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
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

- Incremental approach to flight test - safety
- Protuberance height derived with BLT tool, \( \text{Re}_\theta/M_e \) correlation

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

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

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• 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/in² (hydrogen, helium, nitrogen or combo)
- Driven tube: air, nitrogen, carbon dioxide, helium, hydrogen or combination

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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
### Tunnel Specifications

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Gas</th>
<th>Mach</th>
<th>Re (x10^6/ft)</th>
<th>Run Time</th>
<th>AoA (deg)</th>
<th>Beta (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-Inch Mach 6 Air</td>
<td>Air</td>
<td>6</td>
<td>0.50 - 8</td>
<td>20 min</td>
<td>-5 to 55</td>
<td>-8 to +8</td>
</tr>
<tr>
<td>31-Inch Mach 10 Air</td>
<td>Air</td>
<td>10</td>
<td>0.25 - 2</td>
<td>2 min</td>
<td>-90 to +90</td>
<td>-5 to +5</td>
</tr>
<tr>
<td>20-Inch Mach 6 CF₄</td>
<td>CF₄</td>
<td>6</td>
<td>0.01 – 0.55</td>
<td>20 sec</td>
<td>-10 to +50</td>
<td>-5 to +5</td>
</tr>
</tbody>
</table>
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

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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 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
• 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
### Protuberance

<table>
<thead>
<tr>
<th>Protuberance</th>
<th>Incipient</th>
<th>Effective</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0075-inch</td>
<td>0.73 - 1.15x10^6/ft</td>
<td>1.78 - 2.14x10^6/ft</td>
</tr>
<tr>
<td>0.0150-inch</td>
<td>0.16 - 0.44x10^6/ft</td>
<td>0.77 - 1.16x10^6/ft</td>
</tr>
</tbody>
</table>

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**Re = 0.73x10^6/ft**

**Re = 1.46x10^6/ft**

**Re = 2.14x10^6/ft**
LaRC Phosphor Testing – Reynolds Number Effects

- Range of Reynolds numbers tested
  - 20-Inch Mach 6 CF₄ Tunnel: 0.13-0.31x10⁶/ft
  - 31-Inch Mach 10 Air Tunnel: 0.24-2.08x10⁶/ft
  - 20-Inch Mach 6 Air Tunnel: 0.59-6.95x10⁶/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

Mach 10

Mach 6
LaRC Phosphor Testing – Mach and Gas Effects

- 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
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)

<table>
<thead>
<tr>
<th></th>
<th>Mach 6</th>
<th>Mach 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape Transitional</td>
<td>0.0045</td>
<td>0.0065</td>
</tr>
<tr>
<td>Tape Turbulent</td>
<td>0.0065</td>
<td>0.0090</td>
</tr>
<tr>
<td>Fence Transitional</td>
<td>0.0060</td>
<td></td>
</tr>
<tr>
<td>Fence Turbulent</td>
<td>0.0100</td>
<td>0.0149</td>
</tr>
<tr>
<td>Tape BF</td>
<td>3.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Fence BF</td>
<td>3.7</td>
<td>2.5</td>
</tr>
</tbody>
</table>
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, CF$_4$ 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 CF$_4$ did not recreate all observations

<table>
<thead>
<tr>
<th>Flight</th>
<th>Mach 6 Air</th>
<th>Mach 10 Air</th>
<th>Mach 6 CF$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS-119</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
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<tr>
<td>STS-128</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>
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 ºF exhibited minor shape change
  – 0.35-in protuberance taken to 3100 ºF 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 CF$_4$ 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 CF$_4$
  – 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
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 $0.5 \times 10^6$/ft runs with laser velocimetry (0.039-in, 0.098-in protuberance)