National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

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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

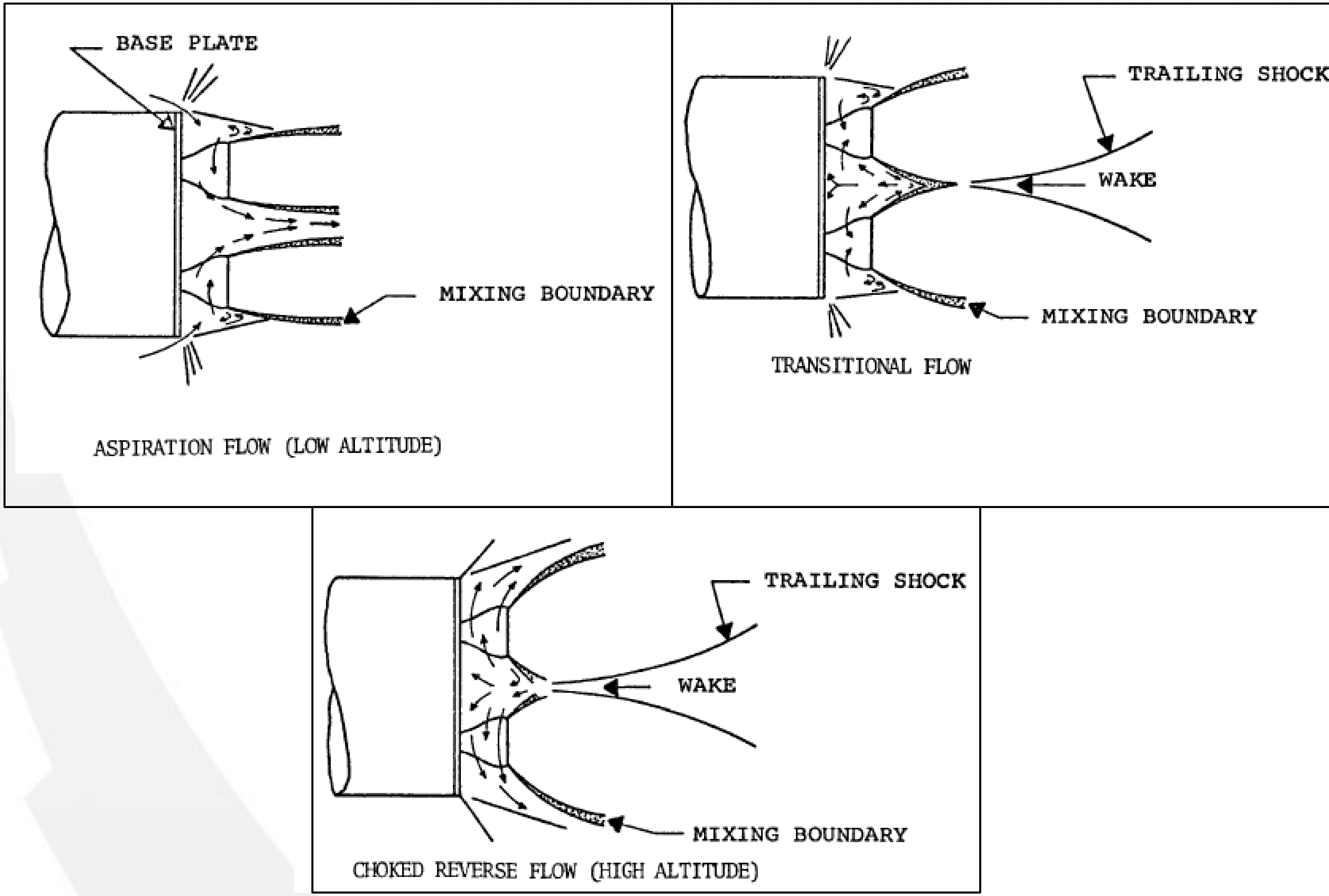
Motivation and Focus

- **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[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[3] described the operation, instrumentation type and layout, facility and propulsion performance, test matrix and conditions and some raw test results.

