An Overview of the
Space Shuttle
Aerothermodynamic Design

Abstract

The Space Shuttle Thermal Protection System was one of the three areas that required the development of new technology. The talk discusses the pre-flight development of the aerothermodynamic environment which was based on Mach 8 wind tunnel data. A high level overview of the pre-flight heating rate predictions and comparison to the Orbiter Flight Test (OFT) data is presented, along with a discussion of the dramatic improvement in the state-of-the-art in aerothermodynamic capability that has been used to support the Shuttle Program. A high level review of the Orbiter aerothermodynamic design is discussed, along with improvements in Computational Fluid Dynamics and wind tunnel testing that was required for flight support during the last 30 years.

The units have been removed from the plots, and the discussion is kept at a high level.

Apollo 13
April 11th, 1970

The
Space Shuttle Legacy
began with
Mercury,
Gemini,
&
Apollo

41 years later...


NASA-S-66-11003
ENTRY INTO EARTH ATMOSPHERE

Entry Heating 101

- Maximum Heat Rate
  - Maximum Surface Temperature & Material Selection
- Maximum Heat Load
  - Integral of the Heat Rate with Time
  - Insulation Requirement
  - Structural Temperature
- Boundary Layer
  - Laminar – Minimizes Heating to the Surface
  - Turbulent – Increased Heating to the Surface

Entry Heating 101 Continued

- Radiation Equilibrium Surface Temperature
  - Surface Temperature Reaches an Equilibrium: Heat Rate to the Surface = Heat Radiated from the Surface + Heat Conducted to the Orbiter Structure
  - Tile Material with RCG Coating, Emissivity is 0.8 to 0.85, Conduction is About 1 Percent
- Catalytic Efficiency of the Surface
  - Metal Surfaces act as a Catalyst, Increasing Heat Transfer to the Surface.
  - Tile RCG Coating Has a Low Catalytic Efficiency

Boundary Layer Transition

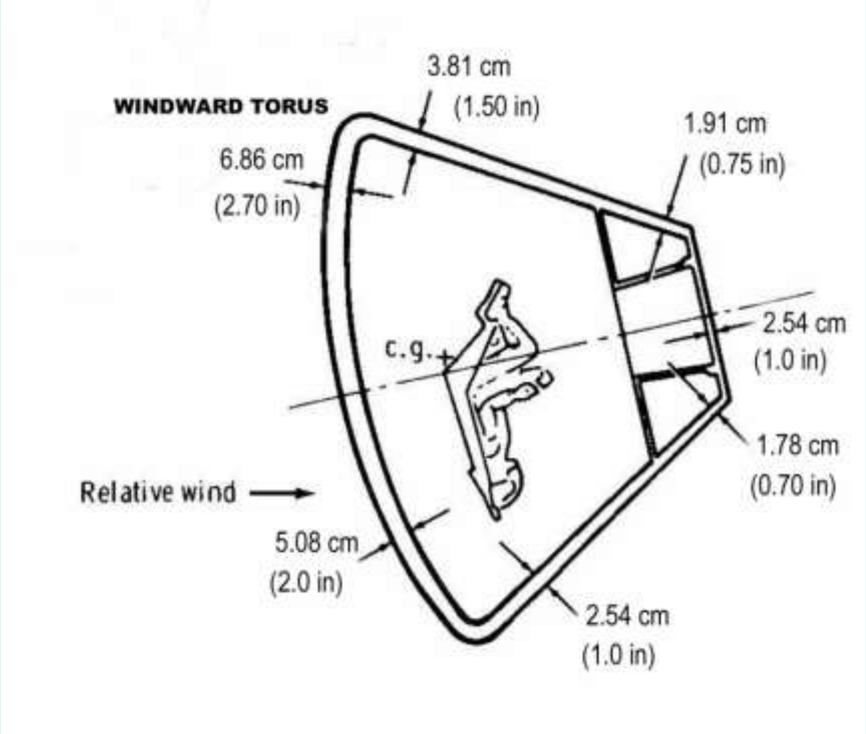
- Function of: Vehicle Geometry, Reynolds Number, Mach Number, Surface Roughness, Pressure Gradient, Free Stream Noise, etc.
- Test or Flight Data is Required For Determining the BLT Location
- Apollo Experience
  - Flight Data Agreed with AEDC Tunnel B at Mach 8
  - Operational Flights Were Laminar
  - Maximum Heat Rate Trajectory Showed Transition to Turbulent Heating

Apollo Heat Shield Design

- Heat Shield Had to be Designed Before the Lunar Trajectories Were Known
    - Heat Rate: 20g Emergency Lunar Return
    - Heat Load: Spacecraft Barely Captured by the Atmosphere
- <u>Compounding of Conservatism from Each Group!</u>

- Ablator used on Lee Side Due to Large Uncertainties

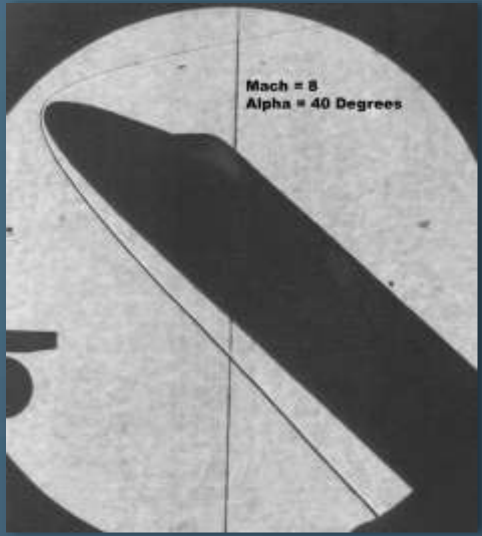
- Factor of 2 Over Design for Operational Missions Except Windward Torus – <u>Structure Reached Design Temperature of 589K (600F)</u>



Space Shuttle Thermal Protection System Design Goals

- <u>Efficient, Reusable, Minimum Weight TPS</u>
- Laminar Boundary-Layer During Peak Heating
- Windward Surface Shape Optimized to Maintain Laminar Flow
- Trajectory Designed to Maintain Laminar Conditions
- All Parties Agreed to Minimize Conservatism
  - Design Based on <u>Nominal Trajectory</u>, <u>Nominal Heating Rates</u>, <u>Nominal Material Properties</u>, & <u>Aerodynamic Smooth Surface</u>

