Orbiter Entry Aerothermodynamics
Practical Engineering and Applied Research

Charles H. Campbell
Orbiter Entry Boundary Layer Transition Flight Experiment
Principal Investigator

Applied Aerosciences and CFD Branch
NASA Johnson Space Center, Houston, TX

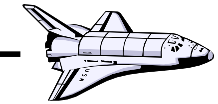
May 12th, 2009
Invited Presentation at Stanford University
Mechanical Engineering Department
Fluid Mechanics Seminar

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

Ref: Campbell et al, AIAA-2006-2917

Boundary Layer Transition
Scott Berry / NASA-LaRC

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

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

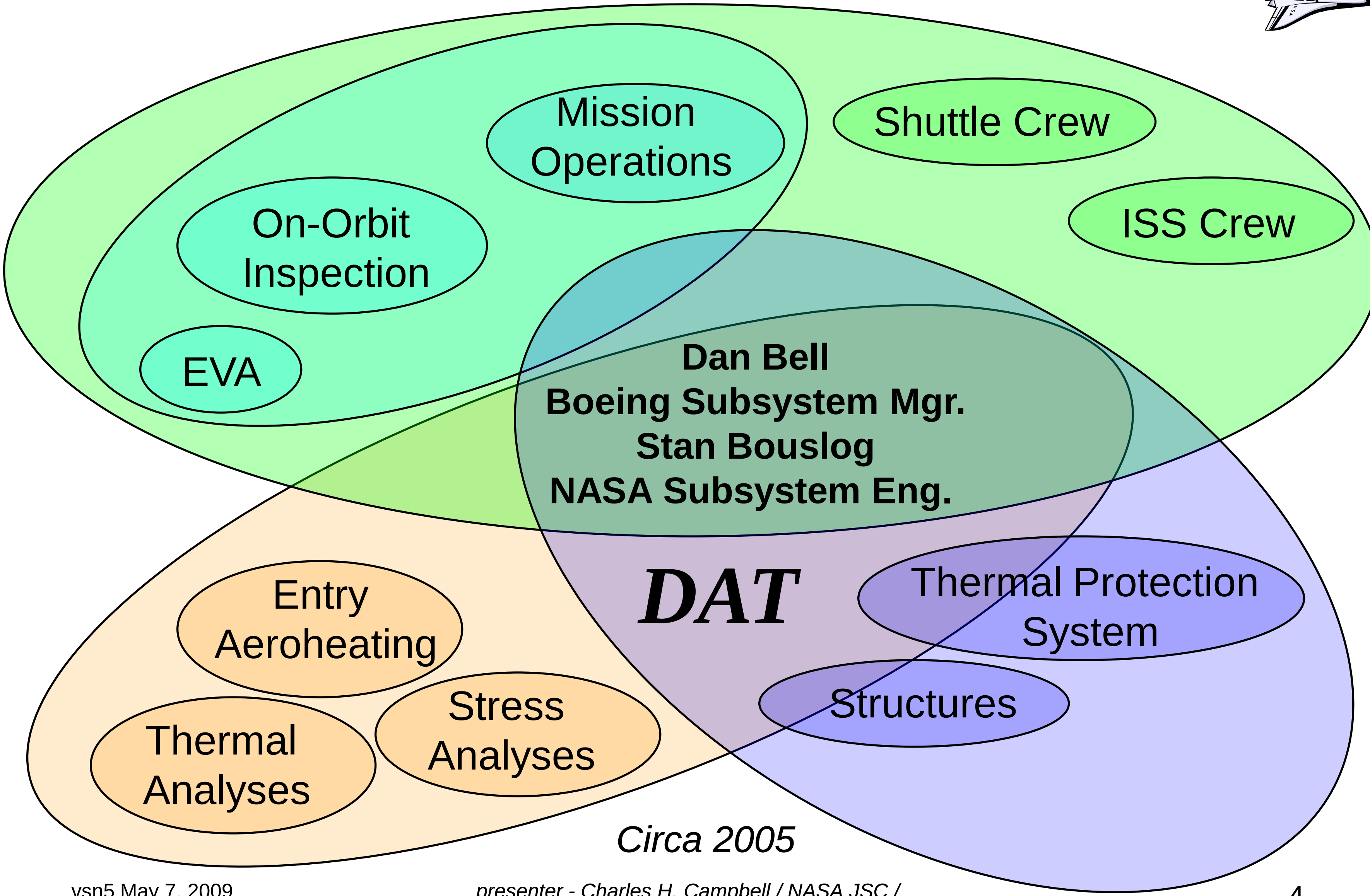
Vehicle Breaches
Don Picetti /
Boeing-Huntington Beach

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

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

Circa 2005

Tile Damage Assessment Team



Circa 2005

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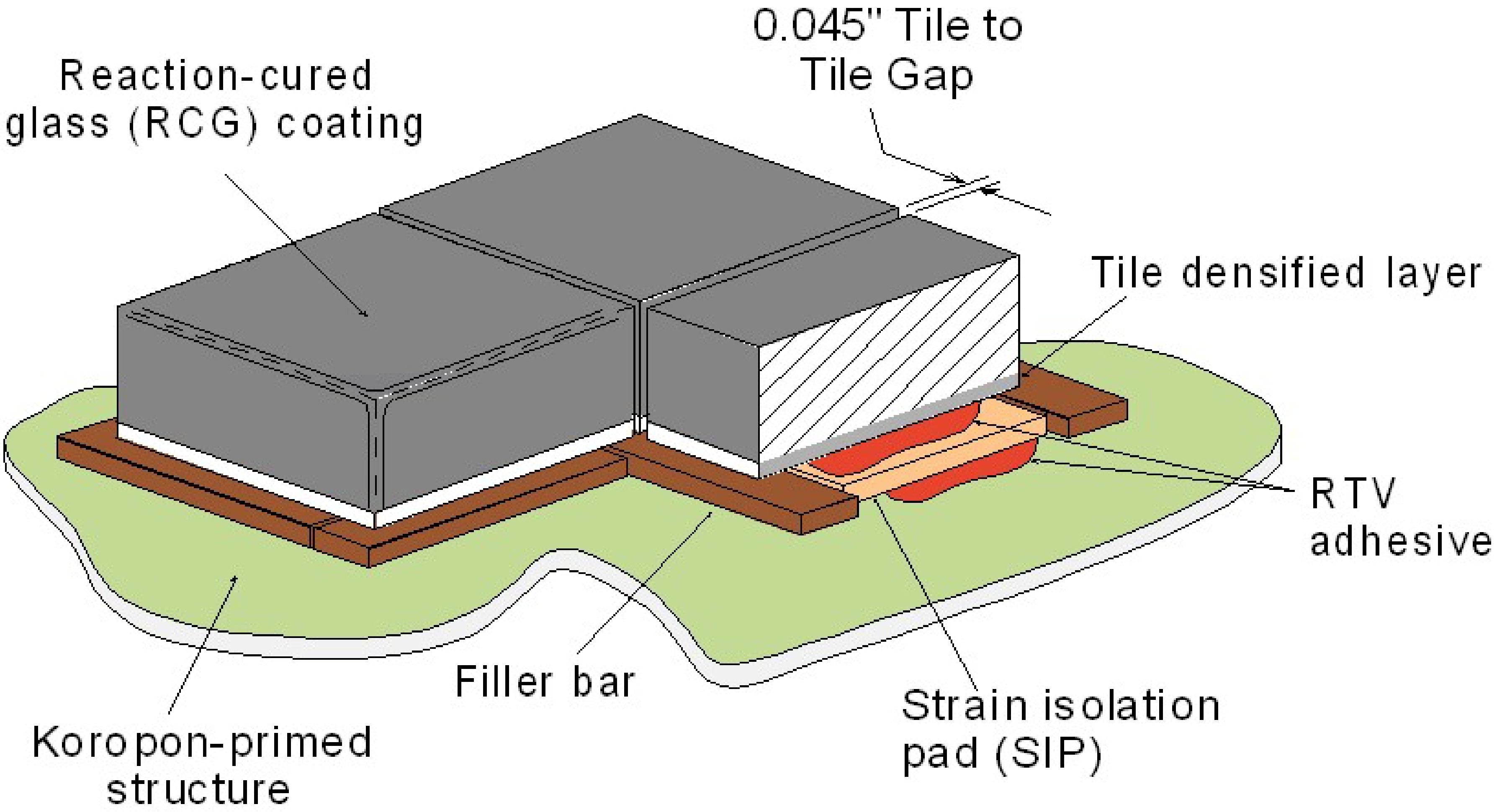
Tile System Description



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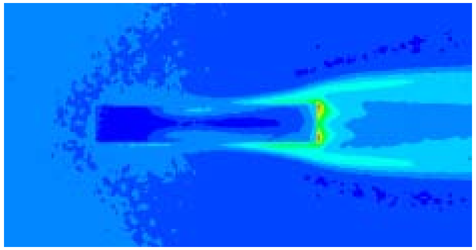
Orbiter Return to Flight Aeroheating

- **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 catalycity**
    - **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)**

