



Space Shuttle Boundary Layer Transition Flight Experiment Ground Testing Overview

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Outline



- Introduction and Motivation
- Flight Experiment Overview
- Ground Test
 - Facilities
 - Models/Techniques
- Ground Testing Results
- Summary



Introduction and Motivation



Flight Experiment Motivations

- Two tile gap fillers observed protruding during STS-114 inspection
- BLT prediction uncertainty risks higher than spacewalk risks - repair spacewalk completed
- Protuberance flight test purposefully tripping boundary layer recommended and approved by Space Shuttle Program following STS-114
- Flown on 4 *Discovery* flights and 1 *Endeavour* flight

Ground Test Motivations

- Provide ground test data to support the planning and safety certification efforts required to fly the flight experiment
 - Verify viability of BRI-18 protuberance tile
 - Provide protuberance and localized area temperature data at representative high enthalpy flight conditions
 - Acquire time-at-temperature slumping performance data on protuberance at representative flight conditions
- Provide validation for the collected flight data
- Gain a better understanding of the flow field characteristics of the flight experiment



Flight Experiment Overview

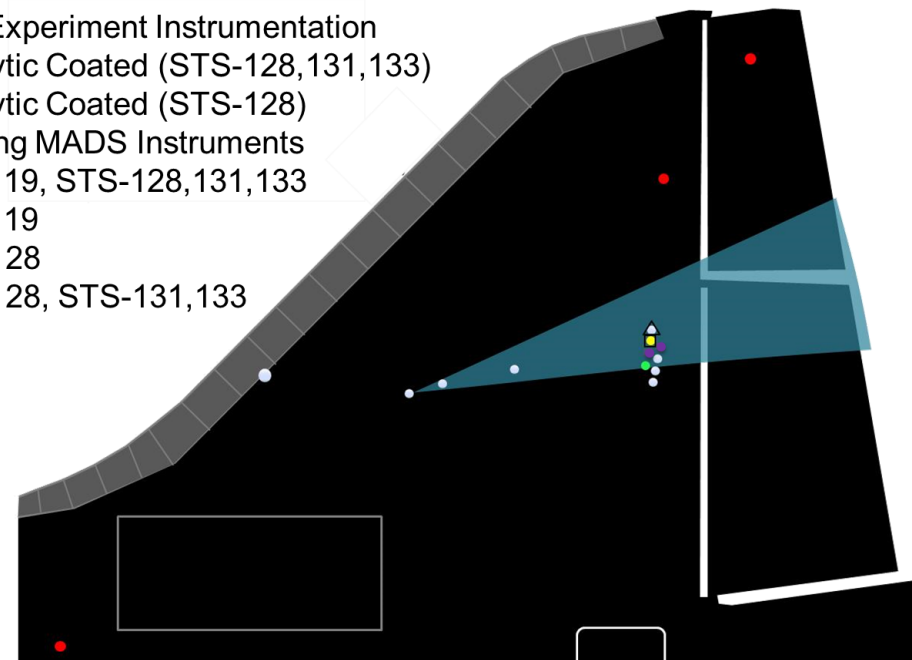


Flight	Protuberance Height (in)	Target BLT Onset (Mach Number)	Vehicle	Landing Date
STS-119	0.25	15	Discovery (OV-103)	March 28, 2009
STS-128	0.35	18	Discovery (OV-103)	September 11, 2009
STS-131	0.35	18	Discovery (OV-103)	April 20, 2010
STS-133	0.50	19.5	Discovery (OV-103)	March 9, 2011
STS-134	0.50	19.5	Endeavour (OV-105)	June 1, 2011

- Incremental approach to flight test - safety
- Protuberance height derived with BLT tool, Re_θ/M_e correlation



- Flight Experiment Instrumentation
- Catalytic Coated (STS-128, 131, 133)
 - △ Catalytic Coated (STS-128)
 - Existing MADS Instruments
 - STS-119, STS-128, 131, 133
 - STS-119
 - STS-128
 - STS-128, STS-131, 133





Outline



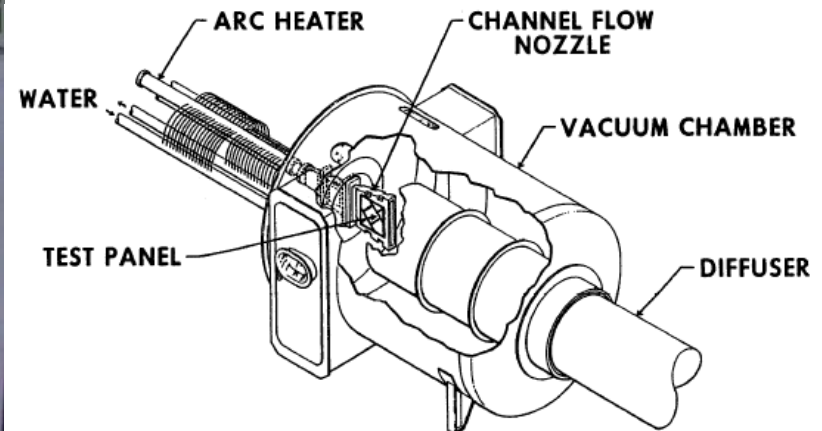
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NASA JSC Arc Jet Facility



- Atmospheric Reentry Materials and Structures Facility (ARMSEF)
- Vacuum chamber corresponds to ~204,000-182,000 ft altitude
- Test position 1:
 - Channel nozzle arc-jet
 - Study flat surface heat transfer at zero degree angle of attack
 - Up to 24x24-in flat plate models
- 10 MW arc heater, 12-ft dia. test vacuum chamber with diffuser
- 5-14 arc heater packs (10 and 14 pack configurations used)

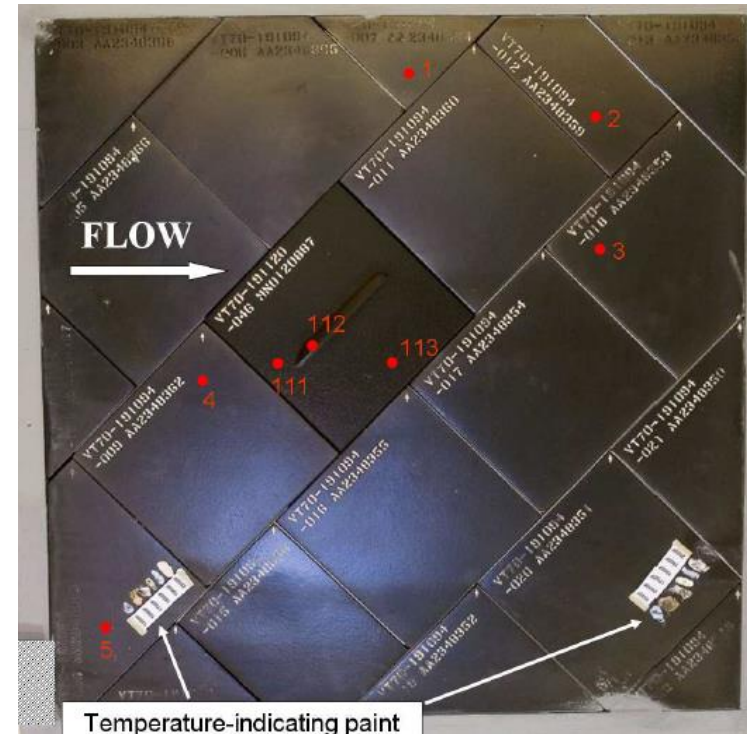




Arc Jet Model

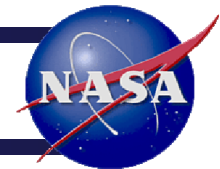


- 0.25-inch and 0.35-inch flight protuberances
- 6x6-in BRI-18 tiles (RCG coated, similar to flight)
- 2x2-ft full article with tile inserts (rapid changes)
- Other tiles were LI-900 or LI-2200
- Protuberance at 45-degrees to local stream line
- Surface, bondline, side wall thermocouples
 - Type R (up to 3200 °F) for surface, sidewall
 - Type K (up to 2490 °F) for bondline
 - X-ray images pre-test - check proximity to tile OML
- Tempilaq® temperature-indicating paint in two locations
 - Locations unlikely to see flow disturbances associated with protuberance heating
 - Six grades that melt at various set temperatures used (1500, 1600, 1700, 1800, 1900 and 2000 °F)
 - Intent to obtain additional indication of smooth tile surface temperature, determine usefulness in flight experiment
- Scanned before/after tests with Advanced Topical Optical Scan system