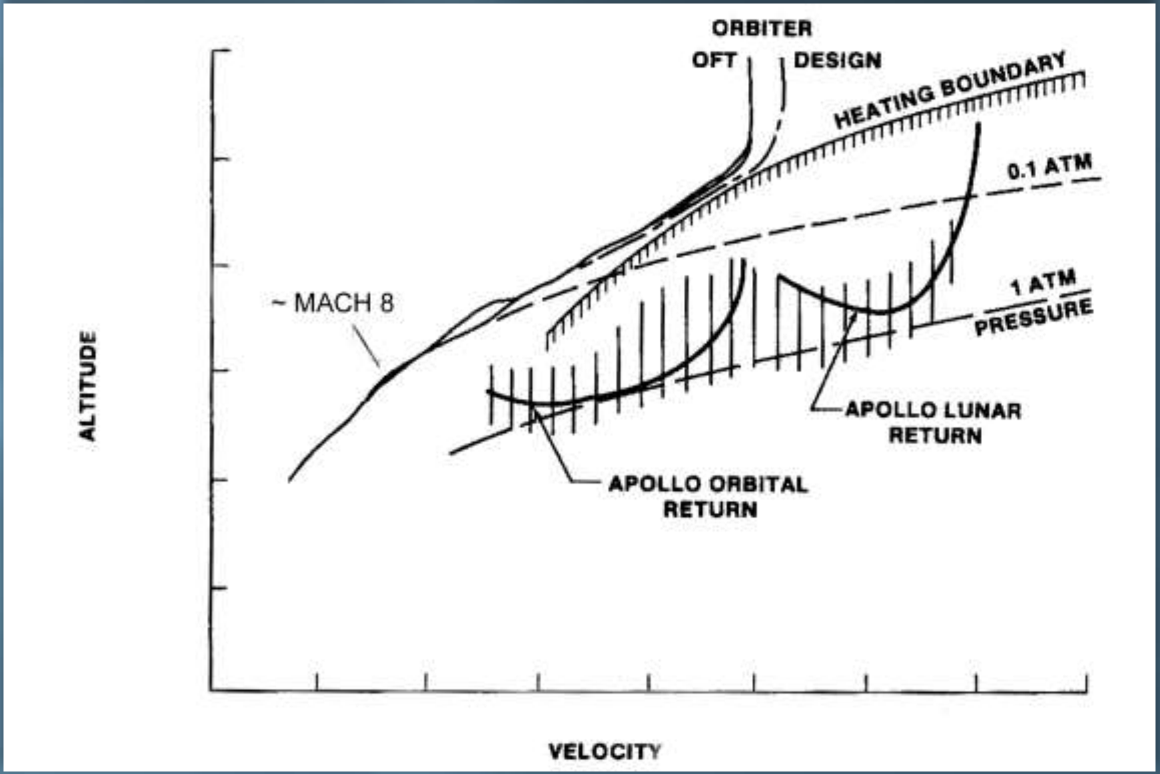
Design Philosophy



- Critical Design Review, 1978
- Polar Orbit – Western Test Range
  - Mission 3b, 25k lbs Payload Retrieval
  - 104 Degree Inclination, 100 NM Altitude
    - Trajectory 14414.14C
- Design for the Polar Orbit Mission
- Fly STS-1 as Conservatively as Possible
- Gradually Increase Entry Conditions During the Orbiter Flight Test (OFT) Program
- Use the OFT Flight Data to Assess the Vehicle Capability

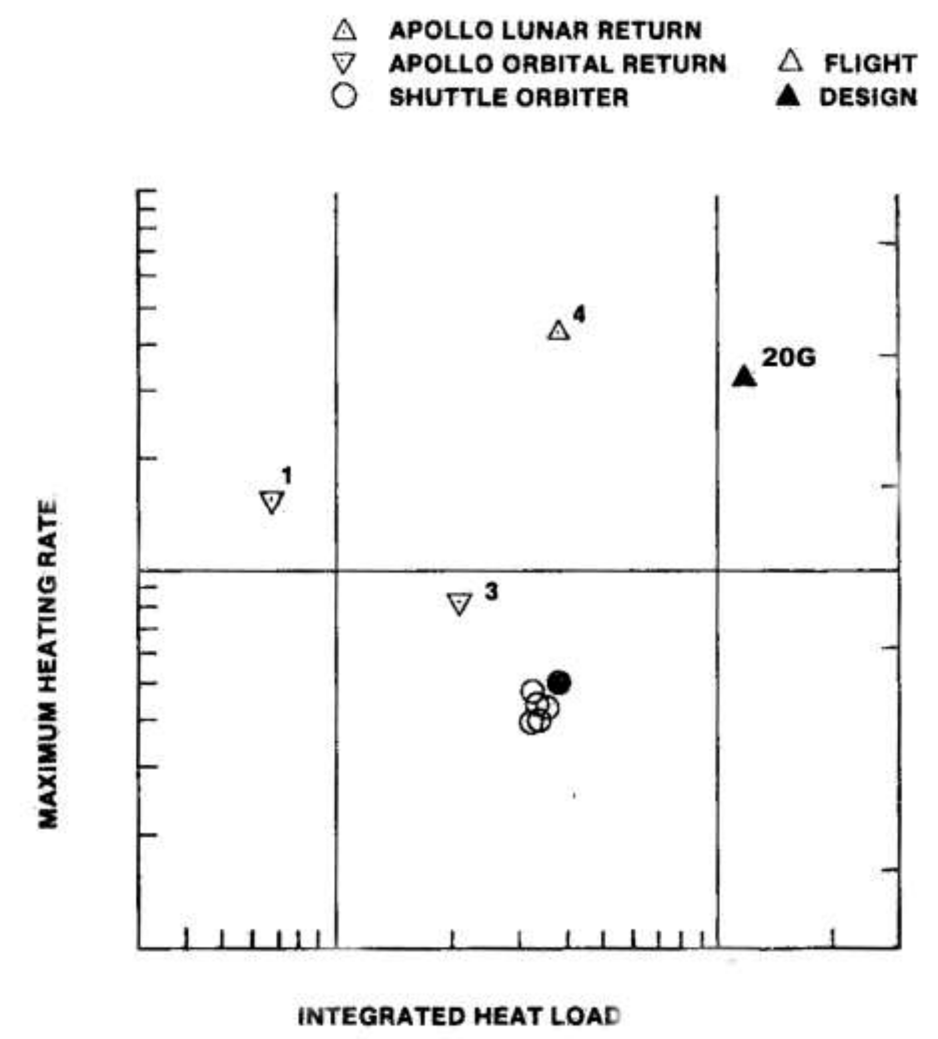
Systems Approach to Entry Design

- Trajectory, Aerothermodynamic Predictions, TPS Materials
- Conservatism from Each Discipline was Combined (RSS) to Produce System Uncertainties



