attention was given during the manufacturing process to ensure no repeat occurrence.
  - If not for the spare billet that had already been through some of the heat treatment cycles flight 3 would not have made schedule.
- Data Acquisition During the Flight
  - Two P-3 Aircraft were needed to capture the entire flight.
  - Due to the P-3 maintenance schedule and the tight schedule for the X-43A project, only one was available to support the flight.
  - P-3 data of the engine test was the best quality for Flight 2.
  - P-3 was placed to capture the primary mission (boost through cowl closed) and capture as much data prior to splashdown as possible.
  - P-3 did not capture the splash point. Loss of signal occurred when X-43A was at 918 kft, descending at a rate of 228 ft/s.

Flight Preparation Challenges (3 of 3)

- Limited funds
  - Following flight 2 discussed feasibility of performing flight 3 within the remaining budget.
  - Projected that flight could occur in September, but different technical issues pushed flight out to November.
  - Money ran out in 1st week of Dec. 2004.
  - Worked so hard to get the data, but no money to analyze it and write reports.

- Schedule impact on testing
  - Very compressed schedule required the elimination of some planned tests.
  - Selected those tests that had been successfully performed with predictable results.
  - Vehicle 3 in fabrication at the same time that we were working toward flight 2.
  - Some Flight 2 testing was performed on Flight 3 hardware.
  - Testing went faster and the eliminated tests were put back in the schedule.

Flight 3 – November 16, 2004

HXRV Flight 3 Results Summary

Stage Separation:

- 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 9.68
- 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, sustained thrust equal to drag, as predicted.
- 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:

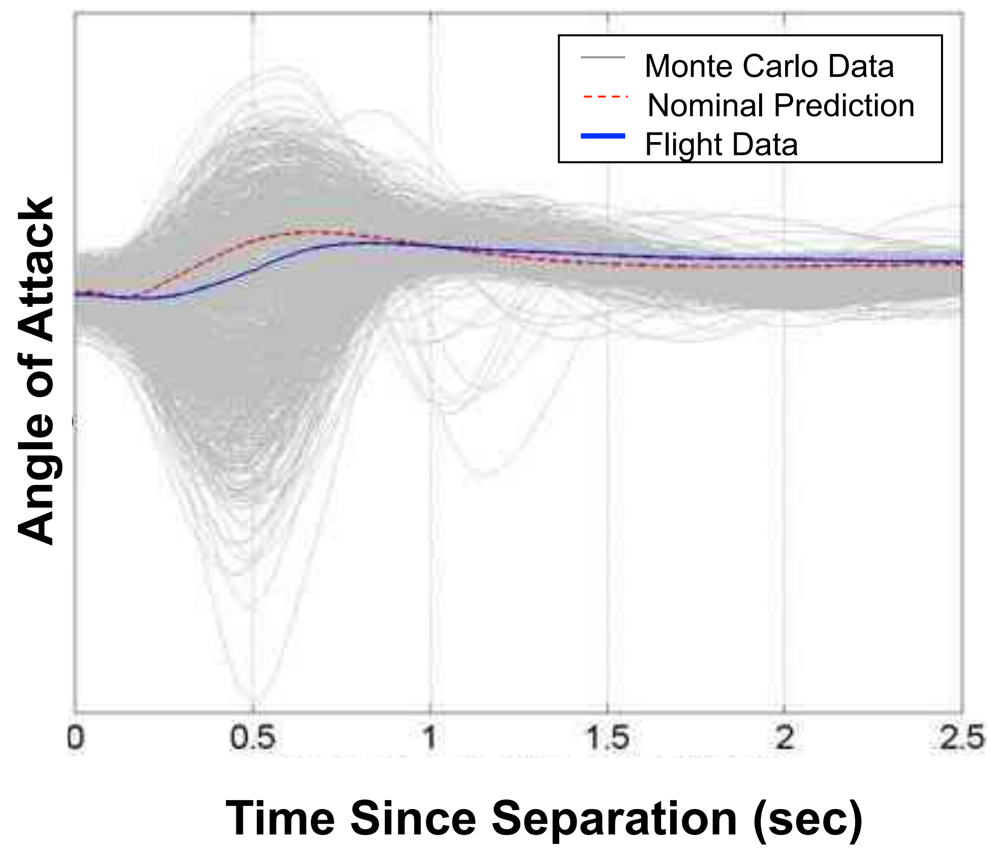
- All systems on both the launch vehicle and X-43A performed well and extensive research quality data was acquired throughout the boost and descent.

Flight 2 Assists Flight 3 Performance

- Following the separation transient, the HXRV took longer to reach the commanded angle-of-attack than predicted by pre-flight analysis.

