X-43A Project Overview

Adventures in Hypersonics

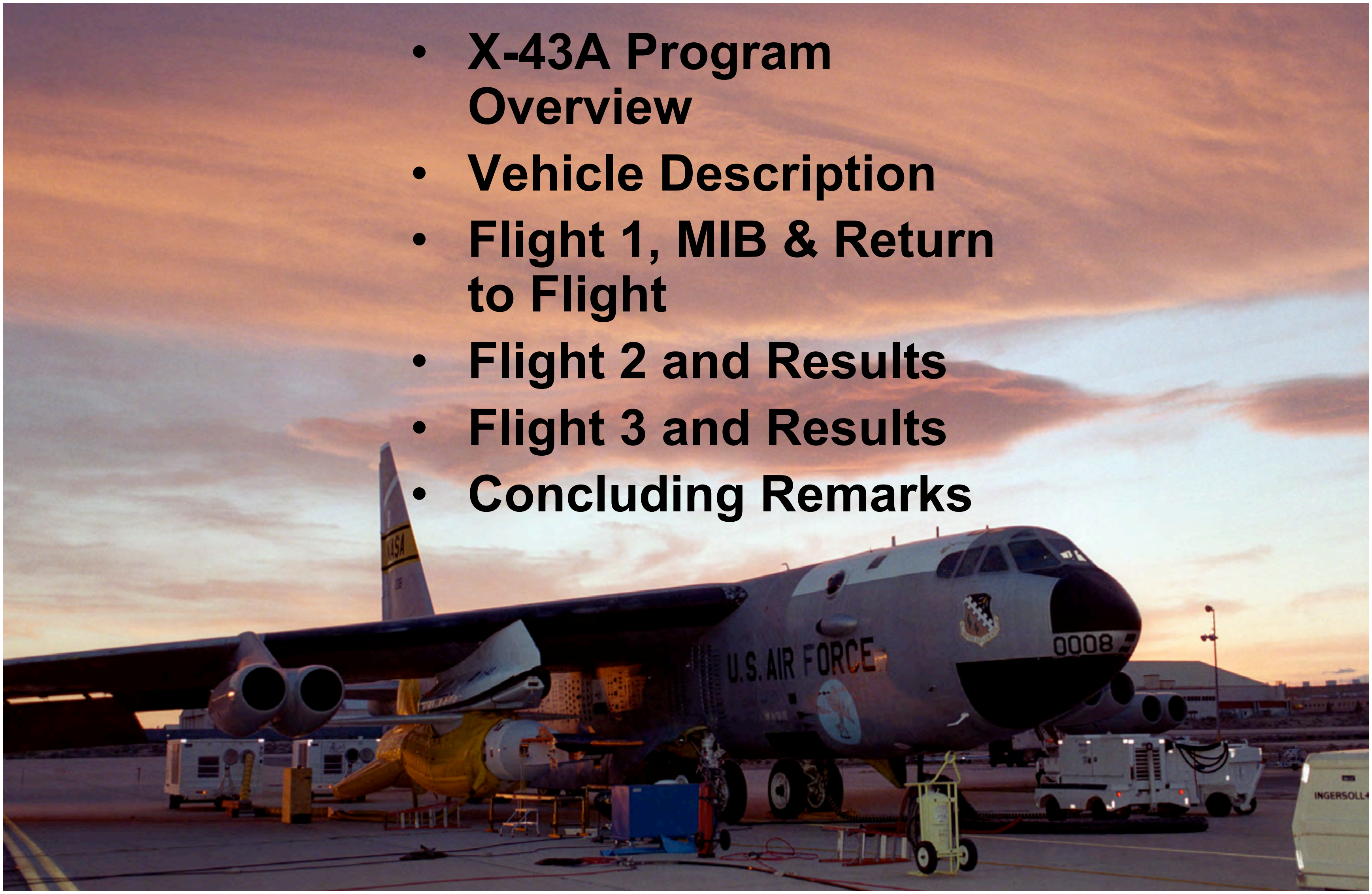
Based on AIAA Papers:

