Recent Langley Aerothermodynamic Laboratory Testing (2019-2022)

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Presented By:
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Thermal & Fluids Analysis Workshop
TFAWS 2022
September 6th-9th, 2022
Virtual Conference

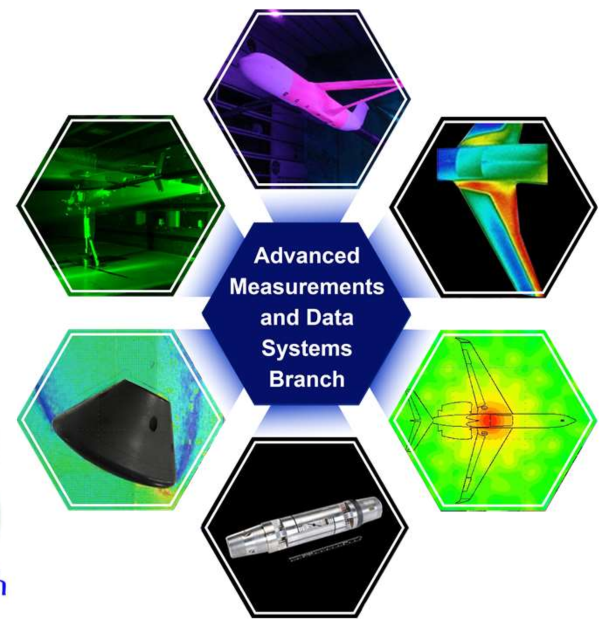
Outline

- LAL Facilities
  - 31-Inch Mach 10 Tunnel
  - 20-Inch Mach 6 Tunnel
  - 15-Inch Mach 6 High-Temperature Tunnel
- LAL Standard Test Techniques
- Phosphor Thermography Highlight
- Other LAL Test Techniques
- Wind Tunnel Test Categories
  - Flight Programs
  - Academic Partnerships
  - Foundational Research
  - Facility Calibration

LAL
Langley Aerothermodynamics Laboratory

AEROTHERMODYNAMICS BRANCH
AB
NASA LANGLEY RESEARCH CENTER

FPCB
Flow Physics and Control Branch

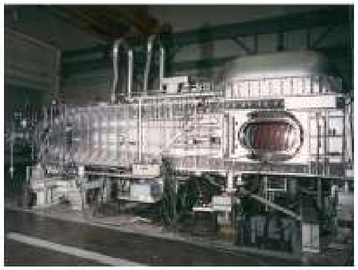


LaRC Aerothermodynamics Laboratory

- Operation:
  - Conventional blow-down wind tunnels
  - Perfect-gas, dry-air facilities provide high flow quality and low-enthalpy test conditions
  - Optical access on three sides for phosphor/IR thermography, PLIF, schlieren, etc.

- Wind Tunnel Features:
  - 31-inch, Mach 10:
    - Re: 0.5-2.1 x 10^6/ft
    - Core Flow: 14” x 14”
    - Max run duration: 2 minutes
  - 15-Inch Mach 6:
    - Re: 1.3-7.0 x 10^6/ft
    - Core Flow: 10” diameter
    - Max run duration: 2 minutes
  - 20-Inch Mach 6:
    - Re: 0.5-8.3 x 10^6/ft
    - Core Flow: 14” x 14”
    - Max run duration: 15 minutes

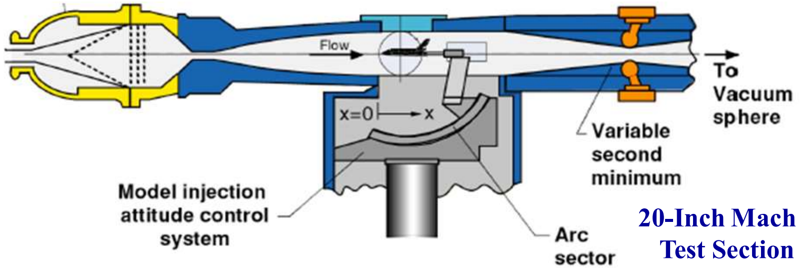
Experimental Facilities



31-Inch Mach 10 Air

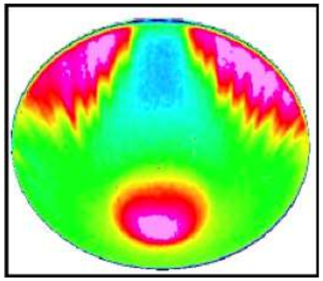
15-Inch High-Temperature Air

20-Inch Mach 6 Air

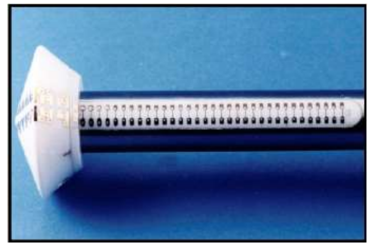


20-Inch Mach 6 Test Section

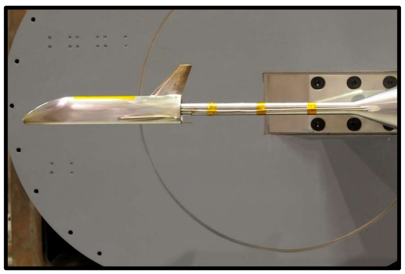
Standard Instrumentation Types & Techniques



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

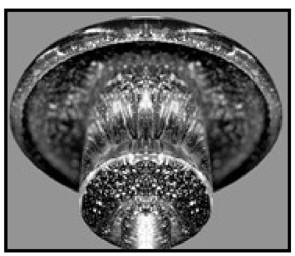


Thin-film, thin-skin, or coaxial thermocouple gages for discrete heat transfer measurements

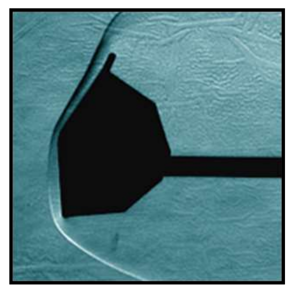


Aerodynamic balance: force and moment

High frequency pressure transducers (Kulites®/PCBs®): $f \leq 1$ MHz



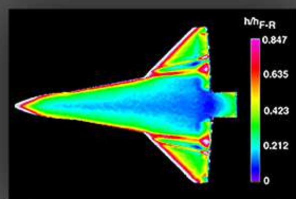
Oil-flow for surface streamline visualization



Schlieren for flow field visualization

Global Phosphor Thermography

Better



Before
Discrete gauges
150 points/run

After
Global data
150,000 points/run

Impact to a study
Increased amount of information: 1000x

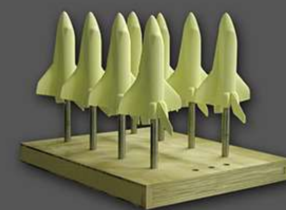
Faster

50 weeks to obtain data on study

5 weeks to obtain data on study

Time savings: 10x

Cheaper



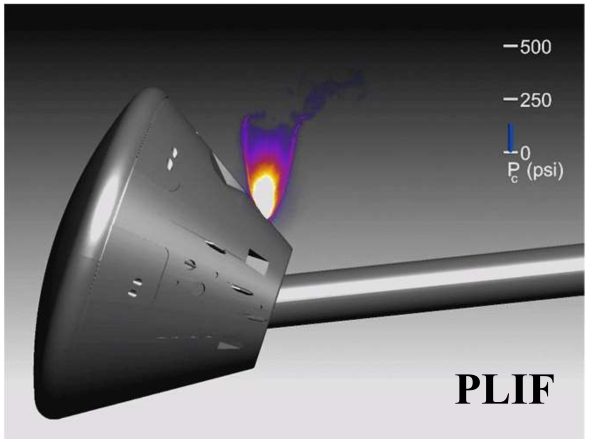
Fabrication cost: 150K (1 model)

Fabrication cost: 15K (5 models)

Cost reduction: 10x

Other LAL Test Techniques

- Nonintrusive techniques:
  - Focused Laser Differential Interferometry (FLDI)
  - Planar Laser Induced Fluorescence (PLIF)
  - High-speed photogrammetry
- Advanced schlieren techniques:
  - Focusing schlieren
  - Background oriented schlieren (BOS)
- Heat Transfer discrete measurements:
  - Atomic Layer Thermopile (ALTP)
  - Hot Wire Anemometry
  - Schmidt-Boelter Gauges
- Laser speckle interferometry
- Laser-based ultrasound
- Developmental Techniques
  - High-Temperature Phosphor Thermography
  - Infrared Radiation Thermography
  - Temperature Sensitive Paint



FLIGHT PROGRAMS

BOLT Fairing and TSM Aeroheating

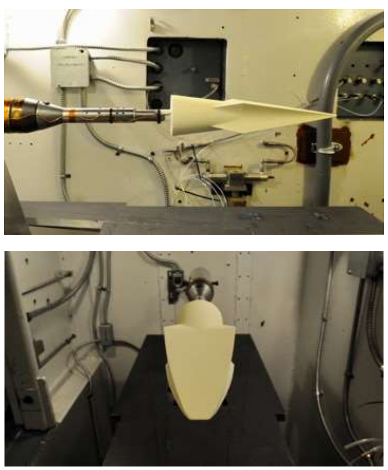
Test Details

- **Test Name**: BOLT Fairing
- **Customer**: BOLT flight test program
- **Test Number(s)/Facilities:** Test 7041, LaRC 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** BOLT geometry with fairings and transition support module (TSM)
- **Test Technique(s):** Global phosphor thermography
- **Duration/Date:** 55 runs, 1 week, Feb. 2019
- **Category:** applied research supporting flight project

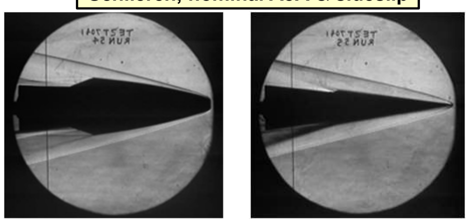
Program Background

- **Issue:** Leading up to the BOLT Critical Design Review, there was concern about the interface between BOLT flight geometry and transition support module of launch stack
- **Objective:** Investigate and identify any aeroheating issues on the TSM downstream of the BOLT geometry
- **Challenges:** Compressed timeline: Fabrication, testing, and reporting of results completed in 1 month
- **Approach:** Tested model at 4 Reynolds numbers at a range of AoA and sideslip; obtained schlieren visualization of flow pattern onto TSM at nominal flight conditions
- **Benefactors/Infusion**: BOLT flight test program, future BOLT II flight testing

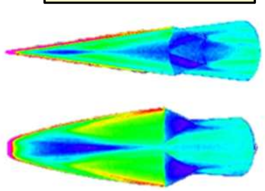
BOLT + Fairings + TSM Ceramic Model



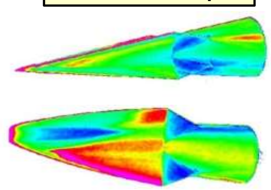
Schlieren, nominal AoA & sideslip



Heating, nominal AoA & sideslip



Heating, extreme AoA & sideslip



Product/Results

- Database of fairing and TSM heating over expected range of possible flight AoA and sideslip
- No high-heating regions of concern due to flow reattachment identified on the transition support module

Impact/Applications

- Data presented at the BOLT CDR, allowing for the team to move forward with flight hardware fabrication and plans to use cork thermal protective system (TPS) on the transition support module

BOLT Discrete Roughness Transition

Test Details

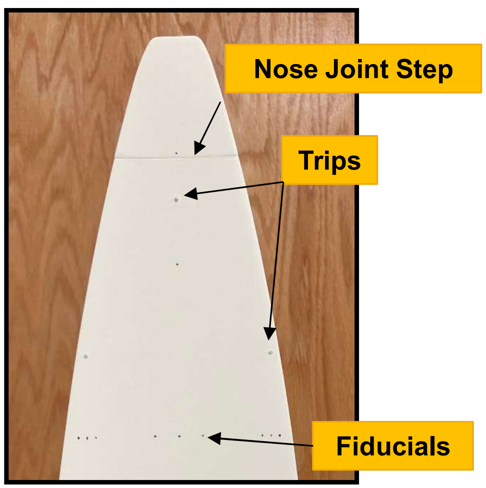
- **Test Name**: BOLT Discrete Roughness Study
- **Customer:** ARMD AAVP Hypersonic Technology Project
- **Test Number/Facility**: T7056, LaRC 20-Inch Mach 6 Air Tunnel
- **Configuration/Models**: Preliminary version of the BOLT2 configuration, called long-BOLT, with & w/o nose-joint steps
- **Test Technique**: Global phosphor thermography
- **Duration**: 48 runs, 6 days, Jan-Feb 2021
- **Category**: Research & technology development for flight project

Program Background

- **Issue**: Intention is to have discrete roughness elements (or trips) on one side of the BOLT2 flight vehicle. Need to investigate trips of various sizes and locations to inform the flight program.
- **Objectives**: Evaluate trip heights and locations on the BOLT2 geometry
- **Approach**: Compare/contrast results with and without nose joint steps, for various trip heights and locations
- **Benefactors/Infusion**: Meant to inform the BOLT2 flight project and HTP

