NASA Langley's Aerothermodynamics Laboratory (LAL) Testing Capabilities

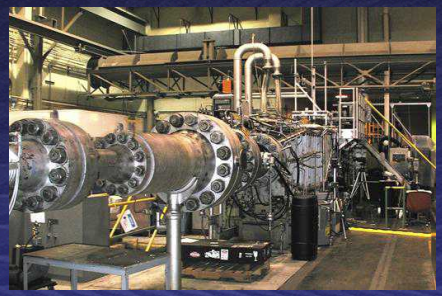
Presented By
John R. Micol

2011 National Space & Missile Materials Symposium
Madison, Wisconsin
June 27 – July 1, 2011

NASA Langley's Aerothermodynamic Laboratory (LAL) Testing Capabilities











Contributions to Hypersonic Flight, Access-to Space, Solar System Exploration, and Technology Development

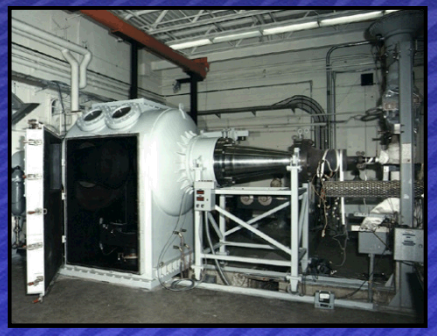
Outline

- Overview of Experimental Hypersonic Facilities at NASA LaRC
- Overview of Experimental Methods
- Historical Contributions and Partners
- Recent Contributions
- Summary Remarks

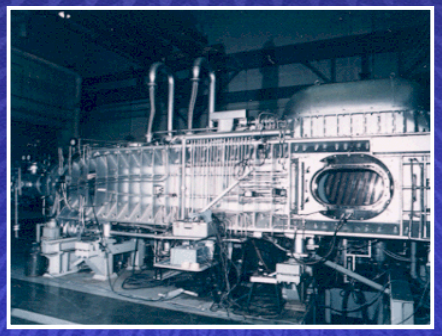
Langley Aerothermodynamics Laboratory (LAL)

- 50% of Nation's conventional type (as opposed to impulse) hypersonic wind tunnel
- Unique heavy and light gas test capability
- Provides wide envelope of flight simulation parameters
  - Mach number (6 to 20)
  - Reynolds number (0.05 to 8 million per foot)
  - Density Ratio (5 to 12); specific heat ratio (1.1 to 1.4)

20-Inch Mach 6 CF_4



31-Inch Mach 10 Air



20-Inch Mach 6 Air



Plus complementary Langley subsonic to supersonic facilities

31-Inch Mach 10 Air Tunnel



Test Conditions

M_∞ = 10

Re_∞ = 0.25 - 2.2E6 /ft

$P_{t,1}$ =125 -1450 psia

$T_{t,1}$ = 1350°F

Test Gas - Air, $\gamma_\infty = 1.4$

Run time 120 sec.

8-10 Runs per Day

Features

- Uniform, clean flow; three-dimensional, contoured, water-cooled nozzle and five micron particle filter to remove flow contaminates
- Ideally suited for both parametric and benchmark aerodynamic, aerothermodynamic and fluid dynamic studies
- Synergism with 20-Inch Mach 6 Air Tunnel allows assessment of compressibility effects at constant Re_∞ and γ_∞

20-Inch Mach 6 Air Tunnel



Test Conditions

M_∞ = 6

Re_∞ = 0.5 - 8.0E6 /ft

$P_{t,1}$ = 30 - 475 psia

$T_{t,1}$ = 410 - 475°F

Test Gas - Air, $\gamma_\infty = 1.4$

Run times up to 15 min.

8-10 Runs per Day

Features

- Ideally suited for both parametric and benchmark aerodynamic, aerothermodynamic and fluid dynamic studies
- Synergism with 31-Inch Mach 10 Air Tunnel allows assessment of compressibility effects at constant Re_∞ and γ_∞
- Synergism with 20-Inch Mach 6 CF4 Tunnel allows determination of real gas aerodynamic effects at constant M_∞ and Re_∞

20-Inch Mach 6 CF_4 Tunnel



Test Conditions

M_∞ = 6 (13-18 Simulation)

Re_∞ = 0.05 - 0.7E6/ft

$P_{t,1}$=100 - 2000 psia

$T_{t,1}$ = 640 - 1000°F

Test Gas - CF_4, γ_∞ = 1.2

Run times - 20 sec.

4-6 Runs per Day

Features

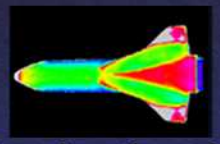
- Only operational, conventional-type hypersonic facility in this country which simulates dissociative real-gas phenomena associated with hypersonic flight
- Synergism with 20-Inch Mach 6 Air Tunnel allows determination of real gas aerodynamic effects at constant M_∞ and Re_∞
- Evaluating use of CO_2 as a test gas to support planetary missions

Aerothermodynamic - Experimental Methods

Measurements



Aerodynamic Forces/Moments



Aeroheating via Phosphor Thermography



Surface Pressure



Shock Wave Characteristics via Schlieren



Surface Streamlines via Fluorescent Oil Flow

Flight Simulation Via Langley Aerothermodynamics Laboratory (LAL)



Low Earth Orbit

Altitude

300,000

250,000

200,000

150,000

100,000

50,000

Ground

20-Inch Mach 6 Air Tunnel



$\gamma_{eff} = 1.40$

$\rho_2/\rho_\infty = 5.3$

31-Inch Mach 10 Air Tunnel



$\gamma_{eff} = 1.38$

$\rho_2/\rho_\infty = 5.9$

20-Inch Mach 15-25 Real Gas Simulation



$\gamma_{eff} = 1.13$

$\rho_2/\rho_\infty = 12$

Hypersonic flow physics

e.g.: Boundary layer/shear layer transition; shock-shock/shock-boundary layer interaction; flow separation - reattachment; plume - flowfield - surface interactions; etc.