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



Hyper-X

X-43A (Hyper-X) Program Overview

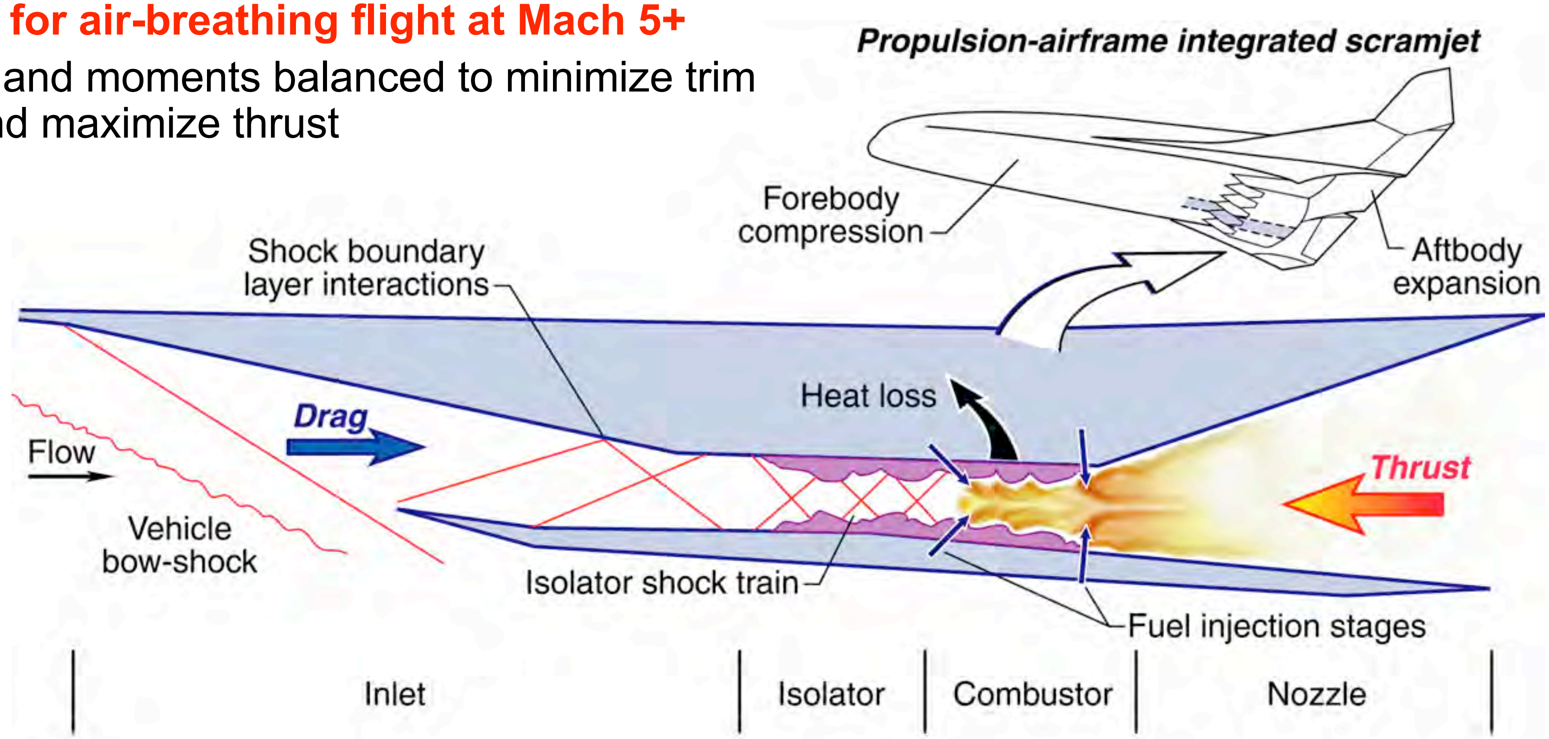
- First ever flight demonstration of an airframe-integrated scramjet powered hypersonic vehicle
- Primary objective was to validate the tools, test and analysis techniques, & design methods of scramjet powered, hypersonic vehicles
- Three flight project
  - Two flights at Mach 7
  - One flight at Mach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