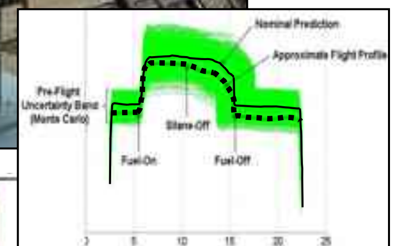
- Wing trim position offset due to difference in trim pitching moment, Cm_o

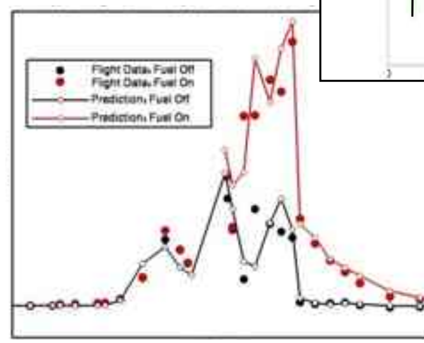
- Gain modification due to flight 2 results did allow a faster recovery.



Concluding Remarks

- Best Possible Outcome: Scramjets Work & Importance of Flight Testing
  - Demonstrated that airframe integrated scramjets are a viable option for future atmospheric and spaceflight applications
- 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.
- 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.
  - Several lessons learned from flights 1&2 applied to flight 3.
  - A dedicated project team that worked for eight years to make these revolutionary flights a reality






Questions ???

Backup Charts

Separation Condition Results

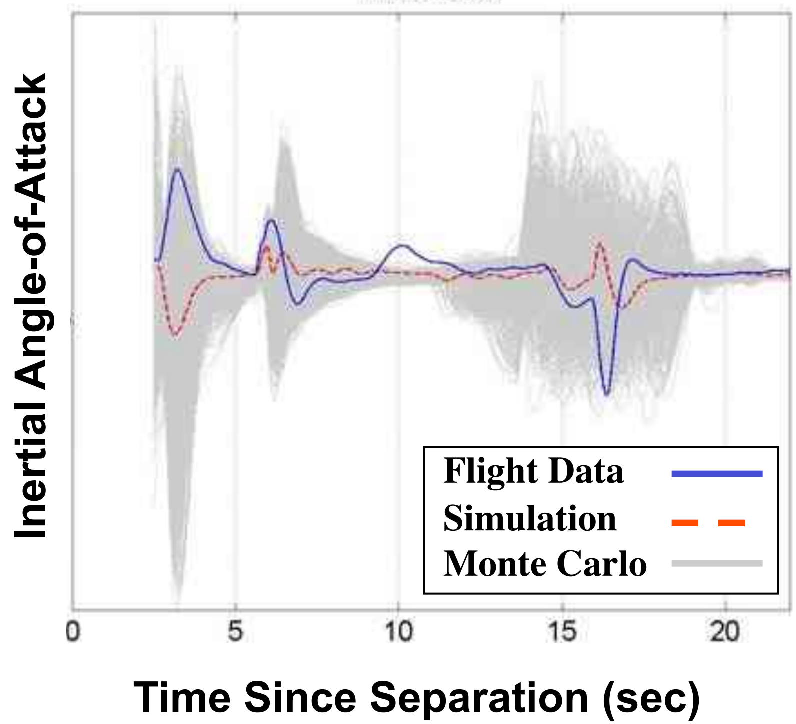
- All separation conditions were essentially nominal and within an acceptable tolerance.

Parameter	Target	Flight No. 3 Values	Deviation
Time to Condition	≤104.0 sec	88.16 sec	0.0 sec
Altitude	109,580 ft	109,440 ft	- 140 ft
Mach*	9.6	9.736	+ .136
Dynamic Pressure*	1000 psf	959 psf	- 41.0 psf
Flight Path Elevation Angle	1.5 deg	1.69 deg	+ 0.19 deg
Booster Angle of Attack	0.0 deg	0.08 deg	+ 0.08 deg
Booster Sideslip Angle	0.0 deg	- 0.13 deg	- 0.13 deg

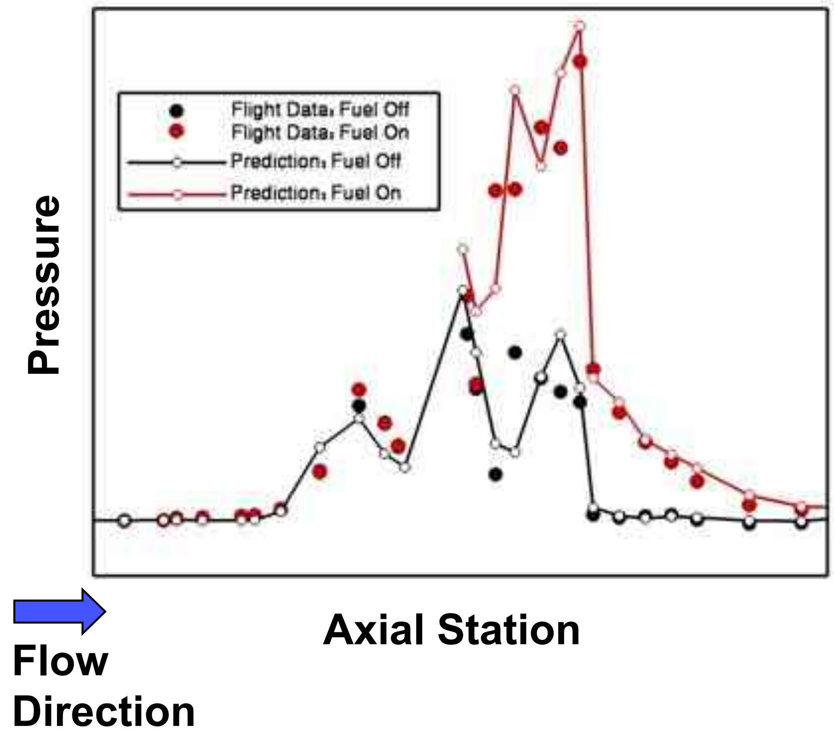
* Computed Using Best Estimate Atmospheric Model

