Aerothermal Ground Testing: How, Where and Why?

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Outline

- Why Test?
  - Blunt Body – Typical Entry, Descent and Landing Configuration
    - Deceleration is prime objective
  - Winged and Slender Body
    - Cross range for added maneuverability
- Where to Test?
  - Types of Facilities
  - Hypersonic Facilities in US
- How to Test?
  - Global Techniques
  - Discrete Gauges

Why Test?

Entry, Descent and Landing Programs

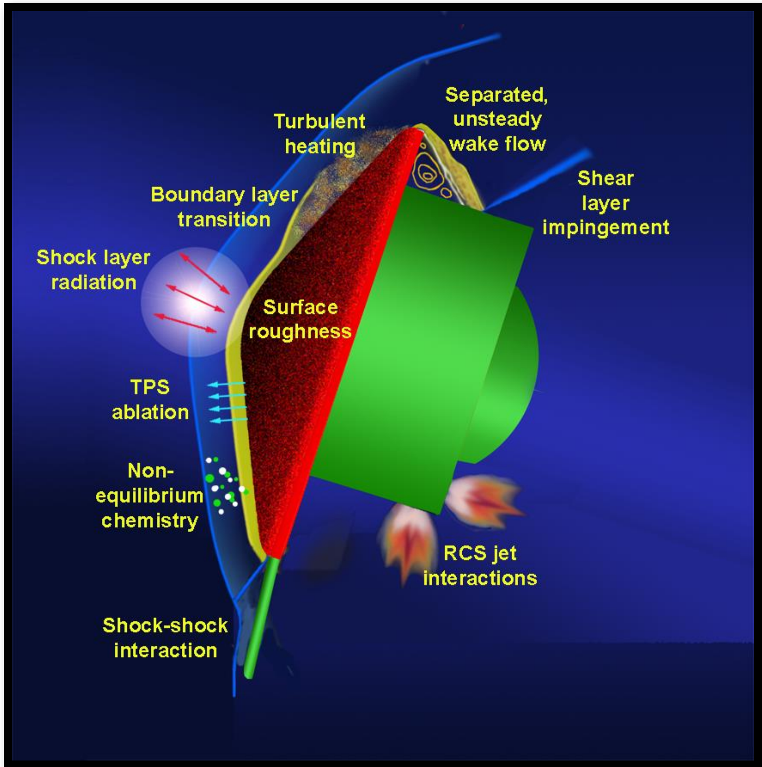
Winged and Slender Body Programs

21st-Century Aerothermodynamic Challenges

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

- Experimental data still required to further the understanding of aerothermodynamic phenomena
  - Shock/shock and shock/boundary-layer interactions
  - Gas/fluid injection for aerodynamic/aeroheating modulation
  - 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

Aerothermodynamic phenomena of atmospheric entry & Hypersonic Flight



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

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

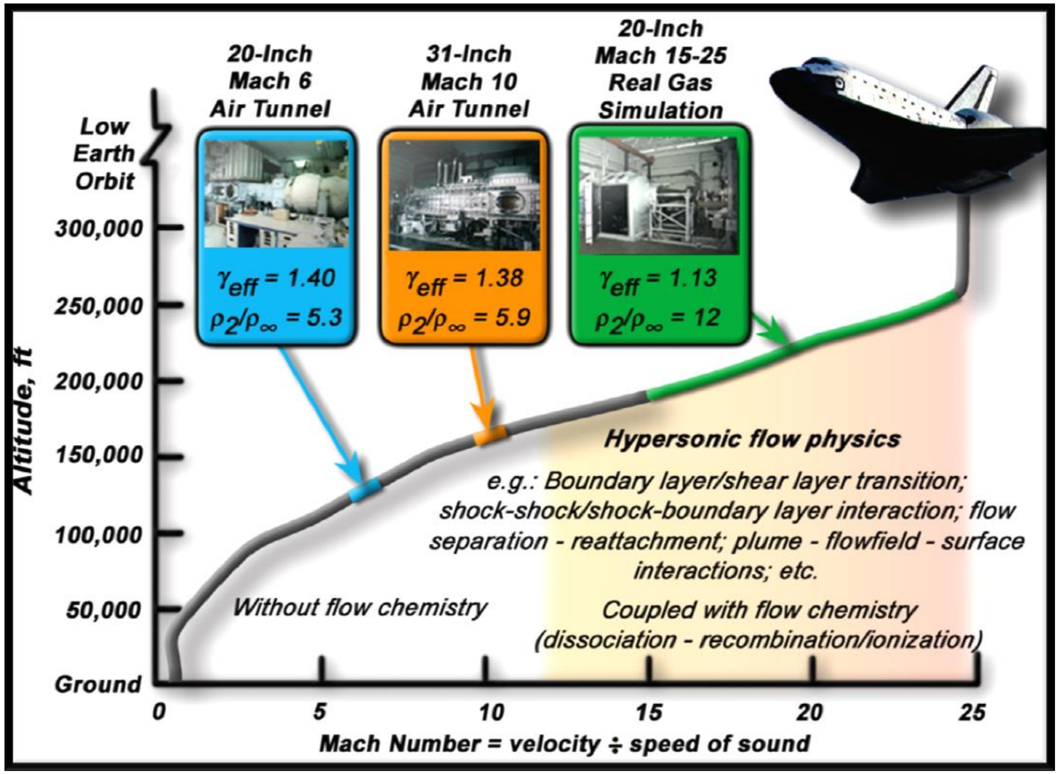
- ✓***LaRC hypersonic tunnels produce design, development, and safety assurance data for NASA's crewed spaceflight capabilities***
- ✓***LaRC hypersonic tunnels provide critical data for the testing and evaluation of new hypersonic technologies for NASA and the Department of Defense***
- ✓***LaRC hypersonic 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

Hypersonic Testing Capabilities at NASA LaRC

- **Background**:
  - NASA LaRC Aerothermodynamic Laboratory currently operates three conventional wind tunnels.
  - Facilities were developed in the 1960s and upgraded in the 1980s-1990s.
- **Operational Characteristics**:
  - Conventional blow-down tunnels.
  - Perfect-gas air (except in CF4 tunnel)
  - High flow quality, low-enthalpy, Mach 6 and Mach 10 test conditions.
  - Heat transfer, aerodynamic and flow visualization measurement techniques
- **Merits**:
  - Rapid turn-around time (~10 runs/day) allows maximum flexibility in test-planning.
  - Ideal capability for parametric screening, fundamental flow phenomena investigations.
  - Unique capability for global aeroheating measurements using Langley two-color phosphor thermography method.
- **Utilization**:
  - all historical NASA programs: Apollo, Shuttle, X-33, X-34, X-38, Viking, etc.
  - Currently involved in MSL, CEV, Shuttle Orbiter, DARPA/DoD***, and commercial programs***

Flight Simulation within the Langley Aerothermodynamic Laboratory (LAL) hypersonic wind tunnels



Partial Resume of LaRC Hypersonic Tunnel Programs

Langley Hypersonic Wind Tunnels have contributed to numerous hypersonic and space-flight and technology-development programs

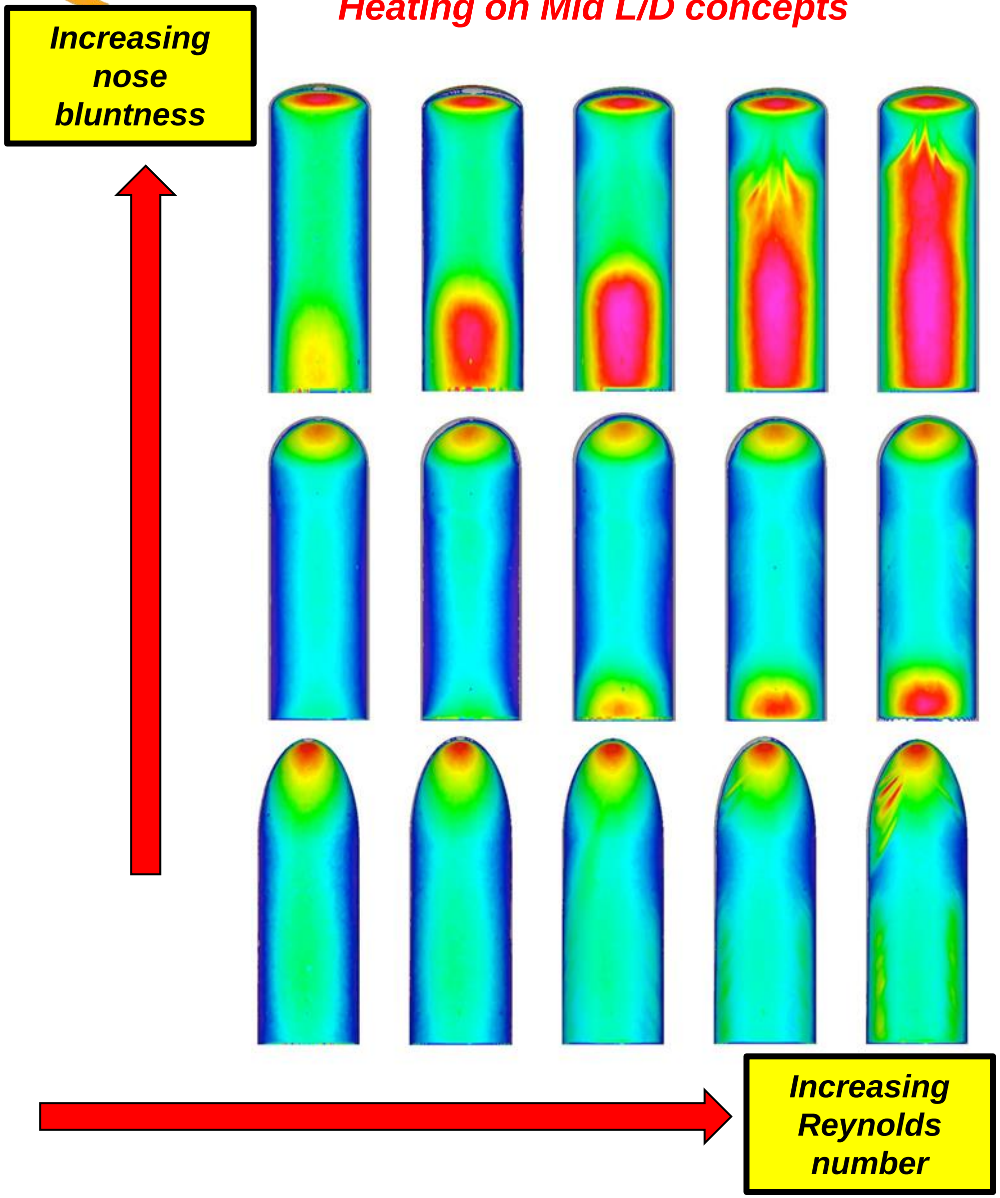
- Human Spaceflight
  - Apollo, Genesis, Mercury capsules
  - Space Shuttle Orbiter development
  - X-38 CRV
  - Shuttle CAIB and RTF
  - Constellation CEV/Orion and Ares/SLS
- Mars Exploration Missions
  - Viking
  - Pathfinder
  - Science Laboratory
- Solar-System Exploration
  - Genesis solar wind sample return
  - Stardust comet sample return
- Technology Development Flight Tests
  - X-43 Hyper-X Airbreathing Propulsion
  - HIFiRE scramjet
  - HYTHIRM imaging
  - Falcon HTV2
  - HyBoLT
  - IRVE
- Research Programs
  - Mid L/D Entry Vehicles
  - Supersonic Retropropulsion
  - Entry Vehicle Trim Tab Performance
  - Wake Flow Behavior
- DoD / DARPA / Air Force
  - Missile technologies
  - X-40 Space Maneuver Vehicle
  - X-37 Orbital Test Vehicle
  - X-51 Waverider
- Commercial Hypersonic / Access-to-Space Capabilities
  - Kistler RV-1 RLV
  - Lockheed-Martin X-33 RLV
  - Orbital Sciences Pegasus Launcher
  - Orbital Sciences X-34 RLV
  - Boeing & Lockheed OSP proposals
- Aerothermodynamic Phenomena
  - Ballute heating aeroelasticity
  - Lifting-body cross-flow transition
  - Discrete and distributed roughness
  - Stage-separation
  - Shock-shock / shock-BL interaction
  - Stagnation-point injection

Blunt Body

Entry, Descent and Landing Configurations

Research & Development – Mid L/D Entry Vehicle Aeroheating

Heating on Mid L/D concepts



- Background: Mid L/D entry vehicle configurations enable future high-mass Mars entry missions. Need to understand aeroheating performance to advance conceptual designs
- Approach: aeroheating testing of multiple mid-L/D configuration in 20-Inch Mach 6 air using phosphor thermography
- Impact: developed database of heating environments and boundary-layer transition behavior including cross-flow transition

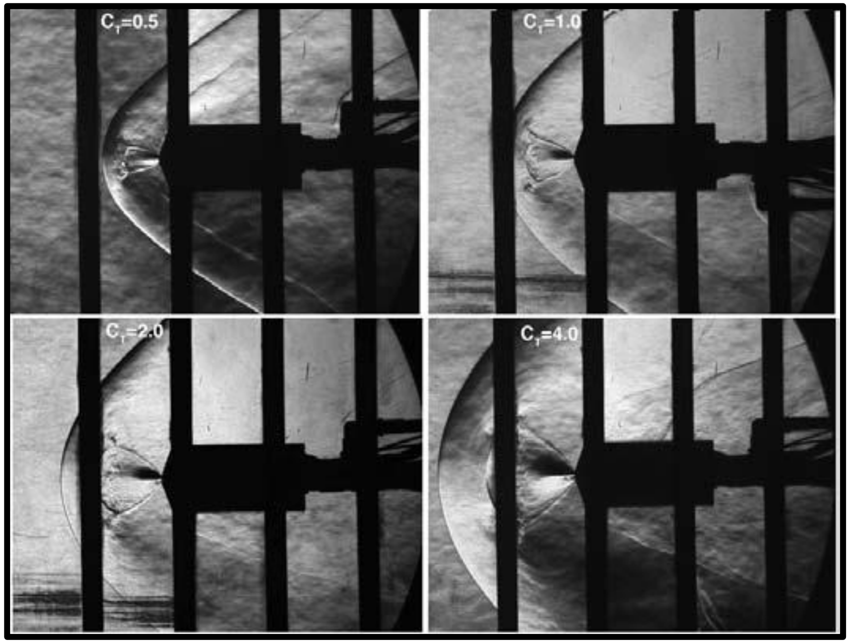
Mid L/D entry vehicle concept

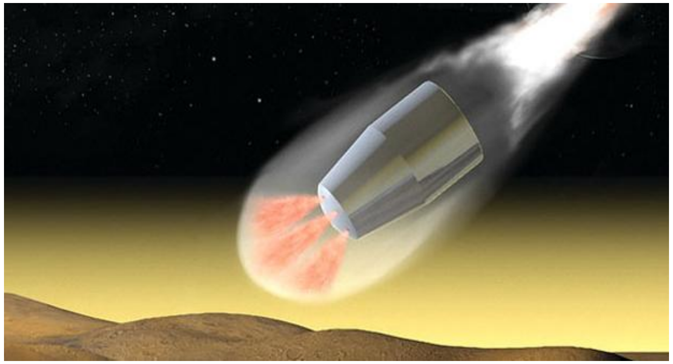
Research & Development – Supersonic Retropropulsion

- Background: Development of alternative technologies such as supersonic retropropulsion will be required to enable future high-mass Mars mission.
- Approach: Develop a performance database on surface pressure and flow-field visualization through testing in Langley and Ames Unitary Plan Wind Tunnels
- Impact: Developed a database on single and multiple-nozzle configurations over a wide range of Mach/Reynolds number conditions for performance evaluation and validation of CFD simulation methodology

Supersonic retropropulsion model with tri-nozzle configuration

Schlieren imagery from Langley UPWT



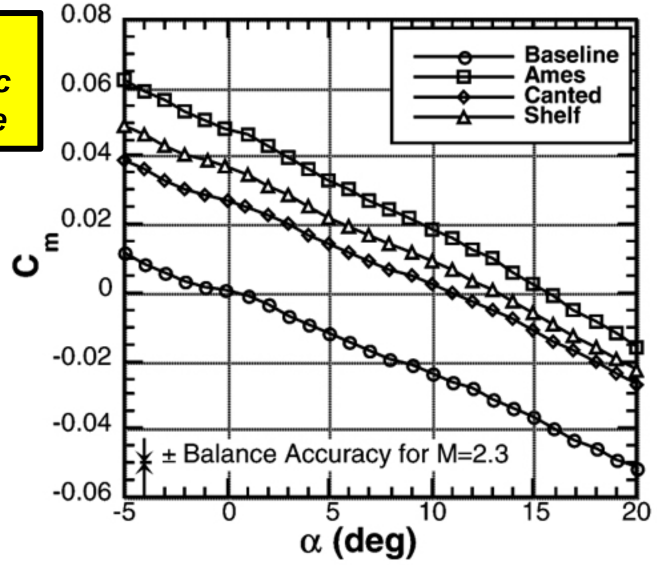


High-mass Mars entry using supersonic retropropulsion (artist's concept)

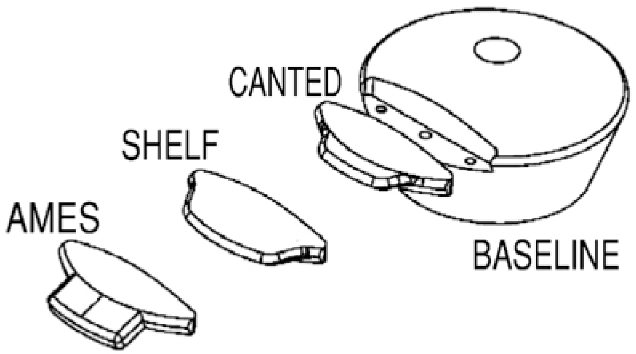
Research & Development – Entry Vehicle Trim Tab Performance

- Background: Trim-tabs are a weight-saving option to offset-CG ballast mass to maintain high trim angle required for high-mass Mars entry
- Approach: develop aeroheating and aerodynamic databases through testing in 20-Inch Mach 6 and UPWT
- Impact: verified required aerodynamic performance, defined heating augmentation on deflected tabs

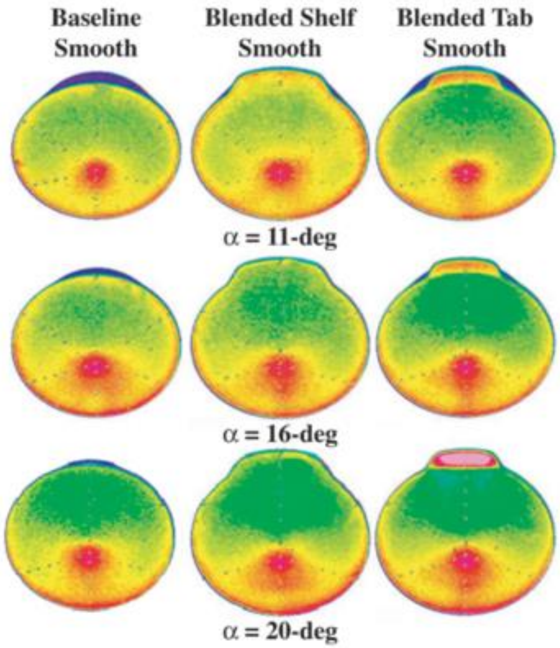
Trim-tab aerodynamic performance



Trim-tab geometry options

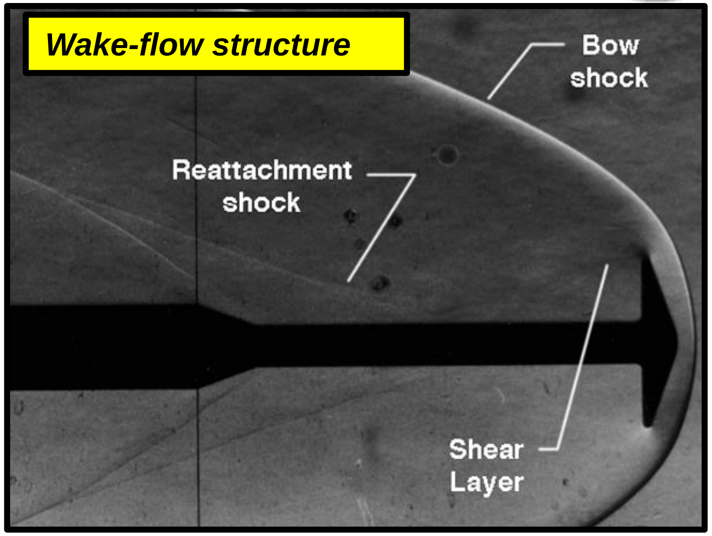


Trim-tab aeroheating

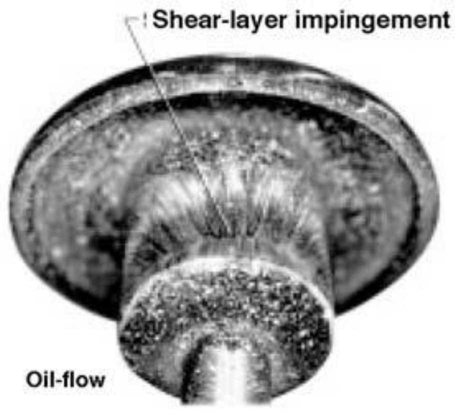


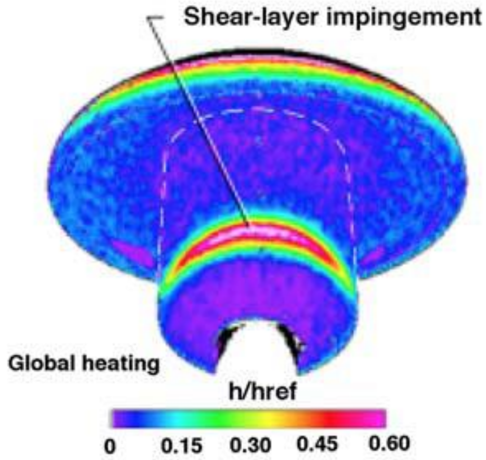
Research & Development – Wake Flow Behavior

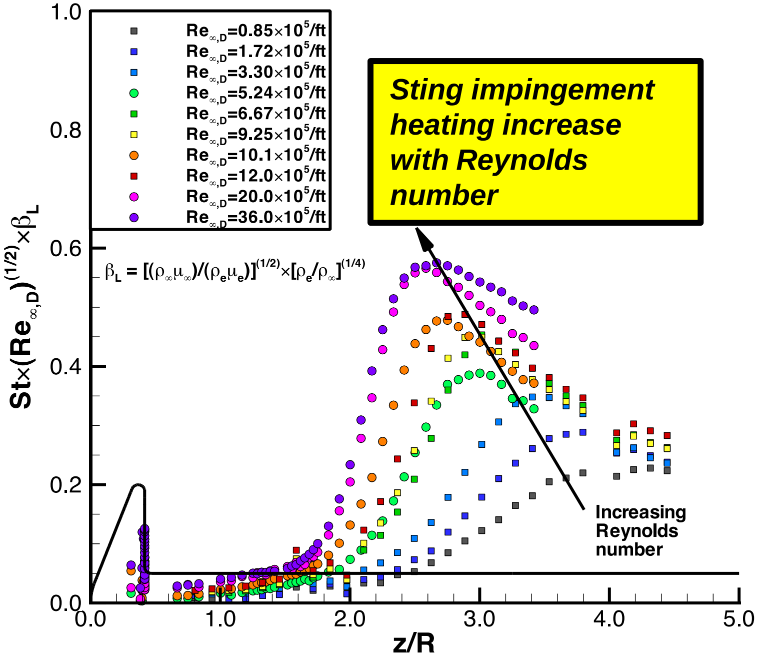
- Background: High uncertainties (>%100) for aftbody/wake-flow environments. Payload protection becomes extremely important for sample return missions
- Approach: Multiple studies performed on entry vehicle configurations to examine shear-layer and wake flow structure, payload impingement, aftbody heating in 20-Inch Mach 6, 31-Inch Mach 10 and 20-Inch CF_4 Tunnels
- Impact: Databases and correlations for shear-layer turning angle, payload impingement location, aftbody heating for use in design of sample-return missions



Shear-layer impingement heating on payload



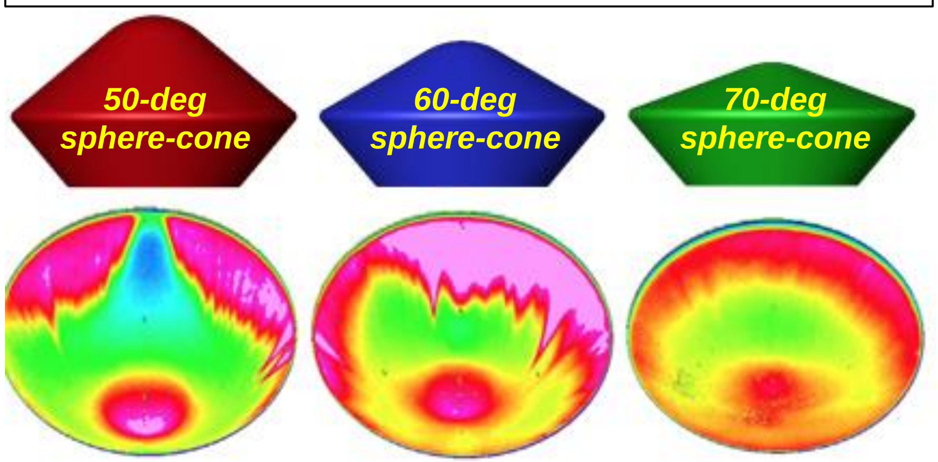


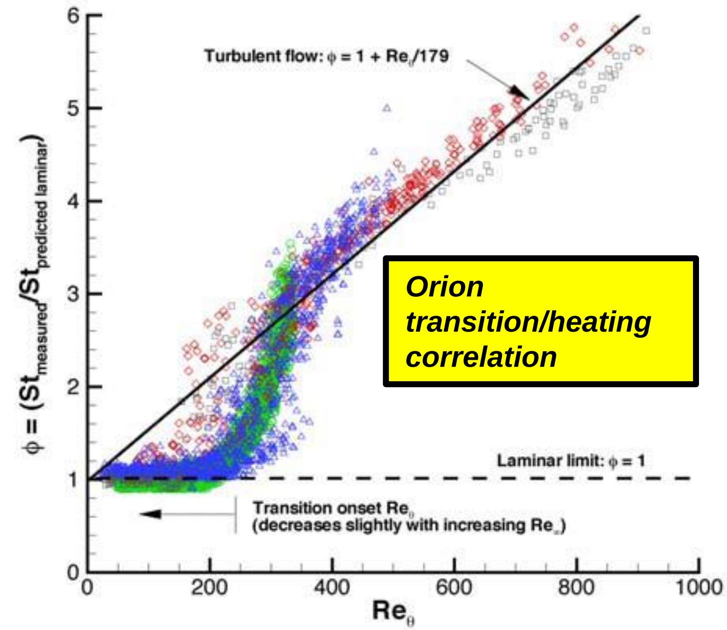


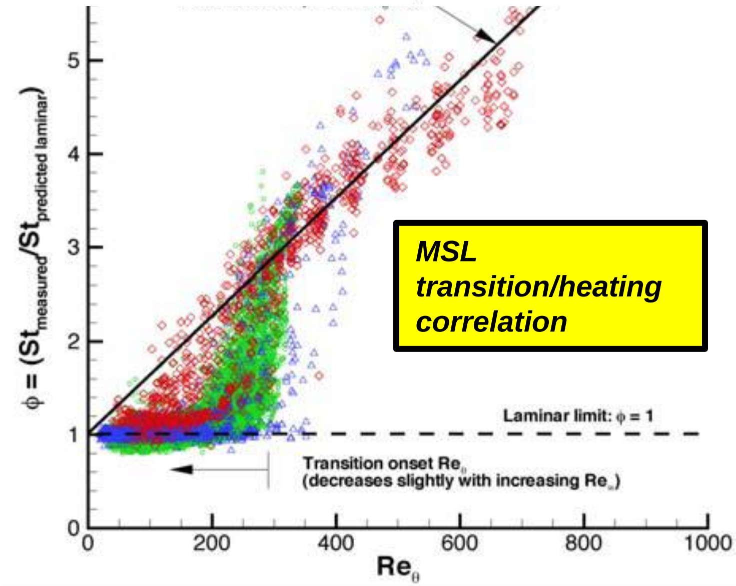
Research & Development – Blunt Body Transition and Turbulence

- Background: Trend towards larger vehicles with higher entry velocities - missions such as as Orion and MSL will experience transition and turbulence.
- Issue: Relatively sparse historical database for blunt-bodies. Need for new datasets to use in development of engineering models and CFD validation
- Approach: Testing of wide range of blunt-body configurations in 20-Inch Mach 6 Air Tunnel to obtain heating and transition data. Additional testing at CUBRC LENS and AEDC Tunnel 9
- Result: Database of smooth-body transition and turbulent heating levels for use in design of future TPS

Transition-onset fronts for different cone-angles



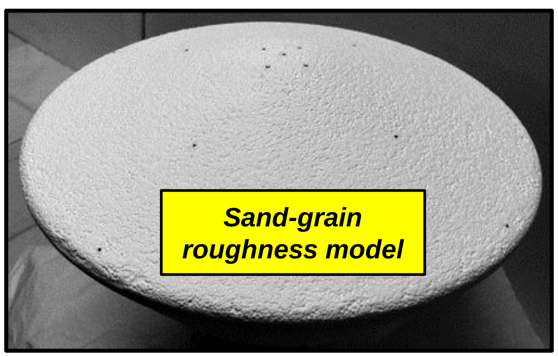


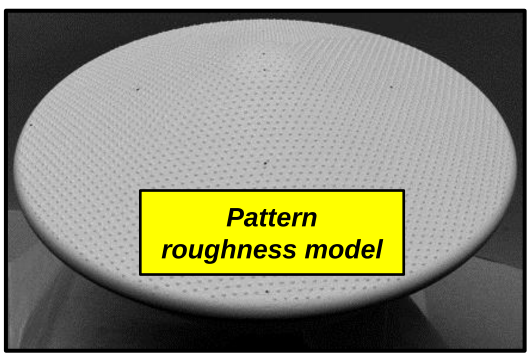


Research & Development – Distributed TPS Roughness

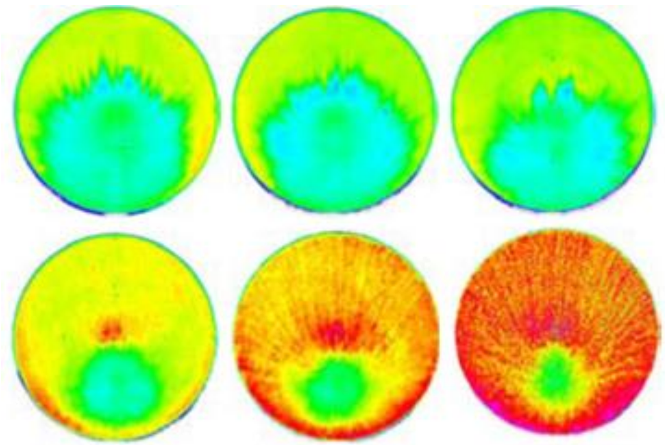
- Background: TPS ablation produces rough surface that promote early transition and cause turbulent heating augmentation
- Issue: Relatively sparse historical database for blunt-bodies. Need for new datasets to use in development of engineering models and correlations
- Approach: Tested wide range of roughness-height models in 20-Inch Mach 6 Air Tunnel to obtain heating and transition data.
- Result: Database of distributed roughness transition and heating augmentation effects for use in design of future TPS

