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...
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
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
- Compounding of Conservatism from Each Group!
- Ablator used on Lee Side
  - Due to Large Uncertainties
- Factor of 2 Over Design for Operational Missions Except Windward Torus – Structure Reached Design Temperature of 589K (600F)
Space Shuttle Thermal Protection System Design Goals

- Efficient, Reusable, Minimum Weight TPS
- 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 Nominal Trajectory, Nominal Heating Rates, Nominal Material Properties, & Aerodynamic Smooth Surface
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
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
“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
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.
96 Locations
- 3 shown
Nominal BLT!

Note: Heating Rate is Proportional to Temp. Raised to the 4th Power
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.
Return to Flight Damage Assessment Tool
- Design (RI) Used Equilibrium Air – Fully Catalytic Surface Chemistry
- Wind Tunnel Derived Boundary-Layer Transition (BLT)

\[ X/L = 0.4, \text{ Center Line} \]
Convective Cooling Was Not Anticipated

Not All Locations Benefit
Windward Surface Structural Temperatures Were Recorded for Each Flight at 20 Locations

STS-73, Early BLT Due to Protruding Gap Filler
- About 105°F of Margin

STS-99, 28, 32, 48, 94, 102,
- About 125°F of Margin

STS-27, Severe Damage During Ascent
- 707 Tile Damage Sites, 298 Greater Than 1 Sq. In.
- About 130°F 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 135°F of Margin
- STS-4 & 5 Were Coolest, About 170°F of Margin
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
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
HiThIRM SLIDES FOR FRED MARTIN
AIAA 2011 SPACE CONFERENCE – SHUTTLE LEGACY SESSION

Thomas Horvath/LaRC
Jay Grinstead/ARC

HiThIRM
Hypersonic Thermodynamic InfraRed Measurements
NASA Langley Research Center
Success Criteria:
To obtain spatially resolved infrared imagery that will provide a quantified surface temperature map of the Shuttle during hypersonic re-entry.
2-D processed data

Operations, Data Collection & Calibration

Comparison to Modeling Tools

Ground to flight extrapolation

An Emerging Thermal Assessment Capability

11/15/2011
Spatial Resolution is a Necessity

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

HYTHIRM and MARS* collaboration

Relative size

Asymmetric turbulence

“Nominal” transition on wing

Carbon-Carbon leading edge panels

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

The Orbiter is a LARGE target!
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
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- 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