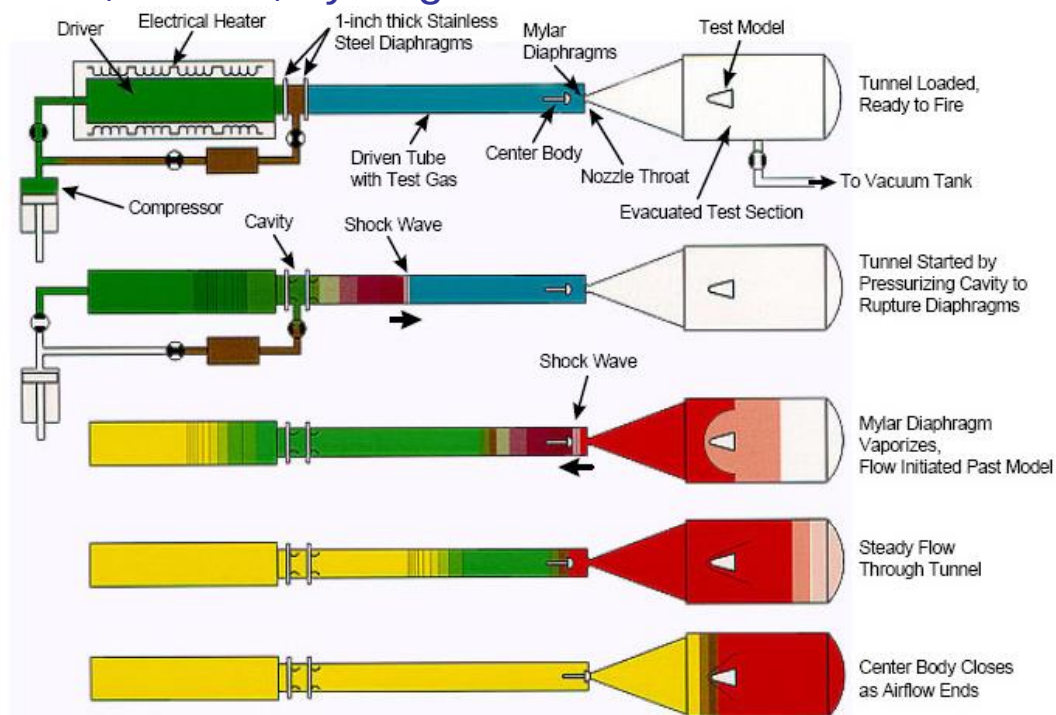
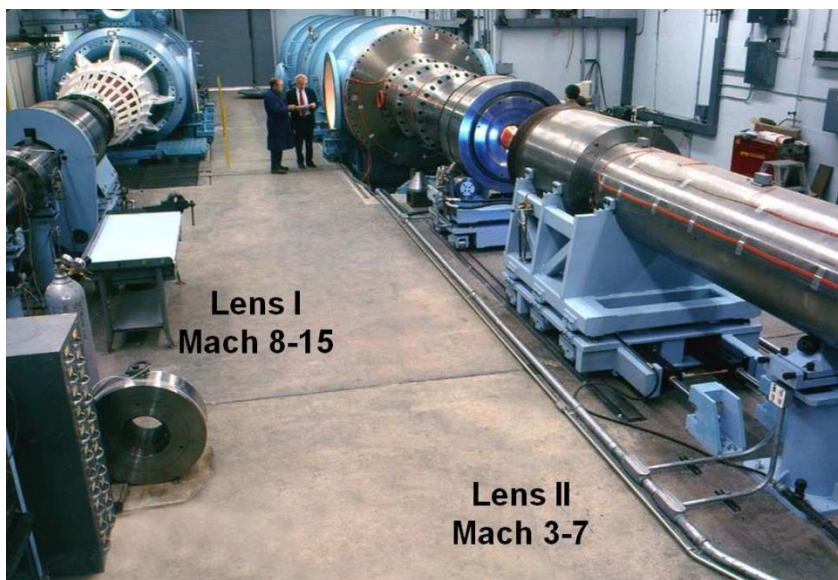




CUBRC LENS-I Facility



- Calspan-University of Buffalo Research Center (CUBRC) Large Energy National Shock (LENS)-I Tunnel
- Hypervelocity reflected shock tunnel
- Duplicate flight conditions at Mach 6-15
- Models up to 3 feet diameter, 12 feet long
- Driver section operates up to 30,000 lb_f/in² (hydrogen, helium, nitrogen or combo)
- Driven tube: air, nitrogen, carbon dioxide, helium, hydrogen or combination

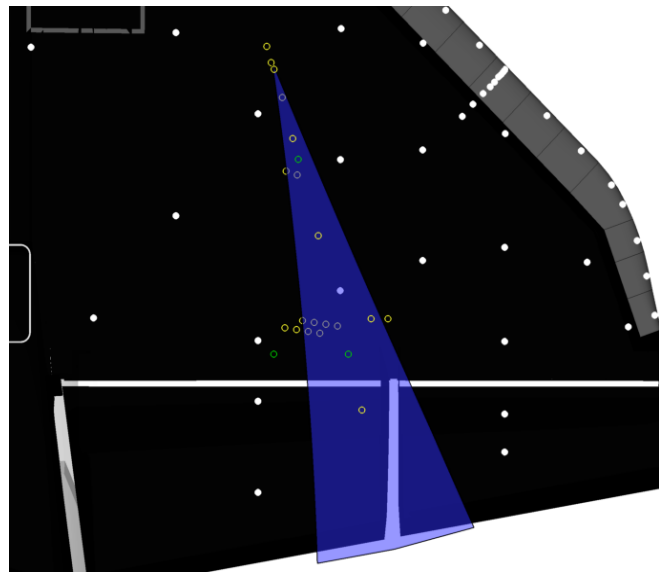




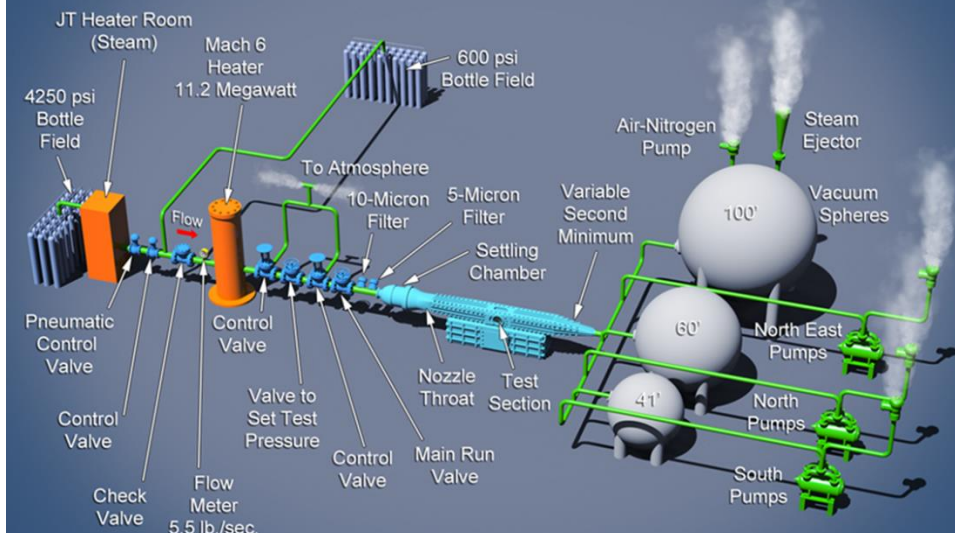
MH-13 Model



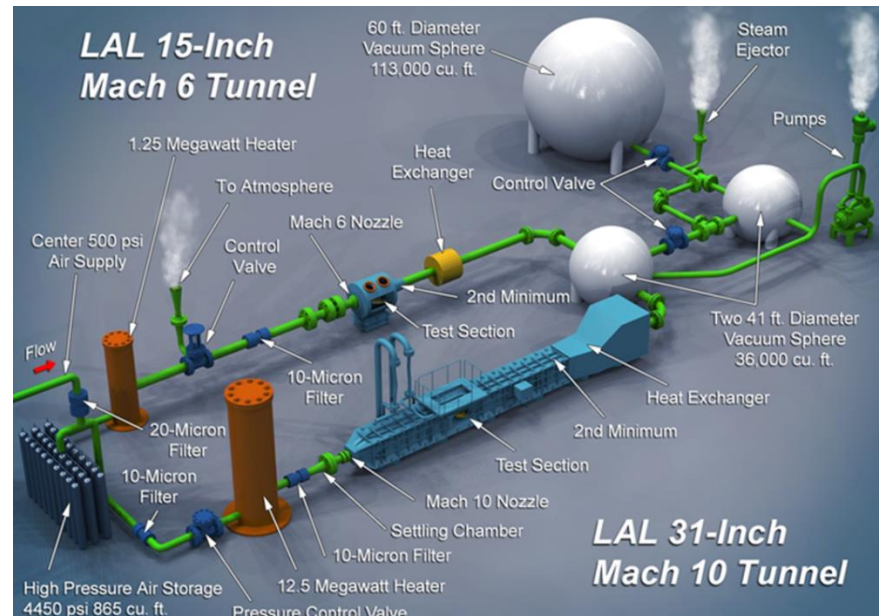
- 1.8% scale steel and aluminum model
- Initially designed to support the Return-To-Flight Program
- Large amount of instrumentation already present (~100 thin film sensors in centerline/wings, ~200 thin films in wing leading edge)
- Temperature sensitive paint added to starboard wing
- 18 thin-film sensors added in locations similar to flight instrumentation
- 0.0075 and 0.015-inch protuberances instrumented to represent flight protuberance on both wings



