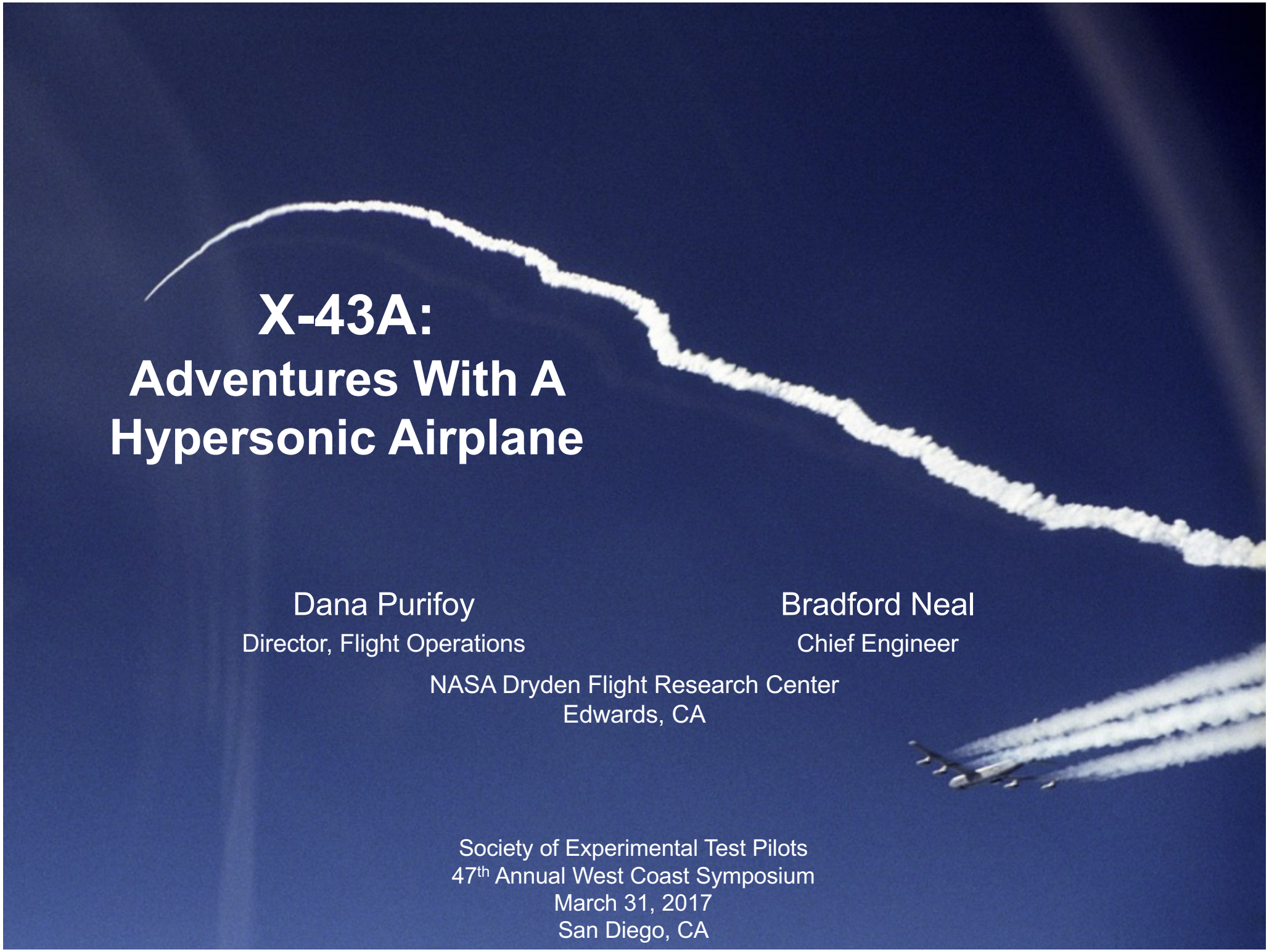

X-43A: Adventures With A Hypersonic Airplane

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Society of Experimental Test Pilots
47th Annual West Coast Symposium
March 31, 2017
San Diego, CA

Program Objectives

- **X-43A project was designed to be the first ever flight demonstration of an airframe-integrated, hydrogen fueled, scramjet powered, hypersonic vehicle**
- **Gather flight data 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**

Project Overview

- Designed to be High-Risk/High-Payoff
- Three-flight Project
  - » 2 at Mach 7
  - » 1 at Mach 10
- Scaled version of a Mach 10 “cruise” configuration
- Air launched on a highly modified Pegasus booster
  - initially using same Orion 50S motor to minimize booster modifications
- 7 year project (1996 – 2004)
- ~ $230M investment
- ~ 220+ people worked the project at any given time

