Entry, Descent and Landing Seminar Series

Wind Tunnel Testing Lecture

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NASA Langley Research Center

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  - Hans Hornung and Joanna Austin at CalTech T5
  - Rodney Bowersox at Texas A&M University
  - Steve Schneider at Purdue University

Outline

- **Why is ground testing important?**
- **Where to conduct ground testing?**
  - Types of Facilities
  - Hypersonic Facilities in US
- **How to Test?**
  - Global Techniques
  - Discrete Techniques
- **What do we learn from testing?**
  - Testing in support of flight programs
  - Testing in support of fundamental research & technology development

Why is Ground Testing Critical?

Different missions, different challenges in the 21st Century

The last 25 years – constrained visions, limited operations, legacy technologies

The next 25(+) years – new challenges, new missions, new technologies

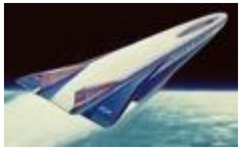

Human operations focus on LEO → **Humans to the "Moon, Mars and Beyond"**



Legacy 1970's-era EDL/Hypersonic architectures → **Innovative architectures for new requirements**



Failed commercial access-to-space ventures → **Viable commercial space market**

Sustained hypersonic flight technologically non-viable → **Sustained hypersonic flight concepts and demonstrations**

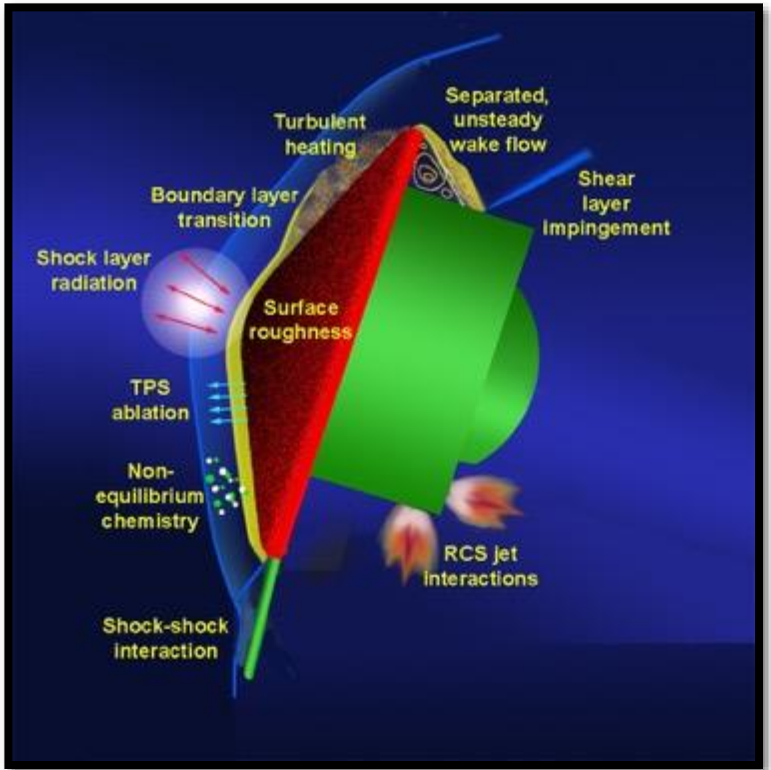

Dominance in subsonic weapon / ISR systems → **Geopolitical rivalry in hypersonic applications**


U.S. perspective on testing infrastructure must be reevaluated as the demand for hypersonic aerothermodynamic testing capabilities increases due to changing National priorities, commercial growth, and international developments

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
  - Limited flight programs with very limited instrumentation
- **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

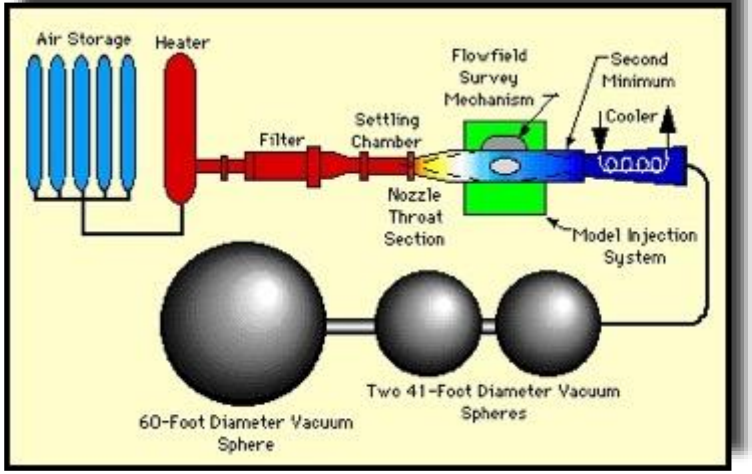
Where to Conduct Ground Tests?

Types of Aerothermodynamic Facilities

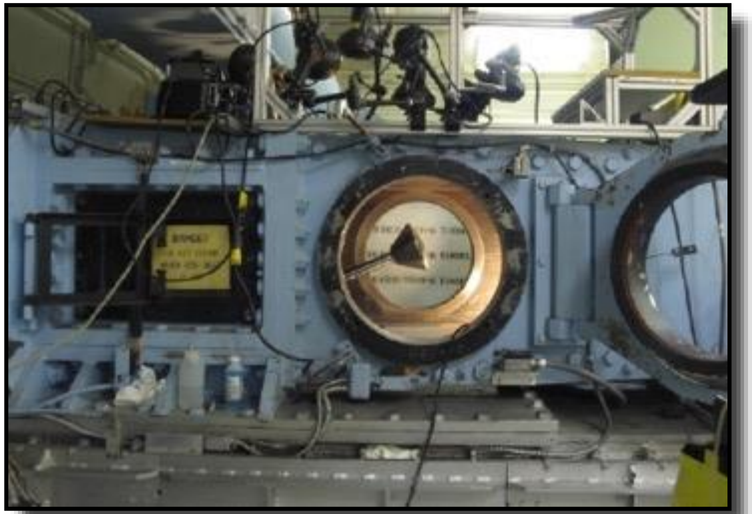
Hypersonic Experimental Facilities: Blow-Down Wind Tunnels

- **Usage: Aerothermodynamic testing of hypersonic vehicles**
  - Provide a wide range of Mach, Reynolds numbers at low-enthalpy conditions
  - Blowdown facilities have relatively high productivity and low cost in comparison to other facility types
- **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**

Schematic of NASA LaRC 31-Inch Mach 10 Air Tunnel



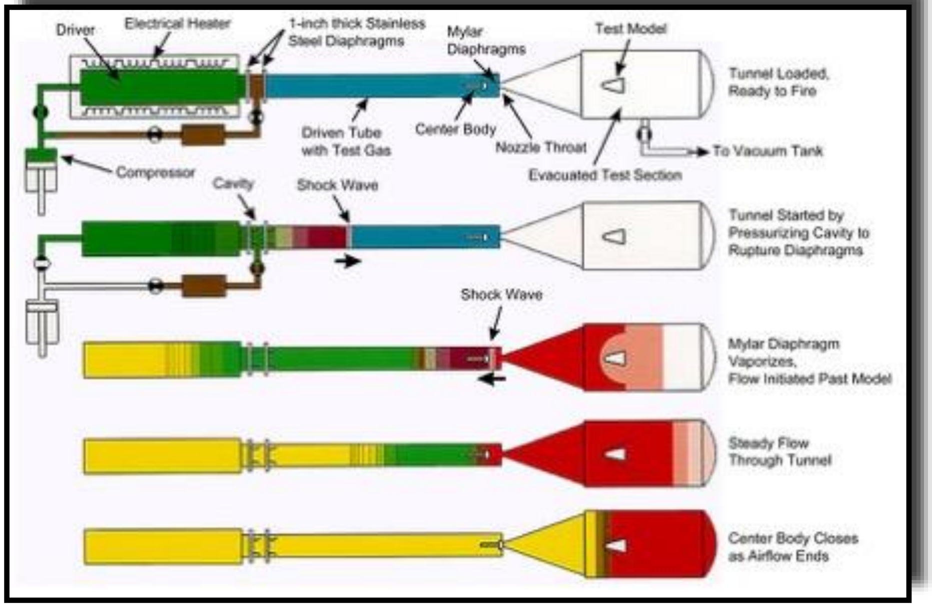
CEV Model in NASA LaRC 20-Inch Mach 6 Air Tunnel



Hypersonic Experimental Facility Types: Reflected Shock and Shock-Expansion 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
  - *Reflected Shock Tunnels*: add enthalpy through pressurization of reflected shock
  - *Shock-Expansion Tunnels*: add enthalpy by acceleration of flow into expansion section
- **Measurements:**
  - Aerodynamic force & moment measurements
  - Surface pressure and heat-transfer measurements
  - Flow-field diagnostics
- **Operators: CUBRC, Purdue, CalTech, Texas A&M**

Schematic of CUBRC LENS Operation

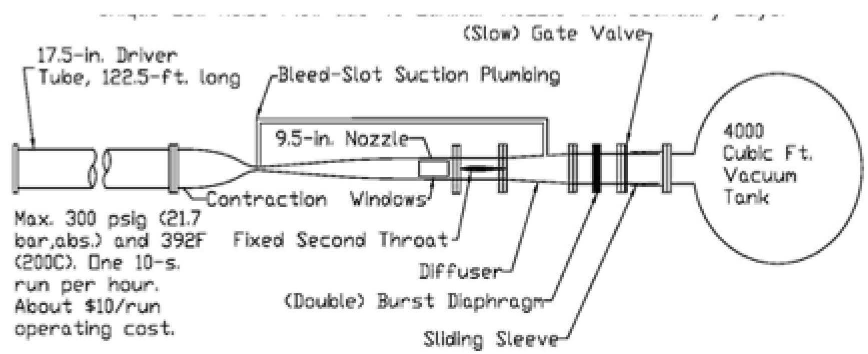


Shuttle Model in CUBRC LENS

Hypersonic Experimental Facility Types: Quiet Tunnels

- **Usage:**
  - Quiet tunnels produce flight-like noise levels in a ground testing environment. Important in the study of "natural" boundary layer transition modes of a hypersonic vehicle
  - "Bypass" transition due to roughness and surface features more relevant to conventional wind tunnel
- **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, Notre Dame**

Purdue University Mach 6 Quiet Tunnel

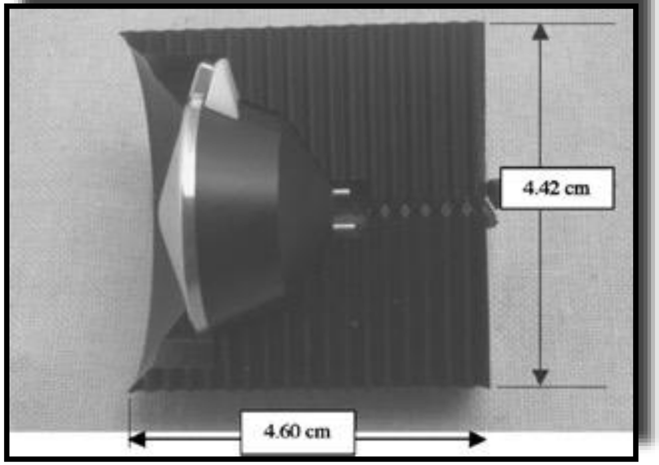


Schematic of Boeing Mach-6 Quiet-Flow Ludwieg Tube

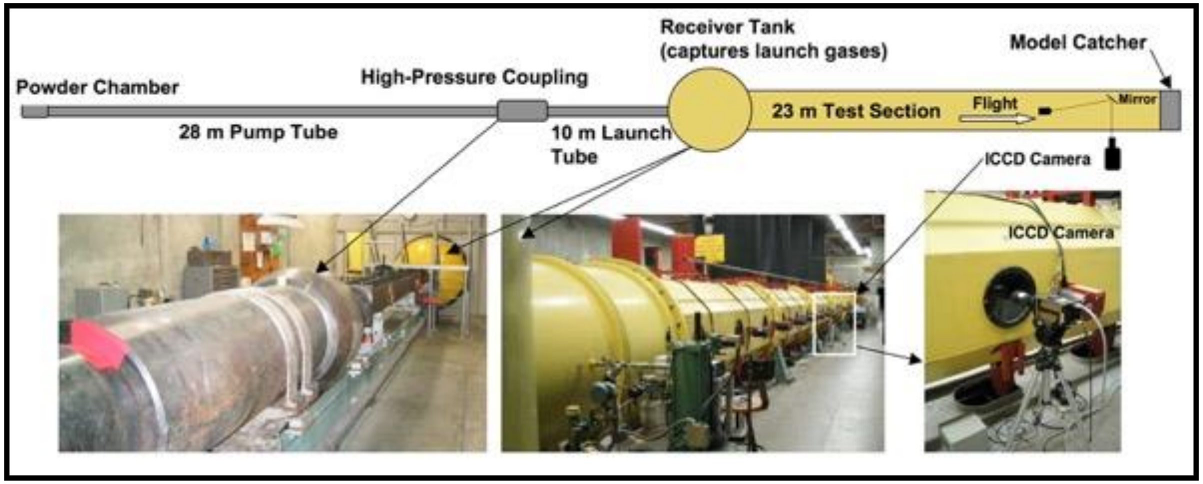
Hypersonic Experimental Facility Types: Ballistics Ranges

- **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)

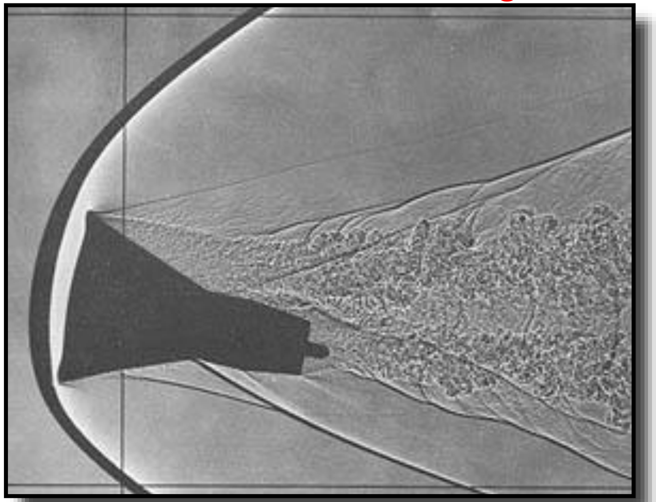
Mars Entry Vehicle model in launch sabot



Schematic of NASA Ames HFAFF Ballistics Range



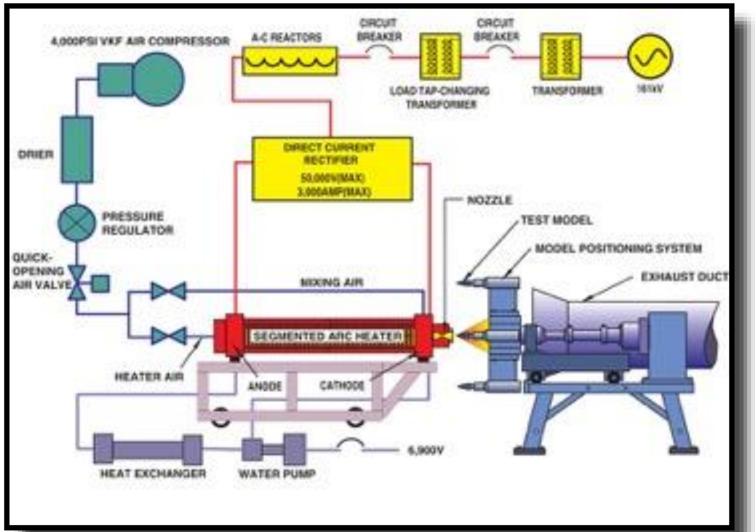
Shadowgraph of Mercury model in ballistics range



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



TPS material exposed to arc-jet flow

TPS material before and after arc-jet testing

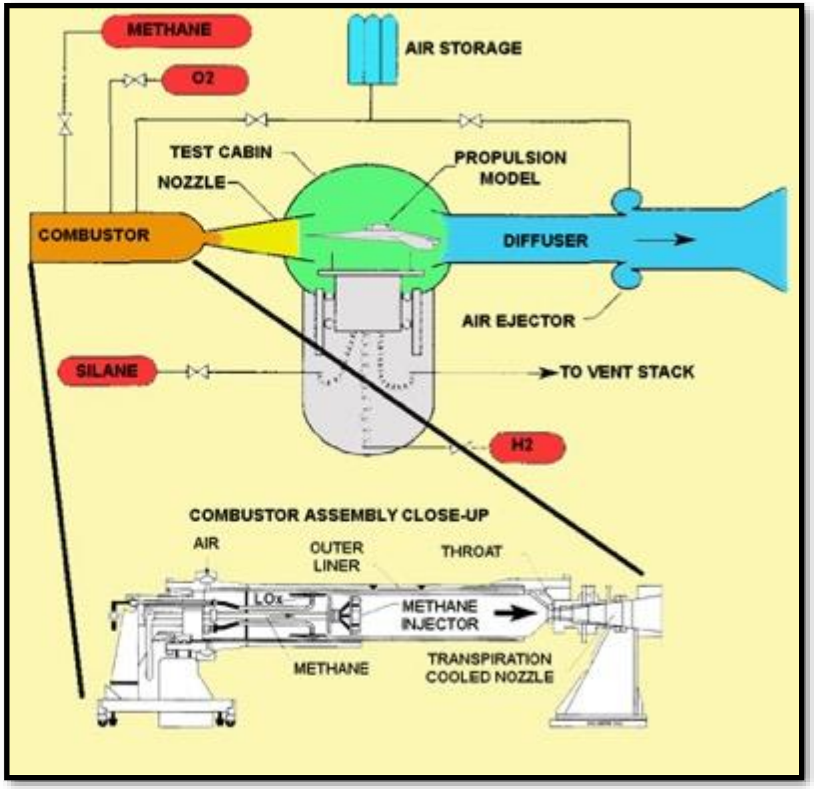
NASA Ames IHF

Hypersonic Experimental Facility Types: Propulsion Tunnels

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

Scramjet testing in NASA LaRC 8-ft HTT

Schematic of NASA LaRC 8-ft High Temperature Tunnel



Where to Test?