LAL 20-Inch Mach 6 Air Tunnel



LAL 15-Inch Mach 6 Tunnel



LAL 31-Inch Mach 10 Tunnel

20 Inch Mach 6 CF₄ Tunnel



Tunnel	Gas	Mach	Re (x10 ⁶ /ft)	Run Time	AoA (deg)	Beta (deg)
20-Inch Mach 6 Air	Air	6	0.50 - 8	20 min	-5 to 55	-8 to +8
31-Inch Mach 10 Air	Air	10	0.25 - 2	2 min	-90 to +90	-5 to +5
20-Inch Mach 6 CF ₄	CF ₄	6	0.01 – 0.55	20 sec	-10 to +50	-5 to +5

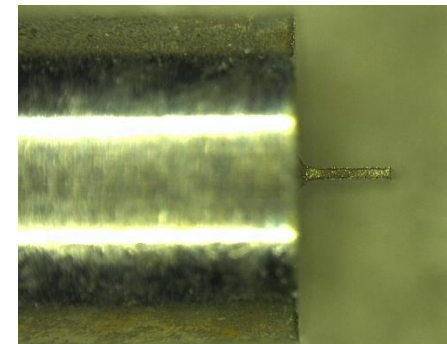
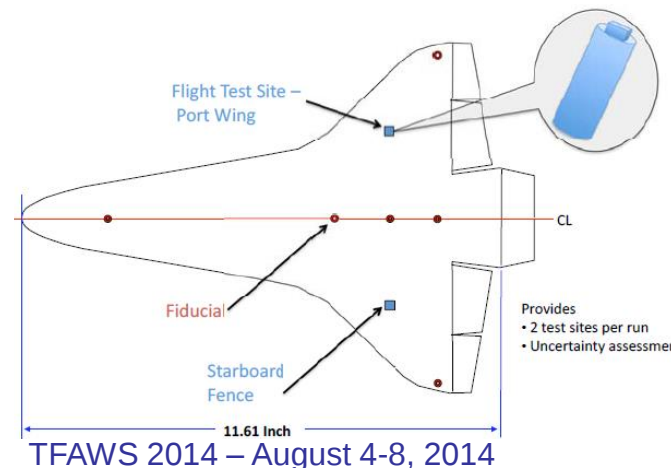


Ceramic Models



2 sets of ceramic models utilized

- 0.75% scale models
 - 0.05x0.05-in tape trips of varying thicknesses (did not represent scaled flight protuberance)
 - Some fabricated with deflected control surfaces to match STS-119 and STS-128
- 0.9% scale models
 - Undeflected control surfaces
 - Fence trips machined into metal rods, represent the scaled flight protuberances
 - Two trips installed per model (port and starboard wings) to maximize the data collected
 - Trips fabricated by EDM Dept., Inc., included 0.006, 0.010, 0.015, 0.0175 and 0.020-in
- Global Phosphor Thermography
 - Two-color relative-intensity technique, dependent on incident light, local surface temps
 - Images converted to temperature mappings via temperature-intensity calibration

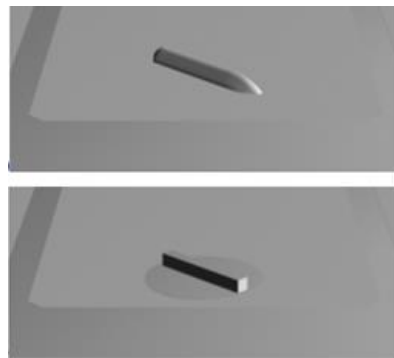
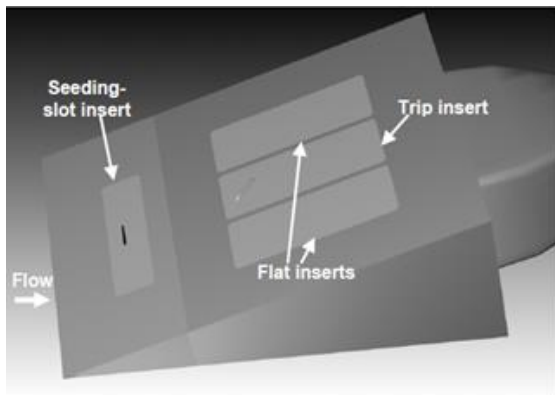




PLIF and TSP Models



- 20 deg full-angle wedge with sharp leading edge, 5 in. wide, 6.4 in. long
- Two protuberance shapes
 - BLT FE, 0.039-in. or 0.098-in. tall, 0.42 in wide, 45° (NanoFormTM)
 - rectangular fence trip, oriented at 45 deg, 0.039 in. high, black, sharp edges/corners
- Temperature Sensitive Paints applied with via conventional spraying over white primer
 - Model illuminated with LED based arrays (400 nm), imaged with 14-bit digital camera
 - ~5-7 sec on centerline, data normalized to Fay-Riddell stagnation point heating
- Planar Laser Induced Fluorescence – Nitric Oxide gas seeded through centerline slot
 - Flow rates of 150 and 300 sccm
 - Images acquired using 2 Princeton Instruments PI-MAX II CCD
 - Laser sheet translated in tunnel, measurements along/away from surface





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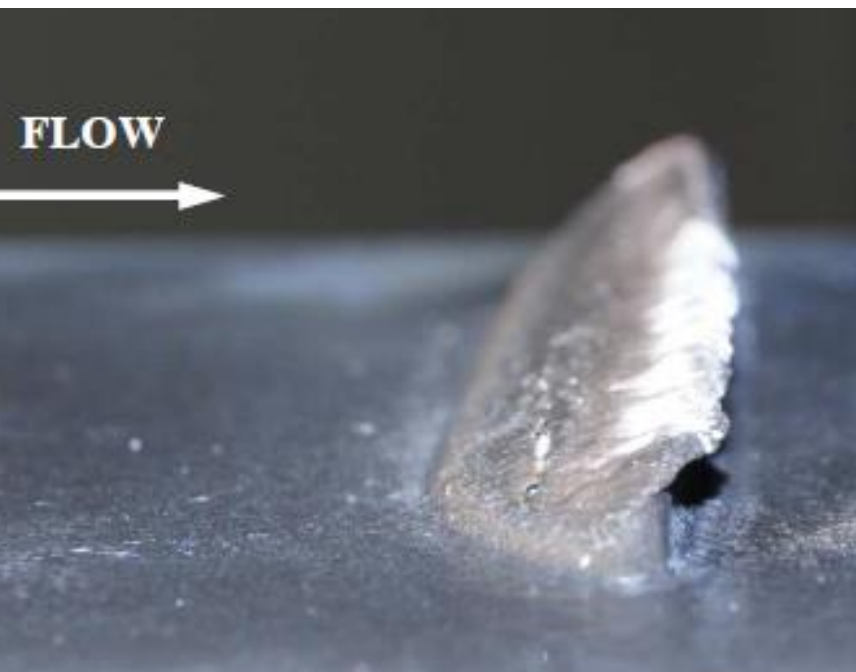
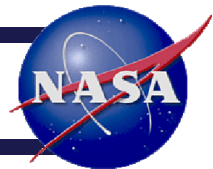
Arc Jet Testing