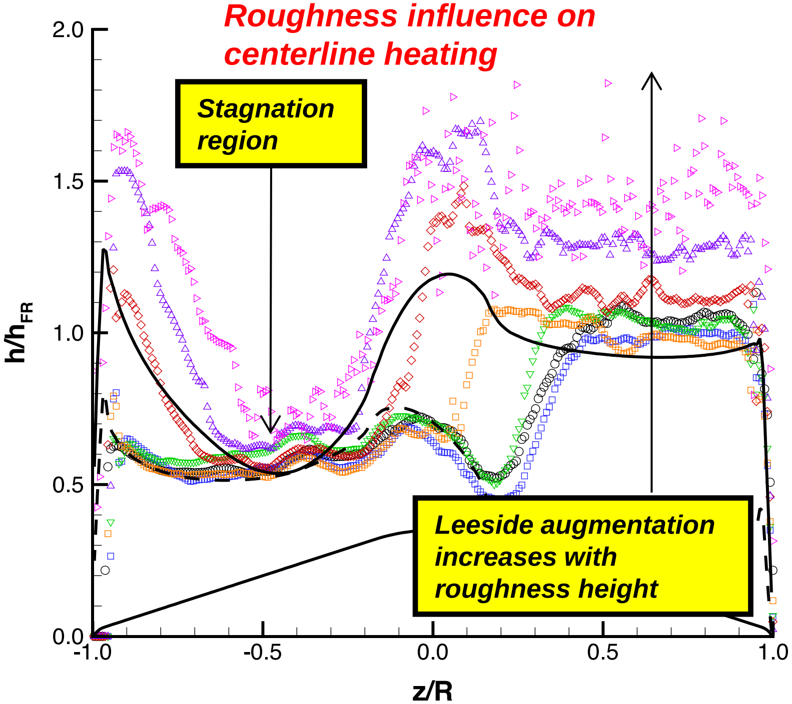
Distributed roughness wind tunnel models





Global heating effects from increasing roughness height



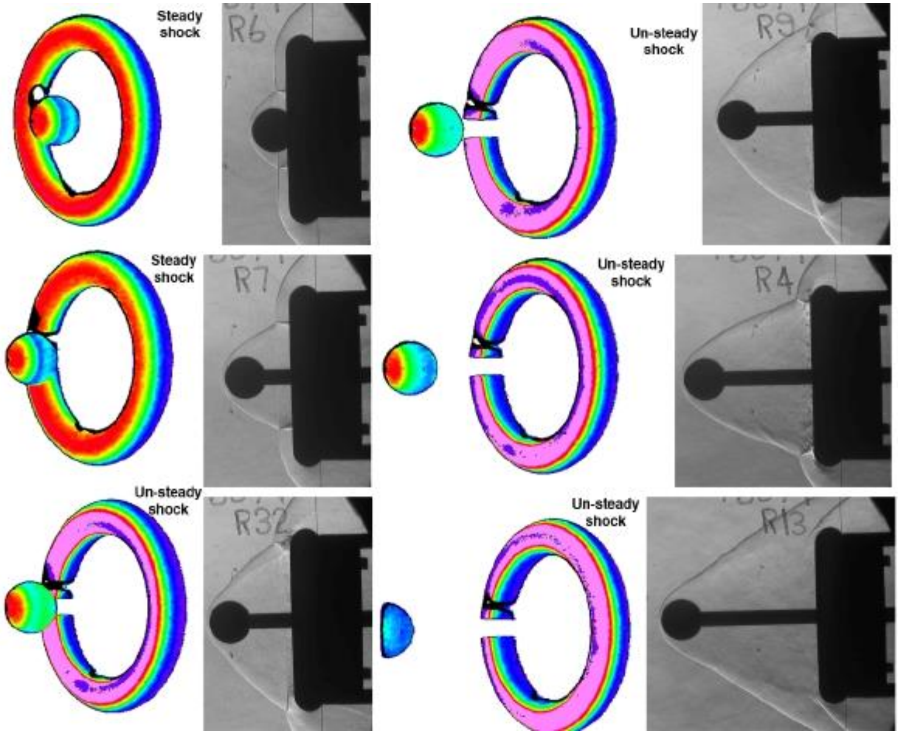


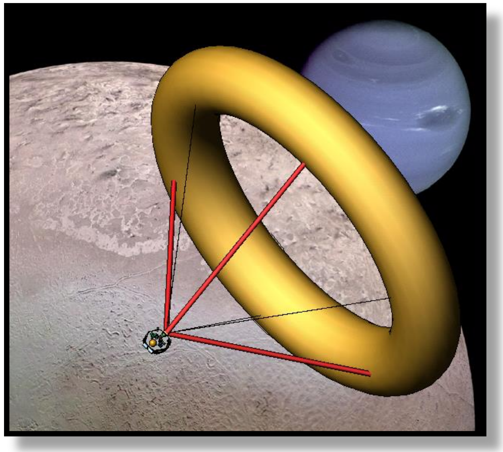
Research & Development – Towed Ballute Flow-field Interactions

- Background: Towed ballutes are large, inflatable, structures that trail a small payload and act as a high-altitude decelerator for orbital aerocapture.
- Issue: For towed ballutes, flow-field interactions between towing spacecraft and ballute (and also tow lines). Flow may be unsteady, spacecraft shock wave may impinge on ballute and affect heating and aerodynamics.
- Approach: Testing of towed ballute models in 20-Inch Mach 6 CF_4 Tunnel to obtain heating data and schlieren flow-field imaging.
- Result: Data in steady and unsteady flows for comparison with results from CFD and DSMC flow-field predictions.

Adjustable-length ballute model installed in LaRC CF4 tunnel

Heating data and schlieren images for various tow lengths



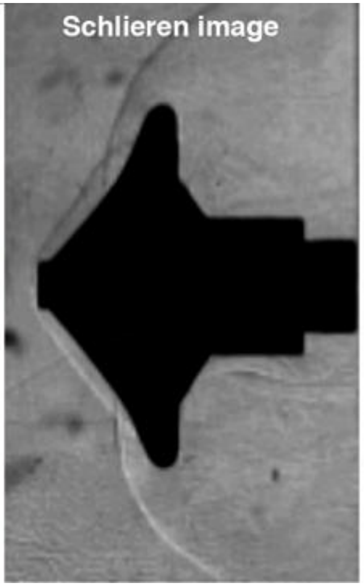


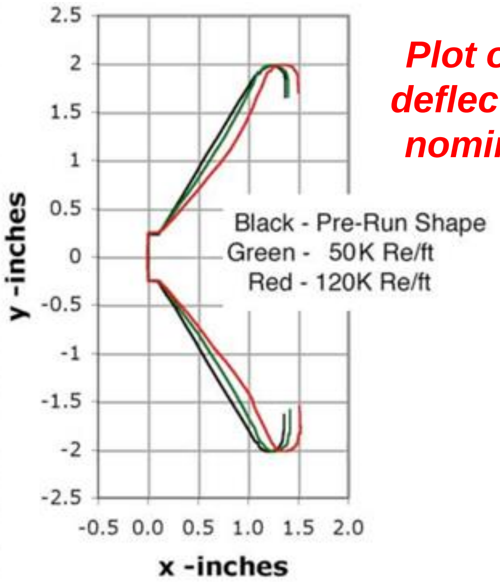
Artist's concept of spacecraft with towed ballute

Research & Development – Attached Ballute Aeroelasticity

- Background: Attached ballutes are inflatable structures mated to a small payload that have been proposed as high-altitude decelerators for orbital aerocapture.
- Issue: For attached ballutes, aeroelasticity (surface deformation due to aerodynamic loads) can affect the aerodynamic performance of the ballute.
- Approach: Testing of attached ballute models with flexible materials in low-density CF_4 tunnel at LaRC.
- Result: Measurements of ballute deflections for comparison with structural response codes.

Aerocapture with Attached Ballute (artist's concept)



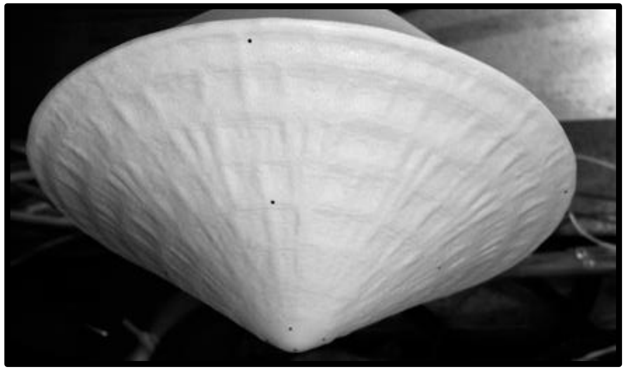


Plot of surface deflections from nominal shape

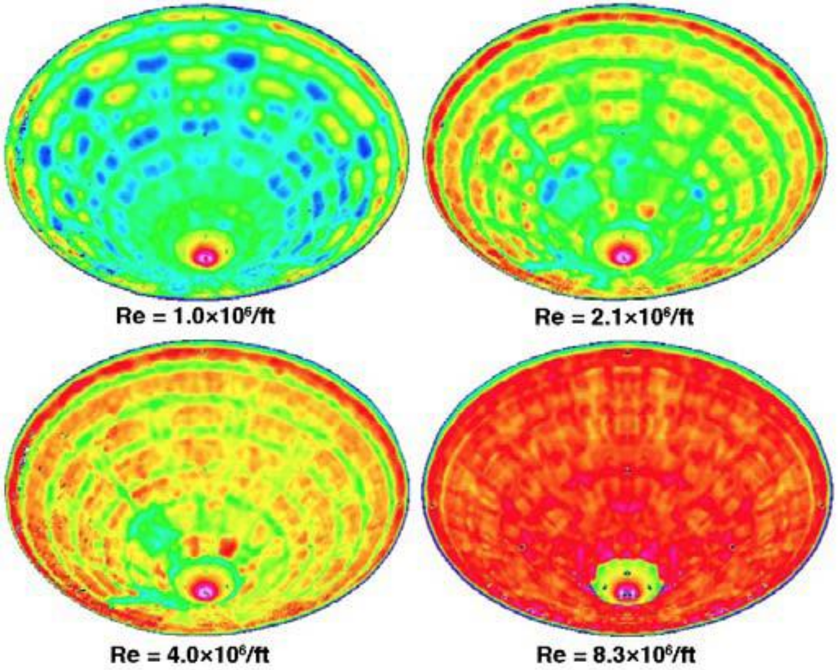
Flight Programs – IRVE Aeroshell Deflection Effects

- Issue: Flexible aeroshell deflection under aerodynamic loading will affect heating and transition
- Approach: Phosphor thermography heating test in 20-Inch Mach 6 Air Tunnel
- Results: measured heating and transition affects for wide range of aeroshell deflections and test conditions
- Impact: augmentation due to deflections found to remain below TPS design limits

Deflected OML Wind Tunnel Model



Heating data on deflected aeroshell

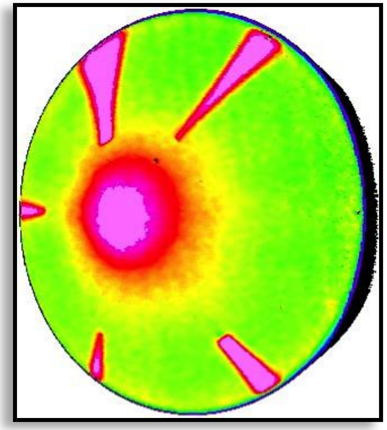


IRVE-3 inflation test article

Flight Programs – Genesis Attachment Point Cavities

- Background: Cruise-stage attachment points on Genesis heat-shield cause early boundary-layer transition and localized increased heating
- Approach: Phosphor thermography heating testing in 20-Inch Mach 6 Air Tunnel of various cavity sizes and locations to determine effects
- Impact: cavity design was based on wind tunnel dataset

Aeroheating data showing turbulent wedges produced by cavities



Boundary-layer transition correlation

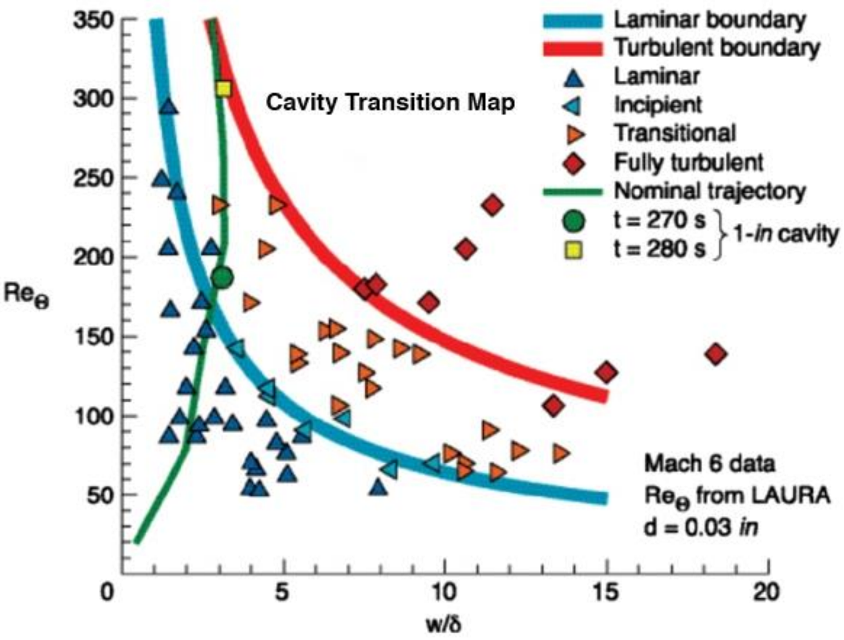
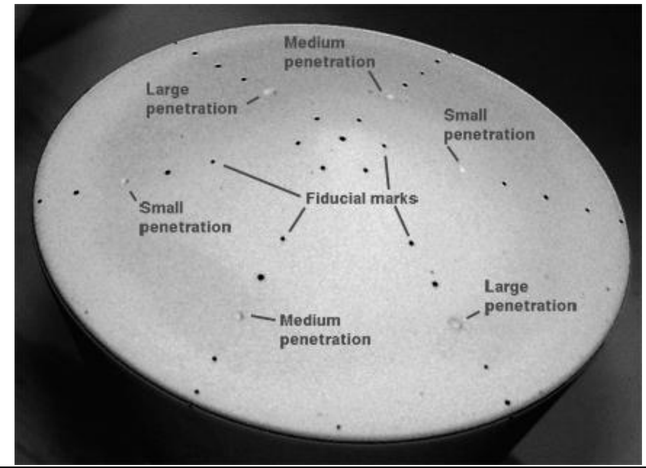


Photo of recovered capsule showing char downstream of attachment point cavity

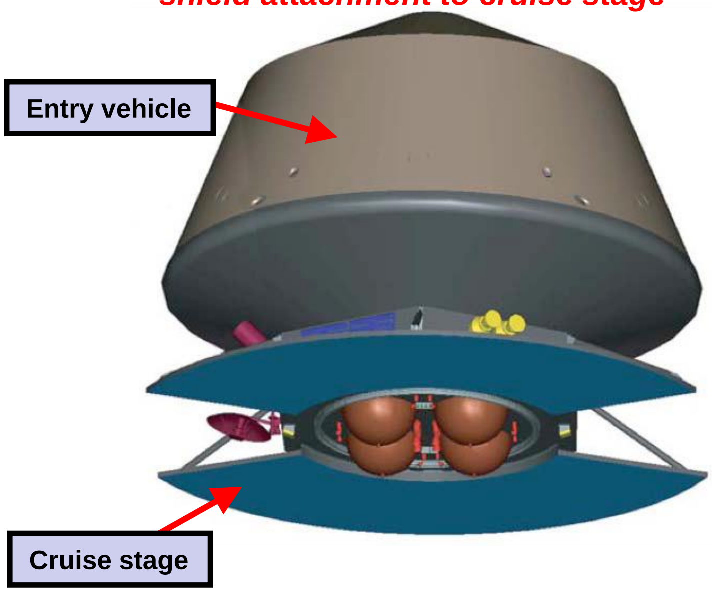
Flight Programs – MSL Attachment-Point Cavities

- Problem: Attachment points for MSL entry vehicle to cruise stage initially located on heat shield. Expected to cause elevated aeroheating
- Approach: Aeroheating testing in 20-Inch Mach 6 Air Tunnel on a wide range of cavity sizes and locations
- Impact: elevated heating levels and early boundary-layer transition led to system redesign with cavities on aftbody instead of heat shield

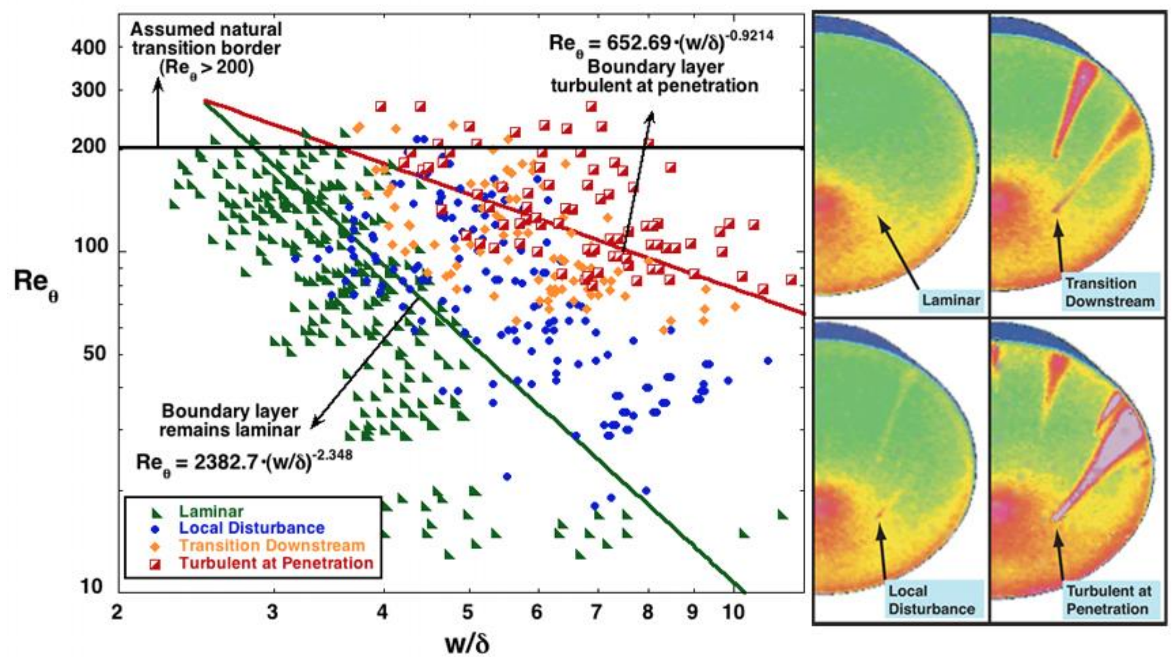
Model with various cavity sizes/locations



Early MSL Configuration with heat-shield attachment to cruise stage



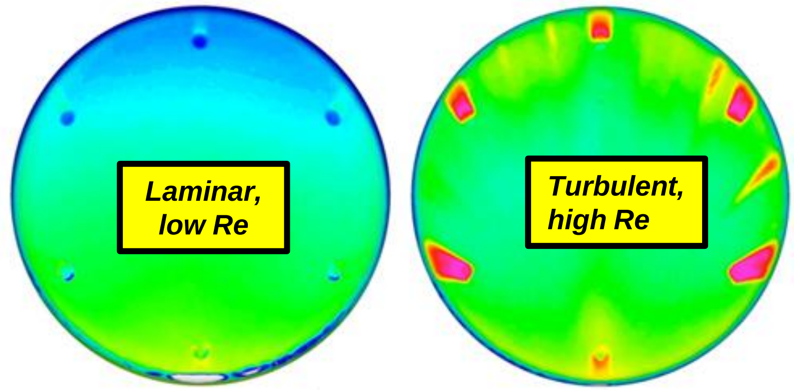
Transition onset correlation for MSL



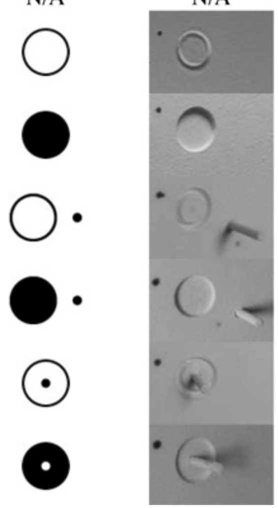
Flight Programs – Orion Compression Pad Environments

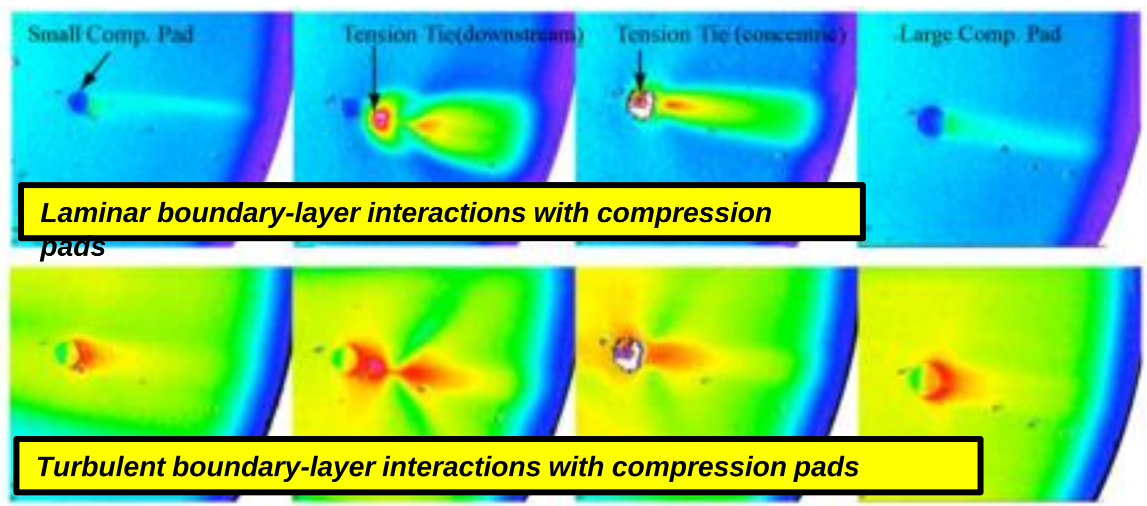
- Background: Orion crew module mated to launch stack by tension ties through the heat-shield which leave cavities after separation
- Approach: phosphor thermography aeroheating testing of multiple compression-pad / tension-tie / cavity configurations
- Impact: developed correlations for compression pad effects on transition, provided heating data for CFD validation

Downstream influence of compression pads



Configuration	Schematic Image	Model Photo
Baseline	N/A	N/A
Annular Compression Pad No Tension Tie		
Recessed Compression Pad No Tension Tie		
Annular Compression Pad Outboard Tension Tie		
Recessed Compression Pad Outboard Tension Tie		
Annular Compression Pad Concentric Tension Tie		
Recessed Compression Pad Concentric Tension Tie		

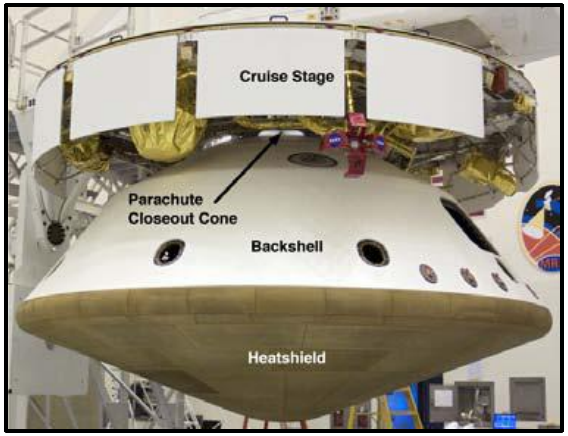


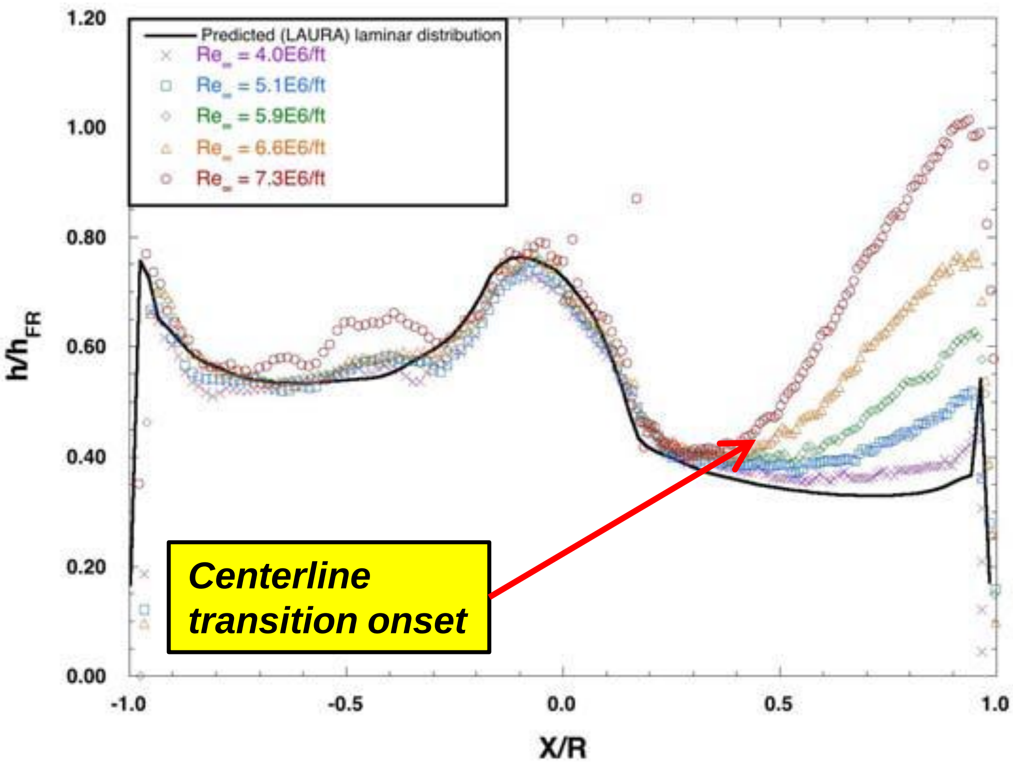


Flight Programs – MSL Heat Shield Transition

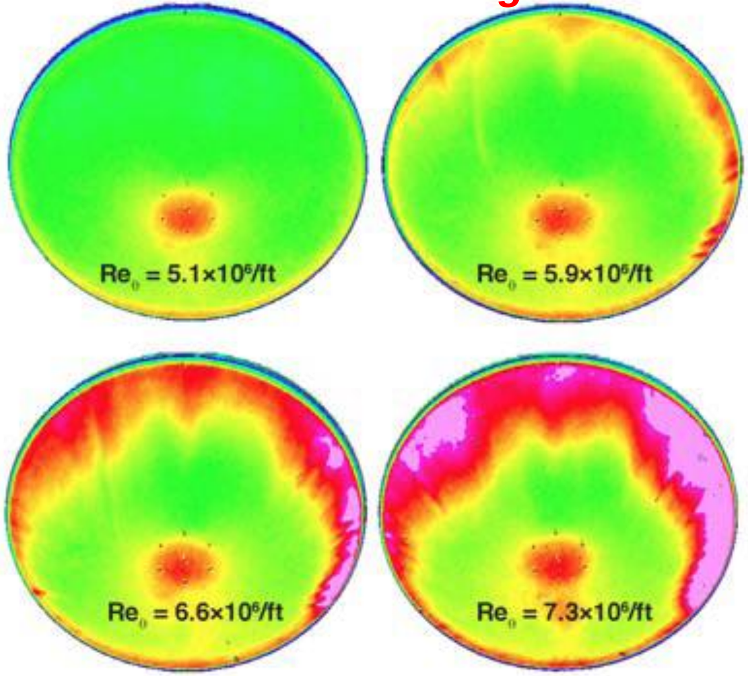
- Problem: High AoA and entry velocity for MSL promotes early transition and turbulent heating
- Test Technique: aeroheating testing in LaRC 20-Inch Mach 6 Air tunnel to obtain transition data
- Impact: transition data confirmed need to design MSL heat-shield to turbulent conditions

MSL Entry Vehicle





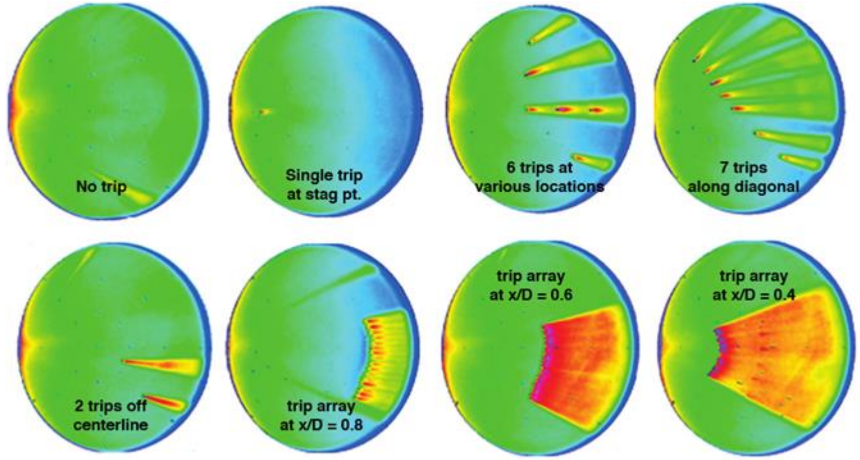
Global aeroheating data



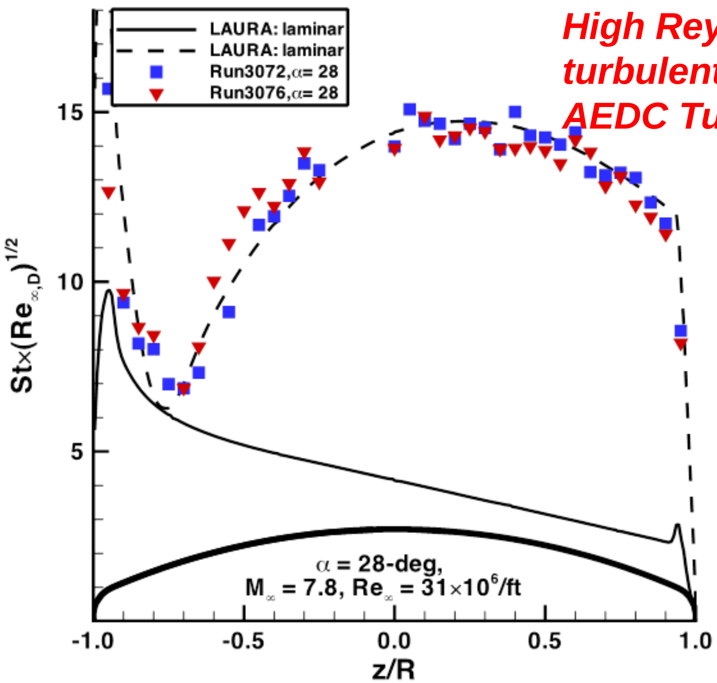
Flight Programs – Orion Heat Shield Transition and Turbulence