US Hypersonic Facilities used by NASA

Hypersonic Facilities & Operators in the U.S.

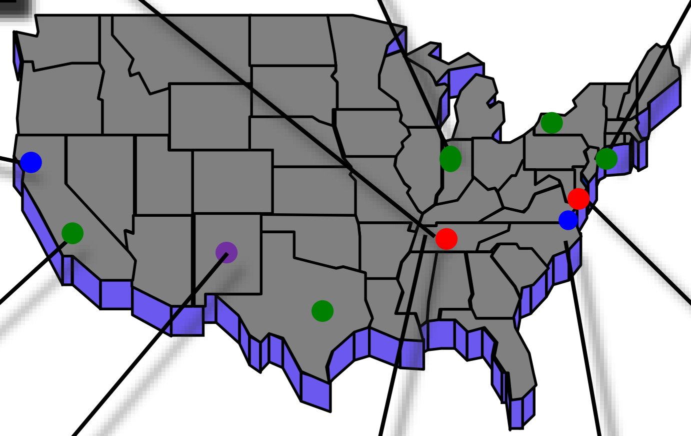
- NASA Centers with Aerothermodynamic Ground Test or Flight Test Capabilities
- Dept. of Defense Aerothermodynamic Facilities (AEDC)
- Dept. of Energy Aerothermodynamic Facilities (Sandia)
- University Aerothermodynamic capabilities

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

Purdue University:
Boeing/AFOSR Mach 6 Quiet Tunnel
HYPULSE Expansion Tunnel

Calspan University of Buffalo Research Center (CUBRC):
LENS I, II, and X Shock Tunnels

Ames Research Center:
HFFAF ballistics range and arc-jets



AEDC: Hypervelocity Tunnel 9

Cal-Tech:
T5 Shock Tunnel
HET Expansion Tunnel

Sandia:
Hypersonic Wind Tunnel

Texas A&M:
Mach 6 Quiet Tunnel, Hypervelocity Expansion 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

AEDC VKF Tunnels B & C and Tunnel 9

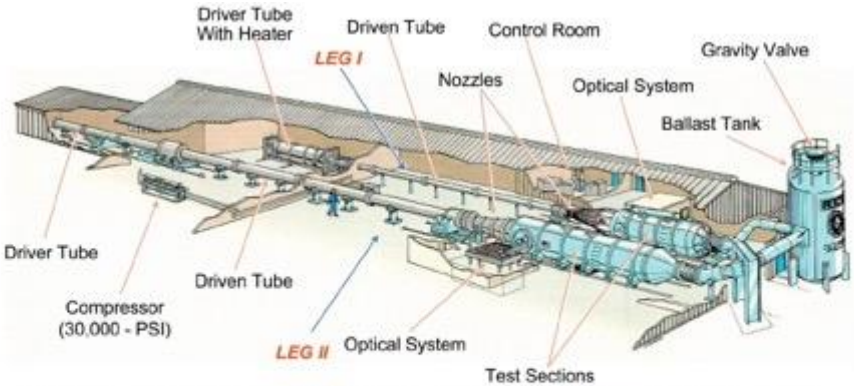
- **Background:**
  - U.S. Air Force capabilities maintained by Arnold Engineering Development Center (AEDC)
  - Von Karman Facility hypersonic Tunnels B & C at Tullahoma, TN (developed in late 1950's)
  - Hypervelocity Tunnel #9 at White Oak, MD (developed in 1970's)
- **Operation:**
  - VKF B & C are 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 VKF Tunnels B & C

AEDC Hypervelocity Tunnel #9

- **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



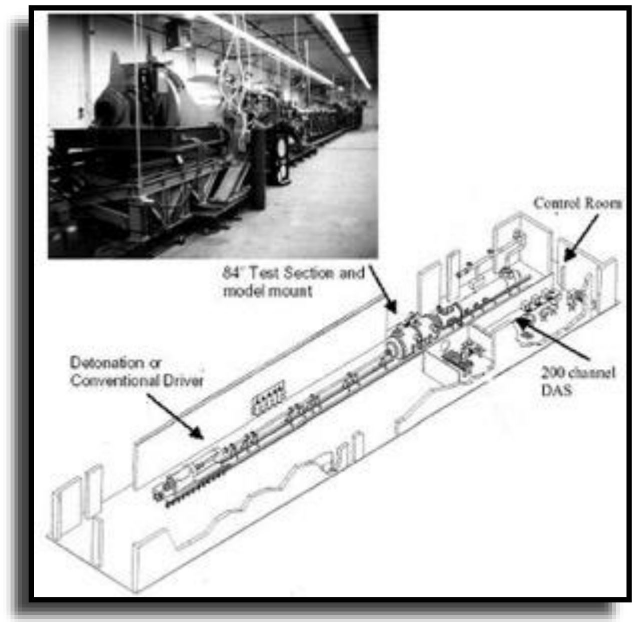
LENS Leg I – full duplication from Mach 7 to 14 for missiles and test articles up to 2-ft diameter and 12-ft long

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 and HYPULSE Expansion Tube

- **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 Ludwig tube, maximum quiet Reynolds number of ~3.5×10^6/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

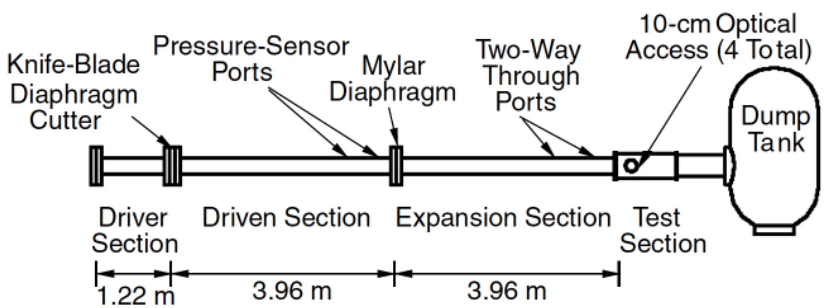
- **Background:**
  - Originally operated at LaRC, transferred to GASL in 1980’s
  - Recently transferred to Purdue University
- **Operation:** Shock-expansion, reflected-shock modes
- **Merits:**
  - High-enthalpy capability, simulate planetary entry
  - Arbitrary test-gas, simulate other atmospheres
- **Utilization:**
  - Hypersonic airbreathing propulsion studies
  - Have tested Mars probe configurations



CalTech T5 Shock Tunnel and HET Expansion Tunnel

HET Expansion Tunnel

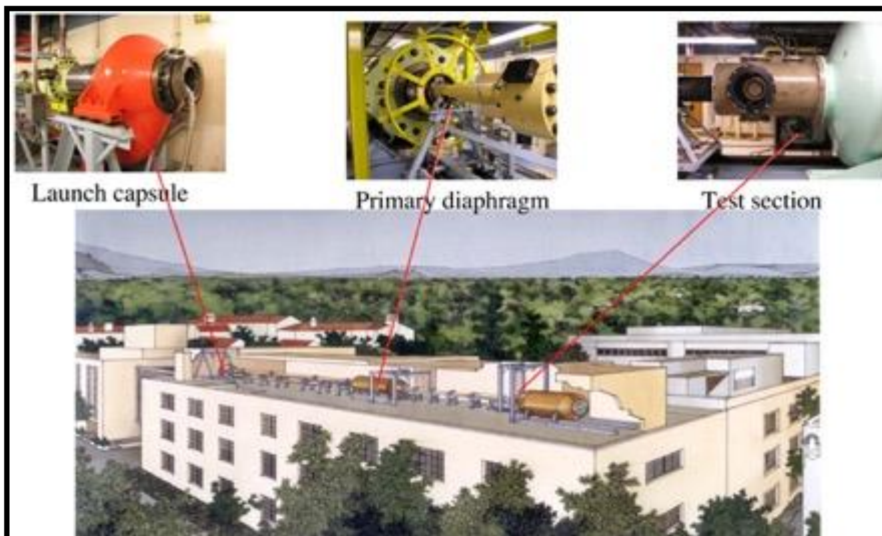
- **Background: Operated by CalTech**
- **Operation: Expansion Tunnel**
- **Merits:**
  - High-enthalpy capability, simulate planetary entry
  - Arbitrary test-gas, simulate other atmospheres
  - Expansion mode minimizes free-stream dissociation
- **Utilization:**
  - Primarily used for university research problems
  - Has been utilized for NASA planetary entry studies (MSL, Orion)



Caltech

GALCIT T5 Shock Tunnel

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



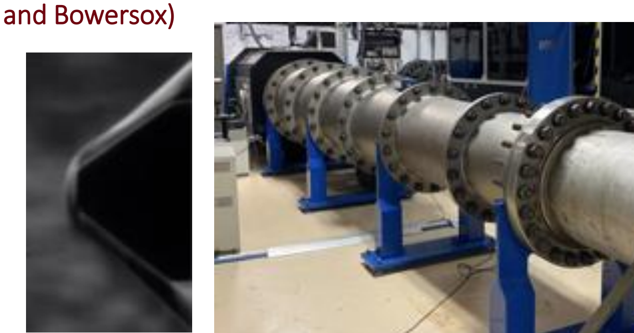
Texas A&M University (TAMU): National Aerothermochemistry and Hypersonics Laboratory

- **Hypersonic Blow-Down Tunnels**
  - Actively Controlled Expansion (ACE) Tunnel
  - Mach = 5 – 8, Re/m = 10^5-10^7
- **Mach 6 Quiet Tunnel (M6QT)**
  - Re/m = 7 – 11.5x10^6 (Quiet)
- **High Enthalpy Dual Mode Facility**
  - Hypervelocity Expansion Tunnel (HXT)
  - Hypervelocity Shock Tunnel (HST)

AFOSR Plasma Thermal Non-Eq. Experiment in ACE (Broslawski, Bowersox, North)

Transition front on HiFIRE 2:1 Elliptic Cone in the M6QT (Neel, Bowersox)

HXT with MHz Pulse Burst Laser (Limbach and Bowersox)

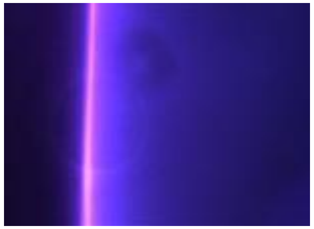


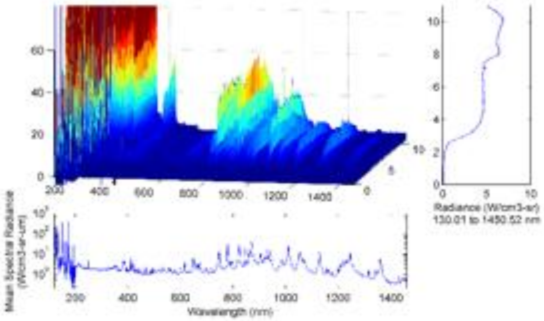
THE TEXAS A&M UNIVERSITY SYSTEM

NASA Ames Hypervelocity Free Flight Aerodynamic Facility (HFFAF) and Electric Arc Shock Tube (EAST)

- **NASA Ames operates high-enthalpy aerothermodynamic facilities unique to the Agency**
  - The Electric Arc Shock Tube (EAST) – NASA's only working shock tube, used for shock layer (entry) chemical-kinetic and radiative processes at Mach 5-50
  - The Hypervelocity Free-Flight Aerodynamic Facility (HFFAF) is NASA's only controlled-atmosphere free-flight ballistic range
- **Ames Research Center experimental testing infrastructure includes**
  - Integration of testing capabilities with CFD and quantum chemistry expertise
  - Decades of Subject Matter Expertise in experimental aerothermodynamics and impulse facility operation for fundamental and applied research
- **Recent activities include support for NASA missions & fundamental research, industry customers and Academia**

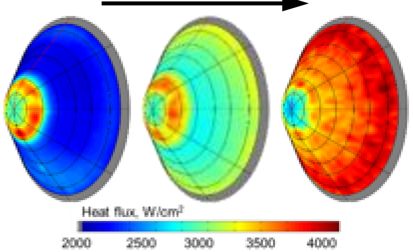
Shock Layer Radiation



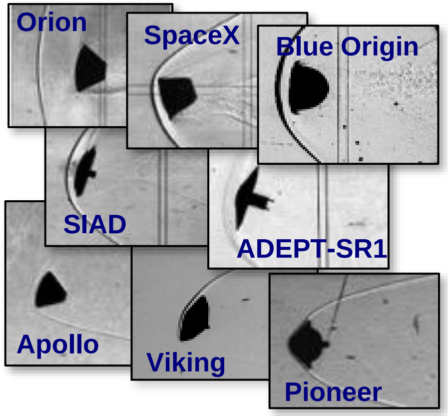


Experimental Aeroheating

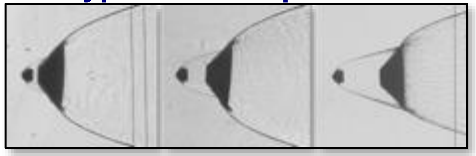
Increasing Surface Roughness



Blunt Body Aerodynamics Subsonic to Hypersonic



Hypersonic Separation



Langley 8-Foot High Temperature Tunnel

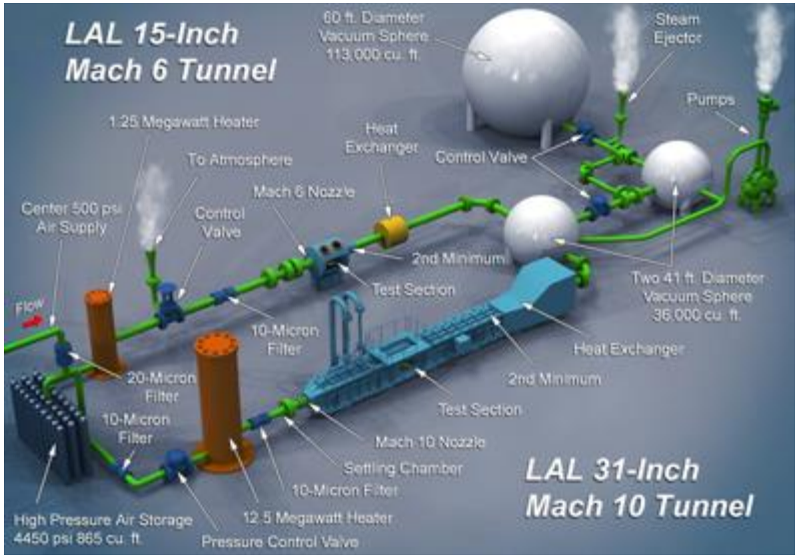
Provides flight-like simulation capabilities (enthalpy, velocity, pressure) for propulsion system performance and interactions testing:

- **Mach 3, 4, 5, 7, vitiated free stream flow**
- **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 only two US facilities in this speed range / operational capabilities**

NASA Langley Aerothermodynamics Laboratory (LAL)

- **LAL operates three hypersonic wind tunnels**
  - Conventional, perfect-gas blow-down tunnels (Mach 6 and Mach 10)
  - High flow quality, low-enthalpy test conditions
  - Reynolds number range of 1E6/ft to 8E6/ft
- **Merits:**
  - Rapid turn-around time (4-12 runs/day) for flexibility in test planning
  - Capability for parametric screening, fundamental flow phenomena investigations, CFD validation, flight database generation
- **Test Techniques**
  - Global aeroheating measurements using Langley two-color phosphor thermography method, IR thermography and/or temperature-sensitive paint
  - Aerodynamic force & moment measurements
  - Optical flow visualization (PLIF, schlieren)
- **Contributions:**
  - All major NASA programs:, Shuttle, MSL, Hyper-X, IRVE, Orion/Artemis
  - Currently supporting Mars Sample Return, LOFTID, BOLT

	31-Inch Mach 10 Air	20-Inch Mach 6 Air	15-In Mach 6 High Temperature Air
Unit Reynolds Number	0.25 - 2.1x10^6/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 +50	-10 to +50
Yaw Angle (deg)	±10	±10	±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