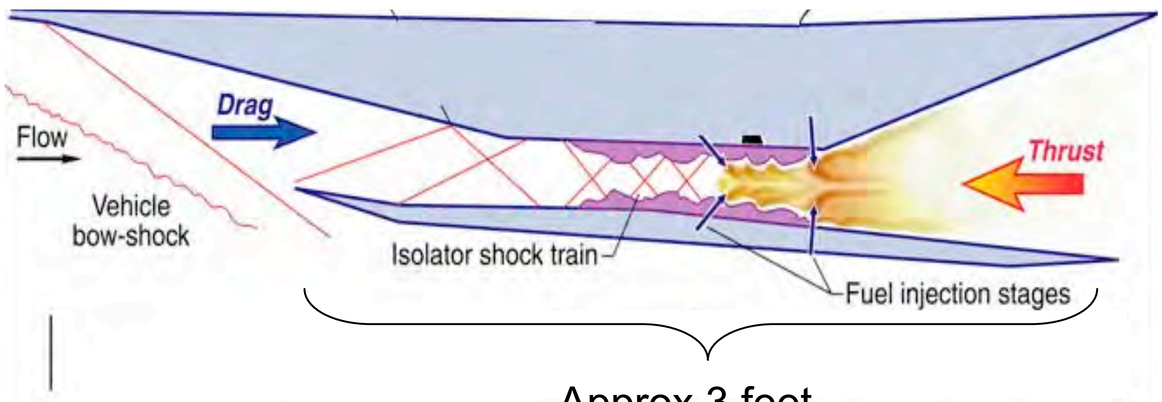
Scramjets

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



- 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

The Challenge



Mach 7
~7,000 ft/sec

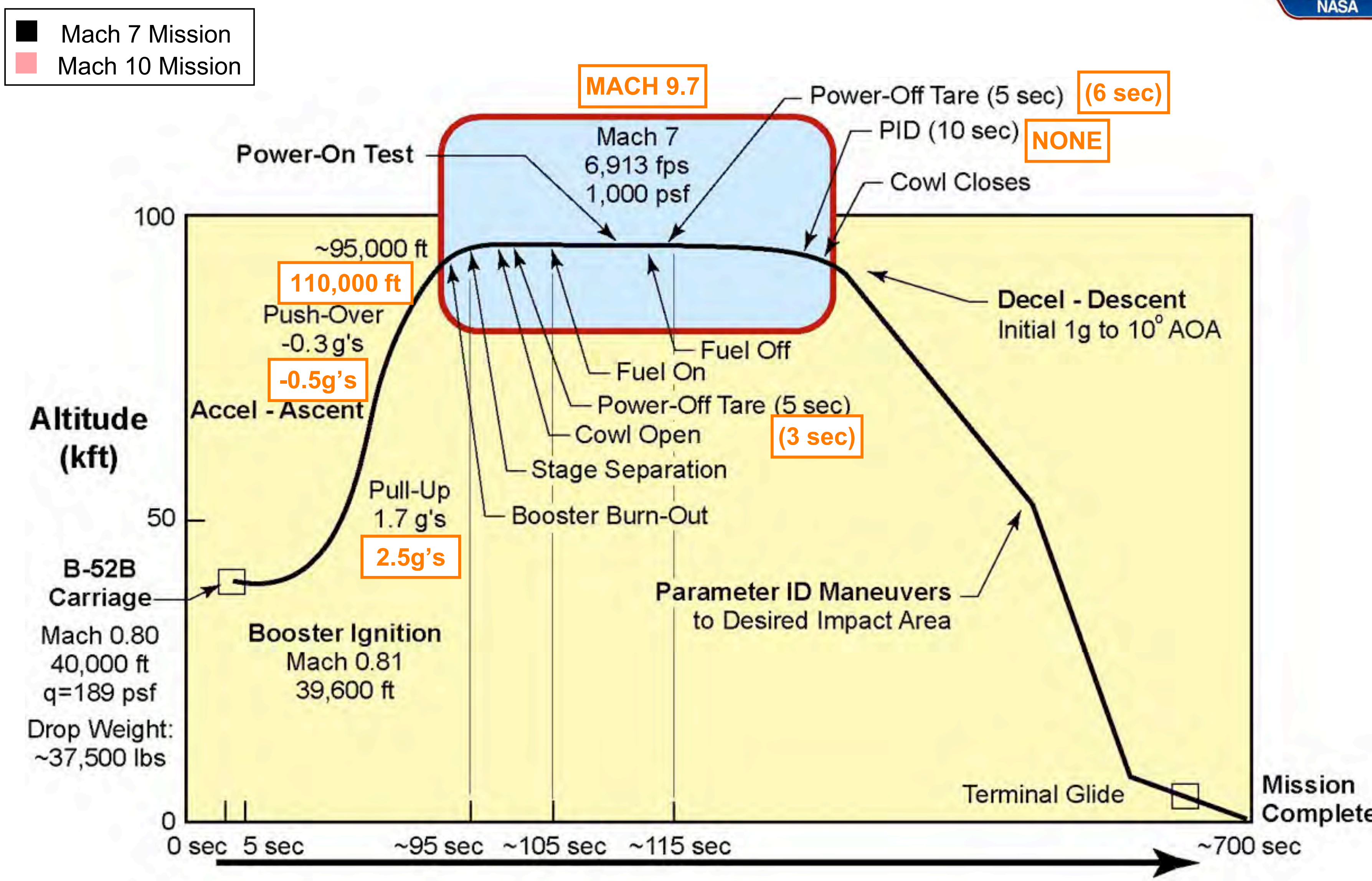
Approx 3 feet
~3,000 ft/sec
O2 residence time ~ 0.001 sec

"Likened to keeping a candle lit in a hurricane"

- During the 0.001 sec
  - Inject the H_2, mix the fuel and air, and ignite the mixture
  - Combust the H_2+O_2 to H_2O (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