Project Team

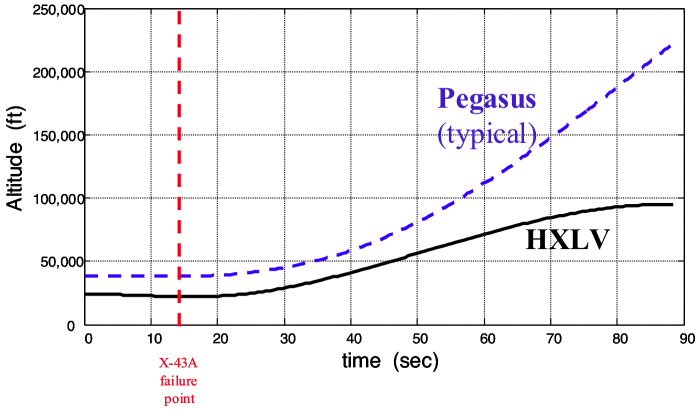
Project Approach

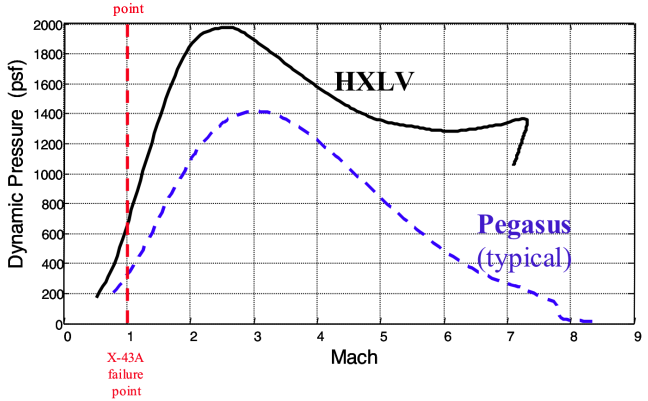
- A Risk Management based approach was applied to project execution
- Doing things that had never been done before
  - Many before we got to the experiment
- The program/project took all practical steps to minimize risks
  - Significant risks remained that were “inherent”
  - Most systems were single string
- Risks were mitigated to maximum practical extent by:
  - Weighing alternative approaches with down selection
  - Design for robustness
  - Extensive testing throughout the project
  - Multiple internal and independent checks along the way

Risk Management Approach

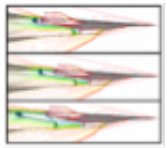
Applied to…Never Done That Before!

Booster Operation Outside "Normal" Flight Profile





High Mach/High q Non-axisymmetric Separation



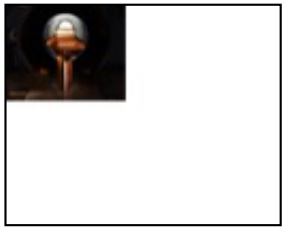
Hypersonic Flight Powered by an Airframe-integrated Scramjet Engine

Programmatic Lessons

- Define and agree to organizational roles and responsibilities before activity begins
  - The more organizations the more important this becomes
- Define and agree to program objectives and success criteria early
  - Review these regularly, as you do learn things along the way
- Use established program management tools and processes
  - Innovation with these AND with the technology makes life really difficult
  - Remember…They work for you, Not you for them

System Integration

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

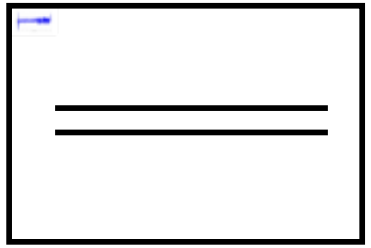


LV, Sep, & RV Sims
- GNC & PSC design & testing
- Monte-Carlo analyses
- Vehicle performance
- S/W & H/W testing
- HIL/AIL testing
- Mission control room training

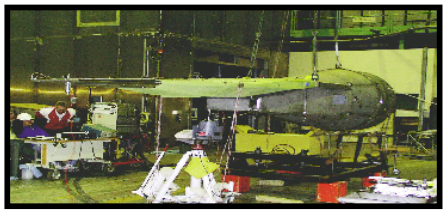
Stage Separation
- Never been done
- High q, asymmetric bodies