NASA LaRC Mach 10
Thermographic Phosphor Cavity Heating

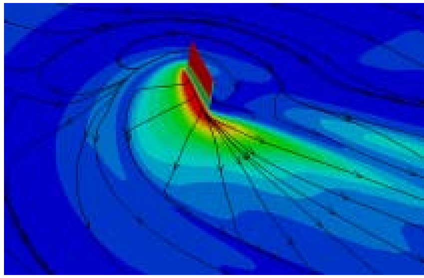


Ref: Everhart et al, AIAA-2006-185

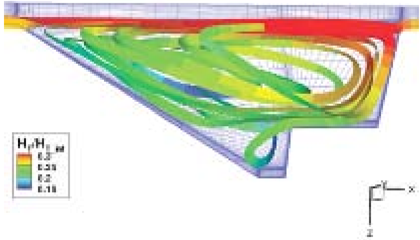
Orbiter Return to Flight Aeroheating

- **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 Nonequilibrium N.S.**

Protrusion CFD Simulation



Flight Cavity CFD Simulation



Ref: Palmer et al, AIAA-2007-4254
Pulsonetti et al, AIAA-2005-4679

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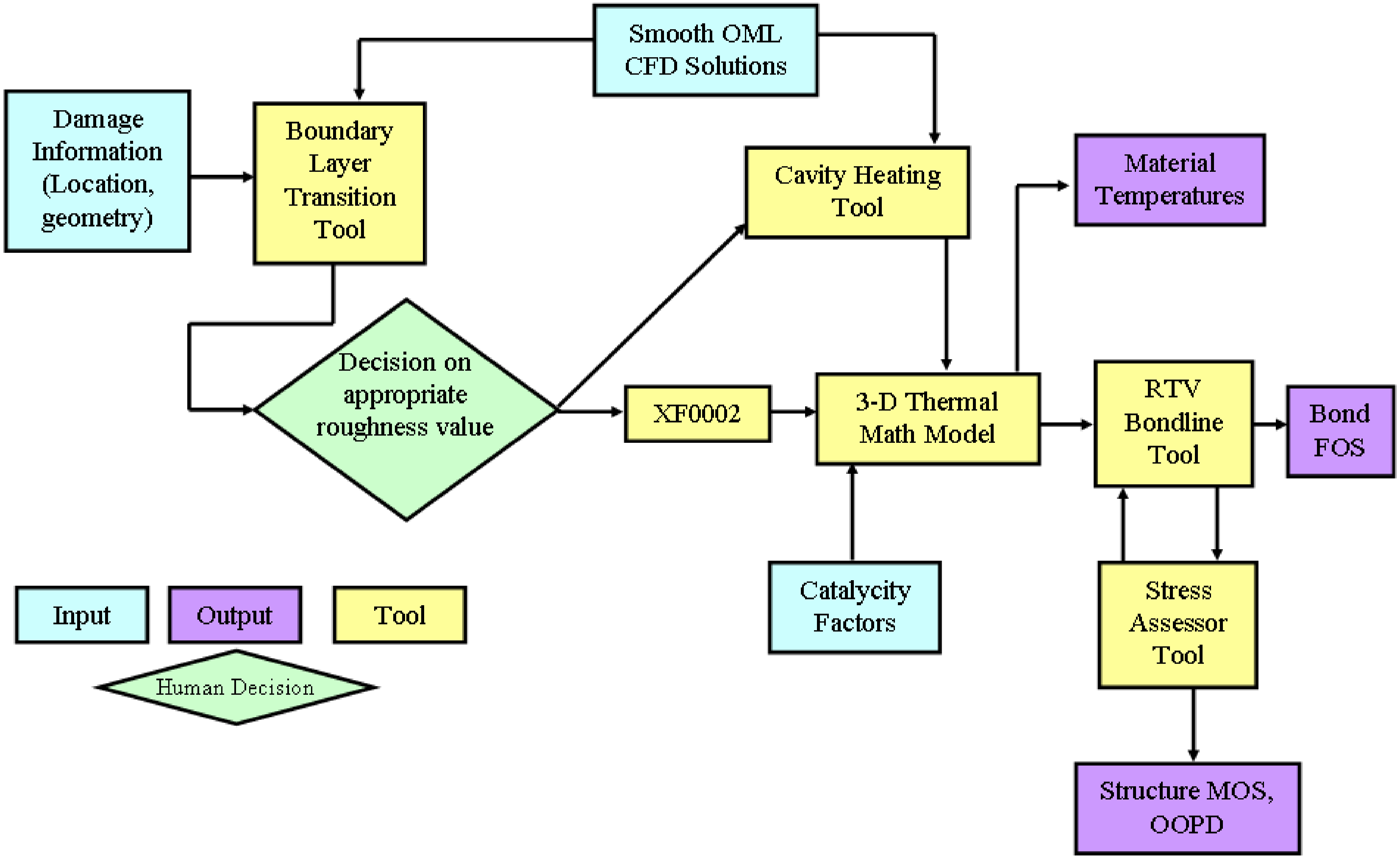
Tile Damage Assessment Team

Flight Support Process



STS-114 Damage Assessment

Assessments Required
4 windward sites
2 protruding gap fillers
1 blanket (leeside)

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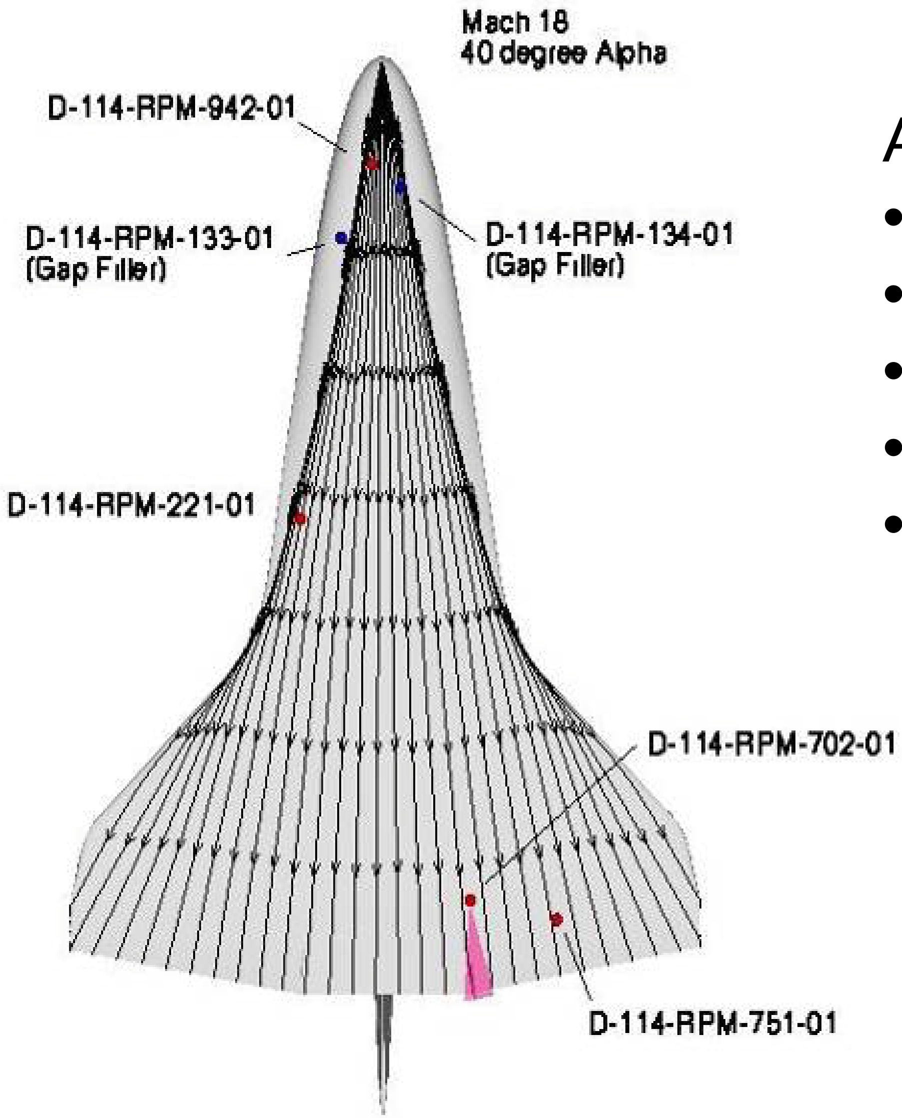
Damage Assessment Since STS-114

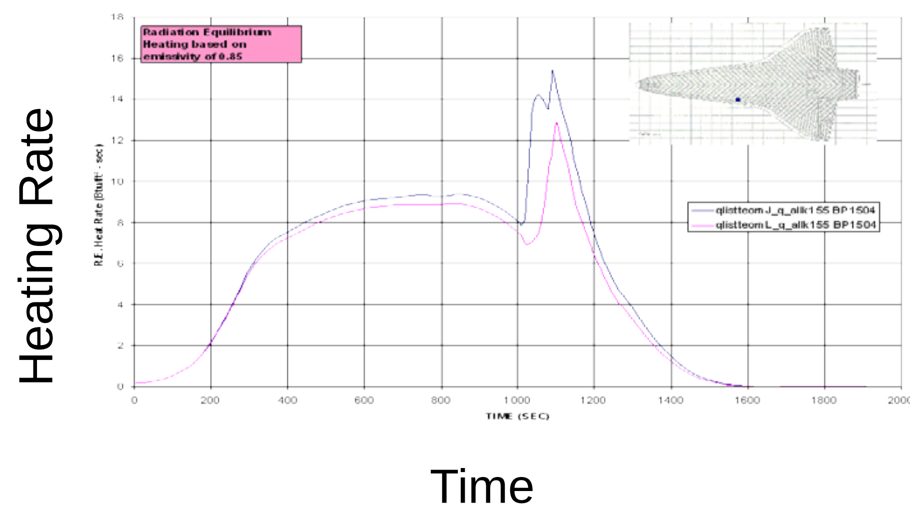
STS Mission	Launch	Entry	Total Damage Sites Examined by Damage Assessment Team
STS-114	July 26, 2005	August 9, 2005	49
STS-121	July 4, 2006	July 17, 2006	13
STS-115	September 9, 2006	September 21, 2006	28
STS-116	December 9, 2006	December 22, 2006	10
STS-117	June 8, 2007	June 22, 2007	11
STS-118	August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