- Test objectives were to
 - Determine if BRI-18 tile protuberance was safe to fly
 - Provide temperature data on protuberance tile at representative high enthalpy conditions
 - Acquire time-at-temp slumping data on 0.25" protuberance at representative conditions
 - Perform arc jet run at conditions that mimic an oncoming turbulent boundary layer
 - Determine if temperature indicating paint could be used for testing and/or on flight vehicle
- Phase I (2008): Three 0.25-in, One 0.35-in protuberance runs, 10-pack heater
 - 0.25" protuberance tested from 1200-2000+ °F, RCG texture changes, no melting/slumping
 - 0.25" protuberance survived arc-jet conditions similar to nominal re-entry environment
 - 0.35" protuberance tested from 1900-2250+ °F, RCG flow, local temps ~2900 °F for ~60 sec
 - Onset of shape change noted for 0.35" protuberance (near material limit)
- Phase II (2009): Three 0.35-in. protuberance runs, 14-pack heater
 - Protuberance temps 3000+ deg F, protuberance slumping noted (max change of 0.123 in)
 - Shown protuberance safe for nominal re-entry (failure mode was shown that protuberance melted until it reached condition where heating not enough to cause further melting)
- Based on test results, temperature indicating paint not used for flight vehicle

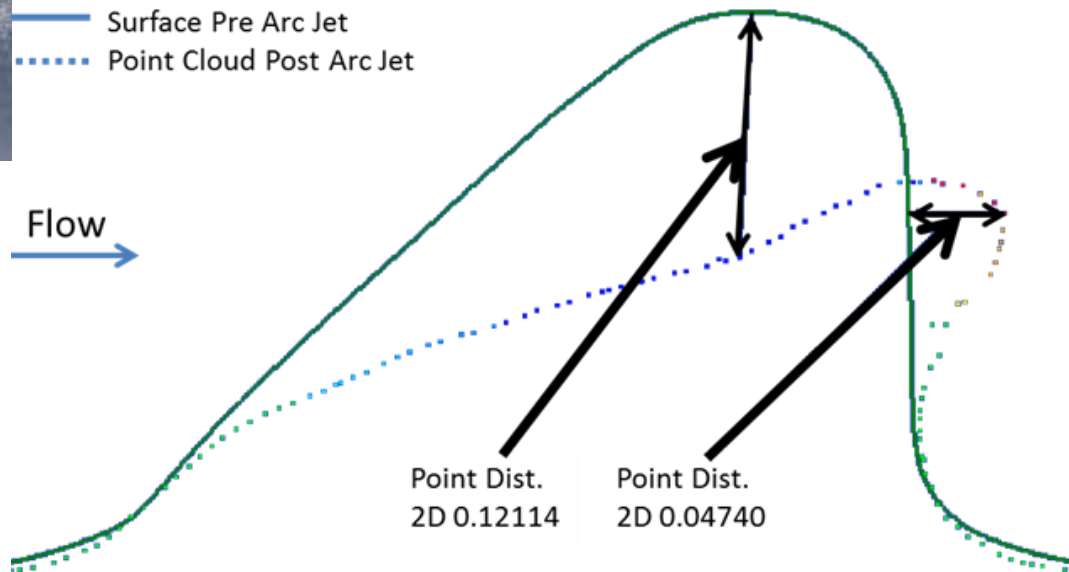


Arc Jet Testing



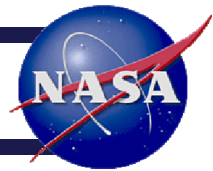
— Surface Pre Arc Jet
... Point Cloud Post Arc Jet

Flow

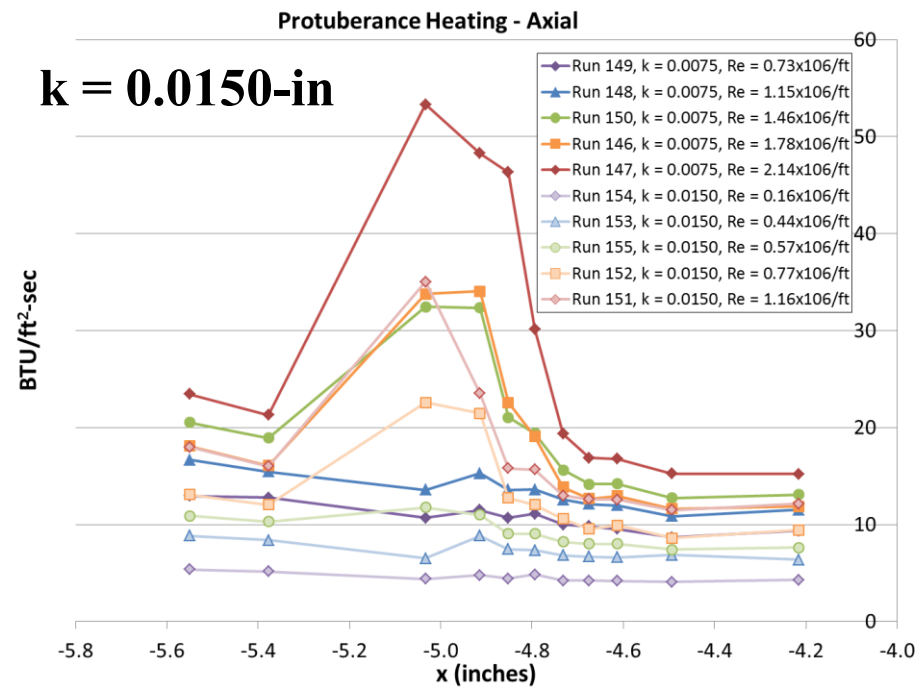
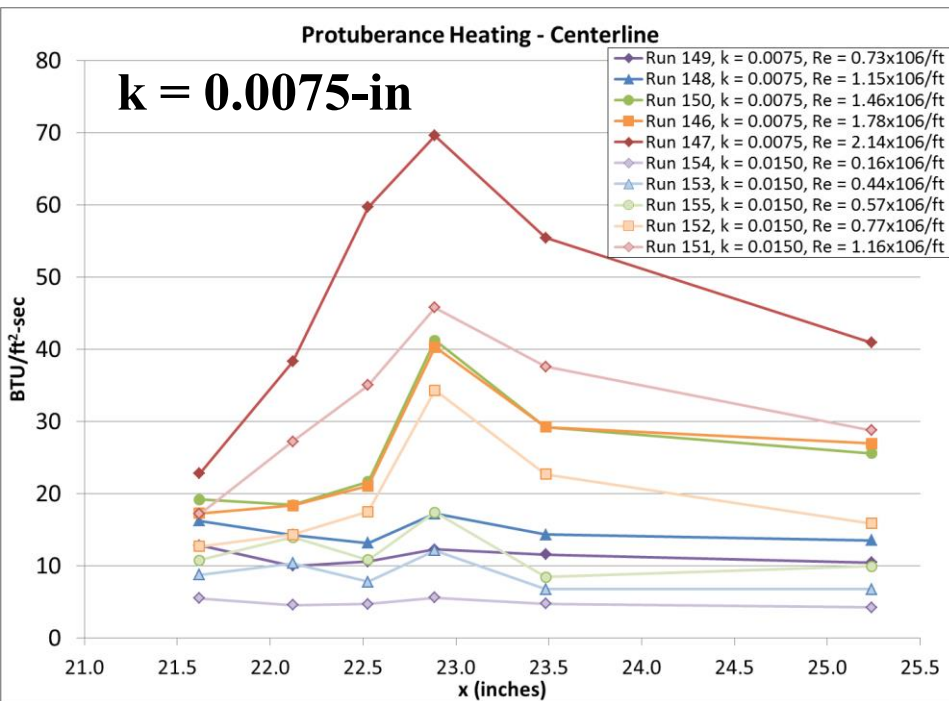




CUBRC Testing



- CUBRC LENS I Facility, Mach 14, 40 deg AoA, 0 deg side slip
- Protuberances: 0.0075 and 0.0150-in (corresponds to flight protuberance heights of 0.42 and 0.83-in scaled geometrically)
- Five runs with each height to identify insipient, effective Reynolds numbers