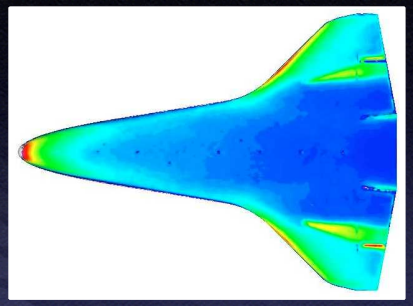
Without flow chemistry

Coupled with flow chemistry (dissociation - recombination/ionization)

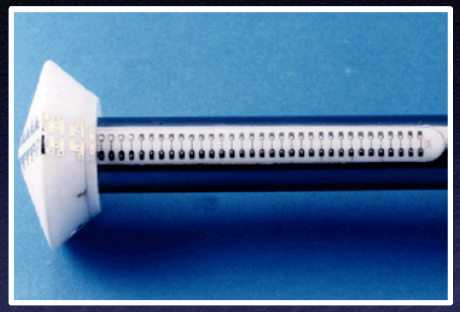
0 5 10 15 20 25

Mach Number = velocity ÷ speed of sound

Hypersonic Testing Techniques and Capabilities



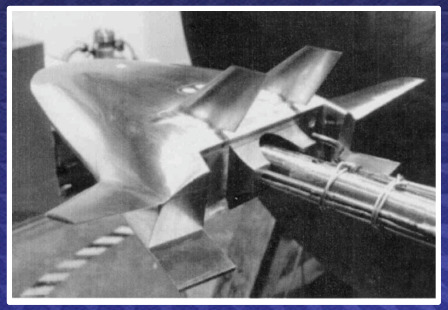
Phosphor thermography to measure global heat transfer and boundary-layer transition



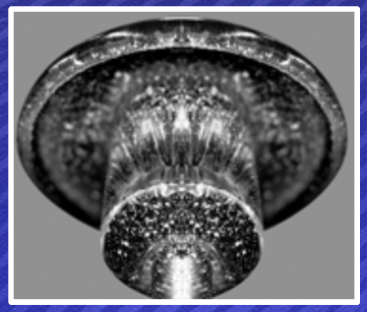
Thin-film or coax gauges to measure heat transfer



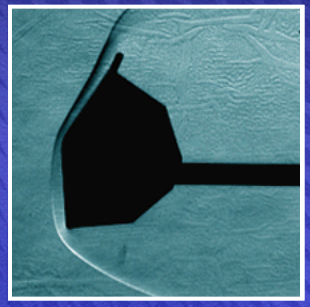
Electronically scanned pressure (ESP) measurements



Strain-gauge balances to measure aerodynamic forces & moments



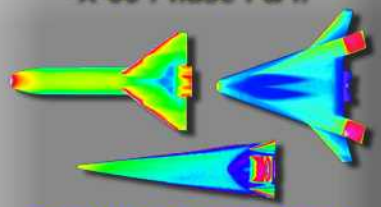
Oil-flow for surface streamline visualization



Schlieren and PLIF for flow field visualization

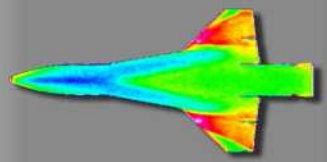
Historical LAL Contributions and Partners

X-33 Phase I & II



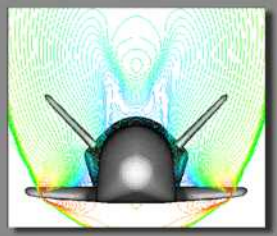
Rockwell International
McDonnell-Douglas
Lockheed-Martin

X-34



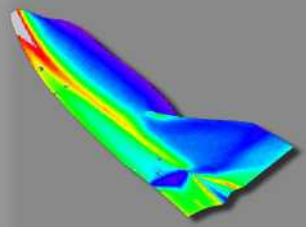
Orbital Sciences Corp.

X-40/X-37



Boeing/DoD

X-38



NASA/ESA

X-43A/X-43C



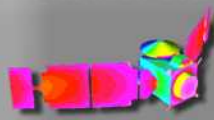
NASA
Orbital Sciences Corp.
DoD

Pegasus



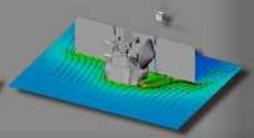
Orbital Sciences Corp.

Aeroassist Maneuvering



Mars Global Surveyor

Mars Odyssey



JPL/Lockheed-Martin

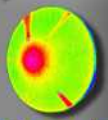
Planetary Entry



Stardust



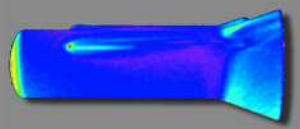
Pathfinder



Genesis

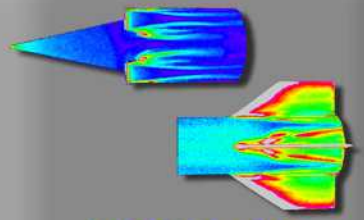
JPL/Lockheed-Martin

Two-Stage-to-Orbit



Kistler Aerospace Corp.

HyFly/Missiles



DARPA/Boeing
DoD

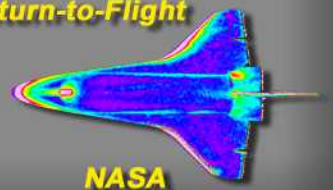
Orbital Space Plane

Proprietary

Boeing
Lockheed-Martin

Space Shuttle

Columbia Accident Investigation
Return-to-Flight



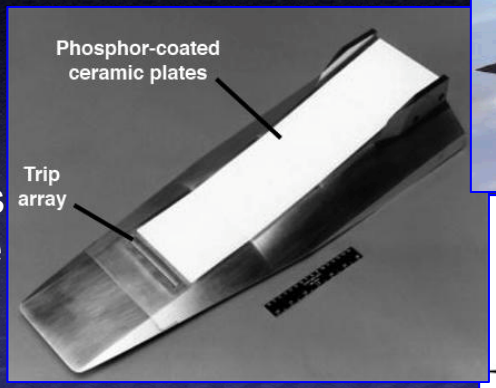
NASA

X-43 Hyper-X Inlet Boundary-Layer Trip

Program: X-43A Hyper-X hypersonic airbreathing propulsion demonstration flights at Mach 7 and 10