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



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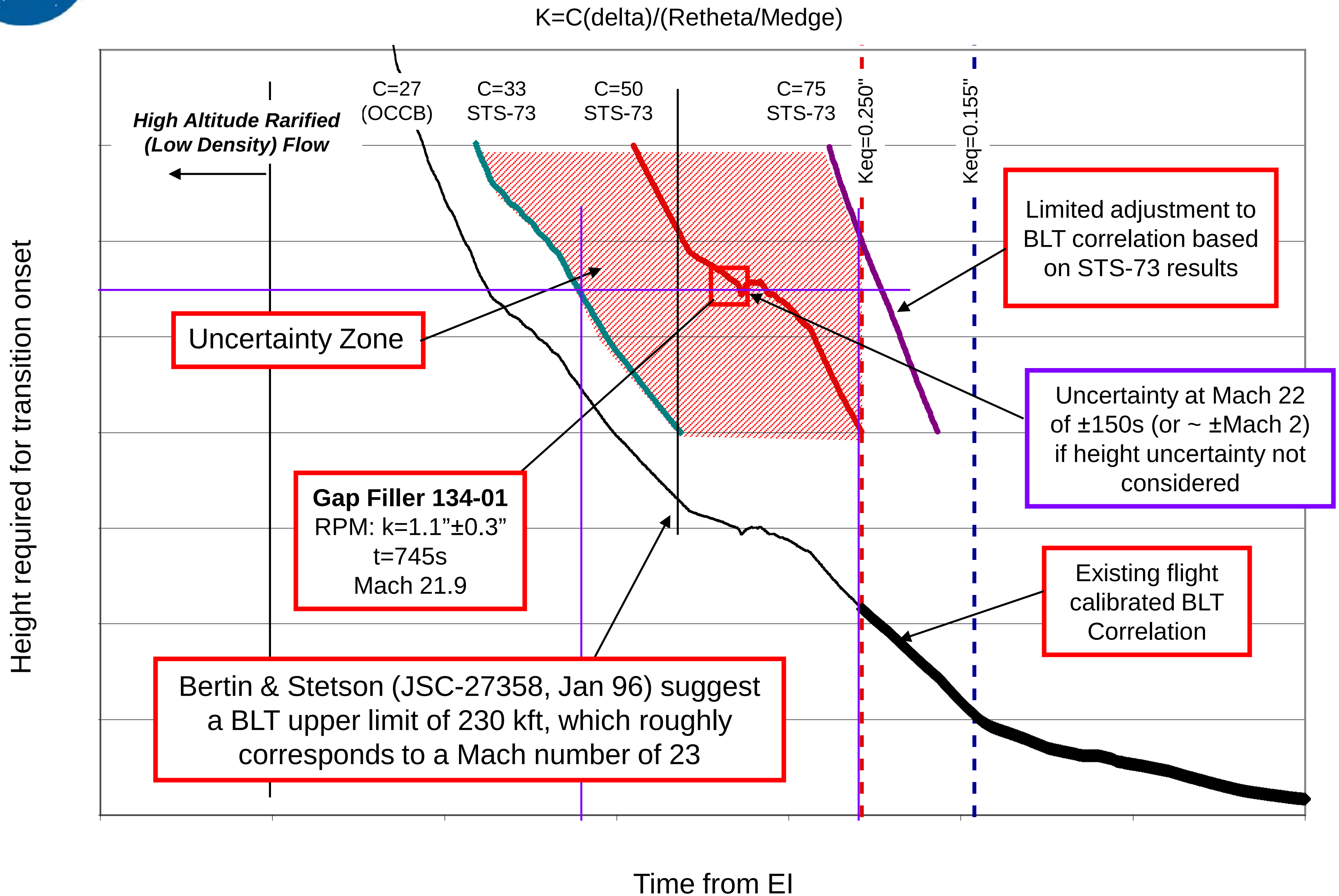
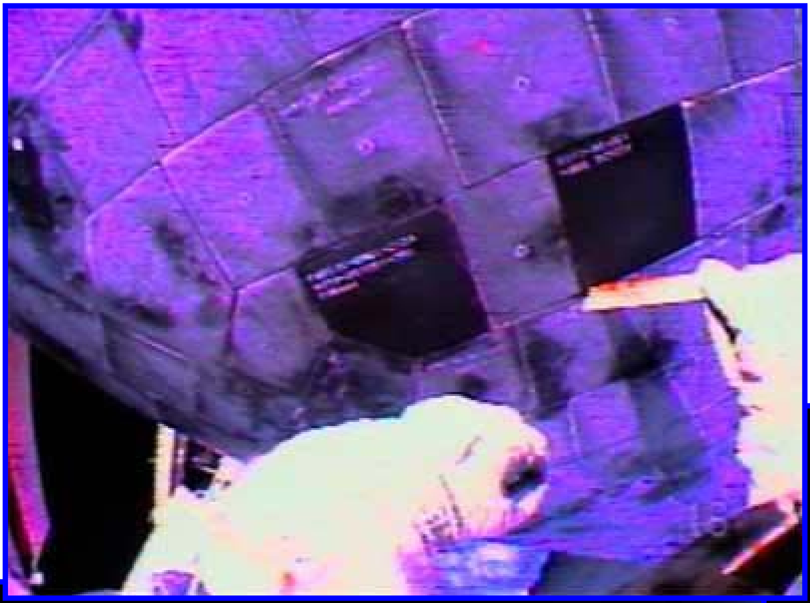
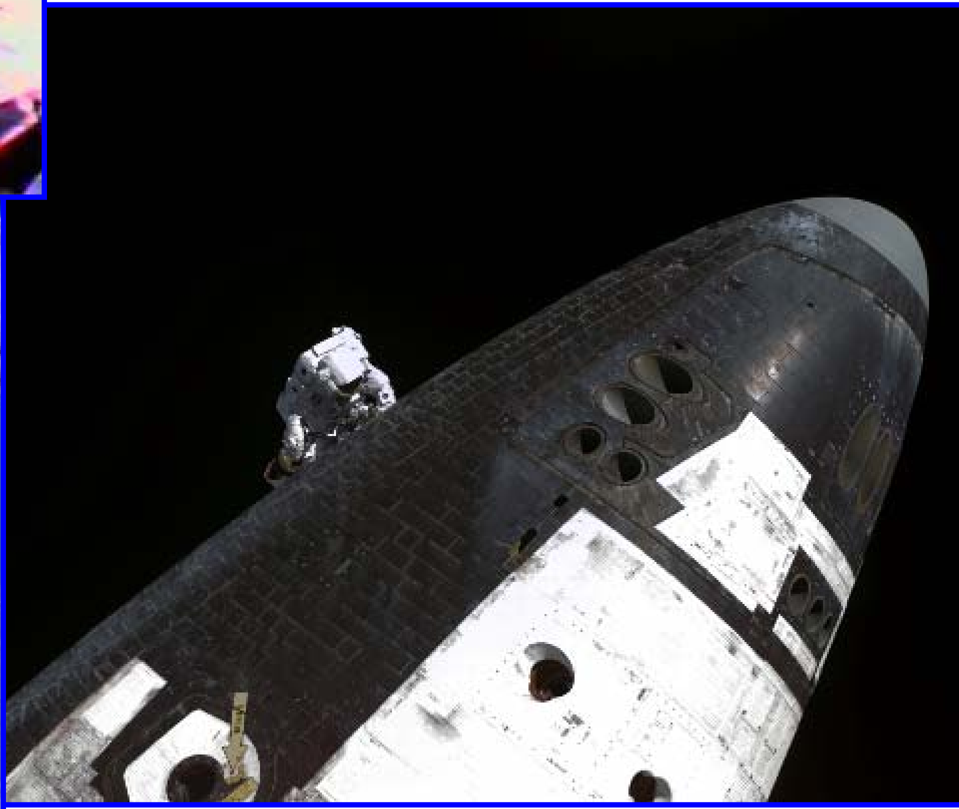
STS-114 Gap Filler Assessment



STS-114 Gap Filler Removal

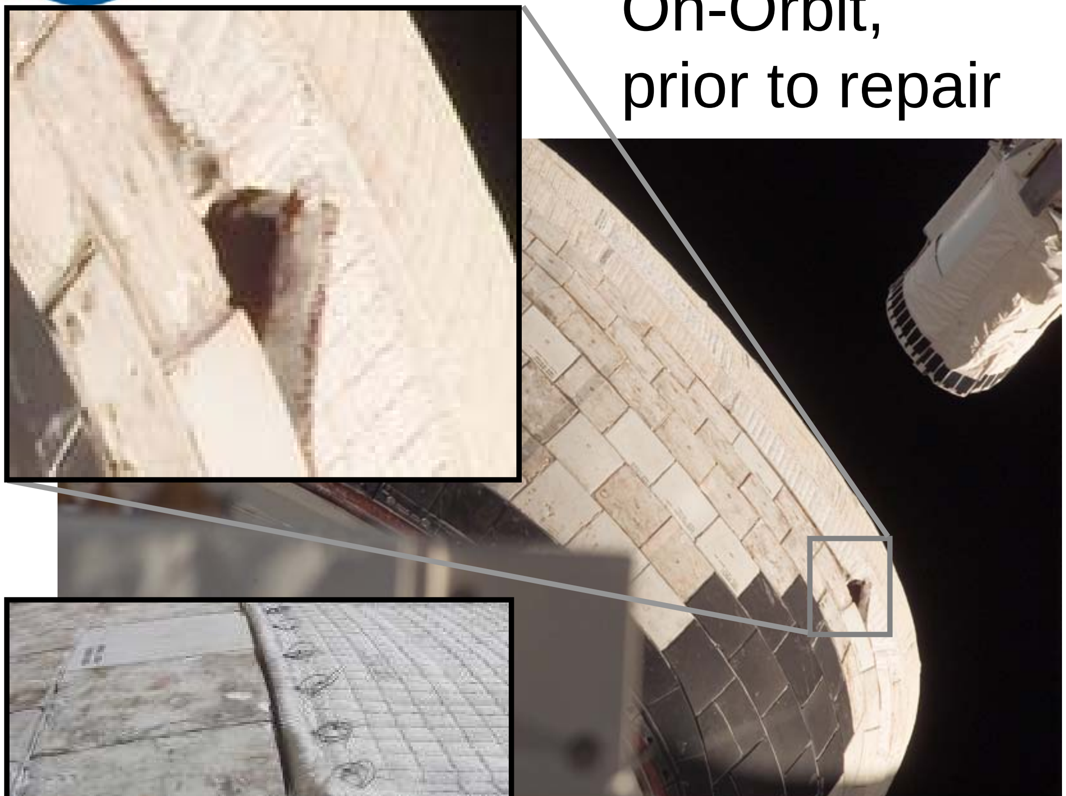


Stephen R. Robinson and Soichi Noguchi performed the first ever on-orbit TPS repair on August 3, 2005

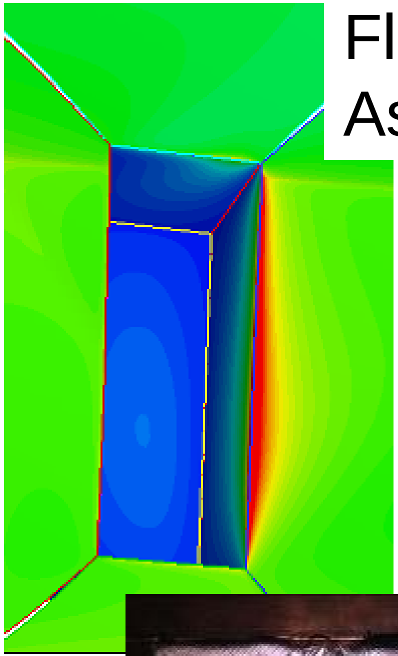


STS-117 OMS Pod Blanket Repair

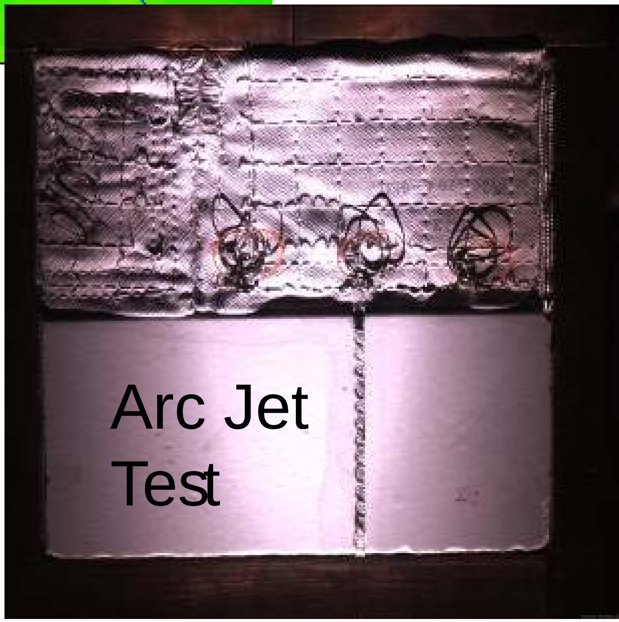
On-Orbit,
prior to repair



Flight CFD
Assessment



Danny Olivas performed the first ever on-orbit OMS Pod repair on June 15, 2007



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

Stephen Robinson portrait after STS-114 Gap Filler Repair

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

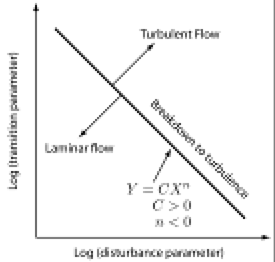
Danny Olivas self-portrait after STS-117 OMS Pod Blanket Repair