X-43A Flight Phases

X-43A Mach 7 and Mach 10 Mission Profiles

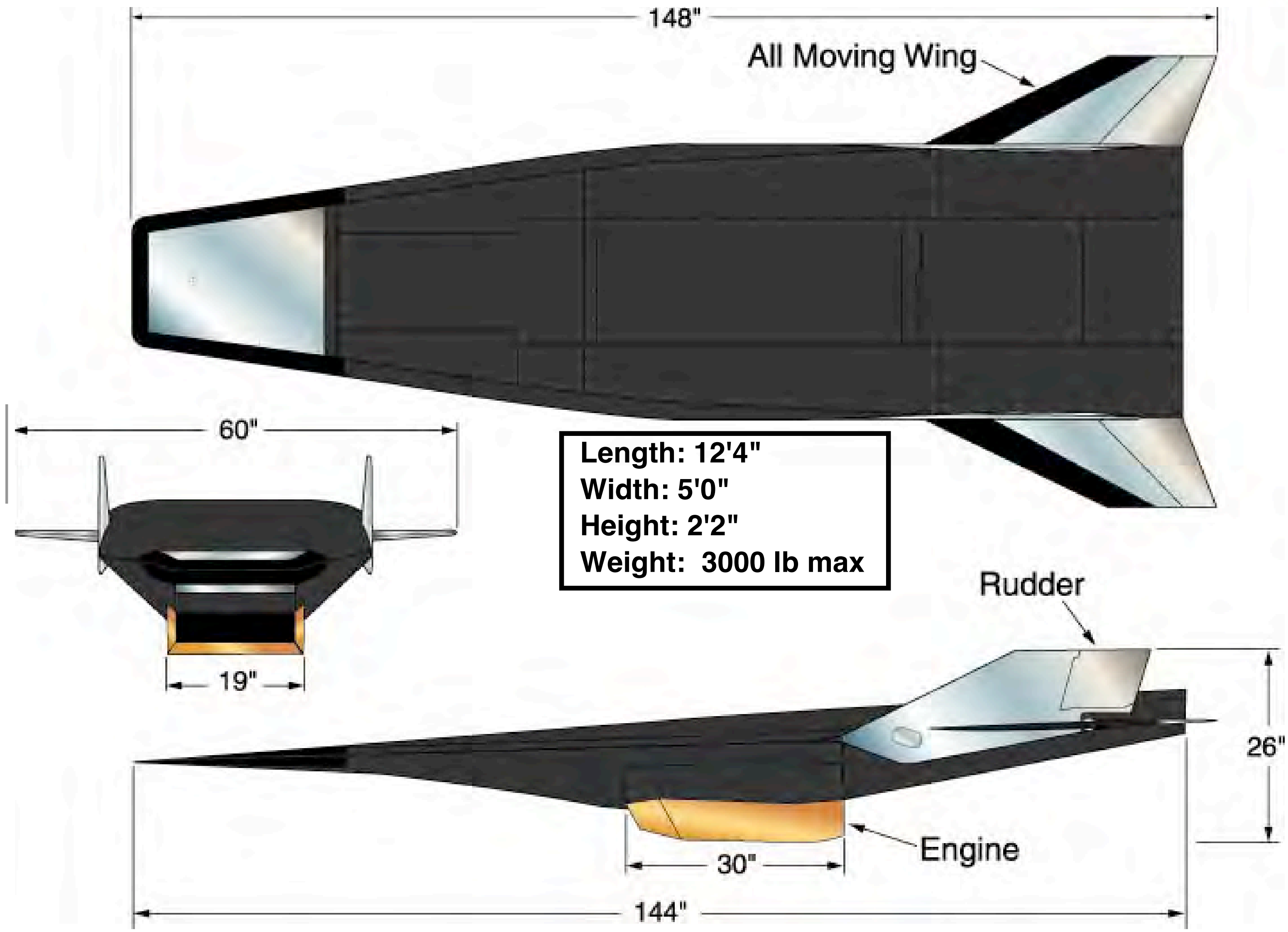


Hyper-X

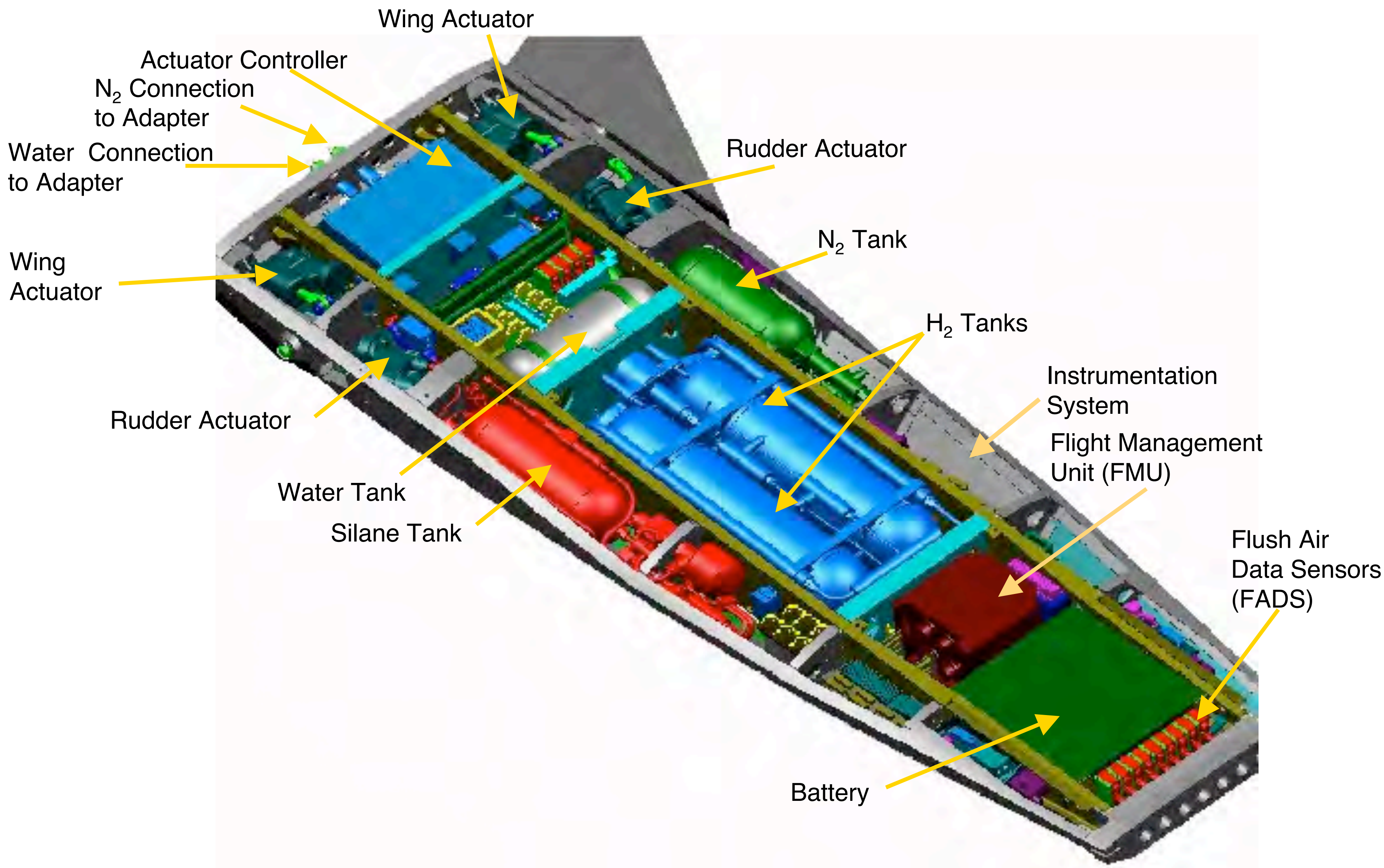
Nominal Timeline

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

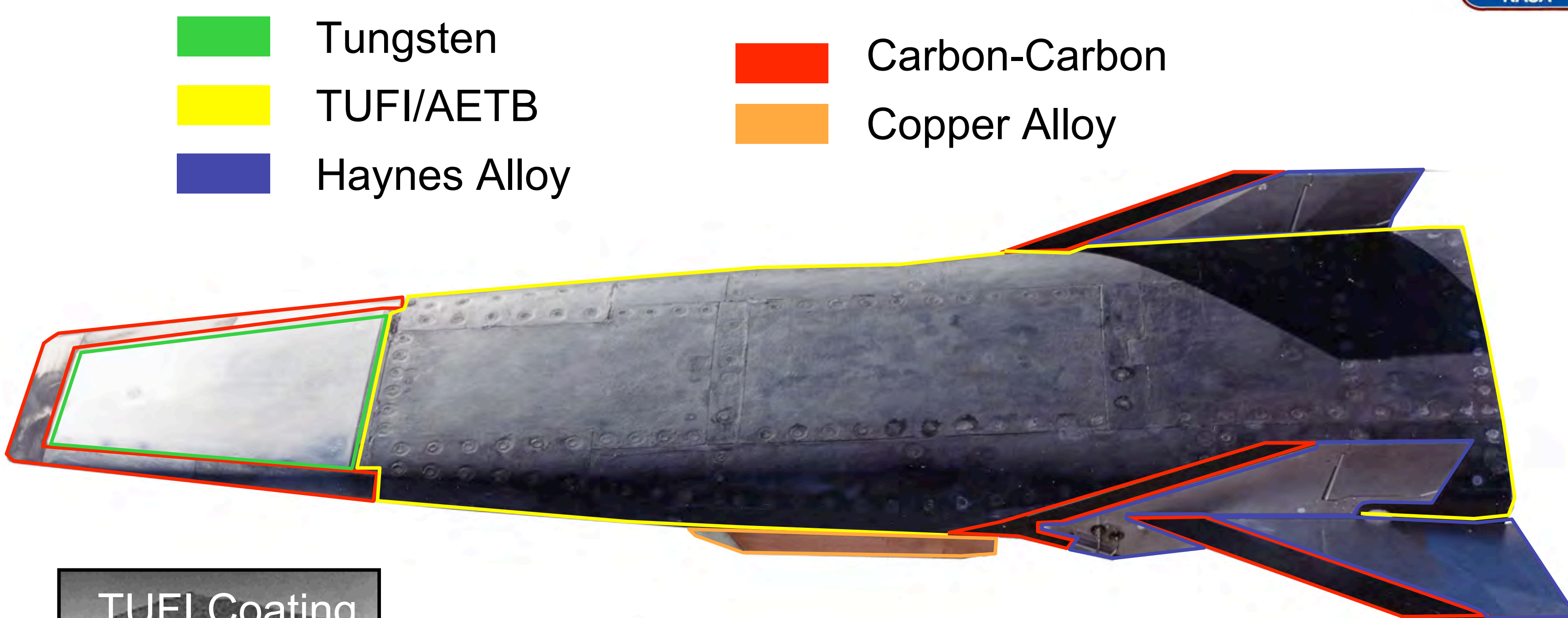
X-43A External Vehicle Configuration

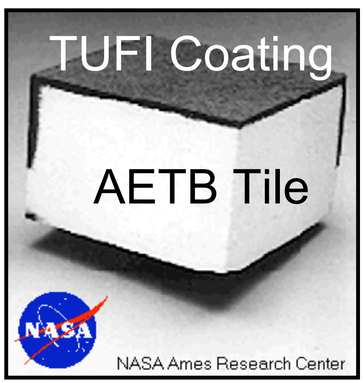


X-43A Internal Vehicle Configuration

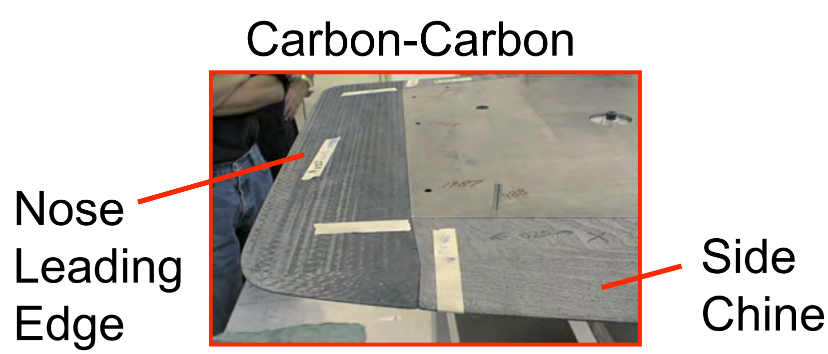


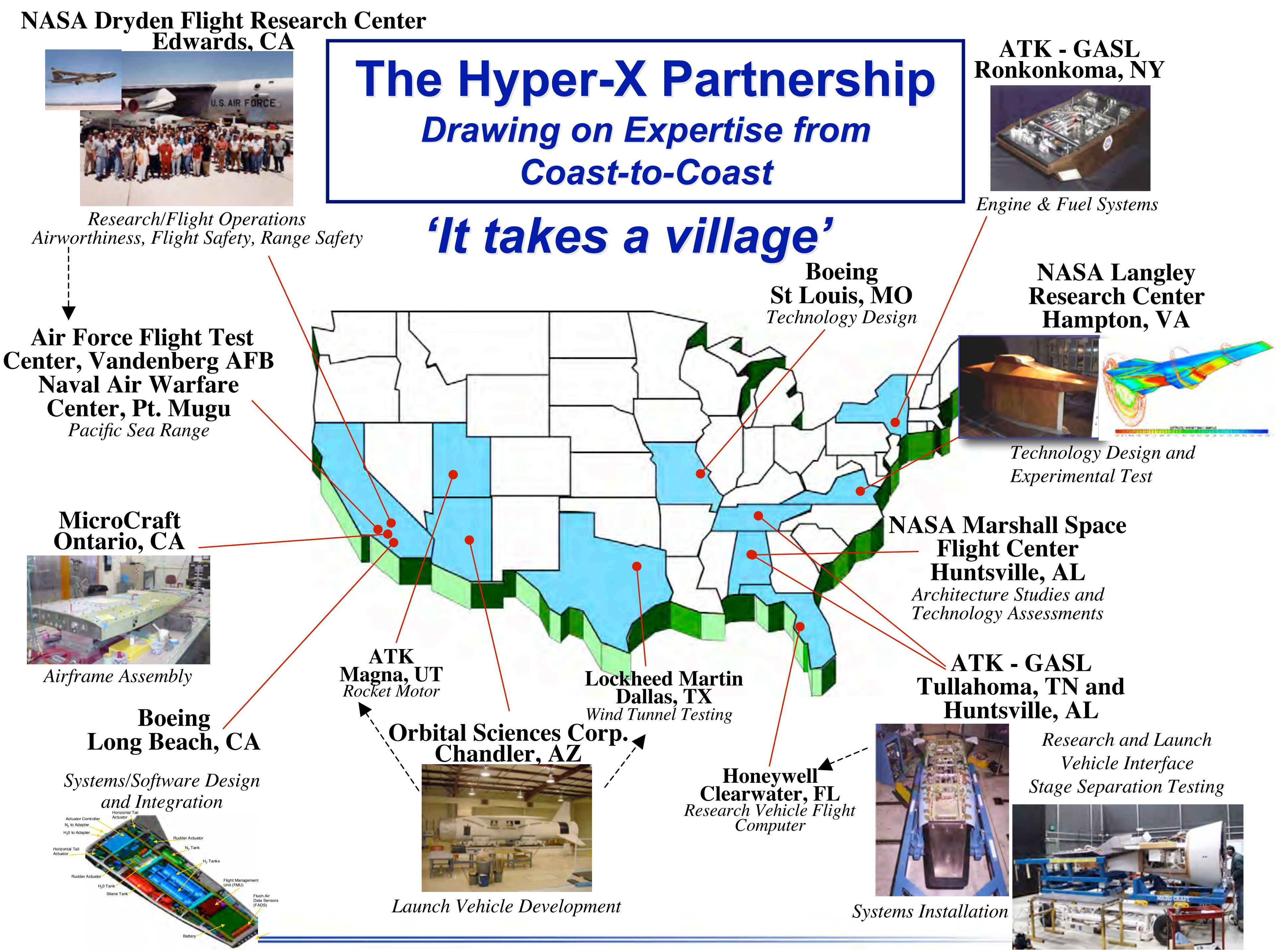
X-43A Material Layout





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



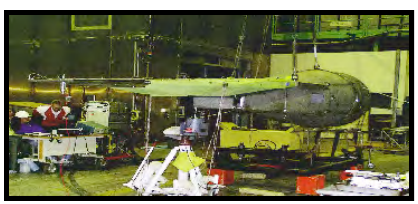

The Hyper-X Partnership
Drawing on Expertise from Coast-to-Coast
'It takes a village'
NASA Dryden Flight Research Center
Edwards, CA
U.S. AIR FORCE
Research/Flight Operations
Airworthiness, Flight Safety, Range Safety
Air Force Flight Test Center, Vandenberg AFB
