Base Heating Test: Environments and Base Flow Physics

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Motivation and Focus

- Not able to generate accurate Space Launch System (SLS) base heating design environments without ground test due to:
  - Historic semi-empirical models based on different aft configurations (e.g. Shuttle, Saturn) than SLS
  - Lack of analytical solutions to predict such complex flow physics

- NASA MSFC and CUBRC developed a 2% scale SLS propulsive wind tunnel test program\(^1,2\) to obtain base heating test data during ascent.
  - Such a test program has not been conducted in 40+ years since the Shuttle Program
  - Dufrene et al paper\(^3\) described the operation, instrumentation type and layout, facility and propulsion performance, test matrix and conditions and some raw test results.

- This paper focuses on the SLS base flow physics and environment results being used to design the thermal protection system (TPS).
RSRMV = reusable solid rocket motor – 5 segment
BHS = base heat shield
EMHS = engine mounted heat shield
BSM = booster separation motor
BT = boat tail
SLS Mission Profile

**Max Q**
Altitude ~47 kft
Mach No. ~2

**Max Boost Stage G**
Altitude ~106 kft
Mach No. ~4

**LAS/ESM Jettison**
Altitude ~277 kft
Mach No. ~7

**MECO**
Altitude ~526 kft
Mach No. ~29

**SRB Separation**
Altitude ~149 kft
Mach No. ~4

**Max Core Stage G**
Altitude ~489 kft
Mach No. ~27

**Payload Separation**
Altitude ~526 kft
Mach No. ~29

**Booster Stage Impact**

**Core Stage Impact**

*Not to Scale*
All values are approximate

Provided by Terry Schmitt (EV42)

www.nasa.gov/sls
Base Flow Physics

Highly over-expanded RS-25 Plumes
- Freestream Entrainment
- Mach Disc NO Plume-Plume Interaction
- Entrained Jet

Moderate under-expanded RS-25 Plumes
- Freestream Entrainment
- Entrainment
- Low Plume-Plume Interaction
- Entrained Jet
- Updraft Plume

Highly under-expanded RS-25 Plumes
- Freestream
- Recirculation Zone
- Wall Jet
- Updraft Plume
- High Plume-Plume Interaction
- Unsteady Recovery Shock
- Shear Layer
- Boundary Layer Flow
- PIFS Afterburning
- Jet Shock
- Shear Layer

Aspiration Regime
Transition Regime
Recirculation Regime

Mehta et al (2013)
Edney Shock-Shock Type I Interaction

Reflected Shocks
(forms a fan)

Core and Booster Plume
Interaction Region

Base Periphery Stagnation
Region

EMHS Stagnation
Region

Edney Shock-Shock Type I
Interaction Point

Base Stagnation Region

Reflected Shock Fan

Base Flow

Core Plume Flow

Wall Jet

SRB Plume Flow

Full-Stack Configuration
BHS Heating Contour Plots

70 kft (I)

131 kft (III)

106 kft (IIa)

156 kft

121 kft (II)

211 kft (IV)

\[
\frac{\dot{q}_c, \text{base}}{\dot{q}_\text{arbitrary}} = \begin{cases} 
1.3 & \text{if } \dot{q}_c, \text{base} > \dot{q}_\text{arbitrary} \\
0.9 & \text{if } \dot{q}_c, \text{base} = \dot{q}_\text{arbitrary} \\
0.5 & \text{if } \dot{q}_c, \text{base} < \dot{q}_\text{arbitrary} \\
0.1 & \text{if } \dot{q}_c, \text{base} = 0 \\
\end{cases}
\]
EMHS Heating Contour Plots

70 kft (I)

106 kft (II)

121 kft (II)

131 kft (III)

156 kft

211 kft (IV)

\[ \frac{\dot{q}_{c, \text{base}}}{\dot{q}_{\text{arbitrary}}} \]

0.1

0.5

0.9

1.3
Base Pressure Spatial Profiles

1\textsuperscript{st} Regime (70 kft)

2\textsuperscript{nd} Regime
(121 kft)

3\textsuperscript{rd} Regime
(130 kft)

4\textsuperscript{th} Regime
(211 kft)
Base Heating Spatial Profiles

1\textsuperscript{st} Regime

Nominal Alt = 70 kft

\[ \dot{q}_{c, \text{base}} / \dot{q}_{\text{arbitrary}} \]

\[ x/De \]

2\textsuperscript{nd} Regime

Nominal Alt = 121 kft

\[ \dot{q}_{c, \text{base}} / \dot{q}_{\text{arbitrary}} \]

\[ X/De \]

3\textsuperscript{rd} Regime

Nominal Alt = 130 kft

\[ \dot{q}_{c, \text{base}} / \dot{q}_{\text{arbitrary}} \]

\[ x/De \]