Heat Rate and Heat Load Comparison With Apollo

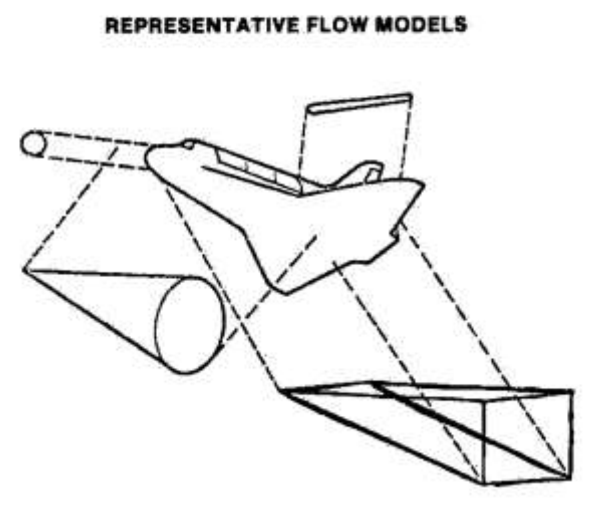
- Apollo Operational Trajectories Were Very Benign Compared to Design
- Orbiter OFT Flights Were Much Closer to Design

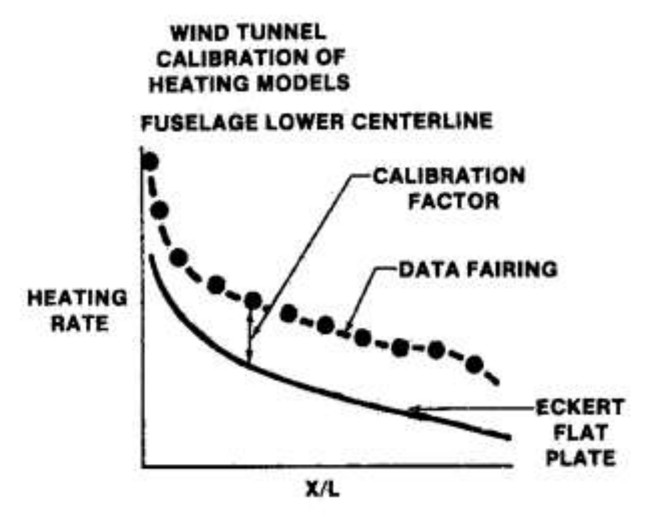


Orbiter Heating Design Approach

❑ Three Levels of Sophistication

- Simplified Heating Model
  Stagnation Heating to a 1 Ft. Sphere
  - BLT Based on Normal Shock Reynolds Number
  - Used for Trajectory Design
- Design Methodology
- Orbiter Wind Tunnel Data, at Mach 8, Scaled to Flight Conditions Using 2-D Flow Models.
- Benchmark 3-D Flow Field Calculations
  - 4 Flight Conditions
  - Used to Check the Design Methodology Before STS-1





Surface Roughness

- “Design” BLT Approach Used Spherical Roughness Elements from RI Experience with Hemisphere/Cone Data
  - Assumed that Single Roughness Elements Would Trip the Boundary Layer.
- Resulted in Very Smooth Surface Roughness Requirements – Tile to Tile Steps and Gaps
- Contrasted With NASA/JSC Approach
  - Mach 8 Normal Shock Reynolds Number Data Matches Apollo Transition Data & Planned Shuttle Flight Reynolds Number
- JSC Conducted a Unique Surface Roughness Test
  - Random Tile Roughness Plated on Model Surface
  - Resulted In Relaxed Roughness Requirement

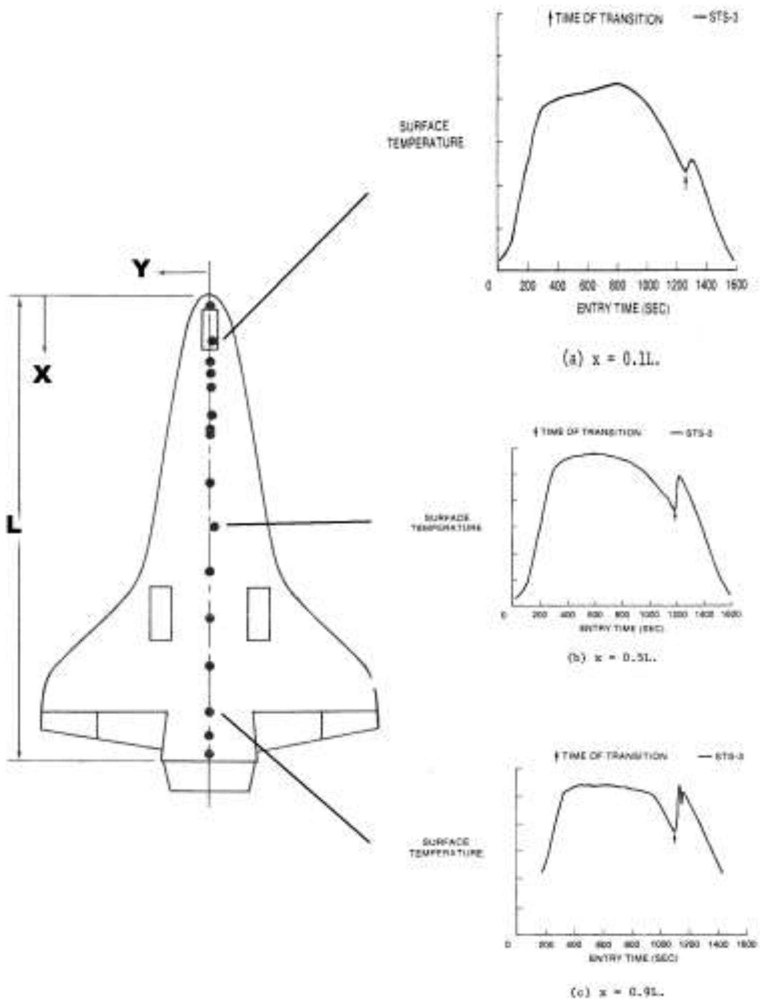
STS-1 Preflight Assessments

- Included Uncertainty and Trajectory Dispersions,
- +3 Sigma Boundary-Layer Transition Data
- NASA "Lost Tile" Analysis
  - Ames Research Center Channel Nozzle Arc Jet Test
  - Johnson Space Center Thermal Analysis
  - Concluded There Was Enough Thermal Conduction to Prevent Local Structural Failure for a Single Lost Tile.