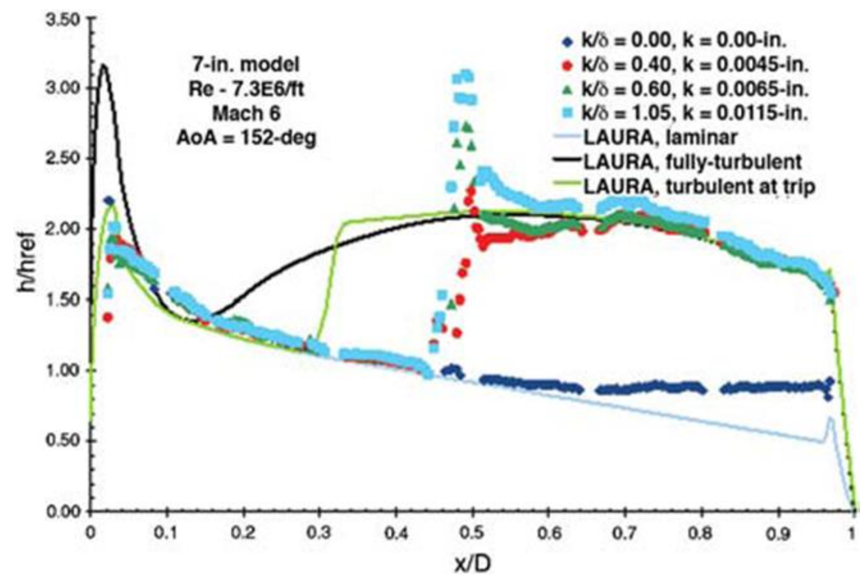
- Background: Large size and high AoA for Orion will produce turbulent flow on heat shield
- Approach: aeroheating testing in 20-Inch Mach 6 Air Tunnel and AEDC Tunnel 9
- Impact: turbulent aeroheating data used to help validate CFD turbulence models employed in flight database

Phosphor thermography data from LaRC 20-Inch Mach 6 Air



High Reynolds number turbulent data from AEDC Tunnel 9

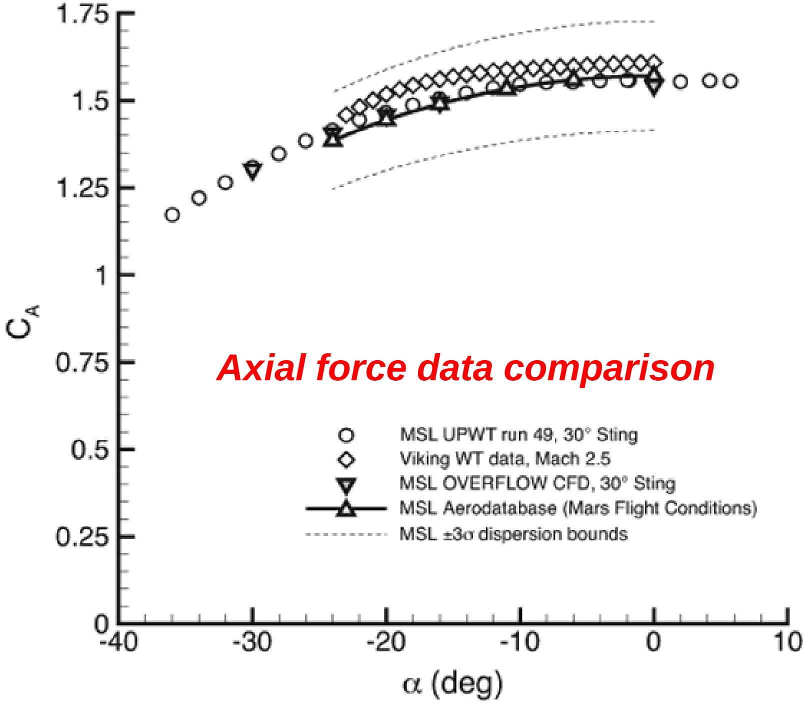




Flight Programs – MSL Supersonic Aerodynamics

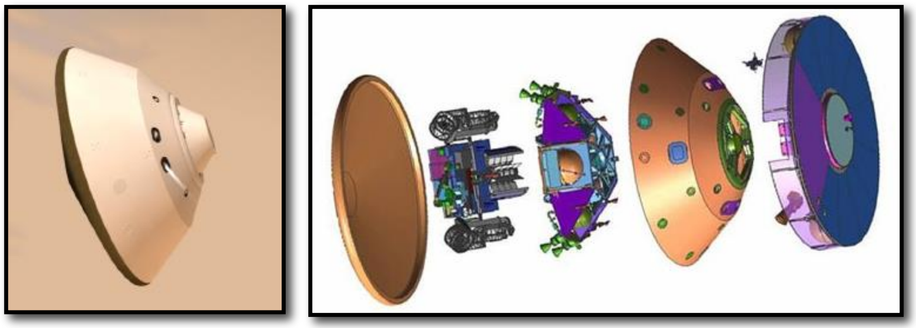
- Background: MSL supersonic aero database built on Viking-heritage test data and modern, but un-validated CFD simulations
- Approach: Aerodynamic Force-and-Moment Testing in Langley Unitary Plan Wind Tunnel at Mach numbers of 1.6 to 4.5 with angles-of-attack up 36-deg
- Impact: New data set in good agreement with heritage Viking data and new CFD predictions – results helped to validate flight database

Schlieren visualization of MSL force-and-moment model in UPWT

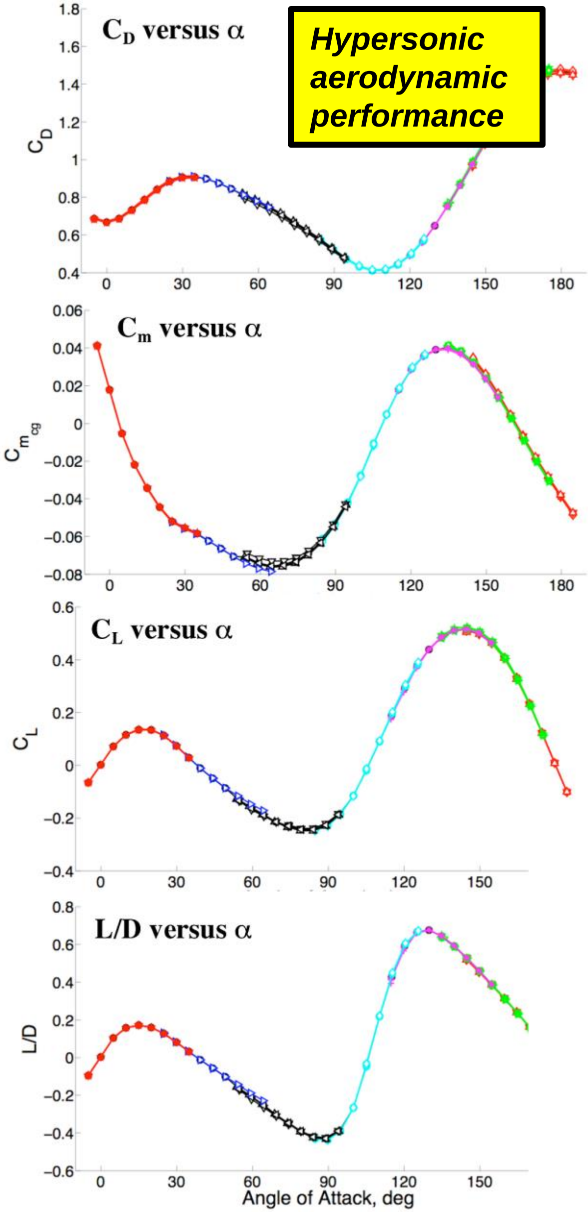


Axial force data comparison

MSL Entry Vehicle

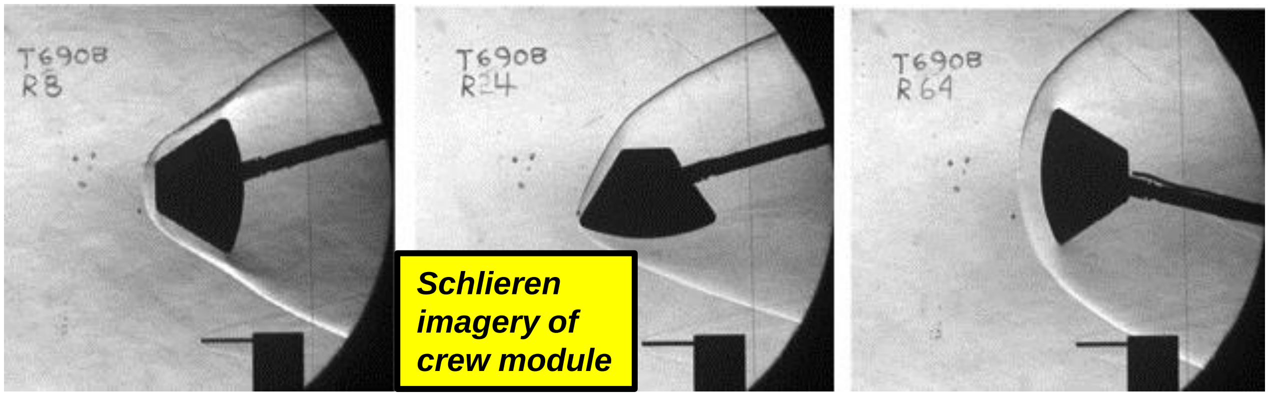


Flight Programs – Orion Command Module Hypersonic Aerodynamics



Hypersonic aerodynamic performance

- Background: aerodynamics of Orion crew module must be quantified at all angles-of-attack in case of abort during flight
- Approach: force-and-moment measurements and schlieren imaging in 20-Inch Mach 6 Air Tunnel and UPWT
- Impact: Supersonic / hypersonic aero database developed to support Orion design

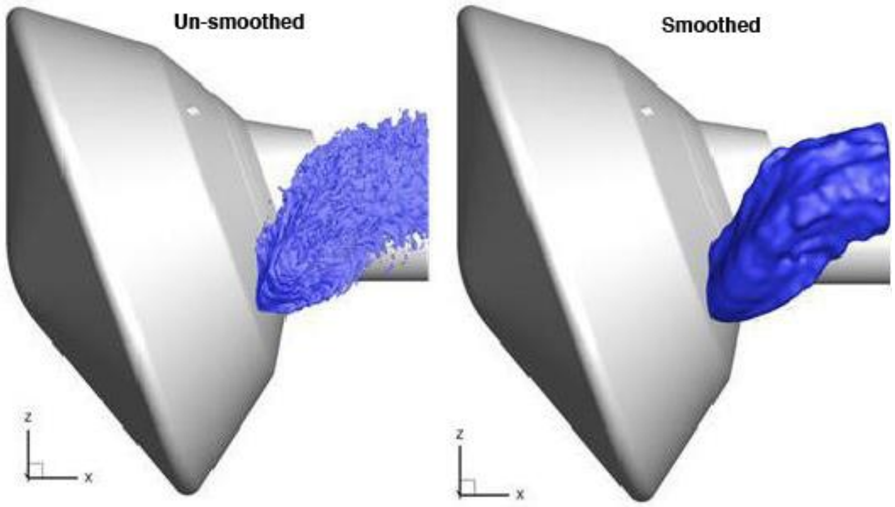


Schlieren imagery of crew module

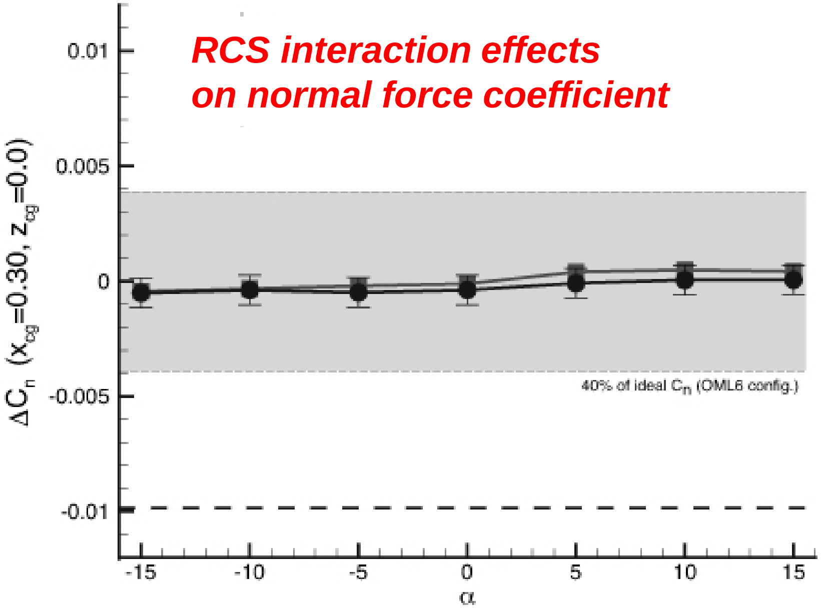
Flight Programs – MSL RCS Interactions

- Background: RCS jet interactions with external flow and vehicle surface can produce non-linear and/or counter-productive aerodynamic effects
- Approach: Aerodynamic force-and-moment and PLIF visualization in Langley Unitary Plan and 31-Inch Mach 10 Air Wind Tunnels to evaluate MSL RCS behavior.
- Impact: Obtained RCS interaction data for multiple Mach / AoA / jet-firing cases at supersonic & hypersonic conditions and determined that RCS interaction effects were within control system authority

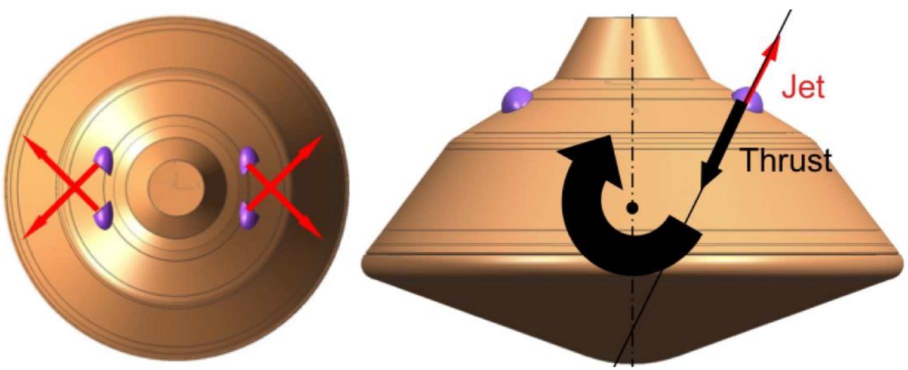
PLIF visualization of MSL RCS jet flow field



RCS interaction effects on normal force coefficient

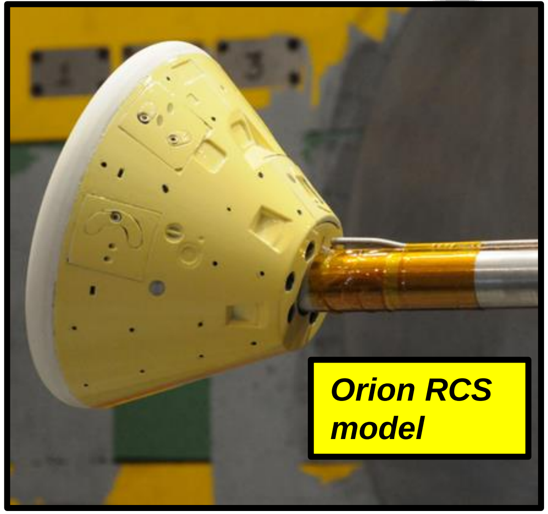


MSL RCS thruster locations and jet plume directions

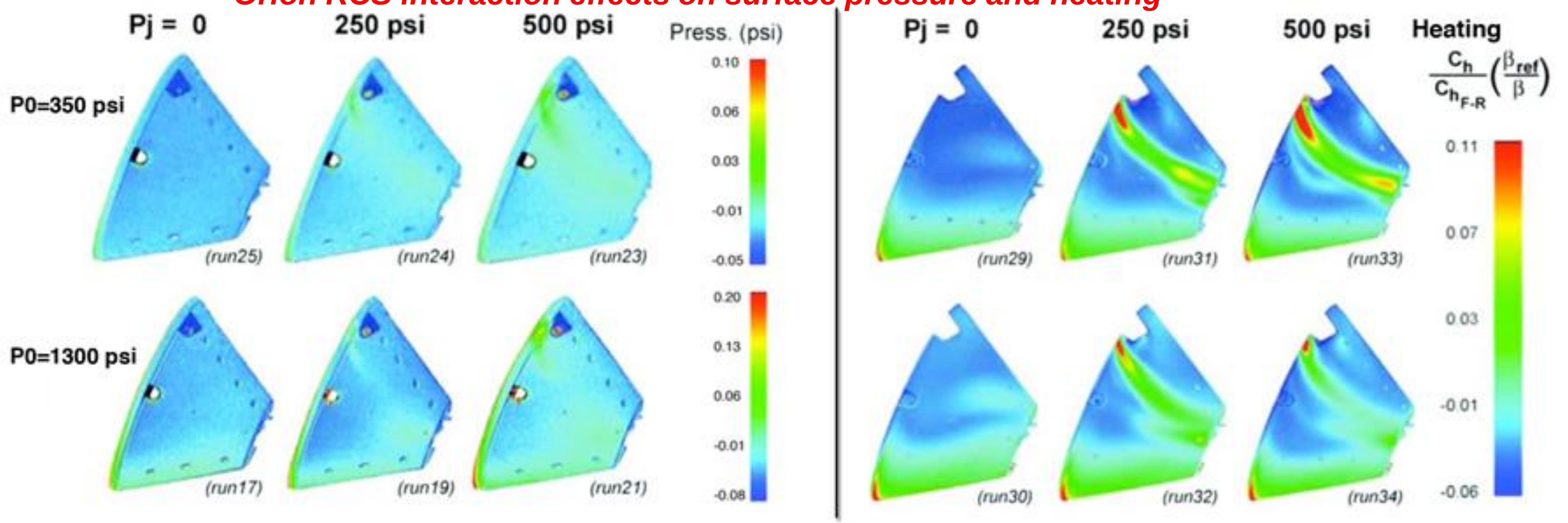


Flight Programs – Orion RCS Interactions

- Background: Orion crew module has multiple pairs of RCS jet for pitch, roll and yaw control. Jet firings will have interactions with surface pressure and heating
- Approach: pressure and temperature sensitive paints used on model with powered thrusters to measure pressure and heating effects
- Impact: interaction database used in crew module TPS design



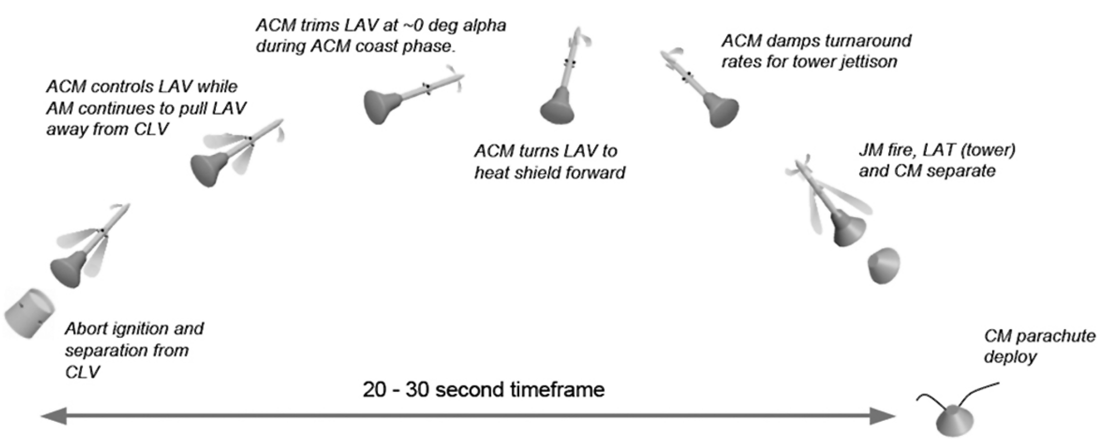
Orion RCS interaction effects on surface pressure and heating

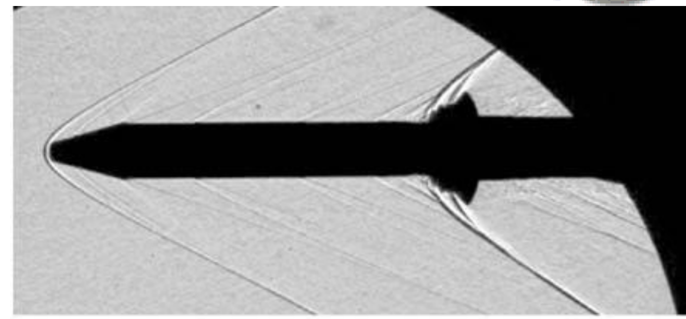


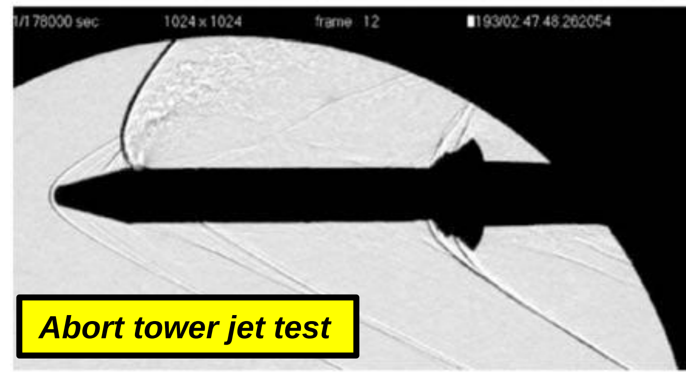
Flight Programs – Orion Launch Abort System

- Background: Orion Launch Abort System (LAS) would be used during emergency on pad or during ascent. Complex aerodynamic interactions between vehicle components and thrusters
- Approach: aerodynamic testing performed in Langley and Ames Unitary Plan Wind Tunnels and AEDC Propulsion Wind tunnel
- Impact: extensive aerodynamic database (~6000 data points) was developed to model LAS performance

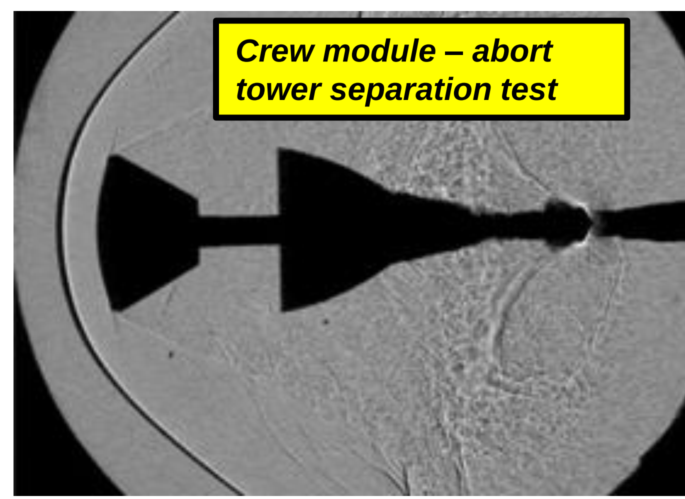
Orion Launch Abort System







Abort tower jet test

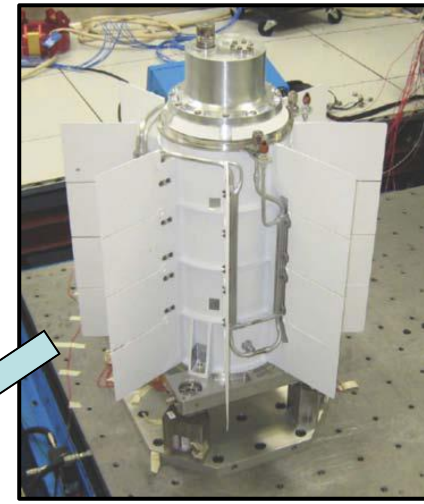


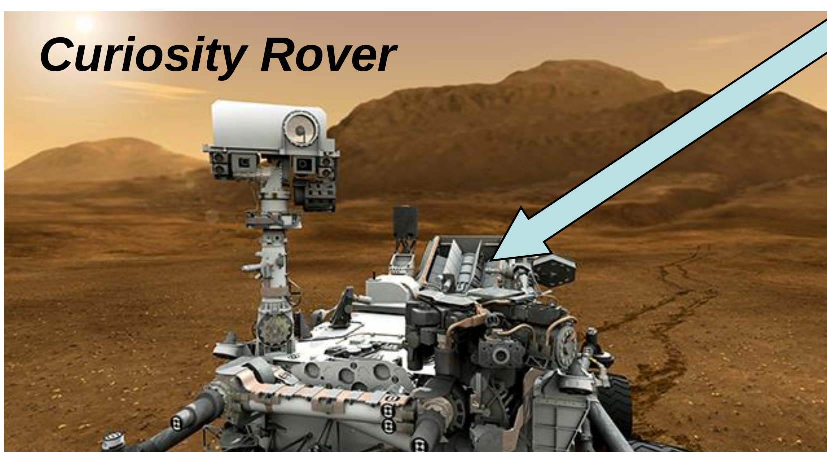
Crew module – abort tower separation test

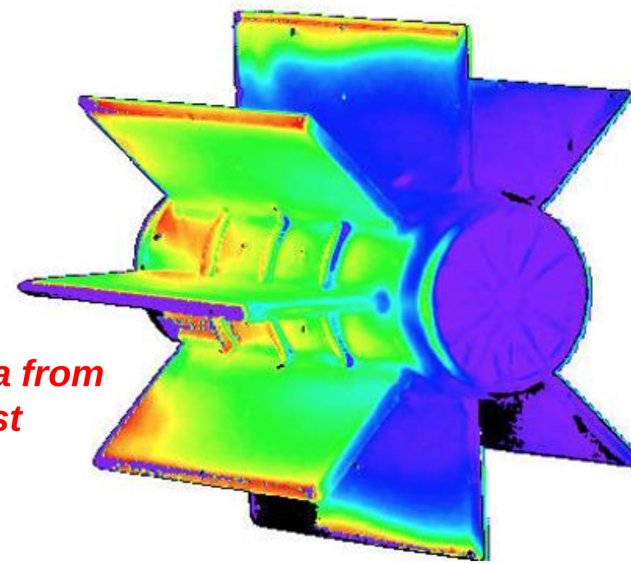
Flight Programs – MSL MMRTG Breakup Analysis

- Background: Aerodynamic and aeroheating data needed to support launch-failure breakup analysis to certify Curiosity's MMRTG for flight
- Approach: Aerodynamic force-and-moment global phosphor thermography aeroheating testing in LaRC 31-Inch Mach 10 Air Tunnel to obtain data over complete range of orientations to simulate tumbling
- Impact: data supported safety analysis for launch of MSL mission

Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) powers Curiosity





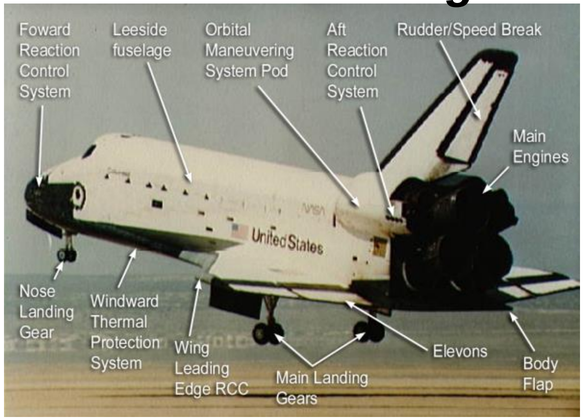


Heating data from Mach 10 test

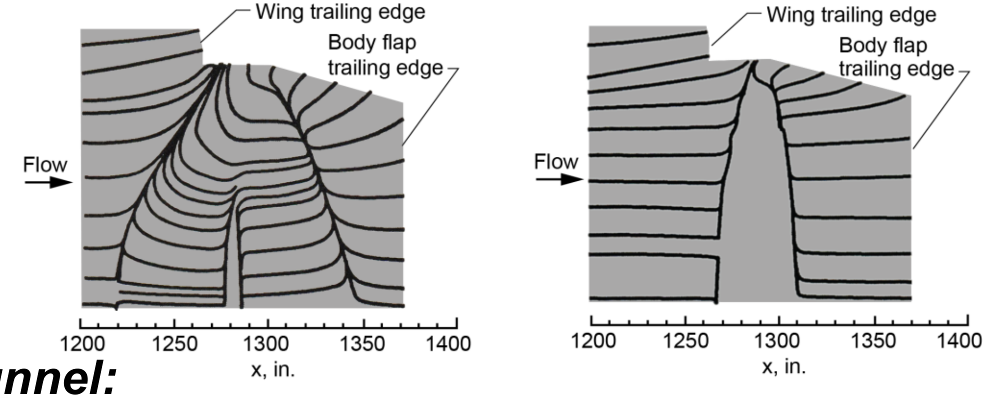
Winged and Slender Body

Shuttle Body Flap Anomaly (1994 – 1995)

STS-1 Landing:



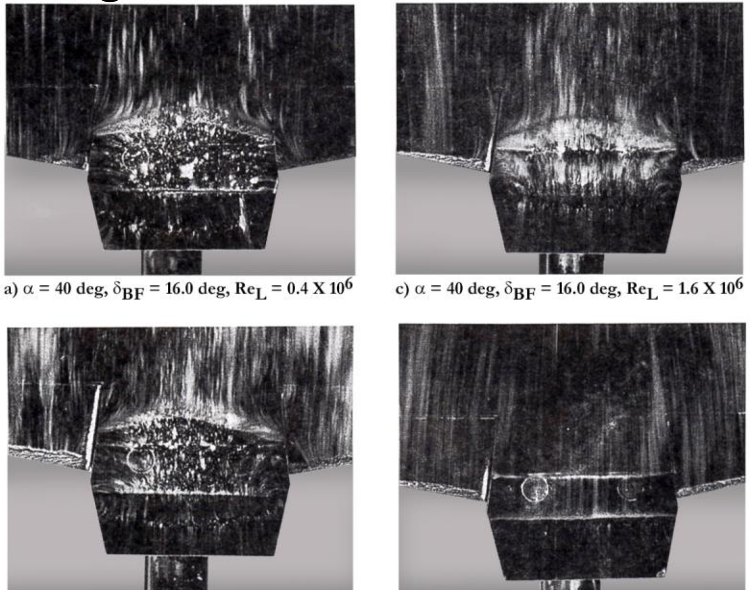
BF region CFD:



a) Wind Tunnel, $\alpha = 40$ deg, $\delta_{BF} = 20$ deg

b) Flight, $\alpha = 40$ deg, $\delta_{BF} = 20$ deg

BF region oil flows from 20" M6 tunnel:



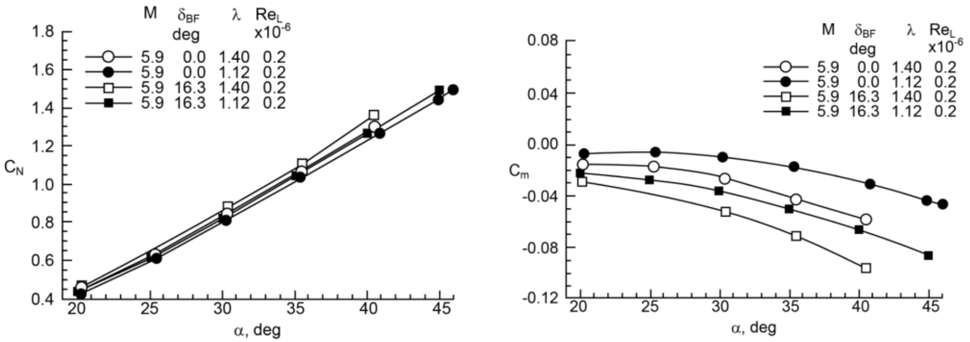
a) $\alpha = 40$ deg, $\delta_{BF} = 16.0$ deg, $Re_L = 0.4 \times 10^6$

c) $\alpha = 40$ deg, $\delta_{BF} = 16.0$ deg, $Re_L = 1.6 \times 10^6$

b) $\alpha = 40$ deg, $\delta_{BF} = 16.0$ deg, $Re_L = 0.8 \times 10^6$

d) $\alpha = 40$ deg, $\delta_{BF} = 16.0$ deg, $Re_L = 3.2 \times 10^6$

Comparison of aerodynamics, air vs. CF_4:



a) Normal force coefficient

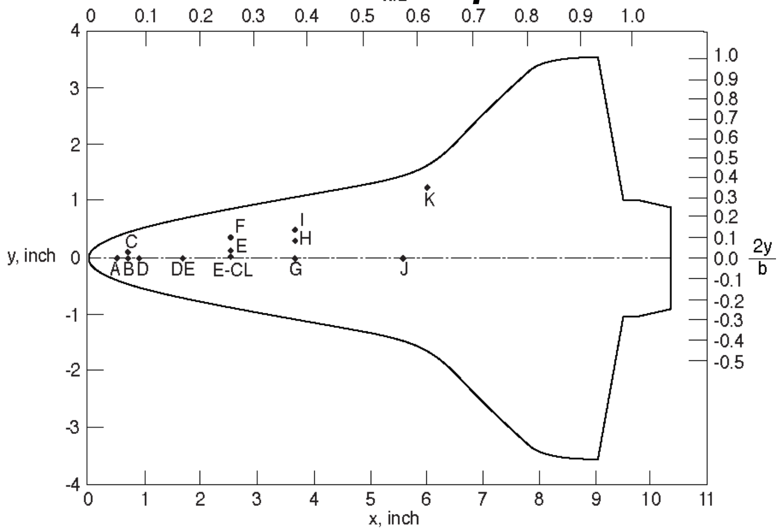
b) Pitching moment coefficient

See Brauckmann, et al., JSR 32.5, 1995, pp. 758-764

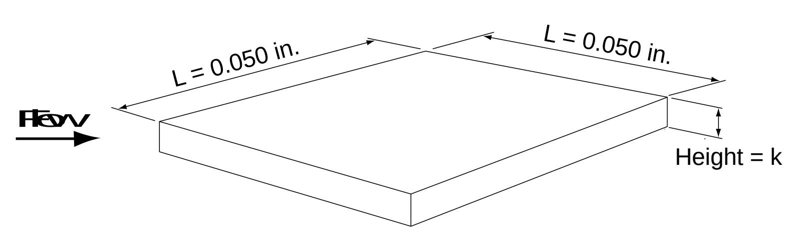
Ground test data and CFD used to resolve/understand anomalous behavior observed in flight – heavy gas pitching moments matched flight

Asymmetric Boundary Layer Transition (1995 – 1996)

Orbiter Windward Trip Locations:

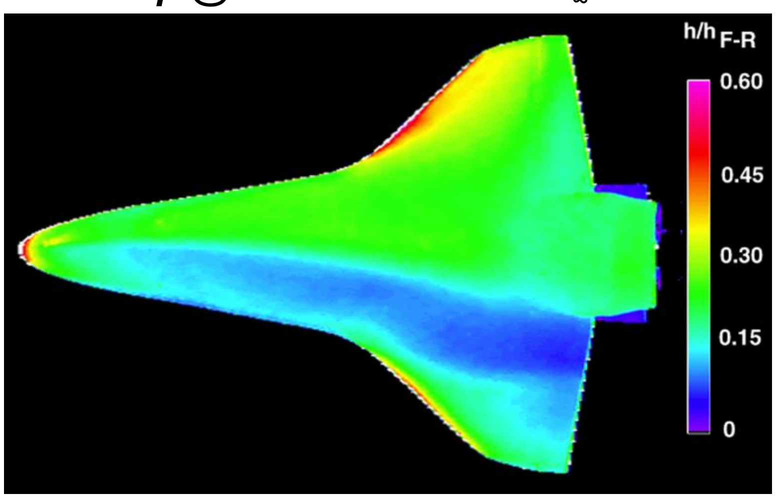


Sketch of Diamond Shaped Trips:

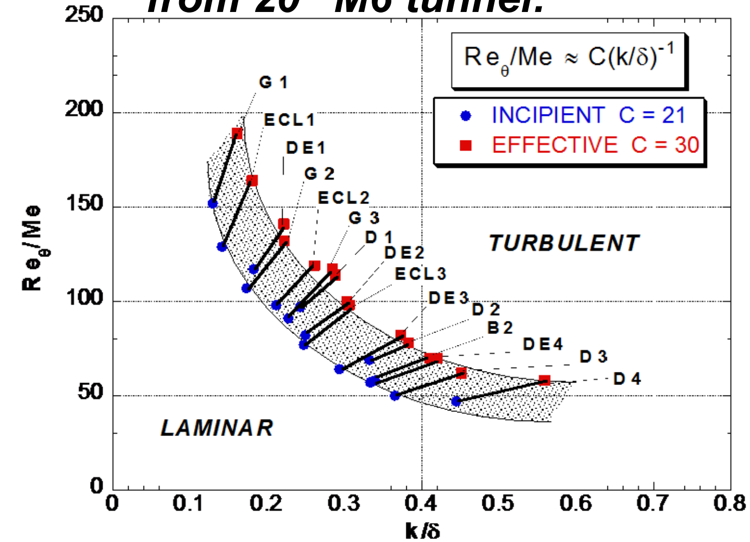


k = 0.0025, 0.0050, 0.0075, 0.0100 in.

0.0075" Trip @ Location C with Re_∞=3.2x10^6/ft:



Centerline Roughness Transition Correlation from 20" M6 tunnel:

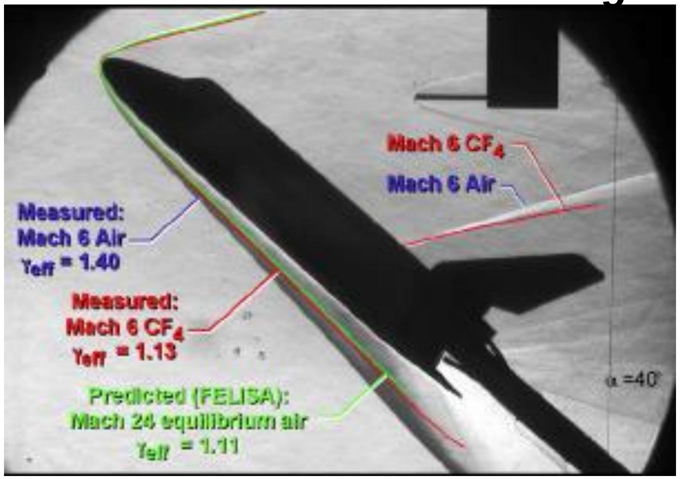


See Berry, et al., JSR 35.3, 1998, pp. 241-248

Ground test data used to understand flight behavior – promising roughness correlation identified

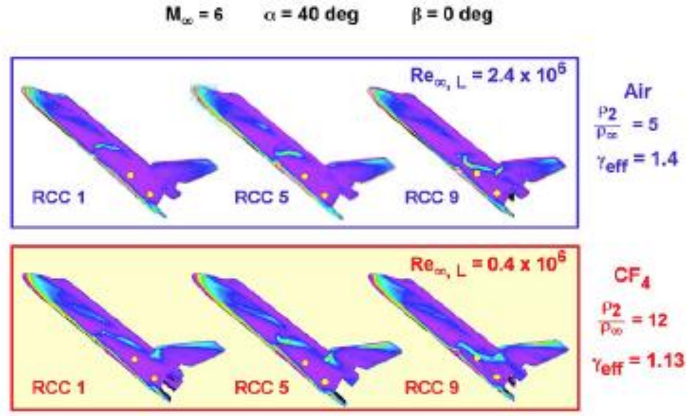
Columbia Accident Investigation (2003 – 2004)

Comparison of Shock Detachment Distance Between Wind Tunnel and Flight:

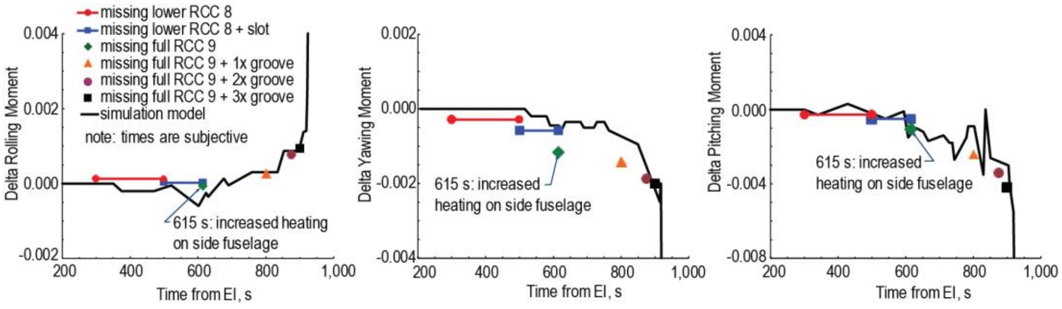


See Horvath, AIAA Paper 2004-2280

Comparison of Fuselage Heating with Different RCC Panels Missing:



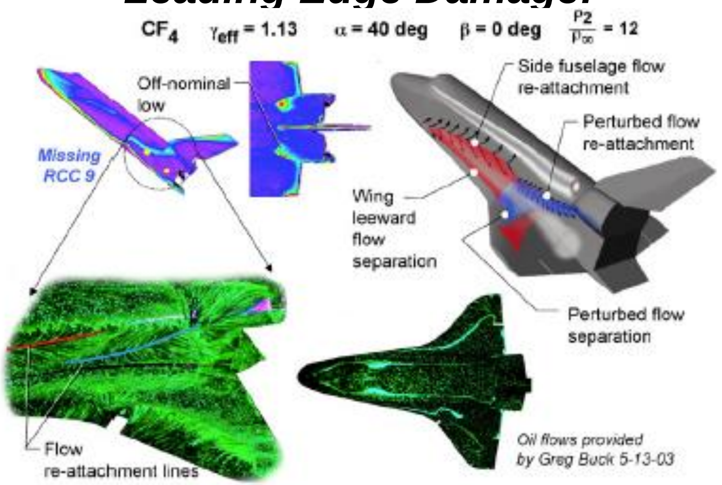
Incremental Moment Coefficients for Progressive Damage Scenarios:



a) Rolling moment b) Yawing moment c) Pitching moment

See Brauckmann & Scallion, AIAA Paper 2004-2280

Postulated Leeside Flow Due to Wing Leading Edge Damage:

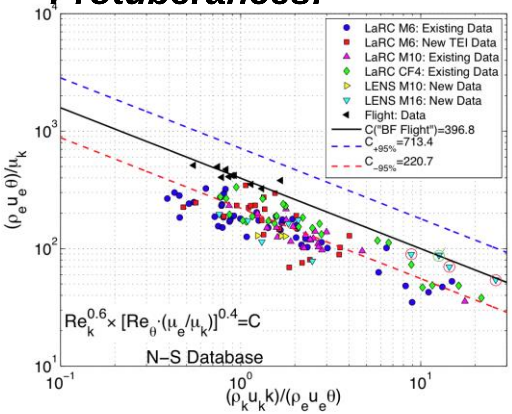


Ground test data instrumental in forensic analysis of Columbia accident – identified plausible damage progression

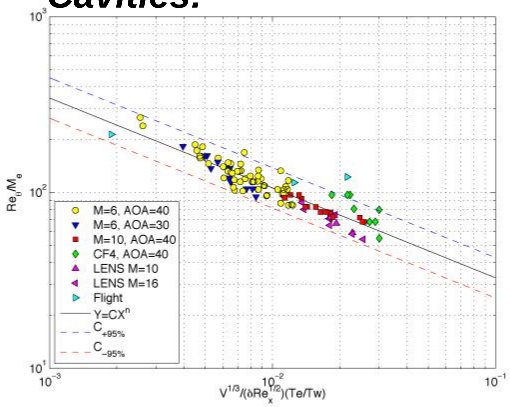
Shuttle Return-to-Flight (2005 – 2010)

BLT Tool V2 Correlations:

Protuberances:

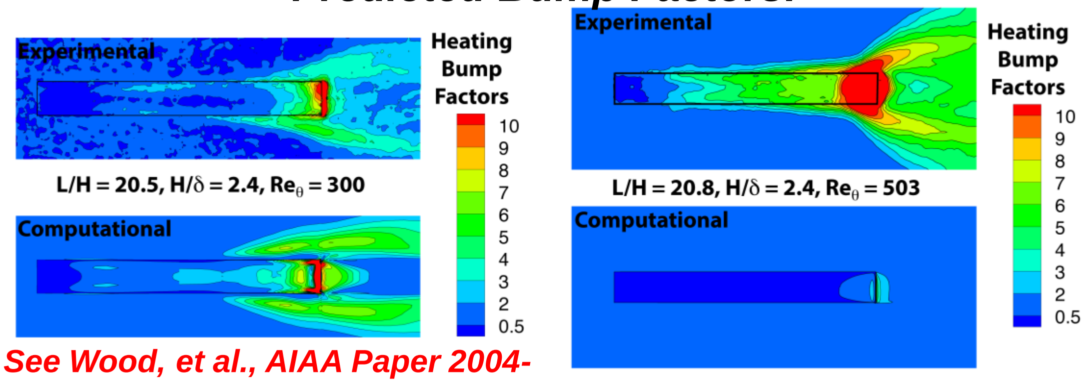


Cavities:



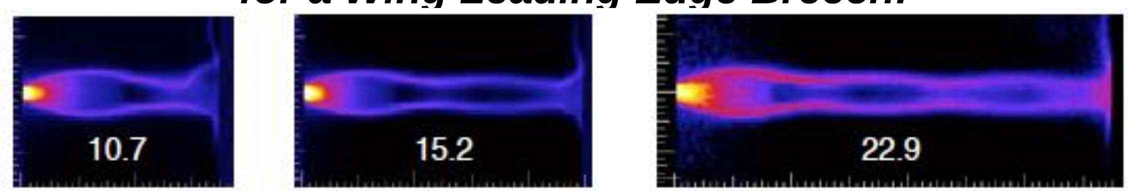
See Berry, et al., AIAA Paper 2010-0246

Comparison of Cavity Heating Measured to Laminar Predicted Bump Factors:

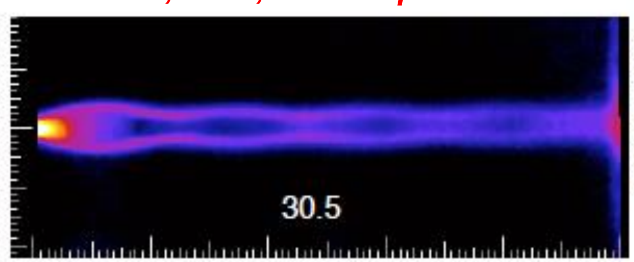


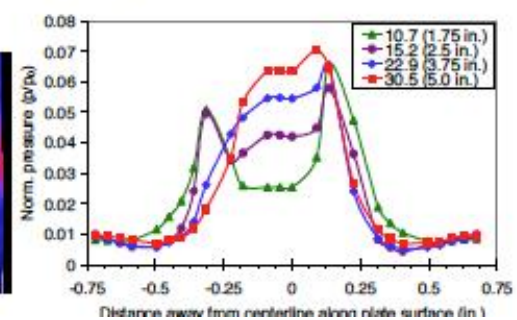
See Wood, et al., AIAA Paper 2004-2639

Effect of Impingement Length on Jet Shock Structure for a Wing Leading Edge Breech:



See Inman, et al., AIAA Paper 2008-619



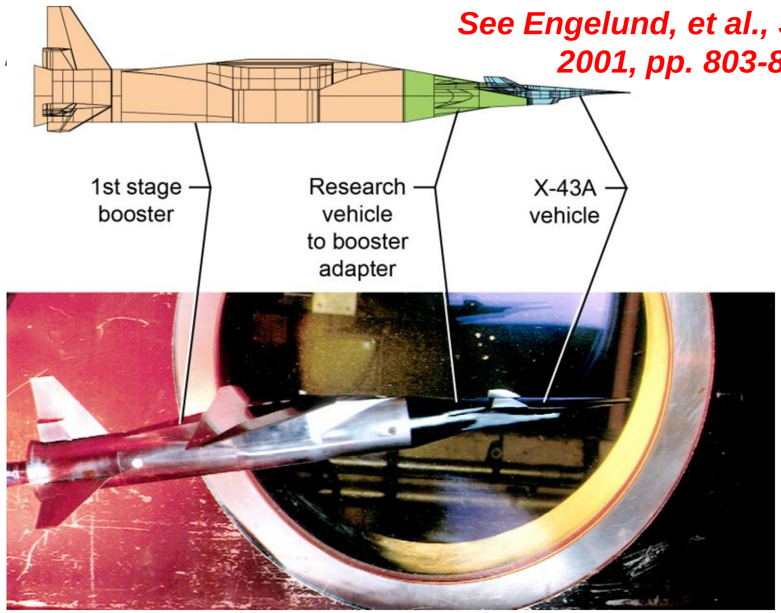


Ground test data and CFD used to support RTF tool development – tools successfully implemented for all subsequent missions

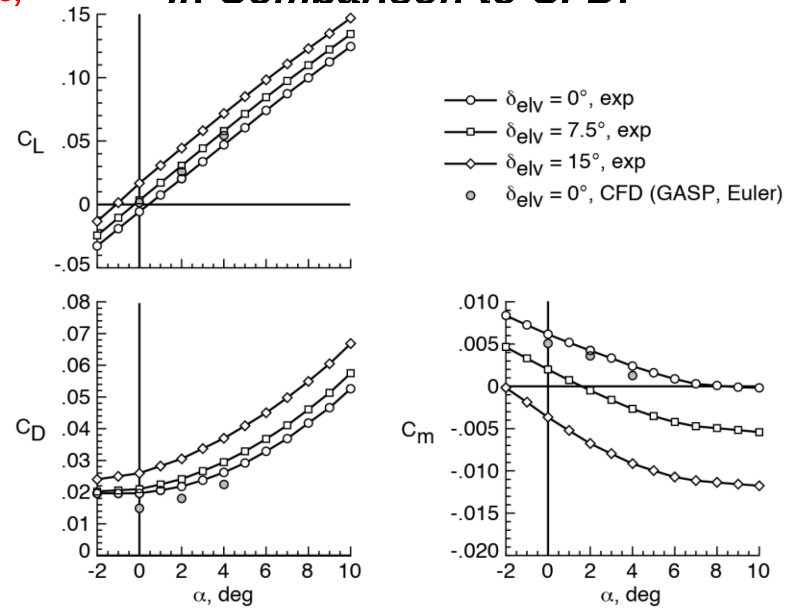
Hyper-X Aero Database (1996 – 2000)

Hyper-X Launch Configuration:

See Engelund, et al., JSR 38.6, 2001, pp. 803-810



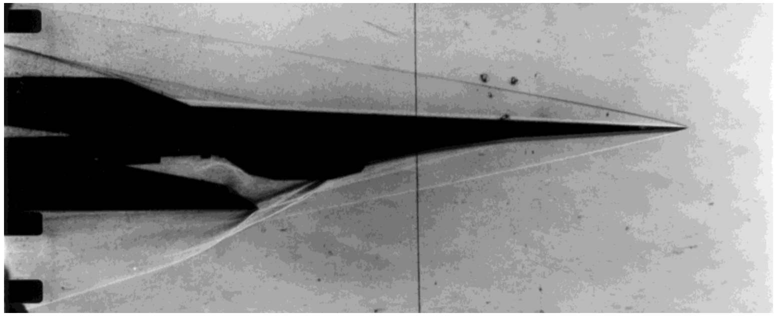
Mach 6 Basic Aerodynamics with Closed Inlet in Comparison to CFD:



Stage Separation Rig for Testing in the 31" Mach 10 Tunnel:

See Woods, et al., JSR 38.6, 2001, pp. 811-819

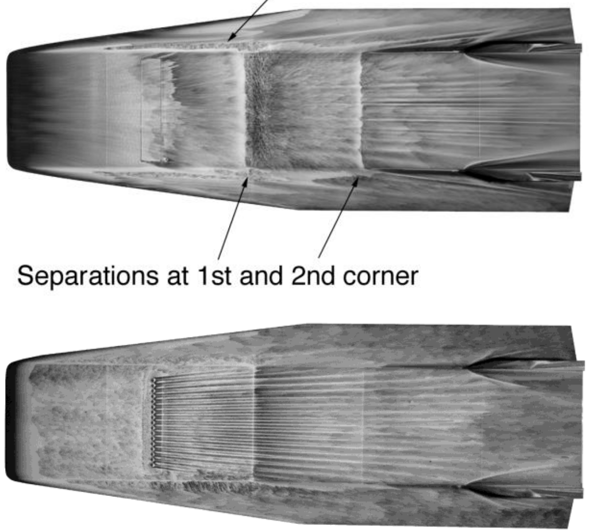
Sample Stage Separation Schlieren from the 20" Mach 6 Tunnel:



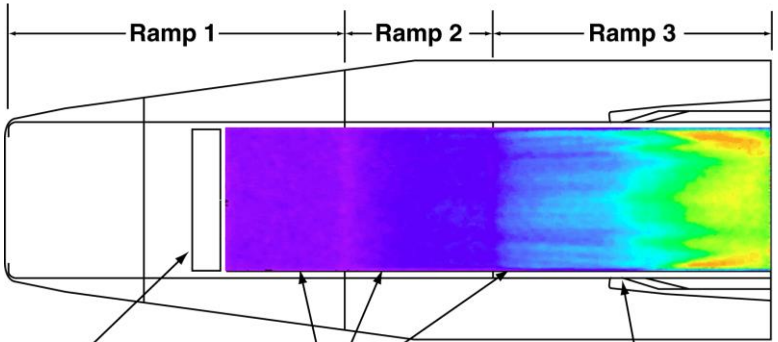
Ground test data and CFD used to derive flight ADB and to understand stage separation effects

Hyper-X Boundary Layer Trips (1997 – 2000)

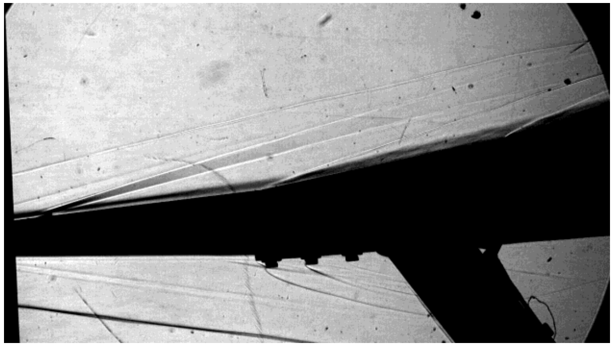
Oil-Flow Test in 20" Mach 6 tunnel:



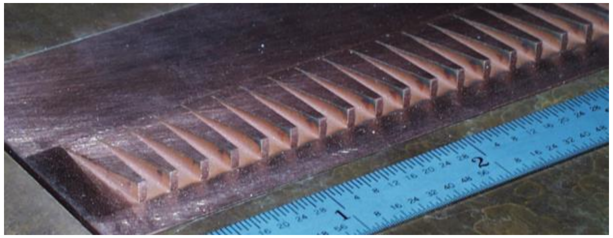
Forebody Heating from 31" Mach 10 tunnel:



Schlieren from GASL Hypulse:



Final Trip Configuration Scaled for Flight:

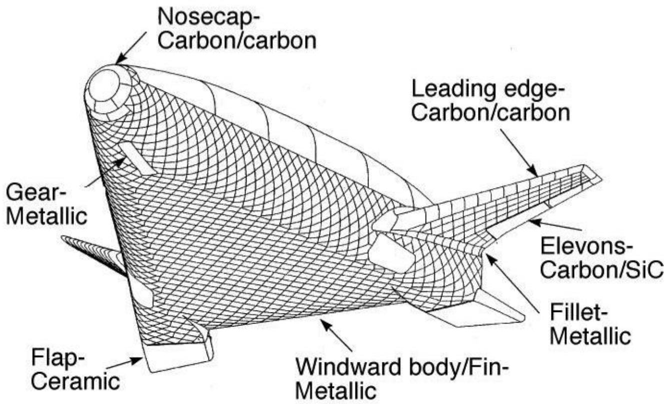


See Berry, et al., JSR 38.6, 2001, pp. 853-864

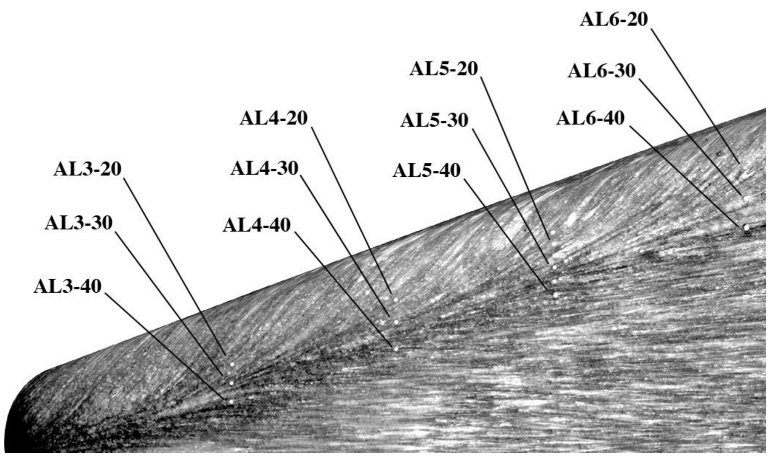
Ground test data used to screen flight trip configurations – engineering analysis used to successfully scale trips for flight

X-33 Boundary Layer Transition (1995 – 2000)

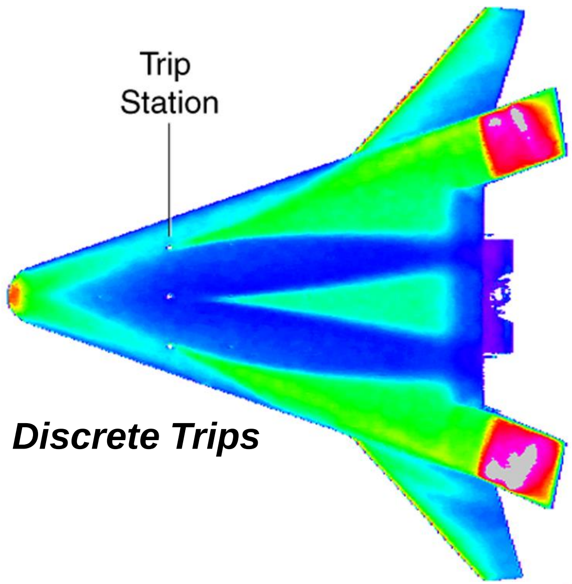
Proposed TPS

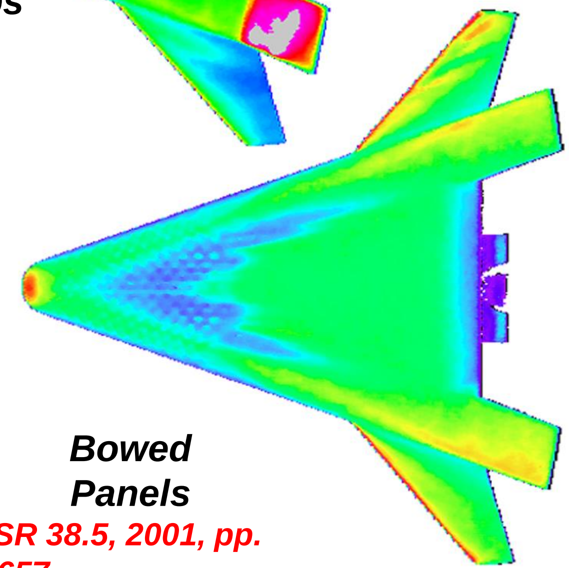


Oil-Flow Test in 20” Mach 6 Tunnel:



Aeroheating from 20” Mach 6 Tunnel:





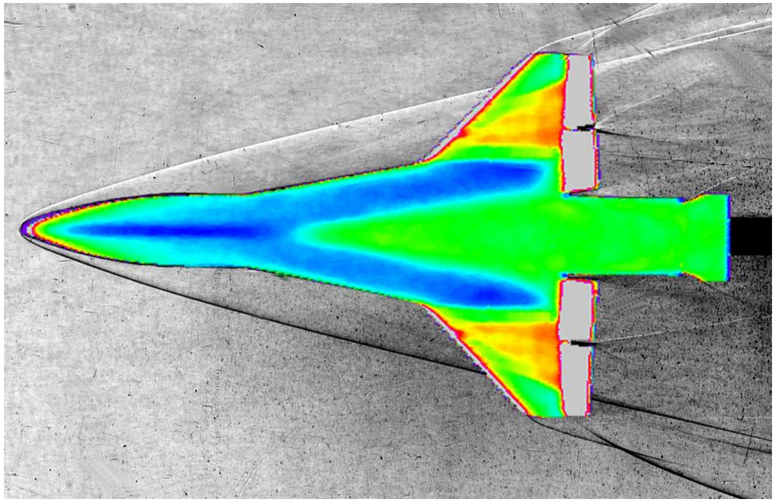
See Berry, et al., JSR 38.5, 2001, pp. 646-657

Ground test data used to study roughness correlations for flight program including wavy wall effects

X-34 Aerothermodynamics (1995 – 2002)