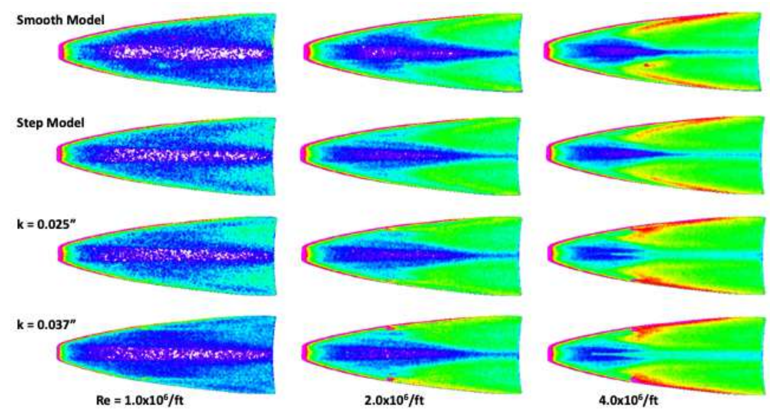
Test Setup/Model Pics/Results

- Photos of models and closeup showing trips and fiducials



Impact/Applications

- Unable to provide tall enough trips using traditional method
- Plan to follow up this test with different approach



Transition onset with increasing Reynolds number

LOFTID Aeroshell Scalloping

Test Details

- **Test Name**: Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) Aeroshell Scalloping
- **Customer**: STMD LOFTID Flight Test
- **Test Numbers/Facility:** Tests 7058 and 7060, LaRC 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** sphere-cone aeroshell with parametric scallop depth variations
- **Test Technique:** Global phosphor thermography
- **Duration/Date:** 7058: 23 runs/1 weeks / April 2021. 7060: 81 runs / July-Aug. 2021
- **Category:** flight mission support

Program Background

- **Issue:** Flexible TPS forms scalloped surface over support structure of inflatable toroids and tension tie straps
- **Objective:** Evaluate effects of flexible TPS scalloping on heating and boundary-layer transition
- **Approach:** Test models of various scallop depths across a range of Reynolds numbers sufficient to produce laminar, transitional and turbulent flow
- **Challenges:** Development of scalloping transition and heating augmentation models; issues with model fabrication
- **Benefactors/Infusion**: Inflatable aeroshell development programs under STMD, direct support to development of LOFTID aerothermodynamic database

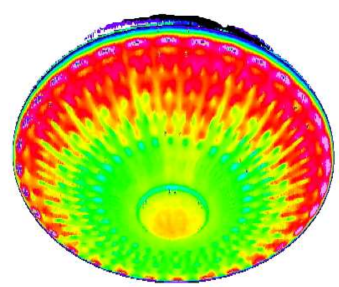
LOFTID Model

Results

- Measured heating and transition on range of parametric scallop depth models
- 3D-mapped all data, extracted streamline-based heating/transition data
- Database encompasses flight test conditions
- Measurements indicate scalloping effects will be minor for LOFTID flight test conditions

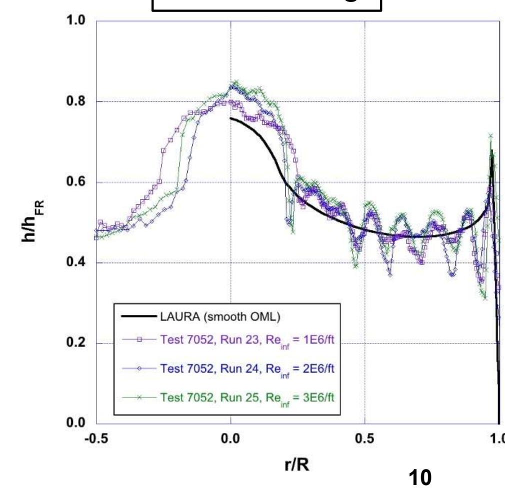
Impact/Applications

- Database can be used in development / validation of CFD transition & heating models and applied to vehicle TPS design



Global heating

Global heating



LOFTID Aftbody Heating

Test Details

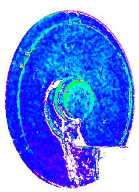
- **Test Name**: LOFTID Aftbody Heating
- **Customer**: STMD LOFTID Flight Test
- **Test Number/Facility:** Test 539, LaRC 31-Inch Mach 10 Air Tunnel
- **Configuration/Models:** Sphere-cone aeroshell with blade mount, smooth or toroid aeroshell aftbody
- **Test Techniques:** Global phosphor thermography, IR thermography
- **Duration/Date:** 56 runs, 3 weeks, Sep-Oct 2019
- **Category:** Flight mission support

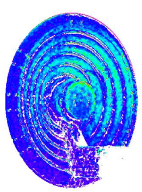
Program Background

- **Issue:** Complicated wake flow field and aftbody heating environment, open-back configuration with large, concave region that exposes inflatable structure and payload to the wake flow environment with no aft side flexible TPS (F-TPS)
- **Objective:** Evaluate heating environment on the payload and the aeroshell aftbody with a smooth and toroid back face
- **Approach:** Test models at a range of Reynolds numbers and angles-of-attack
- **Challenges:** Low heating levels on aftbody and limited optical access stress the phosphor system, high noise in data; IR thermography system still in development
- **Benefactors/Infusion**: Inflatable aeroshell development programs under STMD, direct support to development of LOFTID aerothermodynamic database

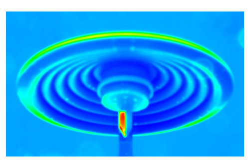
LOFTID Models

Global Heating





IR Temperature



Results

- Measured heating on aeroshell forebody, smooth aftbody, and toroid aftbody
- Acquired IR images for comparison to phosphor thermography technique
- Will 3D-map all data, extract and average heating data on aftbody for noise reduction, create a database of heating profiles

Impact/Applications

- Database can be used in development / validation of CFD wake heating models

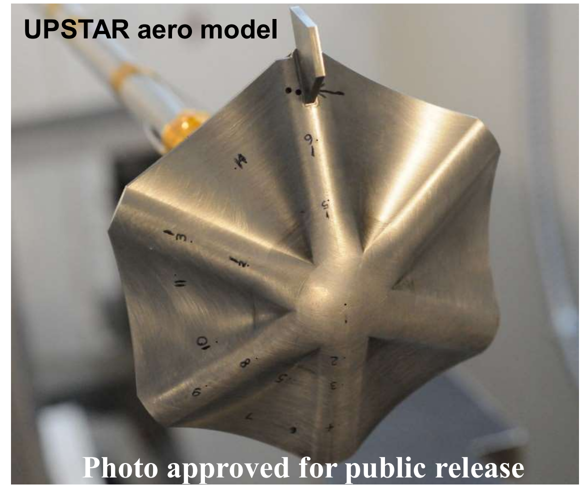
UPSTAR Aerodynamics

Test Details

- **Test Name**: UPSTAR Aerodynamics
- **Customer**: Sierra Space
- **Test Number/Facility**: Test 7062, 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** UPSTAR "Pillow 1" configuration; 0.00983-scale stainless steel model
- **Test Technique(s):** force/moment, pressure
- **Duration/Date:** 37 runs, January 2022
- **Category:** Configuration Aerodynamics; CFD validation

Program Background

- **Issue:** UPSTAR is a deployable decelerator concept developed by Sierra Space to return payloads from Earth orbit to a ground landing within a specified footprint. Experimental data was desired to anchor the aerodynamic database and validate CFD calculations.
- **Objectives:** Determine the aerodynamic characteristics and rudder effectiveness of the UPSTAR configuration and obtain surface pressure coefficient data for comparison with CFD.
- **Challenges:** Packaging a force balance into the payload module aft of the heat shield while maintaining the OML.
- **Approach:** Test over a range of angle of attack, sideslip, rudder deflection angles, and forebody roll orientation angles. NASA also independently ran CFD on the model configuration at wind tunnel test conditions.
- **Benefactors/Infusion**: Sierra Space, NASA



Results

- Obtained experimental aerodynamic data over a range of model attitude and control deflection appropriate for the hypersonic portion of the trajectory.
- Schlieren imagery discovered the presence of a shock/shock interaction producing an impinging jet that could significantly increase aerodynamic heating on the local forebody and rudder

Impact

- Experimental data validated CFD results from both Sierra Space and NASA
- Discovery of impinging shock-shock interaction may affect control surface architecture and/or TPS materials

UPSTAR Aeroheating

Test Details

- **Test Name**: UPSTAR Aeroheating
- **Customer**: Sierra Space
- **Test Number/Facility**: Test 7065, 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** P1-R15 and P2-R30, ceramic phosphor thermography models
- **Test Technique(s):** Phosphor thermography and oil flow
- **Duration/Date:** 114 runs, January/February 2022
- **Category:** Flight Mission Support; CFD validation

Program Background

- **Issue:** UPSTAR is a deployable decelerator concept developed by Sierra Space to return payloads from Earth orbit to a ground landing within a specified footprint. Experimental data was desired to anchor the aeroheating database and validate CFD calculations.
- **Objectives:** Obtain aerothermal hypersonic wind tunnel data for risk reduction of UPSTAR.
- **Challenges:** The uniqueness of the contours/shape of the forebody of the model. Casting a model with a small feature like the rudder; had to extend the spline to the full length of the rudder.
- **Approach:** Test over a range of angles of attack, Reynolds numbers, and forebody roll orientation angles. Test two different model configurations (each model having a different pillow and rudder deflection).
- **Benefactors/Infusion**: Sierra Space, NASA

Results

- Obtained experimental global aeroheating data over a range of Reynolds numbers and angles of attack on 2 different model configurations.
- Oil flow images illustrating streamlined patterns in the flow on forebody of the model.

Impact

- Experimental data will be used to validate CFD results from both Sierra Space and NASA
- Phosphor data from this test was used as a beta case for the new 3D mapping tool in IHEAT

ACADEMIC PARTNERSHIPS

Cone/Fin Multi-Facility Boundary-Layer Transition Study

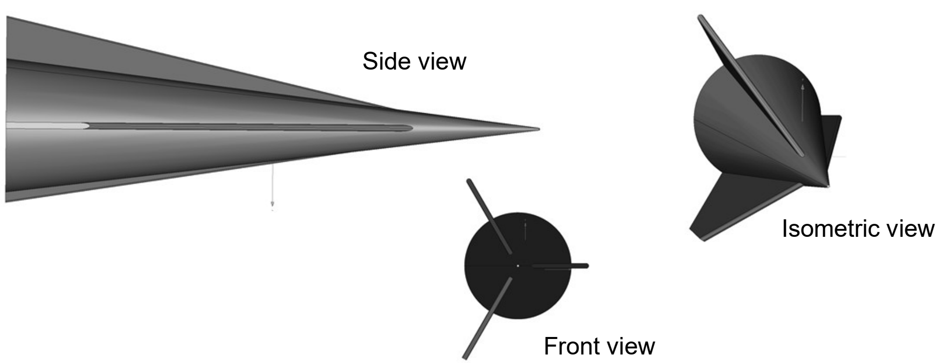
Test Details

- **Test Name**: Office of Naval Research Cone-Fin Study
- **Customer**: NASA Hypersonic Technology Project
- **Test Number/Facility:** Test 7040, LaRC 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** 7-deg ceramic cones with highly swept fins
- **Test Techniques:** Global phosphor and IR thermography
- **Duration/:** 138 runs, 5 weeks
- **Date:** February-March 2019
- **Category:** University Collaboration

Program Background

- **Objectives:** Provide Mach 6 heating and transition data on phosphor-coated ceramic models for comparison to similar results on metal cone-fin models with temperature sensitive paint from Purdue Quiet Tunnel
- Parametric study will provide information on:
  - three different fin thicknesses (1/8", 3/16", 1/4")
  - three highly-swept fin angles (80°, 75° and 70°)
  - two cone nose radii (0.04", 0.08")
- **Challenges:** Tunnel was unavailable for half of FY18 due to repairs

Test Setup/Model Pics



Example geometry of a cone-fin model with varying sweep angles (80, 75 and 70 degrees from perpendicular)

Impact/Applications

- **Significance/Impact:**
- Provide LAL laminar/transitional data at a range of Reynolds numbers
- Enable comparison of conventional LAL data with Purdue results on generic geometries of DoD interest
- Investigate surface roughness effect of coated ceramic models on heating/BLT compared to metal models with temperature sensitive paint
- Advance LAL IR capability by comparing IR and phosphor thermography results on cone-fin models
- **Later Work:** Collaborative testing tested Purdue's PEEK/metal hybrid cone models in the 20-Inch Mach 6 Air and possibly the 31-Inch Mach 10 Air Tunnels

Flat Plate Rake Test

Test Details

- **Test Name**: Flat Plate Rake Test
- **Customer**: HTP and University of Maryland
- **Test Number/Facility:** Test 7050, Mach 6
- **Configuration/Models:** Flat Plate with ramp
- **Test Techniques:** IR, Pressure Rake, Kulites®, Nonintrusive FLDI
- **Duration:** 30 runs in Mach 6
- **Date**: January 2020
- **Category:** NASA/Academia R&D Testing