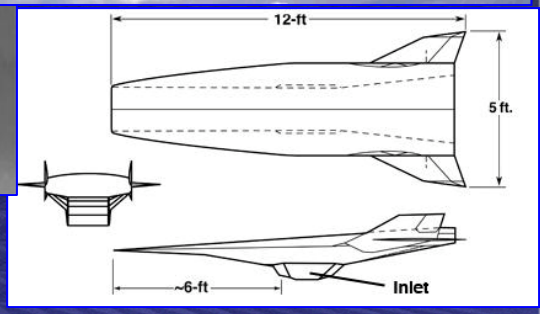
Issue: Program requirement for successful operation of scramjet that incoming flow be turbulent. Available transition onset correlations (mainly from NASP program) did not guarantee that flow would be naturally turbulent at flight conditions.

Approach: An experimental program was conducted to design boundary-layer trips for the vehicle that would force the flow to be turbulent. Testing was conducted in LaRC 20-Inch Mach 6 Air and 31-Inch Mach 10 Air Tunnels.



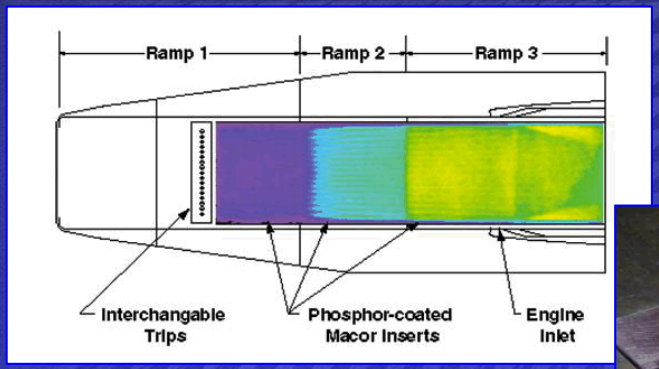
X-43 Inlet model





Sketch of X-43 geometry

Impact: Trip configuration was selected based on tunnel data. **Two successful flights (Mach 7 and Mach 10) of vehicle in 2004.**



Sample inlet heating data



Final trip configuration

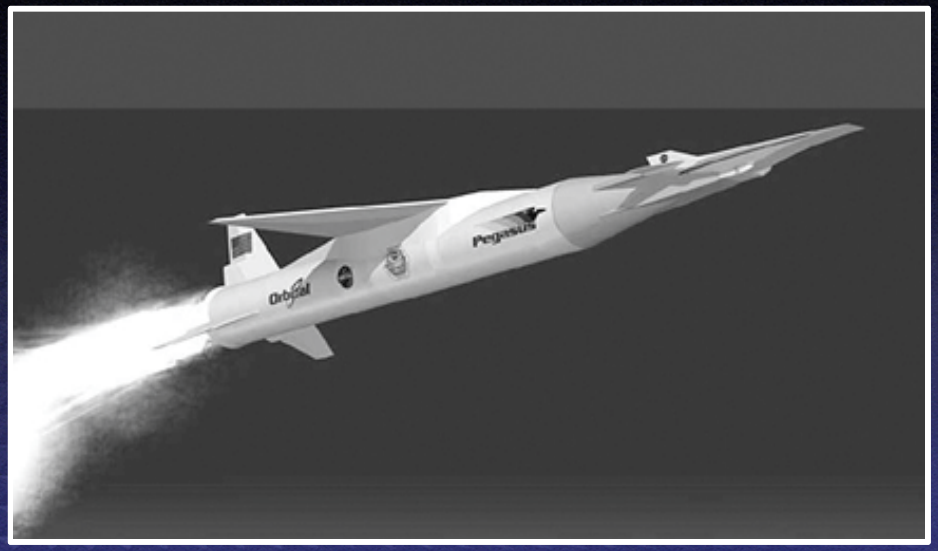


X-43 Hyper-X Stage Separation

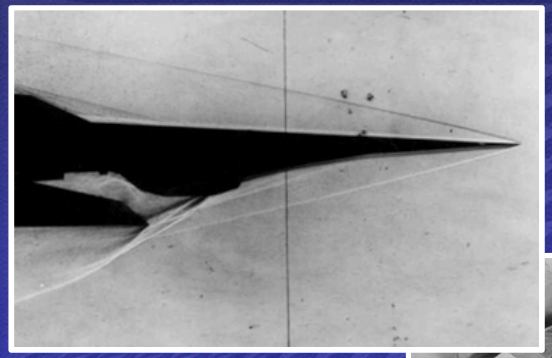
Program: X-43A Hyper-X hypersonic airbreathing propulsion demonstration flights at Mach 7 and 10

Issue: Complex aerodynamic interactions between X-43 research vehicle and Pegasus XL booster during separation. Thorough validation of aerodynamic models required to ensure no re-contact between vehicles.

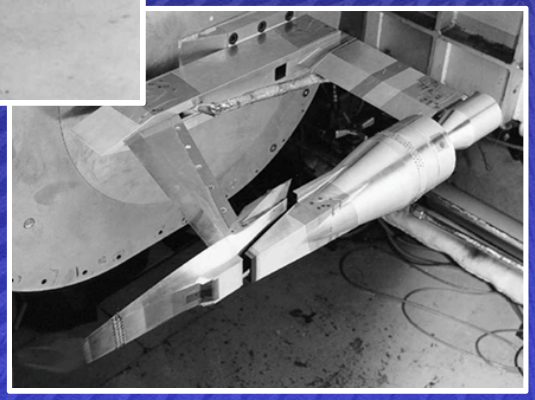
Approach: Extensive aerodynamic test program (5800 runs) carried out across speed range in multiple national facilities including LaRC 20-Inch Mach 6 and 31-Inch Mach 10 Air Tunnels