Engine Test Results

X-43A Angle of Attack

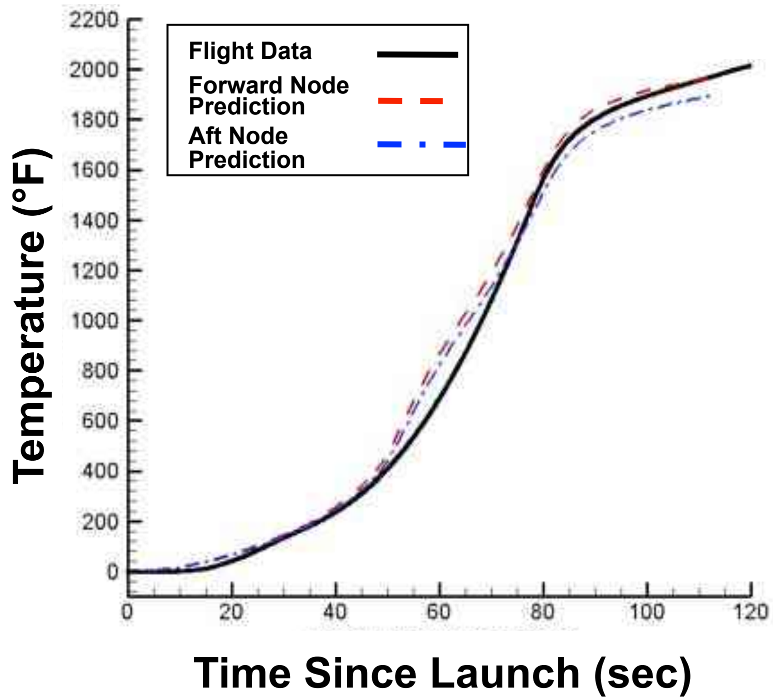


Flight vs. Pre-Flight Propulsion Database

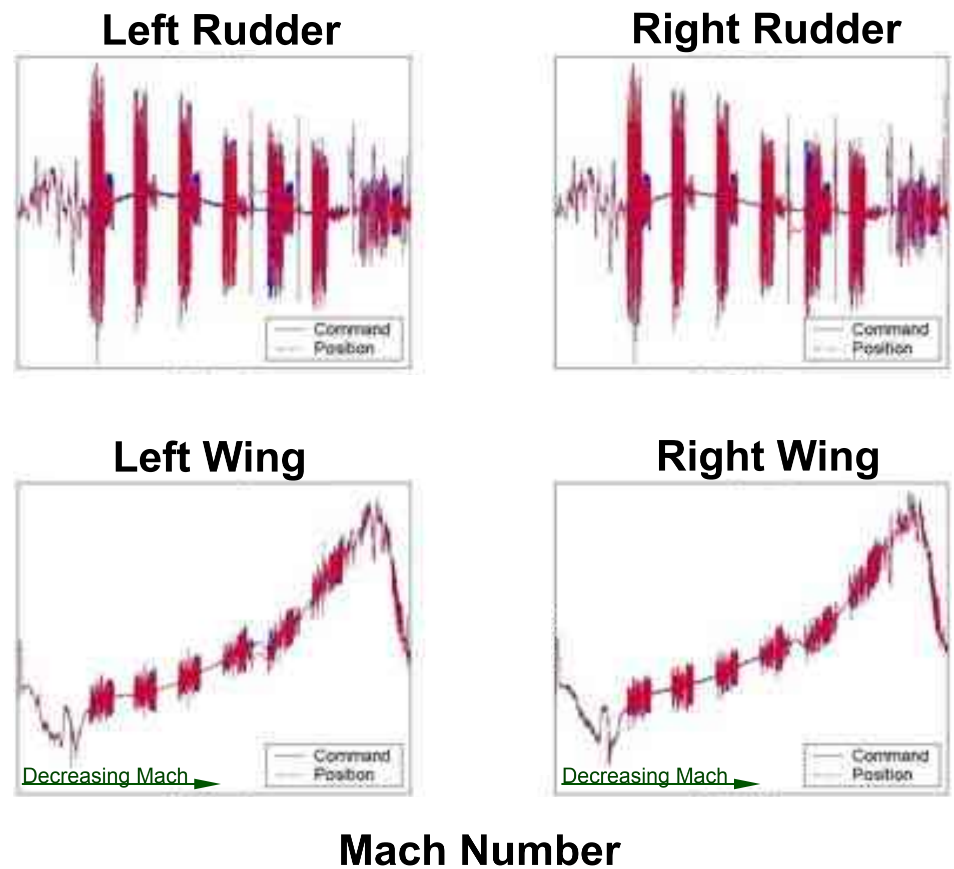