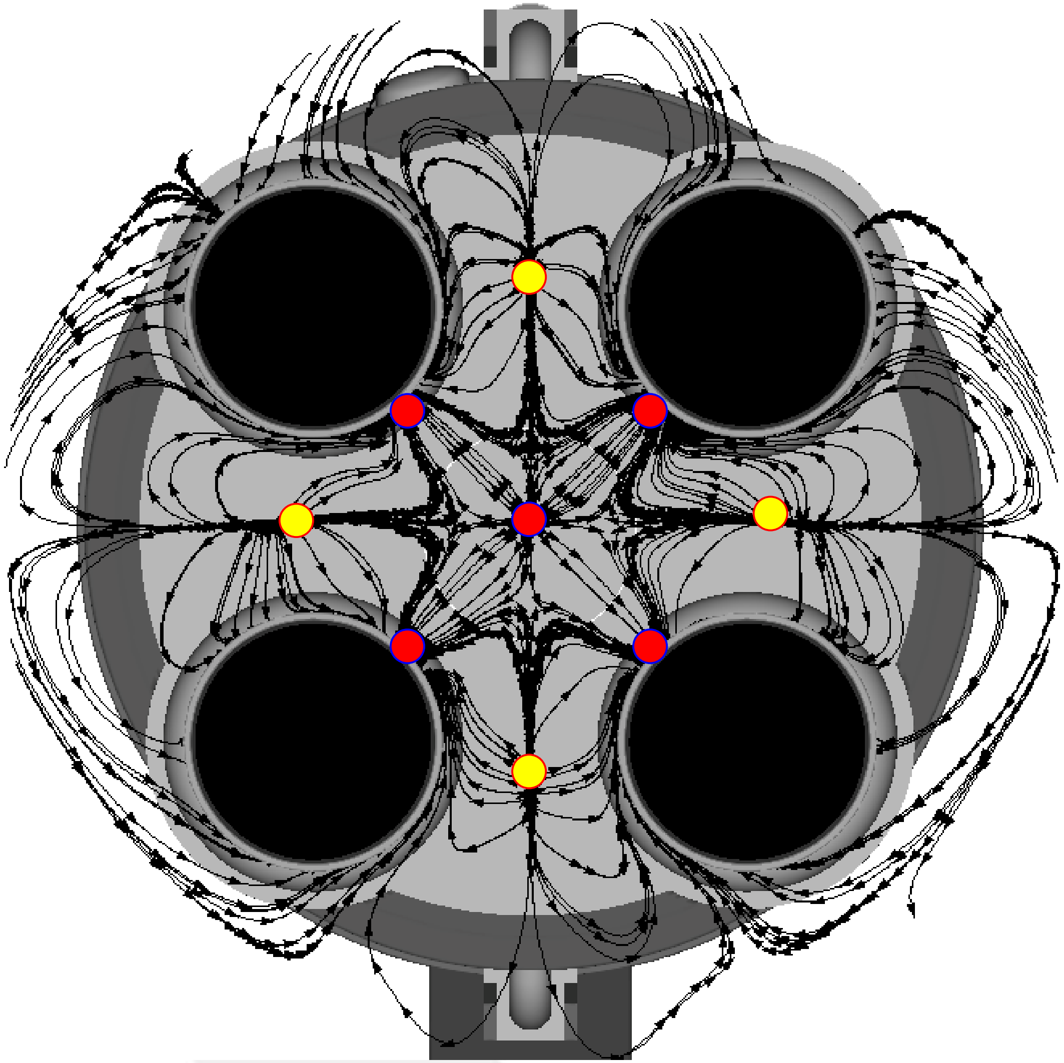
- **This paper focuses on the SLS base flow physics and environment results being used to design the thermal protection system (TPS).**