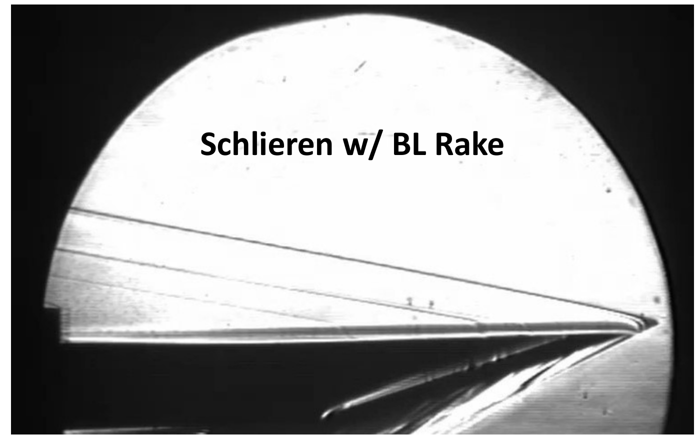
Program Background

- **Issues:** Boundary layer profile information needed for follow-on fluid structure interaction (FSI) testing
- **Objectives:** More accurate analysis of prior/future investigations into response of flexible panels to ramp induced shock-wave / boundary-layer interactions
- **Approach:** Measure inflow conditions on flat plate. Measure surface temperatures on ramps with rigid and flexible panels
- **Benefactors/Infusion**: HTP, UMD, follow-on FSI test will be much more prepared

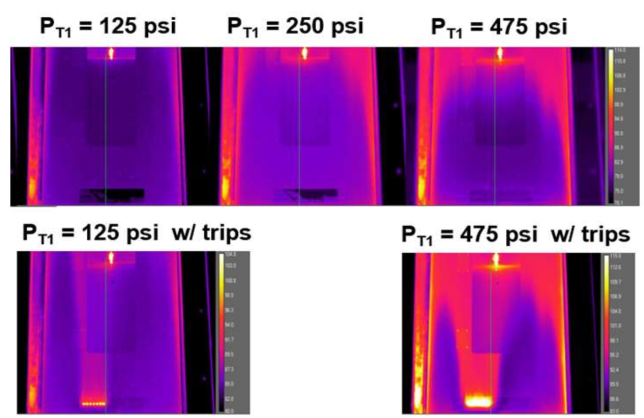
Impact/Applications

- Data collected using BL Rake pressures, LWIR thermography, flush mounted Kulite® pressure and nonintrusive FLDI density fluctuation measurements
- Data will be used to plan for follow-on FSI test with UMD

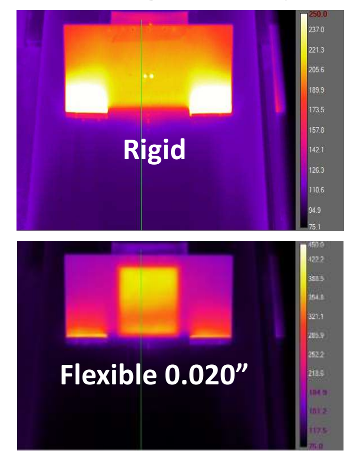
Test Setup/Model Pics/Results



LWIR Thermography/Transition Imaging



35 Degree Ramp



Fluid-Structure Interaction

Test Details

- **Test Name**: Fluid Structure Interaction
- **Customer**: University of Maryland
- **Test Numbers/Facilities**: Test 545 & 7068 / 31-Inch Mach 10 & 20-Inch Mach 6 Air Tunnels
- **Configuration/Models:** Flat plate / Ramps
- **Test Techniques:** High-speed photogrammetry, high-speed focusing schlieren, LWIR thermography, PCBs and Kulite® flush-mounted surface pressure
- **Duration:** 3 weeks / 56 runs
- **Date**: March-April 2022
- **Category:** University research collaboration

Program Background

- **Issue:** FSI produce complex, dynamic flows
- **Objectives:** Measure dynamic surface pressure, deformations, temperature and flow conditions simultaneously for a fluid-structure interacting SWBL over a compliant panel on 10 to 30-degree ramps
- **Challenges:** Align, transmit and filter cameras and lamps through normal and tangential windows for simultaneous stereo-photogrammetry, LWIR, and HSF schlieren
- **Approach:** Use amber-red (616nm) LED lamps for simultaneous photogrammetry & thermography through normal view ZnSe window
- **Benefactors/Infusion**: Flight vehicles with ramp/wedge features such as inlets or controls

Test Setup

Plate/wedge model under amber-red (616nm) LED lamps

Results

Schlieren image

Energy-Matter Interaction

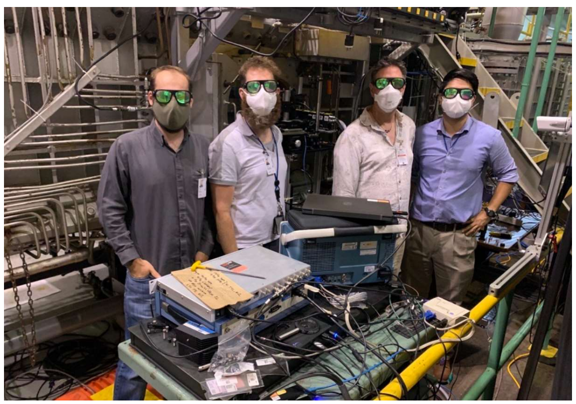
Test Details

- **Test Name/Customer**: Energy-Matter Interaction / Lawrence Livermore National Laboratory (EMI / LLNL)
- **Test Number/Facility**: Test 544, 31-Inch Mach 10
- **Configuration/Models:** Flat plate / Inserts (material & roughness)
- **Test Techniques:** Laser speckle interferometry, laser-based ultrasound, and high-speed schlieren
- **Duration:** 2 weeks / 32 runs
- **Date**: August 2021
- **Category:** Hypersonic research collaboration

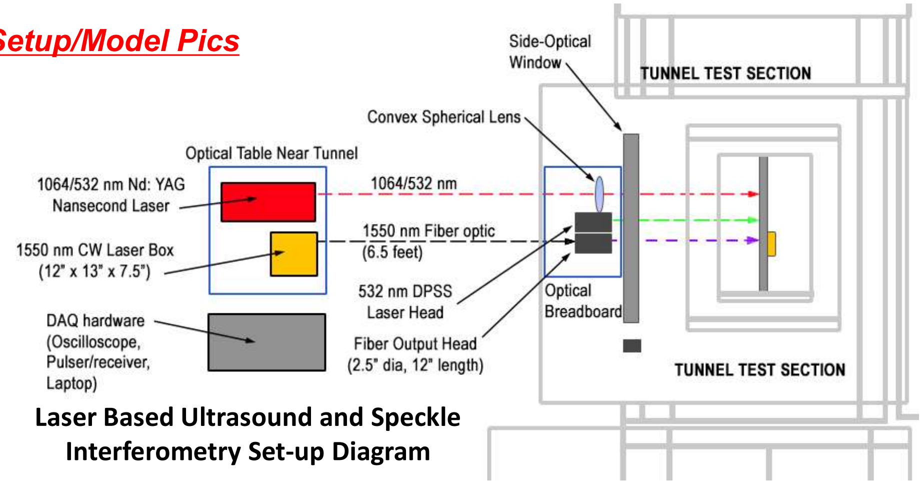
Program Background

- **Issue:** Demonstrate new measurement techniques for hypersonic blow-down wind tunnels applicable to LLNL ablation tests and other material response
- **Objectives:** Obtain successful strain and material properties measurements in hypersonic conditions
- **Challenges:** Arrangement of laser permit, model preparation, and facility operation with a collaborative team during pandemic restrictions
- **Benefactors/Infusion**: New test facility development for LLNL and EMI impact studies

Test Setup/Model Pics



LLNL Team Members



Laser Based Ultrasound and Speckle Interferometry Set-up Diagram

Title: "In-Situ Optical Detection for Ultrasonic Characterization of Materials in a Mach 10 Hypersonic Wind Tunnel",
Authors: Jordan S. Lum, Lionel T. Keene, Benjamin M. Goldberg, Erik Busby, Aric C. Rousso, Brett F. Bathel, Joshua M. Weisberger, Gregory M. Buck, David M. Stobbe, James S. Stolken
Submitted to: Physical Review Applied Letter, April 2022

FOUNDATIONAL RESEARCH

AEDC Tunnel 9 Cone Test

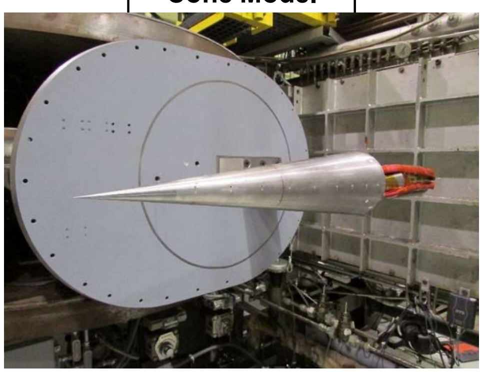
Test Details

- **Test Name**: Arnold Engineering Development Complex (AEDC) Tunnel 9 Cone Test
- **Customer**: HTP, AFOSR, D303
- **Test Number/Facility:** Test 537, LaRC 31-Inch Mach 10 Air Tunnel
- **Configuration/Models:** 7-deg half angle cone
- **Test Technique:** Discrete pressure/temperature
- **Duration/Date:** 38 runs/4.5 weeks (Oct-Nov 2019)
- **Category:** NASA R&D Testing

Program Background

- **Objective:** Independently measured effects of lower tunnel total temperature/nose tip bluntness on second mode instability for 7-deg half-angle cone (used in transition modelling)
- **Approach:** Utilize standard and non-standard (lower temperatures to achieve supercooling) tunnel conditions on a variety of nose tip bluntness configurations to determine impacts on second mode instabilities.
- **Challenges:** Low productivity (2 runs/day) due to lack of steam ejector, multiple days down due to compressor station issues, tunnel heater failed prior to test matrix completion (decision made by customer to pull model/not finish matrix)
- **Benefactors/Infusion**: Hypersonics community (data has potential to improve computational modeling associated with second mode transition as well as impact future tunnel design)

Cone Model



Results

- Most test objectives were achieved
- Lowering the total temperature weakened second mode instability, despite a higher Reynolds number
- Increased bluntness also reduced instability as expected (not able to test all nose tips)

Impact/Applications

- Data relating tunnel total temperature, T_{t2}, to measured total pressure, P_{t2}, will be sent to computationalists looking to model the effects of liquefaction/clustering on second mode measurements
- Not aware of any such measurements acquired at similar test conditions
- The way the instability was reduced with decreasing temperature is an important consideration for future supercooled tests and hypersonic tunnel designs.

Effect of Shaped Roughness on AEDC Tunnel 9 Cone BLT

Test Details

- **Test Name**: Cone Roughness Transition Test
- **Customer**: ARMD HTP
- **Test Number/Facility:** Test 7046, LaRC 20-Inch Mach 6
- **Configuration/Model:** 7º half-angle sharp cone with various shaped roughness elements (cone on loan from AEDC Tunnel 9)
- **Test Techniques:** unsteady surface pressure and temperature
- **Duration/Date:** 43 runs, 1 week, July 2019
- **Category:** basic research

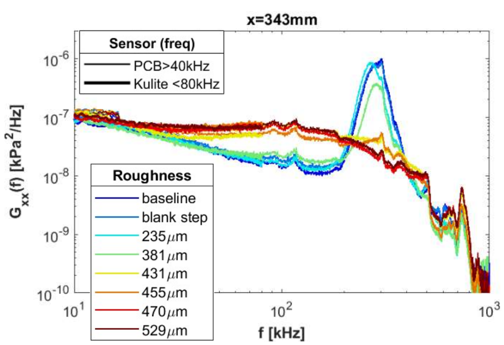
Program Background

- **Issue:** BLT on sharp cones at ~ 0° incidence are dominated by second-mode instabilities. Suppressing the growth of the second mode could delay transition. A large QT is more ideal for these measurements.
- **Objectives:** Measure BL instabilities on a sharp 7-deg half-angle cone with different size/shape roughness elements for ultimate use with transition prediction modelling.
- **Approach/Challenges:** Acquire small-amplitude high-frequency BL disturbances leading to BLT downstream of roughness array. Includes 6-elliptic shaped elements and 2 other shapes of moderate height.
- **Benefactors/Infusion**: NASA, AFOSR, and wider hypersonic community.

T9 Cone Model
Elliptical Roughness at x=9in.

- AEDC T9 Cone Model with a sharp nose tip (r_n=0.006 in.) in the 20-inch Mach 6 tunnel.
- Kulite® and PCB® surface pressure fluctuation measurements on cone where second-mode disturbances are evident.

- PCB® sensitivities were determined by matching rms with Kulites® for overlapping frequencies.
- Examined the effect of different elliptical roughness heights on second-mode instability.



Results

- Acquired surface pressure fluctuation and temperature data.
- Larger roughness elements strongly reduced the second mode, but also increased lower-frequency content.
- Reducing the second mode did not generally result in a measurable delay in transition.

Impact

- Results will be used to improve our understanding of the effect of roughness on transition and to develop improved physics-based transition prediction models.