Partial Resume of LaRC Hypersonic Tunnel Programs

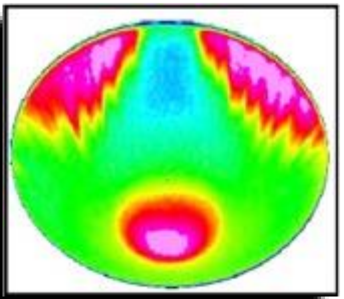
Langley Hypersonic Wind Tunnels have contributed to *all* hypersonic and space-flight and technology-development programs

- **Human Spaceflight**
  - Mercury, Gemini and Apollo capsules
  - Space Shuttle Orbiter: development, flight experiments, accident analysis, return to flight
  - Orion/Artemis capsule and Ares/SLS
  - Commercial Crew (Boeing, SpaceX)
- **Mars Exploration Missions**
  - Mars Science Laboratory and Mars 2020 (development and post-flight assessment)
  - Mars Sample Return (upcoming): Sample Return Lander and Earth Entry Vehicle
- **Solar-System Exploration**
  - Genesis solar wind sample return
  - Stardust comet sample return
- **Technology Development Flight Tests**
  - X-43 Hyper-X Airbreathing Propulsion demonstration
  - HIFiRE series of flight tests
  - IRVE and LOFTID inflatable decelerators
  - BOLT transition flight test
- **DoD / DARPA / Air Force Flight Tests and Missions**
  - Missile technologies
  - X-40 Space Maneuver Vehicle
  - X-37 Orbital Test Vehicle
  - X-51 Waverider
  - Falcon HTV2
- **Commercial Hypersonics / Access-to-Space Capabilities**
  - 1990's: Kistler RV-1 RLV, Lockheed-Martin X-33 RLV, Orbital Sciences Pegasus Launcher and X-34 RLV
  - 2000's: Sierra Nevada Dream Chaser, Boeing CST capsule, SpaceX Dragon and BFR
- **Aerothermodynamic Testing for CFD Validation, Technology Development and Fundamental Research**
  - Supersonic Retropropulsion: aerodynamics and aeroheating
  - Entry Vehicle Trim Tabs: aerodynamic performance
  - Thermal Protection System roughness – discrete, distributed and patterned TPS roughness
  - Wake Flows: flow field behavior, aftbody heating
  - Shock-shock / shock-BL interaction
  - Inflatable aeroshells – surface deflection effects on heating
  - Stagnation-point injection for aerodynamic control
  - Fluid Structure Interactions
  - Mid L/D Entry Vehicles: cross-flow transition
  - Academic partnerships

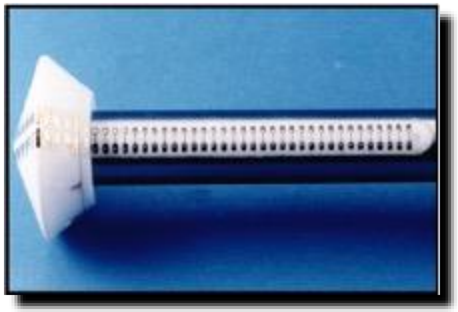
How to Test?

Global (Surface/Flow Field) and Discrete (heating/pressure) Measurement Techniques for LaRC Hypersonic Tunnels

LAL Facilities: Standard Instrumentation Types & Techniques



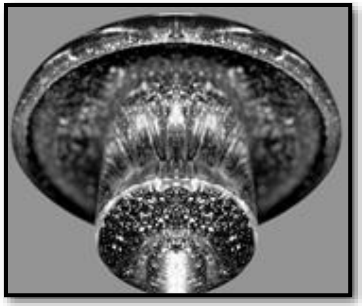
Phosphor and IR thermography, or temperature-sensitive paint for global heat transfer measurements



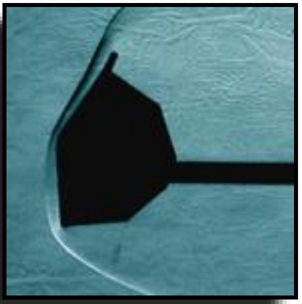
Thin-film, thin-skin, or coaxial thermocouple gages for discrete heat transfer measurements

Electronically Scanned Pressure (ESP) measurements

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



Oil flow for surface streamline visualization

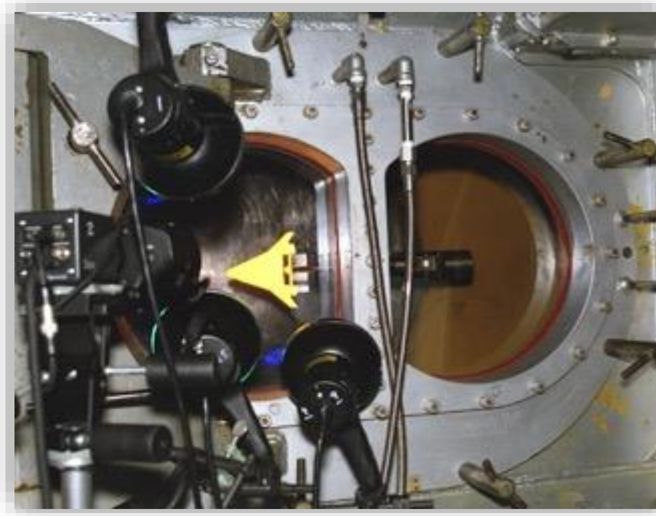


Schlieren and PLIF for flow field visualization

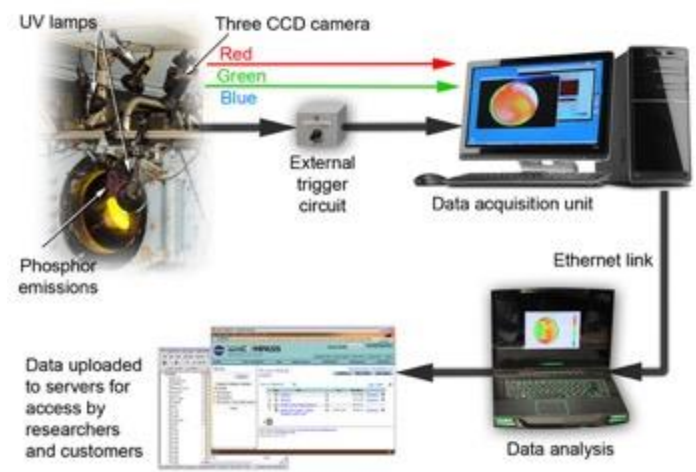
Aeroheating: Global Phosphor Thermography

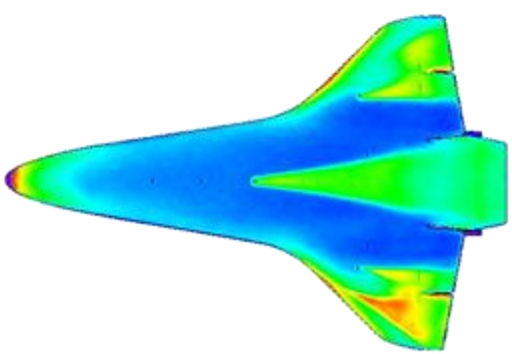
- Thermography provides global measurement of surface temperature, heat transfer and boundary-layer transition location
- Global phosphor thermography is primary aeroheating technique in LaRC hypersonic tunnels
  - Slip-cast silica ceramic models coated with phosphor mixture
  - Phosphor coating fluoresces in red and green under UV light to provide two-color relative-intensity optical measurements
  - Coating emission intensity is dependent on:
    - Incident light - resolved using the two-color ratio
    - Surface temperature – desired quantity. Thermal conduction analysis provide surface aeroheating rates
  - Advantages- rapid/inexpensive fabrication, robust coating, multiple configuration options can be tested at low cost
- Infrared (IR) and Temperature Sensitive Paint (TSP) thermography provide similar capabilities at different optical resolution and temperature ranges

UV illuminated mode



Data Reduction



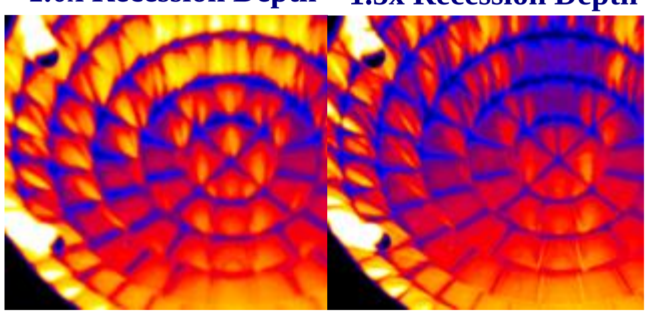


Processed aeroheating data

Aeroheating: Infrared Thermography (IR)

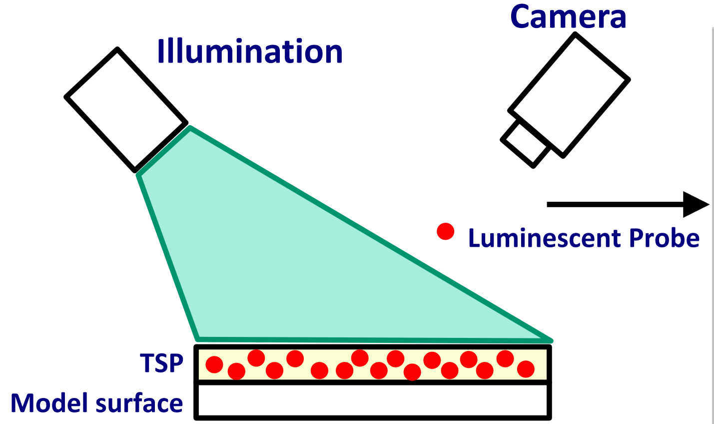
- **Non-intrusive video-based, radiometric measurement technique capable of obtaining real-time global surface temperature data based on blackbody radiation theory**
- **Requires special windows**
- **Surface temperature of model calculated based on radiation at infrared wavelengths**
- **LAL current infrared imaging system**
  - Long Wave Infrared (LWIR) window (Zinc Selenide)
  - Borrowed cameras (from other groups on center or from FLIR)
  - FLIR System ThermaCAM SC 3000 camera
- **LAL system in development**
  - Mid Wave Infrared (MWIR) window (Sapphire glass purchased, frame being designed)
  - FLIR X8500sc (already procured)

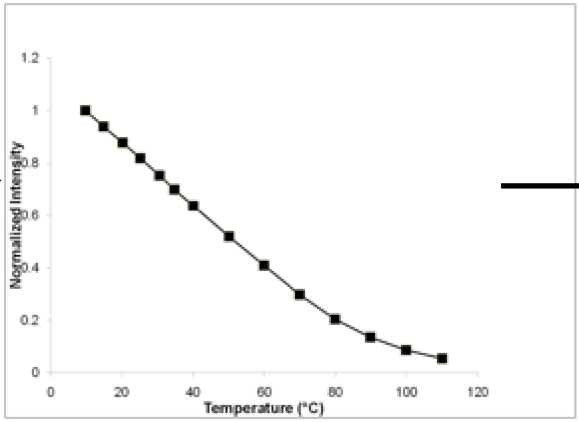
1.0x Recession Depth **1.5x Recession Depth**

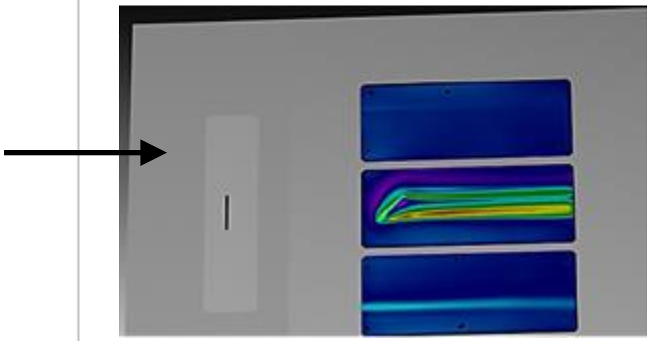


Orion blocked heatshield model, made of PEEK material, in LaRC Mach 6 Tunnel

Aeroheating: Temperature Sensitive Paint (TSP) Thermography







- **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

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 °C)**
- **Temp range can be adjusted using diff. luminescent probes**

Disadvantages

- **Requires a reference image**
  - Does not have an intrinsic reference like two-color phosphor
- **Relatively narrow temp ranges (~50-100°C range at most)**
- **Formulations cannot withstand high temperatures (>150 °C)**
  - Undergoes irreversible changes that alter sensitivity

Aeroheating: Thin Film, Thin Skin, Thermocouples

Discrete, non-intrusive methods for measuring temperature

Thermocouples

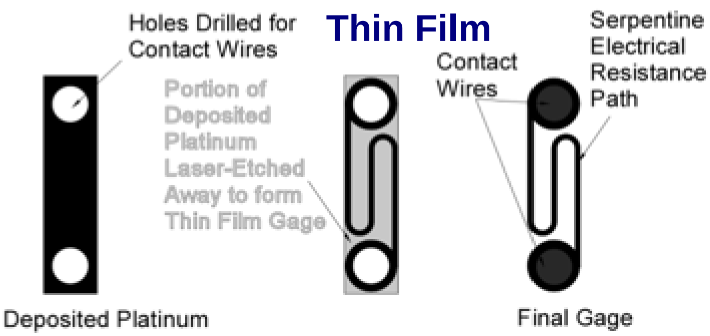
- **Surface thermocouples for direct measurement of surface temperatures**
- **Back-face thermocouple for ”thin-skin” measurement of heating**
- **Multiple types of thermocouples (Type E, K, etc.)**
- **More robust than thin-films, but larger sensor “footprint”**

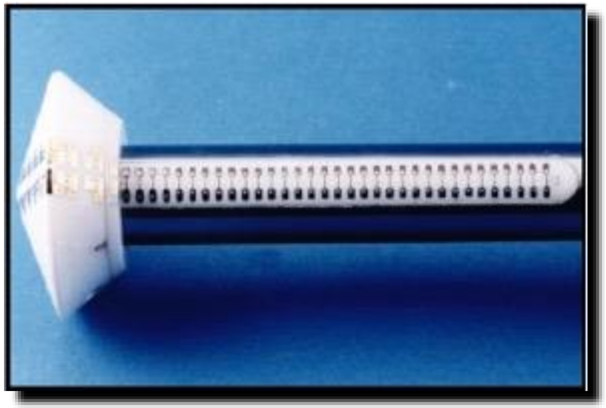
Thin Film Sensors

- **Sampling frequencies as high as 100s of kHz (possibly up to 1MHz)**
- **Laser-etched or hand-painted on models**
- **Small size (relative to thermocouples) allows for placement on leading edges, curved surfaces, etc.**

Heat-Transfer

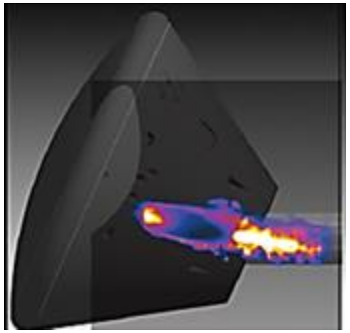
- **Can determine heat flux via conduction analysis of sensor temperature-time histories**
- **Sensor temperature provide boundary-condition for internal conduction analysis**

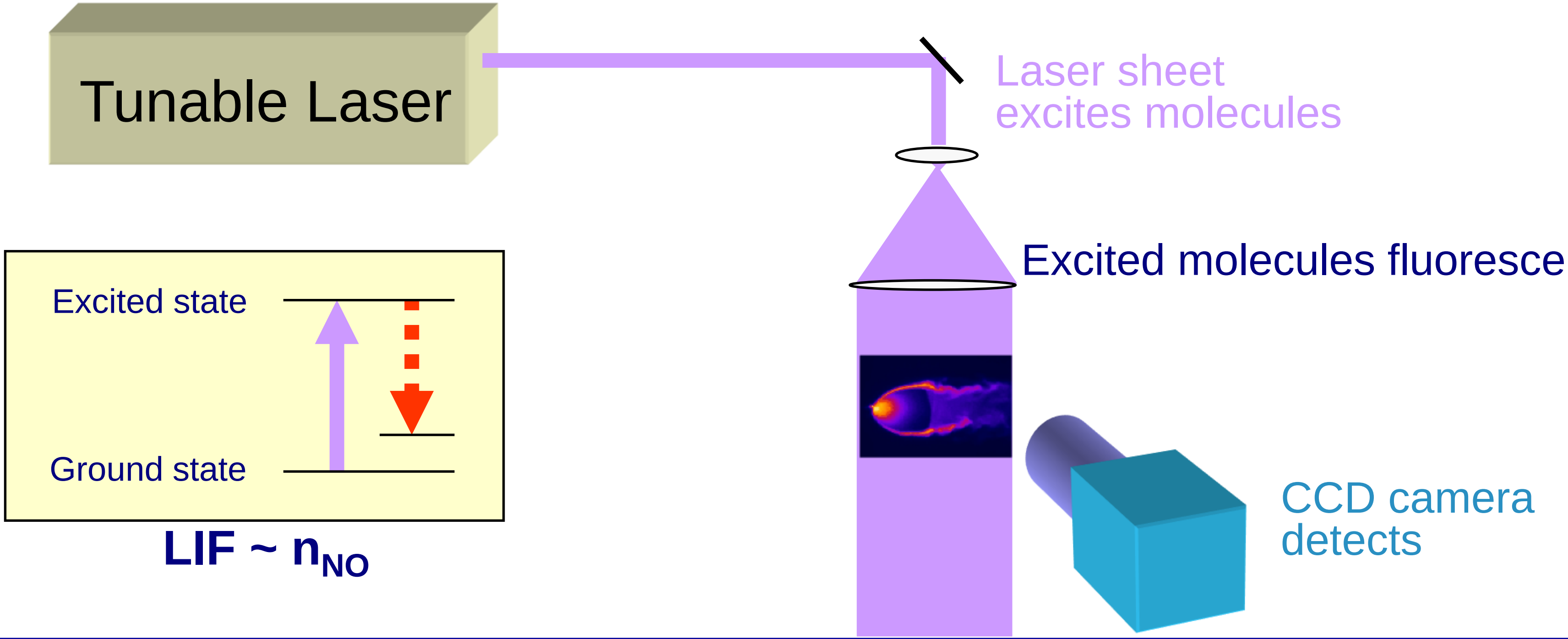




Flow Visualization: Planar Laser Induced Fluorescence (PLIF)