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

GNC
- LV, Sep, & RV control laws

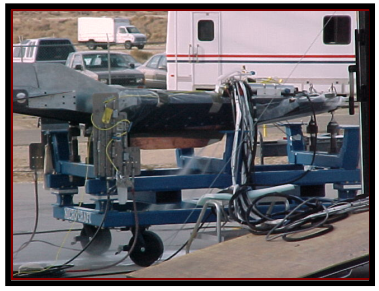


Structures
- Aero & thermal loads
- FEM modeling
- Structural analysis & design



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

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



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

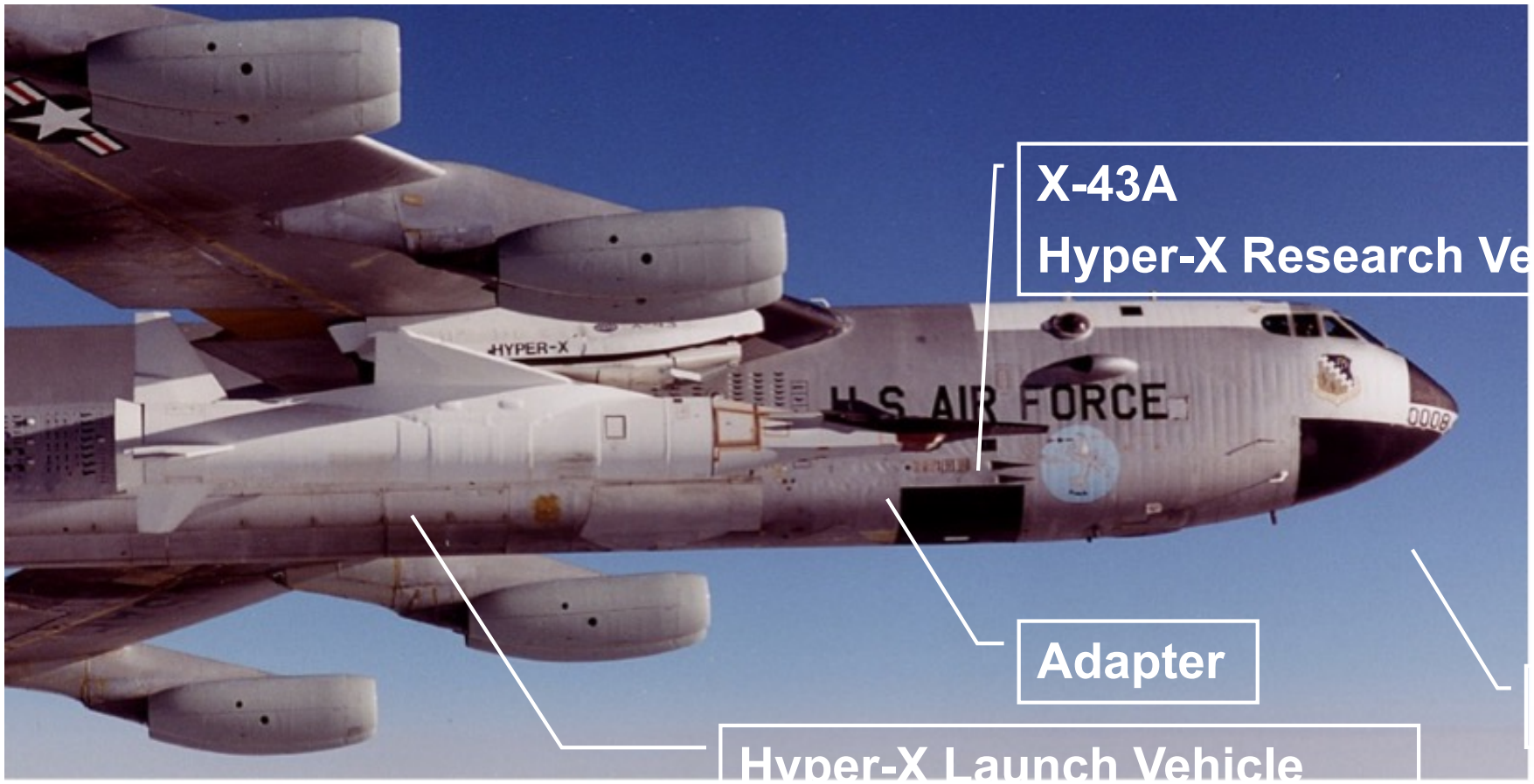
Systems Engineering Lessons

- Define and agree to design and operational standards early
- Ensure appropriate focus at the interfaces
  - Hardware
  - Software
  - Disciplines
- COTS
  - For a development program there is no shelf
  - Heritage parts used outside of their intended/proven application - even slightly - don't have a heritage
  - Arrange for vendors of critical hardware/software to be on site during testing

System Engineering Lessons

- Identify test and flight safety requirements early and integrate them
  - Remember the unmanned system may not always be unmanned
- Test what you fly…Fly what you test
  - But try not to use the flight hardware as the test article
  - Ground tests can be more strenuous to the hardware than the flight
- Define and agree to clear test and success requirements
- Review ALL test data
  - You may learn things even in a nominal test

Flight Test System

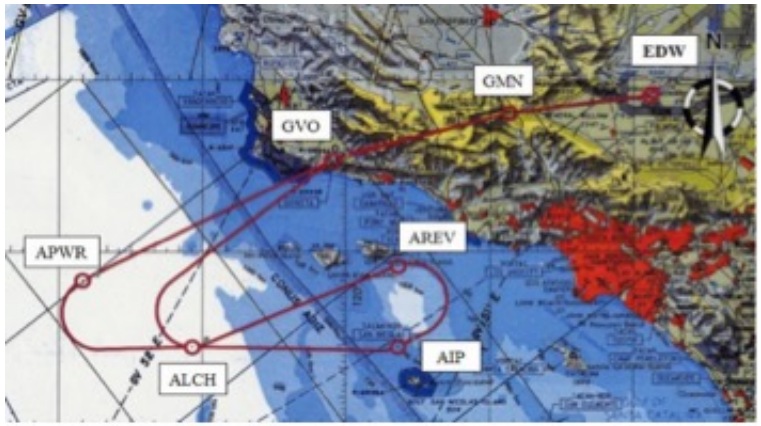


Stack = HXLV + Adapter + HXRV

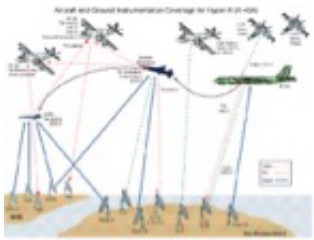
Operations Lessons

- Plan for vehicle maintenance
  - Removing all vehicle systems to work on the top of the engine is not efficient
  - Spares can make you or break you
- Maintenance and operations procedures are also a development effort…treat them as such
- When you have limited operations using all system assets with “Feast or Famine” timelines
  - Plan for dedicated training opportunities
  - Treat every system test as a mission training opportunity
  - Conduct nominal and off-nominal Missions simulations with all organizations