Cone/Slice/Flap Aerodynamics for CFD Validation

Test Details

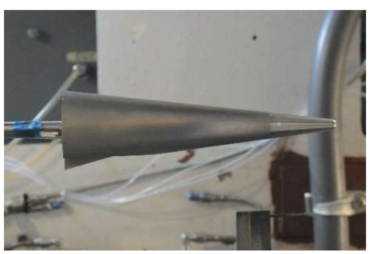
- **Test Name**: Cone/Slice/Flap (CSF) Aerodynamics
- **Customer**: Hypersonic Technology Project
- **Test Number/Facilities:** T7054, 20-Inch Mach 6 Tunnel
- **Configuration/Models:** Multiple parametric geometric variations of CSF configuration
- **Test Technique(s):** Force/moment, pressure
- **Duration:** 81 runs, 120 UOH, Jan, Feb, Dec 2020
- **Category:** Research & technology development

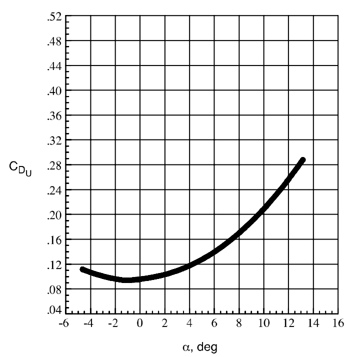
Program Background

- **Issue:** CFD needs proper uncertainty quantification methodology for validation with experimental data
- **Objectives:** (1) Demonstrate design of experiments application to wind tunnel testing for hypersonic configurations; (2) provide experimental validation data for CFD uncertainty quantification; (3) provide aerodynamic characteristics for future LAL check standard model
- **Approach:** Test multiple CSF configurations at varying test conditions to provide CFD validation data
- **Benefactors/Infusion**: Roadmap for CFD UQ for future programs

Test Setup/Model Pics/Results

- Evaluated aerodynamic characteristics of 33 CSF configurations
  - Nose radius, slice length, flap location/deflection
  - AoA ($-4^{\circ} \leq \alpha \leq +12^{\circ}$)
  - Reynolds number

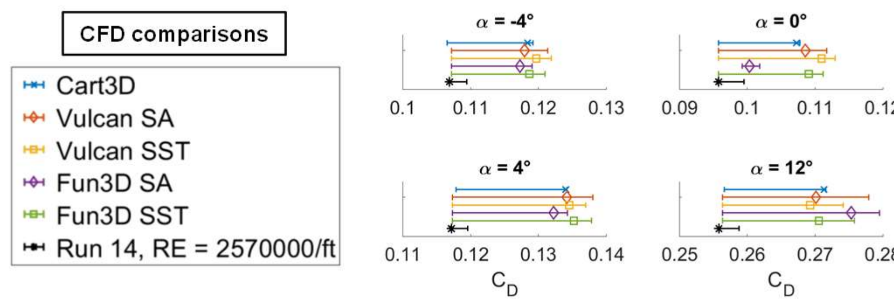




Impact/Applications

(1) Experiment provided data that allowed for the formulation of a validation metric for multiple CFD solvers and models.

(2) The work showed that the CFD model-form uncertainty estimate can account for 86% of the total uncertainty in model predictions.



Blunt Body Block-TPS Roughness

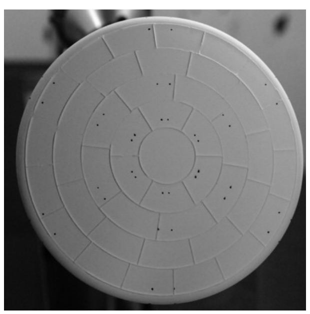
Test Details

- **Test Name**: Block-TPS Mission Relevant Roughness
- **Customer**: STMD Entry Systems Modeling Project
- **Test Number(s)/Facilities:** Test 7057, LaRC 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** spherical-cap aeroshell similar to Apollo/Orion with blocked TPS layout
- **Test Technique(s):** Global phosphor thermography
- **Duration/Date:** 102 runs, 4 weeks, February-March 2021
- **Category:** Research & technology development

Program Background

- **Issue:** Differential ablation of block TPS and gap fillers produce steps or gaps on aeroshell heatshields
- **Objective:** Evaluate effects of heat shield step and gaps between TPS blocks on heating and boundary-layer transition
- **Approach:** Test models of various step height / gap depths across a range of Reynolds numbers sufficient to produce laminar, transitional and turbulent flow
- **Challenges:** Precision fabrication of small surface features gaps/steps < 0.01”; global measurements required to determine transition location
- **Benefactors/Infusion**: NASA or commercial EDL missions using a heatshield with tiled, ablative TPS. Direct connection to Orion/Artemis missions (different TPS block layout, same physics).

Fence Model



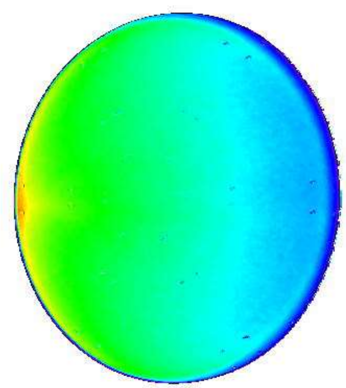
Results

- Measured heating and transition on range of models from smooth OML to 24-mil steps/gaps.
- 3D-mapped all data, extracted streamline-based heating/transition data
- Steps have much greater impact on flow field than gaps
- Transition occurs first at “T-junctions” of TPS blocks

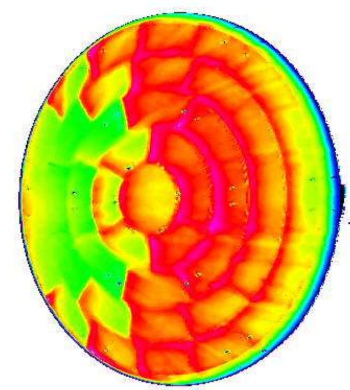
Impact/Applications

- Database can be used in development / validation of CFD transition & heating models and applied to vehicle TPS design

Smooth OML heating



24-mil step heating



Rocket Lab Inflatable Decelerator

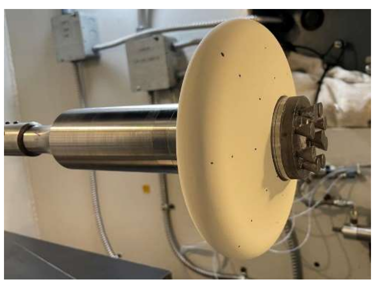
Test Details

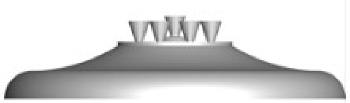
- **Test Name**: Rocket Lab inflatable decelerator
- **Customer**: STMD / Rocket Lab
- **Test Number/Facility:** Test 7069, LaRC 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** Inflatable tension-cone
- **Test Technique(s):** Global phosphor thermography
- **Duration/Date:** 42 runs, 1 week, April 22
- **Category:** Commercial customer / internal research & technology development

Program Background

- **Issue:** Inflatable aeroshell proposed to decelerate Rocket Lab 1^{st} stage booster for recovery and reuse
- **Objective:** obtain aeroheating data on decelerator
- **Approach:** cast ceramic decelerator and 3D printed nozzle cluster mounted on sting with interchangeable insert to allow different positions for decelerator along sting (booster)
- **Challenges:** complex topology not suited for standard structured gridding techniques – test data to be used in validation of new “stacked” block grid topology
- **Benefactors/Infusion**: design and development data to Rocket Lab (customer) and validation date for NASA computational tool development activities

Rocket Lab Model



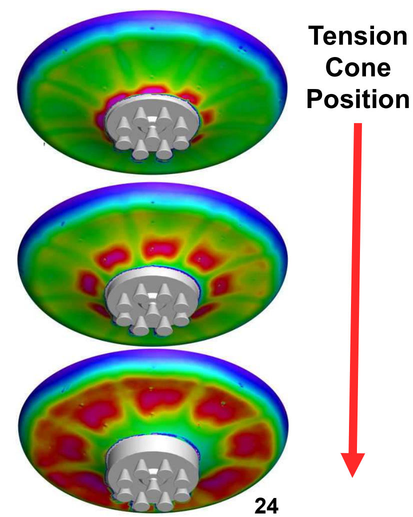


Results

- Measured heating and transition on aeroshell at 3 different positions along booster
- Decelerator position has 1^{st}-order effects on heating. Heating grows higher as decelerator moved “up” booster away from nozzle cluster
- Flow field exiting nozzle cluster changes from small backward facing step to large separation with impingement heating on decelerator

Impact/Applications

- Database can be used by customer for development and design purposes
- Database to used for internal CFD validation exercises



Blunt Body Woven TPS Roughness

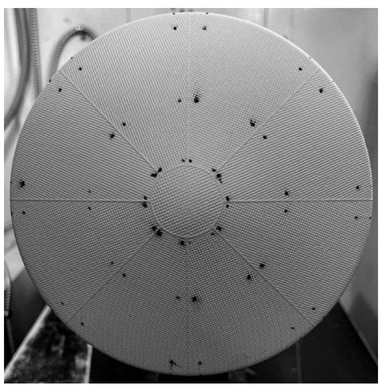
Test Details

- **Test Name**: Woven-TPS Mission Relevant Roughness
- **Customer**: STMD Entry Systems Modeling Project
- **Test Number/Facility:** Test 7070, LaRC 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** MSL and Orion geometries with woven TPS roughness
- **Test Technique(s):** Global phosphor thermography
- **Duration/Date:** 91 runs, 3 weeks, May-June 2022
- **Category:** research & technology development

Program Background

- **Issue:** Woven TPS material texture is a rough surface
- **Objective:** Evaluate effects of woven-TPS heat shield roughness on aerothermodynamic environment
- **Approach:** Test models of various woven texture patterns across a range of Reynolds numbers to produce laminar, transitional and turbulent flow
- **Challenges:** Precision fabrication of small surface features gaps/steps < 0.01"; global measurements required to determine transition location
- **Benefactors/Infusion**: NASA or commercial EDL missions using a heatshield with woven TPS. Direct connection to Mars Sample Return Earth Entry System which will have woven TPS.

Woven TPS Model



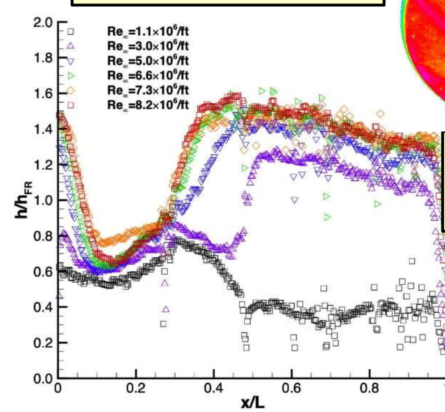
Results

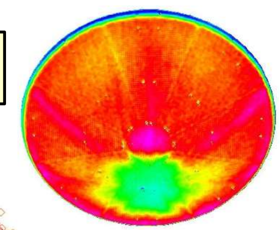
- Measured heating and transition on range of weave patterns with texture heights from 0.005 in. to 0.020 in. over range of Reynolds numbers
- 3D-mapped all data, extracted streamline-based heating/transition data
- Developing correlations for weave-driven boundary-layer transition

Impact/Applications

- Database can be used in development / validation of CFD transition & heating models and applied to vehicle TPS design
- Will feed into design of MSR-EES flight mission TPS design

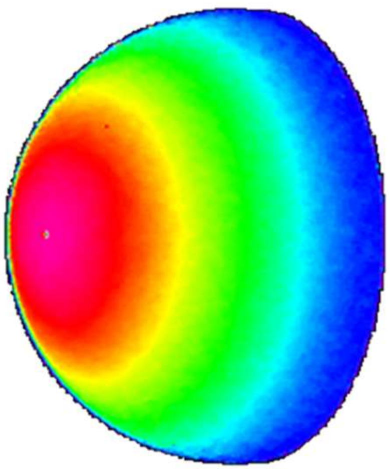
Centerline heating: Reynolds number effects





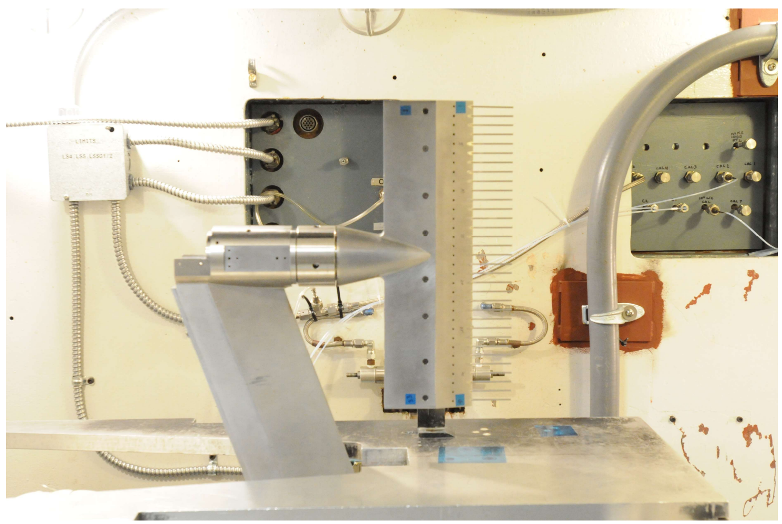
Woven TPS heating distribution

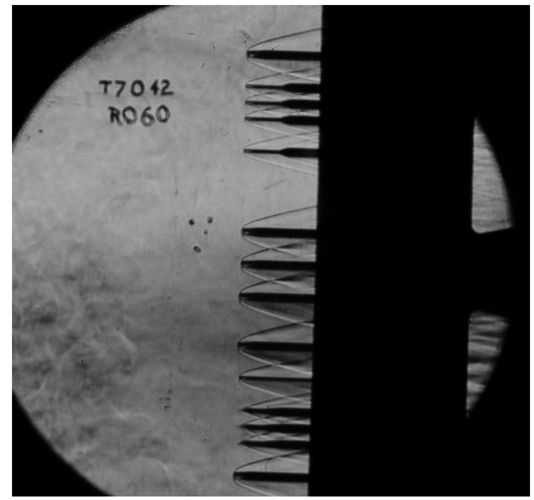
Facility Calibrations



Phosphor Thermography
Calibration Hemisphere

Pressure Rake





Freestream Disturbance Rake

Thank you!