Naval Air Warfare Center, Pt. Mugu
Pacific Sea Range
MicroCraft
Ontario, CA
Airframe Assembly
Boeing
Long Beach, CA
Systems/Software Design and Integration
ATK
Magna, UT
Rocket Motor
Orbital Sciences Corp.
Chandler, AZ
Launch Vehicle Development
Lockheed Martin
Dallas, TX
Wind Tunnel Testing
Honeywell
Clearwater, FL
Research Vehicle Flight Computer
Boeing
St Louis, MO
Technology Design
ATK - GASL
Ronkonkoma, NY
Engine & Fuel Systems
NASA Langley Research Center
Hampton, VA
Technology Design and Experimental Test
NASA Marshall Space Flight Center
Huntsville, AL
Architecture Studies and Technology Assessments
ATK - GASL
Tullahoma, TN and Huntsville, AL
Research and Launch Vehicle Interface
Stage Separation Testing
Systems Installation

Highly Integrated Effort Required

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

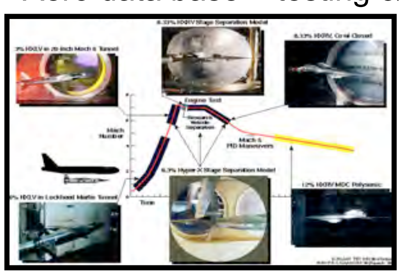
Systems