- 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 (array of 25 lenses focus laser sheet into 25 lines)

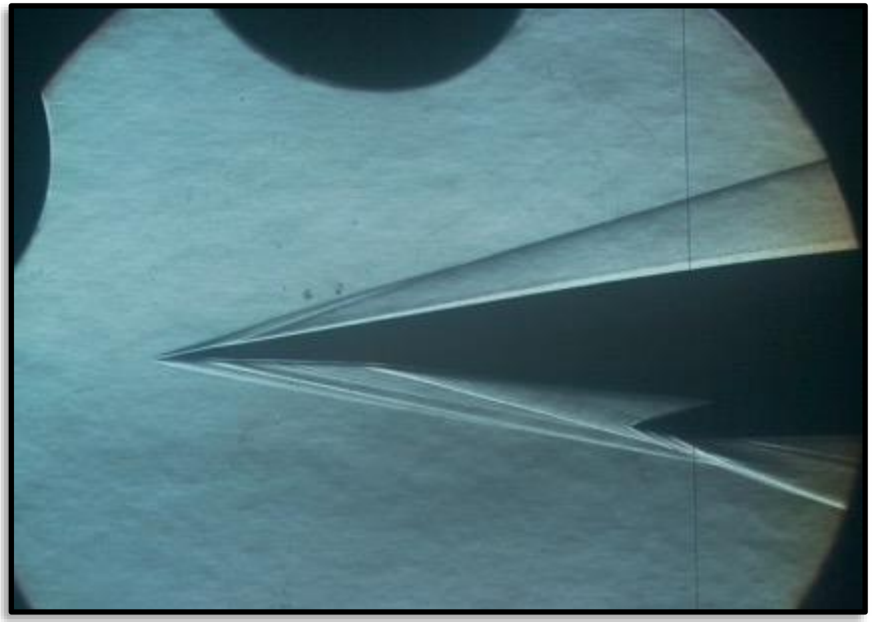


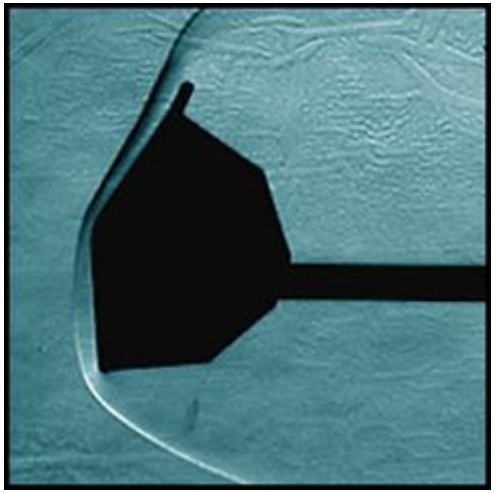


LIF ~ n_{NO}

Flow Visualization: Conventional and High-Speed Schlieren Systems

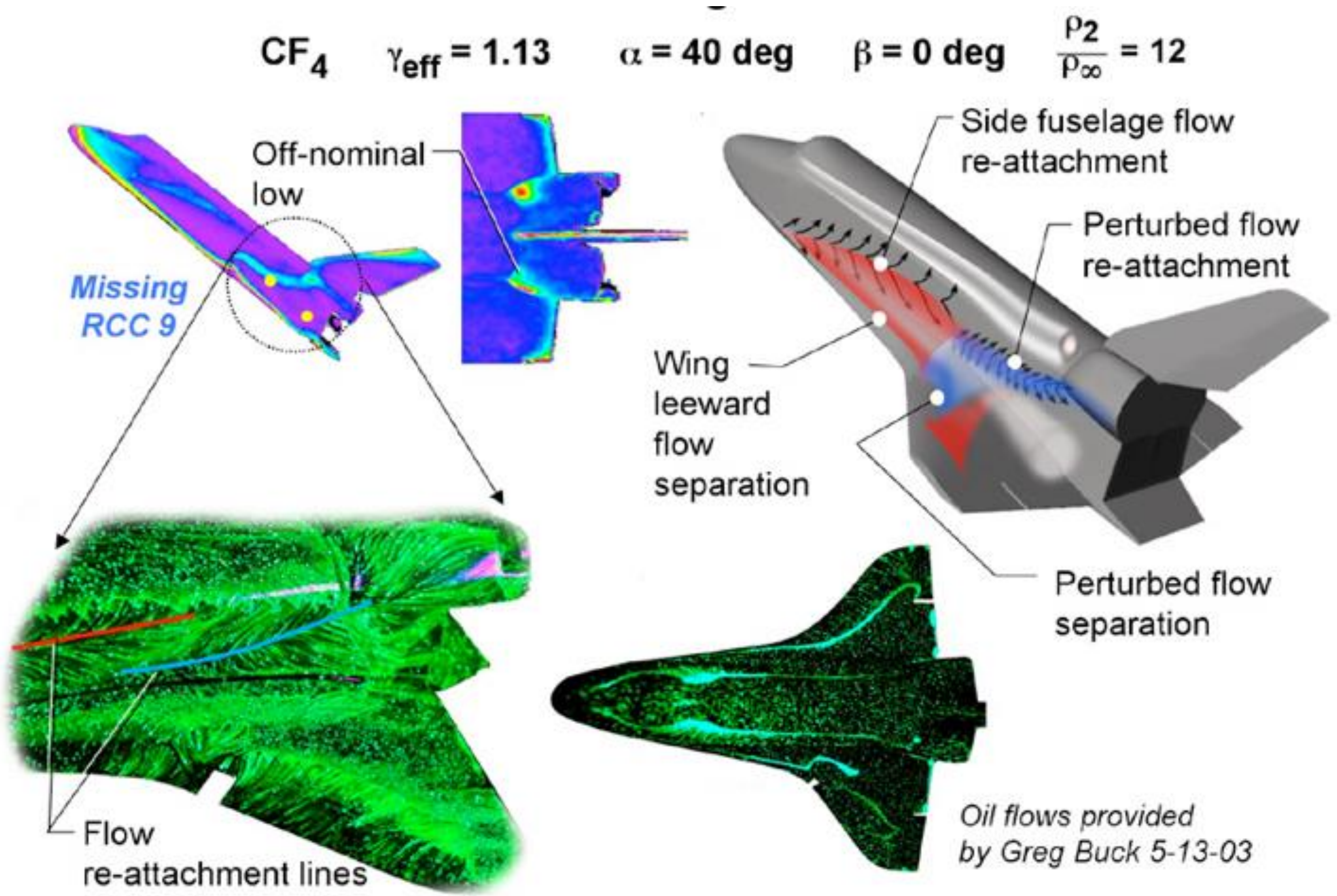
- Visualization of density changes
- Sensitive and low cost
- Displays focused image using system of lenses and light source
  - A knife edge is used for cutoff
- Used in wind tunnels for decades
  - Recently used in full scale aircraft
- LAL owns Photron Fastcam SA-Z camera
  - Megapixel resolution at up to 21K fps
  - Frame rates up to 2M fps with reduced resolution
- High framing rates allow for comparison to high speed data as well as visualization of flow phenomena
  - Frequencies of shocks, etc, can be measured
  - Inlet unstart conditions seen while pitching models
  - Boundary layer state can be seen
  - Unsteady shock conditions can be examined





Flow Visualization: Oil Flow

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



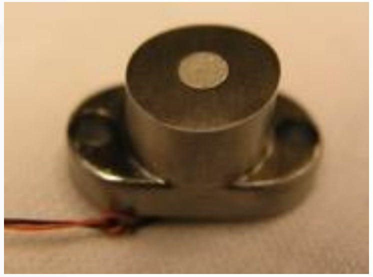
Surface Pressure Transducers

Kulites

- **Measure freestream disturbance and boundary layer measurements**
- **Silicon diaphragms as basic sensing element**
  - Diaphragm has 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

Piezoelectric Pressure Sensor (PCB)

- **Characterize BLT by measuring growth/breakdown of instability waves**
- **PCB113**
  - Dynamic Pressure sensor
  - Resonant frequency greater than 500 kHz
- **PCB132**
  - Measure frequencies 11 kHz to 1 MHz
  - Roll-off begins around 300 kHz
  - Sensor diameter is 0.125 inches
  - Ceramic sensing unit ~0.03” x 0.03”
- **Have successfully measured second-mode instability waves on cones (through all stages of growth, saturation and breakdown) in multiple hypersonic facilities.**

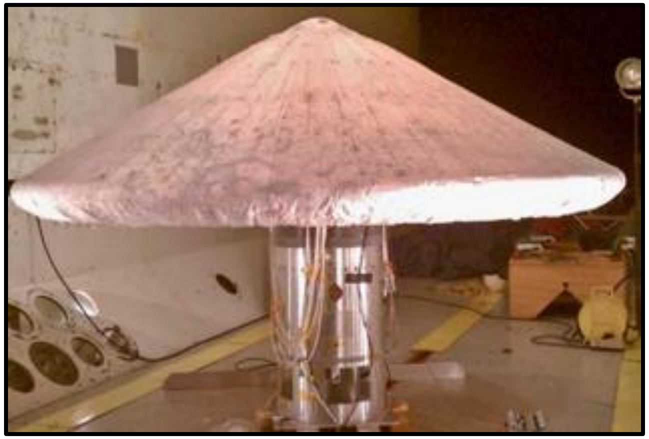


Partial Resume of
LaRC Wind Tunnel Testing for
Flight Missions

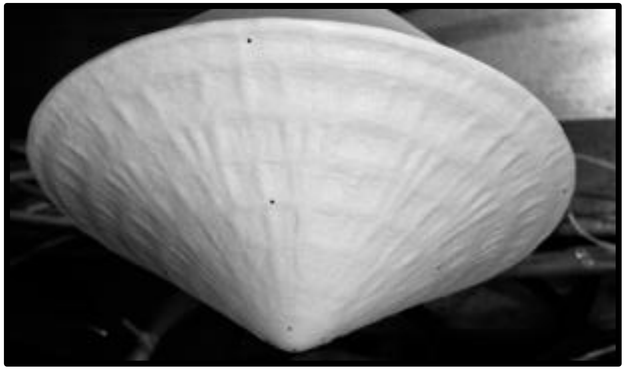
Flight Programs – IRVE Aeroshell Deflection Effects

- 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
  - Successful IRVE-III flight test in 2012
  - Similar testing ongoing for 2022 LOFTID flight test

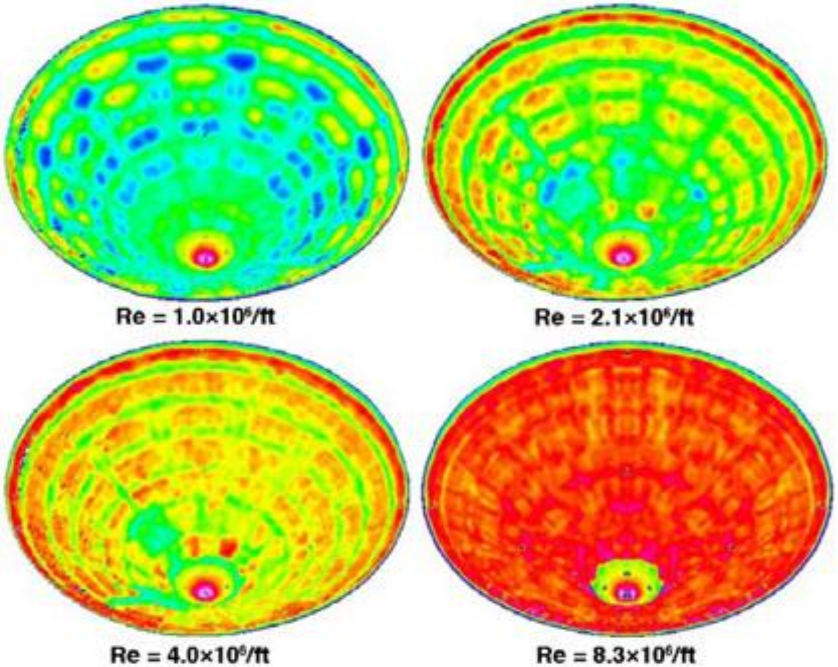
IRVE-3 inflation test article



Deflected OML Wind Tunnel Model



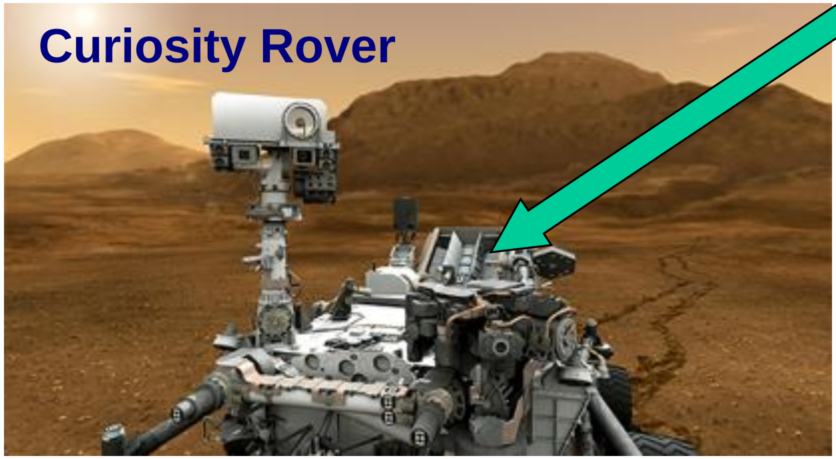
Heating data on deflected aeroshell

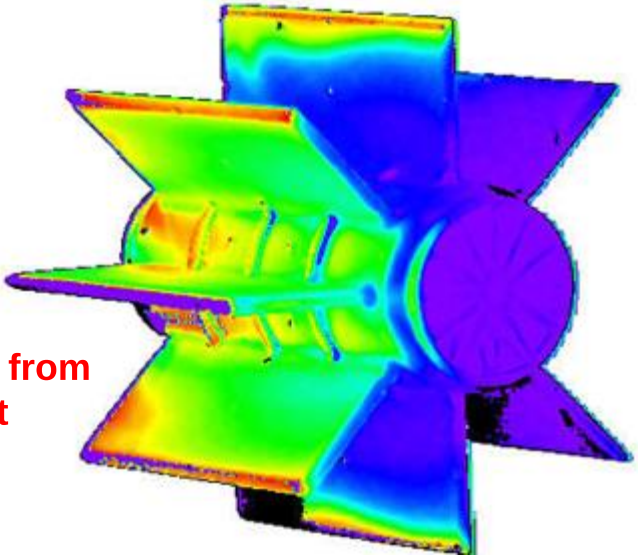


Flight Programs – MSL MMRTG Breakup Analysis

- 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 (successful landing in 2012)

Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) powers Curiosity



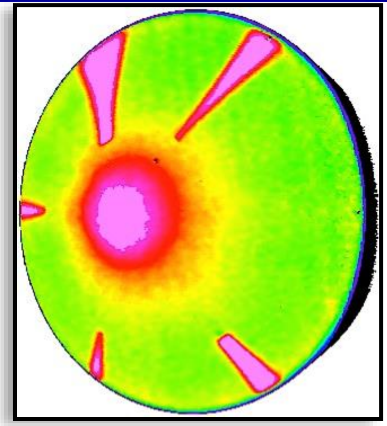


Heating data from Mach 10 test

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 (2004 return to Earth)