STS-3 Surface Temperature Data

- 96 Locations
  - 3 shown
- Nominal BLT!

Note: Heading Rate is Proportional to Temp. Raised to the 4th Power

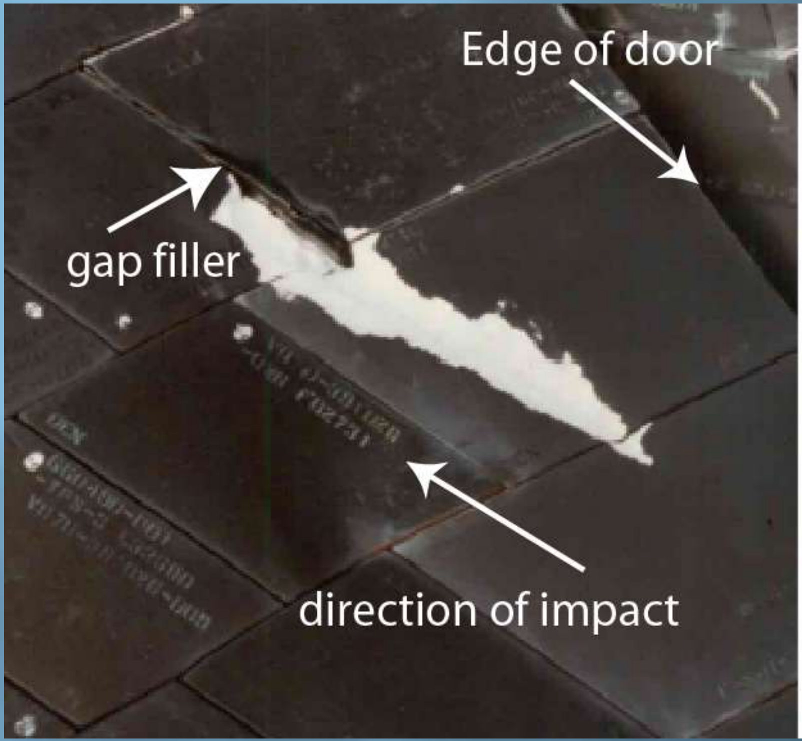


(a) x = 0.1L.

(b) x = 0.5L.

(c) x = 0.9L.

STS-1 Boundary Layer Transition



Nose Gear Door Gouge

12 in X 1 in X 1 in

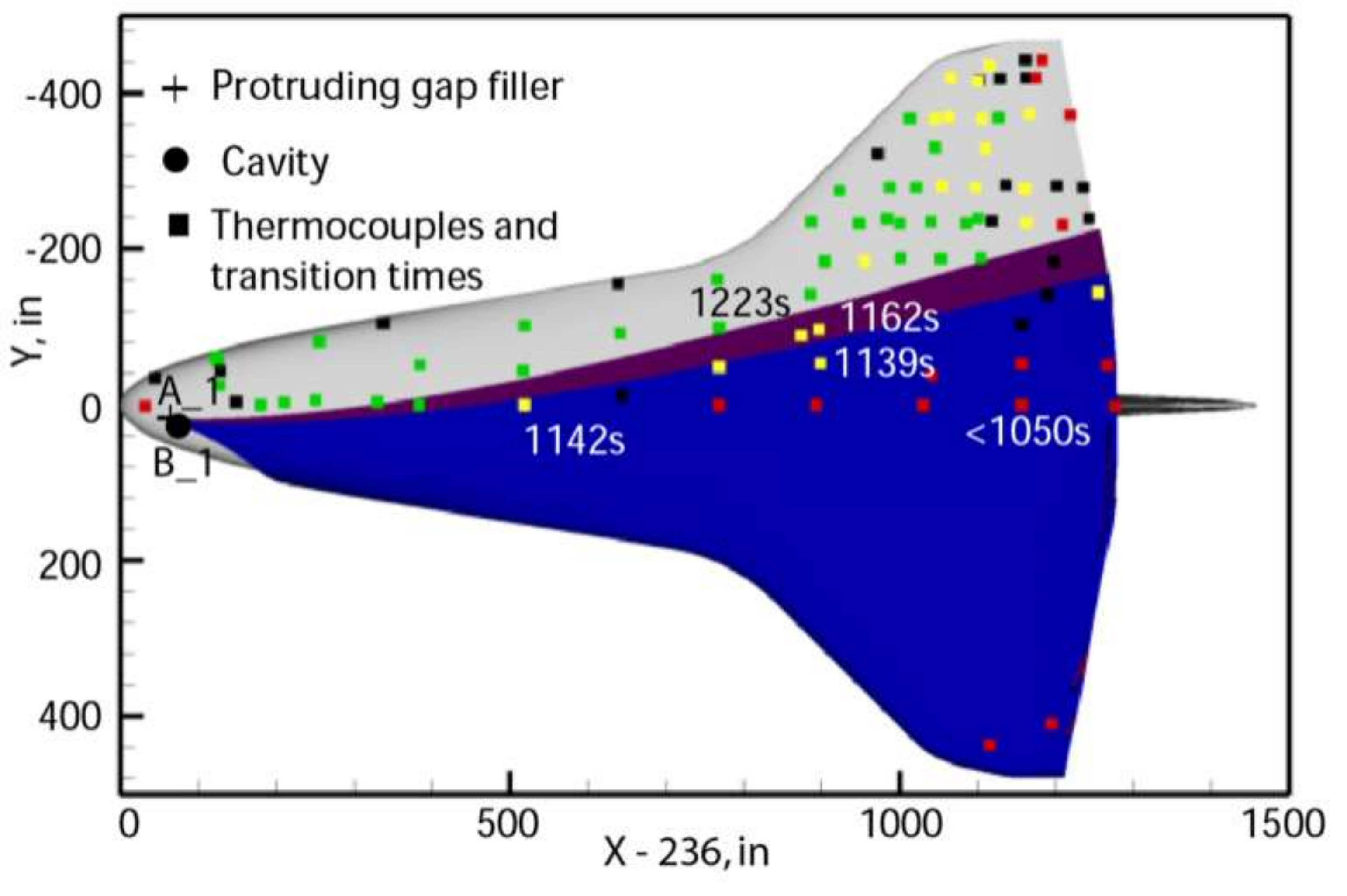
Displaced Gap Filler

Protruding About 0.4 In

From Ref. 17, by Dr. McGinley, et Al.