Mission

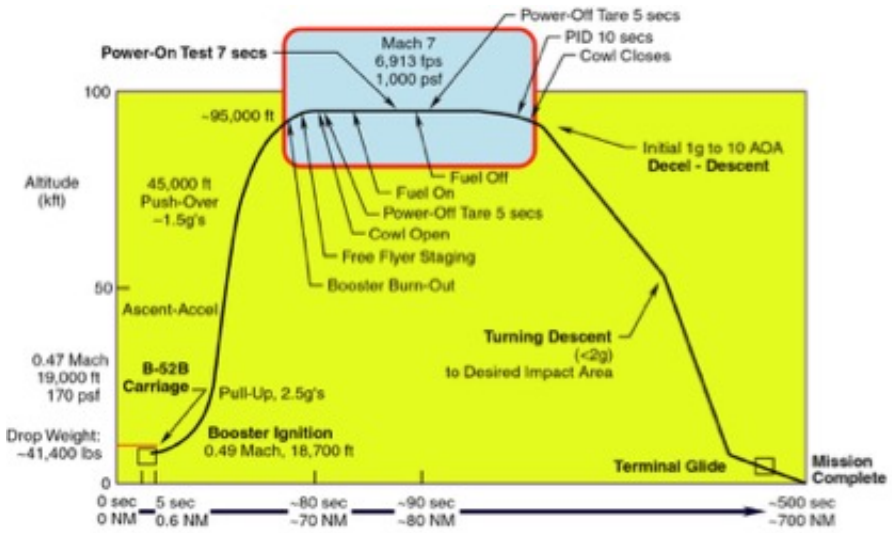


- 11 organizations
- 6 aircraft + Hyper-X Stack
- 2 ranges + FAA controlled space

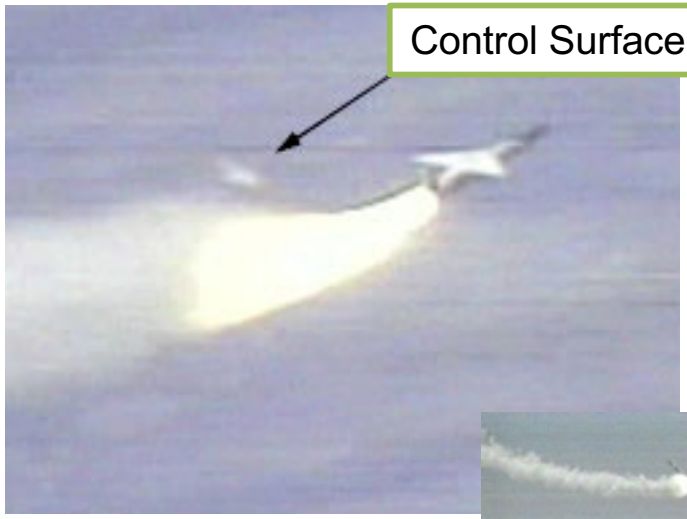


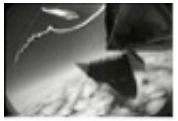
- Days of Ground Ops and Coordination
- An hour plus to get to the launch point

Flight 1 Mission Profile



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

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

Lesson Re-Learned

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

No matter how experienced you are...

Things can go wrong!!!

* No actual beavers were harmed in the making of this slide

…9 months later

- **Following the incident, the X-43A Mishap Investigation Board (MIB) was convened June 5, 2001 and ended March 8, 2002**

"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 3/8/2003

- **Modeling deficiencies caused an over-prediction of autopilot stability margins:**
  - **Fin Actuation System Compliance**
  - **Launch Vehicle Aerodynamics**
  - **Mispredicted roll inertia (I_{xx})**
- **Over-prediction of fin actuator torque margin**
  - **Misprediction of aerodynamic hinge moments**
- **Other areas for improvement**
  - **Validation/Cross Checking/Reviews**
  - **Documentation**