Hyper-X Launch Vehicle



Schlieren photo from 20-Inch Mach 6Air Tunnel



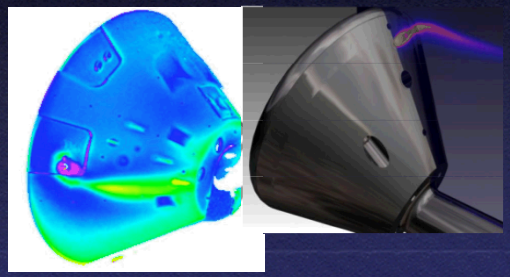
Model in 31-Inch Mach 10 Air Tunnel

Impact: Stage-separation aerodynamics database developed from testing . **Two successful flights (Mach 7 and Mach 10) of vehicle in 2004.**



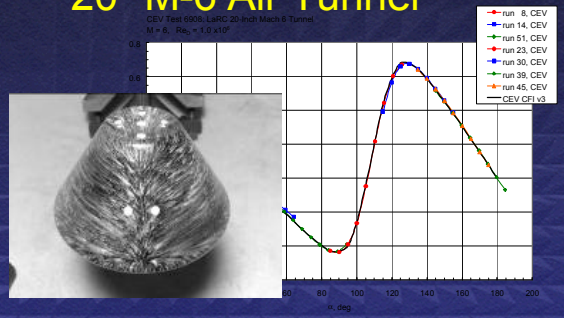
Orion Testing in Langley Aerothermodynamic Laboratory

Reaction Control System
31” M-10 Air Tunnel

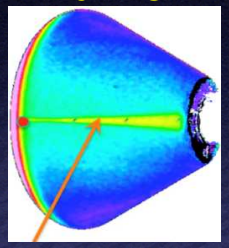


NO2 PLIF Flow Visualization

Aerodynamics
20” M-6 Air Tunnel

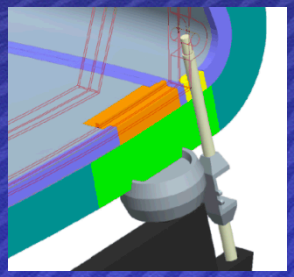


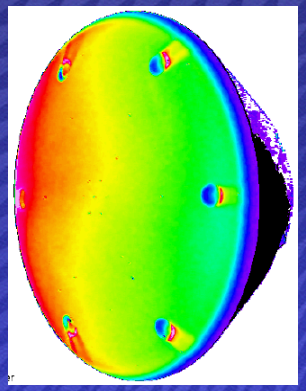
Backshell Boundary Layer Transition
20” M-6 Air Tunnel



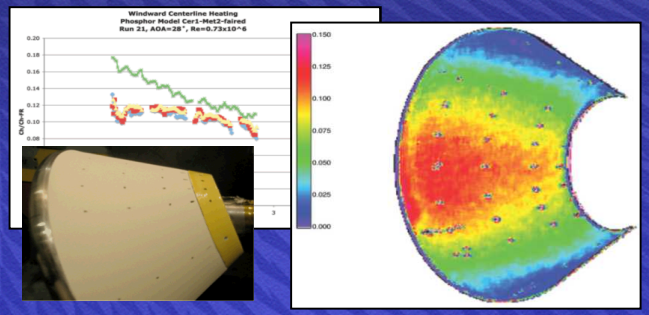
Turbulent wedge from trip

Compression Pads
31” M-10 Air Tunnel/20” M-6 Air Tunnel





Backshell Heating
31” M-10 Air Tunnel/20” M-6 Air Tunnel

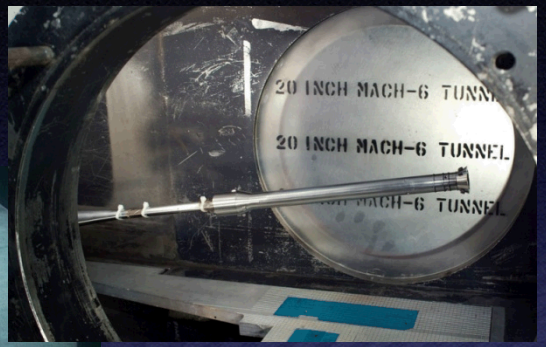


Ares Testing in Langley Aerothermodynamic Laboratory

20” M-6 Air Tunnel

Ares I First Stage Reentry

- Aerodynamics testing supporting first stage reentry database development







Full Vehicle Model

31” M-10 Air Tunnel/20” CF4 Tunnel (April ‘10)

Ares Upper Stage Reentry Aeroheating test

- Heating associated with protuberances/interactions
- Infer failure modes to determine vehicle break-up, identify most likely failure mode(s)



Forward Model



Aft Model

Lifting-Body Boundary-Layer Transition Criteria

Technology: development of boundary-layer transition criteria for lifting-body entry vehicles.

Issue: Early and/or asymmetric transition onset observed in many shuttle missions. Attributed to discrete roughness from damaged or lost TPS tiles. Similar behavior expected for other lifting-body concepts (e.g. X-33, X-38).

Approach: Obtain discrete roughness transition data from testing in LaRC hypersonic tunnels on lifting-body geometries.

Lifting-body spacecraft examples



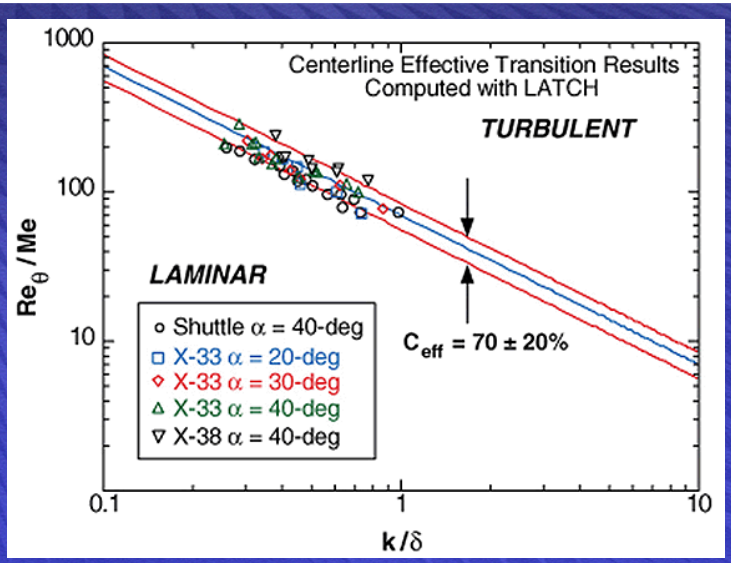




Impact: Test data used to develop effective trip-height correlation applicable to all lifting-body shapes

