Base Heating Test:
Environments and Base Flow Physics

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Outline

◆ Motivation and Focus
◆ Base Flow Physics and Considerations
◆ Design Environment Method
◆ Base Heating Test Data
◆ Design Environments
◆ Conclusions
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 than SLS (e.g. Shuttle, Saturn)
  - Lack of analytical solutions to predict such complex flow physics

- NASA MSFC and CUBRC developed a 2% scale SLS hot fire wind tunnel test program\textsuperscript{1,2} to obtain ascent base heating test data.
  - Such a test program has not been conducted in 40+ years since the Shuttle Program
  - Dufrene et al paper\textsuperscript{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).
Base Heating Flow Regimes

Mullen et al (1972)
Base Flow Computational Fluid Dynamics

- Plume – Plume Interactions
- Stagnation Regions
SLS Mission Profile

Max Q
Altitude ~47 kft
Mach No. ~2

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

Launch
Altitude 0 kft
Mach No. 0.1

SRB Separation
Altitude ~149 kft
Mach No. ~4

Booster Stage Impact

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

MECO
Altitude ~526 kft
Mach No. ~29

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

Payload Separation
Altitude ~526 kft
Mach No. ~29

Core Stage Impact

Not to Scale
All values are approximate

Provided by Terry Schmitt (EV42)

Morris (2015)
SLS Vehicle and Base Region

BHS – Base Heat Shield
EMHS – Engine Mounted Heat Shield
SRB – Solid Rocket Booster
ATA-002 Wind Tunnel 2% Scale Model
SLS Base Design Environment Method

Test Matrix Based on Flight Trajectory

Reynolds Scaling

Aspiration and High Altitude Models

Plume Radiation

Trajectory Dispersions and Events

Core Auxiliary Power Unit Heating

Flight Design Environments
Unsteady Heat Transfer Data

Unsteady Heat Transfer Data, Run 27

Heat Flux Rate

Time (ms)

T85
T106
T75
TW2
$P_c$
Avg Window

$P_c$ (psia)

Heat Flux Rate

Time (ms)
Base Heat Shield Pressure Maps

Alt: 50 kft
Aspiration Flow

Alt: 69 kft
Transitional Flow

Alt: 107 kft
Recirculation Flow
Base Heat Shield Pressure Maps

- Alt: 121 kft
  Peak Recirculation Flow

- Alt: 131 kft
  Booster Tail Off

- Alt: 171 kft
  Choked Reverse Flow
Base Heat Shield Pressure Differential

ATA-002 Base Heat Shield Pressure Differential

\[ P_0 - P_{\infty} \text{ (psid)} \]

Altitude (kft)

- Base Center
- Periphery near SRM
- Periphery Vent
Base Heat Shield Heating Maps

Alt: 50 kft
Aspiration Flow

Alt: 69 kft
Transitional Flow

Alt: 107 kft
Recirculation Flow
Base Heat Shield Heating Maps

Alt: 121 kft
Peak Recirculation Flow

Alt: 131 kft
Booster Tail Off

Alt: 209 kft
Choked Reverse Flow
Long Wave Infrared Imaging

Cameras Provided by D. Gaddy (ER43) and A. Kimberlin (ER24)
Mid Wave Infrared Imaging

H = 121 kft
MWIR Data

H = 182 kft
MWIR Data

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

H = 121 kft
MWIR Data

H = 182 kft
MWIR Data

Cameras Provided by D. Gaddy (ER43) and A. Kimberlin (ER24)
Base Heating – Altitude Profile: BHS Center

Base Heat Shield Off-Nominal

Base Heat Shield Nominal

Heat Flux Rate vs. Altitude (kft)

- Curve Fit
- Nom
- T85 EO
- T85 G
- T85 AOA

Heat Flux Rate vs. Altitude (kft)

- Semi-Empirical Prediction
- Mean Mirrored Test Data
- T85
Engine Mounted Heat Shield Off-Nominal

Engine Mounted Heat Shield Nominal

- Curve Fit
- Nom
- T106 EO
- T108 EO
- T106 G
- T108 G
- T106 AOA
- T108 AOA

Semi-Empirical Prediction
Mean Mirrored Test Data
- T106
- T108

Altitude (kft)
Heat Flux Rate
Base Heating – Altitude Profile: Inboard SRB

Booster Aft Skirt Lip Aft Face Off-Nominal

Booster Aft Skirt Lip Aft Face Nominal

Heat Flux Rate vs Altitude (kft)

- Curve Fit
- Nom
- T121 EO
- T117 EO
- T121 G
- T117 G
- T121 AOA
- T117 AOA

Heat Flux Rate vs Altitude (kft)

- Semi-Empirical Prediction
- Mean Mirrored Test Data
- T121
- T117

www.nasa.gov/sls
Base Heating – Altitude Profile: RS-25 Nozzle

Core Stage Engine Nozzle Off-Nominal

Core Stage Engine Nozzle Nominal

[Graphs showing heat flux rate vs. altitude for both off-nominal and nominal conditions.]

www.nasa.gov/sls
Base Heating Scaling Method

For proper scaling, it’s important to match: \( Pr, \) \( T_c, \) \( T_r, \) \( \left( \frac{P_{lip}}{P_\infty} \right) \)

- \( Nu = C \, Re^m \, Pr^n \)
- \( Nu = \frac{hL}{k} \)
- \( \frac{hL}{k} \propto Re^m \, Pr^n \)
- \( Re = f(P, L) \)
- \( h \propto P_c^m \, L^{m-1} \)
- \( h_F = h_T \left( \frac{P_{c,F}}{P_{c,T}} \right)^m \left( \frac{L_F}{L_T} \right)^{m-1} \)
- \( \dot{q}_F = \dot{q}_T \left( \frac{P_{c,F}}{P_{c,T}} \right)^m \left( \frac{L_F}{L_T} \right)^{m-1} \)
SLS Vehicle Maneuvers

SLS-10005 TD3H

ATA-002 Time Window

ATA-002 Gimbal Test Runs
Design Environment: BHS Center

Flight Design Environment BHS Center

Convective Heat Flux Rate

Altitude (kft)

Total Heat Flux Rate

Altitude (kft)
Design Environment: Inboard EMHS

Flight Design Environment Inboard EMHS

Convective Heat Flux Rate vs. Altitude (kft)

Post Test vs. Pre Test

Flight Design Environment Inboard EMHS

Total Heat Flux Rate vs. Altitude (kft)

Post Test vs. Pre Test
Design Environment: Inboard Nozzle Lip

Flight Design Environment Inboard Nozzle Lip

Convective Heat Flux Rate

Altitude (kft)

0 20 40 60 80 100 120 140 160 180

Post Test
Pre Test

Flight Design Environment Inboard Nozzle Lip

Total Heat Flux Rate

Altitude (kft)

0 100 200 300 400 500

Post Test
Pre Test
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 SRB and RS-25 plumes
  - RS-25 and SRB plume dynamics with freestream
  - Base Configuration

- Design environments show highest heating rate and heat loads at the:
  - Base Heat Shield center
  - Inboard Engine Mounted Heat Shield

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


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