Mach 10 Flight Results

X-43A Nose Temperature Launch to Cowl Closed



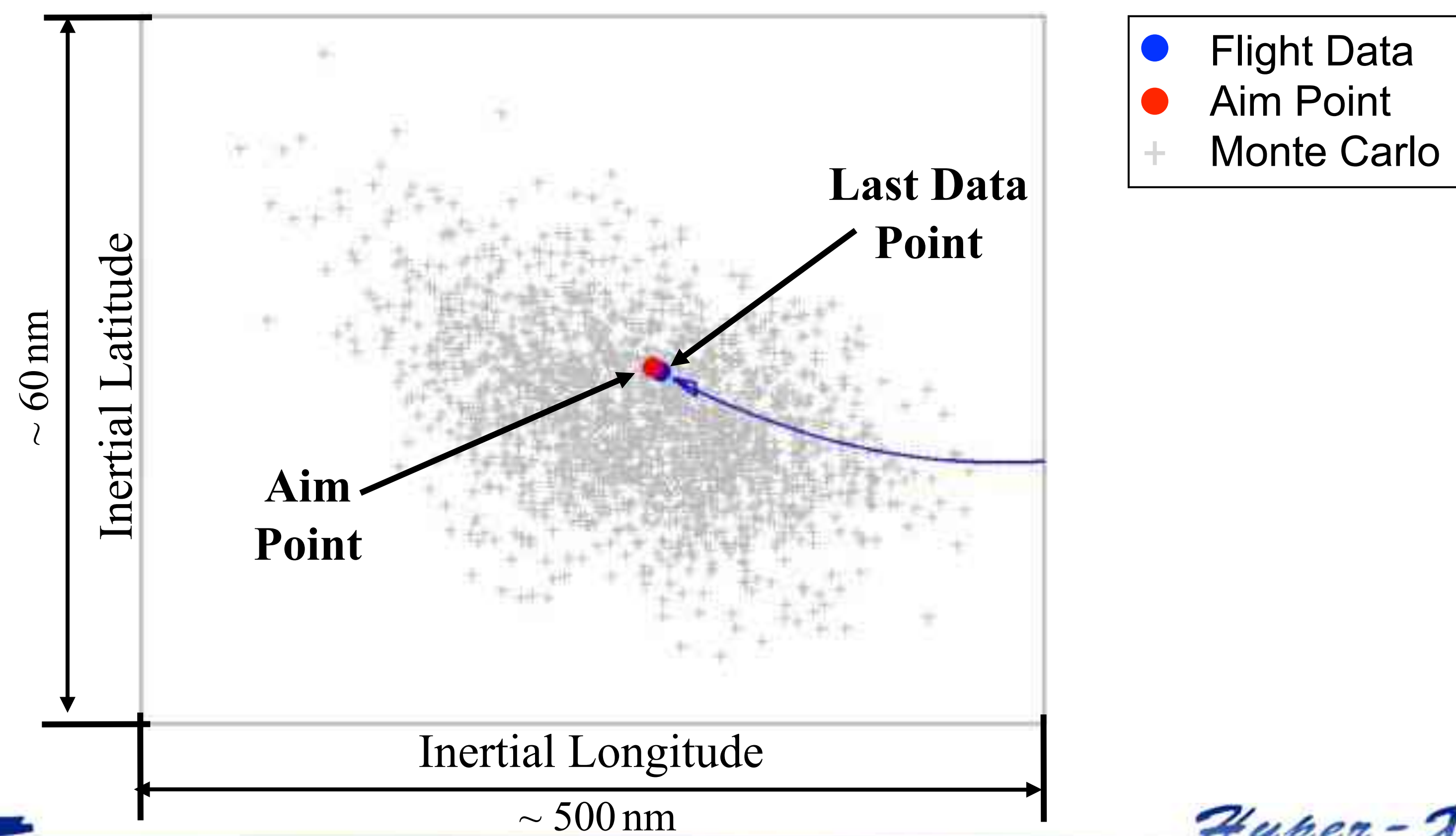
X-43A Control Surfaces Separation to Splash