Post Mishap Lessons

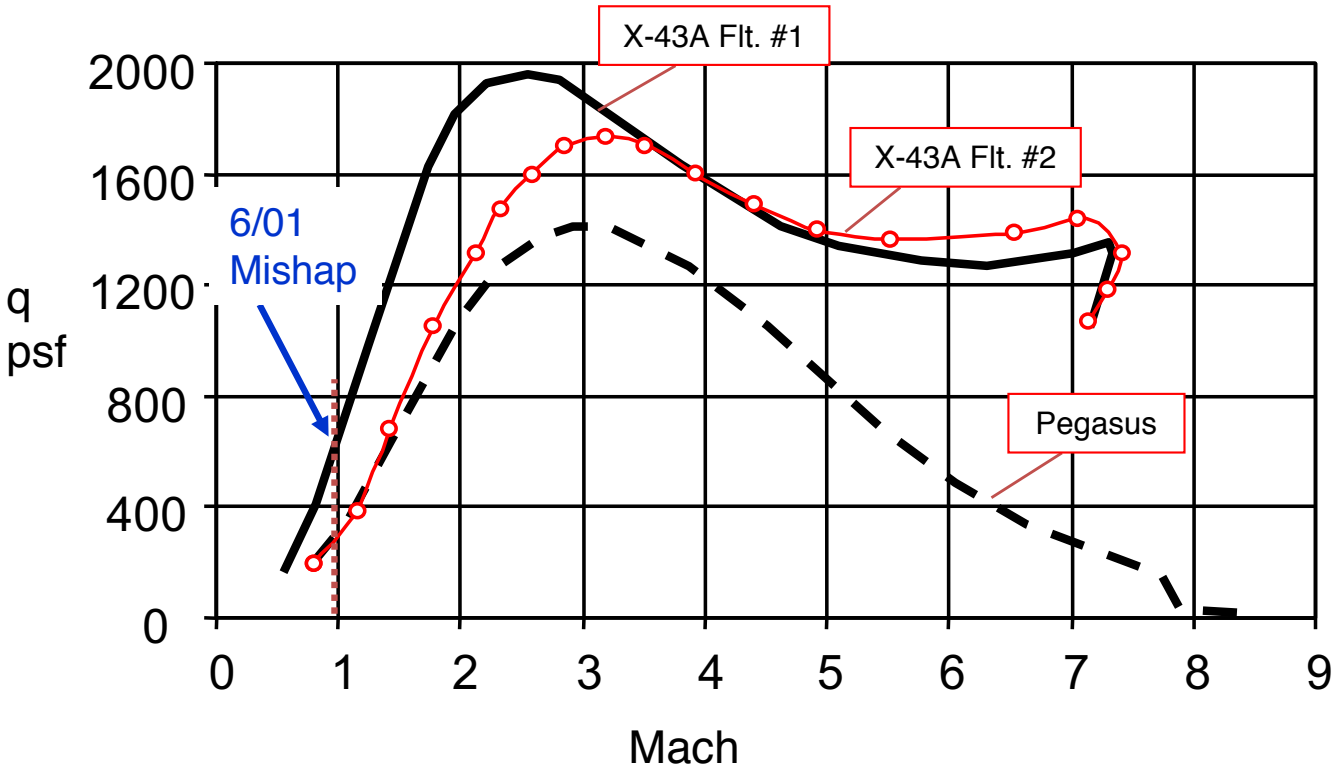
- Co-locate a core team of key stakeholders
  - The location(s) may change throughout the life of the program
  - More information transfer tends to happen in the hallway than on telecons
- Strive to maintain the team
  - Replacing team members in the middle of a smaller, fast moving program will have impact
- Constraints Change
  - Things “not possible” prior to Flight 1 suddenly became available as options

Return to Flight Approach

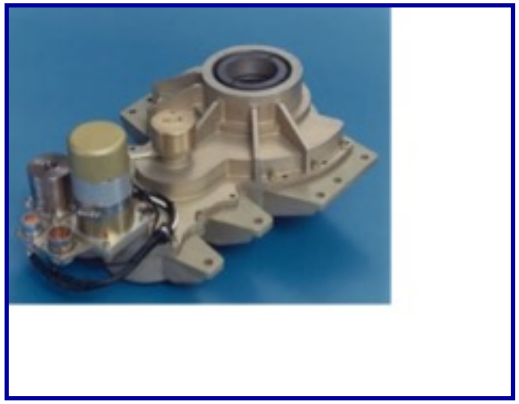
- **Review / improve all models for LV, Sep, & RV**
  - » Emphasis on the aero and FAS models
  - » 12 additional wind tunnel test runs
  - » Independent Simulations