Aeroheating data showing turbulent wedges produced by cavities



Boundary-layer transition correlation

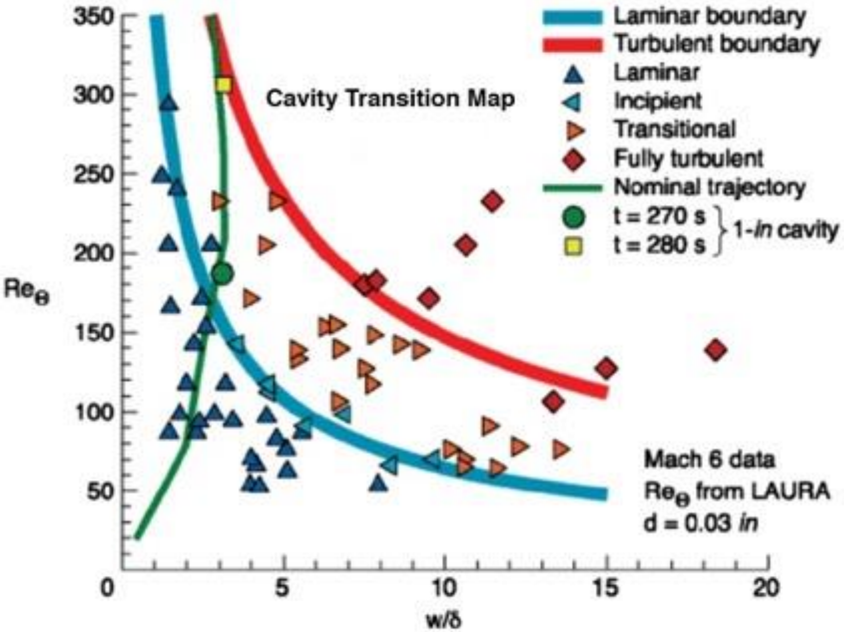
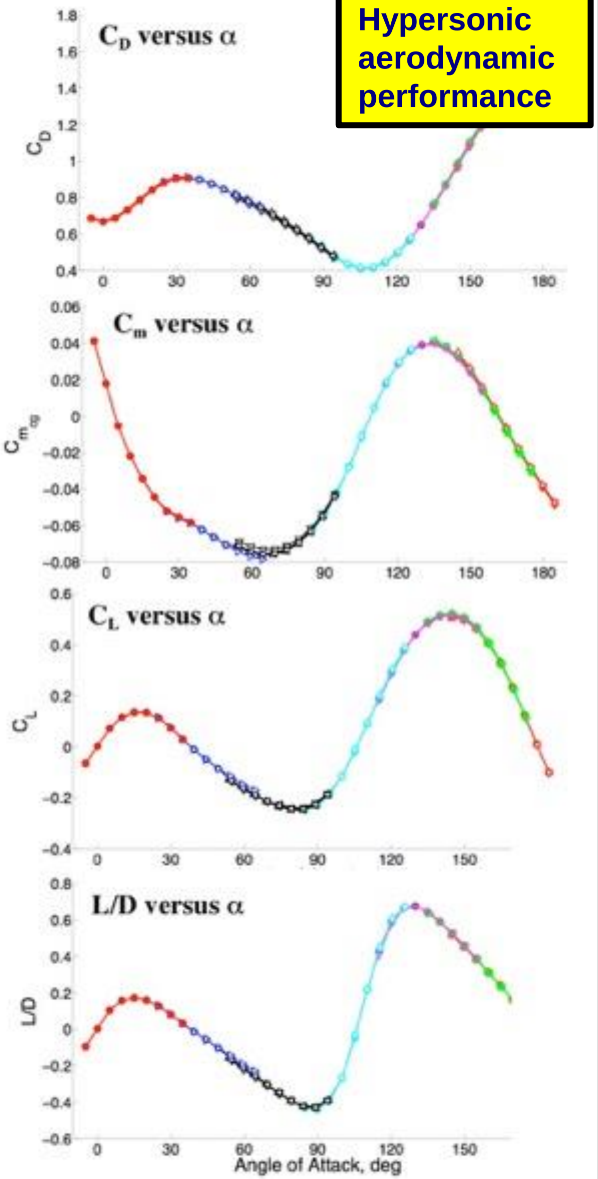


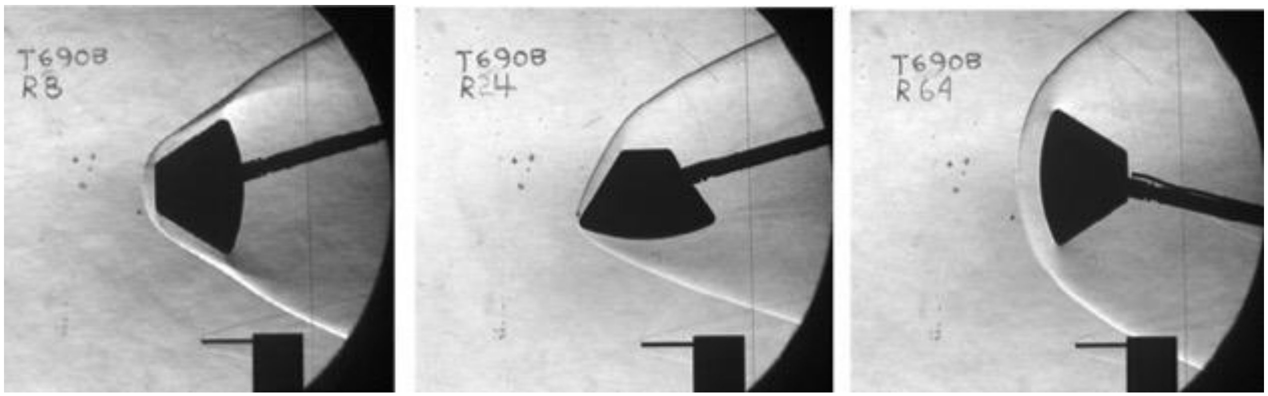
Photo of recovered capsule showing char downstream of attachment point cavity

Flight Programs – Orion (Artemis) CM Hypersonic Aerodynamics



Hypersonic aerodynamic performance

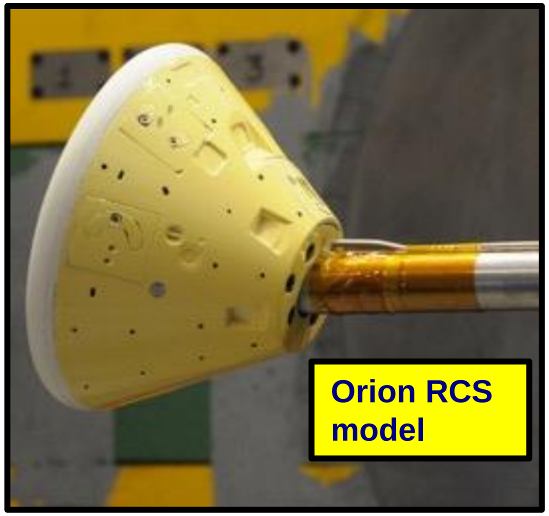
- Background: Aerodynamics of Orion crew module must be quantified at all angles-of-attack in case of abort during flight
- Approach: Force-and-moment measurements and schlieren imaging in 20-Inch Mach 6 Air Tunnel and UPWT
- Impact: Supersonic / hypersonic aero database developed to support Orion design – successful Exploration Flight Test 1 in 2014



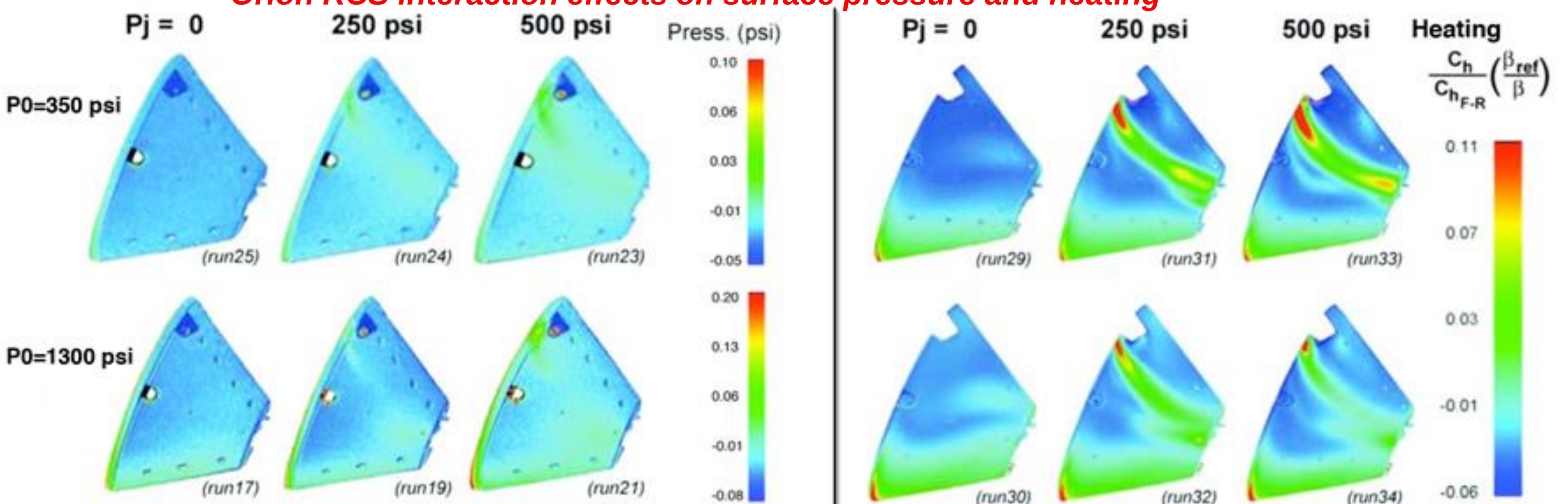
Schlieren imagery of crew module

Flight Programs – Orion (Artemis) 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 - successful Exploration Flight Test 1 in 2014

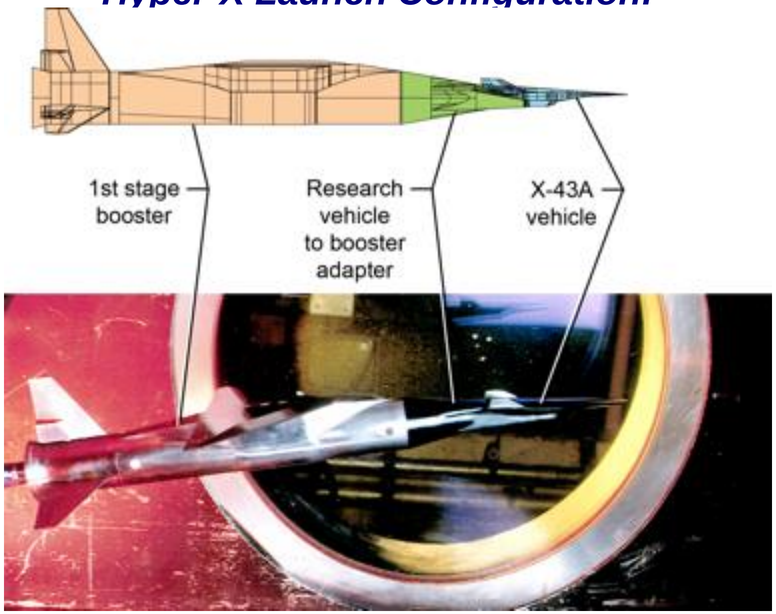


Orion RCS interaction effects on surface pressure and heating

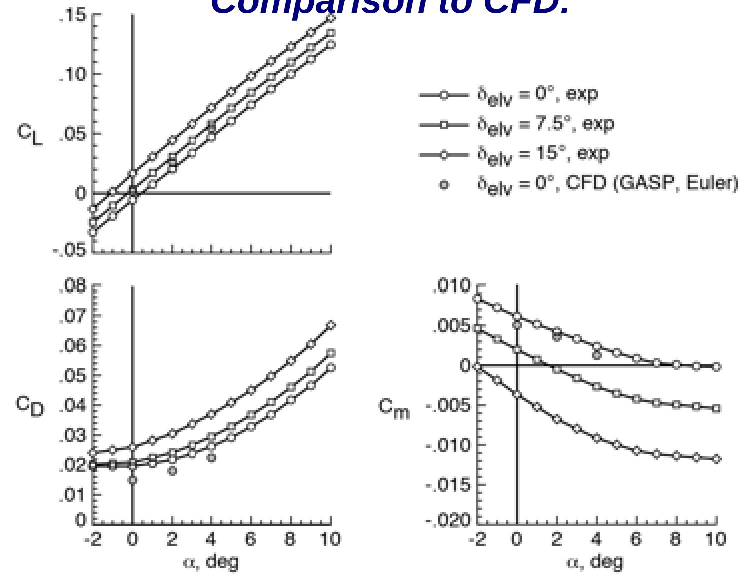


Flight Programs: Hyper-X Aero Database (1996 – 2000)

Hyper-X Launch Configuration:



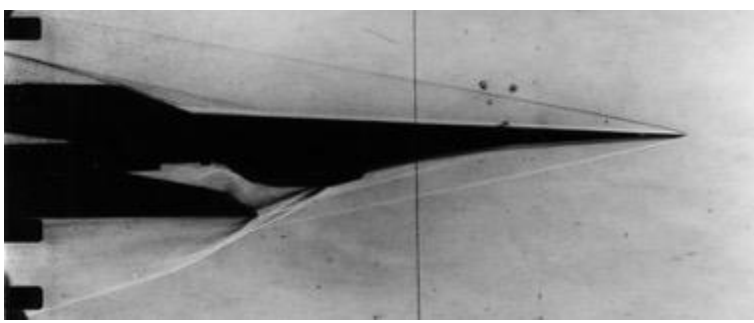
Mach 6 Basic Aerodynamics with Closed Inlet in Comparison to CFD:



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

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

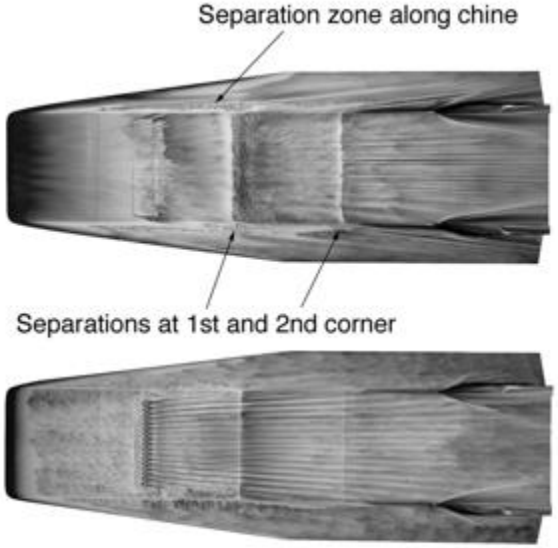
Sample Stage Separation Schlieren from the 20" Mach 6 Tunnel:



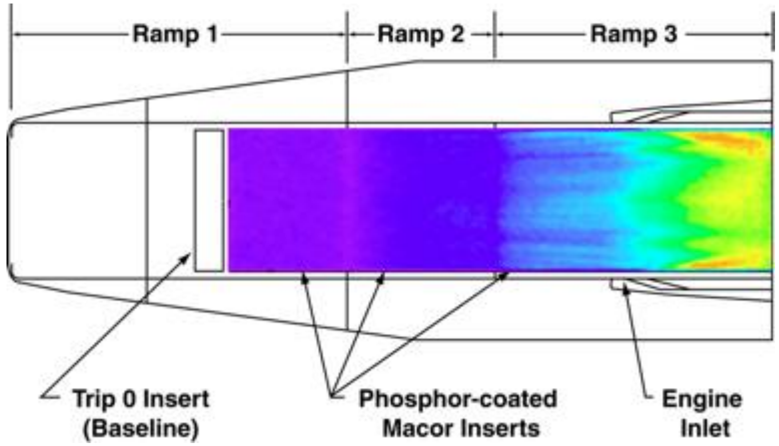
Ground test data and CFD used to derive flight aerodynamic database and to understand stage separation effects – successful flight test in 2004

Flight Programs: Hyper-X Boundary Layer Trips (1997 – 2000)

Oil-Flow Test in 20” Mach 6 tunnel:



Forebody Heating from 31” Mach 10 tunnel:



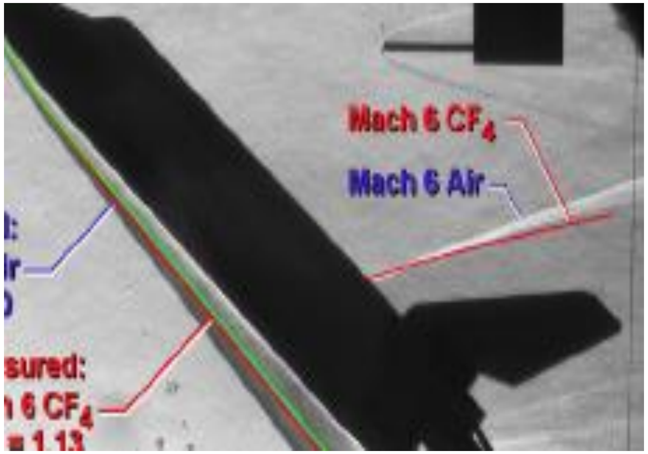
Schlieren from GASL Hypulse:

Final Trip Configuration Scaled for Flight:

Ground test data used to screen flight trip configurations – engineering analysis used to successfully scale trips for flight - successful flight test in 2004

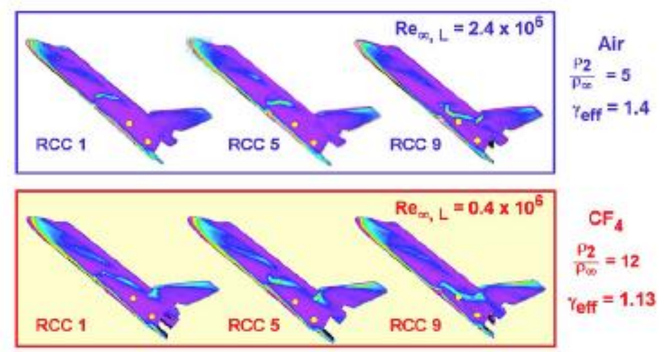
Flight Programs: Columbia Accident Investigation (2003 – 2004)