Descent Performance
Research Vehicle Last Acquired Data Point

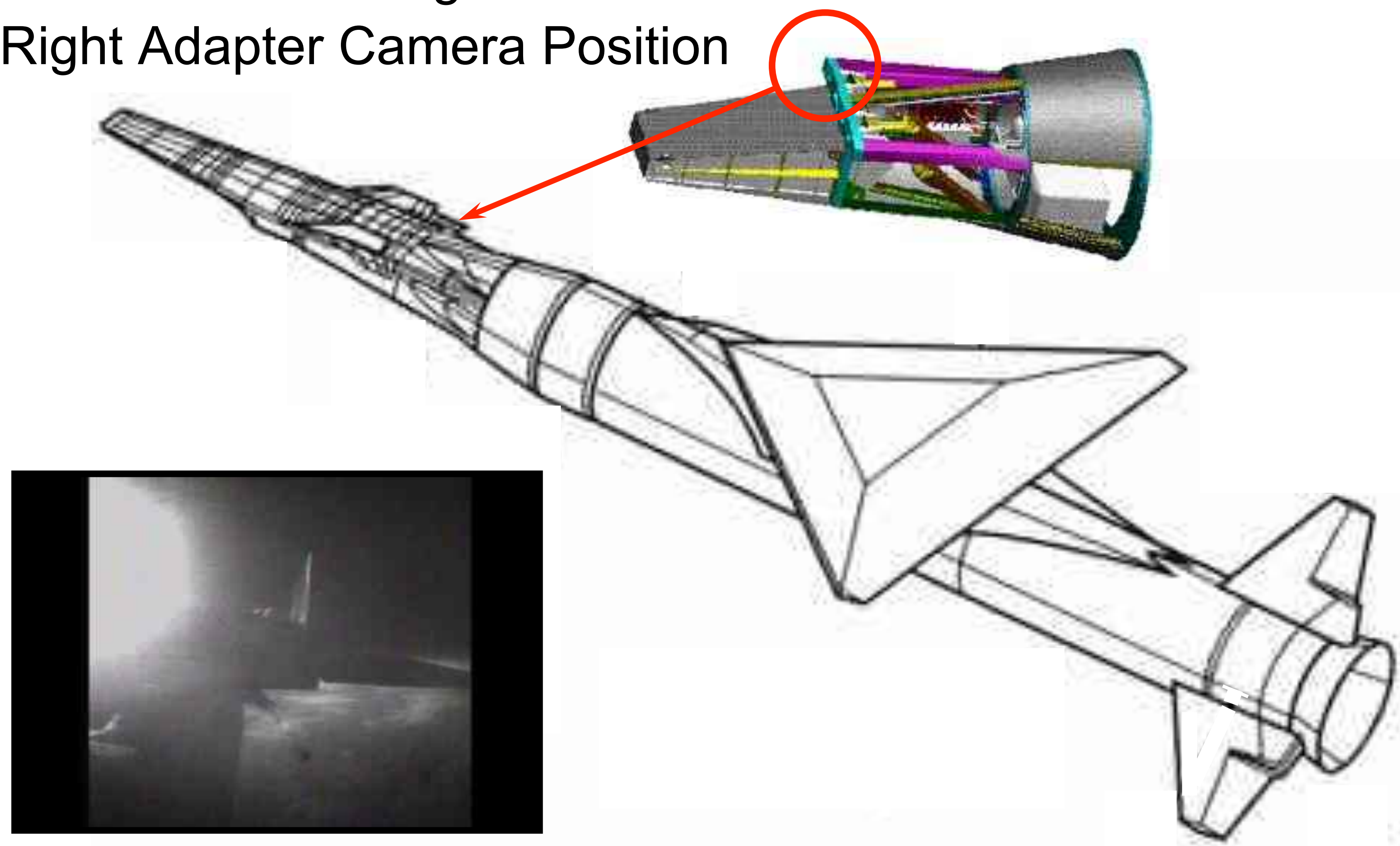
Last Acquired Data Point

Altitude (ft)	Mach No. (-)	Altitude Rate (ft/s)	Alpha (deg)	Flight Path Angle (deg)	Bank Angle (deg)
918.49	0.72	-228.43	7.71	-16.60	1.6



Flight 3 Right Adapter Camera Image

- Time between images is 33.3 milliseconds - 1/30th of real-time.
- Right Adapter Camera Position



Hyper-X

Flight 2 – March 27, 2004


GUINNESS WORLD RECORDS

CERTIFICATE

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

GUINNESS WORLD RECORDS LTD

Flight 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):

Mach 7	Mach 10
•The maximum powered Mach number was 6.8 •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 9.6 •The scramjet was fueled for approximately 10 seconds, 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:

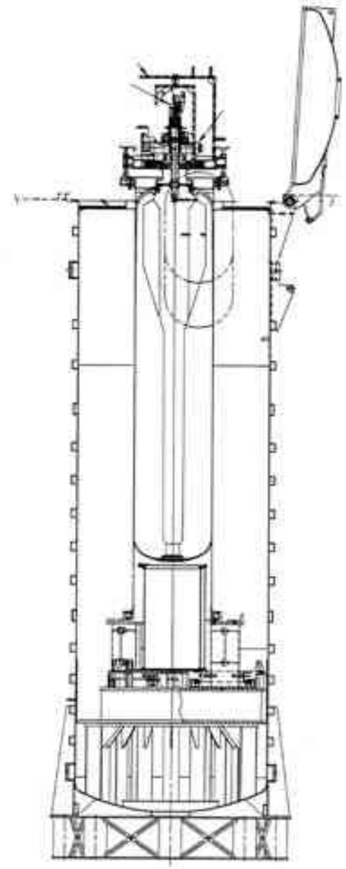
- All systems on both the launch vehicle and X-43A performed well and extensive research quality data was acquired throughout the boost and descent.