Base Heating Flow Regimes



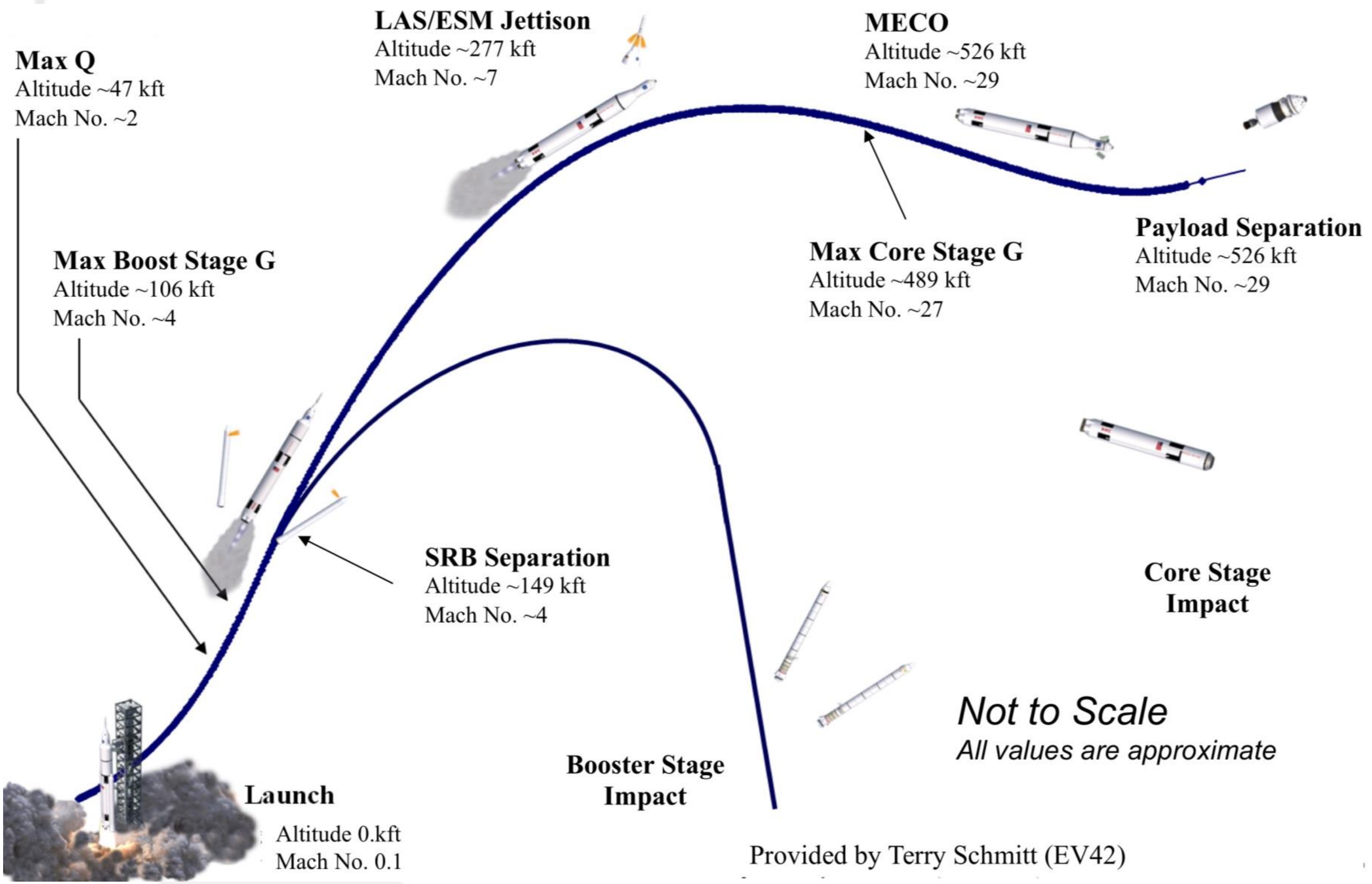
Mullen et al (1972)[8]