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 Flourescence (LaRC / Danehy, et al.)
- Roughness Induced Augmented Heating
  - Crew Exploration Vehicle (CEV) Heat Shield (JSC / Amar, et al.
- Hypersonic Expansion Tunnels
  - CUBRC LENS-XX (Holden, et al.)
- Other topics related to aerosciences

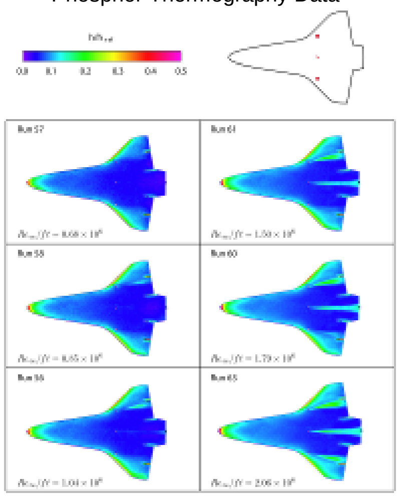
Discrete Roughness BLT

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

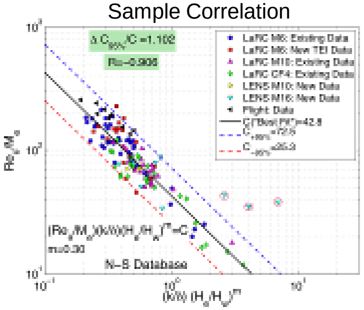


Model in LaRC 20-Inch Mach 6

Phosphor Thermography Data

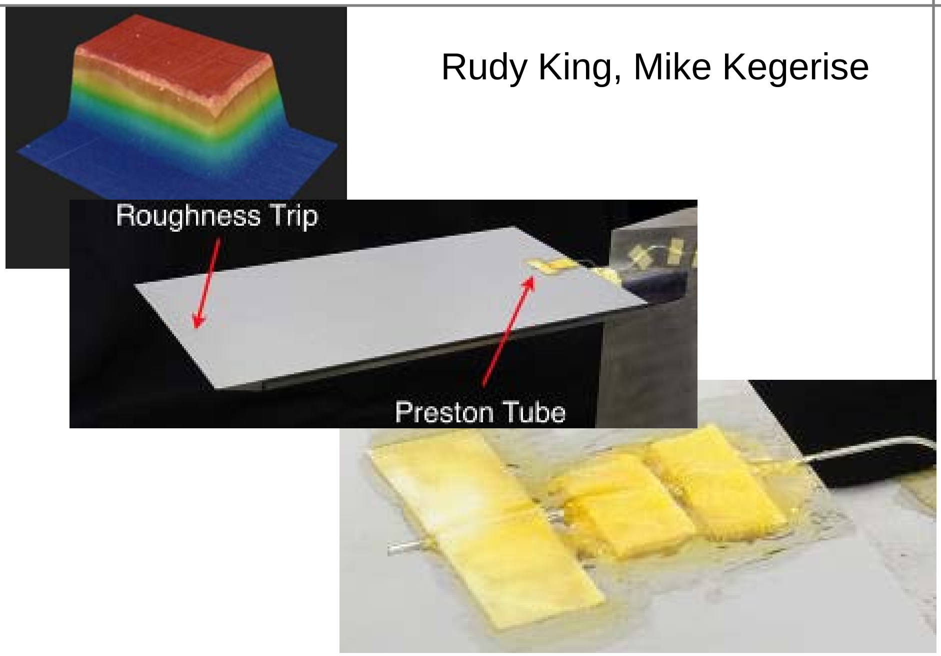


Sample Correlation



References:

- King R.A., et al., JSC EG-SS-07-07, 2007.
- McGinley, C.B., et al., AIAA 2006-2921.
- Liechty, D.S., et al., NASA/TM 2006-214306.
- Cassady, A.M., et al., NASA/TP 2007-214758.
- King, R.A., et al., NASA/TM 2008-215103.

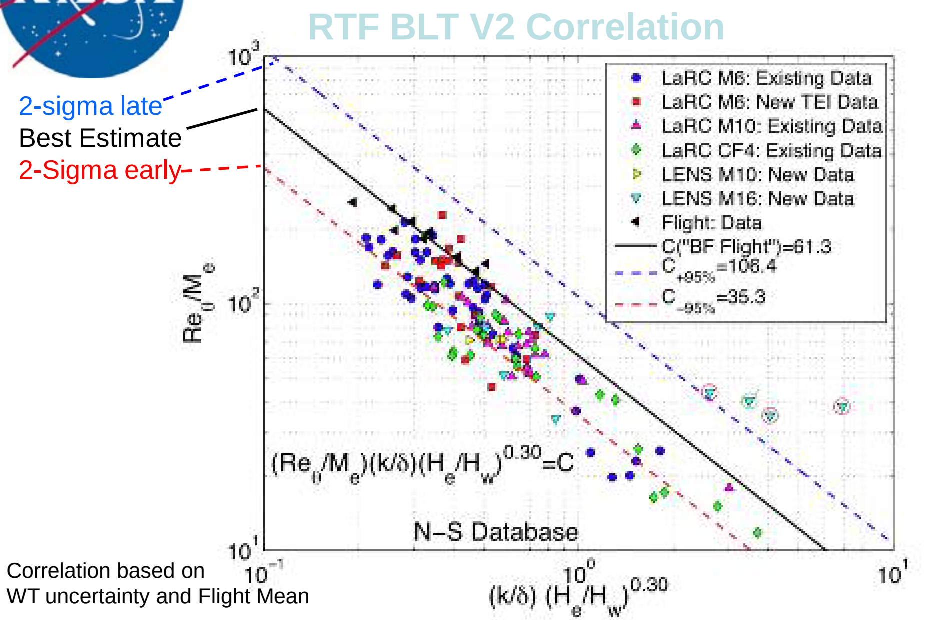


Rudy King, Mike Kegerise

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

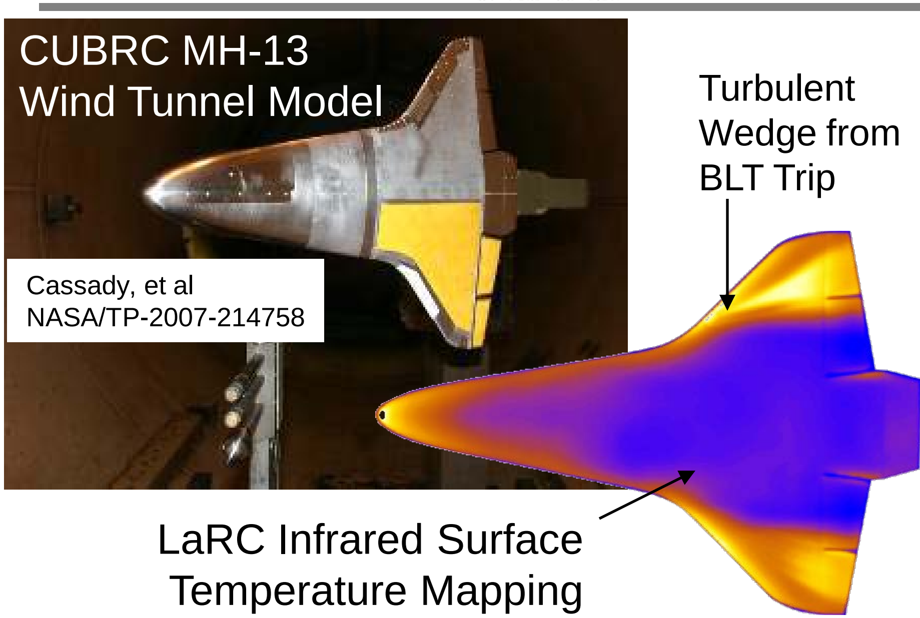


Proposed Correlation	Correlation Equation	Ground-Based R	Ground-Based $\Delta C/C$	Ground-Based $\sigma_C/\overline{C}$	Ground-Based + Flight R	Ground-Based + Flight $\Delta C/C$	Ground-Based + Flight $\sigma_C/\overline{C}$
1	$Re_\theta/M_e \times k/\delta = C$	-0.87	1.26	19.9%	-0.88	1.25	21.2%
2	$Re_\theta/M_e \times k/\delta^* = C$	-0.90	1.08	7.3%	-0.87	1.32	34.9%
3	$Re_\theta/M_e \times (k/\delta)(T_e/T_w)^{0.16} = C$	-0.89	1.14	14.5%	-0.89	1.20	23.6%
⇒ 4	$Re_\theta/M_e \times (k/\delta)(H_e/H_w)^{0.30} = C$	-0.91	1.04	8.9%	-0.91	1.10	19.9%
5	$\rho_k u_k k/\mu_w = C$	-0.79	2.51	30.9%	–	–	–
⇒ 6	$Re_k^{0.6} \times [Re_\theta \cdot (\mu_e/\mu_k)]^{0.4} = C$ *	-0.87	1.09	14.8%	-0.84	1.30	35.0%

* Results are for $n = -0.6$ for all data

Accuracy of various BLT Engineering Correlations with Orbiter RTF Data

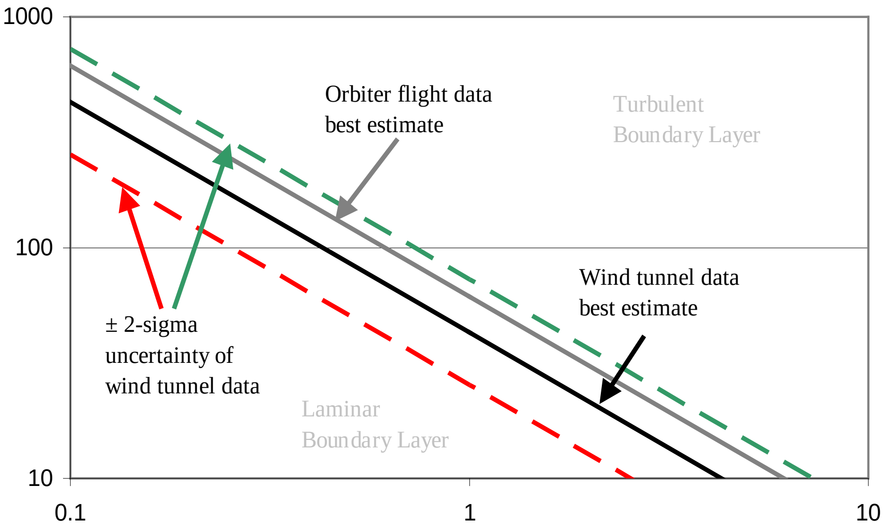
Ref: King, R.A., Kegerise, M.A. and Berry, S.A., "Proposed Protuberance Correlations for the Next Generation BLT Tool (vsn 2)", EG-22-07-07, March 30, 2007