Hyper-X

Getting There: Boost

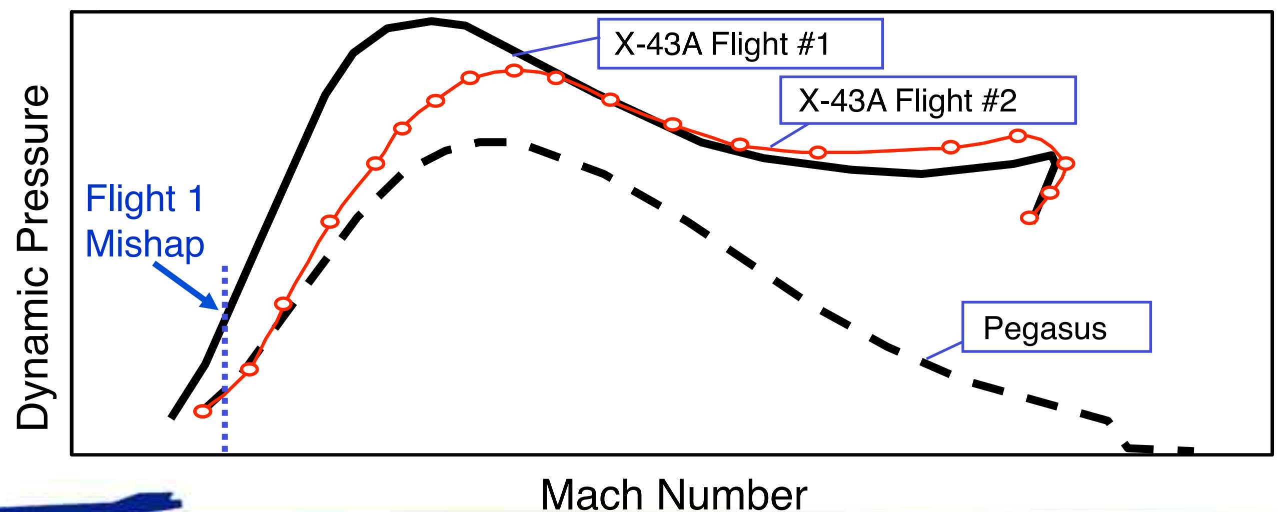
Dual Motor Actuator

Propellant Offload



Machining Stand

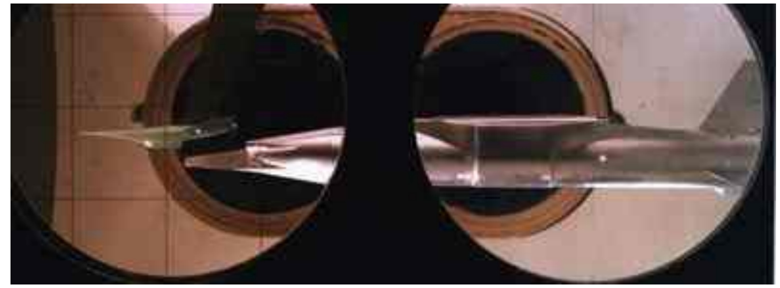
Trajectory Updates



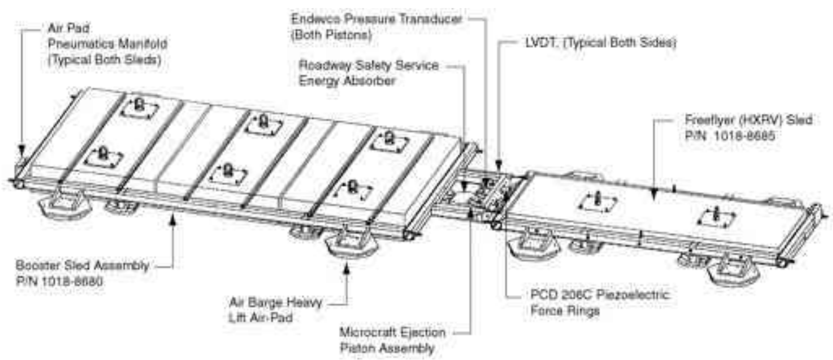
Hyper-X

Getting There: Separation

- **Stage Separation Wind Tunnel Test (AEDC)**
  - Full-Interference
  - Varied separation distance between the two models.
  - Allowed detection of interference effects and influences from one on the other.
  - WT data used in conjunction with CFD in Separation Aerodynamic Database.



- Ejector Piston Test (OSC)
  - Blocks used to simulate mass of vehicles
  - Purpose: assess performance of pistons and gather data for ejector piston model.



