Orbiter Entry Aerothermodynamics
Practical Engineering and Applied Research

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Orbiter Entry Boundary Layer Transition Flight Experiment
Principal Investigator

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May 12th, 2009
Invited Presentation at Stanford University
Mechanical Engineering Department
Fluid Mechanics Seminar

STS-114 Launch on July 26th, 2005
Orbiter Return to Flight Aeroheating

• Outline
  – Organization of the Orbiter Entry Aeroheating Working Group
  – Overview of the Principal RTF Aeroheating Tools Utilized for Tile Damage Assessment
  – Description of the Integrated Tile Damage Assessment Team Analyses Process
  – Space Shuttle Flight Support Process
  – JSC Applied Aerosciences and CFD Branch Applied Research Interests
Orbiter Return to Flight Aeroheating

Orbiter Entry Aeroheating Working Group Organization

Boundary Layer Transition
Scott Berry / NASA-LaRC

Cavity Heating
Jay Hyatt / Boeing-Houston*
Brian Anderson / NASA-JSC
*
- NASA-ARC/Eloret as of 2008

Local Heating Environmnts.
Amy Cassady / NASA-JSC
Brian Anderson / NASA-JSC
Stan Bouslog / NASA-JSC
Ben Kirk / NASA-JSC

Vehicle Breaches
Don Picetti / Boeing-Huntington Beach

Charles H. Campbell
NASA Subsystem Eng.
Dennis C. Chao
Boeing Subsystem Mgr.

CFD
Bill Wood / NASA-LaRC
Dave Driver / NASA-ARC
James Reuther / NASA-ARC
Peter Gnoffo / NASA-LaRC

Circa 2005

Ref: Campbell et al, AIAA-2006-2917
Tile System Description

Reaction-cured glass (RCG) coating

0.045" Tile to Tile Gap

Tile densified layer

Koropon-primed structure

Filler bar

Strain isolation pad (SIP)

RTV adhesive
Orbiter Return to Flight Aeroheating

- **Principal Aeroheating Tools for DAT**
  - **XF0002 / Nominal Convective Heating**
    - Utilizes simplified heating methods for > 2000 OML locations
      - Phenomenology: Temperature based heat transfer coefficient
    - Developed during Orbiter DDT&E
    - Calibrated to Orbiter flight data
  - **Catalytic Heating / Uncoated Tile cataleycity**
    - Based on preliminary arc-jet data
    - Utilizes a simple bump factor relationship
  - **Cavity Heating / Damaged tile cavity heating**
    - Updates for laminar effects based on wind tunnel data
      - Phenomenology: Temperature based heat transfer coefficient
    - Historical turbulent correlation based on extant experimental data
    - Methodology Utilizes Engineering correlations
      - Shallow Cavity (new)
      - Everhart Cavity (new)
      - Closed Cavity (new)
      - Turbulent Cavity (historical Boeing method)
Orbiter Return to Flight Aeroheating

- **Principal Aeroheating Tools for DAT (cont’d)**
  - **Rapid Assessment CFD**
    - Utilizes DPLR and LAURA
      - Nonequilibrium chemistry, Navier-Stokes solvers
    - Calibrated to available cavity experimental data
    - Leverages multiple capabilities to satisfy efficiency needs
      - Automated grid generation
      - Repository of Smooth Baseline Orbiter solutions
      - Sub-zone decomposition to solve local damage region
      - NAS Columbia system for rapid turn-around
  - **Boundary Layer Transition**
    - Methodologies developed for Protuberances and Cavities
    - Principal data sets from NASA-LaRC Mach 6 and 10 air tunnels
      - Complementary data from AEDC MH-11 Orbiter test (ca. 1993) and CUBRC MH-13 Orbiter test
      - Correlations established for wind tunnel data and calibrated to available Orbiter flight data
    - Relies on Boundary Layer Properties tool to provide edge conditions in flight envelope
      - Flight Envelope and Wind Tunnel databases established with DPLR and LAURA

Ref: Palmer et al, AIAA-2007-4254
Pulsonetti et al, AIAA-2005-4679
Tile Damage Assessment Team

Flight Support Process

- Damage Information (Location, geometry)
- Boundary Layer Transition Tool
- Decision on appropriate roughness value
- Smooth OML CFD Solutions
- Cavity Heating Tool
- Material Temperatures
- XF0002
- 3-D Thermal Math Model
- Catalycity Factors
- RTV Bondline Tool
- Bond FOS
- Stress Assessor Tool
- Structure MOS, OOPD
- Input
- Output
- Tool
- Human Decision
Assessments Required

4 windward sites
2 protruding gap fillers
1 blanket (leeside)
## Damage Assessment Since STS-114