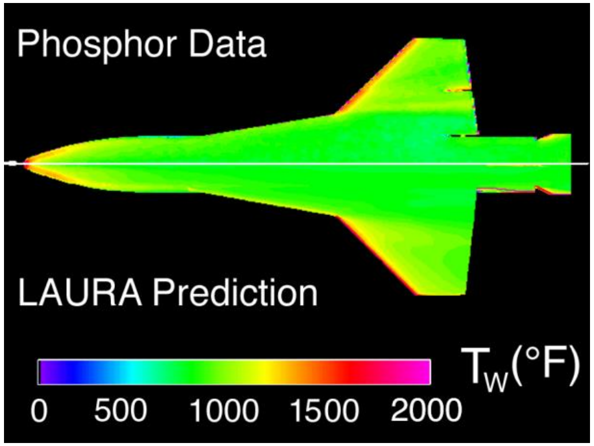
Artist Sketch of X-34 During

Combined Phosphor and Schlieren Image from 20” Mach 6 Tunnel:

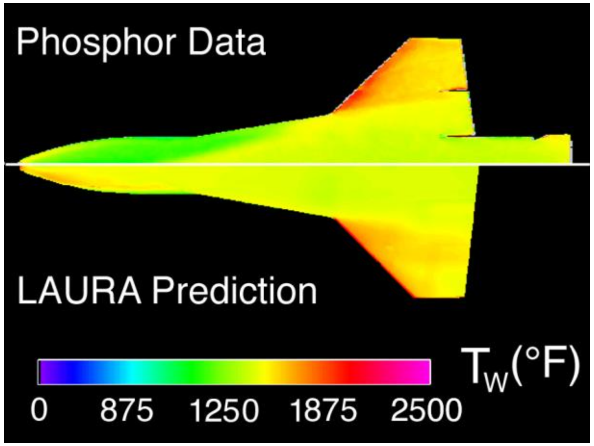


Comparison of Extrapolated Experimental Heating to Predictions:

Laminar



Turbulent



See Berry, et al., JSR 36.2, 1999, pp. 171-178

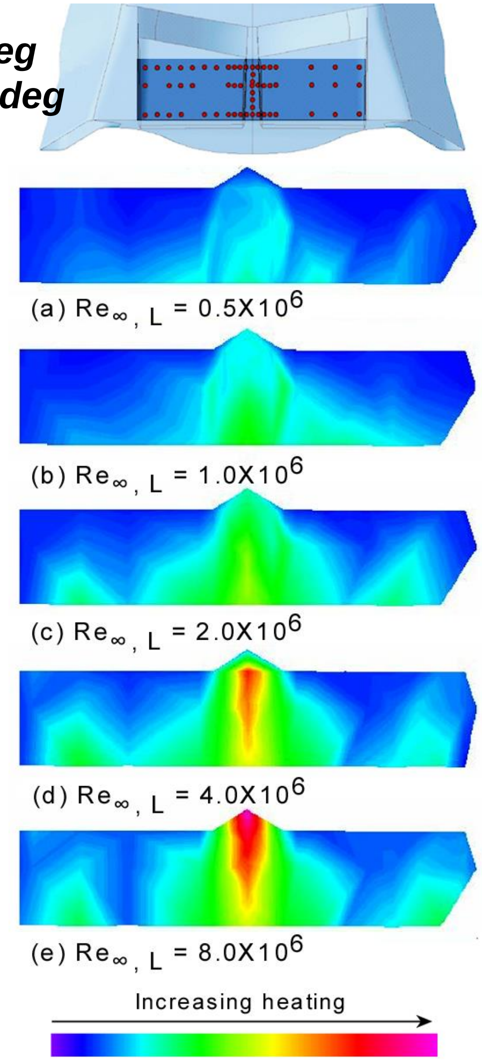
Ground test data used to derive ADB and to predict aeroheating environments for flight

X-38 TPS Environments (1995 – 2001)

Artist Sketch of X-38 as a Lifeboat for ISS:

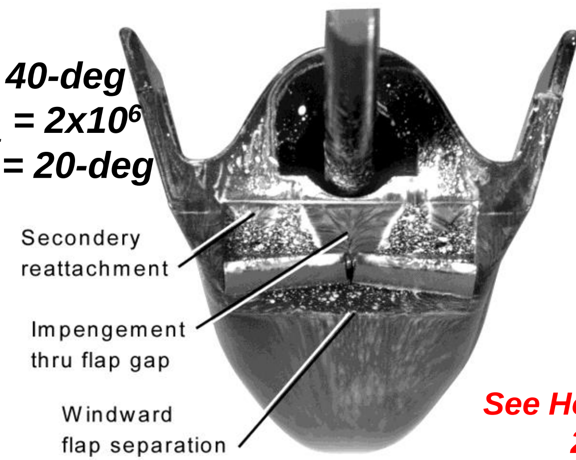
Flap Cavity Heating (Thin-Film Data):

α = 40-deg
δ_{BF} = 25-deg



Surface Streamlines on the Flap Cavity Floor from 20" Mach 6 Tunnel:

α = 40-deg
$Re_L = 2x10^6$
δ_{BF} = 20-deg

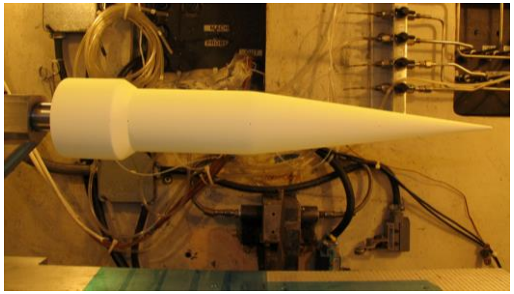


See Horvath, et al., JSR 41.2, 2004, pp. 272-292

Ground test data used for early aerodynamic screening and to derive aeroheating environments, including the BF & cove region

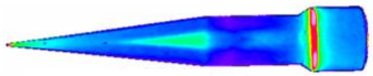
HIFiRE Support (2006 – 2012)

HIFiRE 1 BLT Trip Results:

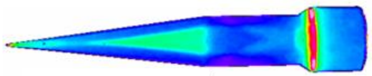


k = 0.000”

k = 0.0045”

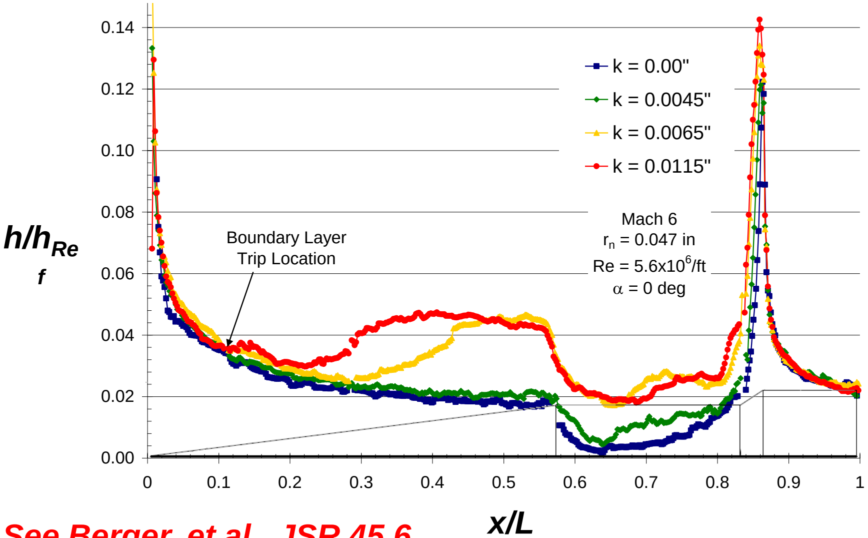


k = 0.0065”



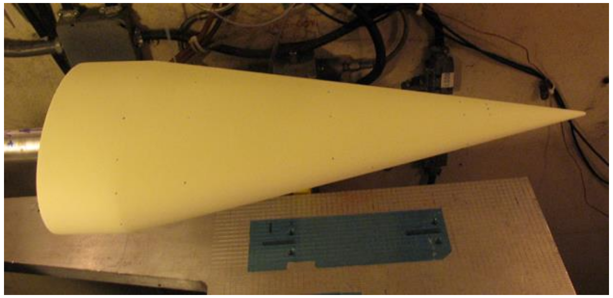
k = 0.0115”

α = 0-deg
Re = 5.6x10^6/ft
r_n = 0.047-in

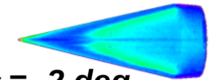


See Berger, et al., JSR 45.6, 2008, pp. 1117-1124

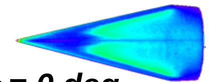
HIFiRE 5 Transition Front w/ AOA:



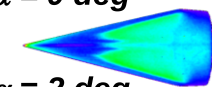
α = -4 deg



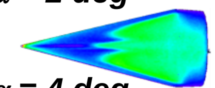
α = -2 deg



α = 0 deg



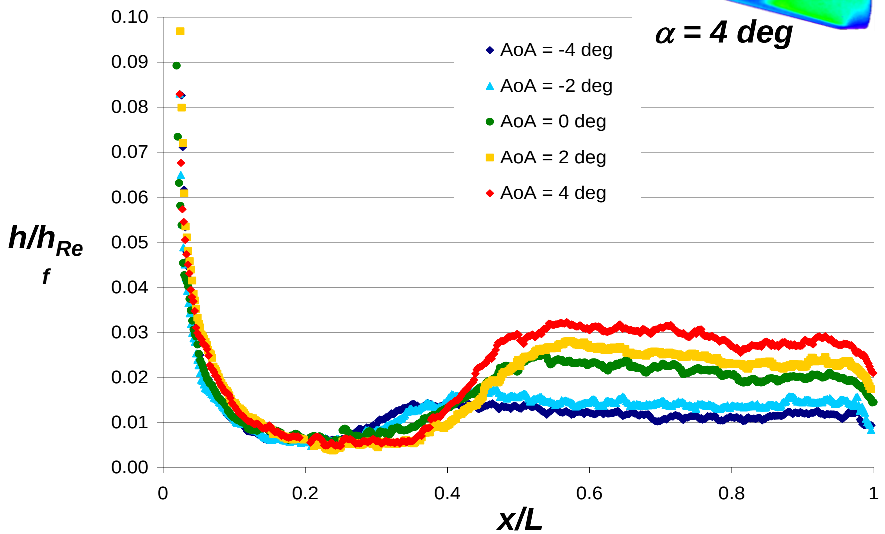
α = 2 deg



α = 4 deg

See Berger, et al., AIAA Paper 2009-4055

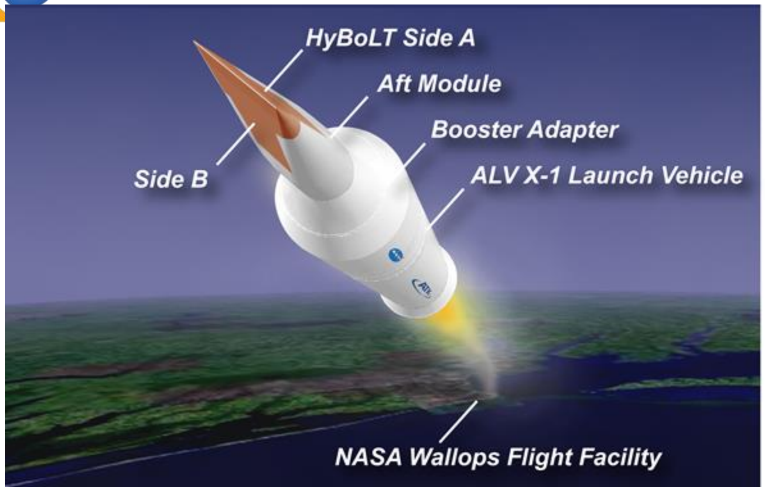
Re = 4.1x10^6/ft

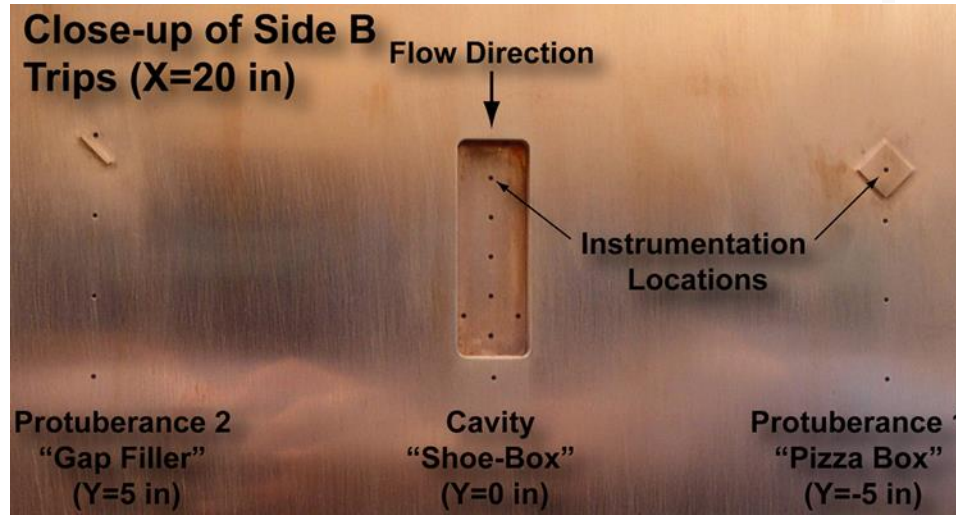


Test Results from 20” Mach 6 Tunnel

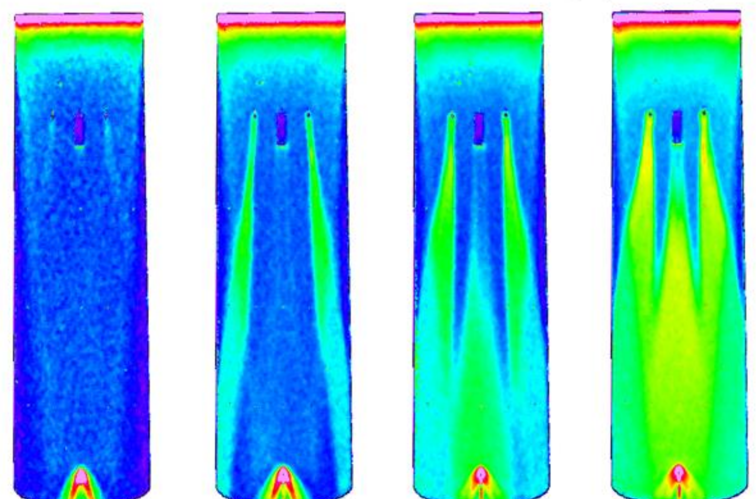
Ground test data used to understand roughness BLT effects and 3D transition front behavior for flight

HyBoLT Support (2006 – 2008)

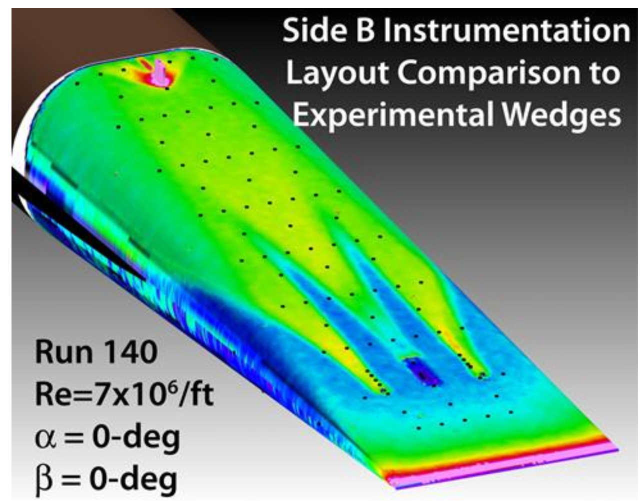




20-In Mach 6 Air Tunnel T6940 α=0-deg β=0-deg



Re=2.1x10^6/ft Re=4.2x10^6/ft Re=5.6x10^6/ft Re=7.2x10^6/ft



See Berry, et al., AIAA Paper 2008-4026

Test Results from 20" Mach 6 Tunnel

Ground test data used to derive roughness experiment for flight and to verify instrumentation coverage

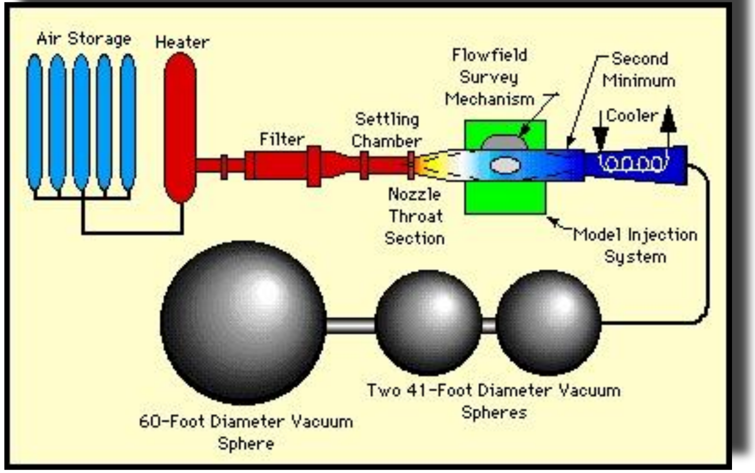
Where to Test?

Types of Facilities

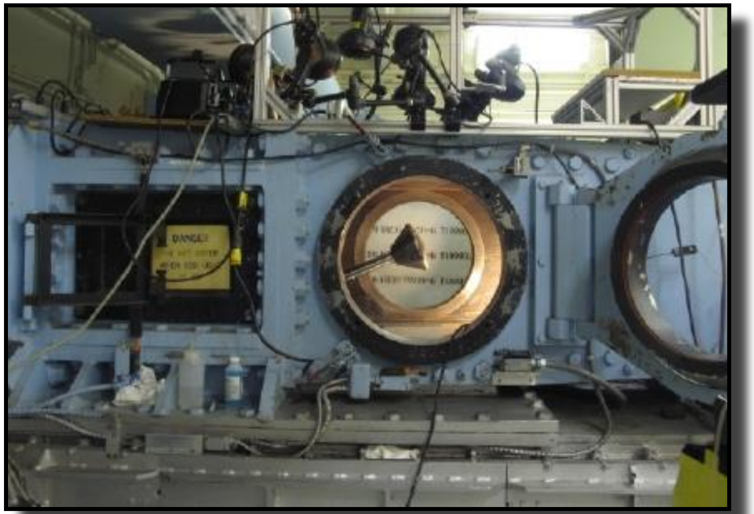
Hypersonic Facilities in US

Hypersonic Experimental Facilities: Blow-Down Wind Tunnels

Schematic of NASA LaRC 31-Inch Mach 10 Air Tunnel



CEV Model in NASA LaRC 20-Inch Mach 6 Air Tunnel

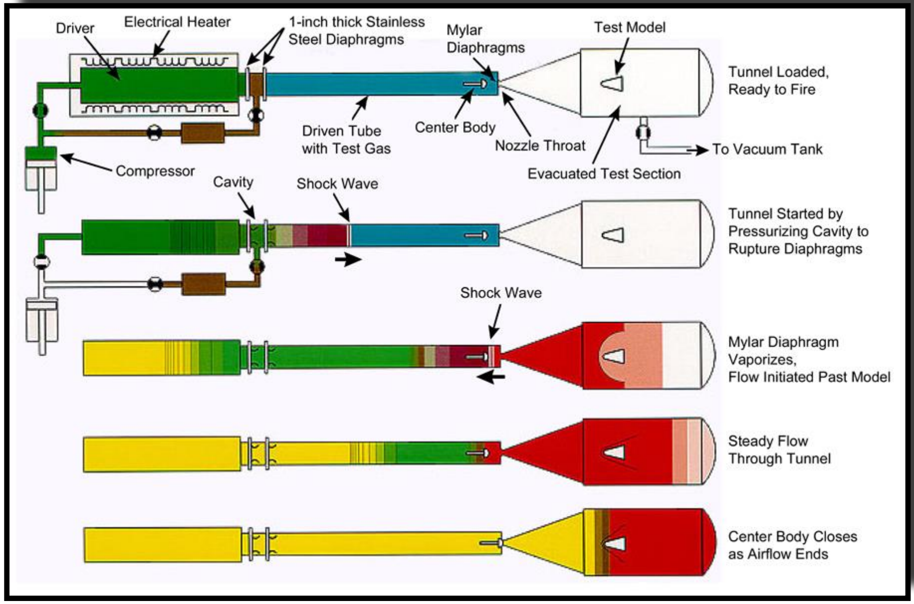


- Usage: aerothermodynamic testing of hypersonic vehicles
- Operation: test conditions are generated by a expansion of test gas through a converging-diverging nozzle
  - aerodynamic force & moment measurements
  - surface pressure and heat-transfer measurements
  - flow-field diagnostics
- Operators: AEDC, NASA LaRC, Sandia

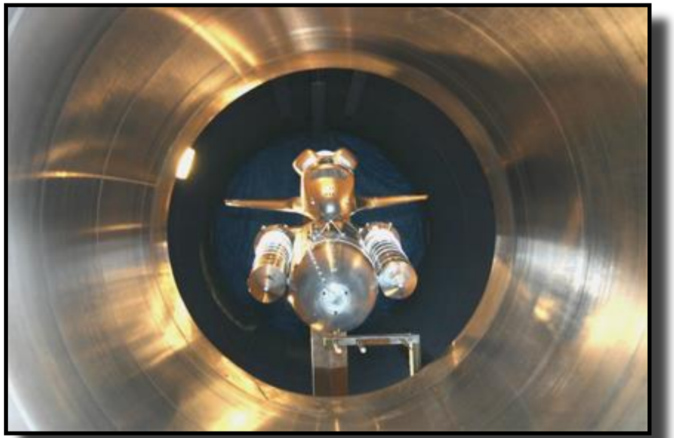
Hypersonic Experimental Facility Types: Shock Tunnels

- Usage: aerothermodynamic testing of hypersonic vehicles at flight-like conditions
- Operation: test conditions are generated by a traveling shock wave that is produced from the rupture of a diaphragm that separates high- and low-pressure gasses
  - aerodynamic force & moment measurements
  - surface pressure and heat-transfer measurements
  - flow-field diagnostics
- Operators: CUBRC, GASL, CalTech

Schematic of CUBRC LENS Operation



Shuttle Model in CUBRC LENS



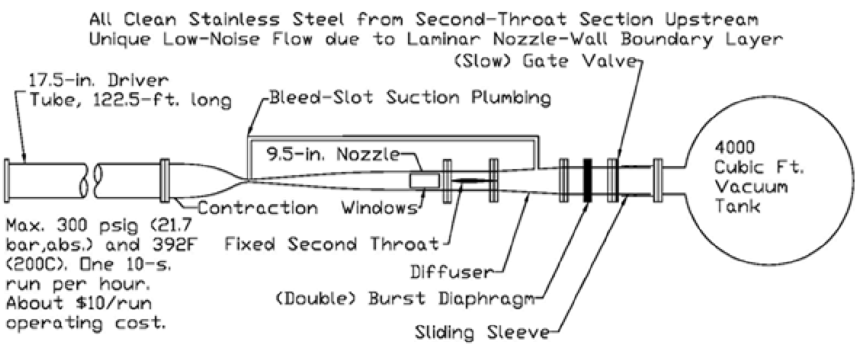
Hypersonic Experimental Facility Types: Quiet Tunnels

- Usage: Quiet tunnels allow for a flight-like noise level in a ground testing environment. This can be important in the study of boundary layer transition characteristics of a configuration.

- Operation: Ludwieg tube or blow down configurations
  - flight-like low-noise conditions are obtained by using highly polished nozzle and bleed-slot suction
  - Noise levels on the order of 0.05% (conventional facilities are ~0.5-3%)
  - Limited size, Reynolds number range and Mach number

- Operators: Purdue University, Texas A&M University (originally NASA's)

Purdue University Mach 6 Quiet Tunnel

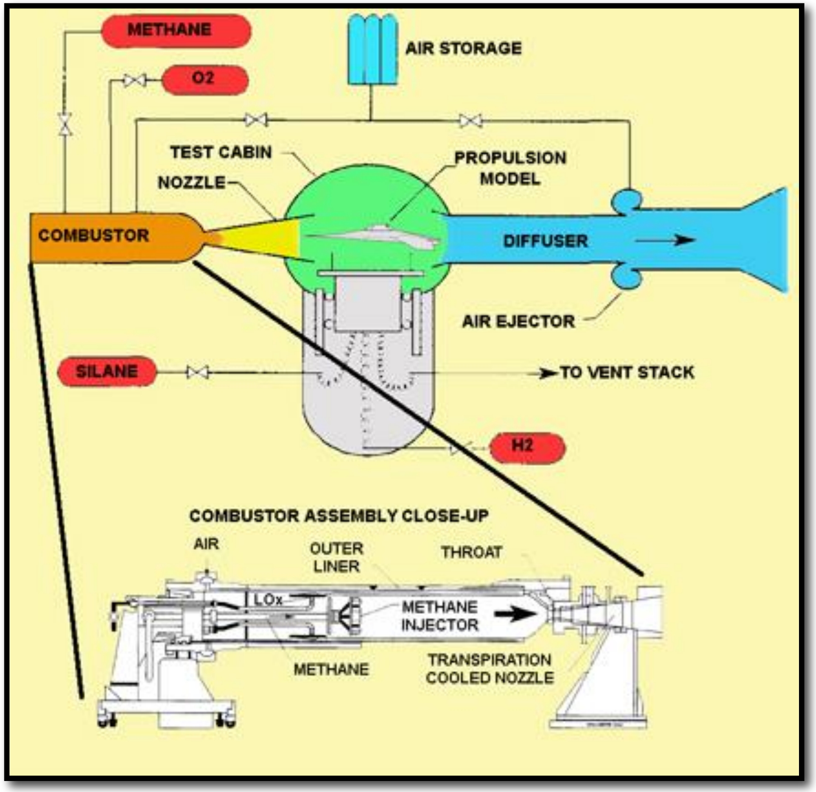


Schematic of Boeing Mach-6 Quiet-Flow Ludwieg Tube

Hypersonic Experimental Facility Types: Propulsion Tunnels

- Usage: testing of air-breathing propulsion system performance at flight-like conditions
- Operation: high-enthalpy test conditions produced addition of combustion-heated gases or by electric arc discharge
- Operators: NASA LaRC, NASA Glenn

Schematic of NASA LaRC 8-ft High Temperature Tunnel

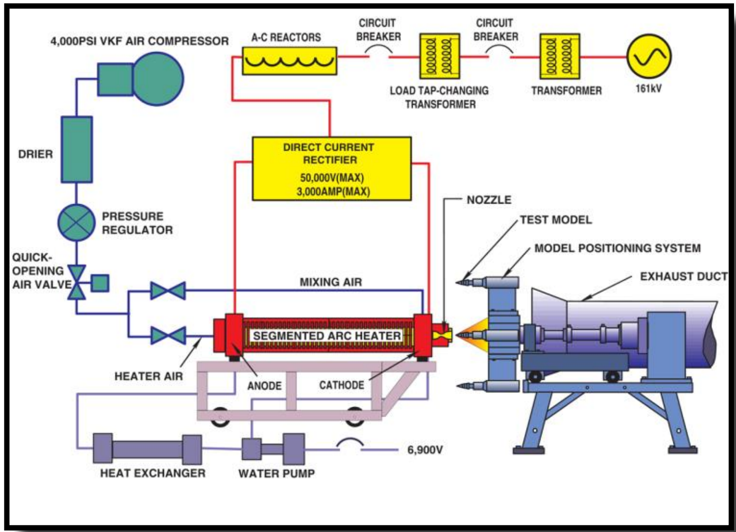


Scramjet testing in NASA LaRC 8-ft HTT

Hypersonic Experimental Facility Types: Arc Jets

- Usage: evaluation of thermal response (heating, ablation, recession) of heat-shield TPS materials
- Operation: High-enthalpy, flight-like conditions generated by passing an electric arc through the test gas
  - temperature & heat-flux sensors embedded in material samples
  - post-test measurements of ablation recession and surface roughness
- Operators: AEDC, NASA ARC, NASA LaRC

Schematic of AEDC H-3 arcjet



NASA Ames IHF

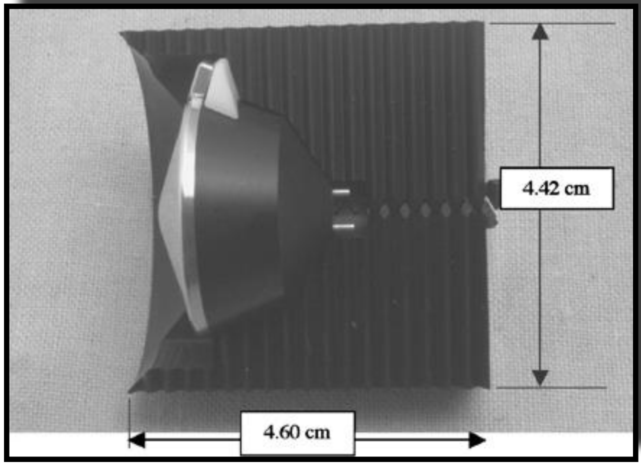
TPS material exposed to arc-jet flow

TPS material before and after arc-jet testing

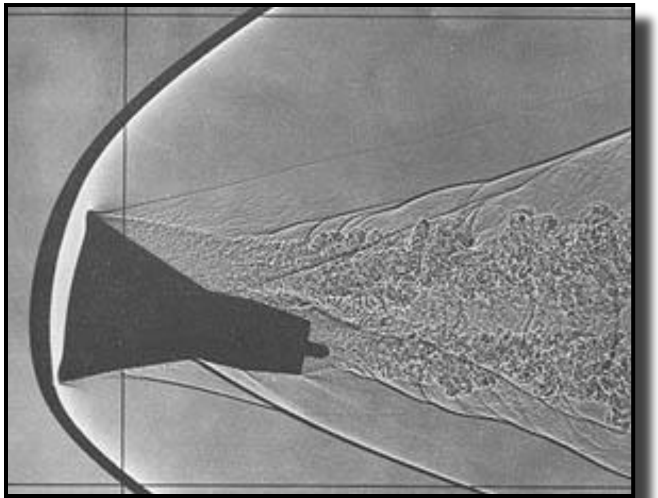
Hypersonic Experimental Facility Types: Ballistic Ranges

- Usage: determination of aerodynamic performance (especially unsteady dynamics) and impact dynamics
- Operation: Models are gun-launched into free flight along the length of a ballistic range
  - high-speed video record of flight path and shock structure for reconstruction of trajectory and aerodynamics
  - onboard instrumentation
- Operators: NASA Ames, US Army (Aberdeen), US Air Force (Eglin, AEDC)

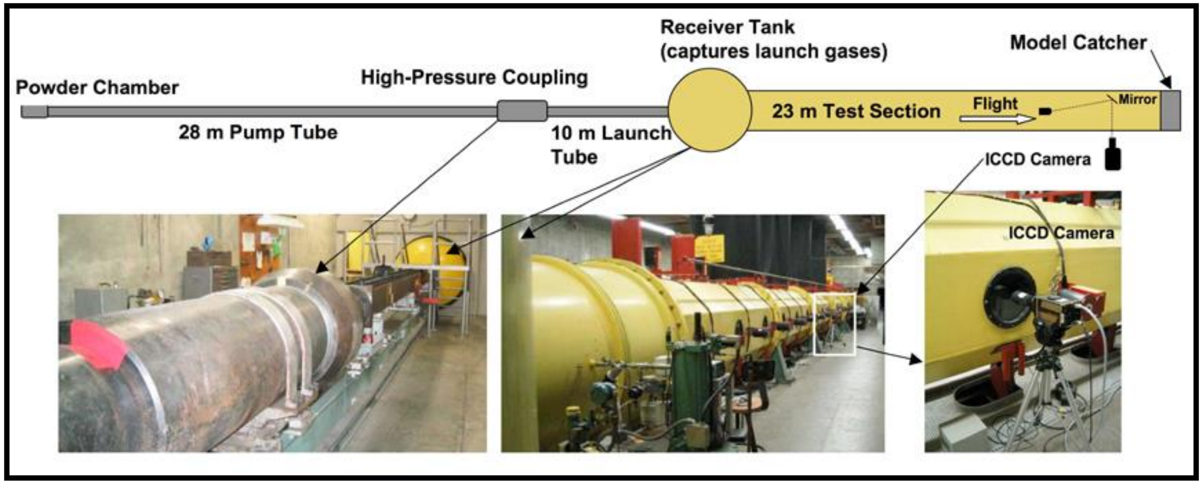
Mars Entry Vehicle model in launch sabot



Shadowgraph of Mercury model in ballistic range



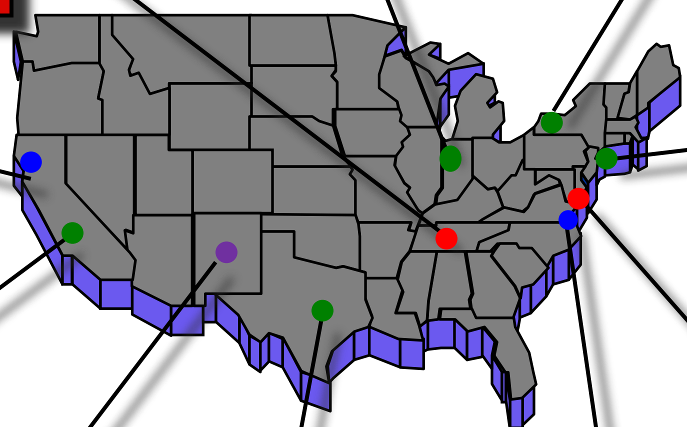
Schematic of NASA Ames HFAFF Ballistic Range



Hypersonic Facilities in US

Hypersonic Facilities & Operators in the U.S.