- Flight computers
- Actuators
- Power
- Software
- V & V testing

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



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

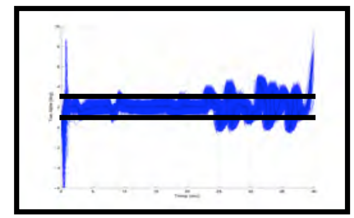
Aerodynamics
- Outer mold line design
- Aero data base – testing & CFD



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

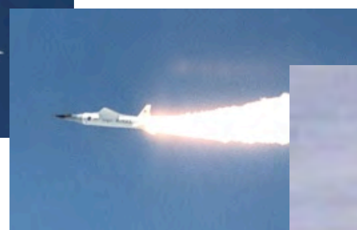
Stage Separation
- Never been done
- High q, asymmetric bodies

GNC
- LV, Sep, & RV control laws

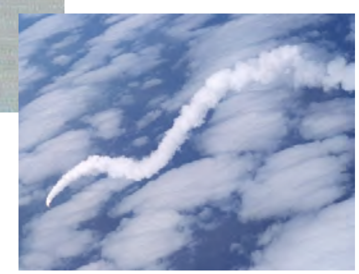


Launch Vehicle
- The ride to Mach 7 and 10
- Modified Pegasus booster

Flight 1 - June 2, 2001



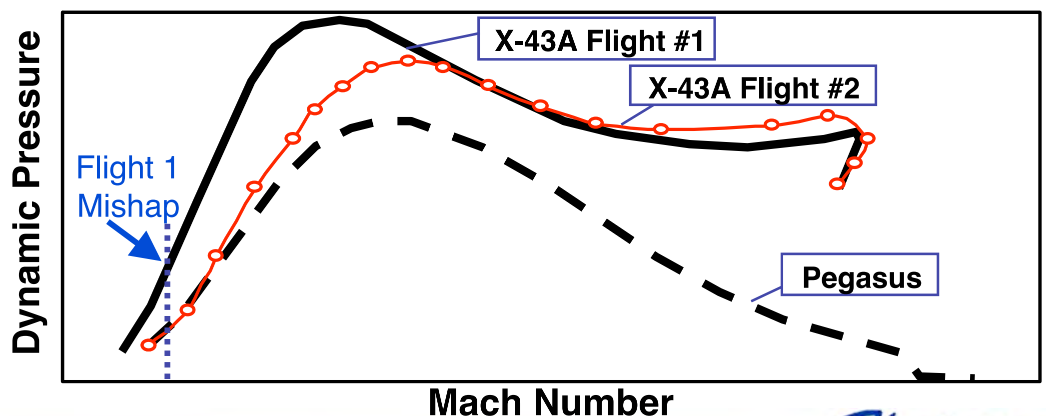
Flight Testing IS Risky Business



- 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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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