Lifting-body transition and heating data generate on various configurations in LaRC hypersonic tunnels





Columbia Accident Investigation Board (CAIB)

Program: NASA Space Shuttle Orbiter

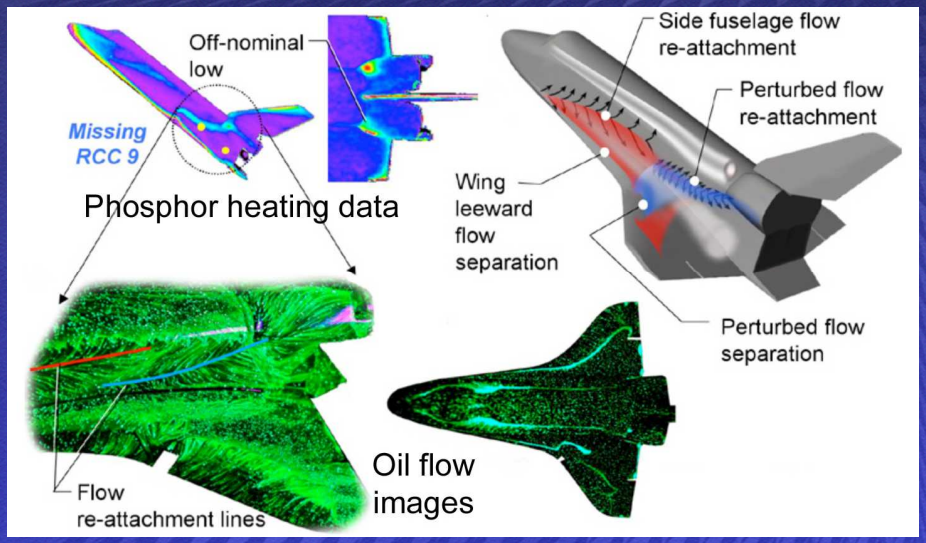
Issue: Determine cause of Columbia loss. Limited flight data available, leading to numerous avenues of speculation & analysis.

Approach: Forensic aeroheating tests in the LaRC Hypersonic Tunnels were immediately initiated to assess wide range of damage scenarios. Goal was to replicate phenomena similar to observed flight anomalies in both aerodynamic and heating characteristics prior to loss of vehicle near Mach 18 on reentry.

Reconstructed wing leading



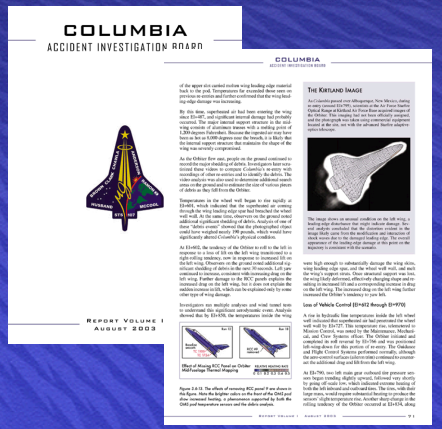
Wind tunnel testing had profound impact on the direction and utilization of agency and other government resources in support of the accident investigation



Damage scenario testing in LaRC wind tunnels

Result: Technical foundation for a most-probable damage scenario reported in CAIB final report derived from LaRC (and other) hypersonic wind tunnel testing that emulated Orbiter aerodynamic and surface temperature responses to various forms of TPS damage





Shuttle Orbiter Return-to-Flight – Damage Assessment

Program: NASA Space Shuttle Orbiter – Return to Flight Activity

Issue: Determine effects of early boundary-layer transition and heating augmentation due to heat-shield damage: lost tiles, tile damage due to debris, protruding tile-gap fillers, etc.

Approach: Extensive testing in all U.S. hypersonic facilities (NASA LaRC, AEDC, CUBRC) to gather data on various damage scenarios and develop analysis tools for on-orbit safety assessment.



Wind Tunnel Simulation	Forms of Shuttle Surface Disturbances	
	Damage-Induced	Repair-Induced
Temperature increase from disturbed flow Cavity	STS-1 Tile impact	
Protuberance	STS-73 Tile gap filler	Tile patch RCC plug
Outgasing		Tile patch

Assessment of possible damage scenarios

Impact: LaRC wind tunnel data used in development of ***Boundary-Layer Transition Tool*** employed to assess damage effects during Shuttle missions and determine if on-orbit repair required (e.g. STS 114)

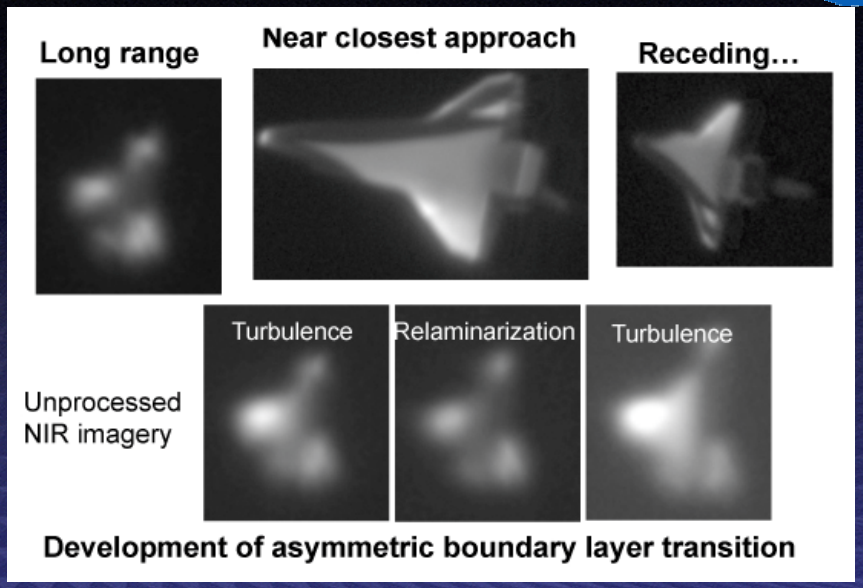


HYTHIRM Observations of Shuttle Re-entry

Program: NASA HYTHIRM program for imaging of shuttle during reentry using infrared thermography