Base Flow Computational Fluid Dynamics

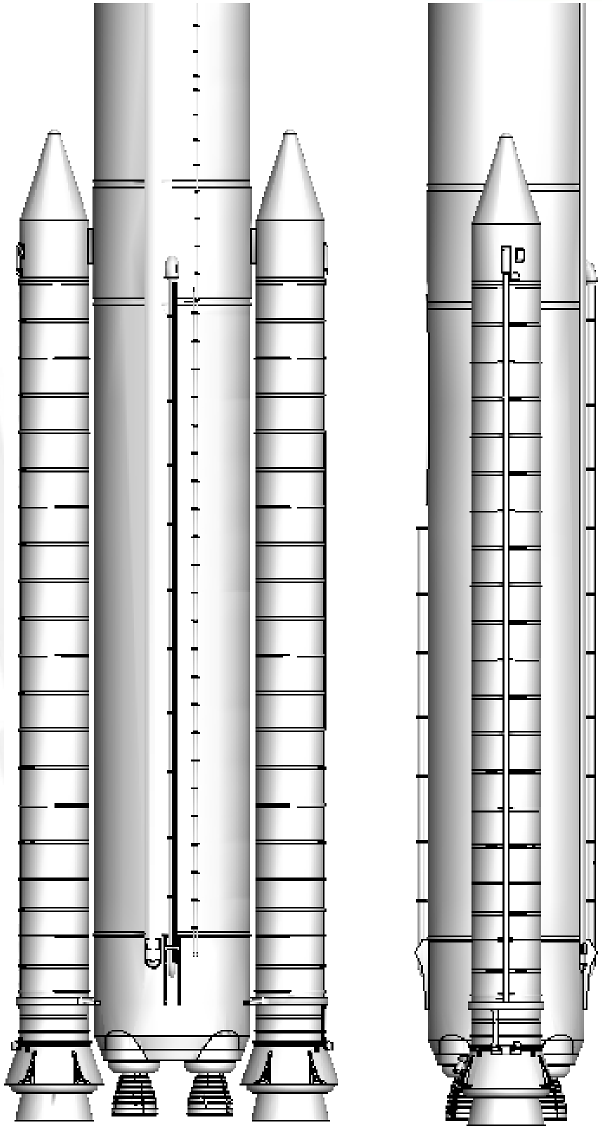


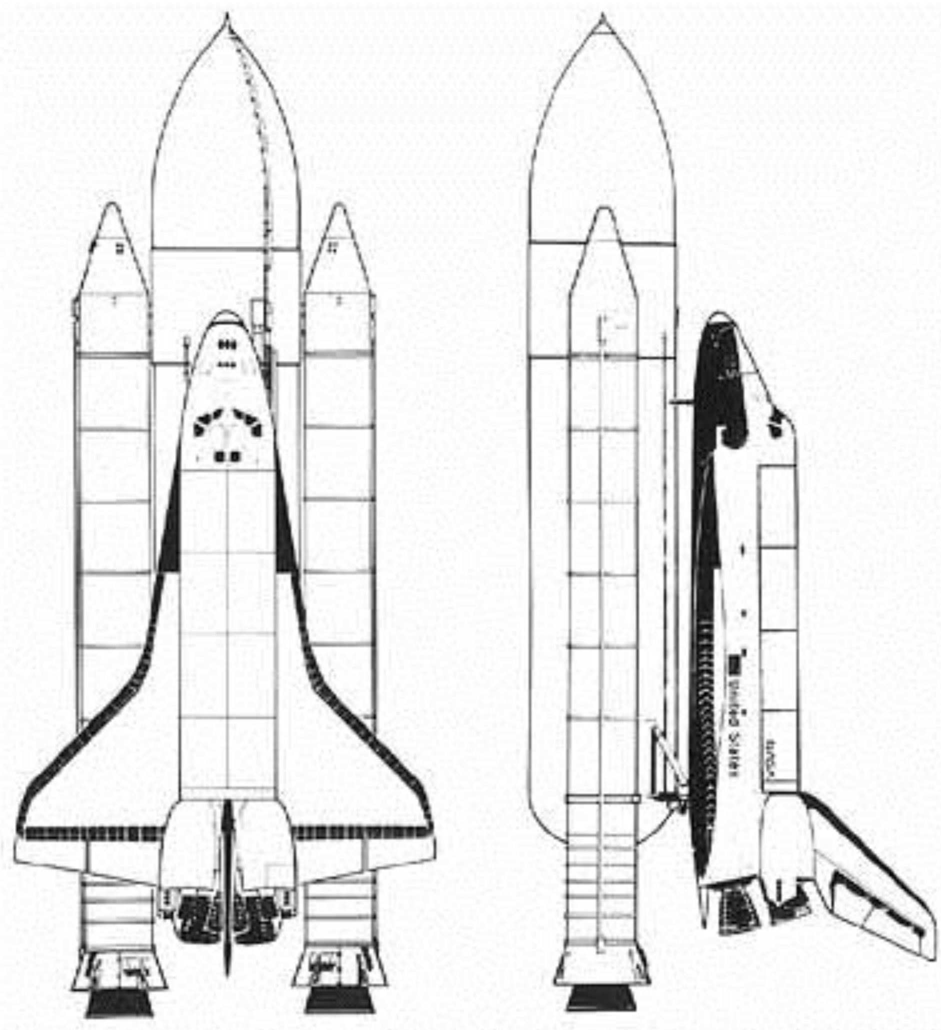
- Plume – Plume Interactions
- Stagnation Regions