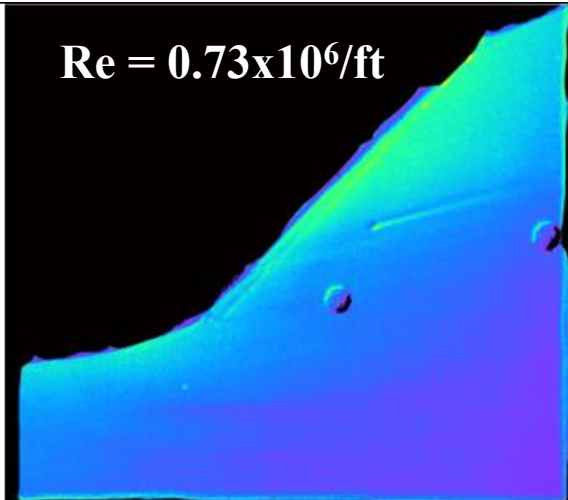


CUBRC Testing

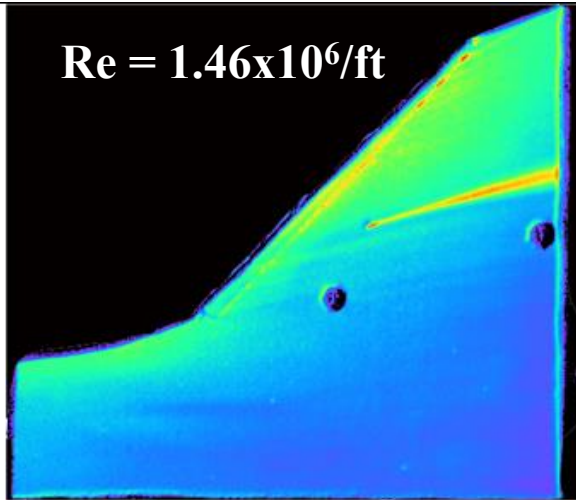


Protuberance	Incipient	Effective
0.0075-inch	0.73 - 1.15x10 ⁶ /ft	1.78 - 2.14x10 ⁶ /ft
0.0150-inch	0.16 - 0.44x10 ⁶ /ft	0.77 - 1.16x10 ⁶ /ft

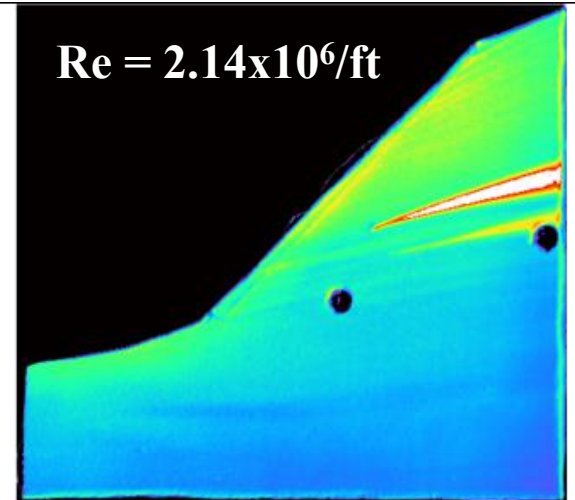
Re = 0.73x10⁶/ft



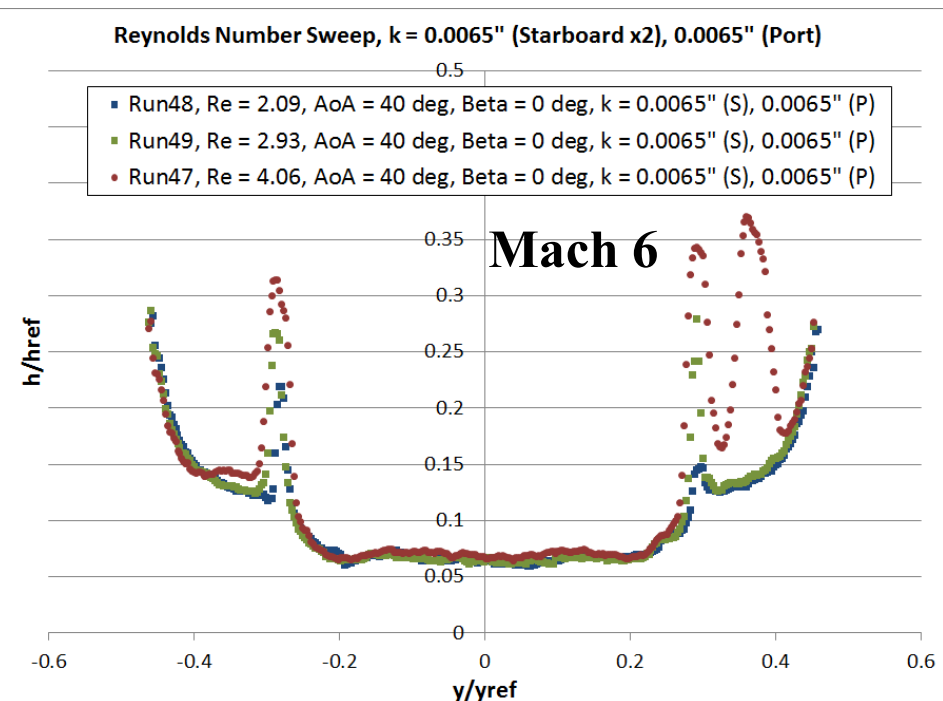
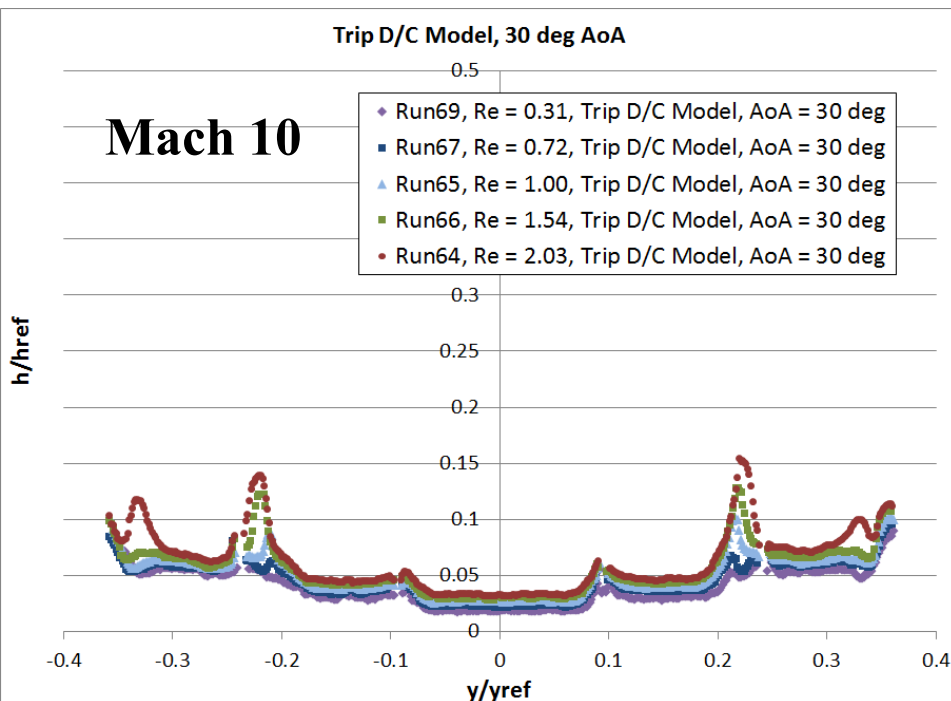
Re = 1.46x10⁶/ft