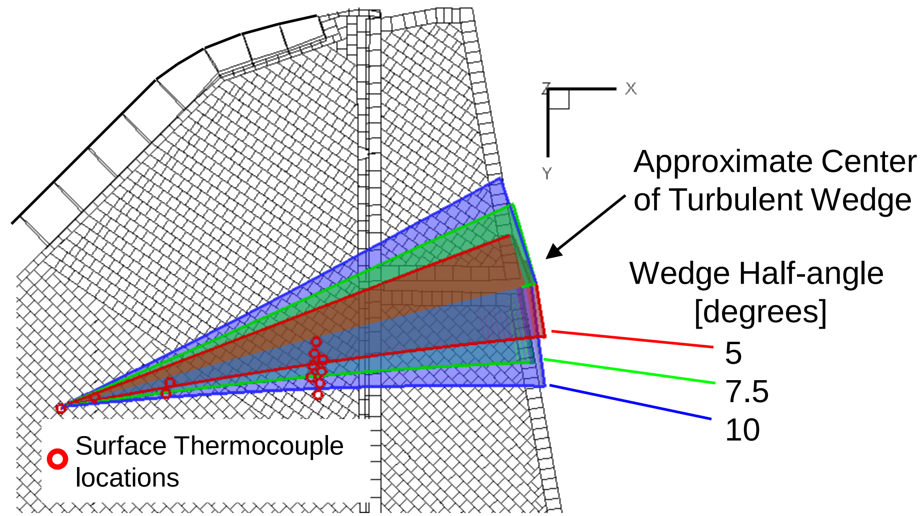
- Wind tunnel data to support correlation acquired in Langley Mach 6 Air, Mach 10 Air, Mach 6 CF4 and CUBRC Mach 10, 14, 16
- Engineering correlations of this type achieve correlation values of >0.8 on Orbiter configuration
- Better correlations are desired, but this is acceptable for providing engineering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

Orbiter BLT Flight Experiment Context

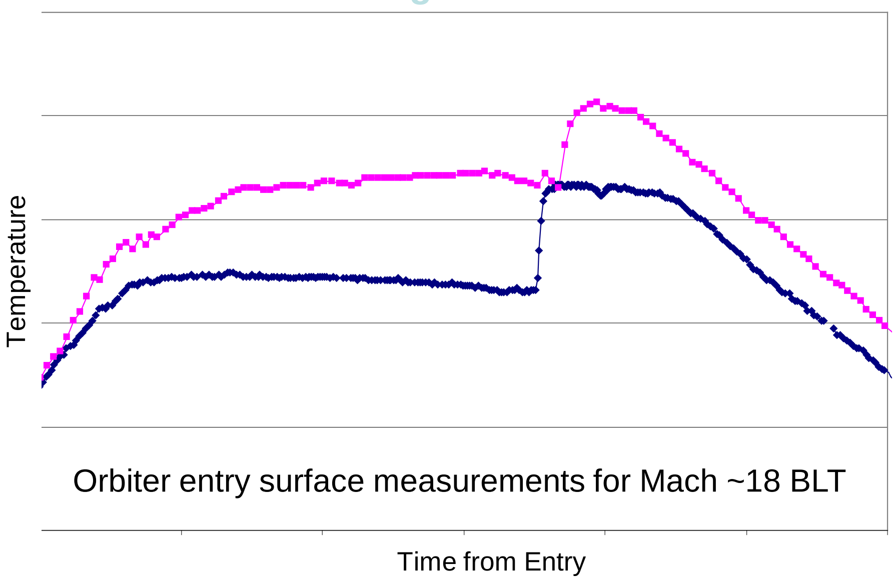
RTF BLT V2 Correlation



Turbulent Wedge



Aeroheating Environments



Comments

- 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

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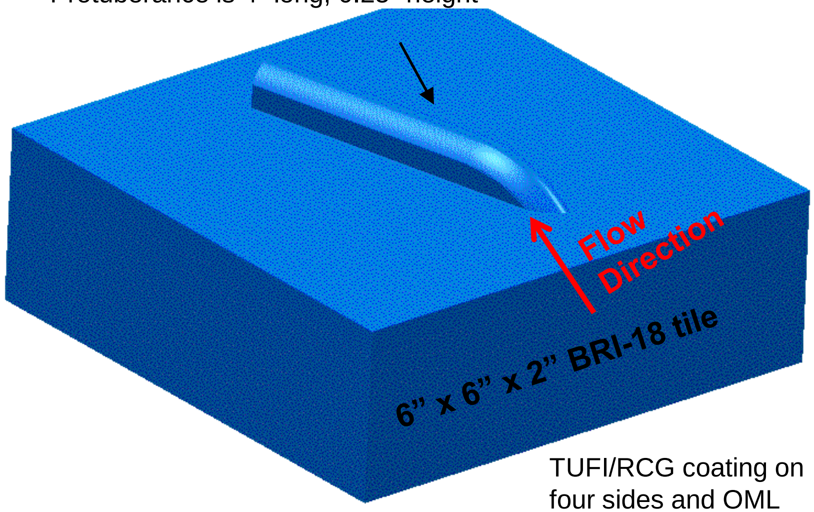
OV-103 Hardware Modifications

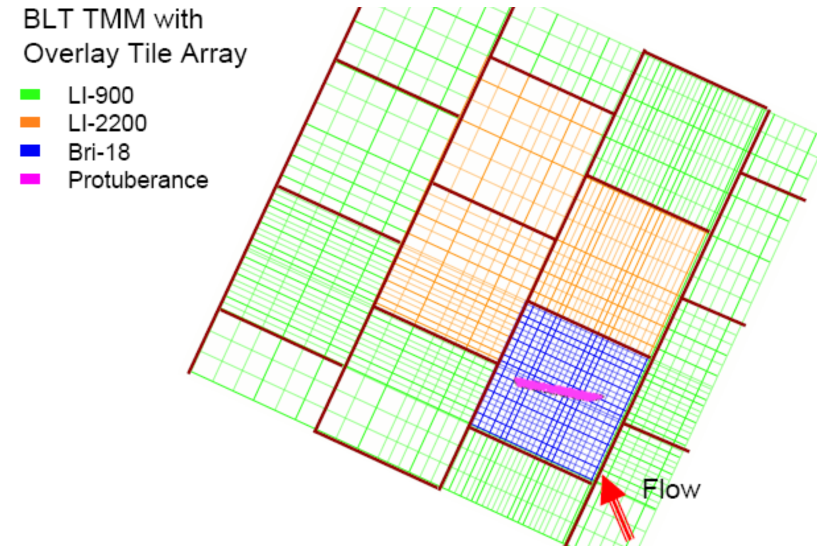
Protuberance Tile

Protuberance is 4” long, 0.25” height

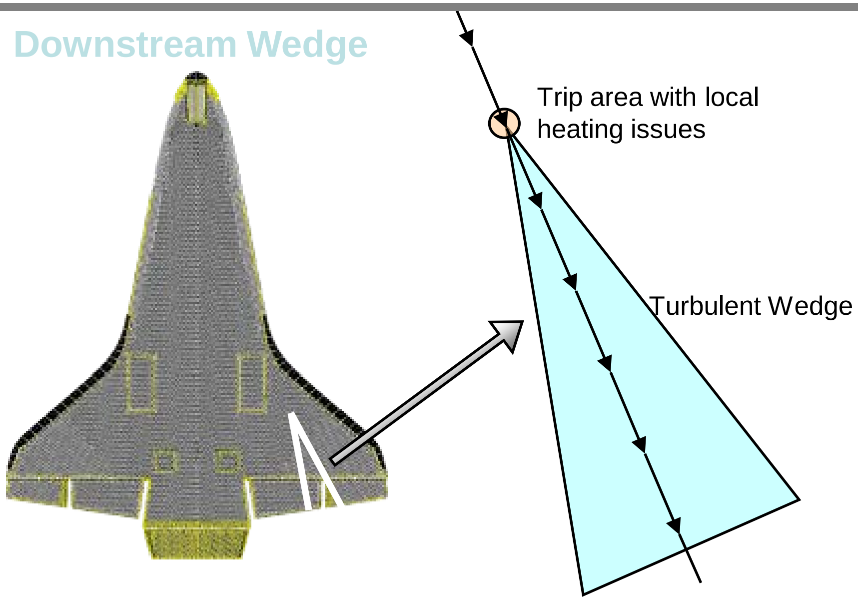


TUFI/RCG coating on four sides and OML

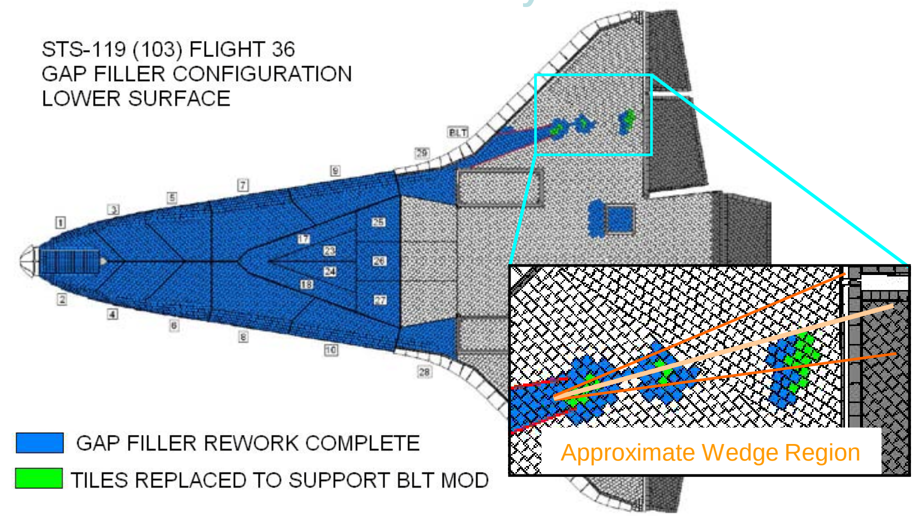
Local Area



Downstream Wedge



TPS Summary



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HyThirm

Hypersonic Thermodynamic Infrared Measurements

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

04/09 – Mission Success!