- NASA Centers with Aerothermodynamic Ground Test or Flight Test Capabilities
- AEDC Aerothermodynamic Facilities
- Other Government Facilities
- Non-governmental organizations with Aerothermodynamic capabilities



Arnold Engineering and Development Center (AEDC) VKF Tunnels B, C and Arc-jets

Purdue University: Boeing/AFOSR Mach 6 Quiet Tunnel

CUBRC: LENS I, II, and X Shock Tunnels

Ames Research Center: Arc-jets, Ballistic Range

GASL: HYPULSE Shock Tunnel

AEDC: Hypervelocity Tunnel 9

Cal-Tech: T5 Shock Tunnel

Sandia: Hypersonic Wind Tunnel

Texas A&M: Mach 6 Quiet Tunnel

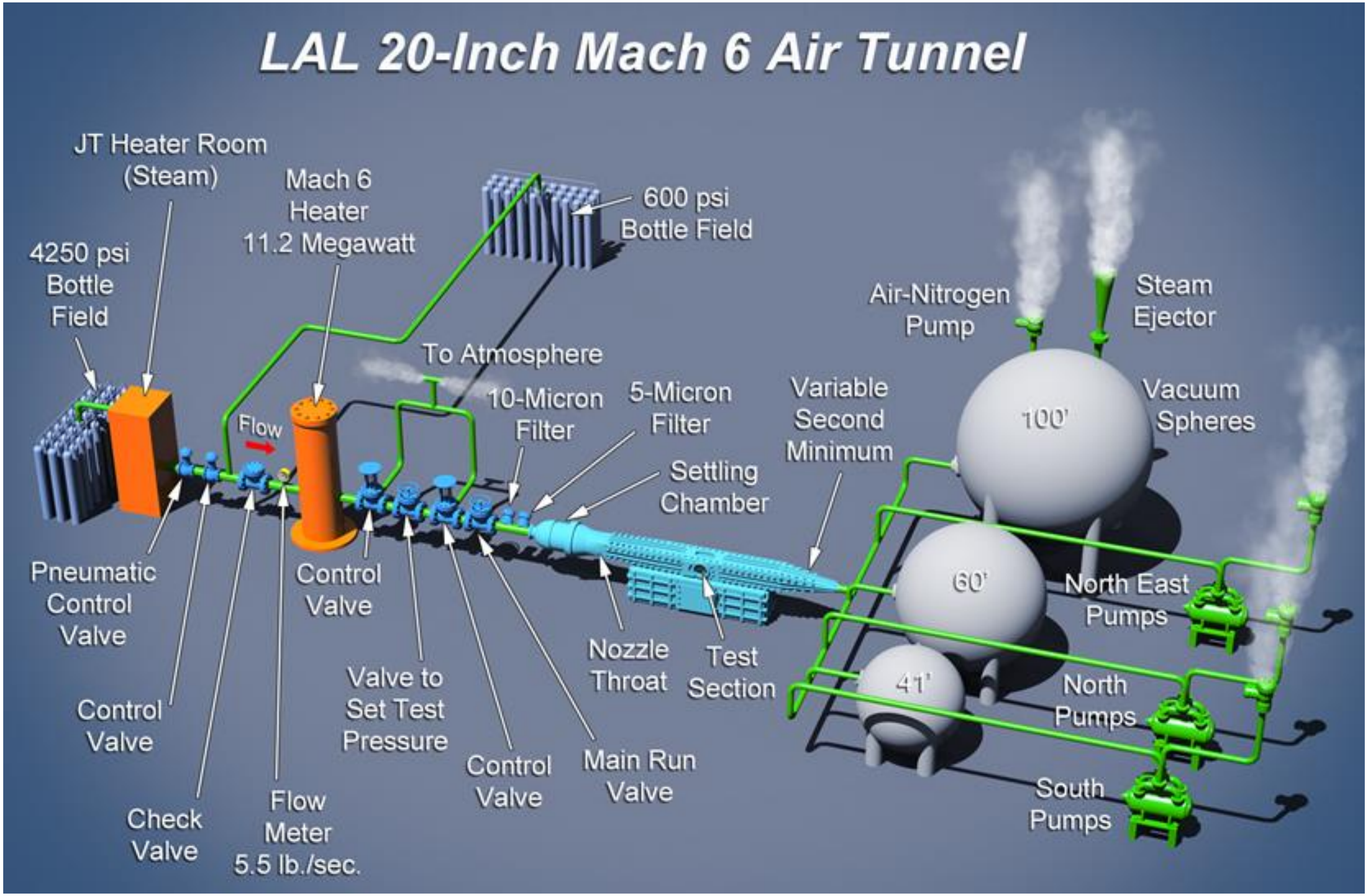
Langley Research Center: 31-Inch Mach 10, 20-Inch Mach 6, 15-Inch High Temperature Tunnels; 8-FT High Temperature Tunnel, Scramjet Test Complex

NASA LaRC Aerothermodynamic Laboratory

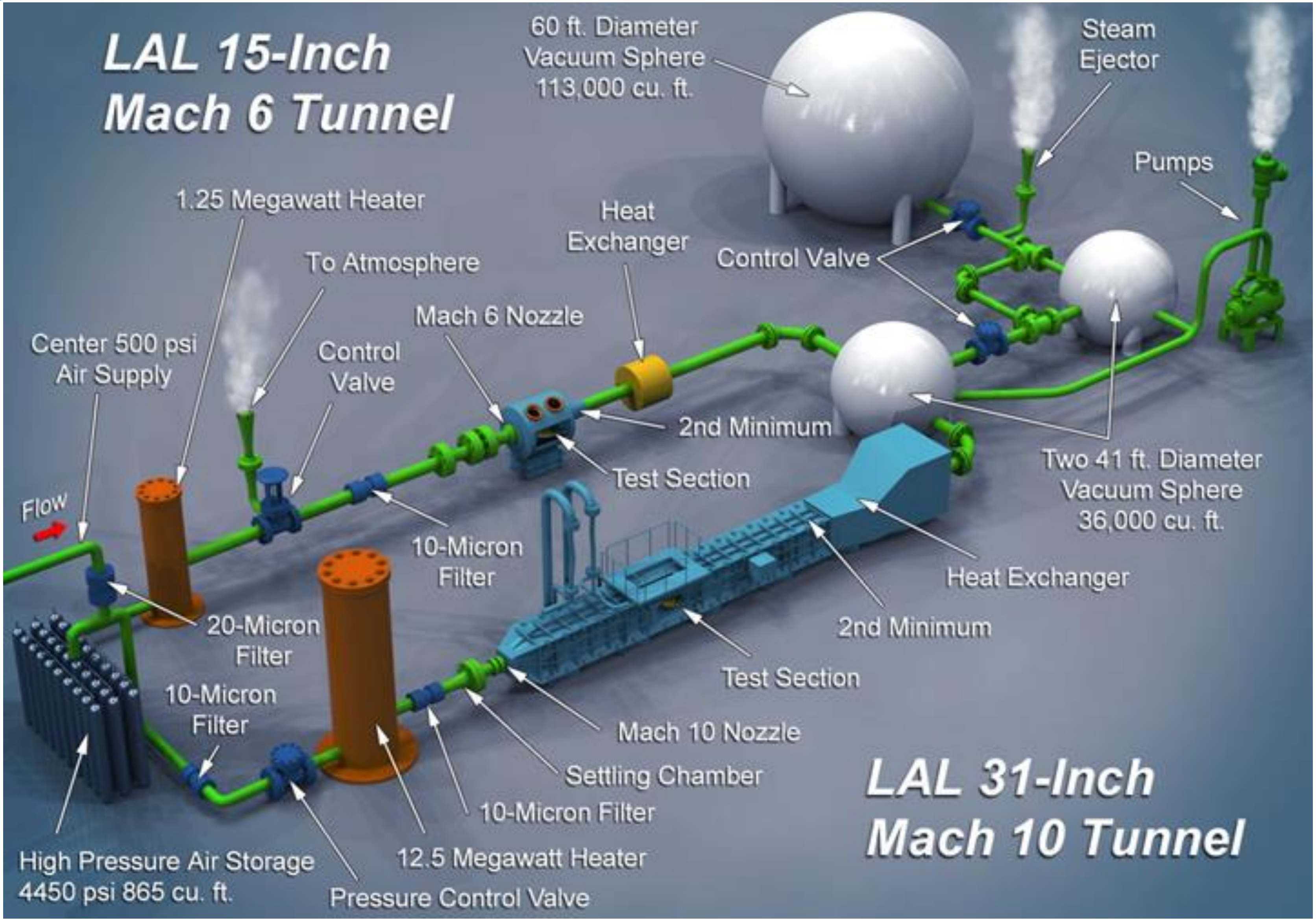
- Background:
  - LAL operates three hypersonic wind tunnels
  - Facilities developed in the 1960's, upgraded throughout the 1980's-now
- Operation:
  - Conventional blow-down tunnels
  - Perfect-gas air
  - High flow quality, low-enthalpy test conditions
- Merits:
  - Rapid operational turn-around time (4-12 runs/day) for flexibility in test-planning
  - Capability for parametric screening, fundamental flow phenomena investigations
  - Global aeroheating measurements using Langley two-color phosphor thermography method
- Utilization:
  - All historical NASA programs: Apollo, Shuttle, X-33, X-34, X-38, Viking, etc.
  - Currently involved in MSL, Commercial Crew, DoD

	31-Inch Mach 10	20-Inch Mach 6	15-In Mach 6 High Temperature
Unit Reynolds Number	0.25 - 2.0x10^6/ft	0.5 - 8.3x10^6/ft	0.5 - 8.0x10^6/ft
Pressure (psi)	150 - 1450	30 - 475	100 - 550
Temperature (ºF)	1300 - 1320	410 - 475	400 – 810
Angle of Attack (deg)	±45	-5 to +55	-10 to +50
Yaw Angle (deg)	±5	±8	±10
Run Time	2 min	20 min	90 sec
Runs per Day	5 – 8	8 – 12	4 – 8
Test Section	Closed Jet	Closed Jet	Open Jet
Tunnel Core Size	14 x 14 in	14 x 14 in	9 x 14 in

20-Inch Mach 6 Air Tunnel



31-Inch Mach 10 and 15-Inch Mach 6 High Temperature Air Tunnels



AEDC VKF Tunnels B & C and Tunnel 9

- Background:
  - U.S. Air Force capabilities maintained by Arnold Engineering Development Center (AEDC)
  - Von Karman Facility hypersonic tunnels B & C at Tullahoma, TN (developed in late 1950's)
  - Hypervelocity Tunnel #9 at White Oak, MD (developed in 1970's)
- Operation:
  - VKF B & C are continuous flow, perfect-gas air tunnels
  - Tunnel #9 is a blow-down tunnel, perfect-gas N2
- Merits:
  - Wide range of Reynolds numbers, large test core size
  - Continuous operation in VKF B & C is ideal for rapid generation of large databases
  - Tunnel 9 has large Reynolds number range capable of simulating vehicle performance at flight-like conditions.
- Utilization:
  - AEDC facilities mainly focused on DoD activities: missiles, interceptors, strike/cruise vehicles
  - Also utilized for Apollo, Shuttle, MSL and Orion programs

AEDC Hypervelocity Tunnel #9

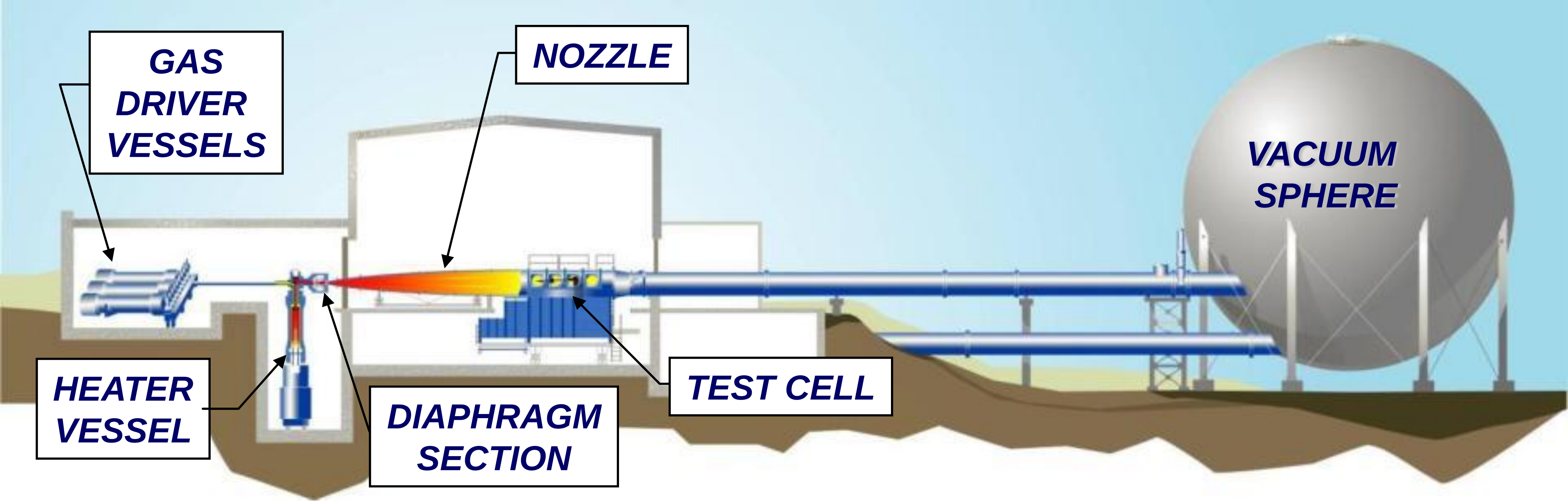
AEDC VKF Tunnels B & C

Facility	Test Section	Mach No.	Reynolds No., mil/ft	Pressure Altitude, kft
A	40 x 40 in	1.5 – 5.75	0.3 - 8.5	17 - 152
B	**50 in diam.**	**6, 8**	**0.4 – 5.2**	**100 - 162**
C	**50 in diam.***	**10**	**0.3 – 3.0**	**130 - 180**

AEDC Tunnel 9

- Blowdown hypersonic wind tunnel
- Mach numbers: 7, 8, 10 & 14
- *Re/L* range: 0.050 to 48×10^6 /ft
- Max P0 ~ 20,000 psia, Max T0 ~ 3,000 °F

- ***Large test cell: 5-foot Diameter***
- ***Run times: 0.2 – 15 sec***
- ***Dynamic pitch capability: 50 deg pitch sweep @ 80 deg/sec***
- ***Natural BL Transition (untripped)***



CUBRC LENS I, II, and X Shock Tunnels

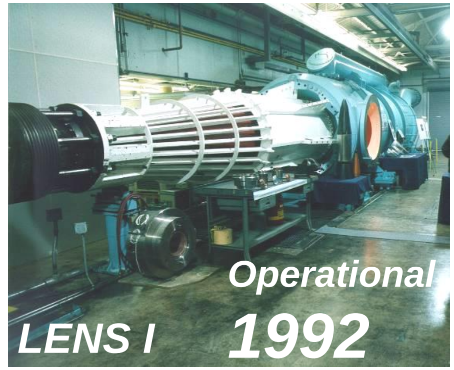
- **Background:**
  - –Operated by Calspan and University of Buffalo (CUBRC)
  - –developed in 1990's, mainly to support DoD programs
- **Operation:**
  - –LENS I & II are reflected shock tunnels
  - –LENS X is a shock-expansion tunnel
- **Merits:**
  - –Wide range of Reynolds numbers and high-enthalpy capability allows for simulation at flight-like conditions
  - –Can utilize arbitrary test-gas for simulation of other atmospheres
  - –Extensive aero-optic capabilities
- **Utilization:**
  - –CUBRC facilities mainly focused on DoD activities: missiles, interceptors, strike/cruise vehicles
  - –Also used by programs including Shuttle and Orion programs

CUBRC LENS I & II

CUBRC LENS Hypervelocity Shock and Expansion Tunnels

Operational
1958

Mach 6 to 20 (Low Reynolds Number)

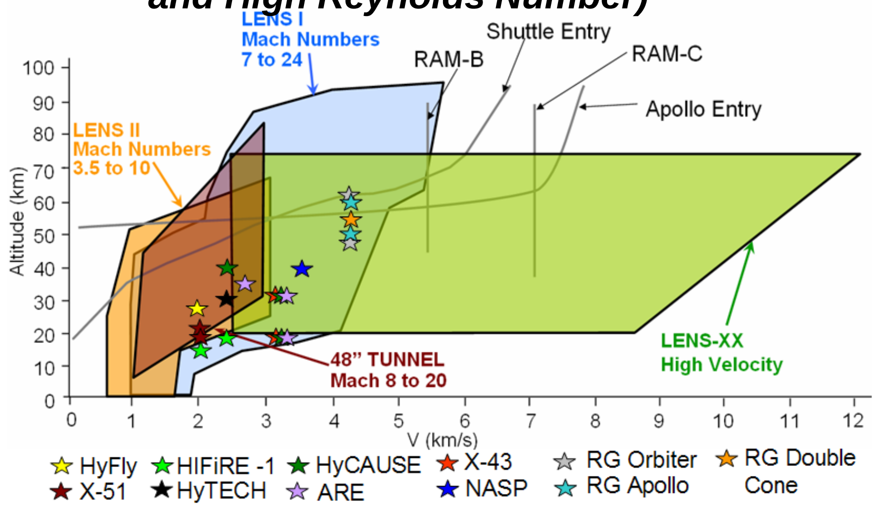


Mach 6 to 20 (High Altitude and High Reynolds Number)

Mach 3 to 10 (High Reynolds Number)

Operational
1998

Mach 2 to 4 (Ludweig Tunnel)



Operational 2015

Expansion Tunnels

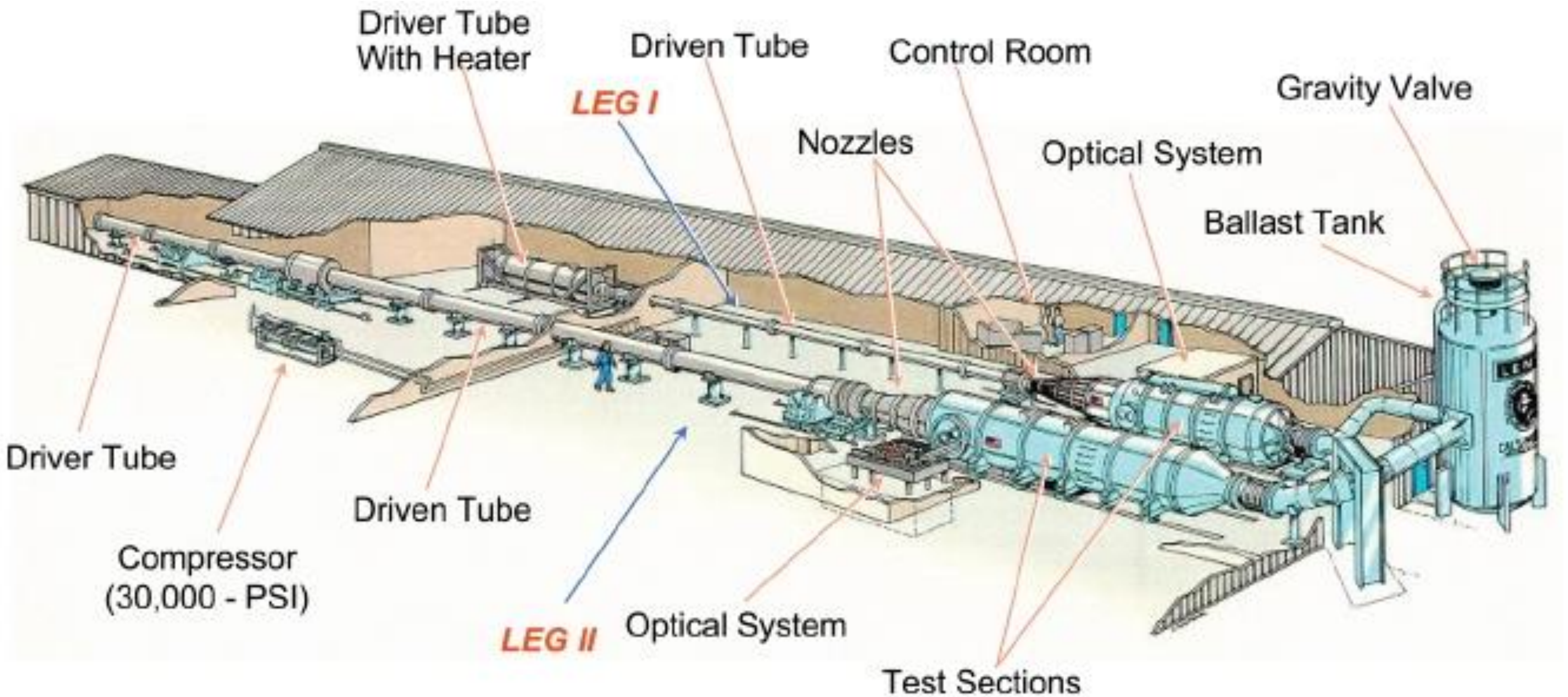
Operational
2004

Velocity 4,000 ft/s to 22,000 ft/s

Operational
2008

Velocity 4,000 ft/s to 30,000 ft/s

CUBRC LENS I and II Tunnels

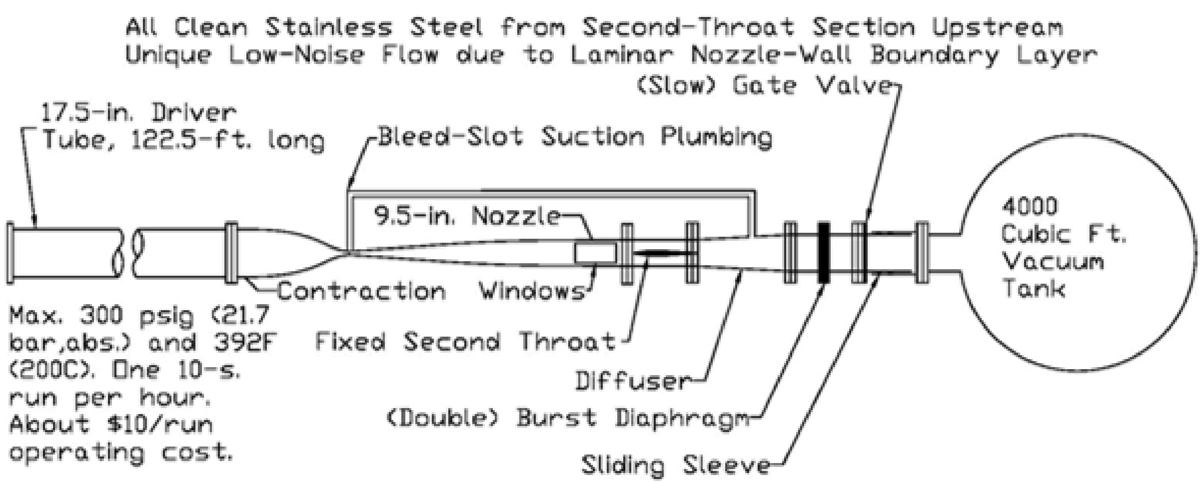


LENS Leg I – full duplication from Mach 7 to 14 for missiles and test articles up to 2-ft diameter and 12-ft long

LENS Leg II – full duplication from Mach 2.5 to 7 from sea level to 30 km for missiles up to 2-ft diameter and 8-ft long

Purdue Mach 6 Quiet Tunnel

- **Background:**
  - –Operated by Purdue University
  - –Built 1995-2001 with funding from Boeing and Air Force Office of Scientific Research
- **Operation:**
  - –9.5-inch exit diameter Ludwieg tube, maximum quiet Reynolds number of ~$3.5x10^6$/ft
  - –Runs for about 10-sec., about once an hour
- **Merits:**
  - –Designed to achieve laminar nozzle-wall boundary layers for study of laminar-turbulent transition processes under low-noise conditions comparable to flight

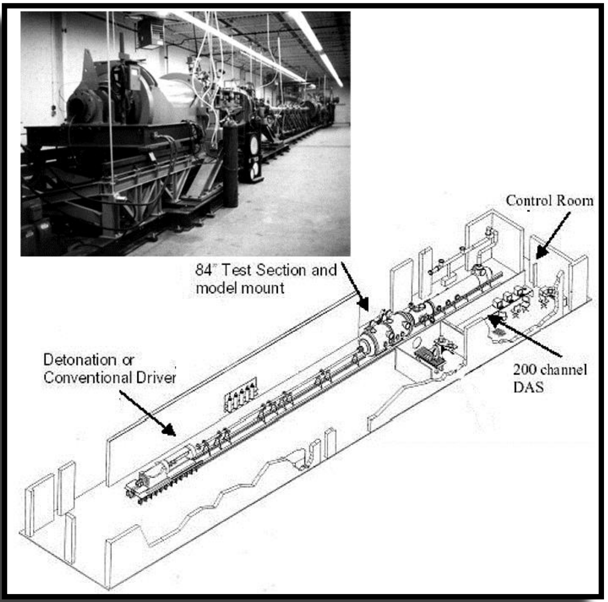


Schematic of Boeing Mach-6 Quiet-Flow Ludwieg Tube

NASA HYPULSE & GALCIT T5 Shock Tunnels

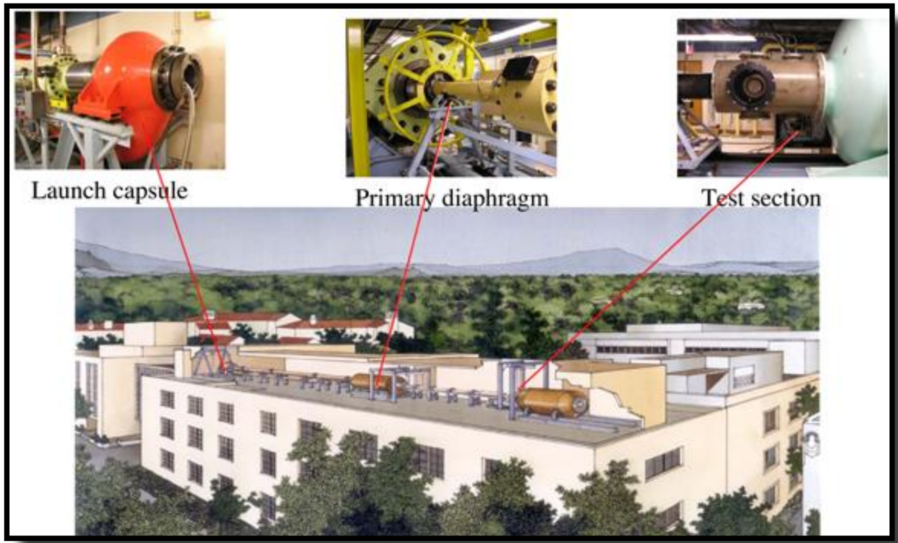
NASA HYPULSE Shock Tunnel

- **Background:**
  - Operated by GASL in Ronkonoma, NY
  - Originally operated at LaRC, transferred to GASL
- **Operation:** Shock-expansion, reflected-shock modes
- **Merits:**
  - High-enthalpy capability to simulate planetary entry
  - Arbitrary test-gas to simulate of other atmospheres
- **Utilization:**
  - Used for hypersonic airbreathing propulsion studies
  - Have tested Mars probe configurations



GALCIT T5 Shock Tunnel

- **Background:** Operated by CalTech
- **Operation:** Reflected-shock tunnel
- **Merits:**
  - High-enthalpy capability to simulate planetary entry
  - Arbitrary test-gas to simulate of other atmospheres
- **Utilization:**
  - Primarily used for university research problems
  - Has been utilized for NASA planetary entry studies (MSL, CEV)

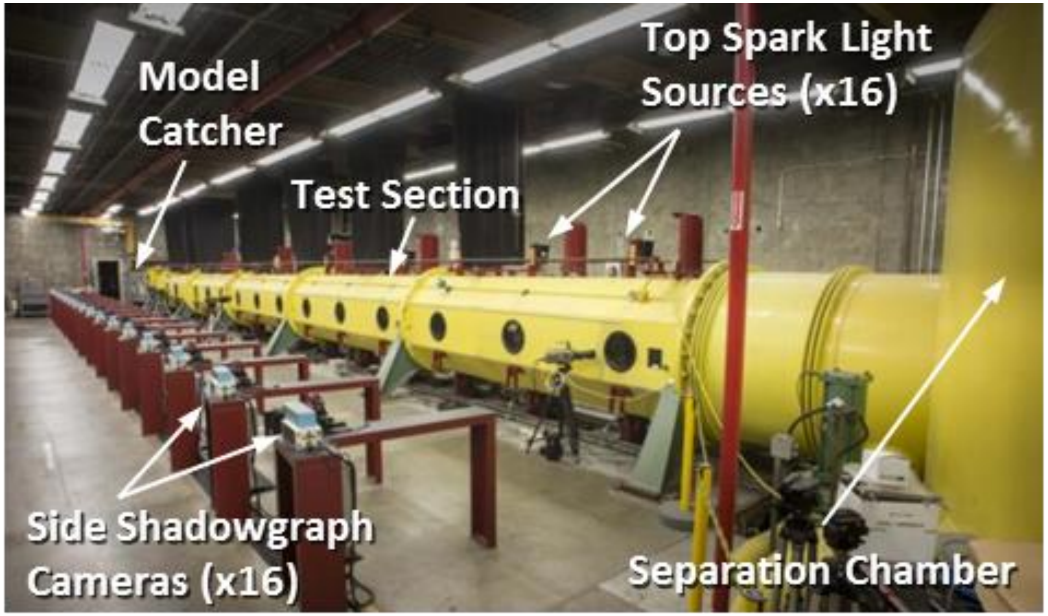


Ames Hypervelocity Free Flight Aerodynamic Facility

- ***Aerodynamic Database Development for Capsule and Probe Configurations***
  - ***Real-gas and γ effects on lift, drag, trim angle, and stability***
- ***Aero-heating***
  - ***Surface roughness effects on transition and heat transfer***

NASA's only controlled-atmosphere free-flight range

Independent control of Mach number, Reynolds number, and test gas composition (Air, N_2, CO_2, Ar, H_2/He, etc.) and pressure



8-Ft. High Temperature Tunnel

- Provides needed flight simulation capabilities:
- Mach 3, 4, 5, 7
- 20,000 – 120,000 ft. altitude
- True flight enthalpy (temperature up to 4000°R)
- Matched flight conditions for NASP CDE, Hyper-X, HyFly, X51, LSETT
- One of two calibrated facilities in this speed range
- Facility tied to NASA’s premier hypersonic CFD team

Other Hypersonic Facilities

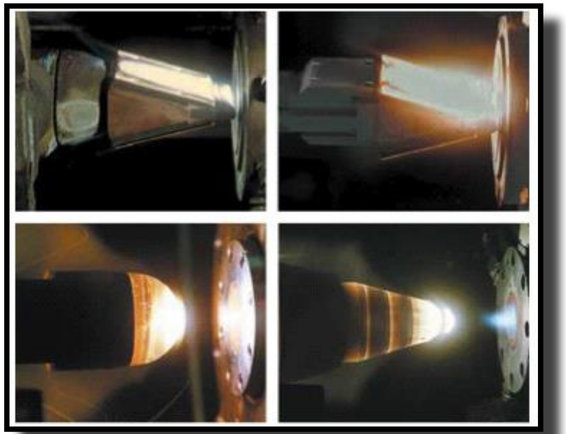
Propulsion Facilities: Testing airbreathing propulsion systems (scramjet operation) at flight-like conditions. Usually combustion heated

- Five facilities in NASA LaRC Scramjet Test complex
- Hypersonic Tunnel Facility operated by NASA Glenn
- Propulsion facilities at AEDC Tullahoma

Engine test in LaRC 8-ft High Temperature Tunnel

Arc-Jets: Testing thermal protection system (TPS) material response (ablation and recession) at flight enthalpies produced by electric arc-jet discharge

- AEDC operates three arc-jets at Tullahoma, TN
- NASA Ames operates three arc-jets

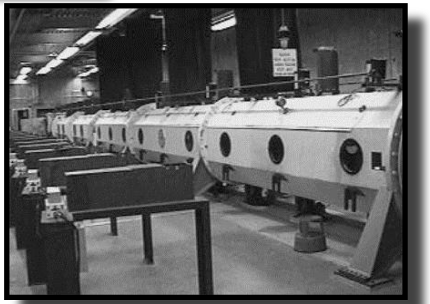


Test articles in AEDC H-1 arc-jet

Other Facilities:

- Shock Tubes: for investigation of thermochemical and radiative properties (e.g., NASA EAST)
- Commercial, academic, and foreign hypersonic facilities: information hard to find; not covered herein
- Subsonic, Transonic & Supersonic Tunnels: Numerous government, military, corporate and academic operators, but not the subject of this work

ARC EAST Shock Tube



ARC HFFAF Ballistic Range

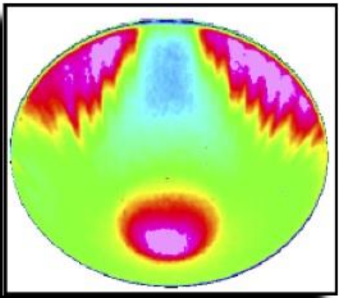
How to Test?