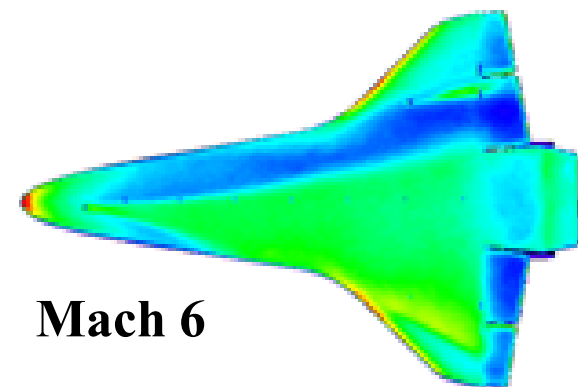
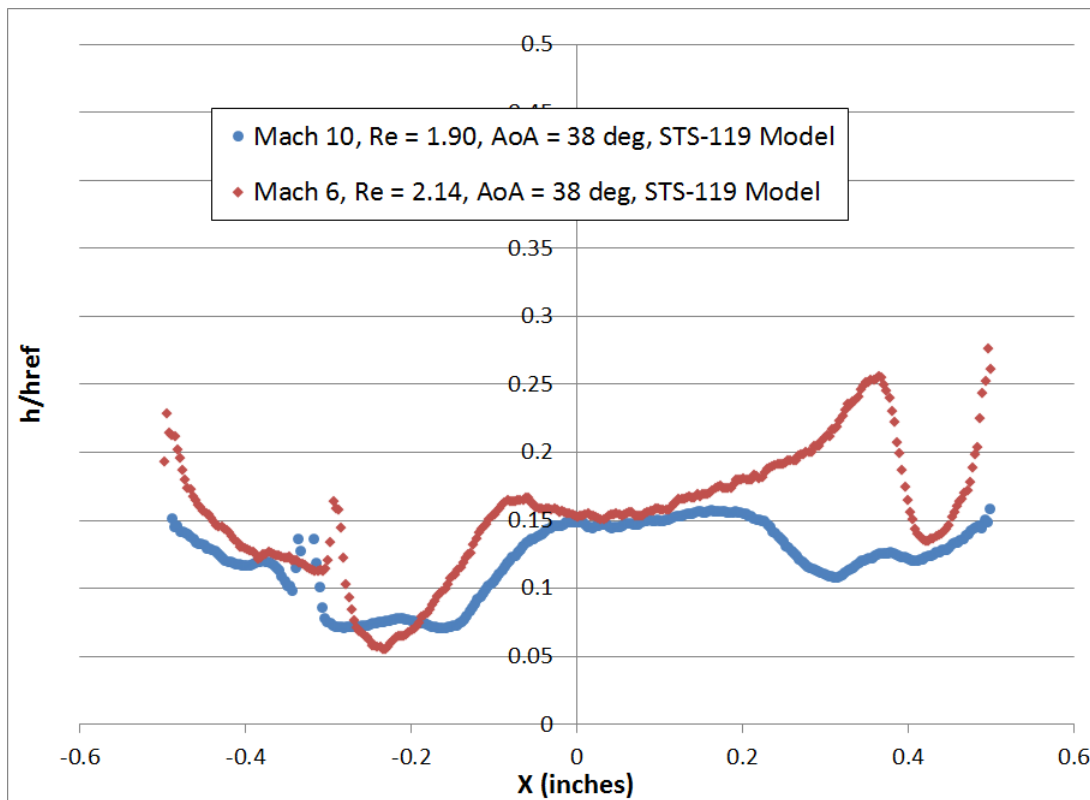
Re = 2.14x10⁶/ft



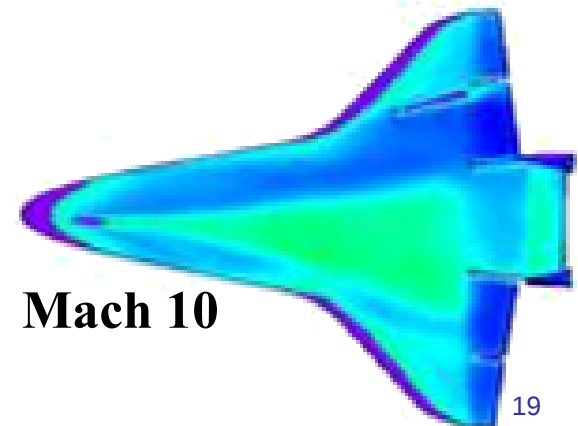
- Range of Reynolds numbers tested
 - 20-Inch Mach 6 CF_4 Tunnel: $0.13\text{-}0.31 \times 10^6/\text{ft}$
 - 31-Inch Mach 10 Air Tunnel: $0.24\text{-}2.08 \times 10^6/\text{ft}$
 - 20-Inch Mach 6 Air Tunnel: $0.59\text{-}6.95 \times 10^6/\text{ft}$
- As Reynolds number increased, natural BLT evident on aft/wings
- Peak heating (BLT wedge) increased as Reynolds number increased
- Mach 10 low Reynolds numbers laminar, no Mach 6 laminar, few transitional



- 3 hypersonic tunnels: 20-Inch Mach 6 Air, 20-Inch Mach 6 CF_4 , 31-Inch Mach 10 Air
- Comparisons made with Mach numbers and test gases
- Differences most evident in spreading angle
- Mach Comparisons: Turbulent spreading in Mach 6 more than Mach 10
- Gas Comparisons: Wing/peak heating and spreading angles increased in air



Mach 6



Mach 10



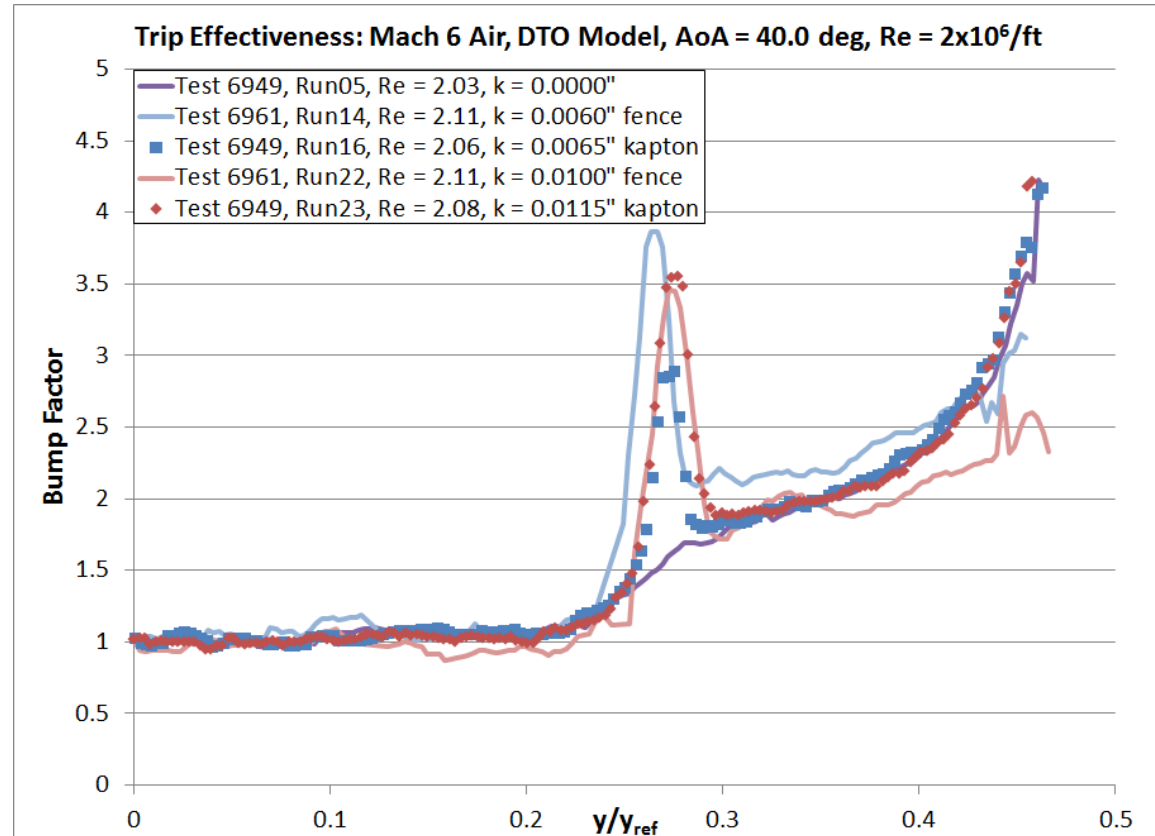
LaRC Phosphor Testing – Geometry Effects



Protuberances tested at LaRC:

- 0.05x0.05-in tape “pizza box” trips (0.0035 to 0.0150-in)
- Fence trips (0.006 to 0.0175-in)

	Mach 6	Mach 10
Tape Transitional	0.0045	0.0065
Tape Turbulent	0.0065	0.0090
Fence Transitional	0.0060	
Fence Turbulent	0.0100	0.0149
Tape BF	3.0	1.8
Fence BF	3.7	2.5