STS-1 & BLT Wedge Tool Comparison

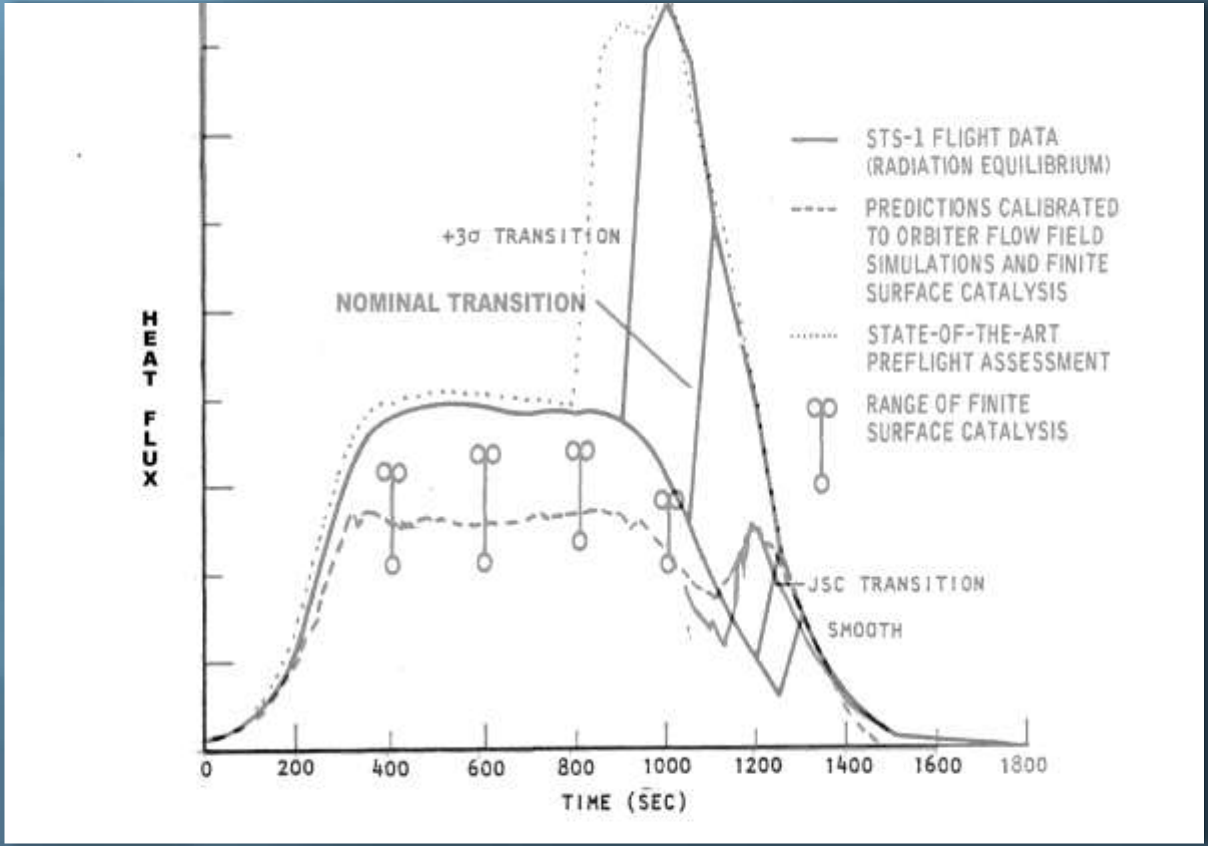
- Return to Flight Damage Assessment Tool



STS-1 Compared to Design

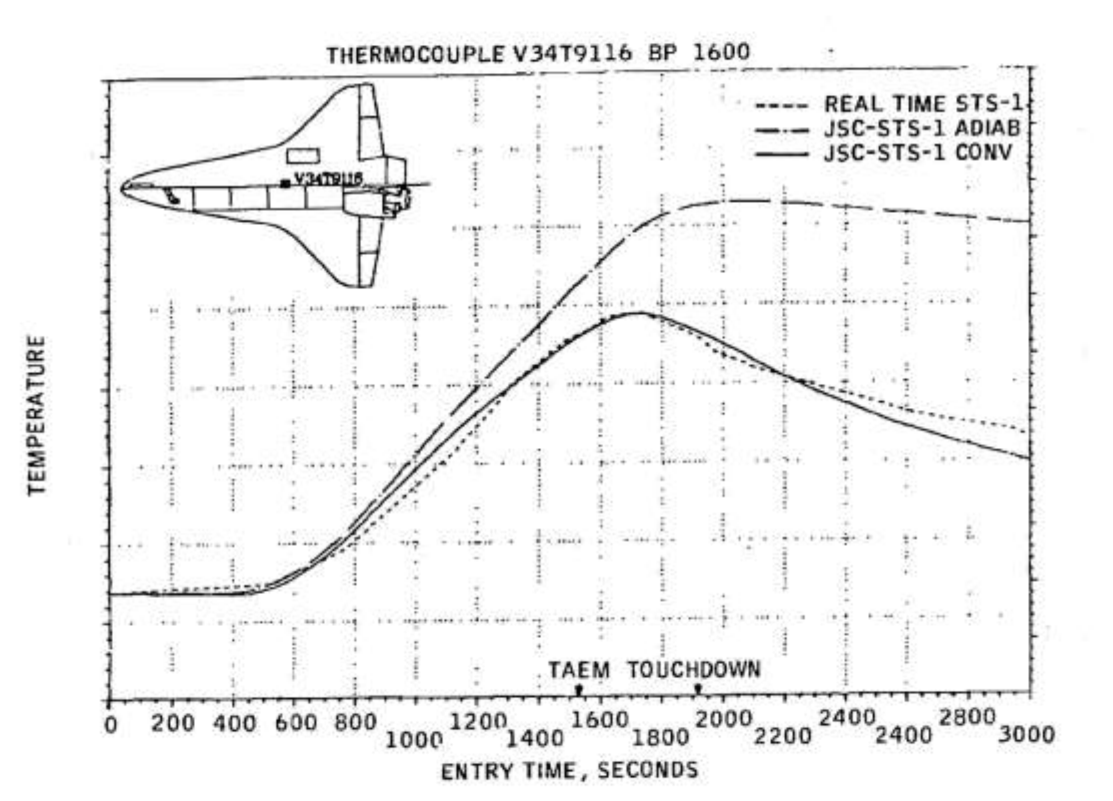
- Design (RI) Used Equilibrium Air – Fully Catalytic Surface Chemistry
- Wind Tunnel Derived Boundary-Layer Transition (BLT)