SLS Mission Profile

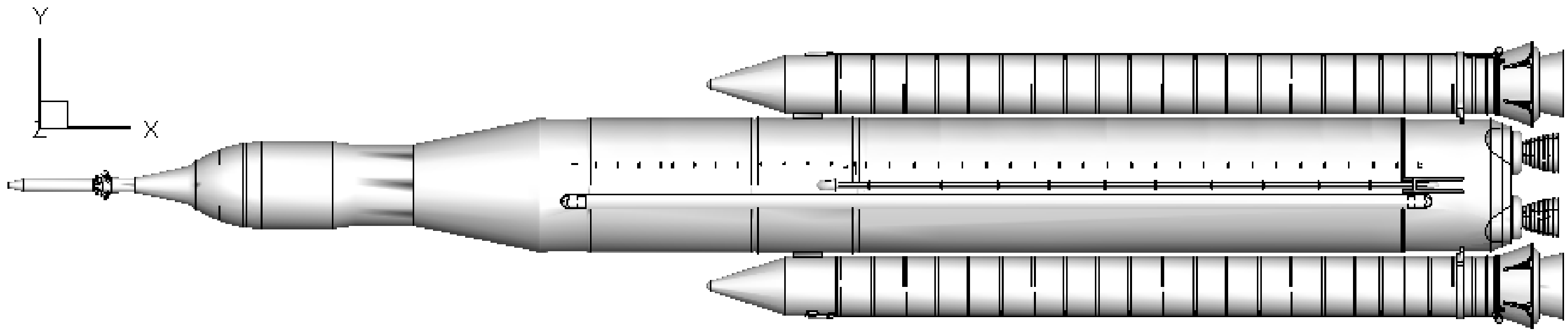


SLS vs Space Shuttle Base Configuration

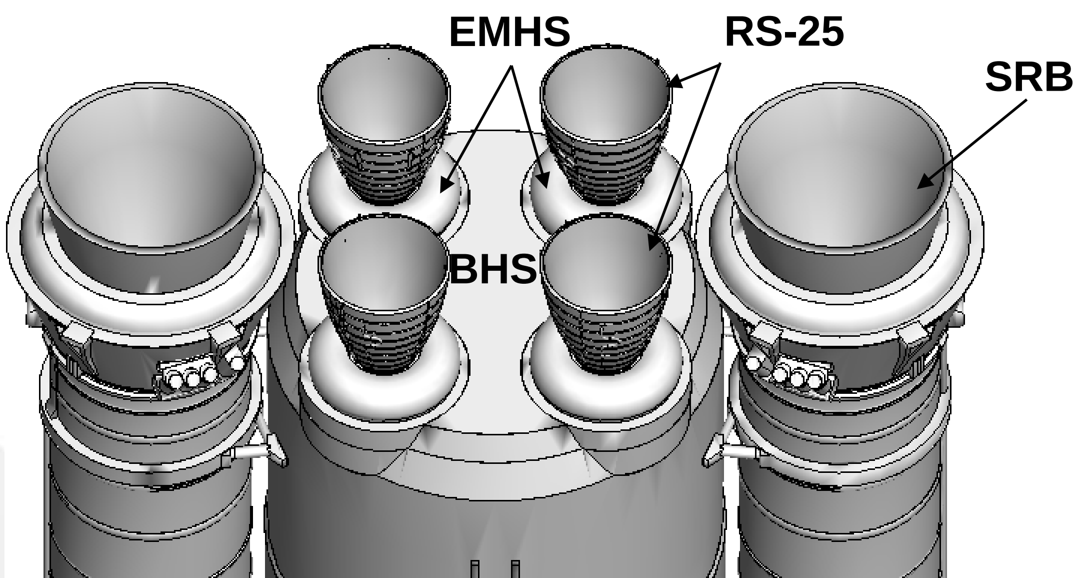




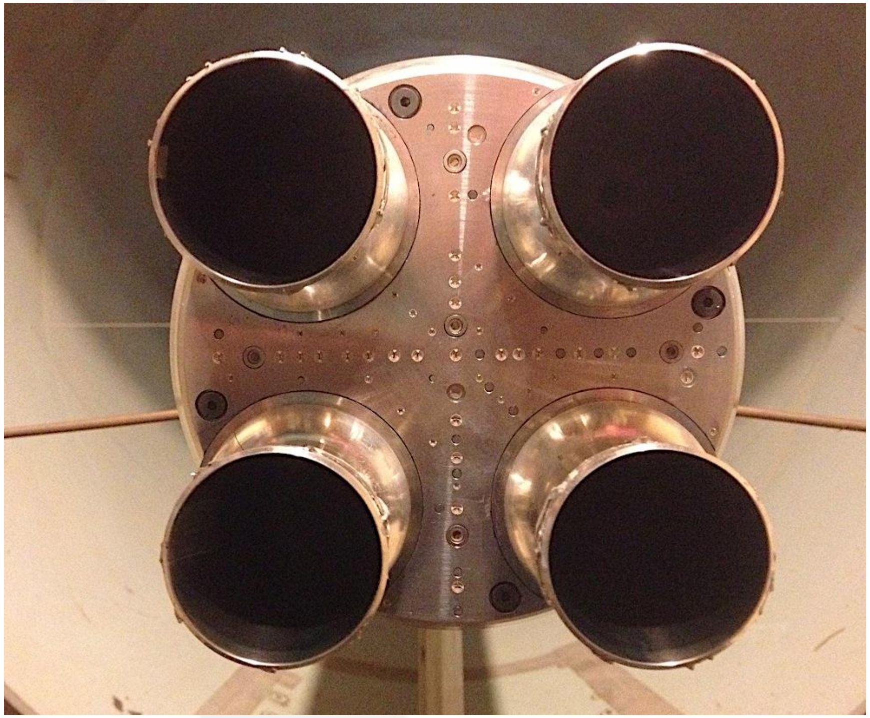