- **Aerothermodynamics Branch POCs:**
  - Presentation Author: Michelle Mason, for the Langley Experimental Aerothermodynamics Discipline Team
  - POC for LAL Facility Capabilities and Information: Karen Berger
  - POC for LAL Entry, Descent and Landing Test Programs: Brian Hollis
  - POC for LAL Hypersonic Flight Test Programs: Scott Berry
- **Flow Physics and Controls Branch POCs:**
  - POCs for T9 Cone Work: Rudy King and Andrew Leidy
  - POCs for Flow Characterization: Amanda Chou and Andrew Leidy

Any Questions?

Back Up Slides

Boeing CST-100 Aeroheating

Test Details

- **Test Name**: Boeing CST-100
- **Customer**: Boeing and NASA
- **Test Number/Facility:** Test 7043 LaRC 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** Boeing CST-100 configurations with and without tension ties including smooth outer mold line (SOML), as-designed compression pads, and deeper compression pads
- **Test Technique(s):** Global phosphor thermography
- **Duration:** 15 runs, 1 week
- **Date**: February 2019
- **Category:** Commercial access to space

Program Background

- **Issue:** The NASA Engineering and Safety Center was concerned about augmented heating from compression pads on the Boeing CST-100 configuration.
- **Objectives:** Provide insight concerning the aeroheating environments to which the Boeing ablator thermal protection system will be exposed for various nominal and off-nominal flight conditions.
- **Approach:** tested smooth OML models for comparisons with Test 7022 tension tie model
- **Challenges:** Smooth body data was higher than heating data on models with compression pads or CFD results in Test 7022. Investigated differences in data by testing additional models with different phosphor mixes in Test 7043

Test Setup/Model Pictures/Results

Boeing CST-100

https://www.aerospace-technology.com/projects/cst-100-starliner/

Impact/Applications

- **Benefactors/Impact**:
  - Boeing and JSC used phosphor thermography data to validate CFD simulations to calculate augmentation factors due to compression pads and tension ties on the Boeing CST-100 commercial crew heat shield.

USAF HIFiRE 6 Inlet Operability

Test Details

- **Test Name**: HIFiRE 6 Inlet Operability
- **Customer**: Air Force Research Laboratory
- **Test Number(s)/Facilities:** Test 7045, 20-Inch Mach 6 Air
- **Configuration/Models:** 25% scale HIFiRE 6 Inlet Model
- **Test Technique(s):** static and fluctuating pressure measurement, temperature, high-speed schlieren video
- **Duration:** 74 runs
- **Date**: 10-30 Jun 2019
- **Category:** customer test

Program Background

- **Issue:** Inlet operability – the range of angle of attack, sideslip, Mach number, and other variables where the inlet flow remains started, is historically difficult to characterize using CFD.
- **Objectives:** Characterize the inlet operability of the HIFiRE 6 configuration over a range of angle of attack, sideslip, and Reynolds number, and provide data for CFD validation.
- **Challenges:** Develop a high-speed data system with enough channels for both static and fluctuating pressure measurement.
- **Approach:** Design of Experiments-based test matrix to allow the development of regression models for prediction of the inlet start/unstart boundary. Also employed a Langley-developed adaptive-sampling method for logistic regression
- **Benefactors/Impact**: AFRL, NASA

Impact/Applications

- The use of statistics-based experiment designs allowed the efficient characterization of the inlet operability envelope using a minimum of test resources.

SpaceX Starship Blockage Study

Test Details

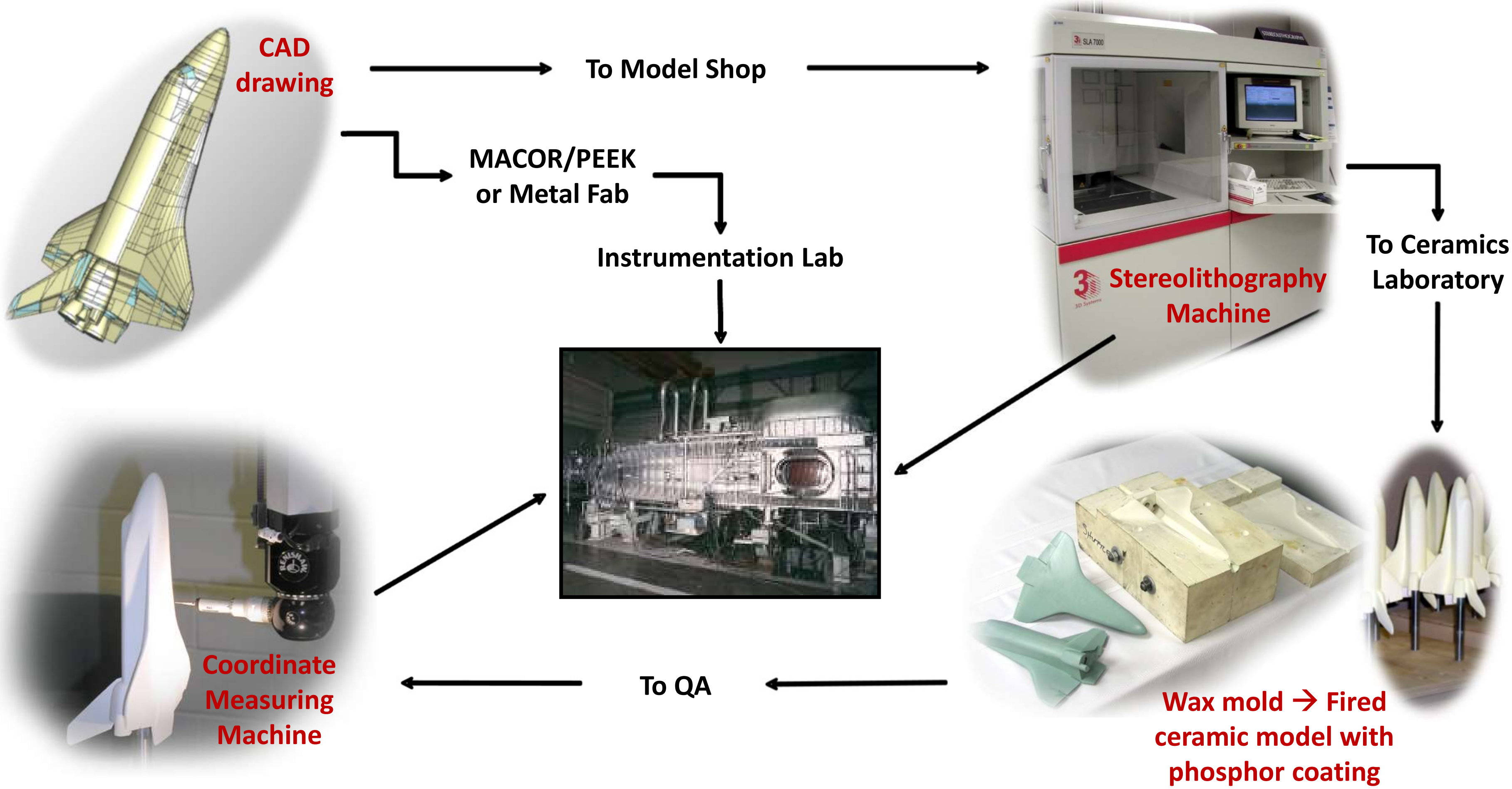
- **Test Name**: SpaceX Blockage Study
- **Customer**: SpaceX
- **Test Number(s)/Facilities:** Test 7066, 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** SpaceX Starship
- **Test Technique(s):** IR, phosphor thermography and schlieren
- **Duration:** 4 days / 32 runs
- **Date**: March 2022
- **Category:** Customer test through Commercial Crew Program

Vehicle Pics

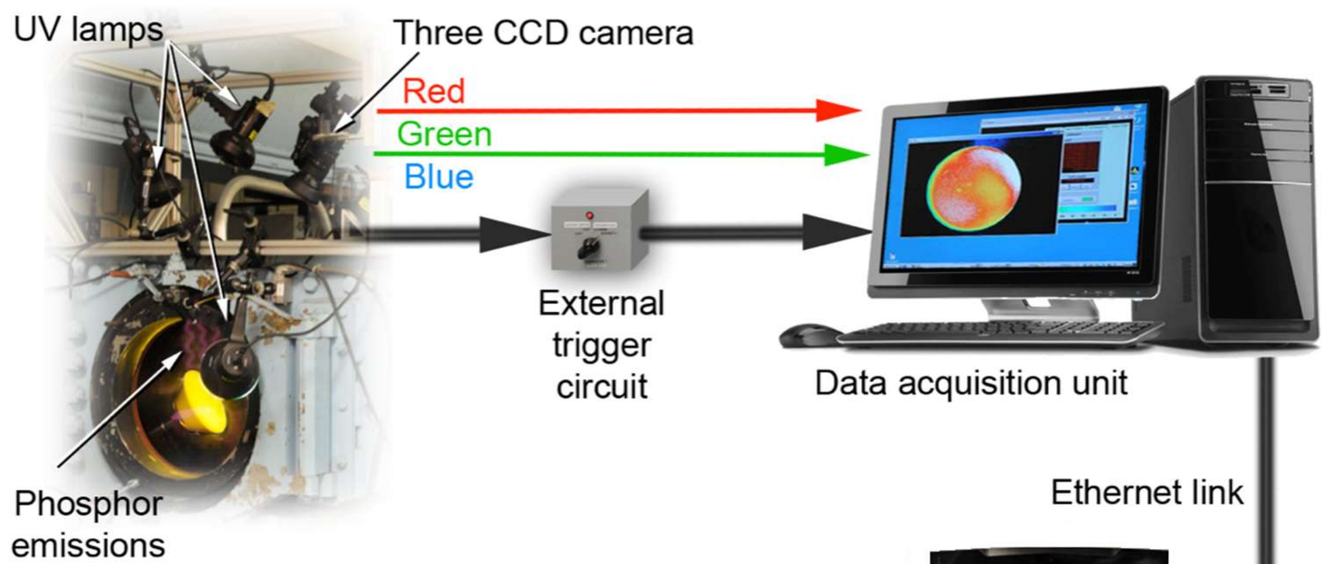
Program Background

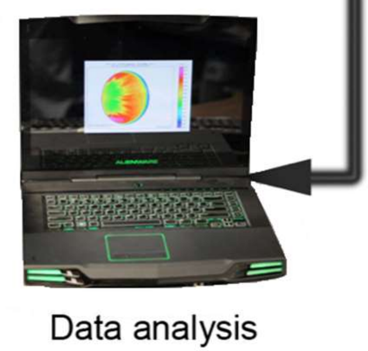
- **Issue:** Starship is long and surface features are very small at the scale needed for Mach 6 tunnel.
- **Objectives:**
  - Maximize the size of surface features to improve data
  - Determine the largest model that can be run without blocking the tunnel flow to cause the tunnel to unstart
- **Challenges:**
  - One wall pressure sensor available (upstream of model) to watch for flow irregularities.
  - Using the Mach probe might unstart the flow
- **Approach:** Test set of models over range of alpha and Re # conditions of interest to customer to see if the tunnel unstarts.
- **Benefactors/Infusion**: Lessons learned about unstarting tunnel, optimized model size for follow-on Starship test.