More Pegasus Like Trajectory

40 kft and Mach 0.8



Too Little Torque

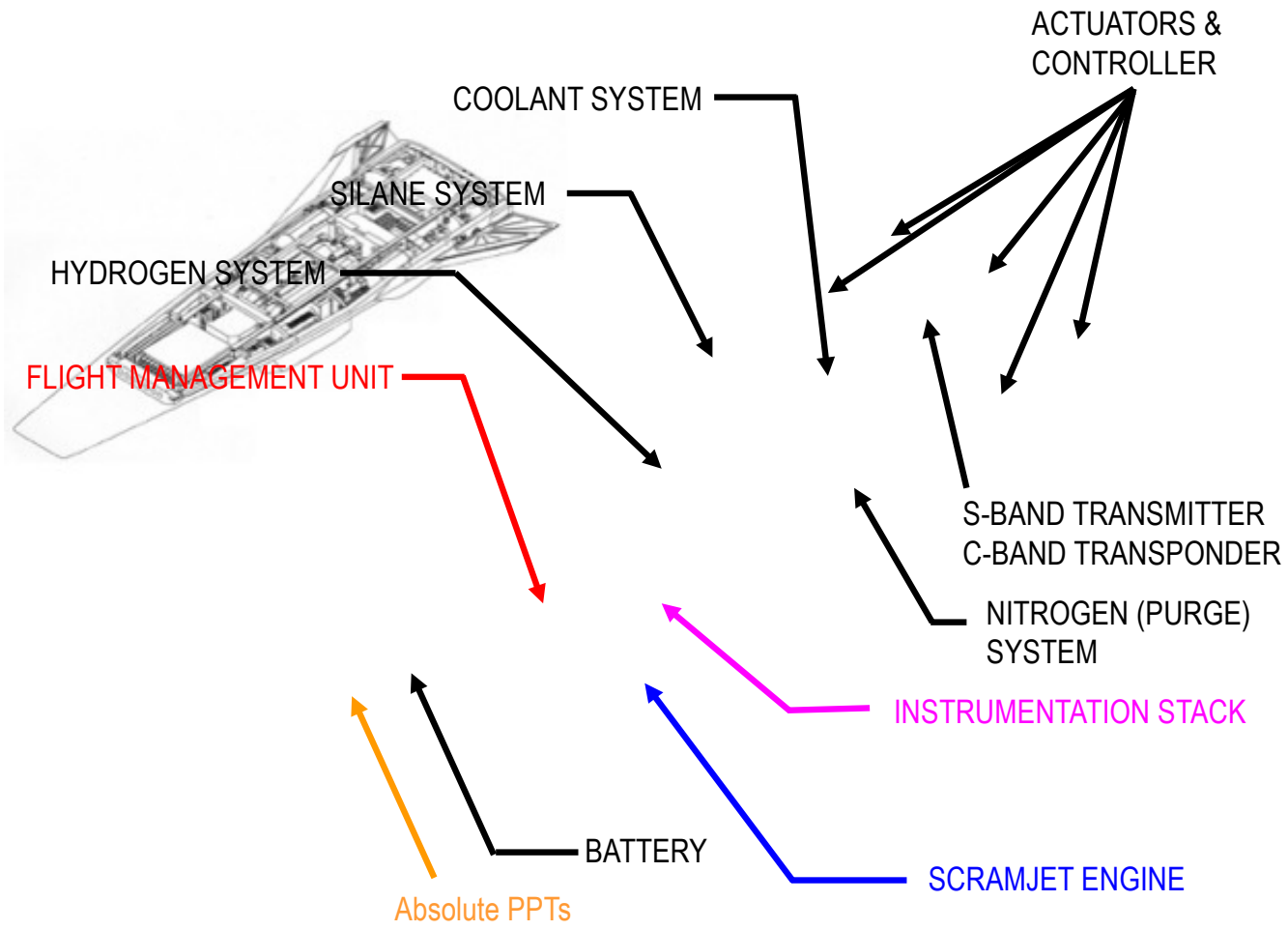


Dual Motor Actuator

Too Much Energy

Propellant Offload

Return To Flight Approach



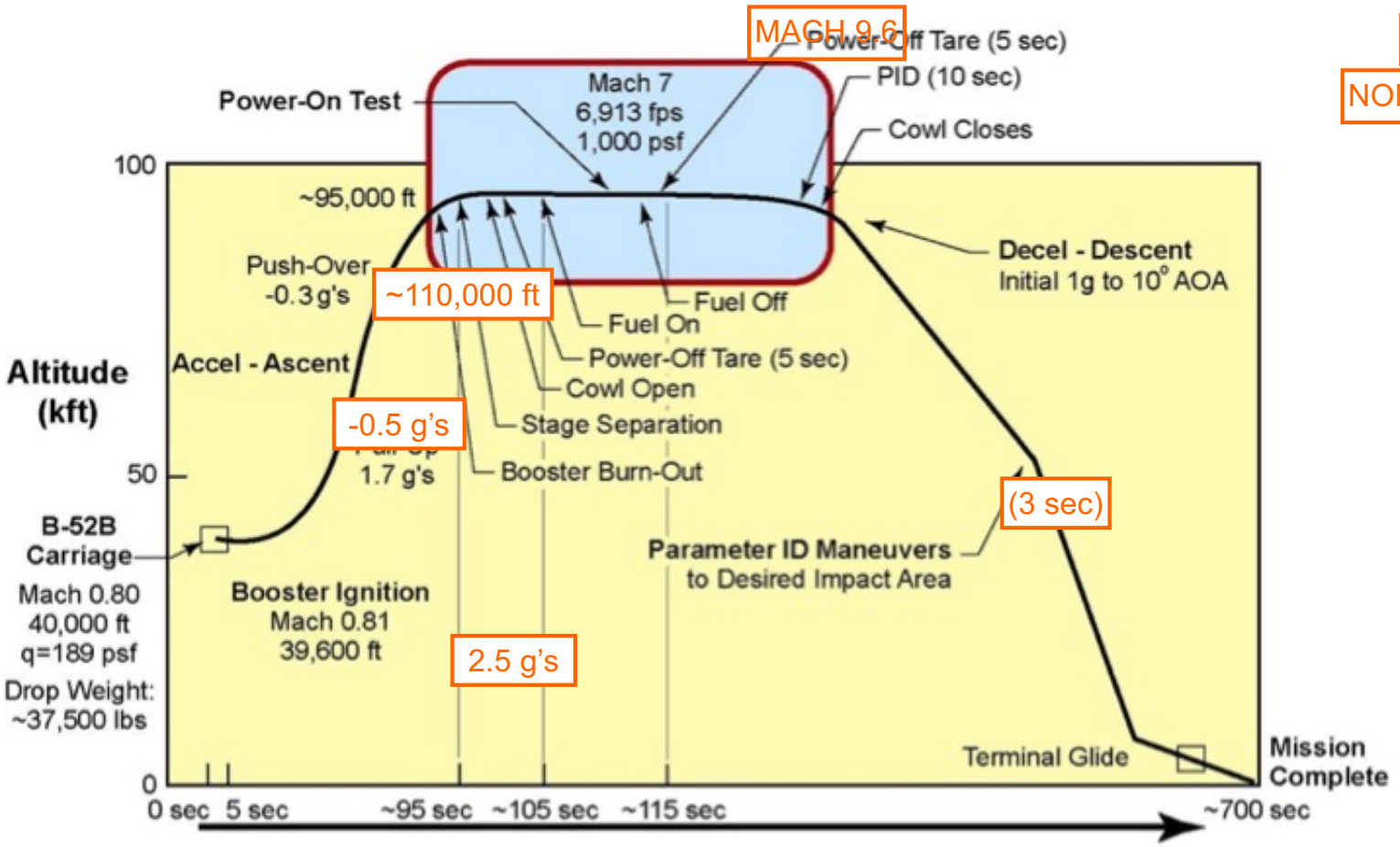
Research Vehicle

- Higher fidelity models
- Increase AOA for flameout robustness and greater thrust
- Upgrade engine control logic for unstart robustness
- Adapter fluid systems improvements
- Redesign of wing control horns
- Aircraft-in-the-loop timing tests
- Independent Simulation Review