General Information

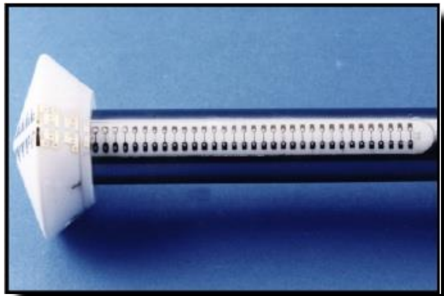
Global Techniques

Discrete Gauges

Standard Instrumentation Types & Techniques



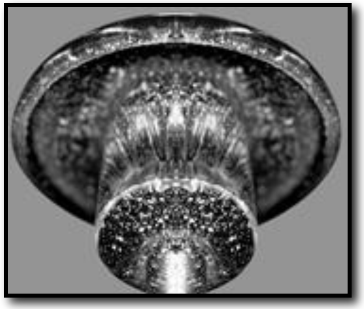
Infrared, phosphor thermography, or temperature-sensitive paint for global heat transfer measurements



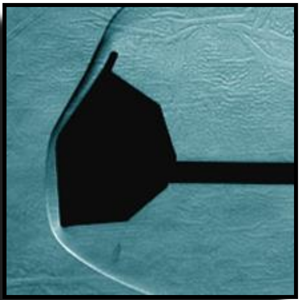
Thin-film, thin-skin, or coaxial thermocouple gages for discrete heat transfer measurements

Electronically Scanned Pressure (ESP) measurements

High frequency pressure transducers:
$f \leq 1$ MHz



Oil-flow for surface streamline visualization



Schlieren for flow field visualization

Experimental Method

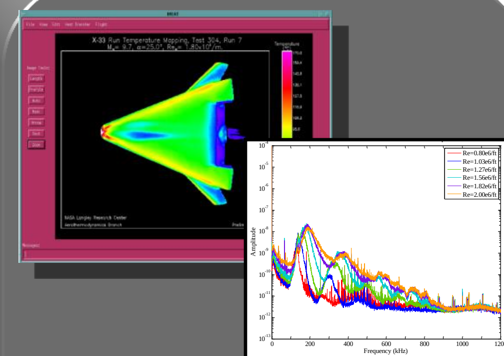
Vehicle Concept

Model Fabrication

- Cast ceramic models fabricated at Langley
- Macor shops
- Metal shops

Wind Tunnel Testing

- 4 hypersonic facilities at Langley (LAL)
- Other national facilities include AEDC Tunnel 9, CUBRC, etc.

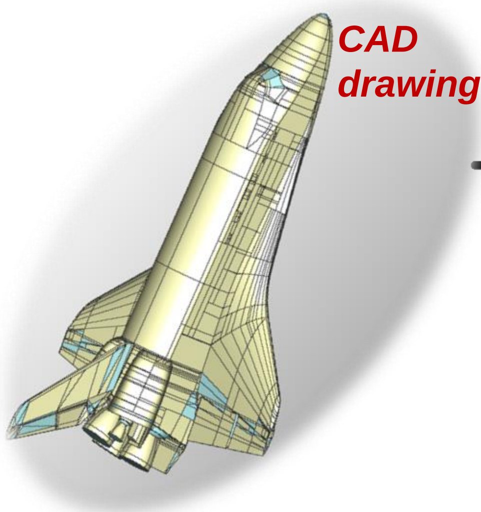


Analysis of Measurements

- IHEAT: in-house phosphor reduction
- MATLAB
- Fortran

Aeroheating data to customers

Ceramic Model Fabrication



CAD drawing

to model shop

MACOR or metal fab

Stereolithography Machine

to ceramics laboratory

Instrumentation lab

Coordinate Measuring Machine

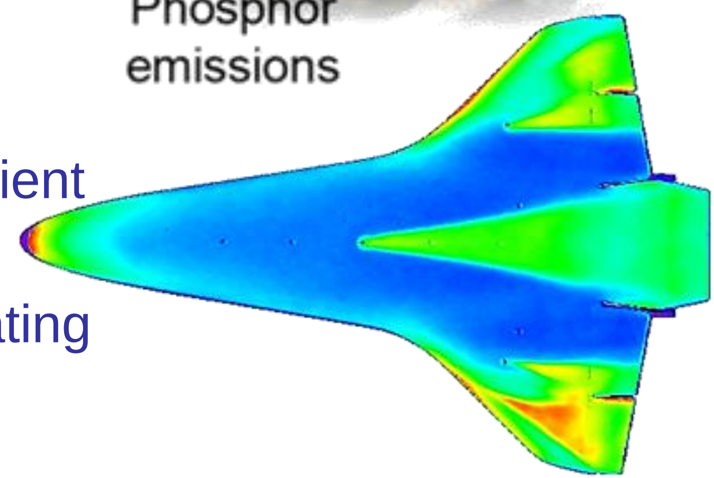
to QA

Wax mold → fired ceramic model with phosphor coating

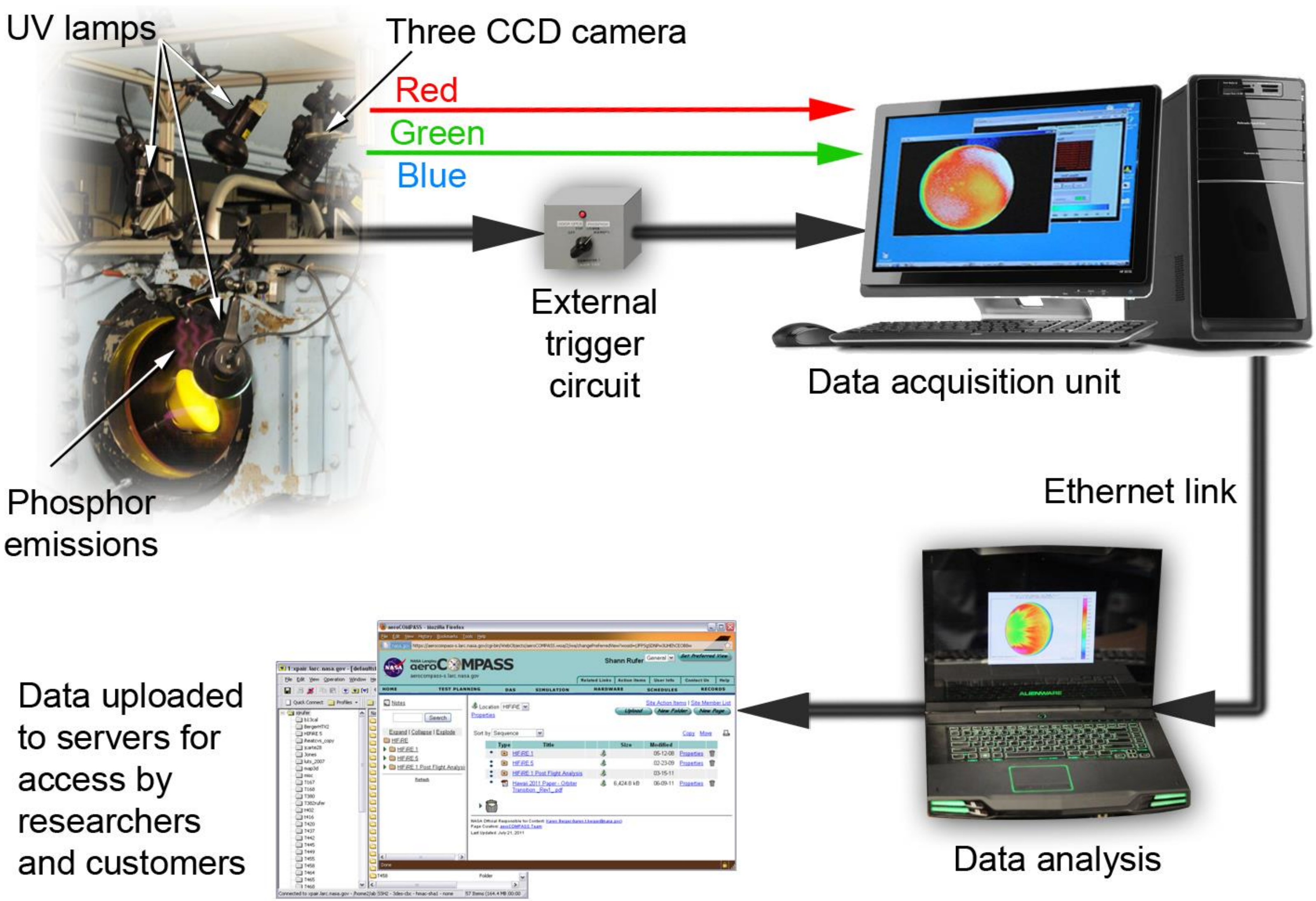
Global Measurements

Global Phosphor Thermography

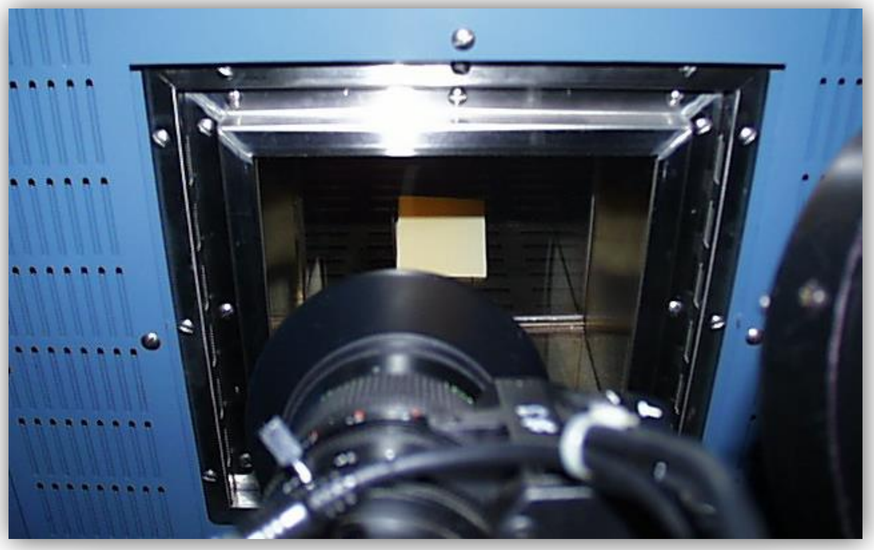
- Two-color relative-intensity
- Slip-cast silica ceramic or Macor models
- Fluoresces in red and green under UV light
- Intensity dependent on incident light, surface temperature
- Intensity images acquired: 30 fps, 8 bit, 3-CCD camera
- Converted to temperature mappings via temperature-intensity calibration (ratio of red/green, computer response, window emissivity)
- Valid from 18 ºC (65 ºF) to 160 ºC (320 ºF)
- Reduced to enthalpy based heat transfer coefficient (1D semi-infinite heat conduction assumption)
- Global, rapid/inexpensive fabrication, robust coating

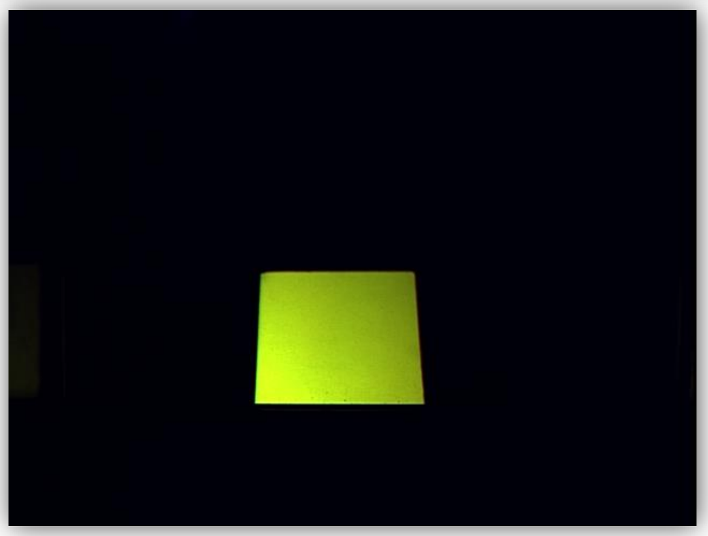


Phosphor Thermography Process

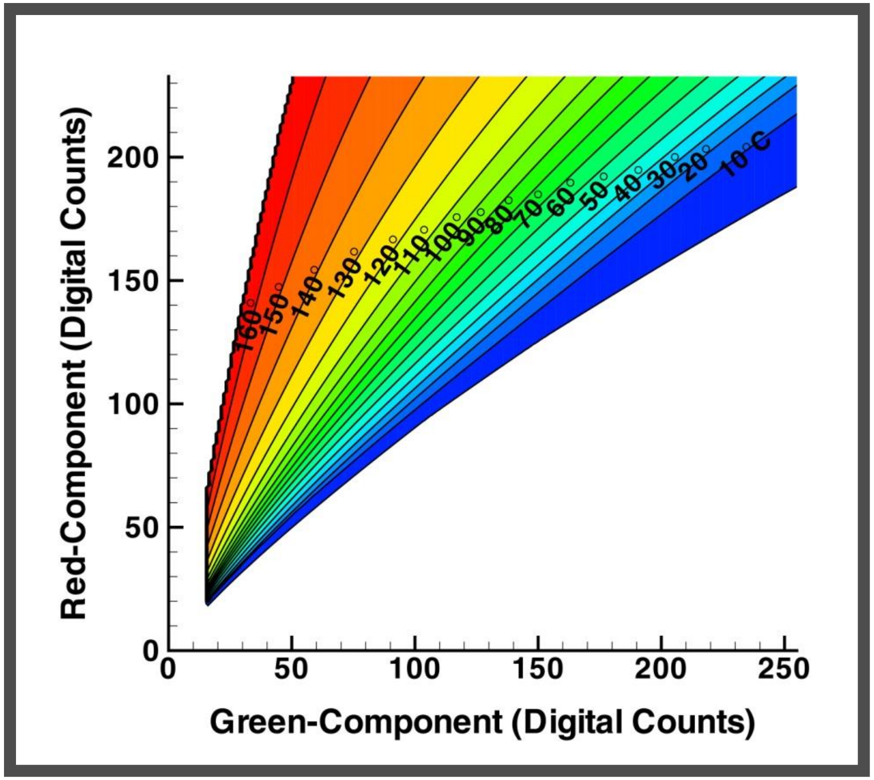


Temperature Calibration Set-up

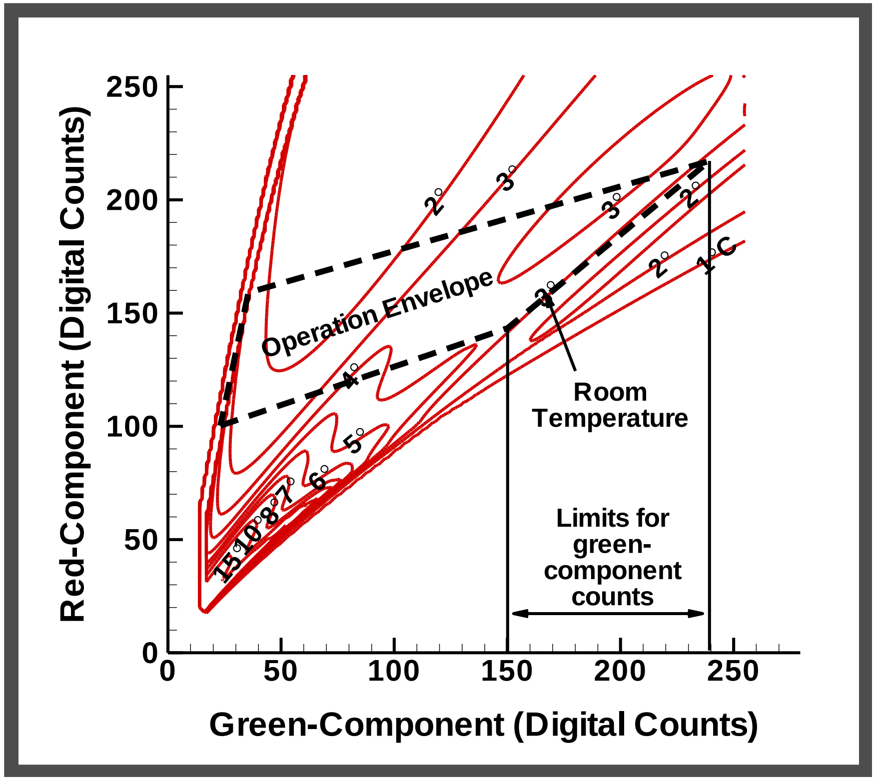




Lookup Table Creation



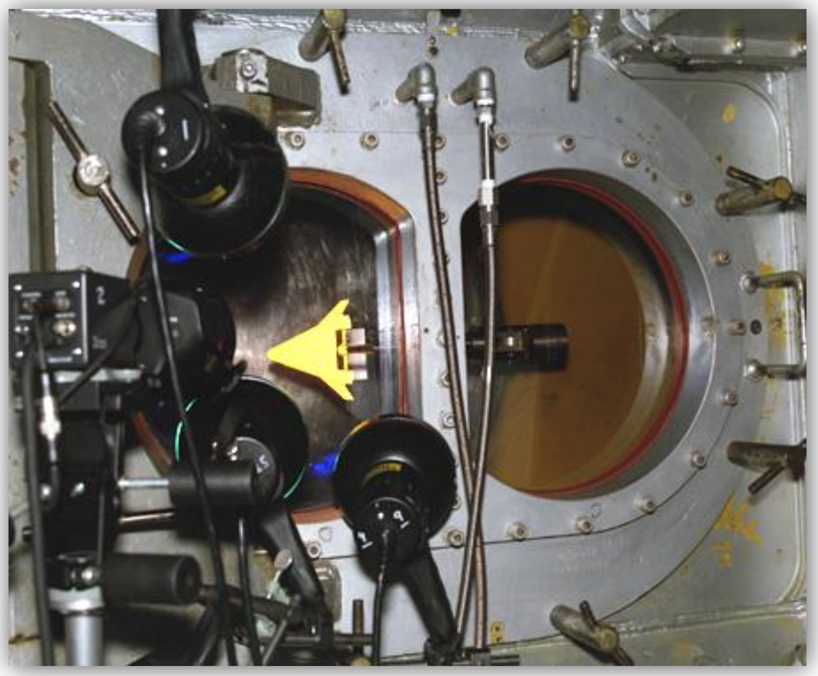
Lookup Table



Total Uncertainties

Tunnel Test Procedures

- Model installed in tunnel
- Model injected into tunnel with no flow and UV lamps set up to illuminate the model
- Model retracted, vacuum applied to tunnel and model briefly injected for pre-run temperature image
- Tunnel brought to flow conditions
- Model injected and images obtained at predetermined times after trigger from tunnel
- Image data saved and compressed and ported over to UNIX network for reduction



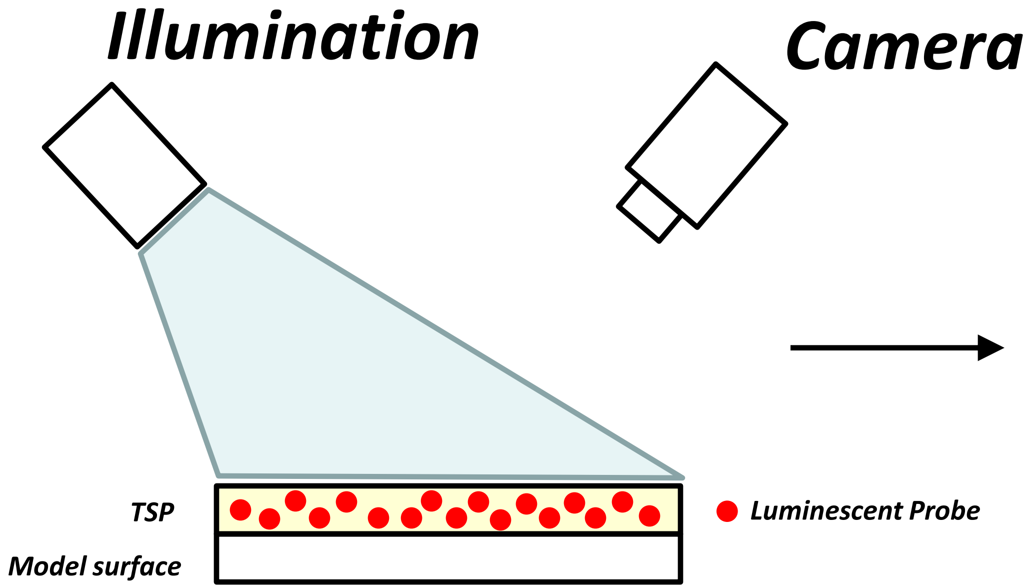
Phosphor Reduction Methods

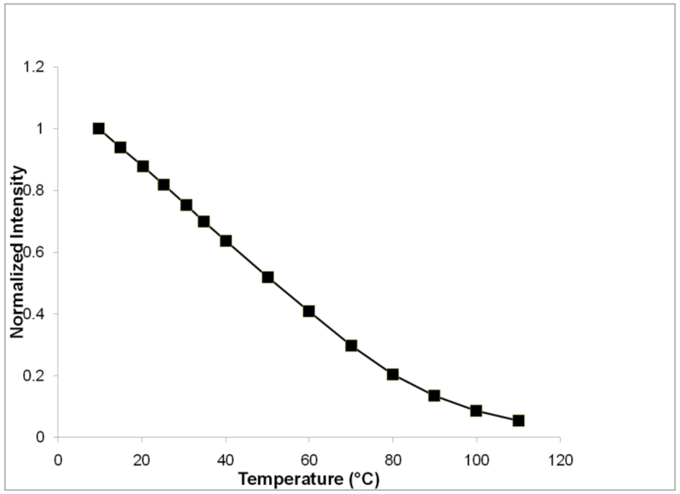
- Maximum of 30 frames per second
- IHEAT – written by Ron Merski (modified by Michelle Mason)
  - 1-D, semi-infinite-solid heat conduction theory
    - Assumes a constant heat transfer coefficient
    - Heating data from code in the form of a heat transfer coefficient, h
      - Absolute heat flux required for CFD comparison
      - Heat flux, q, extracted from h using measured wall temperatures and total enthalpy based on tunnel total temperature
- Global heating images and line cuts
  - Fiducial marks on image used to obtain correct X and Y location of heating data

Infrared Thermography (IR)

- non-intrusive video-based, radiometric measurement technique capable of obtaining real-time global surface temperature data based on blackbody radiation theory
- Requires special windows
- Surface temperature of model calculated based on radiation at infrared wavelengths
- LaRC uses infrared imaging system (FLIR System ThermaCAM SC 3000 camera)

Temperature Sensitive Paint (TSP)

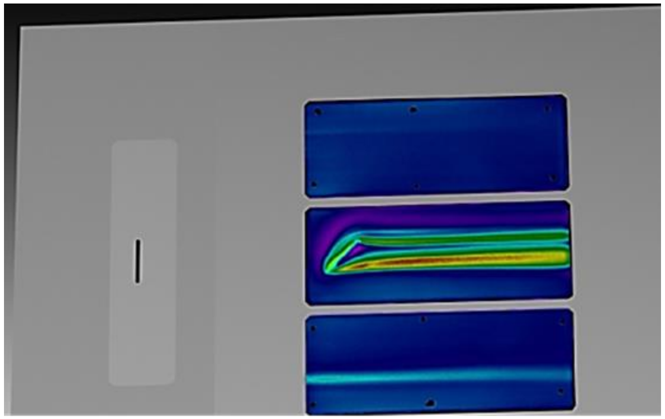




- TSP consists of a luminescent probe dispersed in an oxygen impermeable binder
  - Applied using conventional painting techniques
- TSP illuminated with blue or UV light and imaged with a camera
- Luminescence inversely proportional to temperature
  - Increasing temperature results in a decrease in measured luminescence
  - Decreasing temperature results in an increase in measured luminescence

TSP (cont.)