<table>
<thead>
<tr>
<th>STS Mission</th>
<th>Launch</th>
<th>Entry</th>
<th>Total Damage Sites Examined by Damage Assessment Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS-114</td>
<td>July 26, 2005</td>
<td>August 9, 2005</td>
<td>49</td>
</tr>
<tr>
<td>STS-121</td>
<td>July 4, 2006</td>
<td>July 17, 2006</td>
<td>13</td>
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<td>STS-115</td>
<td>September 9, 2006</td>
<td>September 21, 2006</td>
<td>28</td>
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<tr>
<td>STS-116</td>
<td>December 9, 2006</td>
<td>December 22, 2006</td>
<td>10</td>
</tr>
<tr>
<td>STS-117</td>
<td>June 8, 2007</td>
<td>June 22, 2007</td>
<td>11</td>
</tr>
<tr>
<td>STS-118</td>
<td>August 8, 2007</td>
<td>August 21, 2007</td>
<td>25</td>
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<tr>
<td>STS-120</td>
<td>October 23, 2007</td>
<td>November 7, 2007</td>
<td>14</td>
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<tr>
<td>STS-122</td>
<td>February 7, 2008</td>
<td>February 20, 2008</td>
<td>17</td>
</tr>
<tr>
<td>STS-123</td>
<td>March 10, 2008</td>
<td>March 26, 2008</td>
<td>20</td>
</tr>
<tr>
<td>STS-124</td>
<td>May 31, 2008</td>
<td>June 14, 2008</td>
<td>14</td>
</tr>
<tr>
<td>STS-126</td>
<td>November 14, 2008</td>
<td>November 30, 2008</td>
<td>13</td>
</tr>
<tr>
<td>STS-119</td>
<td>March 15, 2009</td>
<td>March 28, 2009</td>
<td>10</td>
</tr>
</tbody>
</table>
STS-114 Damage Assessment

Aeroheating Team Report Info
- Windward view (to left)
- Turbulent Influence zone
- BLT Predictions for each site
- Reference Heating
- Cavity Heating summary

Heating Rate

Time
STS-114 Gap Filler Assessment

K = C(delta)/(Retheta/Medge)

0 0.2 0.4 0.6 0.8 1 1.2 1.4

0 200 400 600 800 1000 1200 1400

Time (sec)

Keq=0.25”
Keq=0.155”

C=27 (OCCB) C=33 STS-73 C=50 STS-73 C=75 STS-73

Uncertainty Zone

Limited adjustment to BLT correlation based on STS-73 results

Uncertainty at Mach 22 of ±150s (or ~ ±Mach 2) if height uncertainty not considered

Existing flight calibrated BLT Correlation

Gap Filler 134-01
RPM: k=1.1”±0.3”
t=745s
Mach 21.9

Bertin & Stetson (JSC-27358, Jan 96) suggest a BLT upper limit of 230 kft, which roughly corresponds to a Mach number of 23
STS-114 Gap Filler Removal

Stephen R. Robinson and Soichi Noguchi performed the first ever on-orbit TPS repair on August 3, 2005.
Danny Olivas performed the first ever on-orbit OMS Pod repair on June 15, 2007.
Danny Olivas self-portrait after STS-117 OMS Pod Blanket Repair
JSC Aerosciences Branch
Current Applied Research Interests

• Boundary Layer Transition Prediction
  – Engineering Correlations (NASA)
  – Stability modeling (University of Minnesota/Candler, Johnson)

• Quiet Hypersonic Experimental Capabilities
  – Purdue Mach 6 Quiet Tunnel (Schneider, et al.)

• Hypersonic wind tunnel non-intrusive measurement
  – Planar Induced Fluorescence (LaRC / Danehy, et al.)

• Roughness Induced Augmented Heating

• Hypersonic Expansion Tunnels
  – CUBRC LENS-XX (Holden, et al.)

• Other topics related to aerosciences
Discrete Roughness BLT

- Develop engineering tool for rapid Orbiter transition prediction. A generalized correlation approach was implemented.

References:

Future work supported by Hypersonics Program in the Fundamental Aeronautics Program / ARMD.
- Investigate effects of discrete roughness on stability & transition of Zero Pressure Gradient BL in a Mach 3.5 quiet tunnel.
- Objective is to understand the underlying physics leading to BLT that may ultimately lead to improved physics-based correlation methodologies.
- Acquire off-surface measurements of BL disturbance field, both mean and fluctuating components.
Orbiter Return To Flight BLT Correlation

**RTF BLT V2 Correlation**

- 2-sigma late
- Best Estimate
- 2-Sigma early

**Correlation based on WT uncertainty and Flight Mean**

**Accuracy of various BLT Engineering Correlations with Orbiter RTF Data**


- Wind tunnel data to support correlation acquired in Langley Mach 6 Air, Mach 10 Air, Mach 6 CF4 and CUBRC Mach 10, 14, 16
- Engineering correlations of this type achieve correlation values of >0.8 on Orbiter configuration
- Better correlations are desired, but this is acceptable for providing engineering assessments and design input