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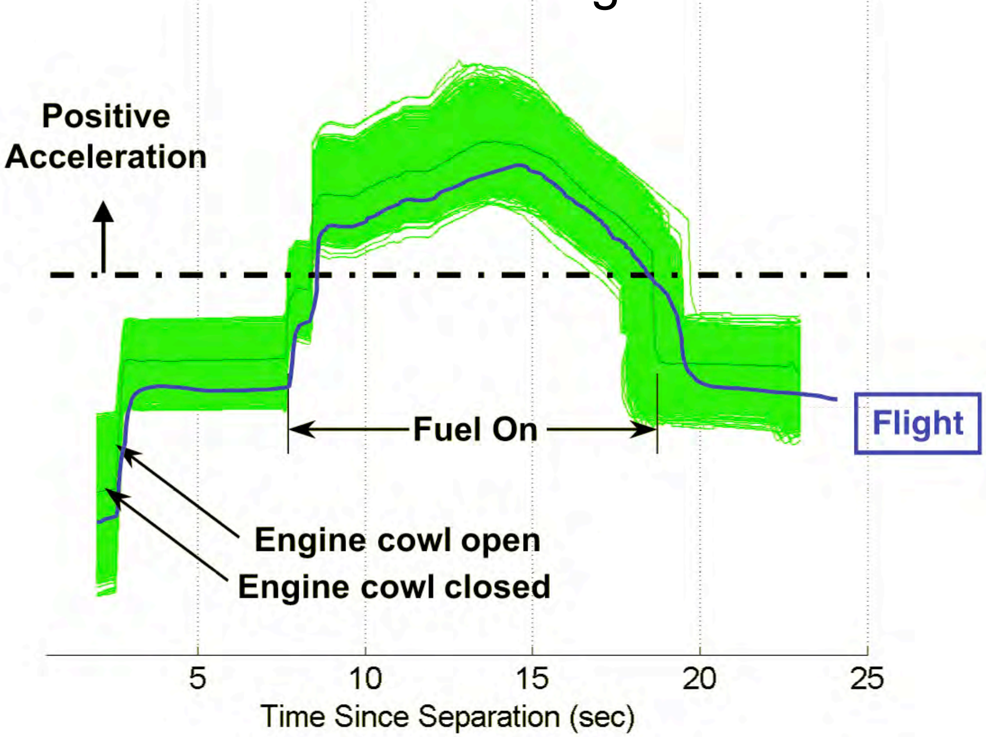
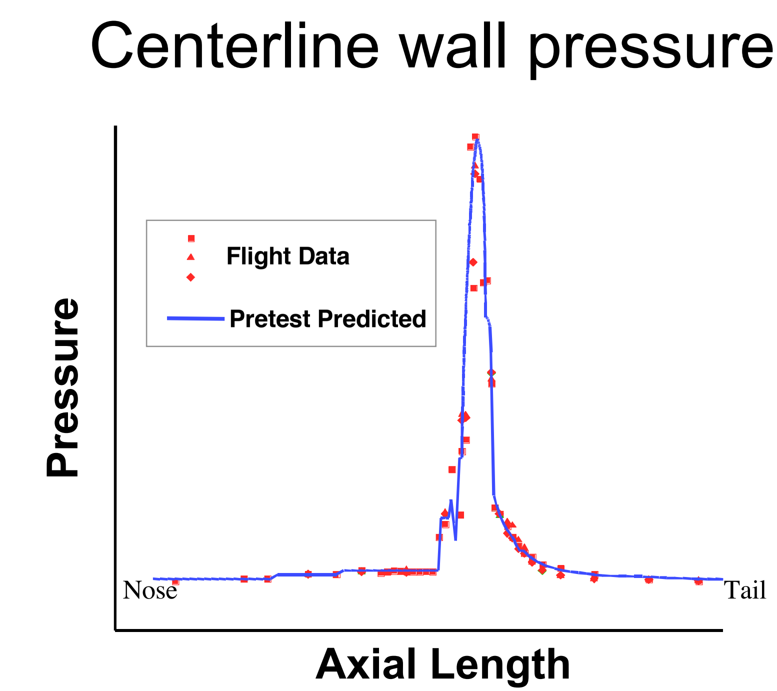
X-43A Research Vehicle Results



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

Acceleration vs. time



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.