Model Fabrication Process



Phosphor Thermography





Enthalpy-based convection: $\dot{q}_{conv} = c_h(h_{aw} - h_w)$

Step function:
(using Laplace transforms)

$$\frac{\theta_w}{D} = 1 - e^{\Lambda^2} erfc\,\Lambda$$

Where:

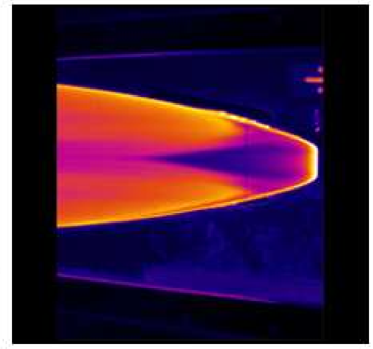
$$\theta_w = T_w - T_{init}$$
$$\Lambda = C\sqrt{t}/\beta$$
$$C = c_h(h_w/T_w)$$
$$D = h_{aw}(T_w/h_w) - T_{init}$$

Infrared (IR) Thermography Technique

LWIR/MWIR Camera

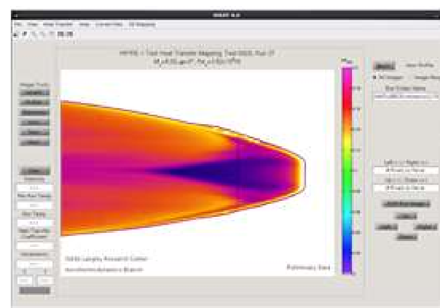
Temperature/Signal Counts

External trigger circuit



Data acquisition

Ethernet link



Data analysis

Enthalpy-based convection:

$$\dot{q}_{conv} = c_h(h_{aw} - h_w)$$

Step function:
(using Laplace transforms)

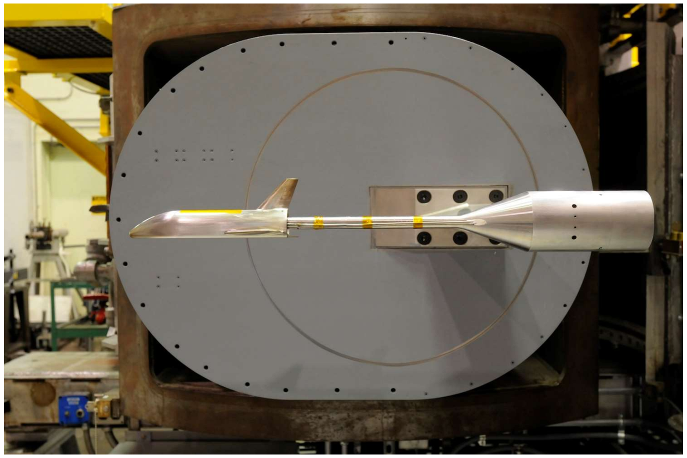
$$\frac{\theta_w}{D} = 1 - e^{\Lambda^2} erfc\,\Lambda$$

Where:

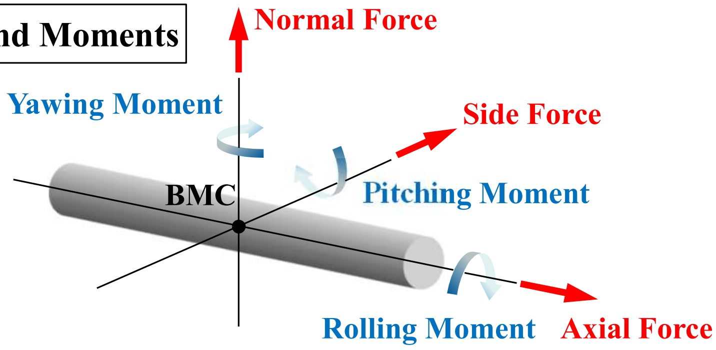
$$\theta_w = T_w - T_{init}$$
$$\Lambda = C\sqrt{t}/\beta$$
$$C = c_h(h_w/T_w)$$
$$D = h_{aw}(T_w/h_w) - T_{init}$$

Balance Force and Moment Measurements

NASA LaRC water-cooled balance mounted on sting



Aerodynamic wind tunnel model mounted to balance in LAL 31-Inch Mach 10 Tunnel



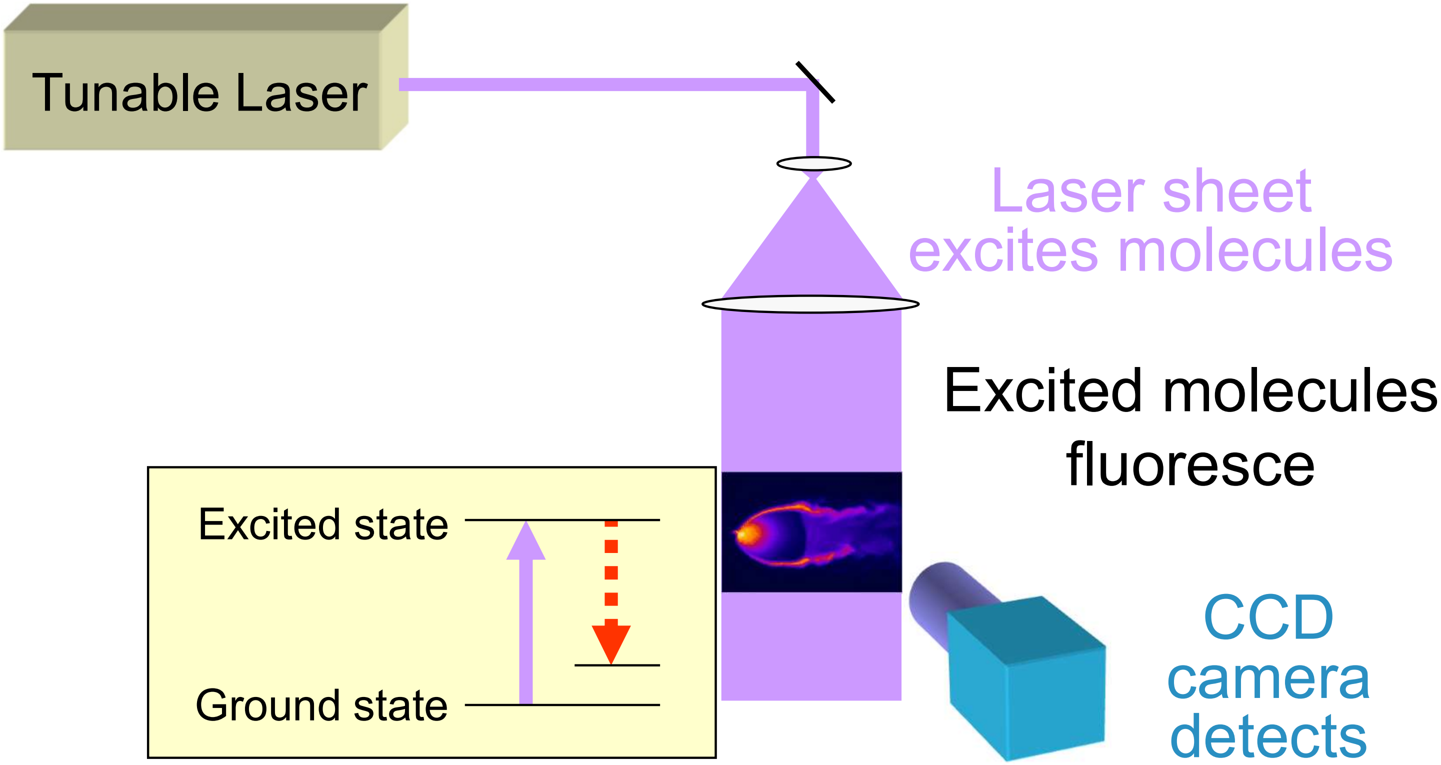
- Model forces and moments are calculated from measured balance loads to account for:
  - Model weight components acting on balance at balance yaw/pitch/roll angles (weight tares)
  - Angle rotations from balance axes to model axes (alignments of balance w.r.t. model)
  - Moment transfers in model coordinate system from balance moment center (BMC) to model moment reference center (MRC or CG)
- Aerodynamic coefficients in the desired aerodynamic axis systems are calculated from model forces and moments, model angles w.r.t. the wind vector, measured or calibrated facility flow conditions, and the model reference dimensions
  - Body axis, stability axis, wind axis
  - Missile axis, aeroballistic axis, vertical axis

$$\begin{bmatrix} C_A \\ C_Y \\ C_N \end{bmatrix}_{BA} = \frac{1}{q_\infty S_{ref}} \begin{bmatrix} AF \\ SF \\ NF \end{bmatrix}_{BA}$$

Body-Axis (BA) Force Coefficients

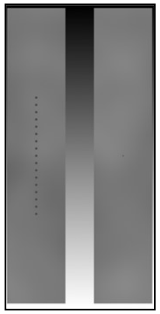
$$\begin{bmatrix} C_l \\ C_m \\ C_n \end{bmatrix}_{BA} = \frac{1}{q_\infty S_{ref}} \begin{bmatrix} RM/b_{ref} \\ PM/l_{ref} \\ YM/b_{ref} \end{bmatrix}_{BA}$$

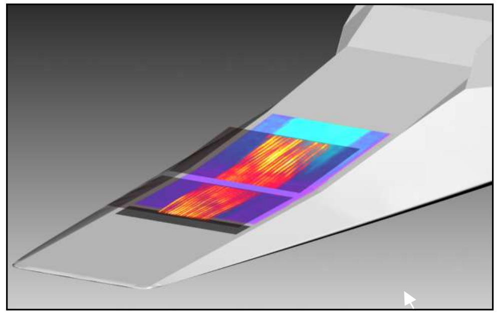
Body-Axis (BA) Moment Coefficients


Tunable Laser
Laser sheet
excites molecules
Excited molecules
fluoresce
Excited state
Ground state
CCD
camera
detects

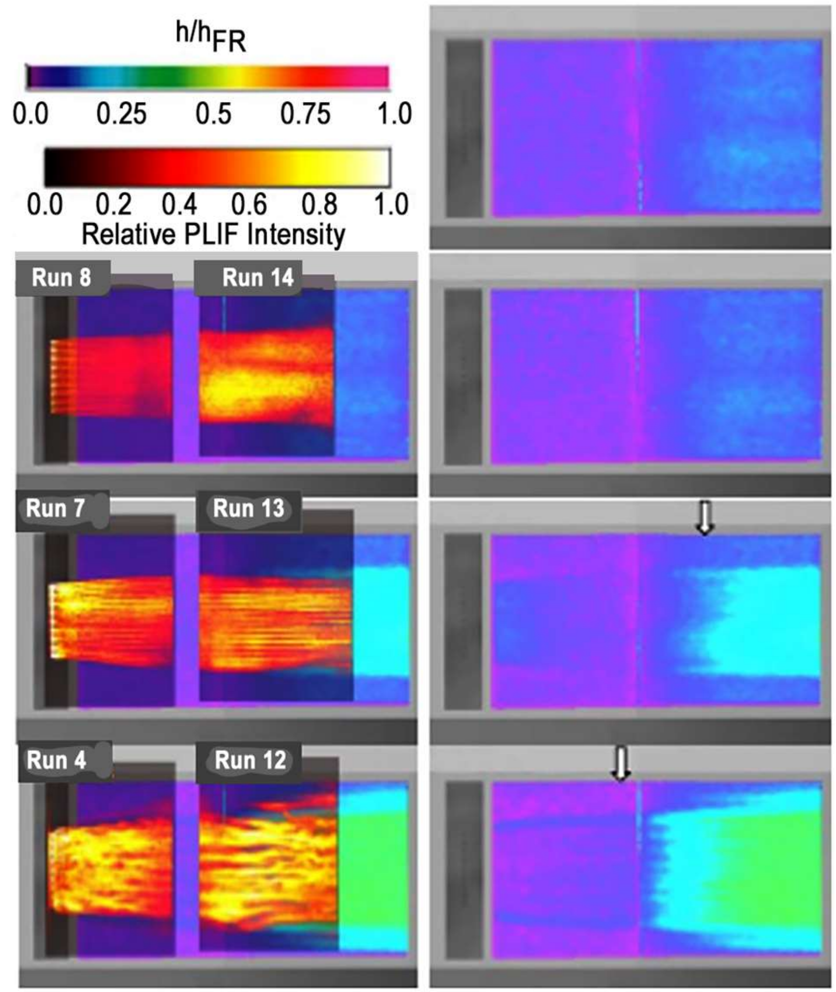
$$LIF \sim n_{NO}$$

PLIF Visualization and Phosphor Thermography



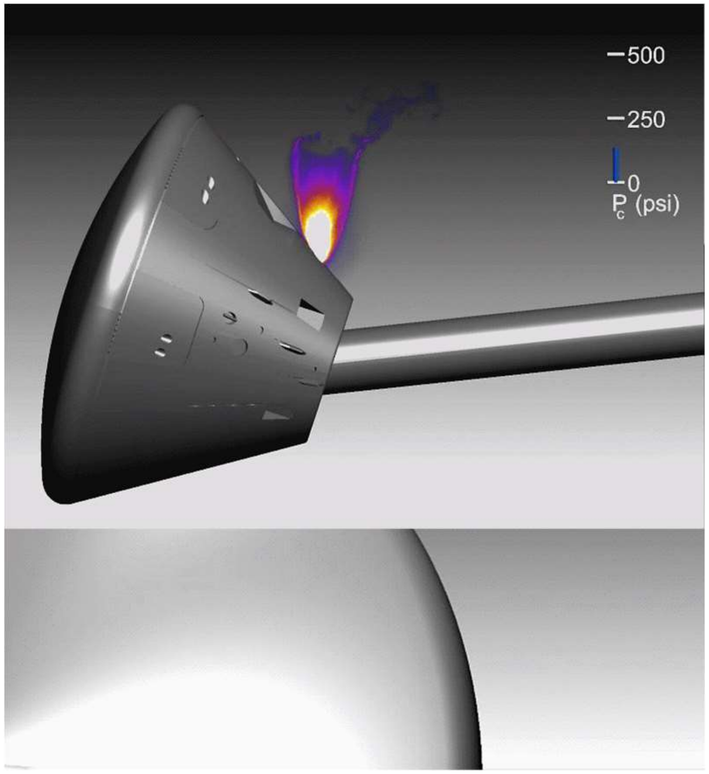


- Hyper-X study
  - Forced boundary layer transition via blowing
  - Comparison between PLIF images and surface heating measurements
  - Determination of transition location
  - Effect of blowing rate
    - Heating patterns
    - Flow structures observed in relation to blowing rate
    - Measurements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