SLS Vehicle and Base Region

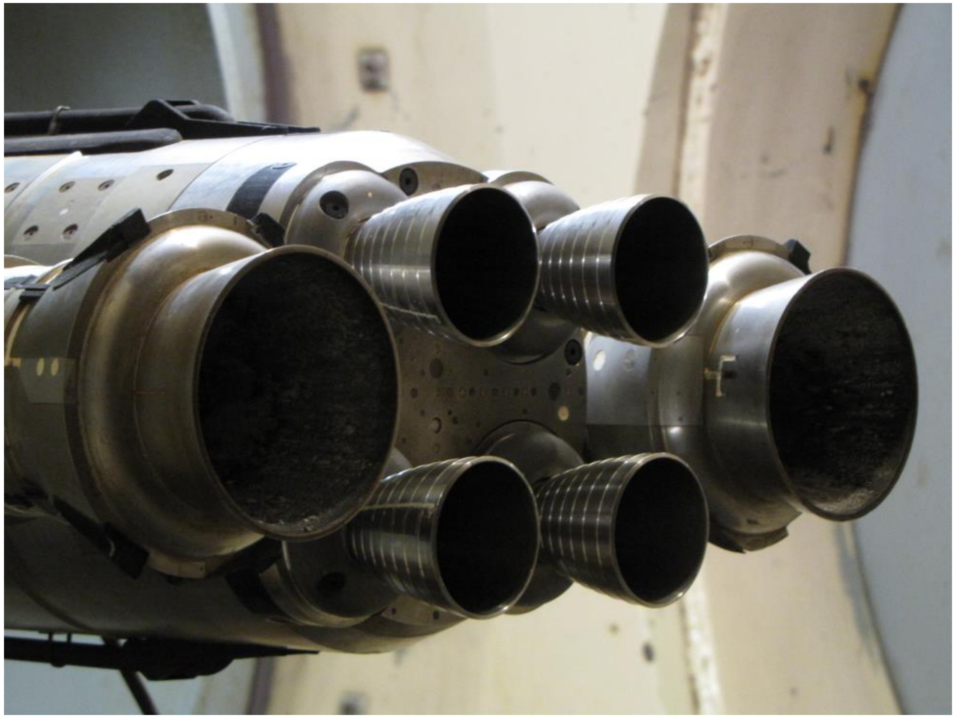


BHS – Base Heat Shield
EMHS – Engine Mounted Heat Shield
SRB – Solid Rocket Booster