### CUBRC MH-13 Wind Tunnel Model

- Wind tunnel data to support correlation
- Cassady, et al
- NASA/TP-2007-214758

### LaRC Infrared Surface Temperature Mapping

- Turbulent Wedge from BLT Trip

- **Proposed Correlation**

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Correlation Equation</th>
<th>( R )</th>
<th>( \Delta C/C )</th>
<th>( \sigma_{C}/C )</th>
<th>( R )</th>
<th>( \Delta C/C )</th>
<th>( \sigma_{C}/C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( Re_{0}/M_{a} \times k/\delta = C )</td>
<td>-0.87</td>
<td>1.26</td>
<td>19.9%</td>
<td>-0.88</td>
<td>1.25</td>
<td>21.2%</td>
</tr>
<tr>
<td>2</td>
<td>( Re_{0}/M_{a} \times k/\delta C )</td>
<td>-0.90</td>
<td>1.08</td>
<td>7.3%</td>
<td>-0.87</td>
<td>1.32</td>
<td>34.9%</td>
</tr>
<tr>
<td>3</td>
<td>( Re_{0}/M_{a} \times (k/\delta)(H_{e}/H_{w})^{0.16} = C )</td>
<td>-0.89</td>
<td>1.14</td>
<td>14.5%</td>
<td>-0.89</td>
<td>1.20</td>
<td>23.6%</td>
</tr>
<tr>
<td>4</td>
<td>( Re_{0}/M_{a} \times (k/\delta)(H_{e}/H_{w})^{0.30} = C )</td>
<td>-0.91</td>
<td>1.04</td>
<td>8.9%</td>
<td>-0.91</td>
<td>1.10</td>
<td>19.9%</td>
</tr>
<tr>
<td>5</td>
<td>( p_{e}u_{e}k/\mu_{e} = C )</td>
<td>-0.70</td>
<td>2.51</td>
<td>30.0%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>( Re_{0}^{0.6} \times [Re_{e} \cdot (\mu_{e} / \mu_{w})]^{1/4} = C )</td>
<td>-0.87</td>
<td>1.09</td>
<td>14.8%</td>
<td>-0.84</td>
<td>1.30</td>
<td>35.0%</td>
</tr>
</tbody>
</table>

* Results are for \( n = 0.6 \) for all data
Orbiter BLT Flight Experiment Context

- Current Orbiter flight data BLT uncertainty is similar to correlation uncertainty (small data sample, geometry uncertainty, etc.)
  - Can not establish conclusions regarding wind tunnel to flight
- Orbiter assessments use 7.5 degrees for turbulent wedge
  - Could be lower, but insufficient data available
- High Mach/High Enthalpy Turbulent flow is relatively unknown regime
  - Current CFD methods based on ground data, Orbiter heating tools (e.g. XF0002) are based on limited flight data of STS 1-5 (heating uncertainty ≈ 20-30%)
  - Orbiter BLT FE flight data could significantly affect tools, physical models and design/operational predictions

Aeroheating Environments

- Orbiter entry surface measurements for Mach ~18 BLT

<table>
<thead>
<tr>
<th>Wedge Half-angle [degrees]</th>
<th>Approximate Center of Turbulent Wedge</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>7.5</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
</tr>
</tbody>
</table>

Comments

- Orbiter flight data BLT uncertainty is similar to correlation uncertainty (small data sample, geometry uncertainty, etc.)
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OV-103 Hardware Modifications

Protuberance Tile

- Protuberance is 4" long, 0.25" height
- Flow Direction
- 6" x 6" x 2" BRI-18 tile
- TUF/RCG coating on four sides and OML

Local Area

- BLT TMM with Overlay Tile Array
  - LI-900
  - LI-2200
  - BRI-18
  - Protuberance

Downstream Wedge

- Trip area with local heating issues
- Turbulent Wedge

TPS Summary

- STS-119 (103) FLIGHT 36
- GAP FILLER CONFIGURATION
- LOWER SURFACE

- GAP FILLER REWORK COMPLETE
- TILES REPLACED TO SUPPORT BLT MOD

vsn5 May 7, 2009

presenter - Charles H. Campbell / NASA JSC /
charles.h.campbell@nasa.gov
**HyThirm**

*Hypersonic Thermodynamic Infrared Measurements*

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**STS-119/STS-125 success criteria:** To obtain spatially resolved infrared imagery that will provide a quantified surface temperature map of the Shuttle during hypersonic re-entry

*Horvath et. al. AIAA-2008-4022*

**Near term goal:** Shuttle as target of opportunity to demonstrate thermal imaging capability with existing technologies during Shuttle (STS-119) boundary layer transition flight experiment