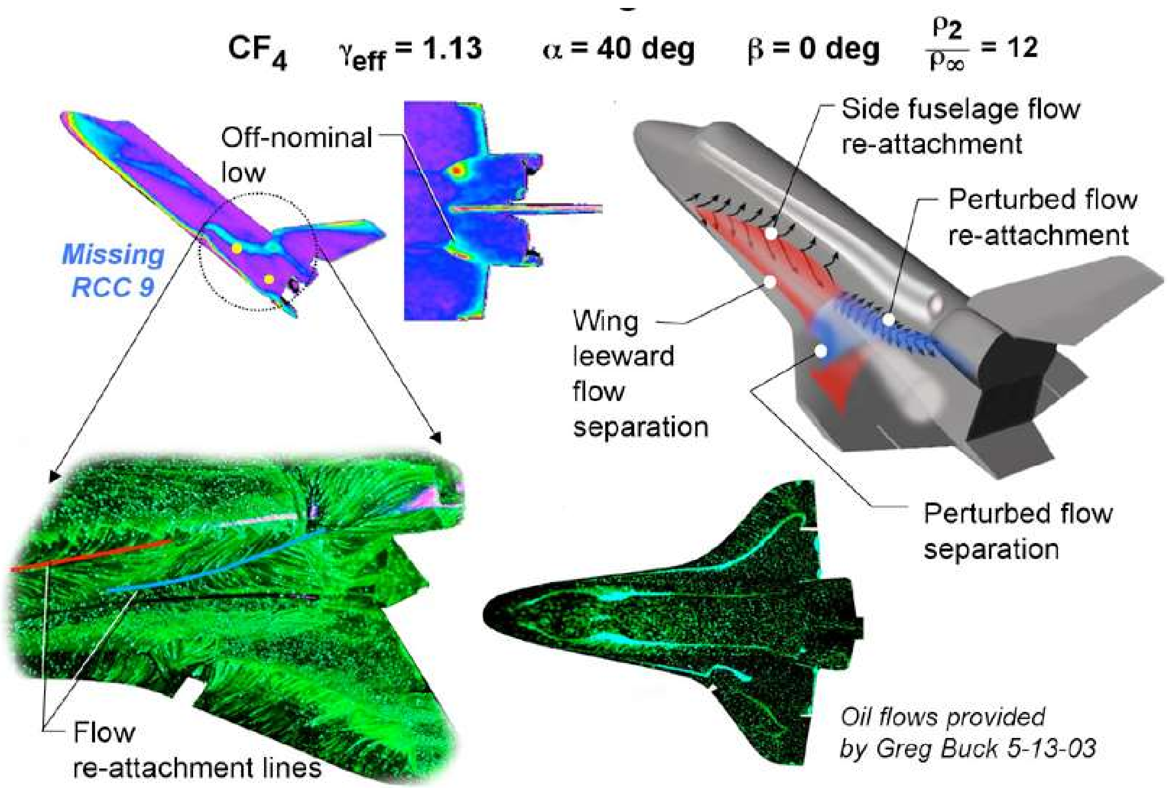
PLIF RCS Jet Visualization and Reconstruction

- 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



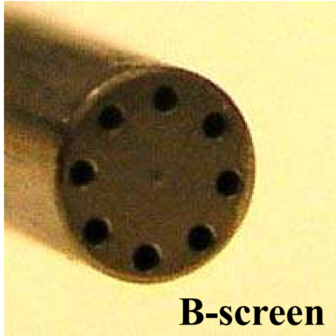
Oil Flow

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

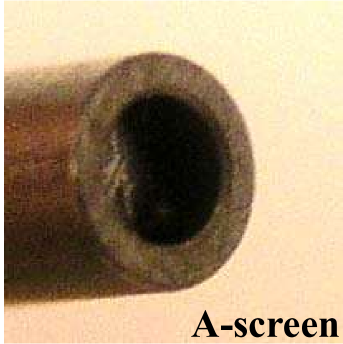


Kulite Pressure Transducers

- 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

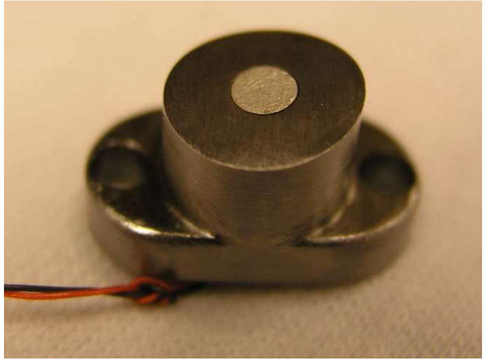
PCB113

- Dynamic Pressure sensor
- Resonant frequency greater than 500 kHz

PCB132

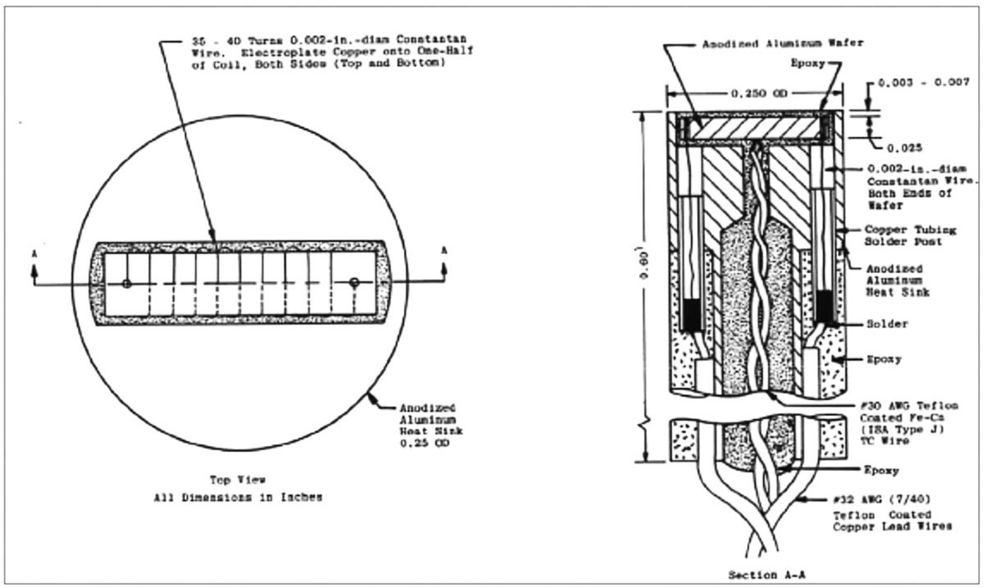
- Measure frequencies between 11 kHz and 1 MHz
- Roll-off begins around 300 kHz
- Sensor diameter is 0.125 inches
  - Ceramic sensing unit approximately 0.03” x 0.03”

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



Schmidt-Boelter Heat Flux Gage

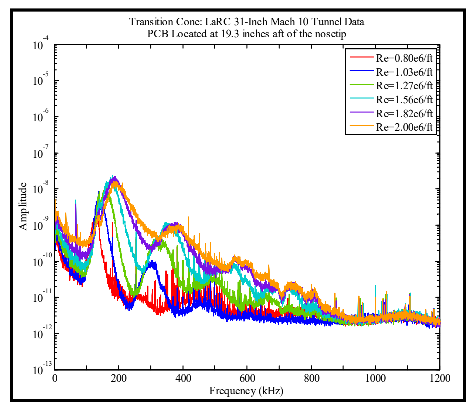
- **Output is directly proportional to heat flux**
- **Operating temperature: 50 - 600°F**
- **Time response on the order of 10 ms**
- **Measures temperature difference between parallel planes**
  - Hot junction on the top of the wafer
  - Cold junction on lower surface of wafer
- **Can conform to curved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



Data Acquisition – High Frequency

- Data Acquisition Systems
  - Portable
  - Tektronix DPO1704 Oscilloscope
    - 4 channels
    - 1GHz Bandwidth
    - 12.5 MB per channel
  - HBM Gen5i
    - Currently 12 channels (expandable to 20)
    - Up to 100 MHz (1.8 GB memory per 4 channel card)

- Data Reduction
  - MATLAB modules



Hot Wire Anemometry

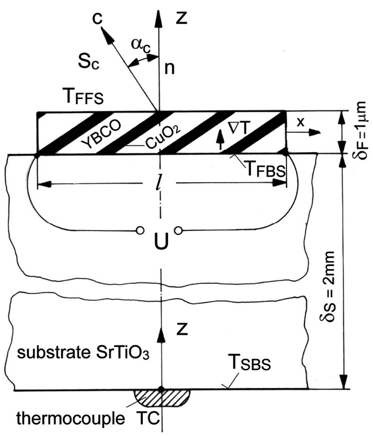
- Hot wires detect changes in temperature and mass flux of the fluid
  - Intrusive
  - Used to study boundary layer flows (laminar, turbulent, transitional), unsteady flows, temperature profiles, etc.
  - Frequency response as high as 300-400 kHz
- Typically made of tungsten, platinum, and platinum alloys
  - small diameters (<0.001 inches)
  - Aspect ratios should be greater than150 to minimize end loss effects

- Types of Anemometers
  - Constant-Current Anemometer (CCA) (not currently available at LaRC)
    - 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

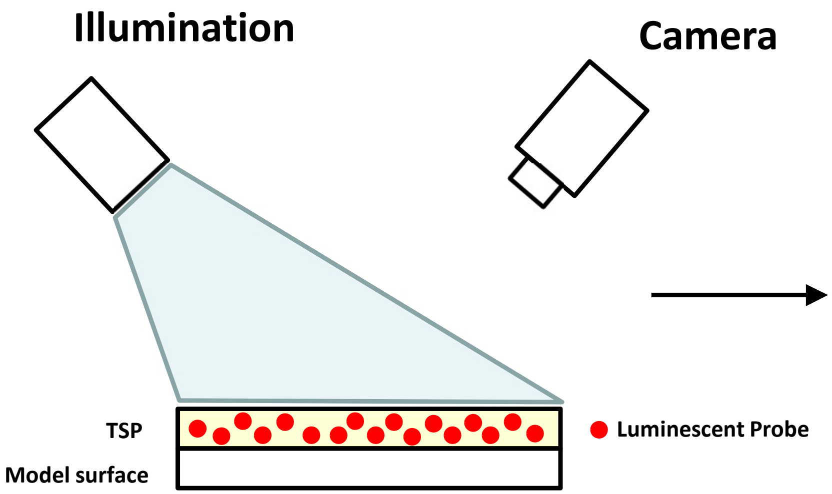
Atomic Layer Thermopile (ALTP) Sensor

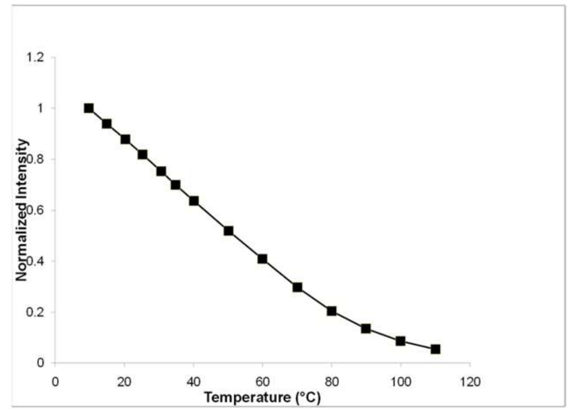
- High-frequency heat-transfer gage.
  - Sensor housing is large compared to Kulite® and PCB132® transducers.
  - 8*mm diameter and 2.5mm*^{2} *sensitive* area.
- Typical electronics provide AC signal between 17 Hz and 1 MHz and separate DC signal.