X/L = 0.4,
Center Line



STS-1 Structural Thermal Response

- Convective Cooling Was Not Anticipated
- Not All Locations Benefit



TPS Tile Acreage Margin

- Windward Surface Structural Temperatures Were Recorded for Each Flight at 20 Locations
- STS-73, Early BLT Due to Protruding Gap Filler
  - About 105F of Margin
- STS-99, 28, 32, 48, 94, 102,
  - About 125F of Margin
- STS-27, Severe Damage During Ascent
  - 707 Tile Damage Sites, 298 Greater Than 1 Sq. In.
  - About 130F Margin (at Measurement Locations)
  - One Missing Tile Over an Antenna Cover
    - Tin Coating Was Hot Enough to Flow
    - Aluminum Was Hot Enough to Change the Anneal State
- OFT Flights
    - STS-1, Asymmetric BLT, About 135F of Margin
    - STS-4 & 5 Were Coolest, About 170F of Margin

TPS Margin Comments

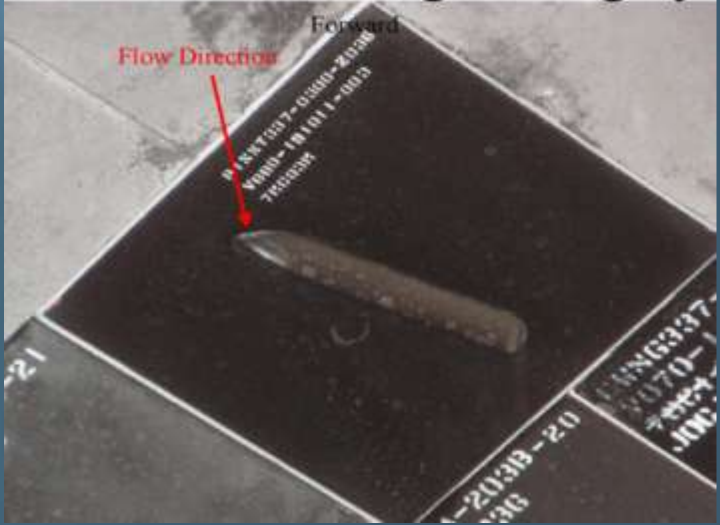
- Considerable Margin Existed in the Acreage Tile System
  - Operational Trajectories Were Slightly More Benign than Design
  - Design Used Conservative Boundary-Layer Transition Models
  - Tile RCG Coating is Almost Non Catalytic
    - Design Assumed Fully Catalytic
  - Convective Cooling is a Significant Effect in Most Locations – Not Anticipated During Design
- Note: Protruding Gap Fillers, Causing Early BLT Was Not Considered During Design
  - However, BLT Model Used For Design Had Similar Heating Effects, Without the Asymmetry

Boundary-Layer Transition DTO

- Motivated by the Two Protruding Gap Fillers During STS-114
- Designed to Obtain BLT Data With a Known Protuberance Height
- Flown 5 Times With 3 Different Protuberance Heights; 6.35 mm (0.25 in), 8.9 mm (0.35 in), 12.7 mm (0.5 in)
  - Data Agreed Well With Predictions of Transition Onset Time
  - Data Showed the Temperature Predictions Were Very Conservative – And Still Under Investigation

8.9 mm (0.35 in)
Protuberance

STS-131 Post Flight Imagery



Sept 27, 2011

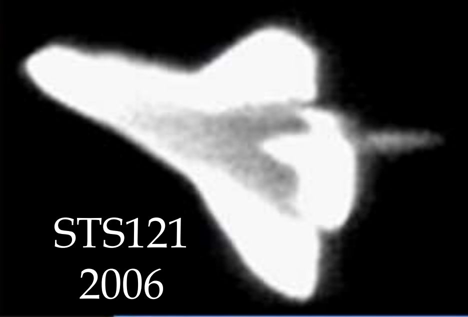
HYTHIRM SLIDES FOR FRED MARTIN AIAA 2011 SPACE CONFERENCE – SHUTTLE LEGACY SESSION