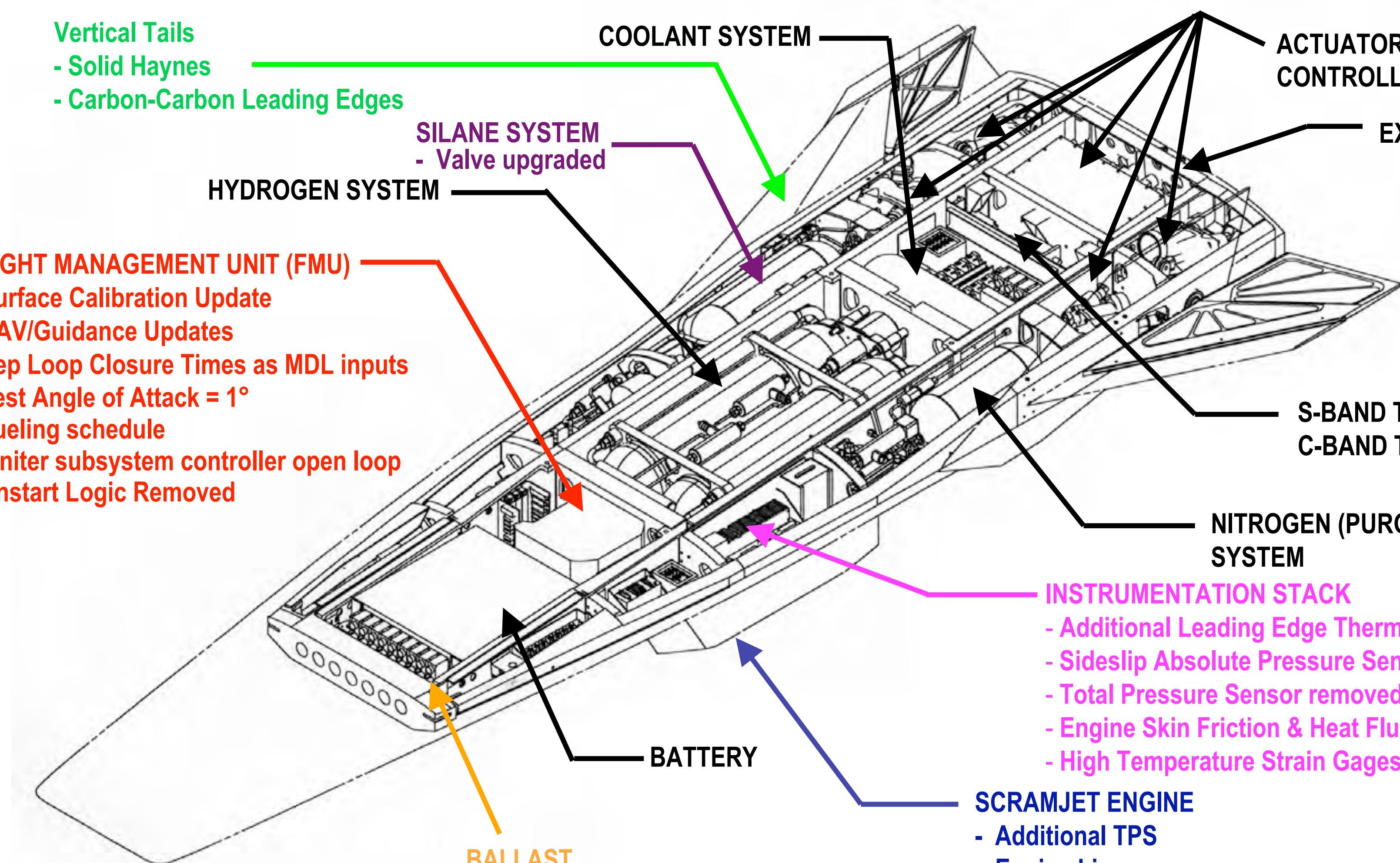
X-43A Descent:

- Following the scramjet experiment, the vehicle remained controlled during the descent and successfully completed a series of descent maneuvers.

Overall Mission Comments:

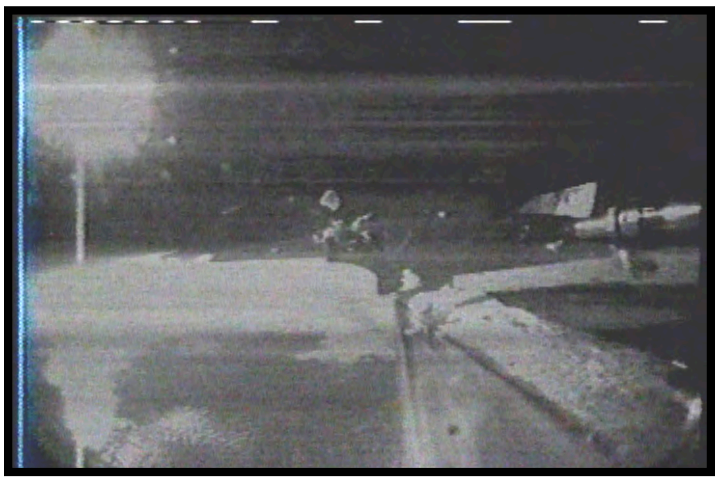
- Aerodynamic stability and control Mach 7 to Mach 0.9 – within 1 sigma uncertainty of prediction
- Boundary layer transition, boundary layer trip effectiveness – within 1 sigma uncertainty of prediction
- Airframe and wing structure, TPS and internal environment – as predicted w/ exception of rudders
- 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



Hyper-X

Flight 3 – November 16, 2004



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CERTIFICATE

On 16 November 2004, NASA's unmanned Hyper-X (X-43A) aircraft reached Mach 9.68. The X-43A was boosted to an altitude of 33,223 m (109,000 ft) by a Pegasus rocket launched from beneath a B52-B aircraft. The revolutionary 'scramjet' aircraft then burned its engine for around 10 seconds during its flight over the Pacific Ocean

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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:

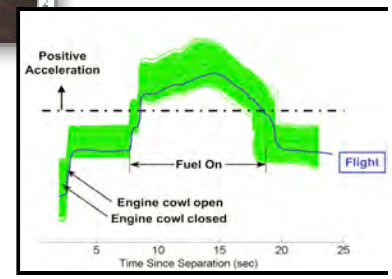
- Following the scramjet experiment, the vehicle remained controlled during the descent and successfully completed a series of descent maneuvers.

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