**Long term vision:** Development of new quantitative state-of-the-art imaging systems (e.g., visual, thermal, spectral) to support a variety of hypersonic flight test programs from an engineering, safety and science perspective

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**Flight Testing Technologies**

- **Flight**
- **CFD**
- **Tunnel**

**Modeling & Simulation**

**Ground Test Facility Technologies**

POC’s: [Thomas.J.Horvath@nasa.gov](mailto:Thomas.J.Horvath@nasa.gov) (PI) and [Paul.W.Krasa@nasa.gov](mailto:Paul.W.Krasa@nasa.gov) (PM)

Sponsors: NASA JSC SSPO; NESC, ARMD

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**Hyfire**

**Hyfly**

**ARES**

**LAS**

**Orion**

**X-37**

**X-51**

**HTV-2**

Provide tools required for an integrated test and evaluation approach in which the proper combination of modeling and simulation, ground testing, and flight testing are employed to address future high speed hypersonic systems

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**Imagery from “ad hoc” flights (pre-HYTHIRM)**

**Turbulent flow from wing protuberance**

**STF-115**

Sept 2006

**STS-121**

July 2006

**STS-119**

Mar 2009

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**04/09 – Mission Success!**

**Horvath et. al. AIAA-2007-4267**

**Turbulent flow from gap filler ~ Mach 13**
Orbiter Entry BLT Stability Modeling

- 128 million element Orbiter grid provided by NASA
- Solved using U of MN US3D finite-volume solver with 1400 cores
- 5-species air finite-rate thermochemistry
- Centerline flow solution extracted and analyzed using Parabolized Stability Equations in STABL

- Demonstrates it is possible to generate stability-quality CFD solutions for Shuttle
- Initial results show N-factor of nearly 2 at rear of shuttle
- Oblique waves dominant near the nose but 2D waves reach higher N
- Currently a centerline flow analysis
- Future results will include off-axis 3D effects in the stability analysis

Mach 15 Orbiter Entry Simulation

University of Minnesota
Purdue Mach 6 Quiet Tunnel

Effect of Tunnel Noise on Roughness-Induced Transition for a Slender Cone at Mach 6

- Effective trips under noisy flow are not always effective under quiet flow
- When transition did occur under quiet flow, it was always delayed

Ref: Casper et al., AIAA Paper 2008-4291
Nitric Oxide PLIF

**Overview**
- Nitric Oxide Planar Laser-Induced Fluorescence (NO PLIF)
  - Pioneered at Stanford in 80’s and 90’s (Hanson)
- Laser/Camera system visualizes slices of flow
- Quantitative measurements
  - Velocity, temperature
- Used in 31” Mach 10 Wind Tunnel
- Primarily Supported by NASA Fundamental Aero Program, Hypersonics Project

**Recent Applications: Transition Studies**
- Triangular trip simulates orbiter gap filler
- NO seeds BL fluid, marks flow structures

**Recent Applications: RCS Jet Imaging**
- Measure shape, transition, trajectory, velocity, of RCS jets for both Aero and Aeroheating applications

**Future Capabilities**
- Velocity Measurement
  \[ \text{velocity} = \frac{\text{distance}}{\text{time}} \]
  - High speed imaging, velocimetry:
    - MHz Frame Rate Laser/Camera system (NRA with Ohio State)
  - Temperature measurement

**Recent Applications: RCS Jet Imaging**
- Inman et al., AIAA Journal (accepted; in press).

**Recent Applications: Transition Studies**
- Danehy et al., AIA Paper 2007-0536
Measurements of NO in Freestream and Shock Layers Employing Tunable Diode Laser Spectroscopy

Roughness and Heating Augmentation

Adam Amar and Brandon Oliver / NASA JSC

CFD corroborates wind tunnel trend

Heat Flux Orion/CEV testing
- Agrees with historic data
- Shows existing correlations are reasonable

Model will be a function of:
- Roughness geometry
- Smooth wall boundary layer properties

Forward work
- Examine blowing effects on roughness
- Get augmentation data for Avcoat patterns

Geometry/Spacing/Height
Back-up
CFD Repository

- CFD Point 3, Mach 22.9
- CFD Point 2, Mach 24.2
- CFD Point 1, Mach 24.9
- CFD Point B, Mach 25.7
- CFD Point 4, Mach 20.3
- CFD Point 6, Mach 17.9
- CFD Point 7, Mach 16.5
- CFD Point 9, Mach 13.5

Surface Heating vs. Time from Entry Interface

- STS107-BET
- ISSHVFW
Boundary Layer Properties DB

Transition Database
Angle of Attack Dispersions

Past STS Trajectories
ISSHVFW
\( \alpha \) Limits GN & C

CART3D
LAURA/LATCH Solution
DPLR or LAURA Solution

Upper and lower limits taken from Fig. 4.2.2.1 in SODB
Simplified Cavity from Point Cloud

13°

10.26

16.65