Hypersonic Thermodynamic Infrared Measurements

Thomas Horvath/LaRC

Jay Grinstead/ARC

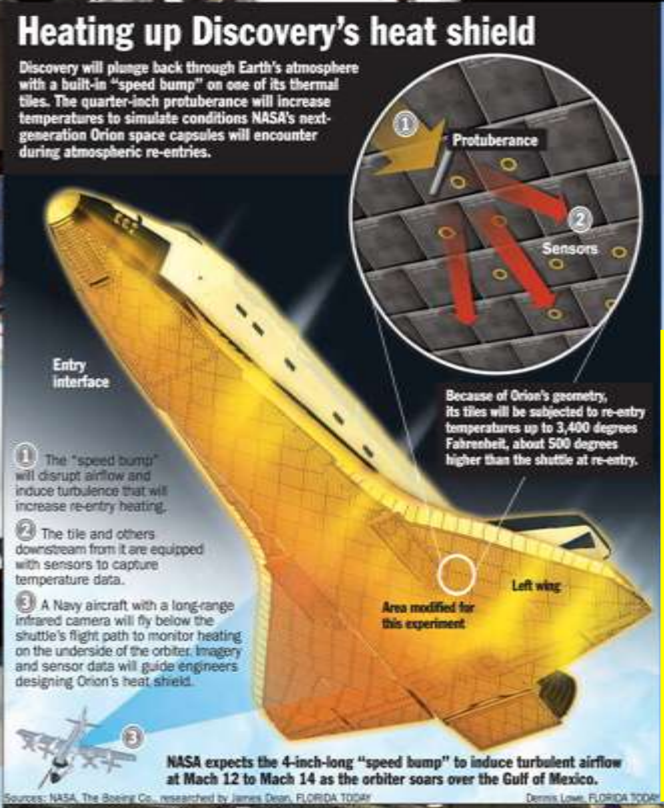

STS114
2005


STS121
2006


STS115
2006


2009


2009


Heating up Discovery's heat shield

Discovery will plunge back through Earth's atmosphere with a built-in "speed bump" on one of its thermal tiles. The quarter-inch protuberance will increase temperatures to simulate conditions NASA's next-generation Orion space capsules will encounter during atmospheric re-entries.

① The "speed bump" will disrupt airflow and induce turbulence that will increase re-entry heating.

② The tile and others downstream from it are equipped with sensors to capture temperature data.

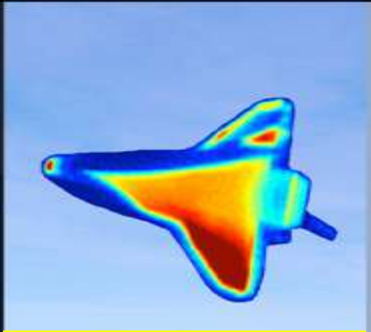
③ A Navy aircraft with a long-range infrared camera will fly below the shuttle's flight path to monitor heating on the underside of the orbiter. Imagery and sensor data will guide engineers designing Orion's heat shield.

Because of Orion's geometry, its tiles will be subjected to re-entry temperatures up to 3,400 degrees Fahrenheit, about 500 degrees higher than the shuttle at re-entry.

NASA expects the 4-inch-long "speed bump" to induce turbulent airflow at Mach 12 to Mach 14 as the orbiter soars over the Gulf of Mexico.

Sources: NASA, The Boeing Co., researched by James Dean, FLORIDA TODAY

Dennis Lowe, FLORIDA TODAY




2007

Success Criteria: To obtain spatially resolved infrared imagery that will provide a quantified surface temperature map of the Shuttle during hypersonic re-entry