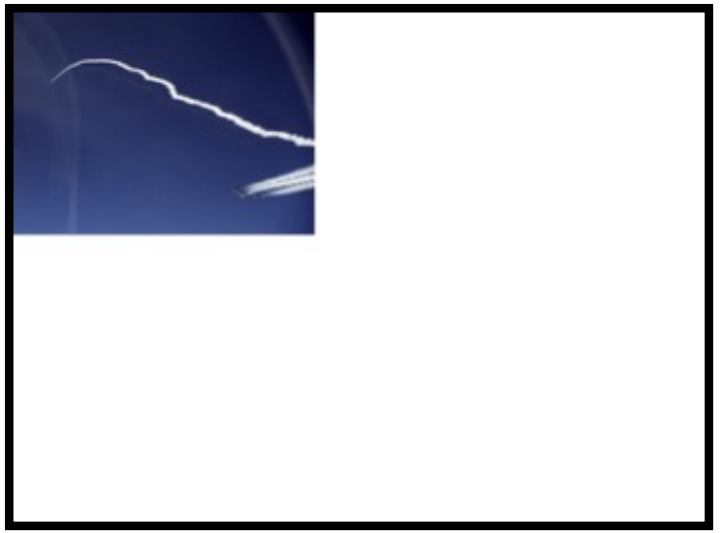
Flight 3 Approach

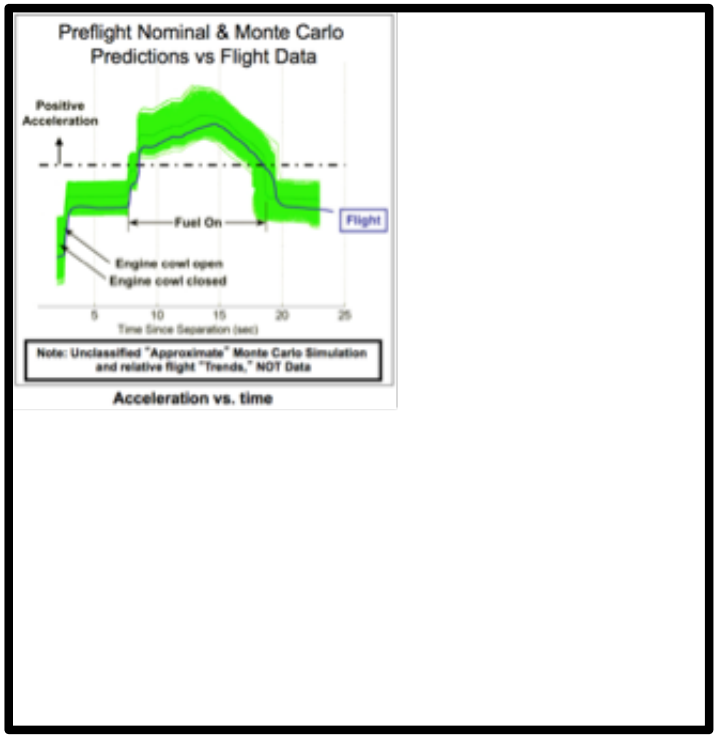
- The Flight 3 hardware was worked in parallel with Flight 2
- Final models and analysis were not available until after Flight 2 and initial post-flight analysis was complete
- Quick turnaround, goal for flight was 6 months after initial model release in early April
  - Capitalized on recent Flight 2 experience and Return-to-Flight Approach
  - 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 modification 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