Comparison of Shock Detachment Distance Between Wind Tunnel and Flight:

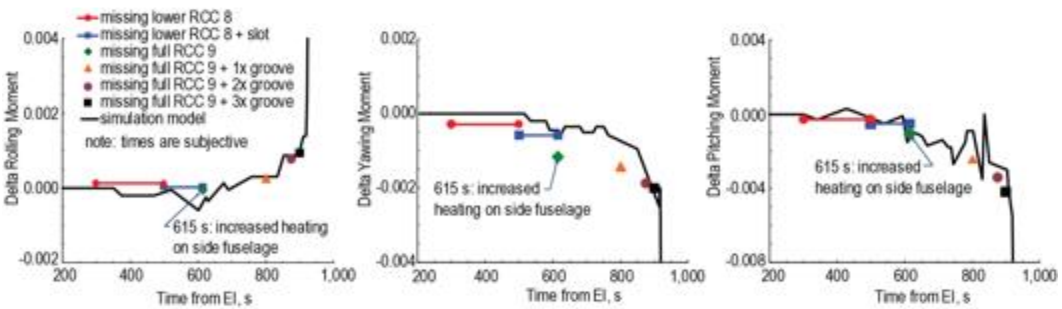


Comparison of Fuselage Heating with Different RCC Panels Missing:

$M_\infty = 6$ $\alpha = 40$ deg $\beta = 0$ deg



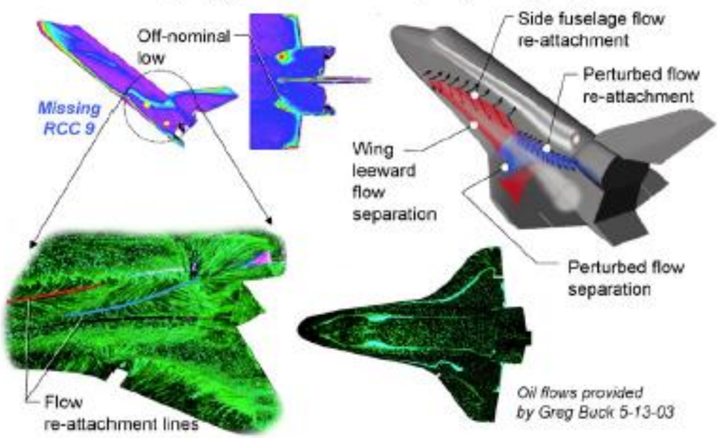
Incremental Moment Coefficients for Progressive Damage Scenarios:



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

Postulated Leeside Flow Due to Wing Leading Edge Damage:

CF_4 $\gamma_{eff} = 1.13$ $\alpha = 40$ deg $\beta = 0$ deg $\frac{\rho_2}{\rho_\infty} = 12$

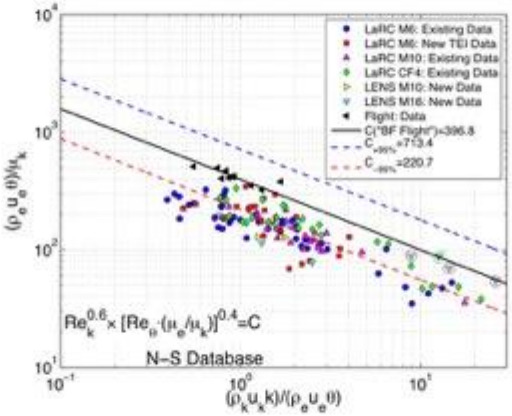


Ground test data instrumental in forensic analysis of Columbia accident – identified plausible damage progression

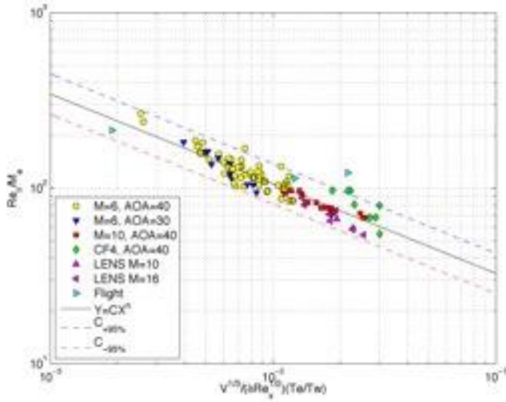
Flight Programs: Shuttle Return-to-Flight (2005 – 2010)

BLT Tool V2 Correlations:

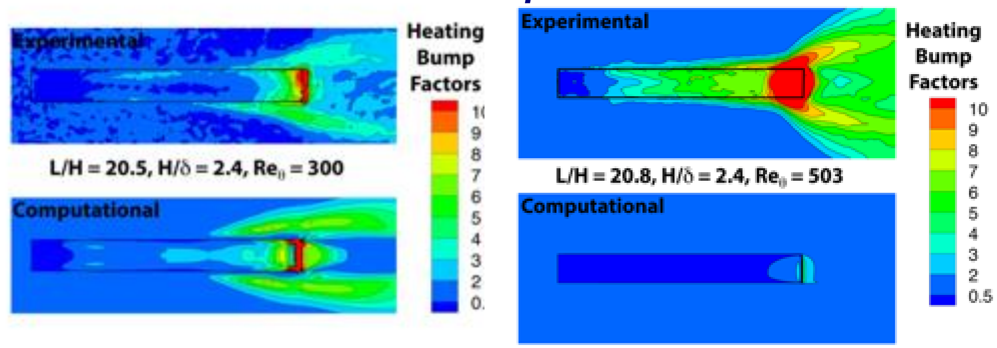
Protuberances:



Cavities:



Comparison of Cavity Heating Measured to Laminar Predicted Bump Factors:



On-orbit tile damage inspection

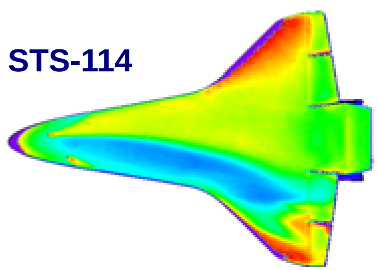
Ground test data and CFD used to support RTF tool development – tools successfully implemented for all subsequent missions

Space Shuttle Orbiter Mission Support and HYTHIRM

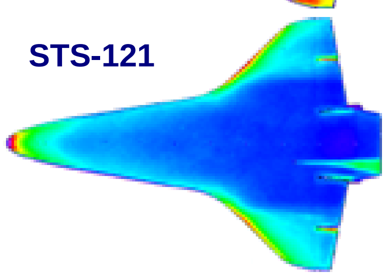
On-Orbit Mission Support

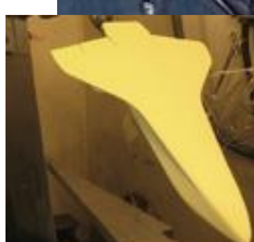
- Protruding gap fillers on STS 114 and -121 exceeded safety limits, potentially required on-orbit repairs
- Boundary layer transition data rapidly collected (4 hours between call and test start) in 20-Inch Mach 6 Tunnel based on observed shuttle damages
- Real time testing for STS-114 completed concurrently with repair space-walk (in event first space walk did not completely resolve issues, testing would determine if second walk necessary)
- Real-time testing completed during STS-121 helped confirm repair not necessary

STS-114



STS-121

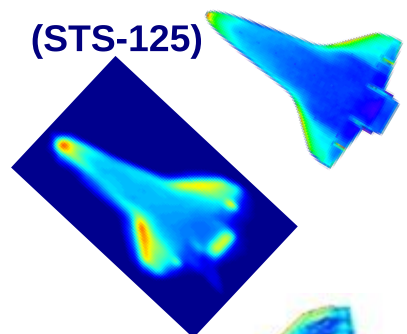




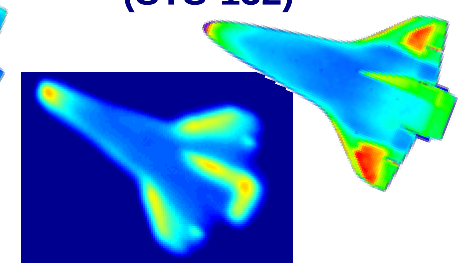
Hypersonic Thermodynamic Infrared Measurements

- Post flight ground testing in three tunnels (Mach 10, Mach 6, Mach 6 CF_4) to recreate HYTHIRM flight data from four flights (STS-119, -128, -128 and -132)
- Ground data matched flight AoA, yaw and flap deflections, tried to re-create turbulent wedge with correct spreading angle to improve CFD
- Data assisted computational analysis of flight data

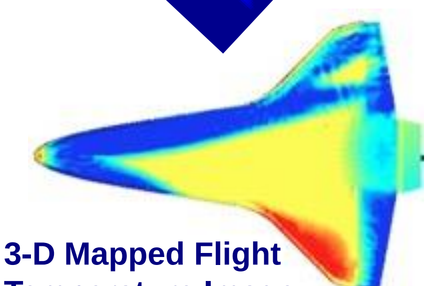
(STS-125)



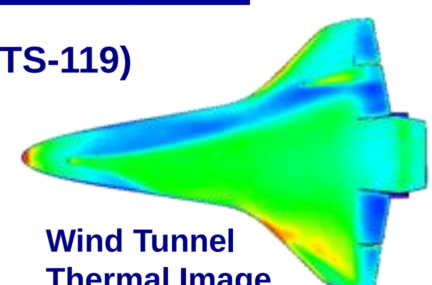
(STS-132)



(STS-119)



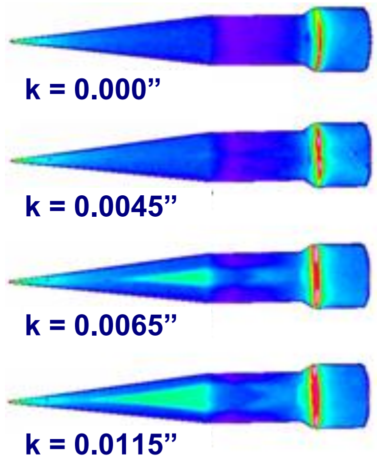
3-D Mapped Flight Temperature Image



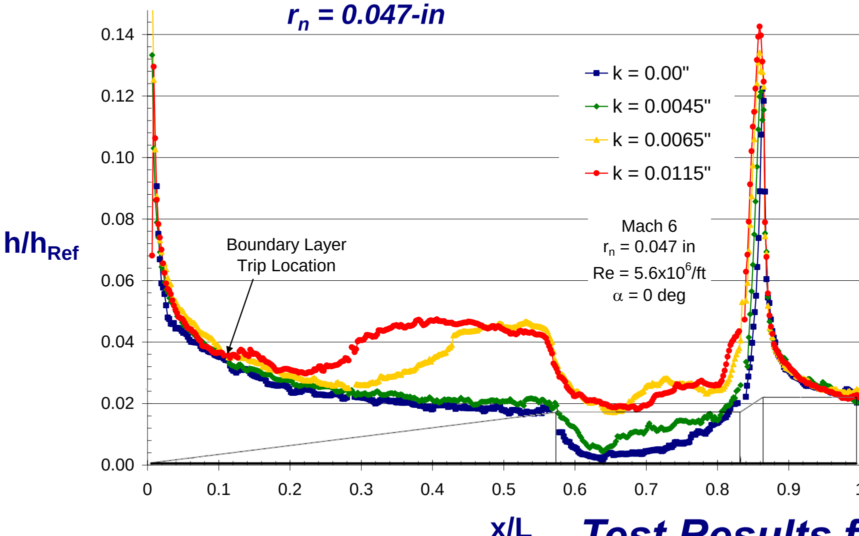
Wind Tunnel Thermal Image

HIFiRE Support (2006 – 2012)

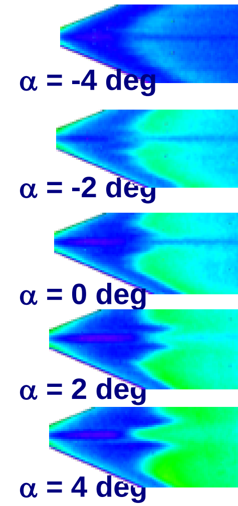
HIFiRE 1 BLT Trip Results:



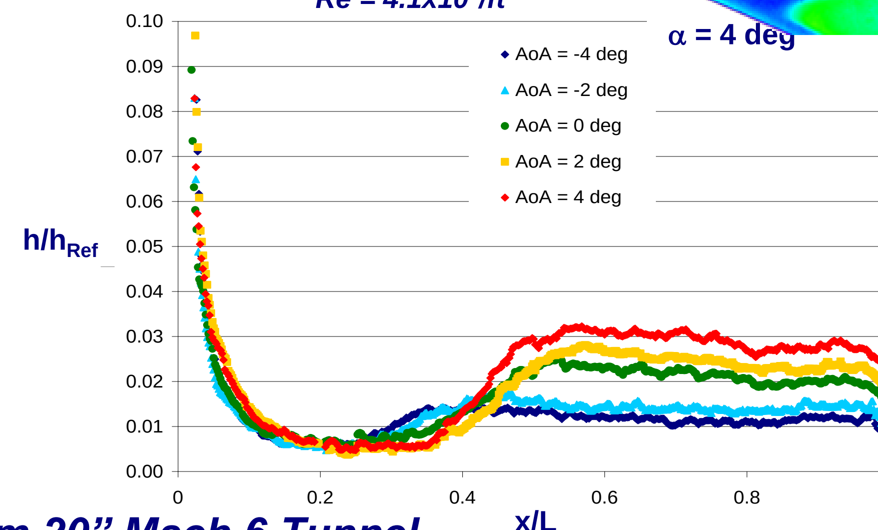
α = 0-deg
Re = 5.6x10⁶/ft
r_n = 0.047-in



HIFiRE 5 Transition Front w/ AOA:



Re = 4.1x10⁶/ft



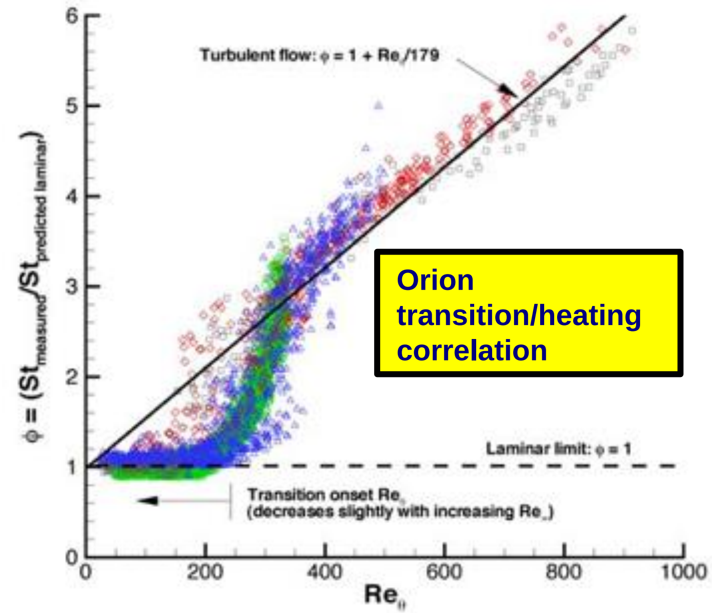
Test Results from 20” Mach 6 Tunnel

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

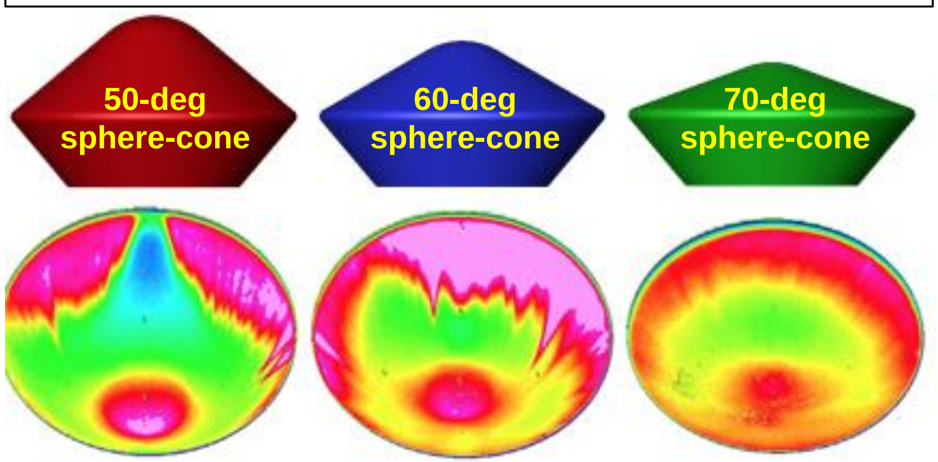
Partial Resume of
LaRC Wind Tunnel Testing for
Research & Technology Development