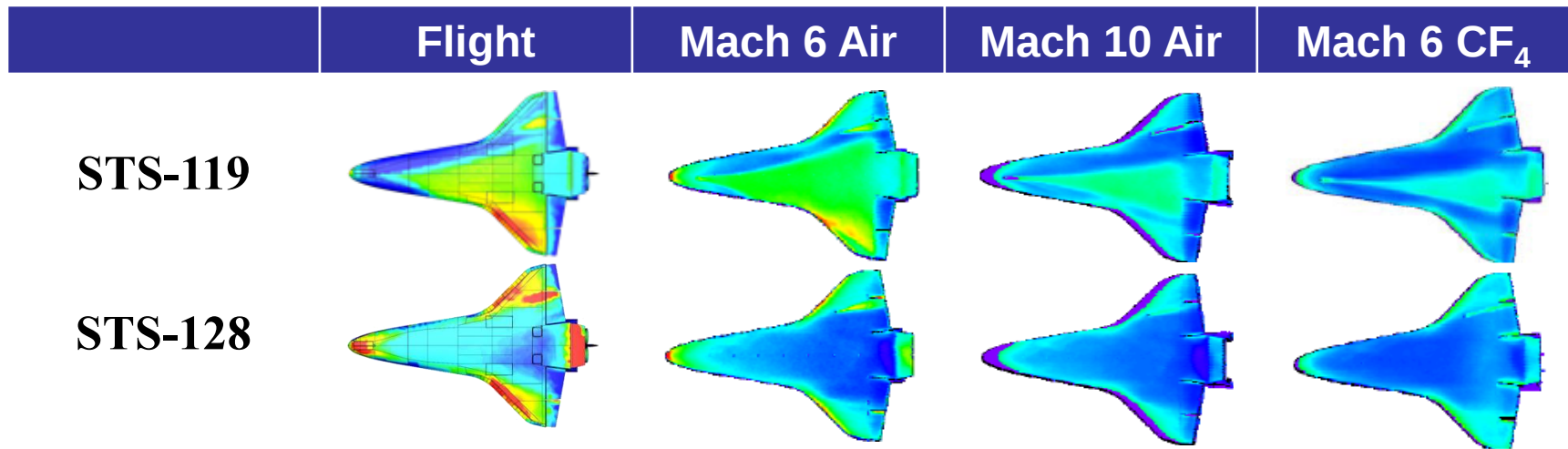




LaRC Phosphor Testing – Mission Specific Effects



- Tests supported HYTHIRM flights, STS-119 and STS-128
- Models had body flaps, elevons representing flight, actual AoA
- Tested in 20-Inch Mach 6 Air, CF₄ and 31-Inch Mach 10 Air
- STS-119 (Mach 8.5) had BLT FE (port) and ABLT (starboard)
- STS-128 (Mach 15) had BLT FE (port)
- Ground data able to qualitatively match flight data (spreading/ acreage)
- Smaller trips required, larger spreading angles in Mach 6 Air
- Reynolds numbers in Mach 10, Mach 6 CF₄ did not recreate all observations

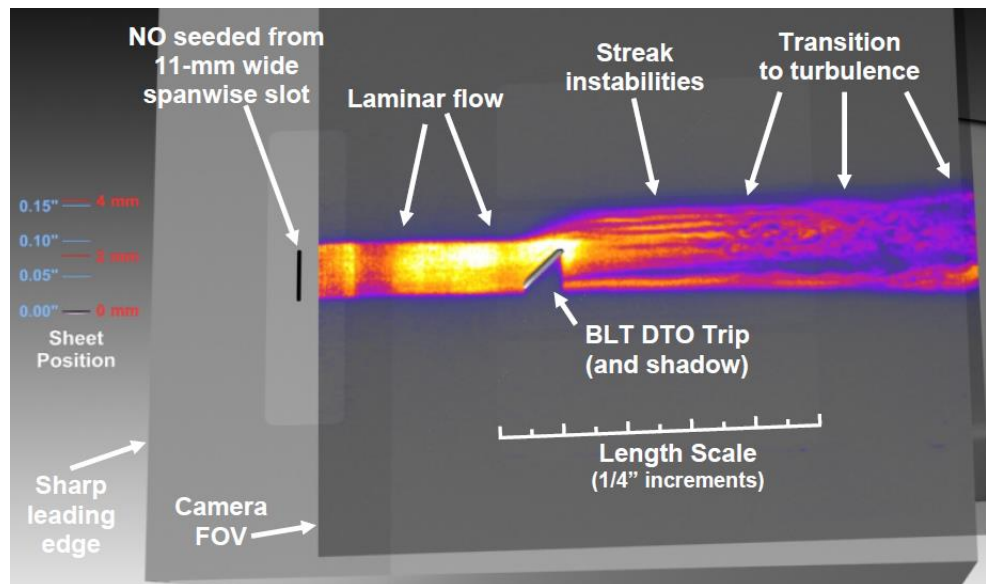




LaRC PLIF Testing

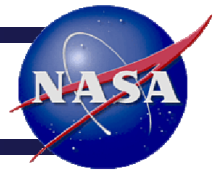


- Examined flow field and heating surrounding/downstream of trips
- Protuberance pushed flow to side of trip, instability streaks downstream
- Instability streaks transitioned to turbulent flow in most cases
- Lower Reynolds numbers: laminar to trip, streamwise streaks downstream
- Streaks present 0.059 inches above model (with 0.039-in protuberance)
- Increased Reynolds numbers show instability away from surface
- Flow at highest Reynolds numbers appeared turbulent downstream of trip

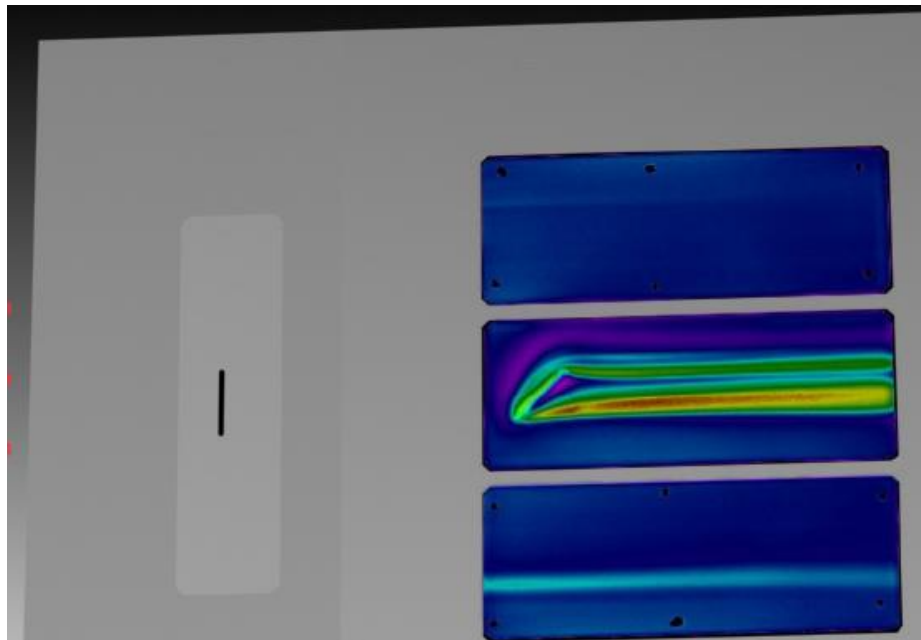




LaRC TSP Testing



- With TSP, increased heating with strong streak below and weaker above trip
- Increased heating immediately in front of protuberance
- Lower than baseline heating noted upstream and directly downstream of trip
- As Reynolds number increased, streaks increased in intensity and size
- TSP inserts (made of NanoForm) degraded similar to arc jet test articles





Summary



- Ground tests completed at NASA JSC, NASA LaRC, CUBRC to support Space Shuttle BLT FE
- Pre-flight certification/safety requirements, provided discrete/global data for comparisons
- Arc jet testing in the NASA JSC ARMSEF
 - 0.25 and 0.35-in protuberances tested, flight-like temperatures demonstrated
 - 0.35-in protuberance taken to 2900 °F exhibited minor shape change
 - 0.35-in protuberance taken to 3100 °F exhibited major failure, yielded info on material failure
 - Safe for flight, protuberance failure slumps until small enough won't melt further
- CUBRC testing at Mach 14
 - Insipient and effective Reynolds numbers for each protuberance height determined
 - Global TSP data taken for comparison to flight data
- NASA LaRC 20-Inch Mach 6 Air, 31-Inch Mach 10 Air and 20-Inch Mach 6 CF₄ Tunnels
 - Reynolds number increases caused BLT on wing/aft fuselage, increased protuberance peak heating
 - Mach 6 air spreading angles larger, difficult to get turbulent conditions in Mach 10 Air and Mach 6 CF₄
 - Trip effectiveness (tape squares vs. fence trips) compared and insipient/effective heights determined
 - Recreated STS-119 and -128 data collections made by HYTHIRM yielding global images for comparison
- PLIF and TSP used in Mach 10 Tunnel
 - Various protuberance configurations tested
 - TSP images compared qualitatively to PLIF data
- Part of larger data set (computational, discrete/global ground test data, discrete/global flight data)
- May be useful in advancing computational prediction, ground-to-flight extrapolation techniques