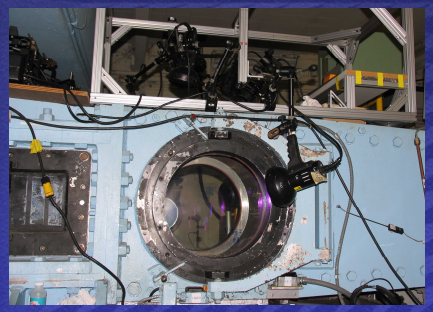
Issue: validation of turbulent flow patterns observed in flight data and development of ground-to-flight data scaling methodology.

Approach: Use phosphor thermography to obtain global aeroheating and boundary-layer transition effects data on shuttle models in LaRC 20-Inch Mach 6 Air, 31-Inch Mach 10 Air, 20-Inch Mach 6 CF4 Tunnels.



HYTIRM Flight Data

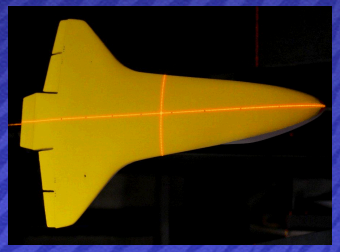
Impact: Turbulent thermal patterns observed during multiple Shuttle reentries successfully replicated (color scales not matched) in wind tunnel test leading to increased confidence in HYTHIRM capabilities.



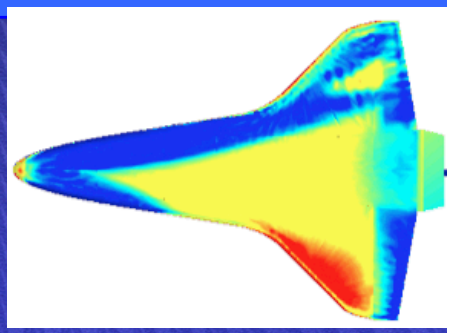
Phosphor Thermal Imager



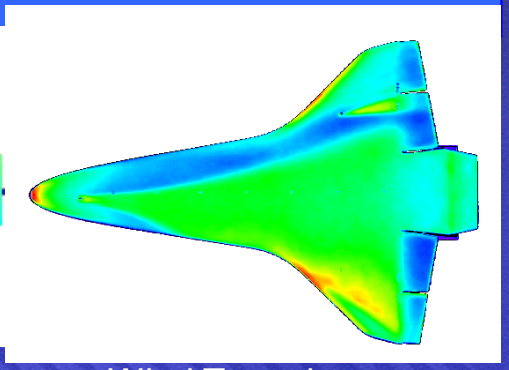
LaRC 20-In Mach 6 Air Tunnel Setup



Laser Alignment system



3-D Mapped Flight Temperature Image (STS-119)



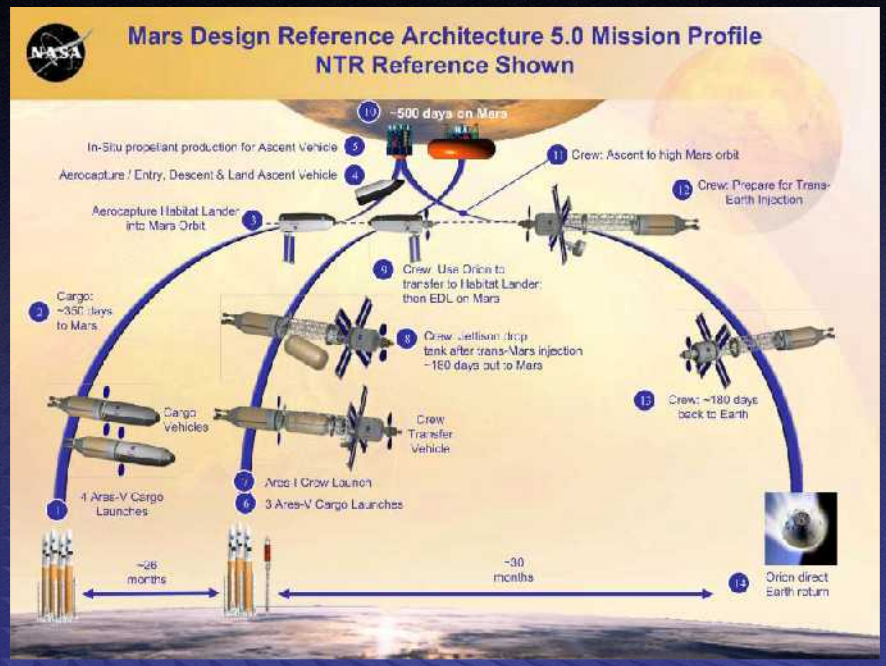
Wind Tunnel Thermal Image

Mid L/D Ellipsled Configuration for HMMES

Technology: development of new architecture for a High-Mass Mars Entry System (HMMES) enabling payloads an order of magnitude greater than heritage Viking/Pathfinder/MSL configuration.

Issue: Ellipsleds (slender, blunted geometries) are subject to both cross-flow and straight-line boundary-layer transition. Little data available on transition behavior for use in mission trade studies.