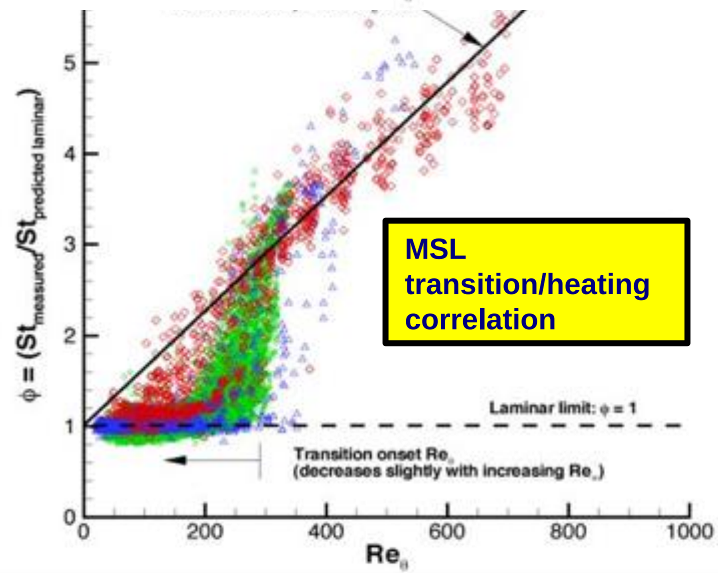
Research & Development – Blunt Body Transition and Turbulence

- 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

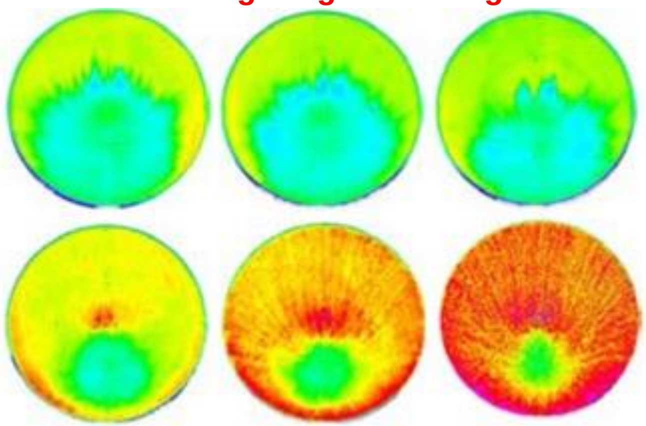




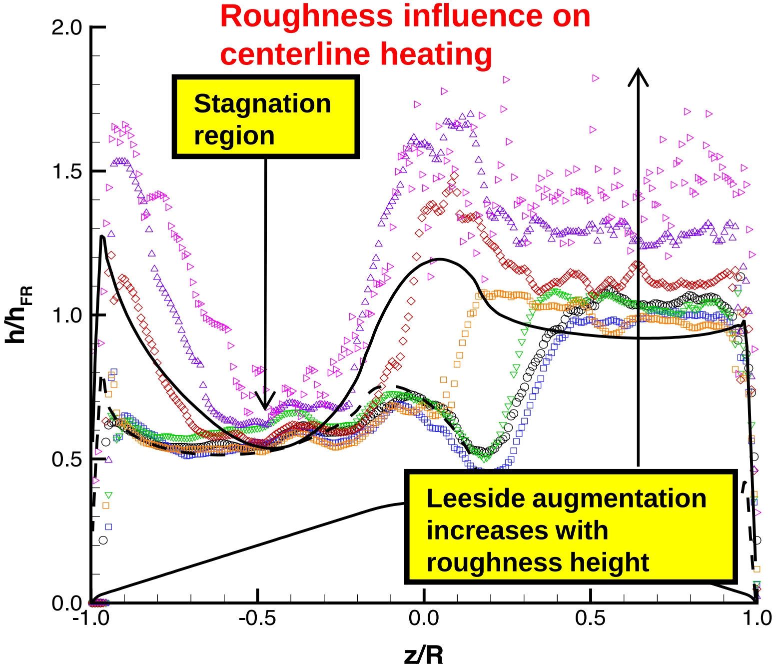
Research & Development – Distributed TPS Roughness

- 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

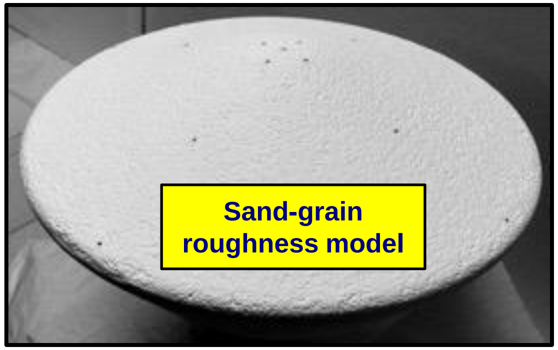
Global heating effects from increasing roughness height

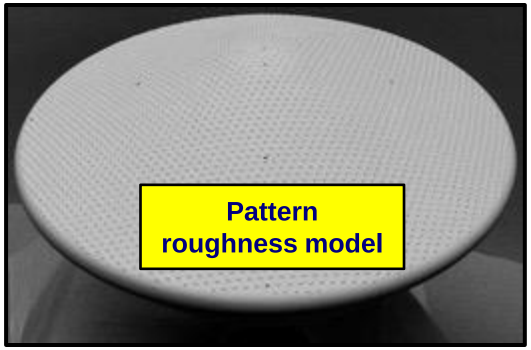


Roughness influence on centerline heating



Distributed roughness wind tunnel models



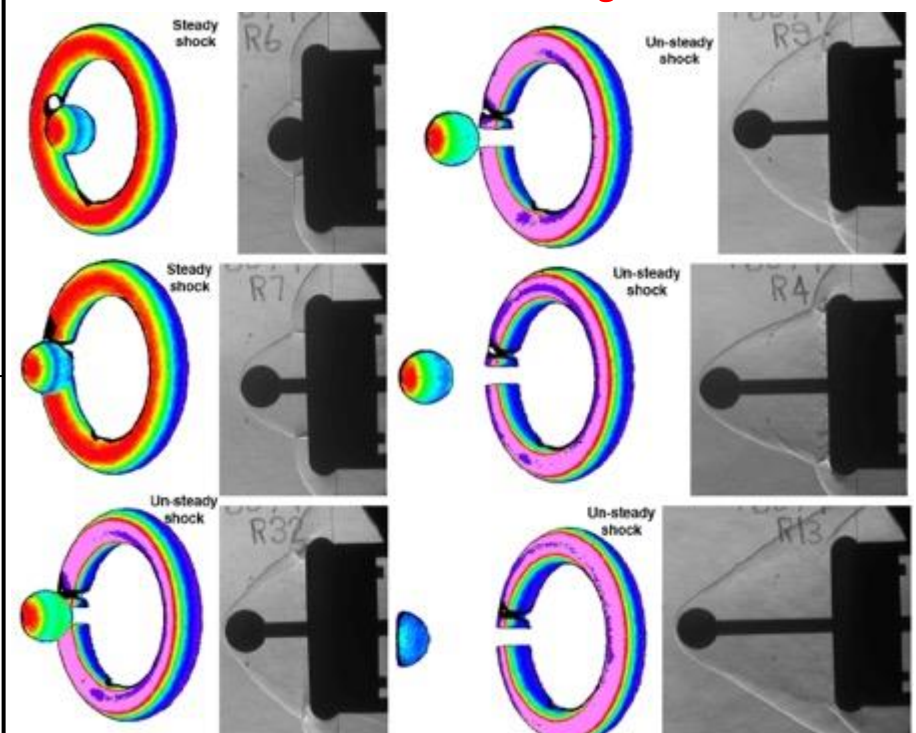


Research & Development – Towed Ballute Flow-field Interactions

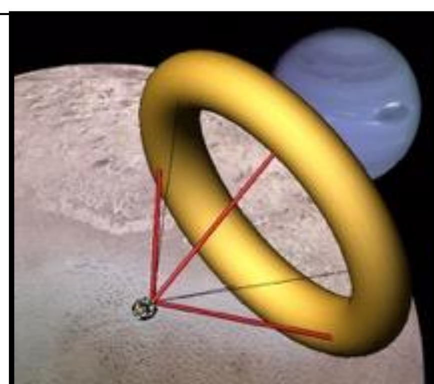
- Background: Towed ballutes are large, inflatable, structures that trail a small payload and act as a high-altitude decelerator for orbital aerocapture.
- Issue: For towed ballutes, flow-field interactions between towing spacecraft and ballute (and also tow lines). Flow may be unsteady, spacecraft shock wave may impinge on ballute and affect heating and aerodynamics.
- Approach: Testing of towed ballute models in 20-Inch Mach 6 CF_4 Tunnel and 20-Inch Mach 6 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 CF_4 tunnel

Heating data and schlieren images for various tow lengths



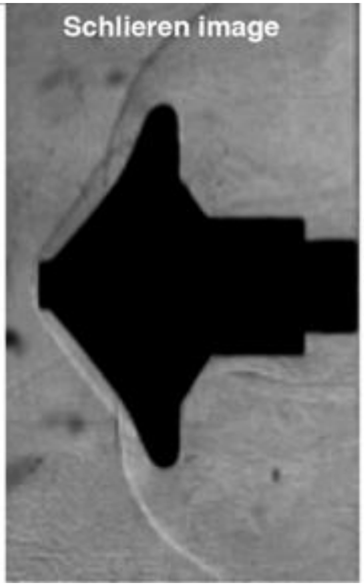
Artist's concept of spacecraft with towed ballute

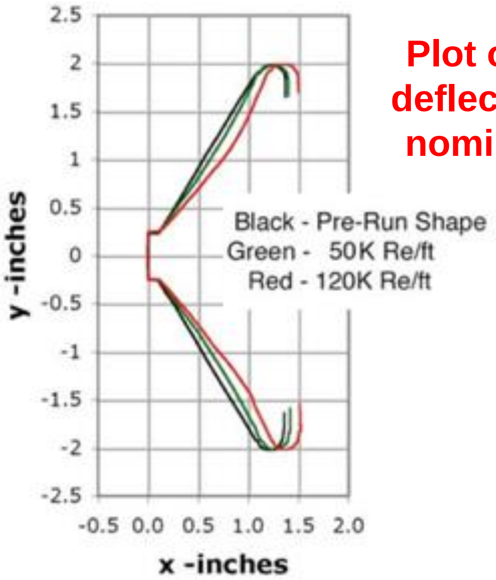


Research & Development – Attached Ballute Aeroelasticity

- 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: Test models with flexible materials in LaRC 31-Inch Mach 10 and low-density CF_4 Tunnels
- Result: Measurements of ballute deflections for comparison with structural response codes.

Aerocapture with Attached Ballute (artist's concept)

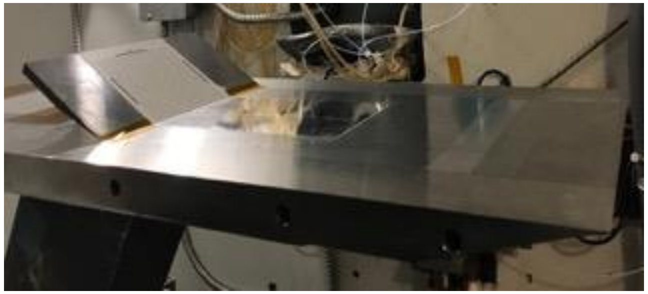




Plot of surface deflections from nominal shape

Fluid Structure Interactions (2018 - present) – UMD Partnership

Initial Demonstrations of Test Techniques



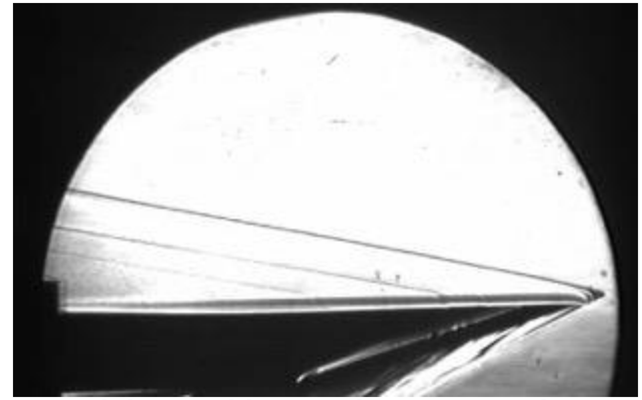
Flat Plate Model with Wedge in 20 M6 Tunnel

Schlieren of flow at base of wedge

Demonstrations of:

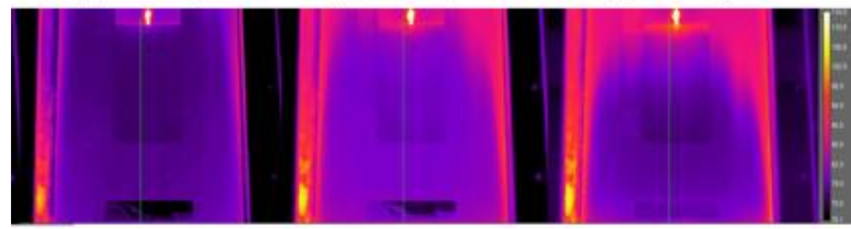
- High-speed photogrammetry (30 KHz)
- Fast temperature sensitive paint (6 KHz)
- High-speed focusing Schlieren (40KHz - sequential image pairs taken at much higher rates using the burst mode)
- Used simultaneously with high-frequency surface pressure sensors

Inflow conditions and surface temperatures

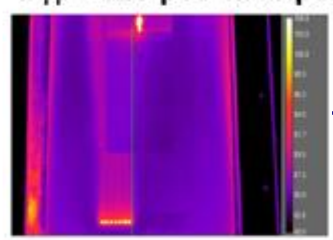


Schlieren with Boundary Layer Rake

P_{T1} = 125 psi P_{T1} = 250 psi P_{T1} = 475 psi

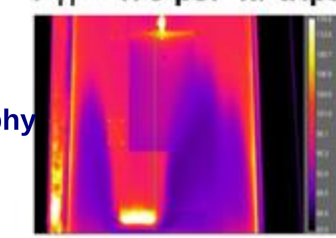


P_{T1} = 125 psi w/ trips



LWIR Thermography

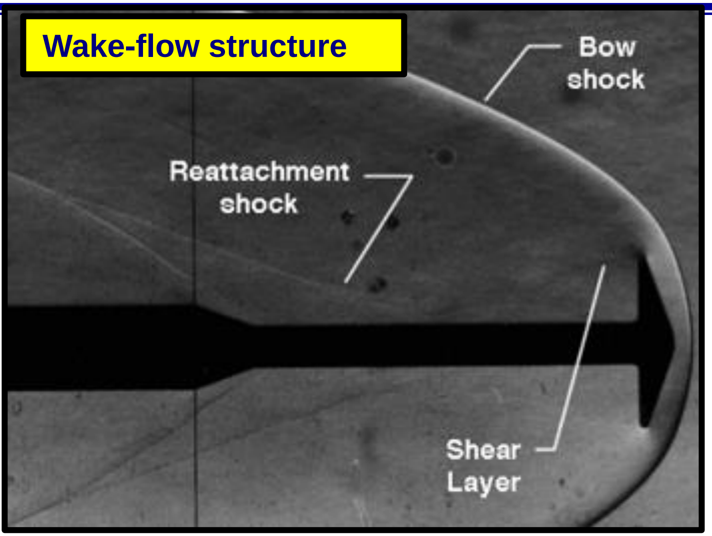
P_{T1} = 475 psi w/ trips



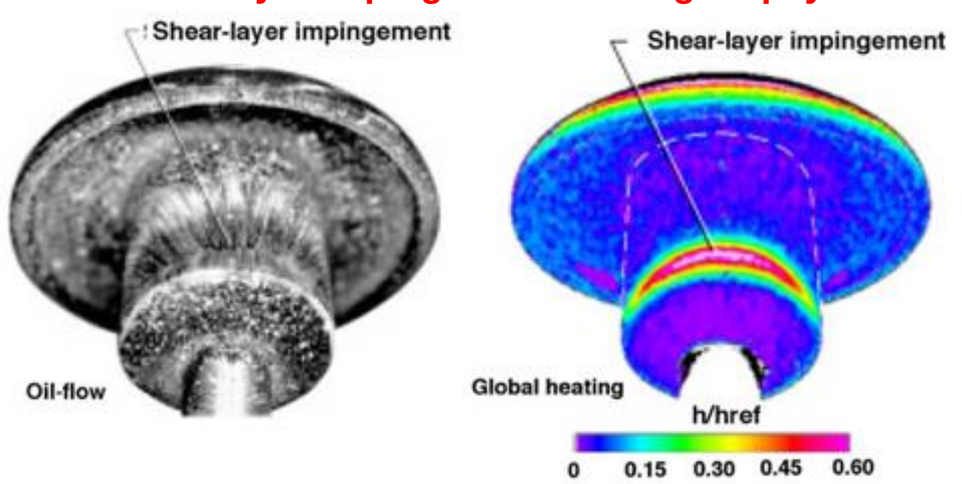
Partnership has resulted in demonstration of multiple test techniques in preparation for upcoming compliant panel entry