4\textsuperscript{th} Regime

Nominal Alt = 182 kft

\[ \dot{q}_{c, \text{base}} / \dot{q}_{\text{arbitrary}} \]

\[ x/De \]
LWIR Imaging

H = 82 kft

H = 121 kft

H = 130 kft

H = 172 kft

LWIR Data
Low Temp

LWIR Data
Med Temp

Cameras Provided by D. Gaddy (ER43) and A. Kimberlin (ER24)
MWIR Imaging

H = 121 kft
MWIR Data

H = 182 kft
MWIR Data

Cameras Provided by D. Gaddy (ER43) and A. Kimberlin (ER24)
SLS and Shuttle Orbiter Base Configurations

- **ATA-002 SLS Core Base (Wind Tunnel)**

- **Space Shuttle Orbiter Base (STS-124)**

- **SLS RS-25 nozzle spacing within the base is about two times the spacing for the Shuttle Orbiter base**

Both images are to scale.
Base Pressure – Altitude Profile

Flight Normalized Base Pressure Environments

- SRB Transition Point (I)
- Core Transition Center Point (I)
- SRB Tail-off Effect (III)
- Peak Recirculation (II)
- SRB Sep
- Choked Flow (IV)

\[ P_b - P_\infty / P_{\text{arbitrary}} \]

Altitude (kft)

50 100 150 200

50 0 0.05 0.1

-0.15 -0.1 -0.05 0

BHS Center
SRB in-board
BHS Mid-Way
Base Heating – Altitude Profile: BHS Center

- Scaled test data, mean and mean + 1 sigma data profiles
- Mean data and prediction profiles
Base Heating – Altitude Profile: EMHS

- Scaled test data, mean and mean + 1 sigma data profiles
- Mean data and prediction profiles
Base Heating – Altitude Profile: SRB Base

- Scaled test data, mean and mean + 1 sigma data profiles
- Mean data and prediction profiles

Flight In-Board SRB Environment

\[ \frac{q_{c, base}}{q_{\text{arbitrary}}} \]

Altitude (kft)

- Transition Point (I)
- SRB Tail-off Effect (III)
- Shutdown Spike
- Peak Recirculation (II)
- Recirculation (IIa)
- Aspiration
Base Heating – Altitude Profile: RS-25 Nozzle

- Scaled test data, mean and mean + 1 sigma data profiles
- Mean data and prediction profiles
SLS Base Design Environment Methodology

1. Reynolds Scaling Analysis (m = 0.85)
2. ATA-002 Raw Test Data (from 50 to 211 kft)
   - Mean data based on averaging mirror gauges and removed dead gauges
3. Scaled Base Flight Mean Data
4. Uncertainty Analysis
   - Applied 1 Sigma and 1.0 UF
5. Verification of off-nom bounding data
6. Base Flight Data + Margin for Unique BP (50 kft to 211 kft)
   - Incorporate PEG Maneuver effect
   - Incorporate PTI Maneuver effects (1.05/1.09)
   - Aspiration and High-Altitude Models Incorporated
7. Design Environment (0 kft to 550 kft)
   - Incorporate CAPU
   - Verification of Environment
   - MINIVER (applied BSM Impingement + Shutdown Spike)
8. Plume radiation GASRAD
9. Base Flight Data + Margin (0 kft to 550 kft)
Base Heating Scaling Methodology

\[ \text{Nu}_b = C \text{Re}_b^m \text{Pr}_b^n \]

Assuming:
1. \( \text{Pr}_{\text{test}} = \text{Pr}_{\text{flight}} \) (O/F ratio matched)
2. \( T_{g,\text{test}} = T_{g,\text{flight}} \) (O/F ratio matched)
3. \( \left( \frac{P_{\text{lip}}}{P_\infty} \right)_{\text{test}} \approx \left( \frac{P_{\text{lip}}}{P_\infty} \right)_{\text{flight}} \)
4. \( P_{\text{base}} = k_2 P_c \) (Valid based on theory)

\[ \dot{q} \propto k_1 P_{b}^m D^{m-1} = k_1 k_2 P_{c}^m D^{m-1} \quad \text{(assuming} \quad P_{b} = k_2 P_{c}^l) \]

\[ \frac{\dot{q}_{\text{test}}}{\dot{q}_{\text{flight}}} \propto \left( \frac{P_{c,\text{test}}}{P_{c,\text{flight}}} \right)^m \left( \frac{D_{\text{test}}}{D_{\text{flight}}} \right)^{m-1} \]

\[ h_{\text{flight}} = \frac{\dot{q}_{\text{flight}}}{T_{r,\text{test}} - T_{w, \text{0}}^\circ F} \]