2007

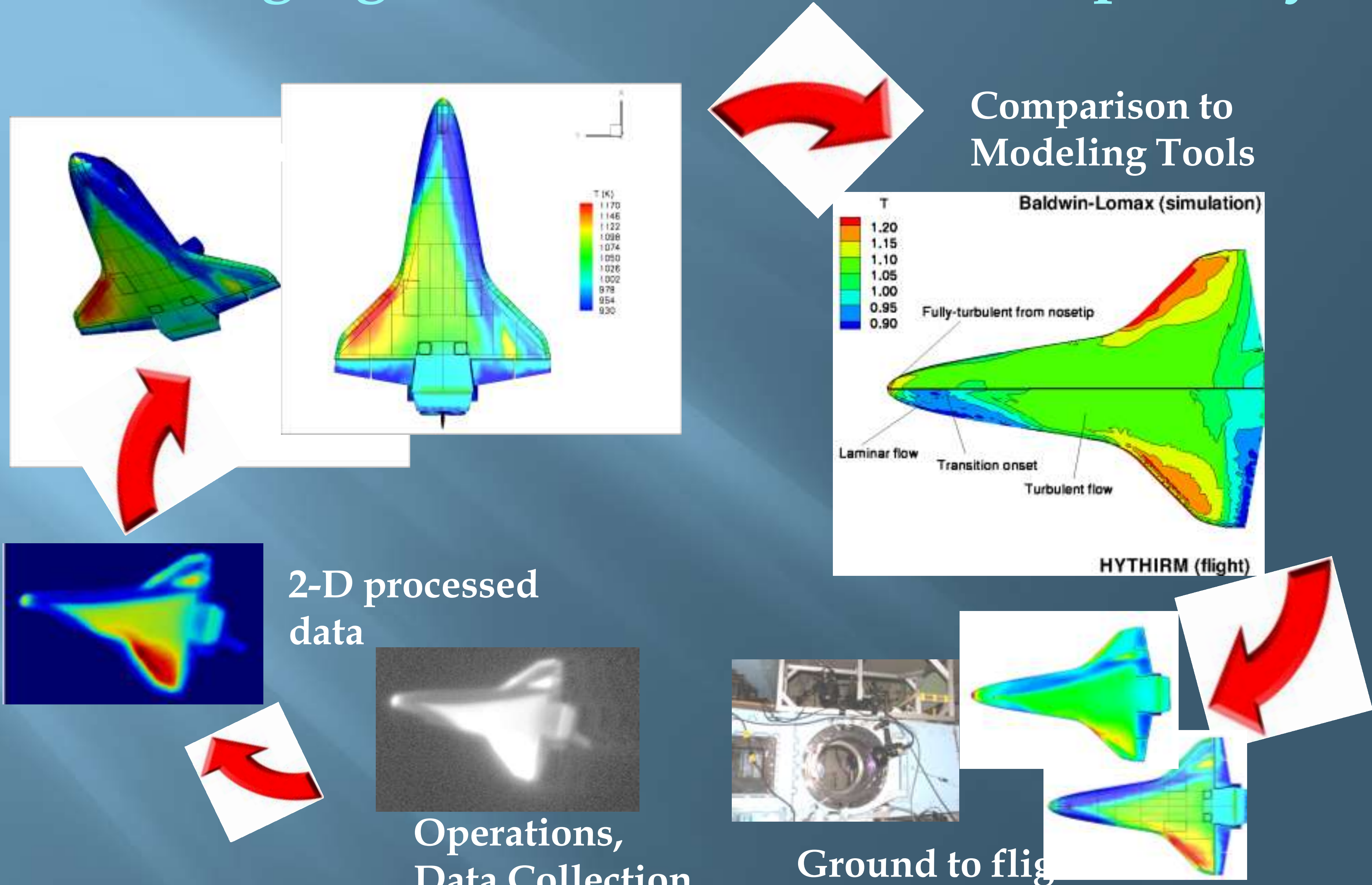

2009


2009


2008


2007

An Emerging Thermal Assessment Capability



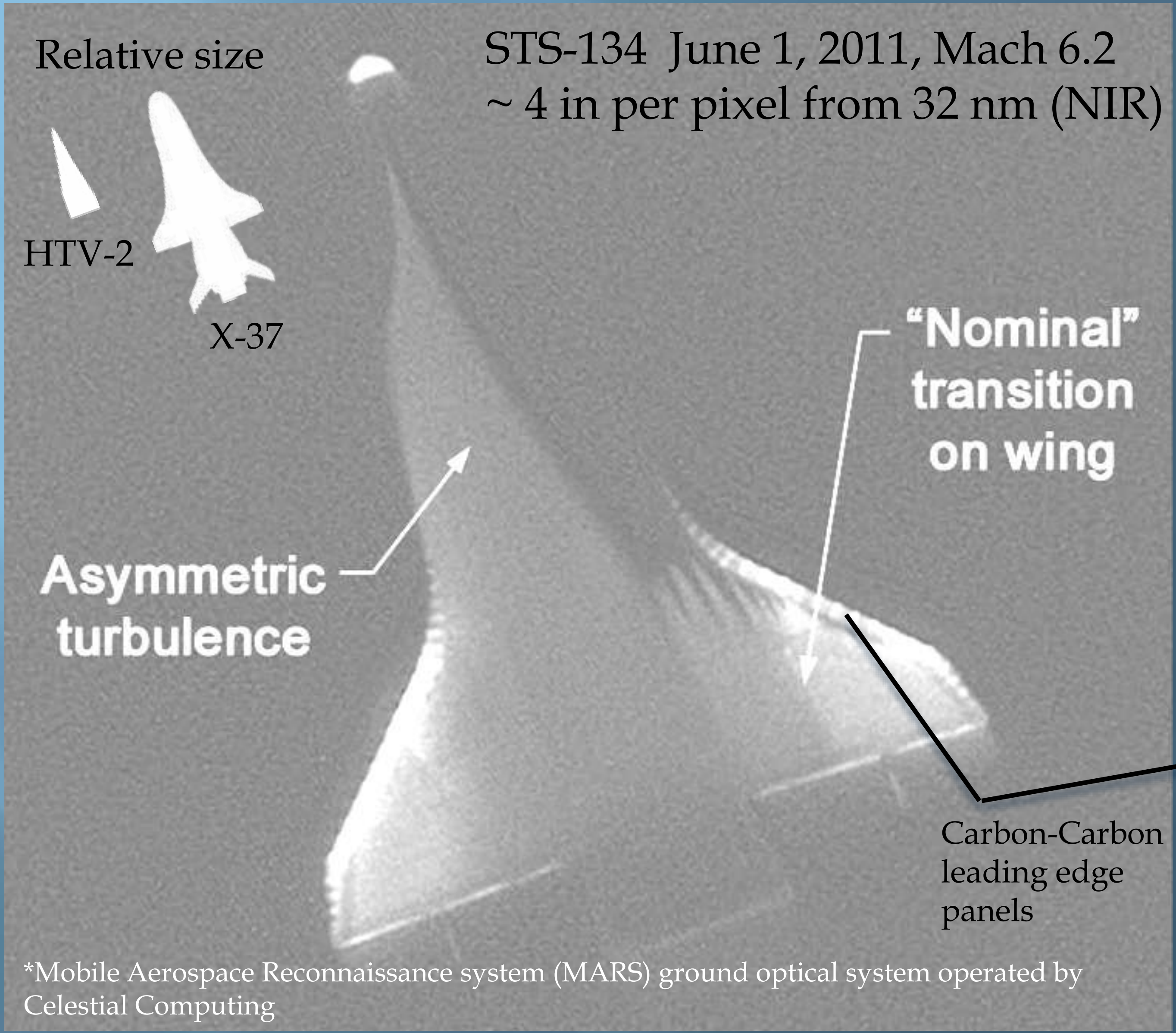
Comparison to Modeling Tools

2-D processed data

Operations, Data Collection & Calibration

Ground to flig extrapolation

Spatial Resolution is a Necessity



STS-134 June 1, 2011, Mach 6.2
~ 4 in per pixel from 32 nm (NIR)

*Mobile Aerospace Reconnaissance system (MARS) ground optical system operated by Celestial Computing

HYTHIRM and MARS* collaboration

On-orbit photo of Shuttle

The Orbiter is a LARGE target!

Space Shuttle Program Issues Motivated Development of Analysis Capability

- STS-1 Hypersonic Pitching Moment
  - LAURA CFD Code by Dr. Peter Gnoffo
- Orbiter On Orbit Plume Impingement
  - Direct Simulation Monte Carlo Methods for Rarefied Flows – DAC Code by Jay LeBeau
- Launch Vehicle Transonic Aerodynamic Issues
  - Chimera Grid Scheme, F3D CFD Code by Dr. Joe Steger
  - OVERFLOW CFD code by Dr. Pieter Buning
- TPS Damage Assessment Tools for Flight Support
  - Hypersonic Flow Field Codes: LAURA, DPLR

Acknowledgements

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- Dr. Chuck Campbell/JSC
- Mr. Gerald LeBeau/JSC
- Mr. Steve Derry/JSC
- Mr. Reynaldo Gomez/JSC
- Dr. Georgi Ushev/Boeing
- Dr. Catherine McGinley/LaRC
- Dr. Tom Horvath/LaRC

LEGACY

“That Which is Left to Future Generations”

- Thirty Years of Experience with the First Reusable Thermal Protection System
- Hypersonic Data - National Asset
  - Orbiter Flight Test (OFT) Data
  - Boundary Layer Transition DTO
  - HYTHIRM
  - Orbiter Vehicle Surface Geometry Scans for Future CFD Analysis
- Incredible Improvement in Analysis Capability
  - Motivated by Space Shuttle Issues
  - 10 Orders of Magnitude improvement in Computing Capability During the 30+ Years!
    - Transonic Ascent Issues, Entry Issues, Debris Damage Assessment, Internal Flows
  - Computational Fluid Dynamics
    - LAURA, OVERFLOW, DPLR, codes
  - Direct Simulation Monte Carlo methods
    - DAC Code for Rarefied Flows
- Personnel with 30+ Years of Experience