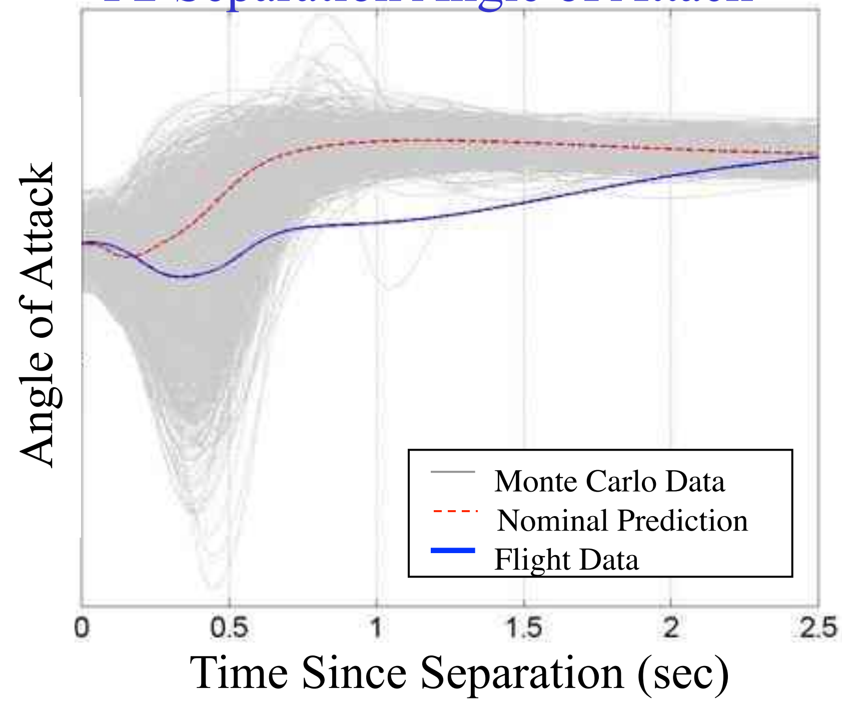
- Full-Scale Separation Test (OSC)
  - X-43A ballasted for flight weight and CG location.
  - Purpose: demonstrate that mechanical systems function as expected, test adapter cameras, and validate separation simulation.

Hyper-X

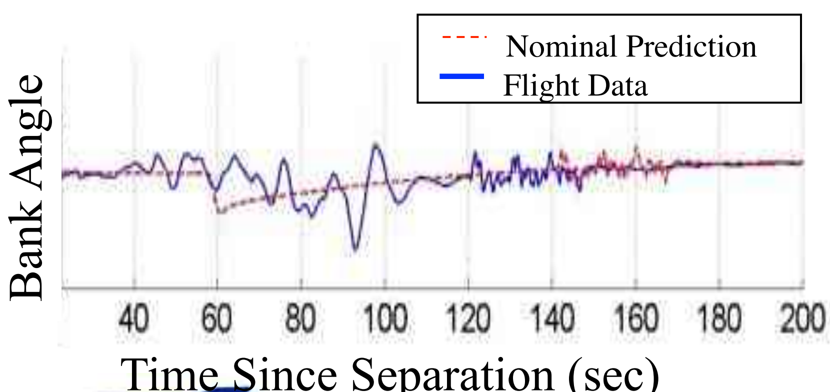
Value of Flight Testing

- Following the Flight 2 separation transient, the X-43A took longer to reach the commanded angle-of-attack than predicted by pre-flight analysis.
- Most likely caused by a miscalculation in trim pitching moment.
- Flight 3 modifications based on Flight 2 results did allow a faster recovery.

F2 Separation Angle of Attack



F3 Recovery Maneuver Bank Angle



- X-43A roll oscillations and large trim required during the recovery maneuver.
- Preliminary analysis indicates that this was most likely caused by airflow through the engine post cowl closed.

The End of an Era

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.

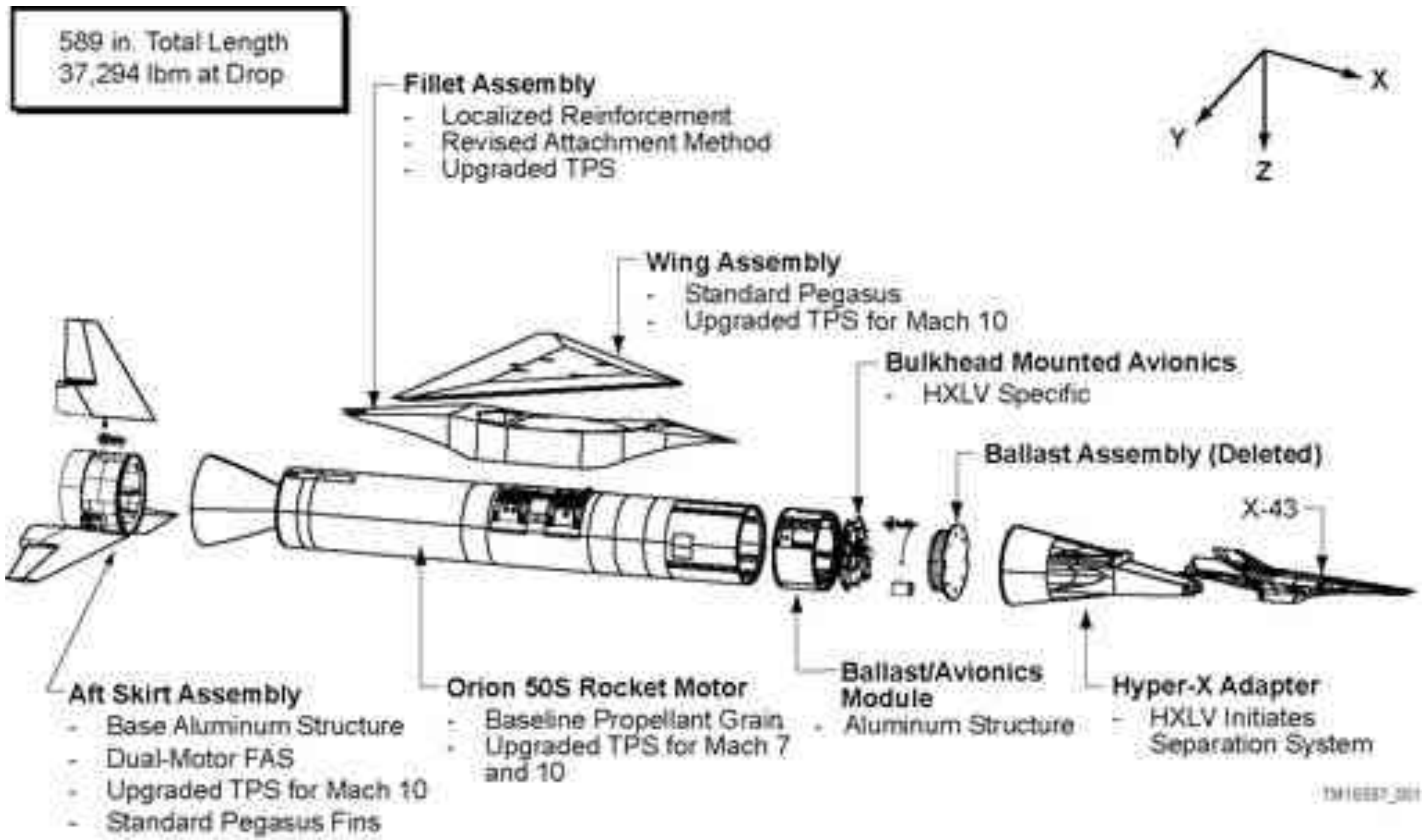
Mishap Investigation & Return to Flight Effort