ADVANTAGES



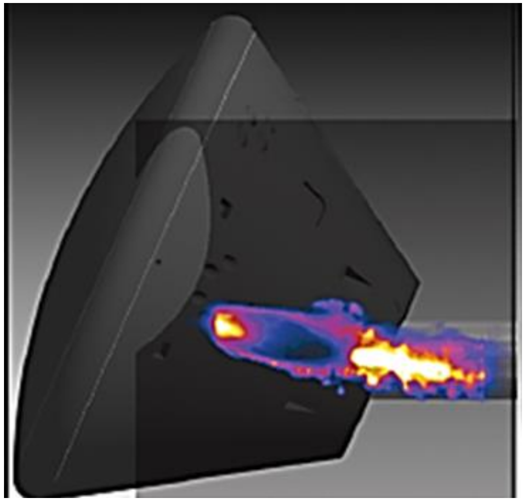
- Can be applied to most surfaces
  - Use conventional painting techniques
  - Creates a robust, hard, smooth coating
- Relatively benign
  - Organic dye dispersed in commercial clear coat
- Good sensitivity at low temperature ranges (<80 ^{o}C)
- Temperature range can be adjusted using different luminescent probes

DISADVANTAGES

- Requires a reference image
  - Does not have an intrinsic reference like two-color phosphor
- Relatively narrow temperature ranges (typically 50-100 ^{o}C range at most)
- TSP formulations cannot withstand higher temperatures (>150 ^{o}C)
  - Undergoes irreversible changes that alter sensitivity

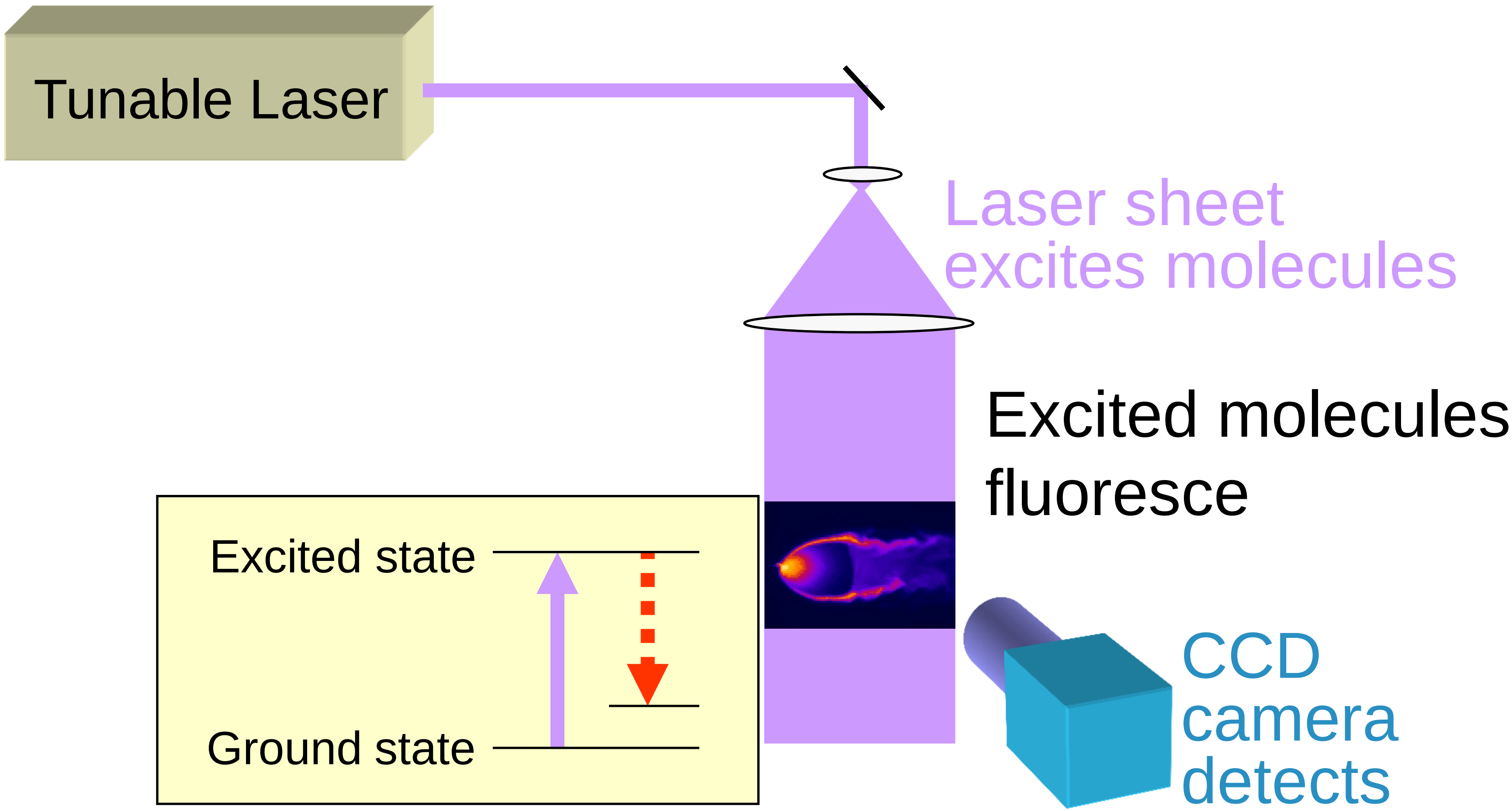
Flow Field and Surface Measurements

Planar Laser Induced Fluorescence (PLIF)



- 3D, spatially-resolved, off-body visualization
- Investigate laminar to turbulent BLT, RCS effects, wake flow phenomena
- Nitric Oxide gas used to image flow field off the surface of models
- Images can be acquired using multiple cameras
- Laser sheet translated in tunnel, measurements both along and away from surface
- Custom built PLIF imaging system with maximum frame rate of 1 MHz
- MTV capability under development (array of 25 lenses focus laser sheet into 25 lines)

What is PLIF?

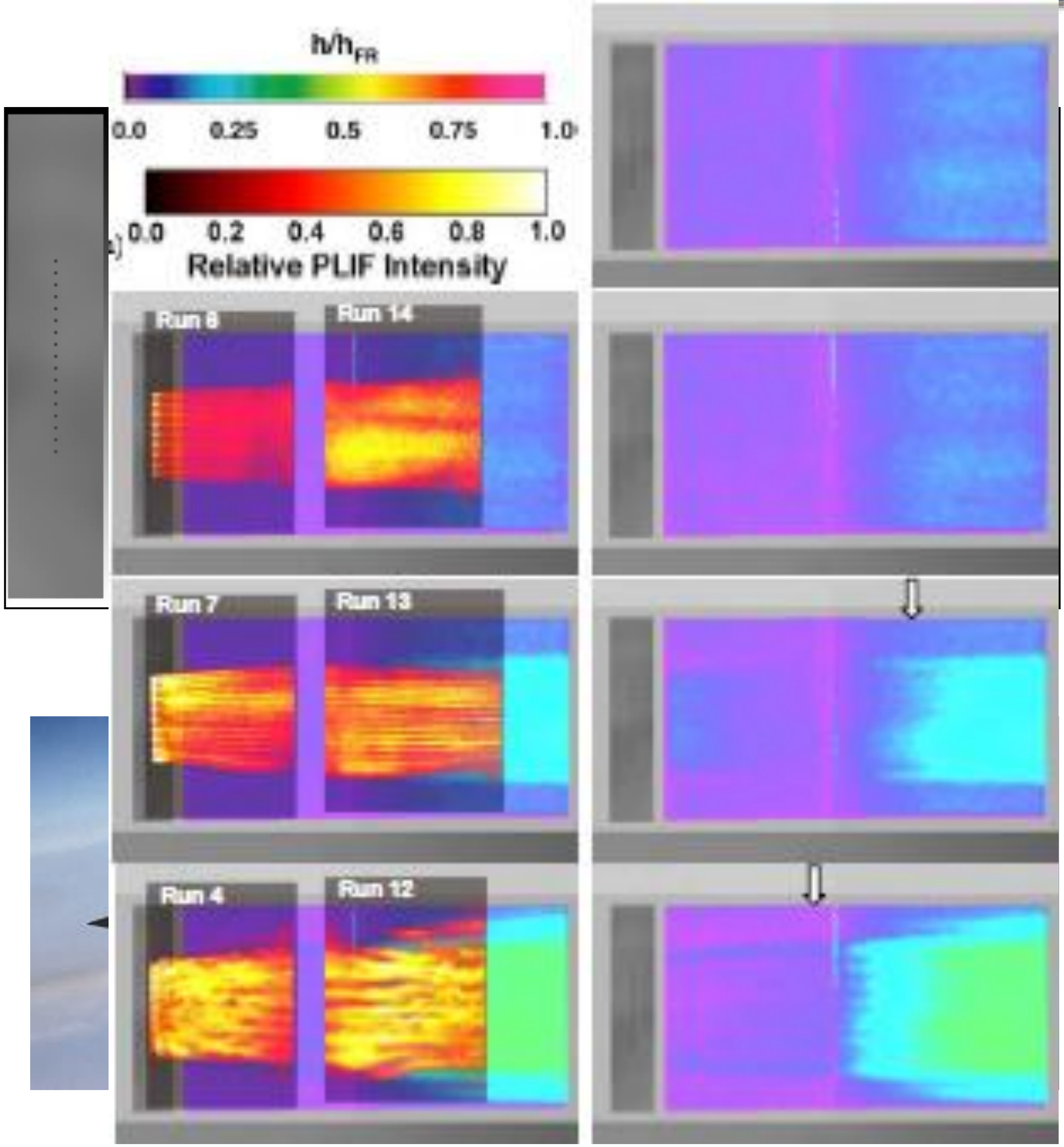


LIF ~ n_{NO}

PLIF Visualization and Phosphor Thermography

Hyper-X study

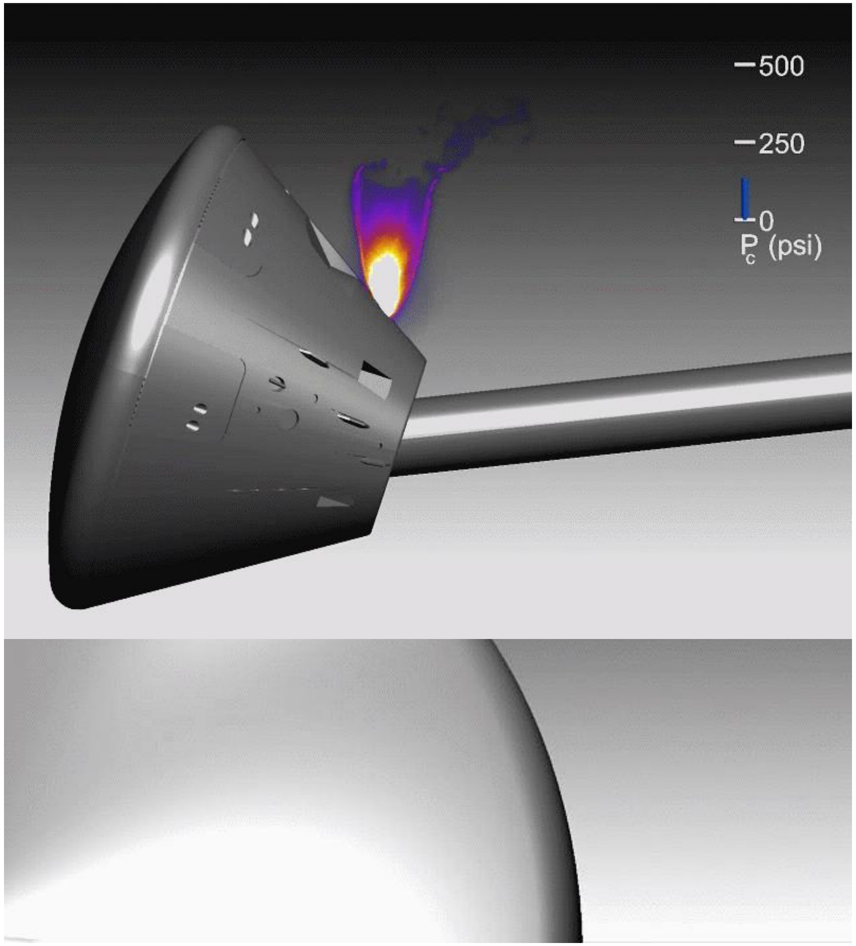
- Forced boundary layer transition via blowing
- Comparison between PLIF images and surface heating measurements
- Determination of transition location
- Effect of blowing rate
  - Heating patterns
  - Flow structures observed in relation to blowing rate
  - Measurements at multiple off-body locations



PLIF RCS Jet Visualization and Reconstruction

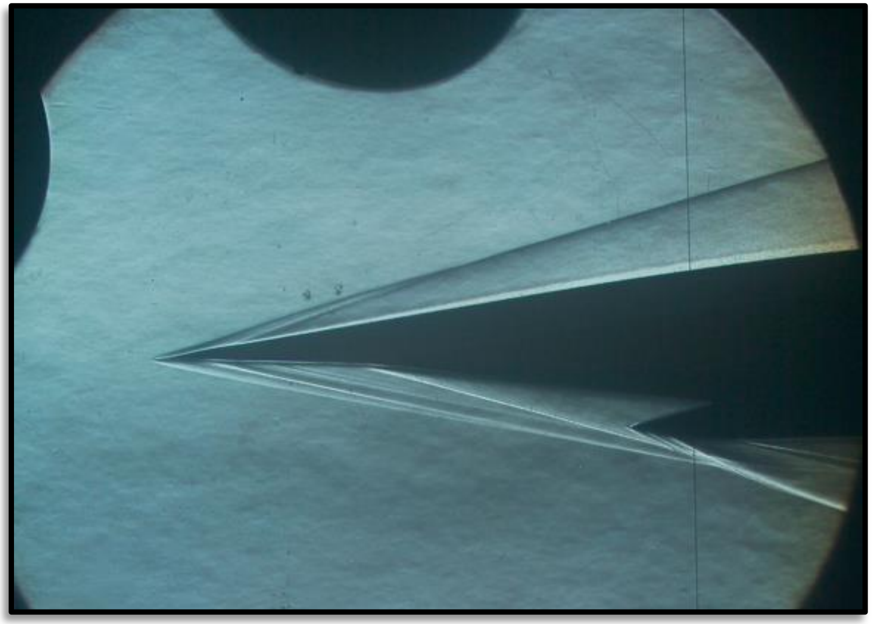
Orion Crew Exploration Vehicle

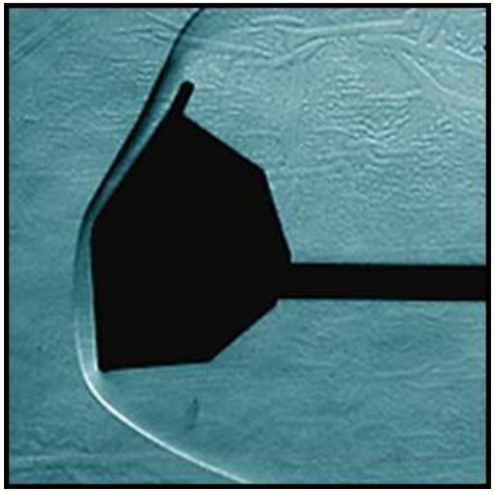
- **Visualization of pitch RCS jet**
  - **Observe interaction with shear layer and wake flow**
- **Volumetric image reconstruction of roll RCS jet**
  - **Laser is scanned through RCS jet flowfield**
  - **Planar images are superimposed over virtual model**
  - **Reconstruction provides RCS jet shape and trajectory information**



Schlieren

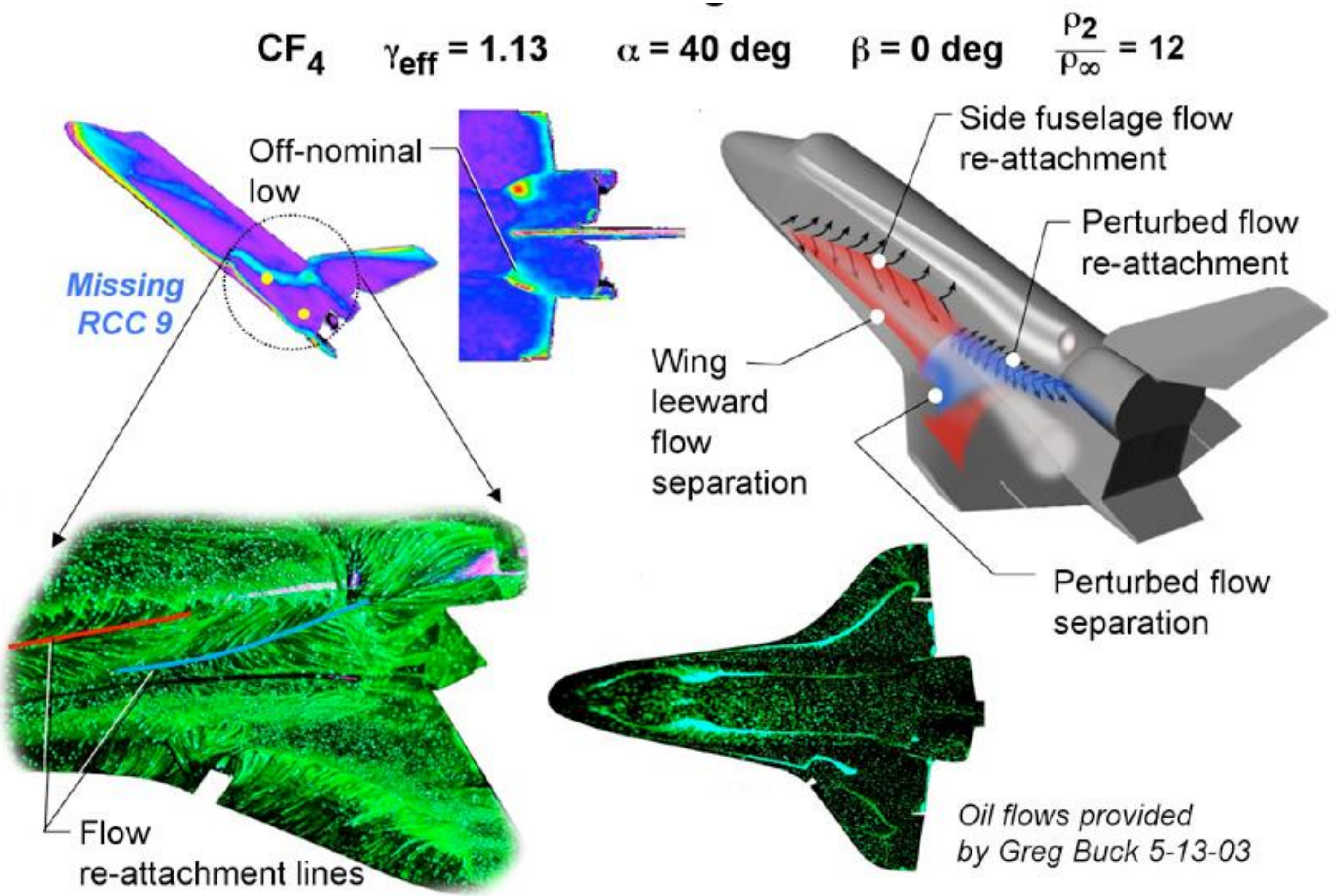
- Visualization of density changes
- Sensitive and low cost
- Displays focused image using system of lenses and light source
  - A knife edge is used for cutoff
- Used in wind tunnels for decades
  - Recently used in full scale aircraft
- High framing rates allow for comparison to Kulite data
  - Frequencies of shocks, etc, can be measured





Oil Flow

- Streamline patterns can be compared to heating patterns
- Can show areas of flow separation and reattachment



Discrete Measurements

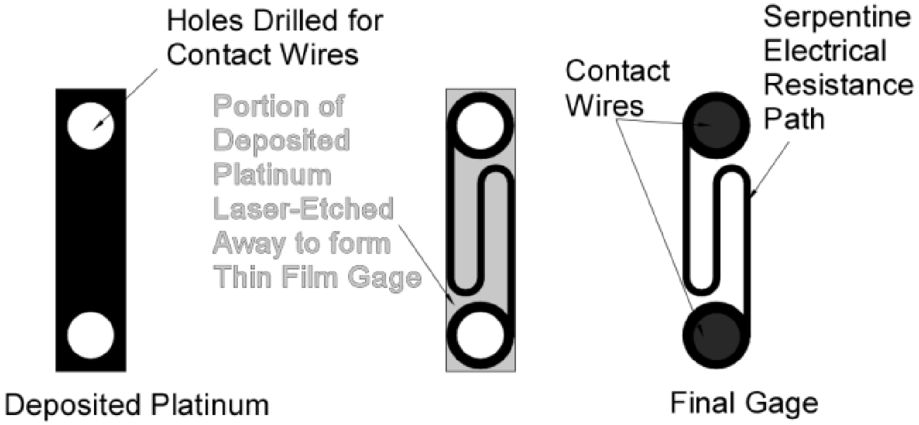
Thin Film, Thin Skin, Thermocouples

Discrete, non-intrusive method for measuring temperature

- Heat flux can be calculated from temperature changes

Thin Film

- Sampling frequencies as high as 100s of kHz (possibly up to 1MHz)
- Historically have been hand-painted on models
  - New techniques include laser-etching the gauges on the model
- Size allows for placement on leading edges, curved surfaces, etc.



Thermocouple

- Multiple types of thermocouples (Type E, K, etc.)

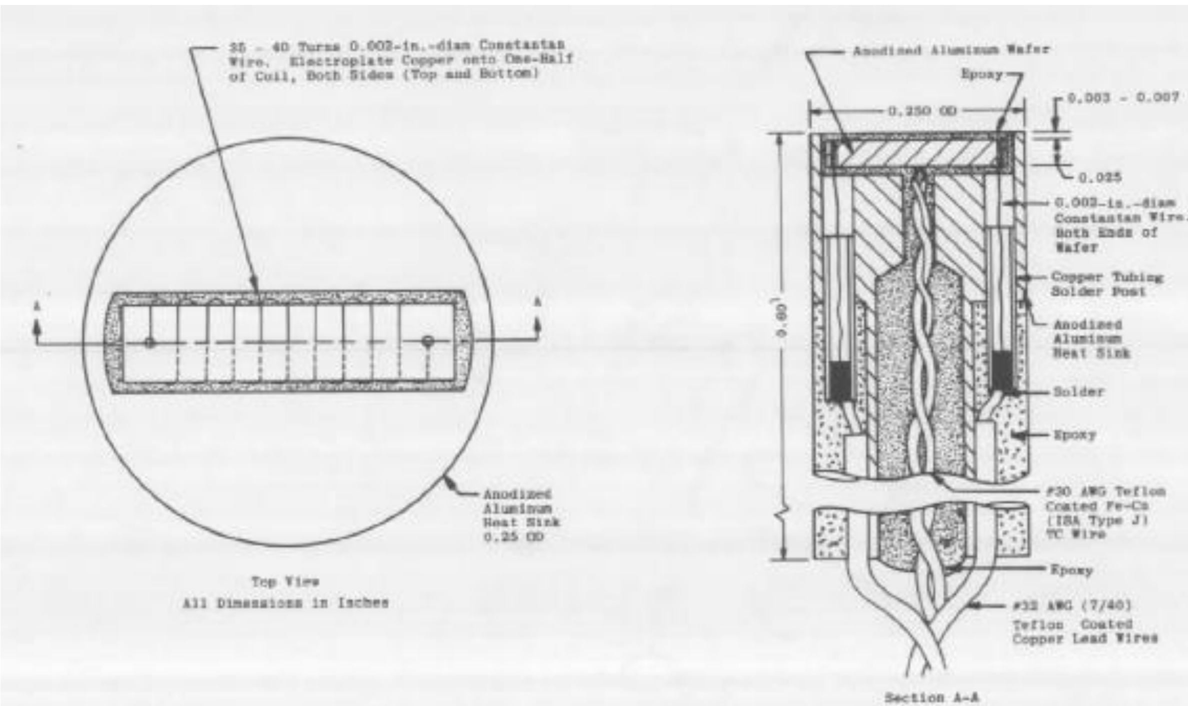
Thin Film Data Reduction Method

- 1DHEAT – written by Brian Hollis
  - Have option of solving using either finite-volume (FV) method or numerical method (Kendall-Dixon or Cook-Felderman)
  - Input files include
    - tunnel flow conditions and temperature versus time
    - FV method: number of layers plus thickness and material of each layer
    - Initial Condition: gauge temperature at t=0
    - Boundary Conditions:
      - Front wall BC
      - Back wall BC

- Also used to reduce data from coax gauges

Schmidt-Boelter Heat Flux Gage

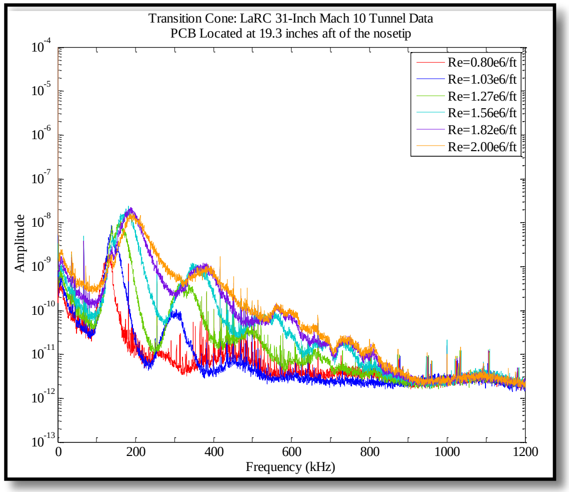
- **Output is directly proportional to heat flux**
- **Operating temperature: 50 - 600° F**
- **Time response on the order of 10 ms**
- **Measures temperature difference between parallel planes**
  - Hot junction on the top of the wafer
  - Cold junction on lower surface of wafer
- **Can conform to curved surfaces**



Data Acquisition – High Frequency

- Data Acquisition Systems
  - Portable
  - Tektronix DPO1704 Oscilloscope
    - 4 channels
    - 1GHz Bandwidth
    - 12.5 MB per channel
  - HBM Gen5i
    - Robust and expandable
    - Up to 100 MHz (1.8 GB memory per 4 channel card)

- Data Reduction
  - MATLAB modules

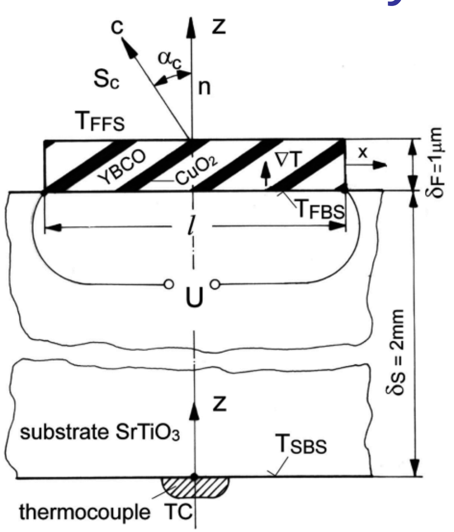


Hot Wire Anemometry

- Detect changes in temperature and mass flux of the fluid
  - Intrusive
  - Used to study boundary layer flows (laminar, turbulent, transitional), unsteady flows, temperature profiles, etc.
  - Frequency response as high as 300-400 kHz
- Typically made of tungsten, platinum, and platinum alloys
  - small diameters (<0.001 inches)
  - Aspect ratios should be greater than150 to minimize end loss effects
- Types of Anemometers
  - Constant-Current Anemometer (CCA)
    - Low current
    - Used to obtain temperature profile – temperature of wire a direct function of resistance
  - Constant-Temperature Anemometer (CTA)
    - Maintains the hot wire at a constant temperature by varying the voltage
    - High overheat ratios used to obtain mass flux profiles

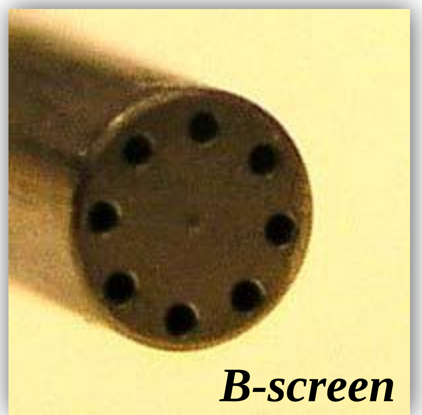
Atomic Layer Thermopile (ALTP) Sensor

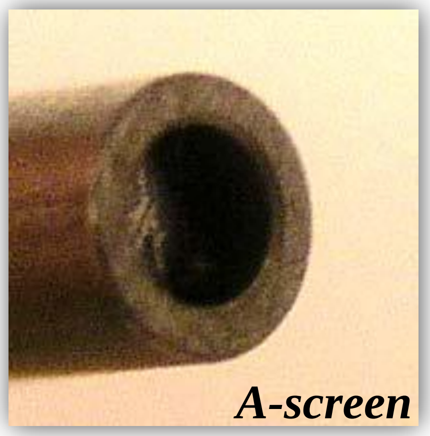
- High-frequency heat-transfer gage.
  - Sensor housing is large compared to Kulite and PCB132 transducers.
  - 8*mm diameter and* 2.5*mm*^{2} *sensitive* area.
- Typical electronics provide AC signal between 17 Hz and 1 MHz and separate DC signal.
- Product of Cosytech and Fortech



Kulite Pressure Transducers

- Use silicon diaphragms as the basic sensing element
  – Each diaphragm contains a fully active Wheatstone bridge
- Protective screens
  – A-screen
    - Flatter frequency response
    - Less protection
  – B-screen
    - Frequency rolls off much earlier
    - Greater protection
- Specific Types
  – Mic-062
    - Differential pressure sensor
    - Resonant frequency near 125 kHz
  – XCQ-062
    - Absolute pressure sensor
    - Resonant frequency near 300 kHz





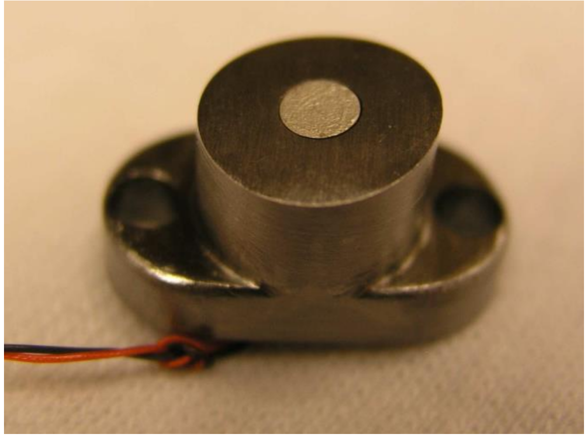
PCB Pressure Transducers

PCB113

- Dynamic Pressure sensor
- Resonant frequency greater than 500 kHz

PCB132

- Measure frequencies between 11 kHz and 1 MHz
- Roll-off begins around 300 kHz
- Sensor diameter is 0.125 inches
  - Ceramic sensing unit approximately 0.03” x 0.03”



Have successfully measured second-mode instability waves on a cone (through all stages of growth, saturation and breakdown) in multiple hypersonic facilities.

Other Measurements

Non-Aerothermal Test Techniques

- Aerodynamics
  - Forces and Moments
  - Variety of balances
- Discrete Pressure
  - Electronically Scanned Pressure (ESP)
  - Kulite – freestream disturbances
    - Resonant frequencies between 100 and 300 kHz
    - Uses include freestream disturbance and boundary layer measurements
  - Piezoelectric Pressure Sensor (PCB) – BLT due to instability waves
    - Useful for measuring frequencies between 11kHz and 1MHz
    - Characterize boundary layer transition by measuring growth/breakdown of instability waves
- Global Pressure
  - Pressure Sensitive Paints (PSP)

Summary and Conclusions

Summary

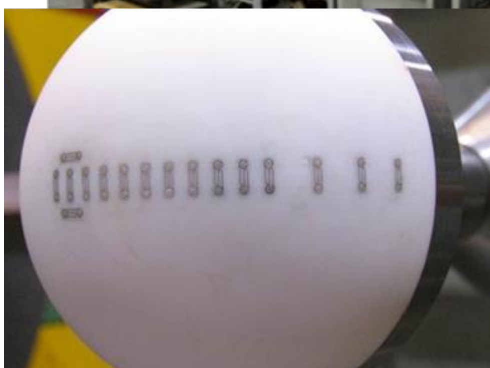
- A summary of limited experimental aerothermal contributions to flight programs was presented
  - Entry, Descent and Landing, blunt body configurations
  - Slender Body and/or winged configurations
  - Examples provided show:
    - Significant contributions to successful flight programs
    - Effective and expedient resolution of in-flight anomalies
    - Development of flight ADB and TPS environments
    - Generation of V&V data for computational studies of complex phenomena
    - Criticality of robust hypersonic experimental capability to reduce uncertainties with future flight programs
- Wind tunnel types discussed, more detailed information presented for a variety of national hypersonic resources
- Types of wind tunnel instrumentation/test techniques shown

Conclusions

So **<u>why</u>** does Wind Tunnel Testing matter to aerothermodynamics?

- Computational Code Validation
  - Provide invaluable data to validate new codes, capabilities and configurations
  - Less expensive than flight testing
- Ability to study of complex flow phenomena that cannot be assessed in computational codes
  - Physics not properly understood and/or modeled
  - Complex interactions (control surfaces, blowing, RCS jets, etc.)
  - Wake flow and separated regions
  - Boundary Layer Transition!!!
- Better understanding of heating environments on a vehicle
  - Can be a function of multiple complex physical phenomena
  - Boundary layer transition can lead to higher than turbulent heating levels
  - Vehicle characteristics can augment heating further

Aerothermal ground testing has historically, is currently and will continue to be a critical part of the design of hypersonic vehicles, alongside computational techniques and flight testing



Questions ???