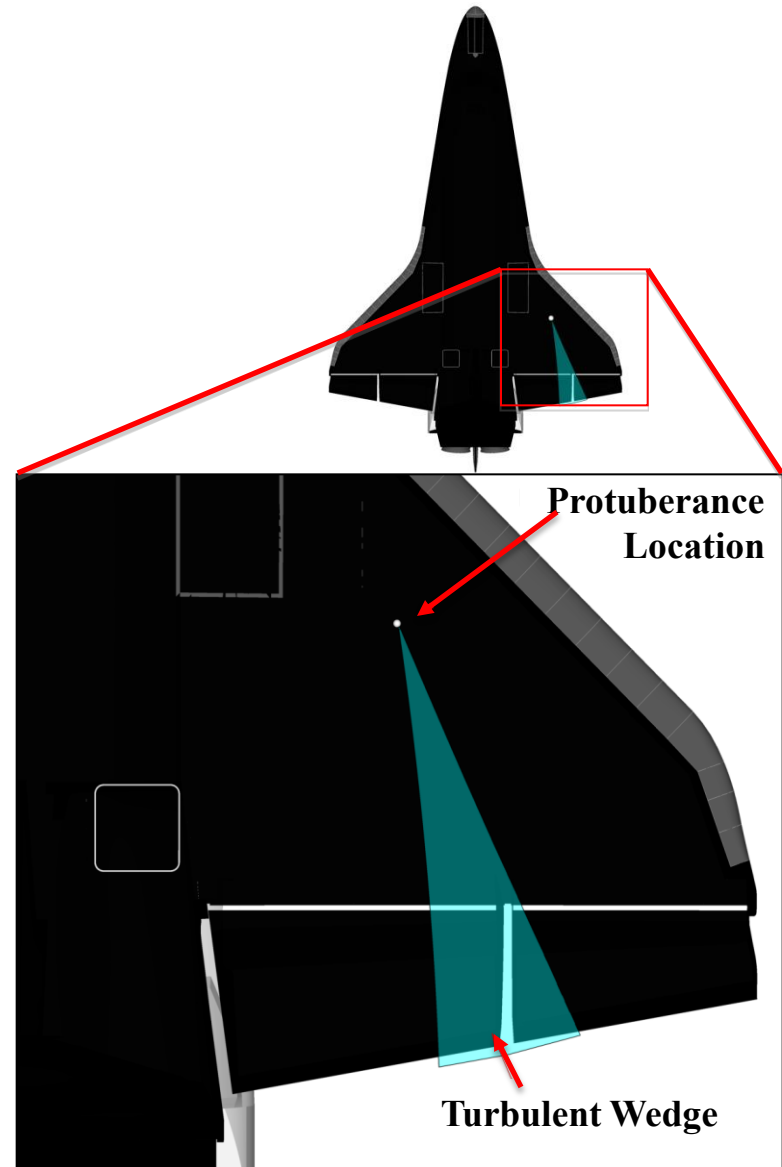
Backup



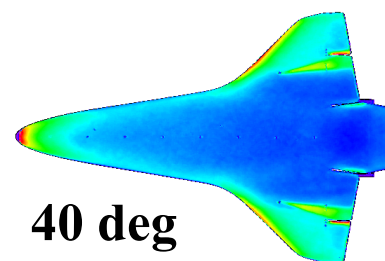
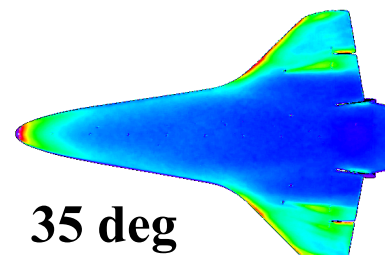
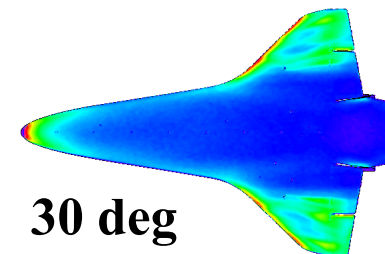
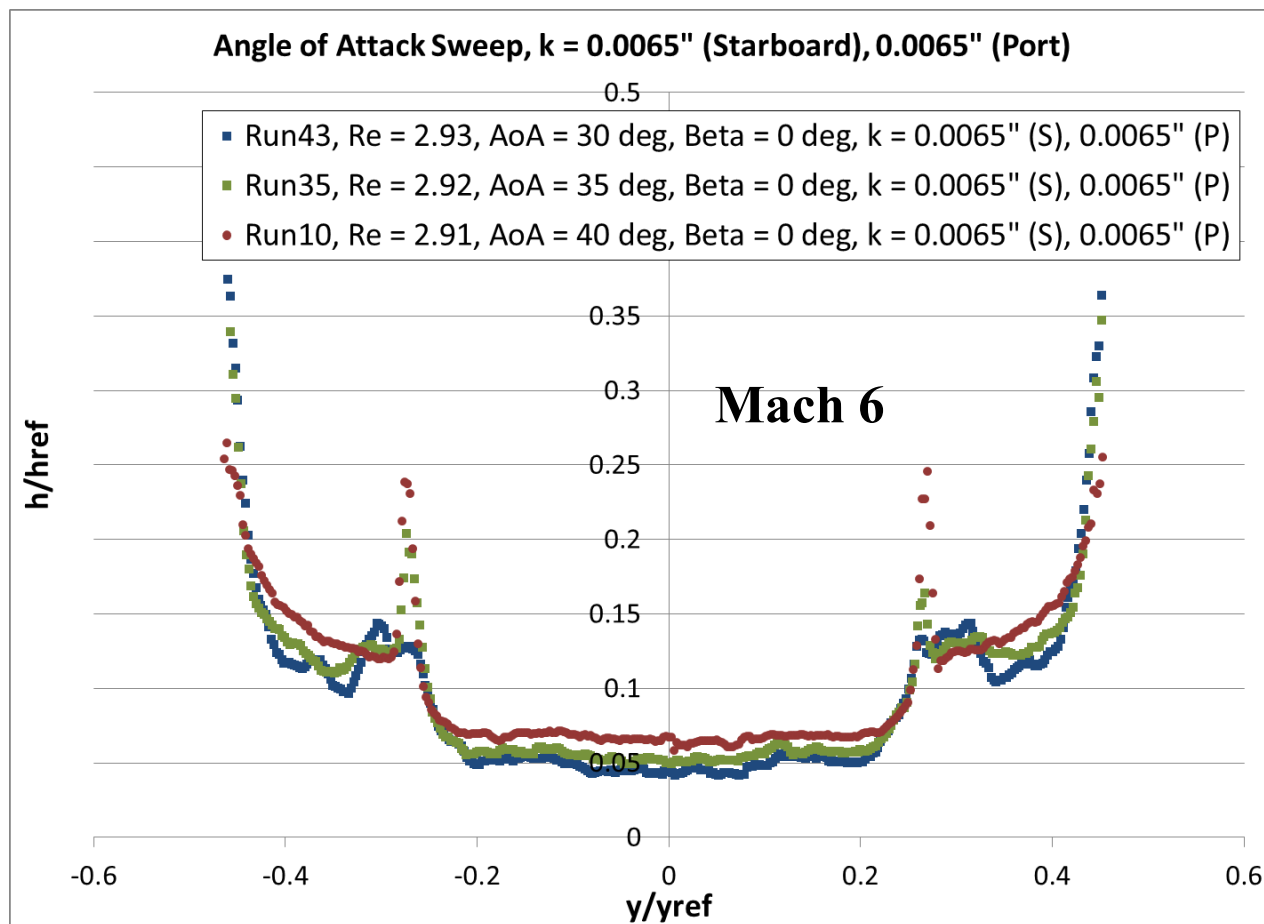
Design Overview: Placement



- Top design constraint for flight experiment was safety
- Region of turbulent flow (aka, turbulent “wedge”) downstream of surface disturbance causing boundary layer transition
- Protuberance placement based on:
 - Instrumentation channels/wiring
 - Ascent debris: some areas less prone to damage
 - TPS/Structural margins: turbulent wedge heating can reduce TPS/structural capabilities
- Analysis results showed risk of critical damage within wedge $< 1:10,000$



- Most testing at 40 deg, limited other AoA between 30-50 deg
- Mach 10: Peak heating did not differ 40-50 deg, slightly lower for 30-35 deg
- Mach 6 Air: 30 deg not turbulent. Peak heating increased from 35 to 40 deg





LaRC PLIF Velocimetry



Two 0.5×10^6 /ft runs with laser velocimetry (0.039-in, 0.098-in protuberance)