- Product of Cosytech and Fortech



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

High-Temperature Phosphor Thermography

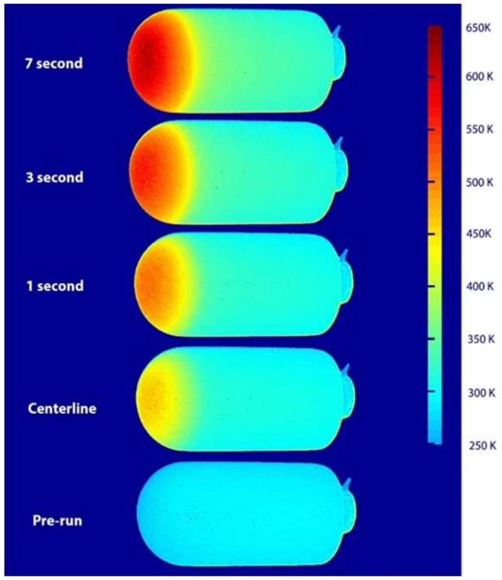
Test Details

- **Test Name**: High-temperature phosphors
- **Customer**: NASA
- **Test Number(s)/Facilities:** Test 542, LaRC 31-Inch Mach 10 Air Tunnel
- **Configuration/Models:** ceramic hemisphere-cylinder model
- **Test Technique(s):** prototype high-temperature phosphor system
- **Duration:** 1 week, 14 runs
- **Date**: July 2021
- **Category:** Test technique development

Program Background

- **Issue:** current thermographic phosphor mixture has upper temperature limit of ~400K, which limits data acquisition on high-heating features like leading edges and over general acreage at high Reynolds number conditions in 31-Inch Mach 10 Air Tunnel
- **Objectives:** demonstrate capability to obtain temperatures of up to 600 K with new phosphor mixture
- **Challenges:** development of new model coating process, coating calibration / data acquisition / data reduction
- **Approach:** develop – test - refine
- **Benefactors**: all aeroheating test programs

Hemisphere-cylinder temperature distributions



Results/Impact

- Obtained surface temperature measurements at 100K beyond range of current phosphor mixture
- Equipment worked well with a new power source and pulse generator. Solved previous problems with triggering and camera framing
- Implementation will lead to dramatic increase in data return for high-heating areas (e.g., leading edges, sharp cones) and at Mach 10 tunnel high-temperature conditions

FACILITY CALIBRATION

Global Phosphor Thermography Hemisphere Calibration

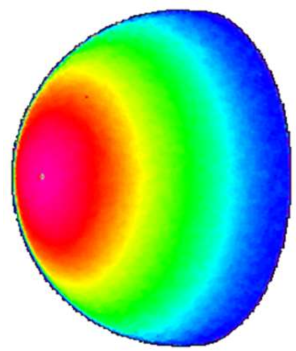
Test Details

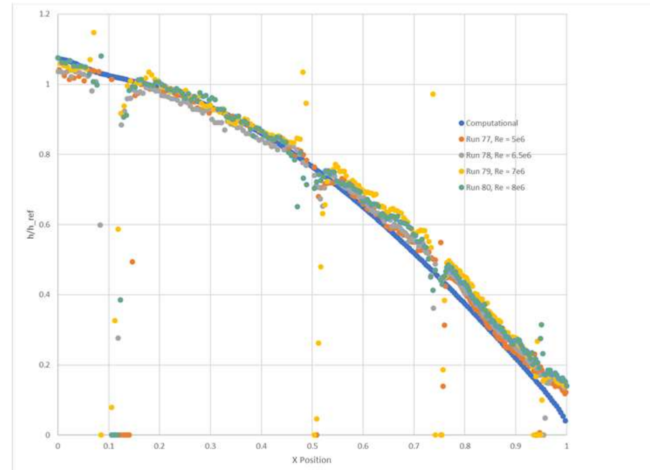
- **Test Name**: Calibration Hemisphere
- **Customer**: NASA
- **Test Number/Facility:** Test 7015, LaRC 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** Ceramic hemisphere
- **Test Technique(s):** Global Phosphor Thermography
- **Duration**: 10 runs
- **Date**: July 2016
- **Category:** NASA Test Technique Maintenance

Program Background

- **Issues:** Hemisphere verification completed anytime a new phosphor mix is created or calibrated or when issues arise
- **Objectives:** Demonstrate that data with the phosphor system is performing as expected on a known configuration
- **Approach:** Use phosphor thermography coating on 4-inch diameter hemisphere models, ensure collected data matches previous results and computational predictions
- **Benefactors/Infusion**: All programs using phosphor thermography

Test Setup/Model Pics/Results





Impact/Applications

- Results of calibration checkouts are used by all programs that use global phosphor thermography
- Checkouts must be completed successfully before a new mix of the coating is put into operations
- Checkouts on the known hemisphere configuration are used to
  - Ensure proper operations of system (coating, camera, window, calibration, etc.) in tunnel environment
  - Increase the confidence in the test technique
  - Troubleshoot and diagnose issues as they occur and aid in return to service of the technique

Flow Survey, 20-Inch Mach 6 Air Tunnel

Test Details

- **Test Name**: 20-Inch Mach 6 Tunnel Flow Survey
- **Customer**: NASA
- **Test Number(s)/Facilities:** Test 7035, 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** LAL Flow Survey Rake
- **Test Technique(s):** pressure measurement
- **Date**: 2-14 Aug 2018
- **Category:** Facility characterization

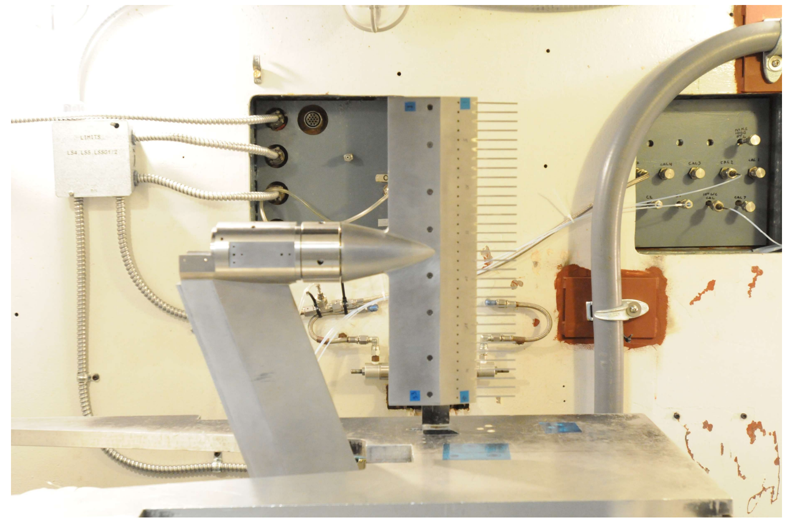
Program Background

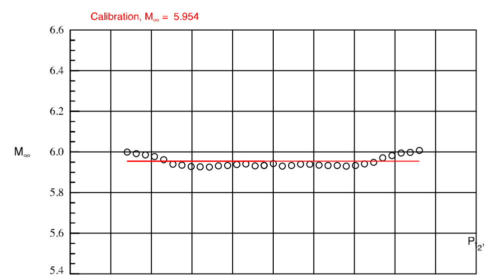
- **Issue:** Time-dependent variations observed in flow conditions
- **Objectives:** Obtain Mach number distributions over range of Reynolds number conditions for several axial stations in the test section. Obtain flow survey information to help plan follow-on full calibration of facility. Also shake down new rake hardware.
- **Approach:** Design adapter beam that mounts to the model support system and allows the rake strut to be positioned at various axial locations in the test section.
- **Benefactors/Impact**: LAL

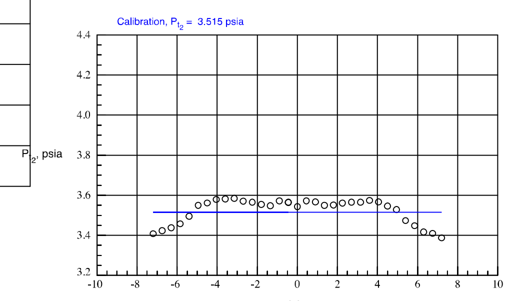
Impact/Applications

- Observed that Mach number changes over time (hours, days) due to thermal deformation/growth of uncooled nozzle.
- An improved Mach probe system is required to obtain freestream measurements during each run so that we reduce data using the actual Mach number in the flow.

Test Setup/Model Pictures/Results







Flow Physics and Control Branch

Freestream Disturbance Characterization

Langley Aerothermodynamics Laboratory

Test Details

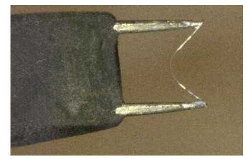
- **Test Name**: Tunnel Noise Characterization Study
- **Customer**: Hypersonics Technology Project RT3
- **Test Number(s)/Facilities:** Test 7042 in 20-Inch Mach 6 Air Tunnel
- **Configuration/Models:** 15" Rake, 10" Rake
- **Test Technique(s):** Probe measurements with high-bandwidth pressure transducers, hot wires, and focused laser differential interferometry
- **Duration/Date:** 124 runs - March/April 2019
- **Category:** Fundamental research

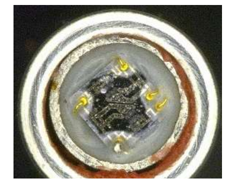
Program Background

- **Objectives:** Perform a comprehensive characterization of the 20-Inch Mach 6 Tunnel freestream disturbances (acoustic and mass flux) and develop appropriate techniques for use in the 31-Inch Mach 10.
- **Challenges:** Hot wires are fragile and prone to breakage. Laser-based techniques are not quantitative yet. Skillsets and understanding how both these techniques work take considerable time to cultivate.
- **Approach:** Install interchangeable hot-wire and pressure sensor probes in a rake body. Take profiles of the flow at various streamwise locations and orientations of the rake. Perform spectral analysis of the data.
- **Benefactors/Infusion**: Future transition studies will incorporate the frequency content and freestream noise levels into their analysis. CFD will use the amplitude and frequency content to better model expected boundary layer instabilities. This effort was also tied into the NATO RTO STO AVT-240 activity of characterizing noise in hypersonic facilities in NATO countries.

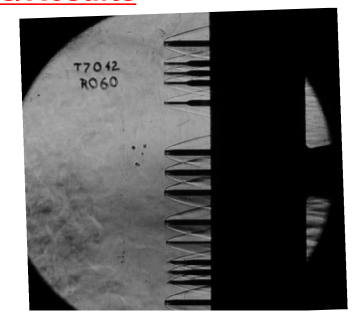
Test Setup/Model Pics/Results

Closeup of Hot Wire probe tip at 50x

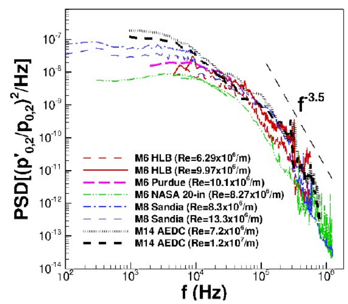




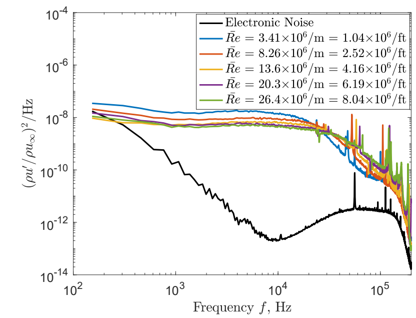
Closeup of Kulite probe tip at 100x



Schlieren image of 15" Rake in the Tunnel at Re=8x10^6/ft



Typical power spectra of freestream pressure fluctuations compared across multiple hypersonic facilities



Typical power spectra of hot wire measurements of freestream mass flux fluctuations

Impact/Applications

- Provides flow quality measurements for customers performing boundary layer transition studies, also used for comparison to other hypersonic facilities (e.g., Duan et al. JSR 2019, v. 56:357-368)
- Spectral content of pressure fluctuations have been used to predict the growth of boundary layer instabilities (e.g., Balakumar et al. AIAA J 2018, v. 56:193-208)

Settling Chamber Temperature Issues

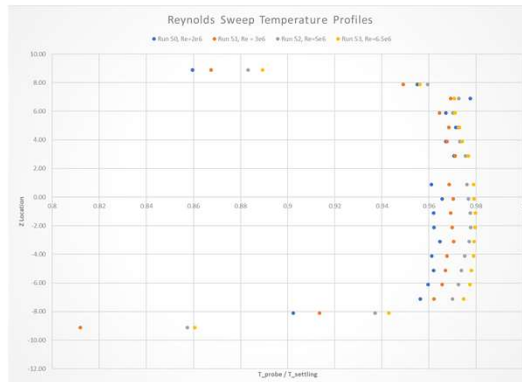
Test Details

- **Test Name**: Facility Diagnostics
- **Customer**: Langley Aerothermodynamics Laboratory
- **Test Number/Facilities:** Tests 7051, Mach 6
- **Configuration/Models:** Temperature and Pressure Rakes
- **Test Technique(s):** Discrete Temperature and Pressure
- **Duration:** 30 runs in Mach 6
- **Date**: December 2019
- **Category:** NASA Test Technique Maintenance

Program Background

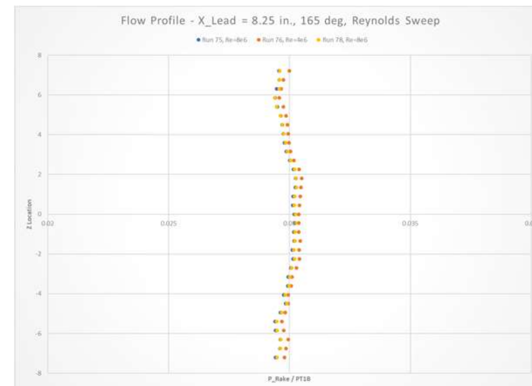
- **Issues:** Abnormal temperatures in settling chamber observed, impacting test section conditions
- **Objectives:** Determine cause of abnormal temps in settling chamber, then confirm tunnel operating as expected
- **Approach:** Utilized temperature rake to confirm nonuniform flow. Pressure rake used once resolved to confirm tunnel performance
- **Benefactors/Infusion**: All test programs

Test Setup/Model Pics/Results



Initial temperature data showing non-uniform temperatures across test section

Later pressure data showing much more uniform flow and resolved settling chamber issues



Impact/Applications

- Understanding of test section conditions and uniform flow critical to all tunnel testing
- Problem observed/confirmed with temperature rake
- Attempts to see in settling chamber unsuccessful
- Over time/runs the situation seemed to improve. Confirmed with pressure rake data
- Likely cause was debris in settling chamber, eventually burned out
- Facility added ability to monitor settling chamber temperatures in the event of another nonuniformity