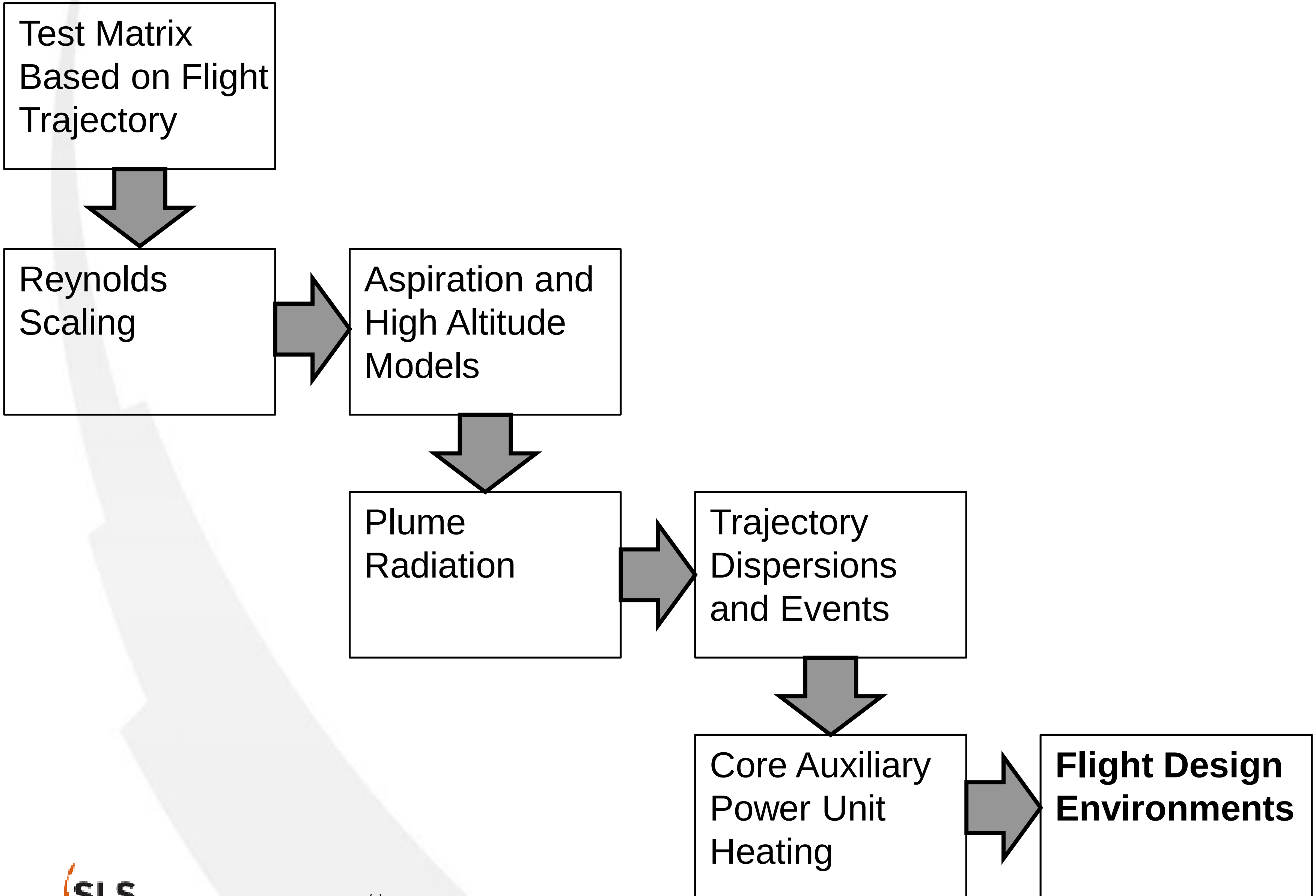


ATA-002 Wind Tunnel 2% Scale Model

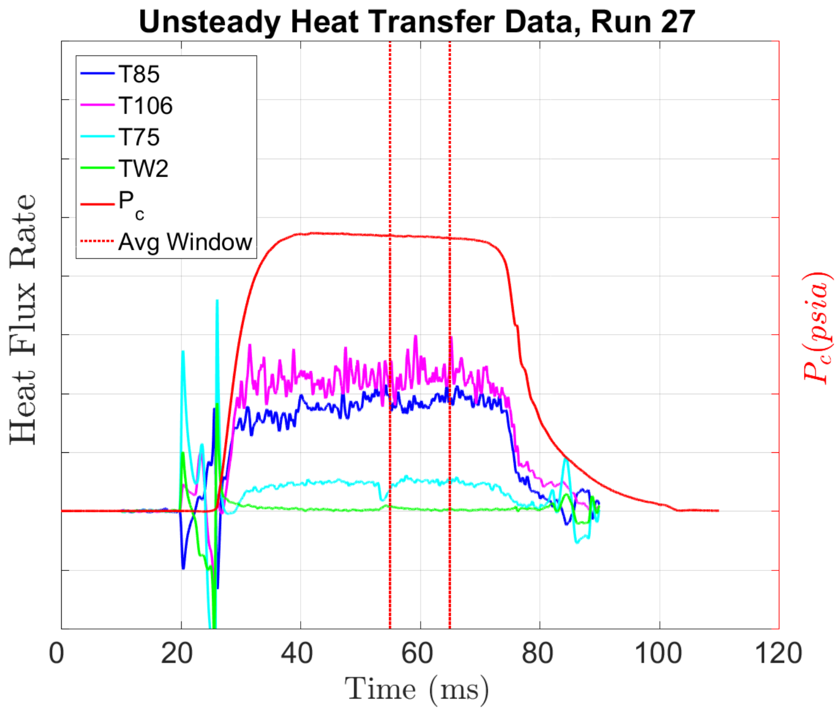