Flight 2 & 3 Mission Profile



Flight 2 – March 27, 2004

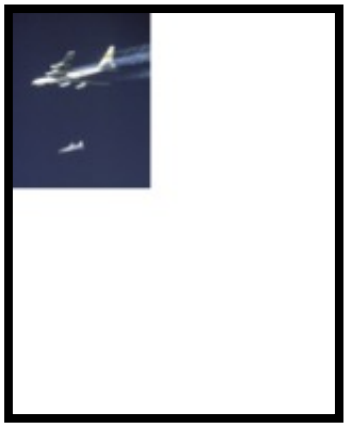


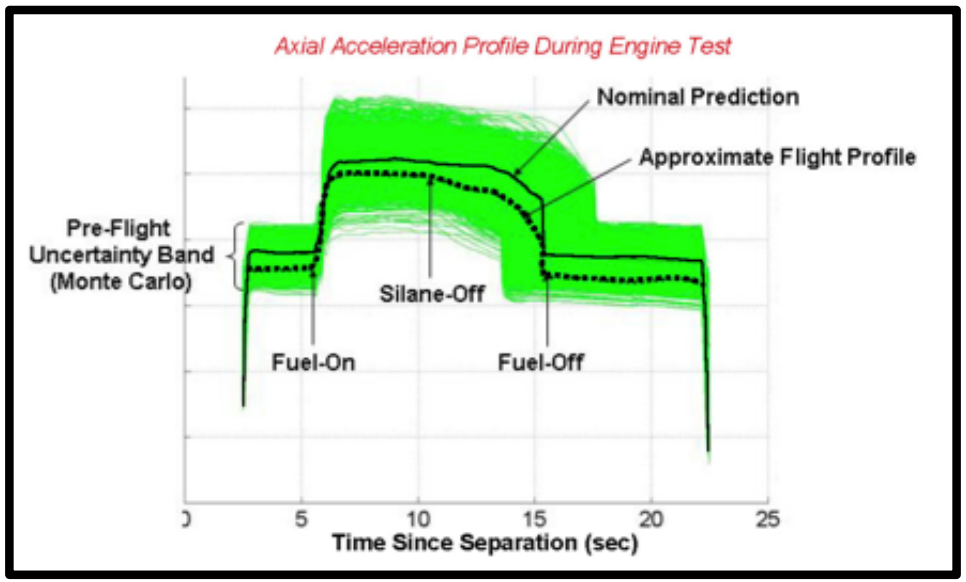


Acceleration vs. time

- All systems on both the LV and X-43A functioned well throughout the flight
- Maximum Powered Mach 6.83
- X-43 airframe drag (and lift) were higher than expected, but w/i uncertainties
- Scramjet engine performance within 3% of predictions – achieved net positive thrust
- Data quality was very good and acquired all the way to splash down

Flight 3 – November 16, 2004

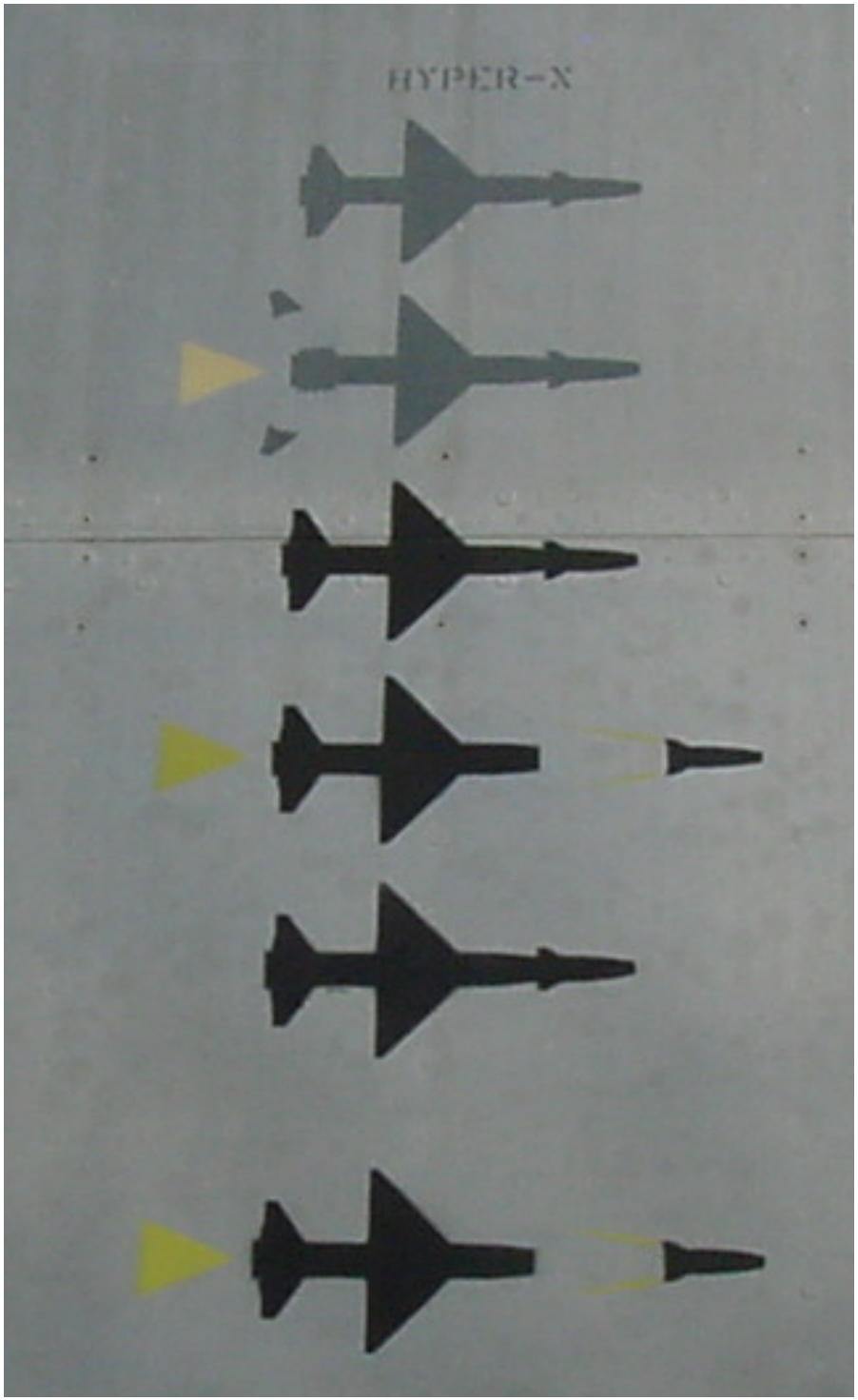




- All systems on both LV and X-43A performed well throughout the flight
- Maximum powered Mach 9.68
- During engine operation the vehicle achieved cruise condition, sustained thrust equal to drag
- The data collected during the engine test was by far the largest amount of data acquired for a Mach 10 scramjet. The quantity, quality, and type of the data acquired is well beyond what had been acquired in wind tunnels

The Best Lessons

Scramjets Work AND Flight Test Is Still Necessary



Questions ?