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

Imagery from "ad hoc" flights (pre-HYTHIRM)

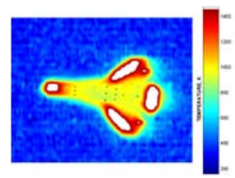
Turbulent flow from gap filler ~ Mach 13

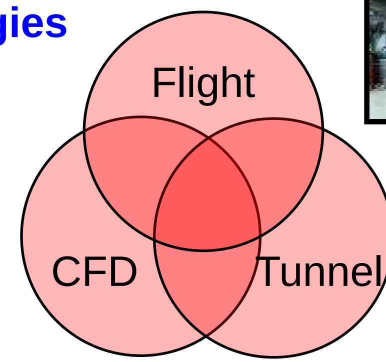
Horvath et. al. AIAA-2007-4267

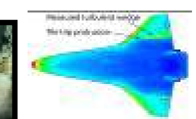
Turbulent flow from wing protuberance

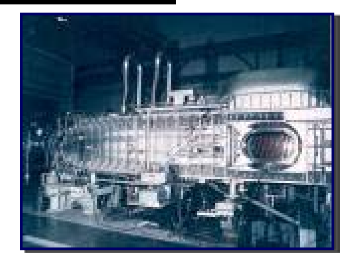
Provide tools required for an integrated test and evaluation approach in which the proper combination of modeling and simulation, ground testing, and flight testing are employed to address of future high speed hypersonic systems

Flight Testing Technologies









Modeling & Simulation

Ground Test Facility Technologies

POC's: Thomas.J.Horvath@nasa.gov (PI) and Paul.W.Krasa@nasa.gov (PM)

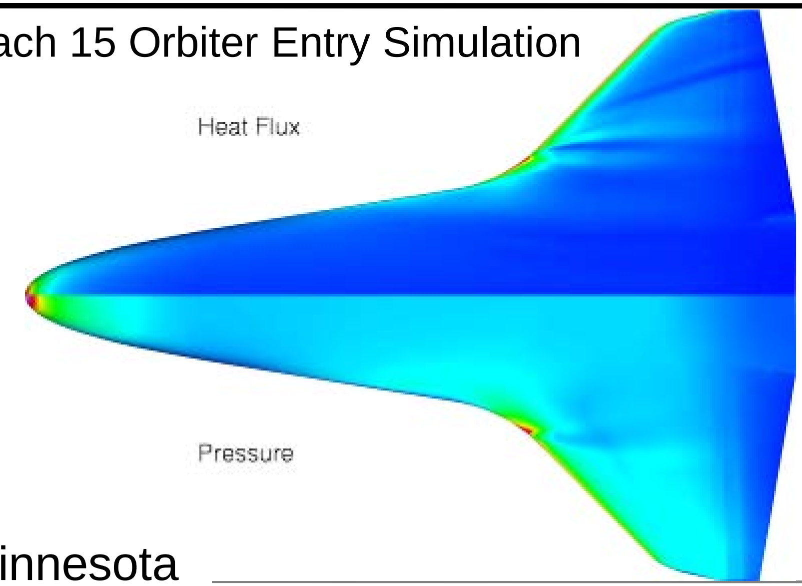
Sponsors: NASA JSC SSPO; NESC, ARMD

Orbiter Entry BLT Stability Modeling

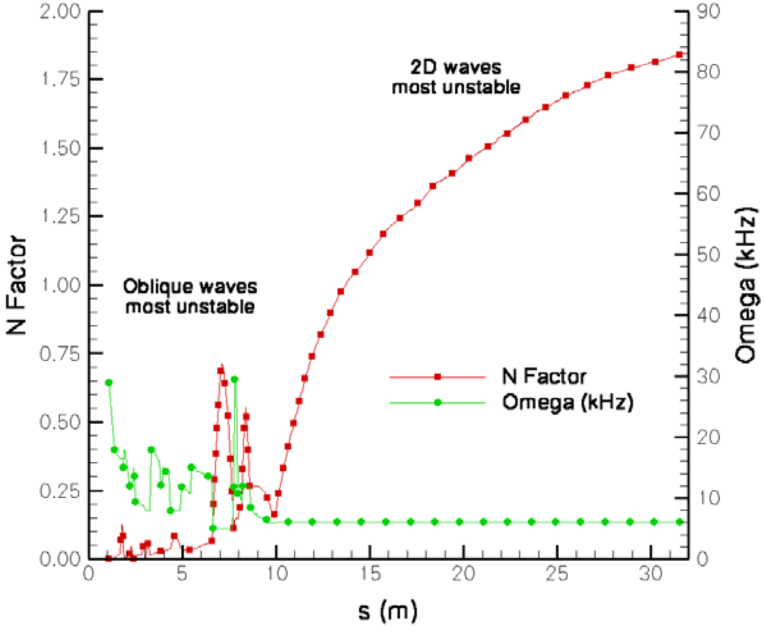
Graham V. Candler
Heath B. Johnson

- 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

Mach 15 Orbiter Entry Simulation



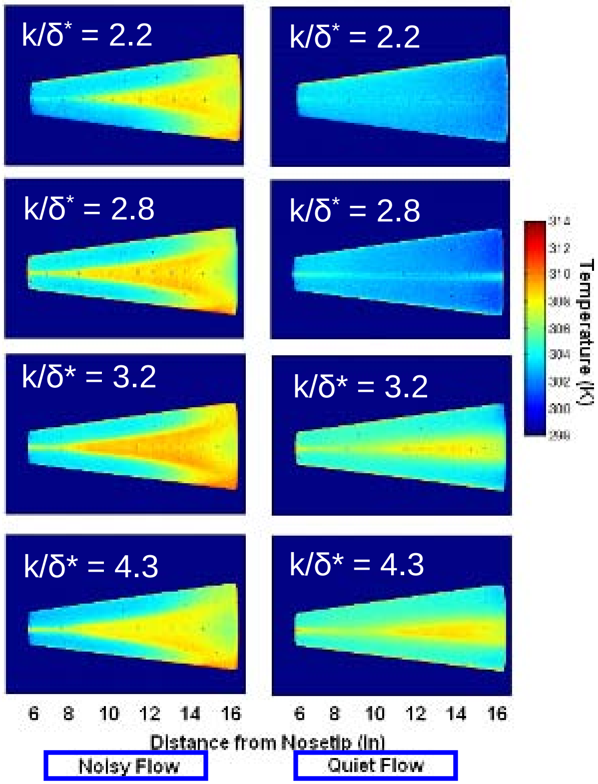
University of Minnesota



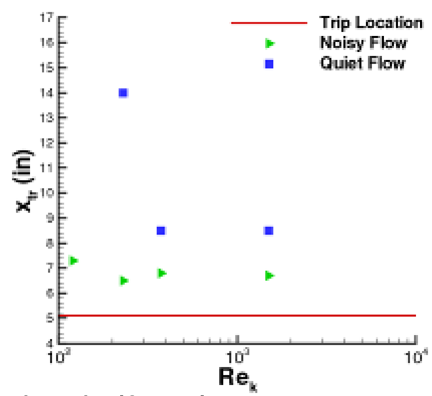
- Demonstrates it is possible to generate stability-quality CFD solutions for Shuttle
- Initial results show N-factor of nearly 2 at rear of shuttle
- Oblique waves dominant near the nose but 2D waves reach higher N
- Currently a centerline flow analysis
- Future results will include off-axis 3D effects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

Purdue Mach 6 Quiet Tunnel

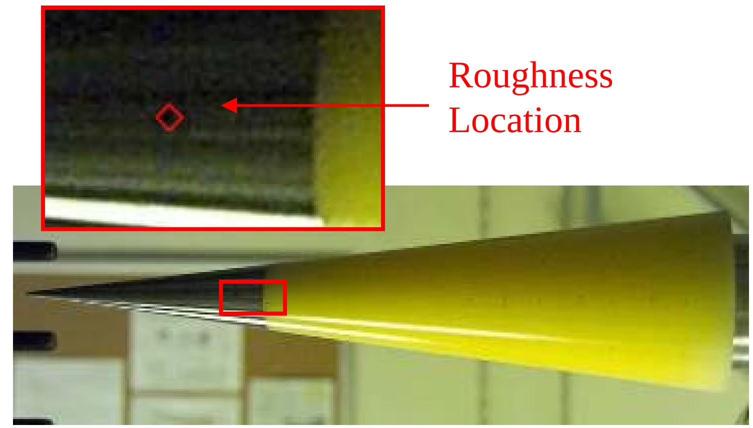
Steven P. Schneider



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



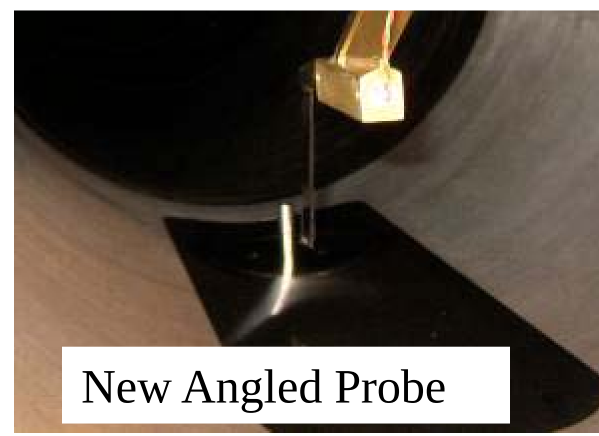
7-deg. half-angle cone,
0.047-in. nose radius, about 3E6/ft.



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

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

Hot Wire in Wake of Isolated Roughness



Nitric Oxide PLIF

Danehy, Inman, Bathel, Jones
NASA Langley Research Center

Overview

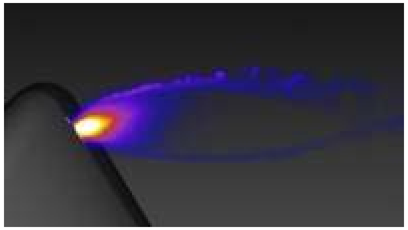
- Nitric Oxide Planar Laser-Induced Fluorescence (NO PLIF)
  - Pioneered at Stanford in 80's and 90's (Hanson)
- Laser/Camera system visualizes slices of flow
- Quantitative measurements
  - Velocity, temperature
- Used in 31" Mach 10 Wind Tunnel
- Primarily Supported by NASA Fundamental Aero Program,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

Recent Applications: Transition Studies

Danehy et al., AIAA Paper 2007-0536

- Triangular trip simulates orbiter gap filler
- NO seeds BL fluid, marks flow structures

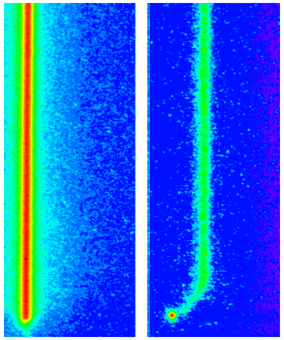
Recent Applications: RCS Jet Imaging



- Measure shape, transition, trajectory, velocity, of RCS jets for both Aero and Aeroheating applications

Inman et al., AIAA Journal (accepted; in press).
Danehy et al., Journal of Spacecraft and Rockets, vol. 46m p. 93-102 (2009).