\( T_{r,\text{flight}} \sim T_{r,\text{test}} \rightarrow \text{TDLAS - Parker et al.} \text{ Paper}^6 \)

\[ h_{\text{flight}}, \frac{\dot{q}_{\text{conv,flight}}}{T_{r,\text{flight}}, \left( \frac{P_{\text{lip}}}{P_\infty} \right)_{\text{flight}}} \]

\[ \Rightarrow \dot{q}_{\text{conv,flight}} \]

\[ \Rightarrow \text{ATA-002 data scaled to flight conditions using classic Colburn scaling methodologies}^7 \]

Reynolds exponent is within a narrow band of values of 0.88 and 0.82

<table>
<thead>
<tr>
<th>Flow</th>
<th>m exponent</th>
<th>Re</th>
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</thead>
<tbody>
<tr>
<td>Incompressible*</td>
<td>0.844</td>
<td>1E5 – 1E9</td>
</tr>
<tr>
<td>Compressible**</td>
<td>0.883</td>
<td>1E5 – 1E9</td>
</tr>
<tr>
<td>Incompressible*</td>
<td>0.822</td>
<td>1E5 – 1E7</td>
</tr>
<tr>
<td>Compressible**</td>
<td>0.861</td>
<td>1E5 – 1E7</td>
</tr>
<tr>
<td>Re Scale Tests***</td>
<td>0.820</td>
<td>4E3 – 1E4</td>
</tr>
</tbody>
</table>

*Mean Value
**Karman-Schoenherr Skin Friction Law with Spalding and Chi Compressibility Correction
*** Difficult to estimate edge conditions and flow potentially tripped due to complex plume interactions

Recommend a mean Reynolds exponent (m) of 0.85 – most representative exponent for expected Re range
SLS Vehicle Maneuvers

SLS-10005 TD3H

ATA-002 Time Window

Post SRB Sep PEG (Powered Explicit Guidance)

Gimbal pattern – ATA-002 Data

PTI (Program Test Inputs)
**Design Environment: BHS Center**

- **Post-test and pre-test convective heating design environments**

- **Post-test and pre-test total heating design environments**

![Flight BHS Center Design Environment](chart1.png)

![Flight BHS Center Design Environment](chart2.png)
Design Environment: EMHS

- Post-test and pre-test convective heating design environments
- Post-test and pre-test total heating design environments
Design Environment: SRB Base

- Post-test and pre-test convective heating design environments
- Post-test and pre-test total heating design environments
Design Environment: RS-25 Nozzle

- Post-test and pre-test convective heating design environments
- Post-test and pre-test total heating design environments
Design Environment: Base Heat Load

- Heat load drives the TPS thickness and heating rate drives TPS type
- Highest heat load deviation from the pre-test environments are: BHS, EMHS in-board and RS-25 nozzle HB #3

<table>
<thead>
<tr>
<th>Base Regions</th>
<th>Normalized Values</th>
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<tbody>
<tr>
<td></td>
<td>Post-Test Heat Load</td>
</tr>
<tr>
<td>BHS Center</td>
<td>9.9</td>
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<tr>
<td>EMHS 45-deg In-Board (phi = 45 deg)</td>
<td>9.4</td>
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<tr>
<td>EMHS 45-deg In-Board (phi = 0 deg)</td>
<td>8.2</td>
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<tr>
<td>SRB In-Board Base</td>
<td>4.1</td>
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<tr>
<td>RS-25 In-Board Nozzle Lip</td>
<td>4.9</td>
</tr>
<tr>
<td>RS-25 In-Board Nozzle Hat-Band 3</td>
<td>10.0</td>
</tr>
</tbody>
</table>
Preliminary thermal assessment suggests that high EMHS heat loads leads to exceedance in the in-board thermal blanket temperature requirement.

High BHS heating rates and loads leads to higher TPS ablation as compared to pre-test environments.

Thermal Blanket

Attatch Brackets

Battens

EMHS

Pre-Test Heating

Post-Test Heating

BHS

Numerical Predictions

Max Thickness

TPS left at MECO

Min Thickness
Conclusions

- Successfully established a working theory of the flow physics and generated base heating design environments

- SLS base flow physics is dependent on:
  - Plume flow physics coupling between RSRMV and RS-25 plumes
  - RS-25 and RSRMV plume dynamics with freestream
  - RS-25 nozzle spacing
  - RSRMV proximity to base
  - RSRMV and RS-25 thrust profiles

- Design environments show highest heating rate and heat loads at the:
  - BHS
  - EMHS in-board
  - RS-25 nozzle base

- NASA and Boeing are currently working on SLS base TPS design


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