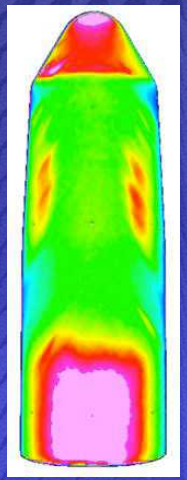
Approach: Testing of multiple ellipsled geometries in LaRC 20-Inch Mach 6 Air Tunnel to obtain aeroheating and boundary-layer transition data



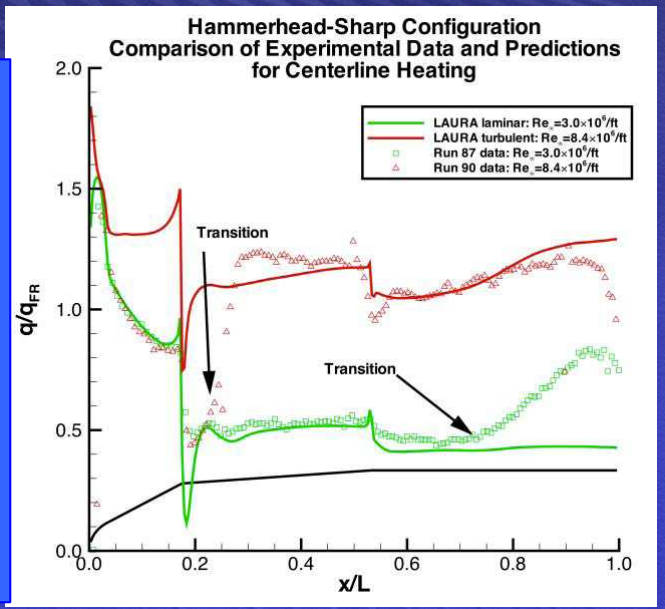


Mid L/D Ellipsled model in LaRC 20-Inch Mach 6 Air Tunnel

Heating data showing cross-flow and axial transition



Impact: Test data being used in the development of transition correlations and for validation of computational tools



Australian DSTO / USAF HIFiRE 1

Program: Hypersonic International Flight Research Experimentation (HIFiRE) is a collaborative effort to develop and test technologies for hypersonic scramjet through subscale flight tests

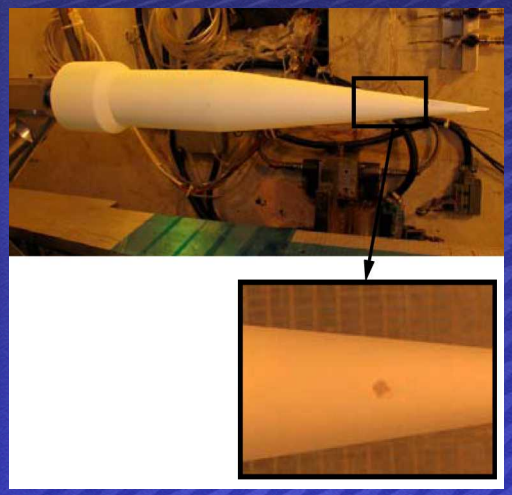
Issue: Validation of design configuration (7-deg Cone-Cylinder-Flare) to insure mission requirements for laminar flow on one side of body and tripped turbulent flow on other side.

Approach: Ground test program conducted in LaRC (and other) hypersonic facilities to evaluate configurations and obtain heating and transition data.

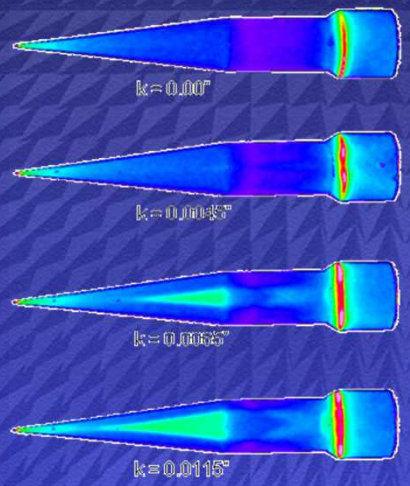
HIFIRE 1 on launch vehicle







HIFiRE Model with trip in LaRC 20-Inch Mach 6 Air Tunnel



HIFiRE Heating Data

Impact: Test data used for sizing and placement of trip on flight vehicle as well as criteria for allowable roughness (joint height step) on laminar side.
Successful HIFIRE-1 flight in March 2010



DARPA/USAF: Falcon HTV-2

Program: DARPA-developed maneuvering re-entry vehicle with sharp leading edges. Intended to push frontiers of aerodynamics and materials.

Issue: concerns raised on whether pre-flight modeling & analysis were sufficient to ensure successful flight without ground test data for design validation

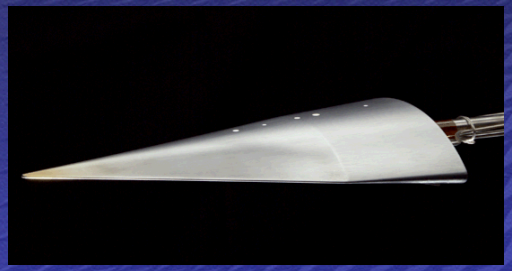
Approach: Aerodynamic and aeroheating/transition testing conducted in 31-Inch Mach 10 Air and 20-Inch Mach 6 Air Tunnels

Comments from Dr. Mark Lewis: AIAA president, Air Force Chief Scientist (2004-2008)

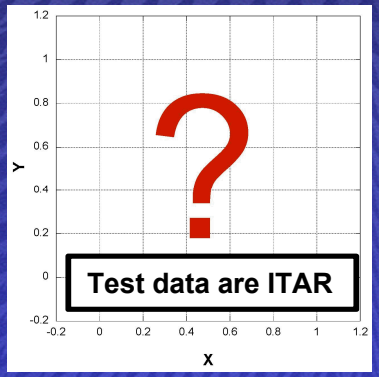
I mention the HTV-2 as my favorite example of the importance of testing infrastructure. The Air Force and DARPA led the development effort in that program. The Air Force was co-funding it, but DARPA had program management oversight. When it started we actually had a pretty big battle over that program because the original DARPA program manager insisted he didn't need to do any testing. ***He was just going to fly that thing without any ground test whatsoever.*** Fortunately, we had some smart people in the Air Force Research Lab who said, "You know, you really need to put the darn thing in a wind tunnel." Finally, DARPA gave in, though the Air Force actually wound up footing the bill for those wind tunnel tests.