- 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

RTF Technical Approach

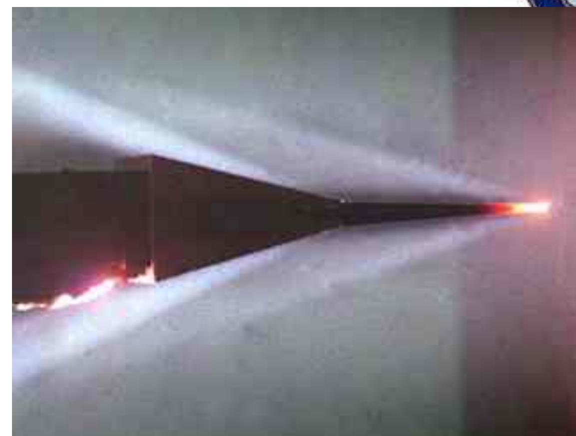
- Launch more like a standard Pegasus booster
  - Capitalize on Pegasus flight heritage
  - Reduce hinge torque loads on the fins
  - B-52 drop at 40 kft and Mach 0.8
- Increase the hinge torque capability of the fin actuator system
- Review and improve all models for LV, Sep, & RV
  - Emphasis on the aero and actuator models
  - Perform additional wind tunnel test
    - Performed 12 additional LV wind tunnel tests following Flight 1
  - Develop independent simulations
    - Independent simulations were developed for LV and Separation. Detailed independent review of the RV simulation was performed.

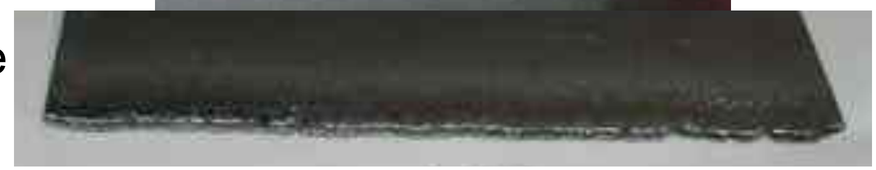
Flight 3 Launch Vehicle Configuration



Flight 3 Top Technical Issues

- Leading Edge Radius Erosion (February '04)
  - Results of the arc jet tests performed on ship 3 C-C test samples showed ablation of the C-C nose leading edges at heating conditions and durations more severe than final Mach 10 trajectory.
  - Machined a new leading edge incorporating a larger leading edge radius and altering the upper OML of the nose so as to not change the nose plan form to reduce the likelihood of material ablation





- Heat Exchanger (May '04)
  - Integrated leak and functional testing results showed unacceptable leak rates in Hydrogen System Motorized Control Valve.
  - Inspection indicated contamination as cause.
  - Heat Exchanger was replaced; No leaks.

Flight 3 Top Technical Issues

- Carbon-Carbon Delamination (June ’04)
  - Observed during fit check.
  - New Chine Fabricated
  - Tap tests & thermographic inspection to ensure all pieces are intact.

- RV Left Rudder & Left Wing (June ’04)
  - RV Lt. Rudder & Lt. Wing contact while returning the wing to zero after the carbon-carbon trim
  - Assessment performed by a large team incl. LaRC materials fractures group, Moog, DCI, BNA, and DFRC
  - Actuators/controller not stressed beyond existing qualification loads.
  - Rudder spindle damaged. Software fix implemented to accommodate.
  - Significant margin remained on rudder spindle to successfully perform mission with high confidence. Replacement not necessary.