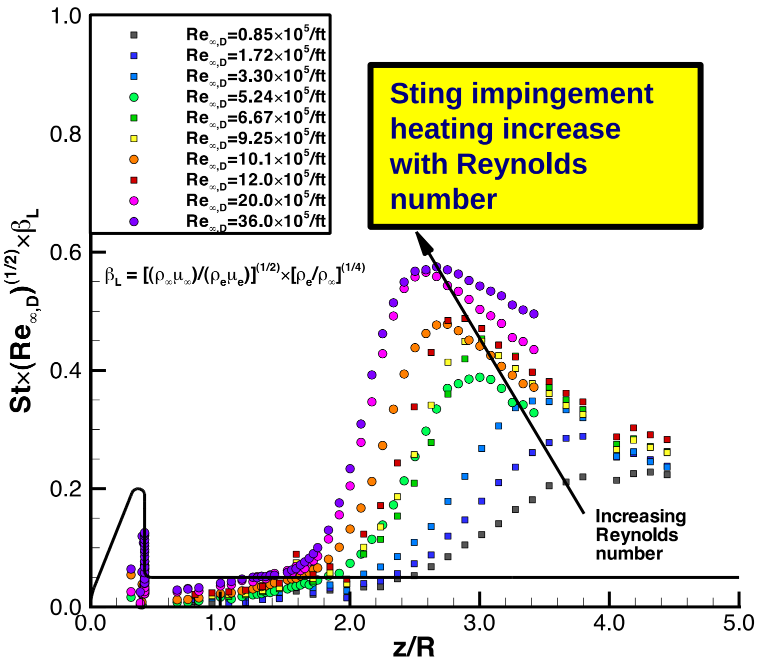
Research & Development – Wake Flow Behavior

- 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



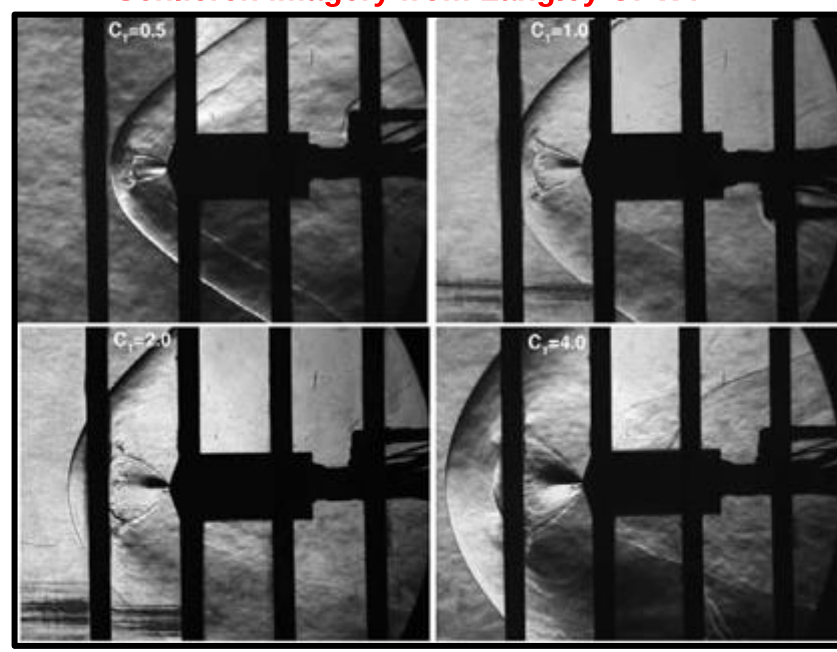


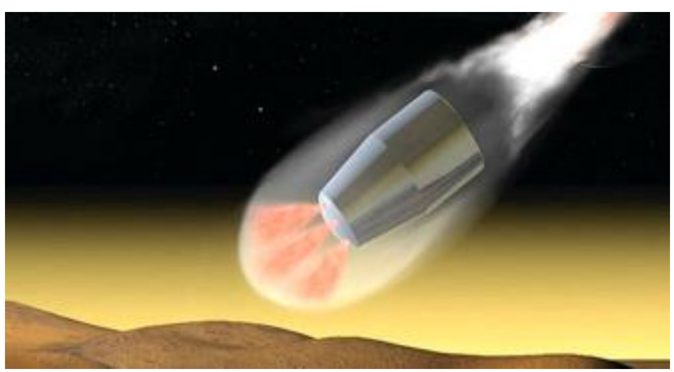
Research & Development – Supersonic Retropropulsion

- 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



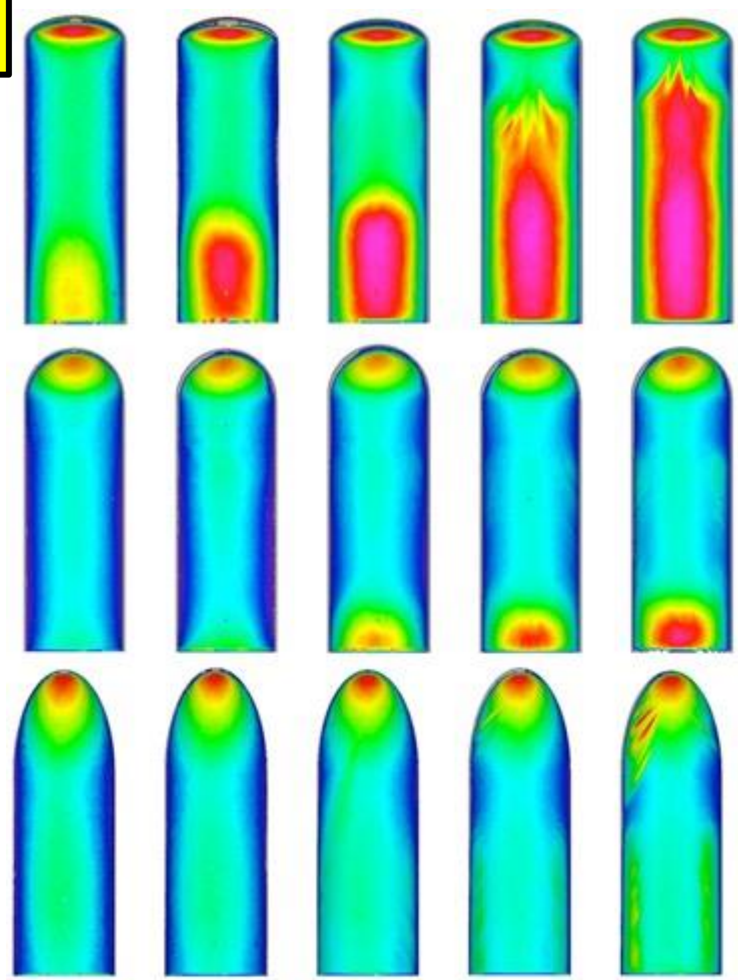


High-mass Mars entry using supersonic retropropulsion (artist's concept)

Research & Development – Mid L/D Entry Vehicle Aeroheating

Increasing nose bluntness

Heating on Mid L/D concepts



Increasing Reynolds number

- 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

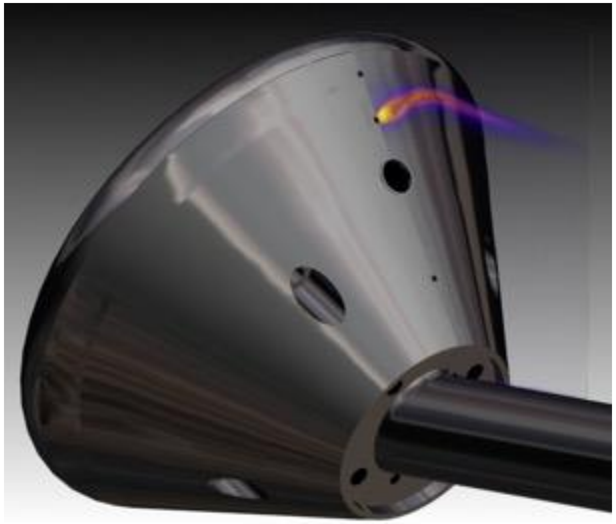
Mid L/D entry vehicle concept

PLIF RCS Jet Visualization and Reconstruction

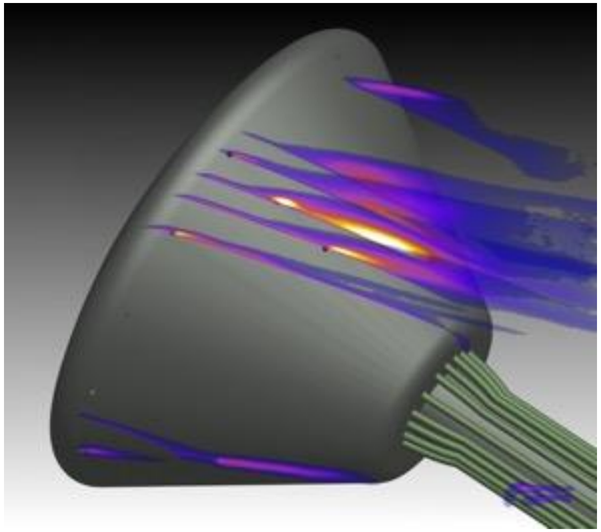
Orion Crew Exploration Vehicle used for proof-of-concept

- **Volumetric image reconstruction of roll RCS jet**
  - Laser is scanned through RCS jet flow field
  - Planar images are superimposed over virtual model
  - Reconstruction provides RCS jet shape and trajectory information
- Streamline tracing
  - Multiple seeding locations around shoulder
  - Trace streamline progress through wake

RCS Jet



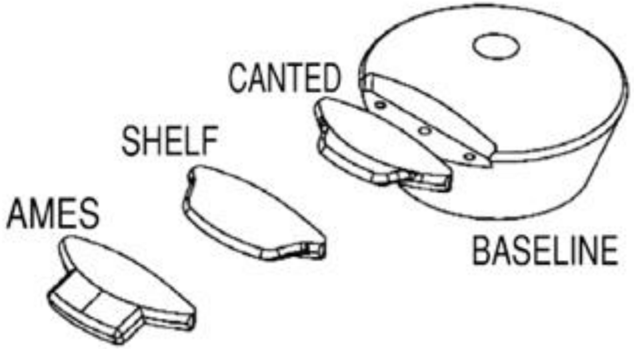
Streamline tracing



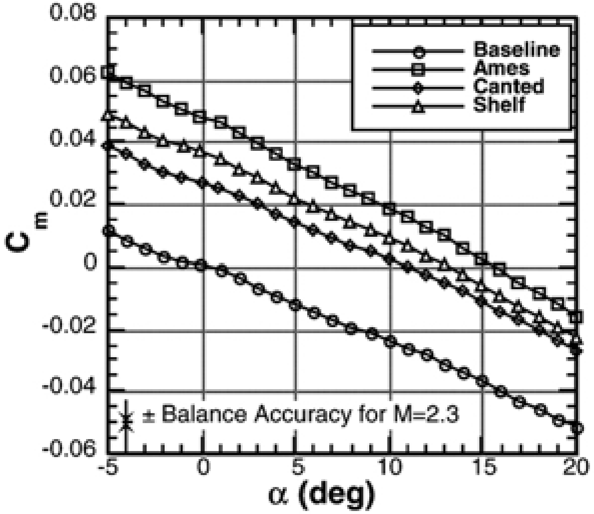
Research & Development – Entry Vehicle Trim Tab Performance

- 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

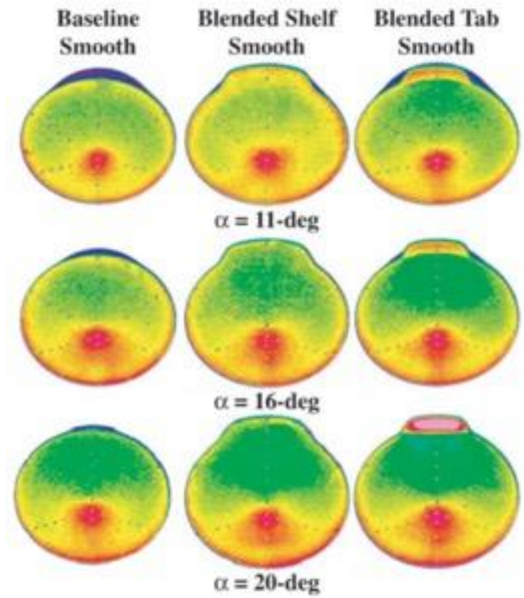
Trim-tab geometry options



Trim-tab aerodynamic performance



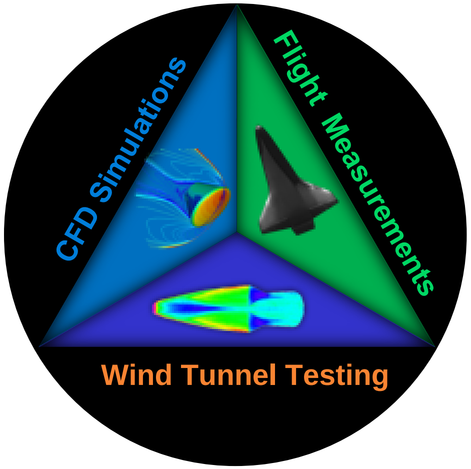
Trim-tab aeroheating



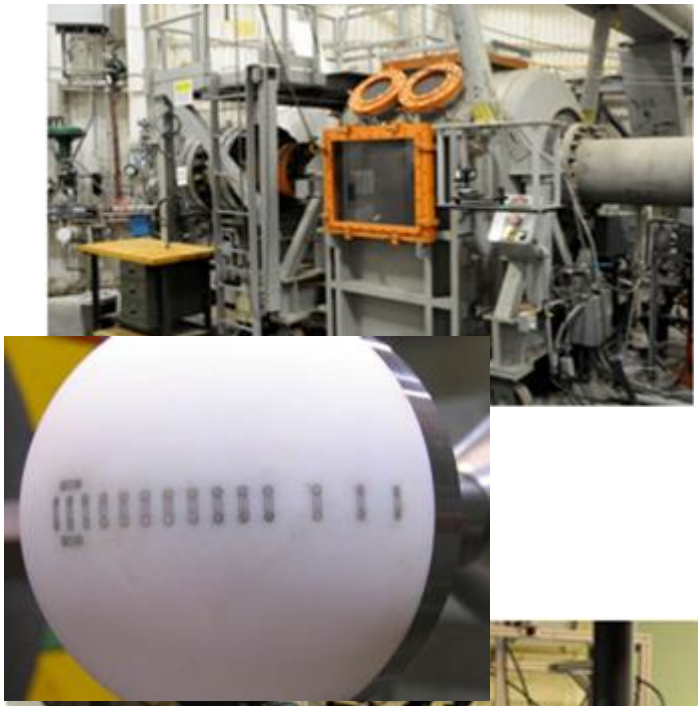
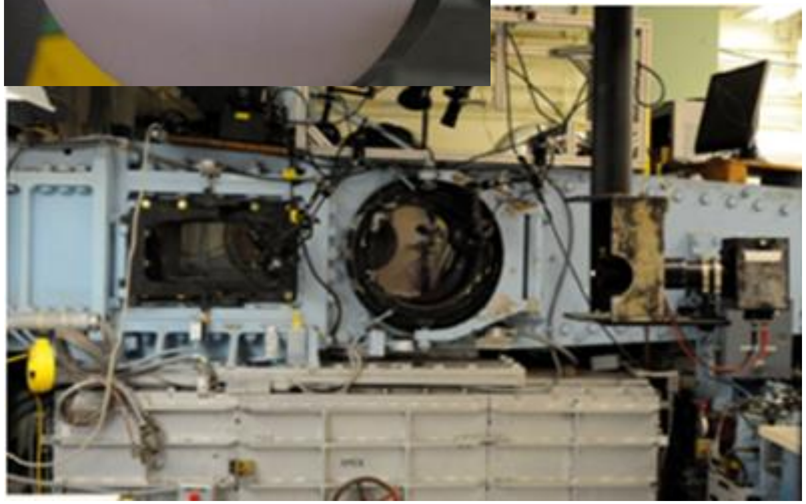
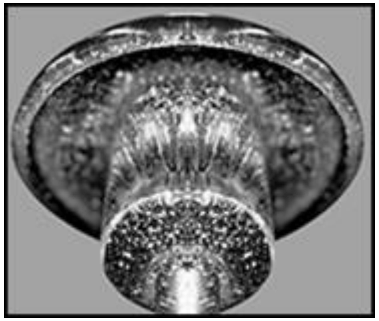
Summary and Conclusions

Aerothermodynamic Ground Testing provides:

- **Direct support to flight vehicle database development**
  - Extrapolation of unit-testing to very high-energy problems (Mars atmospheric entry)
  - Direct overlap for low-mid energy problems (stage/booster recovery, low ballistic coeff. inflatables)
- **Data for Computational Fluid Dynamics validation**
  - Less expensive than flight testing – which often is limited in quantity and quality of instrumentation
  - Ability to study complex flow phenomena that are not properly understood and/or modeled such as:
    - Flow-field interactions – retropropulsion and reaction-control systems
    - Wake flows and separated regions
    - Boundary layer transition
    - Fluid-structure interactions
- **Fundamental/Applied Research and Technology Development**
  - Advancing new technologies such as inflatable/deployable heat shields
  - Obtaining data on complex physics such as boundary-layer transition
  - Evaluation of new candidate vehicle architectures and configurations



Ground testing is a critical component of the Aerothermodynamic Triad, along with computational techniques and flight testing, for the development, design and validation of Entry, Descent & Landing and Hypersonic Flight vehicles

Questions ???