Future Capabilities



Delay= 0ns 500 ns

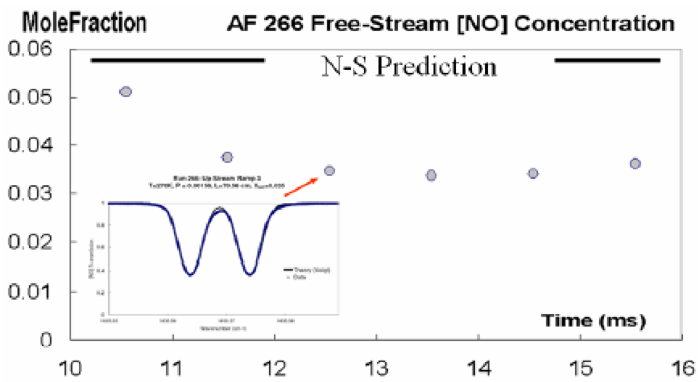
Velocity Measurement

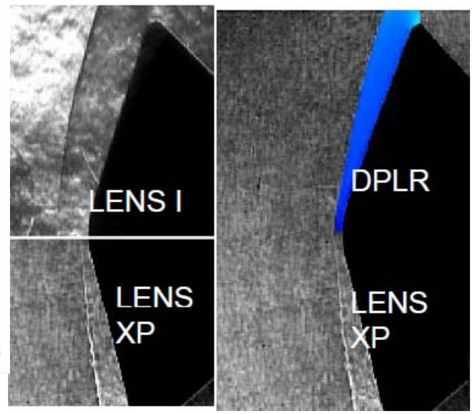
$$\textit{velocity} = \frac{\textit{distance}}{\textit{time}}$$

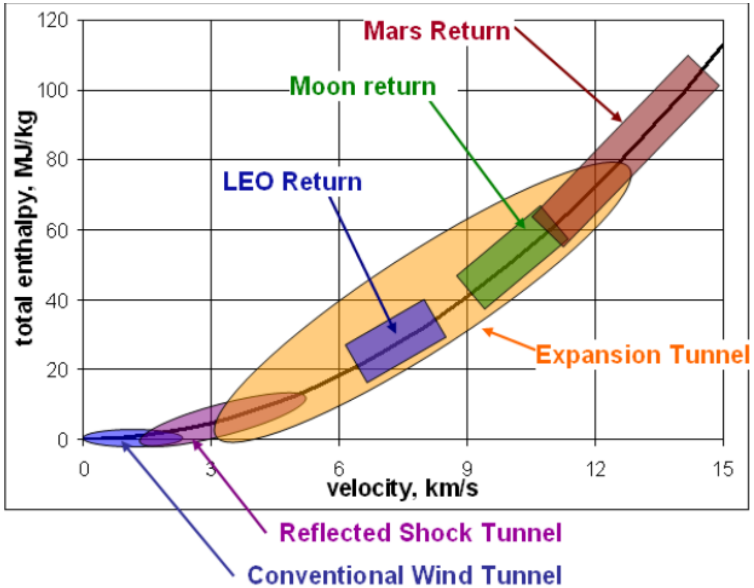
Danehy et al, AIAA Journal v.41, n.2, p. 263-271 (2003).

- High speed imaging, velocimetry:
  - MHz Frame Rate Laser/Camera system (NRA with Ohio State)
- Temperature measurement

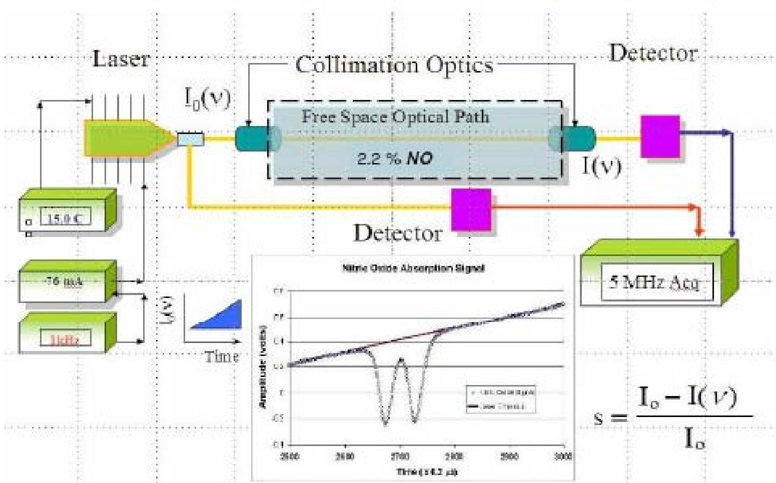
Michael Holden, Tim Wadhams

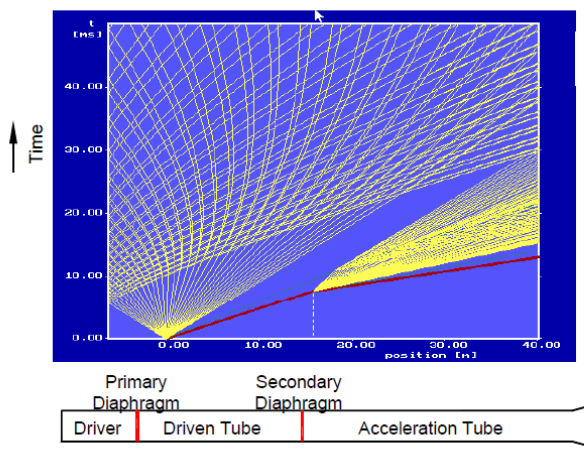




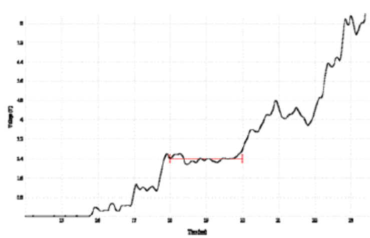


Measurements of NO in Freestream and Shock Layers Employing Tunable Diode Laser Spectroscopy





2ms Test Time for 10 MJ/kg

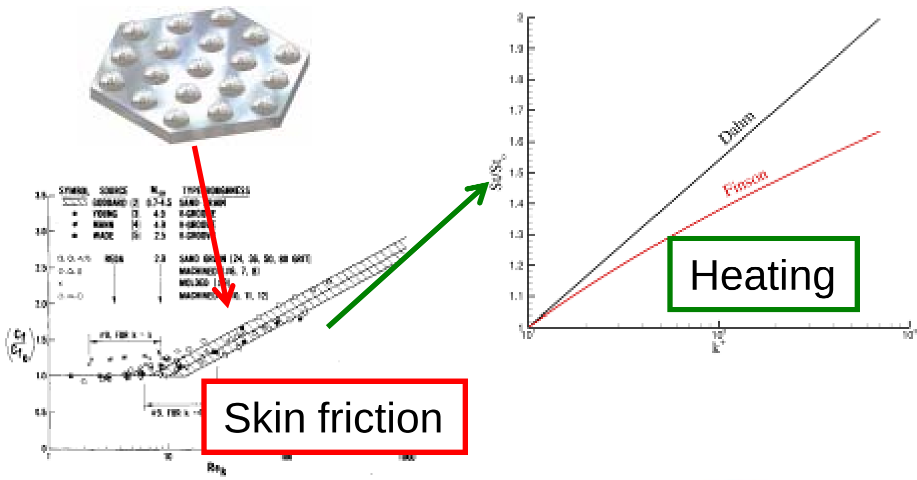


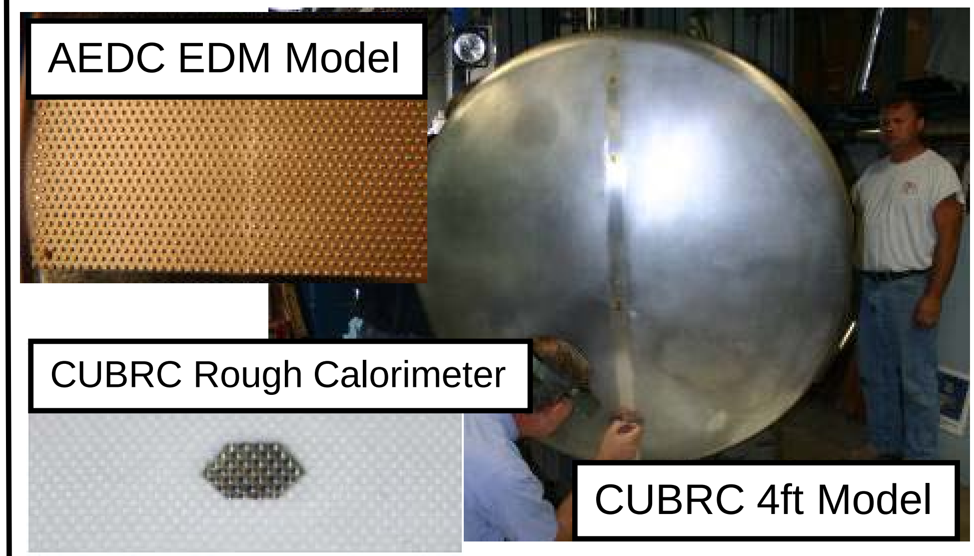
Ref: Wadhams, et al AIAA 2007-551,
Holden et al, AIAA 2008-2505,
MacLean et al, AIAA 2007-121