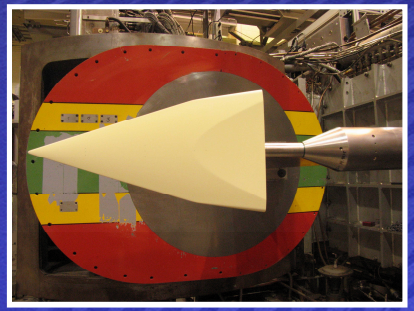
The first thing we discovered when HTV-2 was tested on the ground was that the models that predicted behavior were wrong, and the vehicle was redesigned. The Air Force wanted to do more testing. DARPA pushed back, claiming there was no point to further testing. They thought they had the performance fully characterized. They flew it, and it didn't work. Now again, to their credit, DARPA, after it didn't work, after the flight, DARPA did turn around and say, "All right, now let's do the ground test." In part, that was because there was a new program manager, and that program manager came out of the Air Force Research Lab, so he understood why we needed to do more ground tests.

To my mind, that's a perfect example of why we need test facilities. I further point to the fact that ***you can make the investment up front in the test facility, or frankly, you can pay for it in a failed flight, but one way or another, you're going to pay for testing***. It's just a matter of when you pay for that testing.



Falcon aerodynamics model





Falcon aeroheating model

Impact: LaRC data contributed to (partial) redesign of Falcon vehicle



Partially successful first flight in April 2010. Flight anomaly due to "higher than predicted yaw" (DARPA Engineering Review Board)

Overview

For more than 50 years, NASA Langley Research Center's hypersonic wind tunnels have played a vital role in the development of hypersonic flight and atmospheric entry systems and technologies for manned and robotic missions

LaRC hypersonic tunnels produce design, development, and safety assurance data for NASA's crewed space flight capabilities

LaRC hypersonic tunnels provide critical data for the testing and evaluation of new hypersonic technologies for NASA and the Department of Defense

LaRC hypersonic tunnels support the exploration of the solar system through the development of entry-vehicle aerothermodynamic databases for planetary exploration and sample return missions

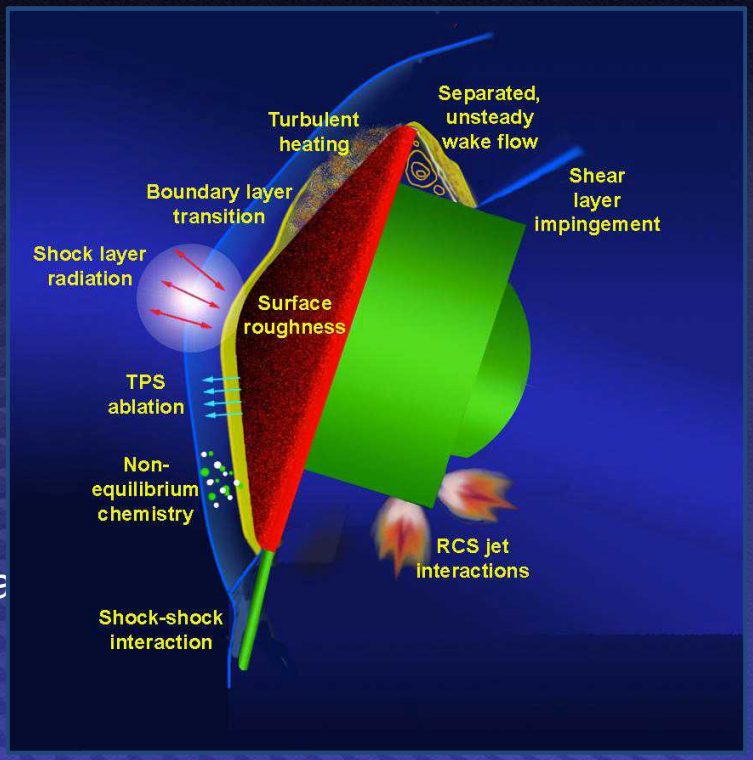
LaRC hypersonic tunnels are employed in the development of commercial space-flight capabilities

Langley Research Center's hypersonic testing capabilities must be maintained and expanded to support the aerothermodynamic challenges of 21st century missions and technology development

21st-Century Aerothermodynamic Challenges:

Aerothermodynamic phenomena of atmospheric entry & Hypersonic Flight LaRC

- **After more than 50 years of progress in the field of aerothermodynamics, many challenging problems still remain in the design of aerospace vehicles**
  - –Every hypersonic vehicle is different and presents unique aerothermodynamic challenges
  - –Many gaps existing in CFD predictive capabilities that lead to decreased performance margins and/or mass gain
  - –CFD, ground-testing, and flight-testing must all contribute to vehicle development



- **Experimental data are still required to further the understanding of aerothermodynamic phenomena**
  - –Shock/shock and shock/boundary-layer interactions
  - –Gas / fluid injection for aerodynamic or aeroheating modula
  - –Axial and cross-flow boundary-layer transition
  - –High Reynolds number turbulent heating augmentation
  - –Surface roughness effects on transition and heating
  - –RCS jet interactions on aerodynamics & heating
  - –Heat-shield penetrations, gaps, protrusions and damage
  - –Aeroelasticity of deployable structures
  - –Separated and unsteady wake flows
  - –Stage and shroud-separation interactions & dynamics
  - –Ablation blowing and recession
  - –Radiation transport
  - –Non-equilibrium chemistry

Flight LaRC hypersonic tunnels provide experimental data for parametric design & optimization of vehicles, CFD validation & uncertainty assessment, flight database construction and technology development

Summary Remarks

- Overview of experimental hypersonics facilities; description, capabilities, utilization, and testing techniques employed at NASA LaRC
- Complex represents approximately half of the conventional (as opposed to impulse) -type hypersonic wind tunnels operational in this country.
- Contributions to NASA, DoD and Commercial Hypersonic Programs
- Contributions to Flight Test Programs and Technology Development
- LaRC Capabilities in the National Perspective on Hypersonics as noted within this session
- Overall and Continued Mission: LAL facilities used to assess and optimize the hypersonic aerodynamic performance and aeroheating characteristics of aerospace vehicle concepts and to provide benchmark aerodynamic/aeroheating data for generating the flight aerodynamic databook and final design of the thermal protection system (TPS).