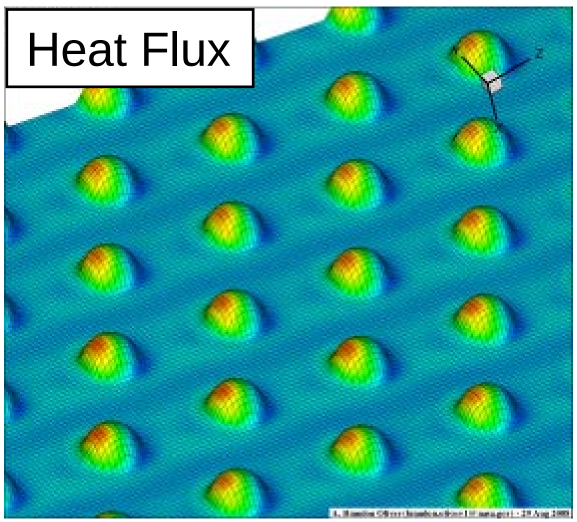
Roughness and Heating Augmentation

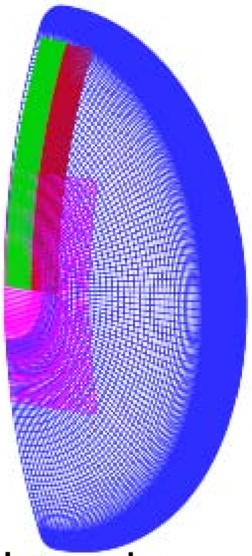
Adam Amar and Brandon Oliver / NASA JSC

Geometry/Spacing/Height









CFD corroborates wind tunnel trend

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

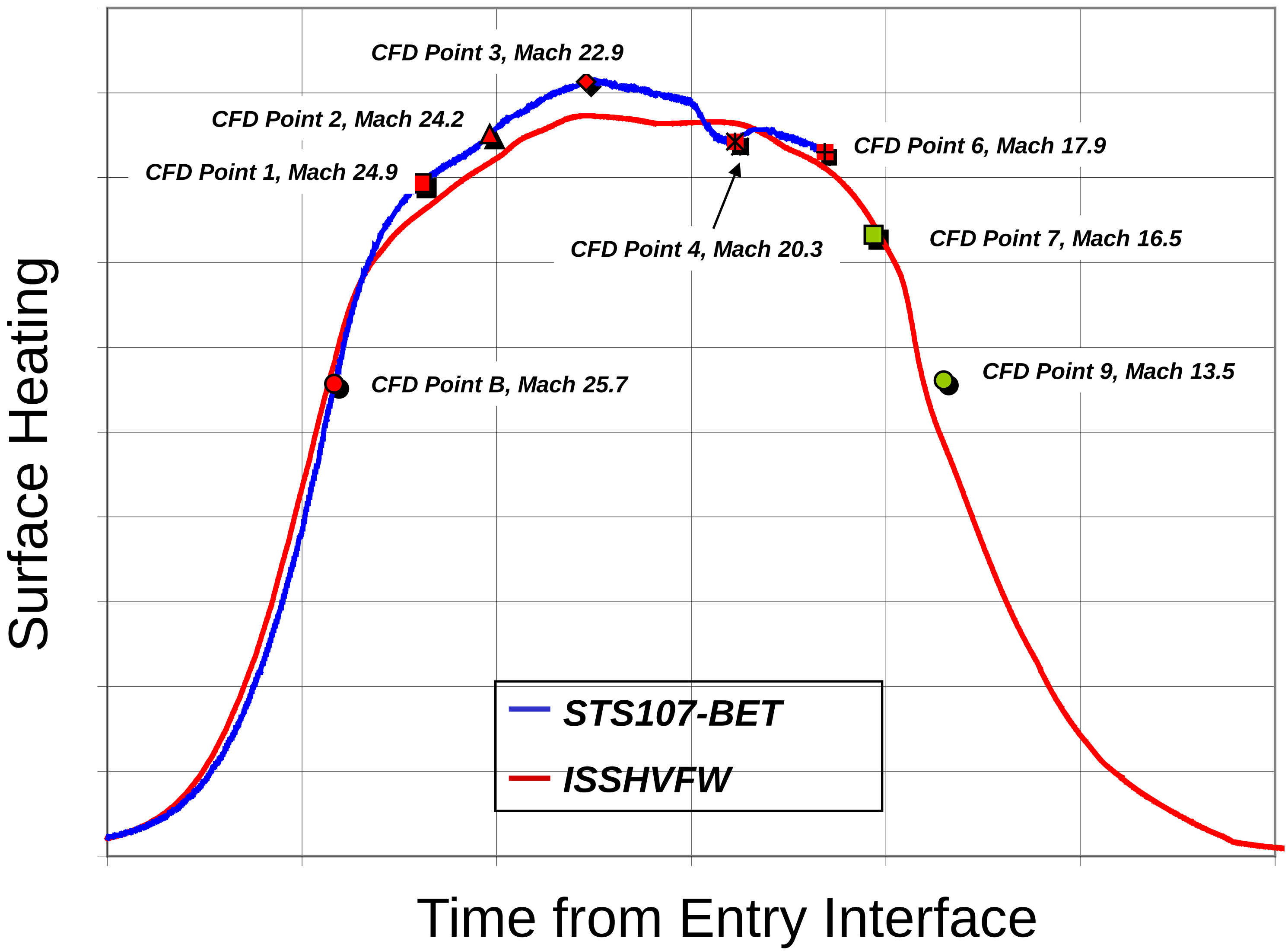
- Examine blowing effects on roughness
- Get augmentation data for Avcoat patterns

STS-119 Launch Photo

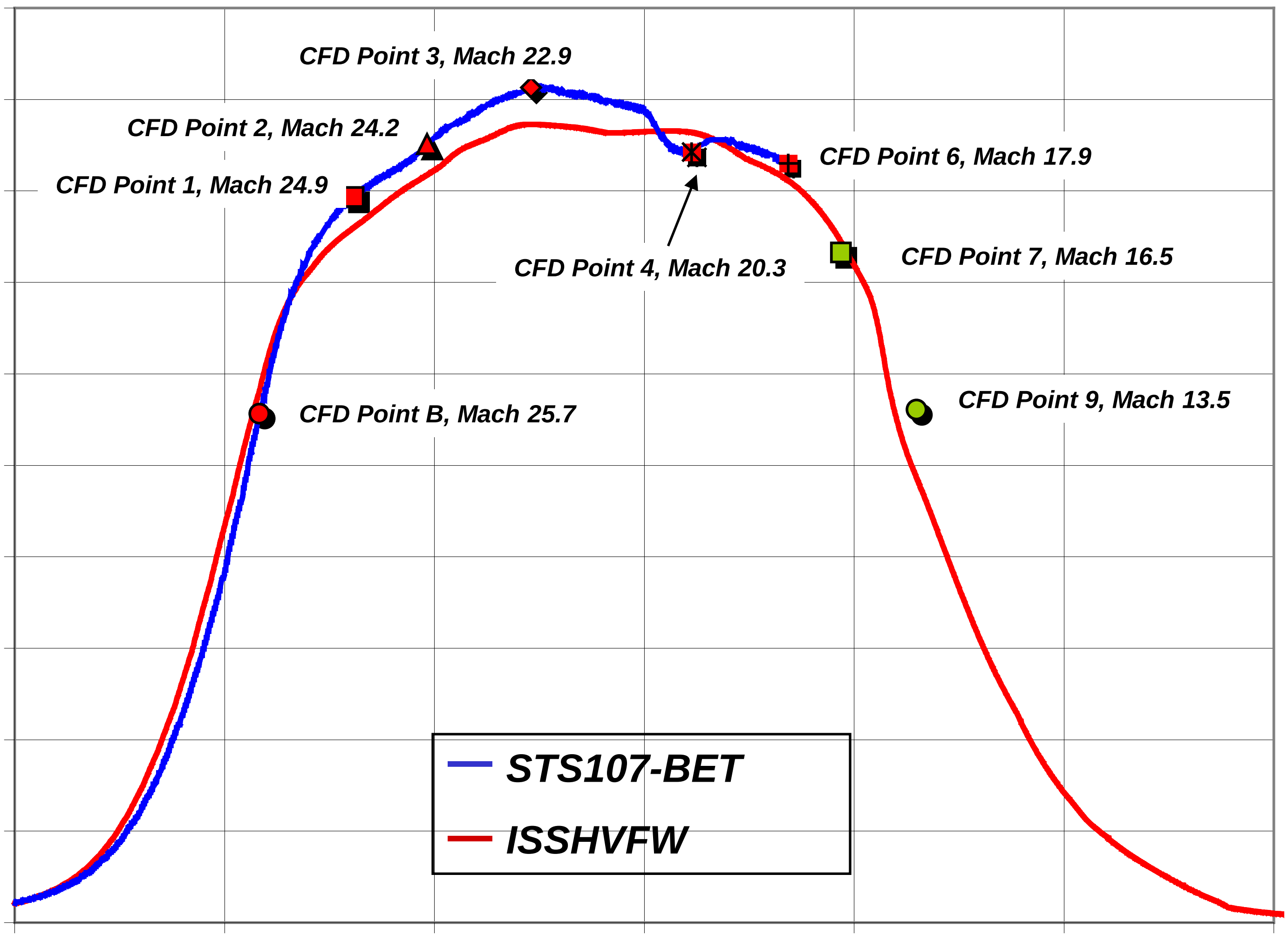
Back-up

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

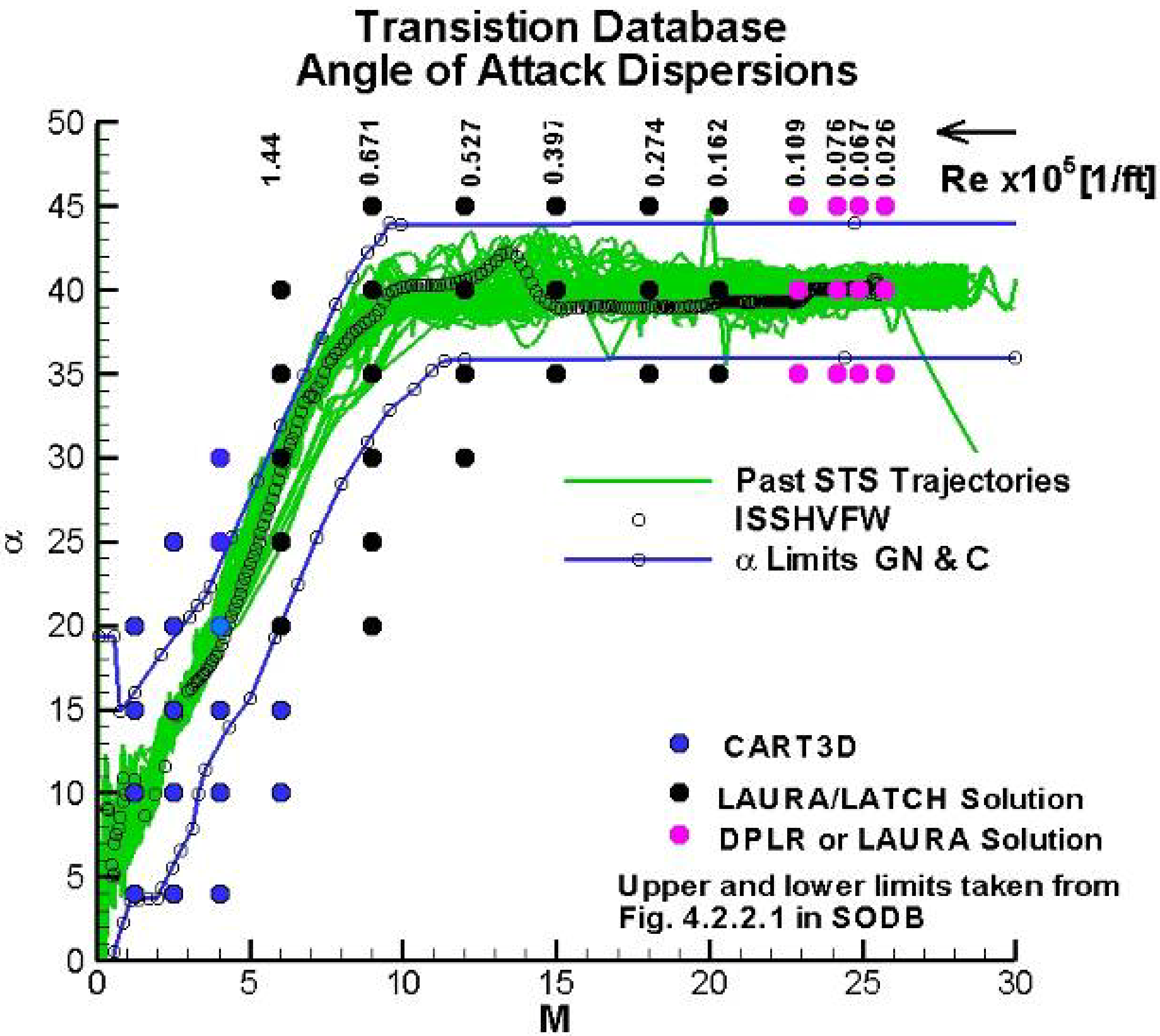
CFD Repository



CFD Repository



Boundary Layer Properties DB



Simplified Cavity from Point Cloud