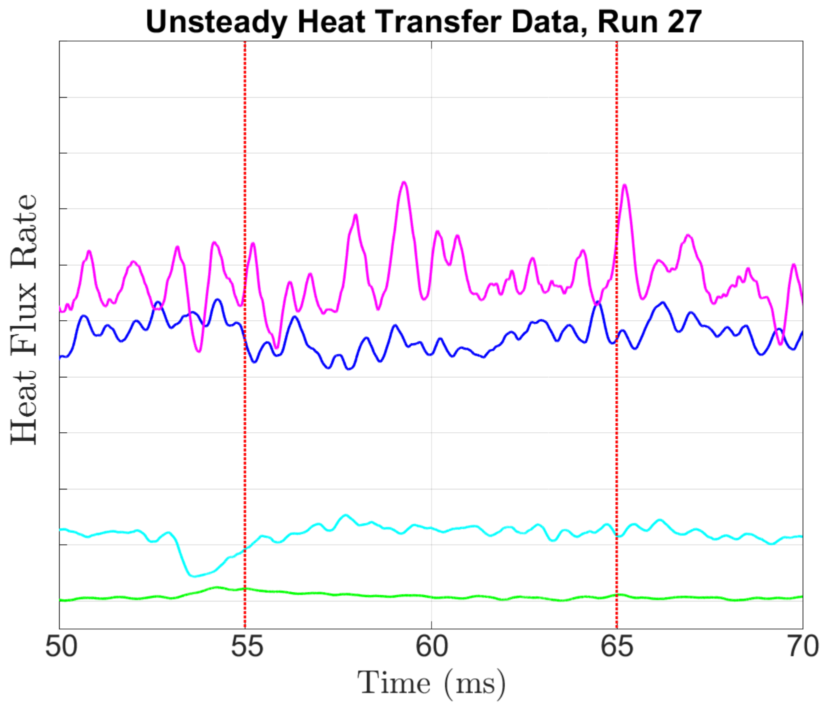


SLS Base Design Environment Method

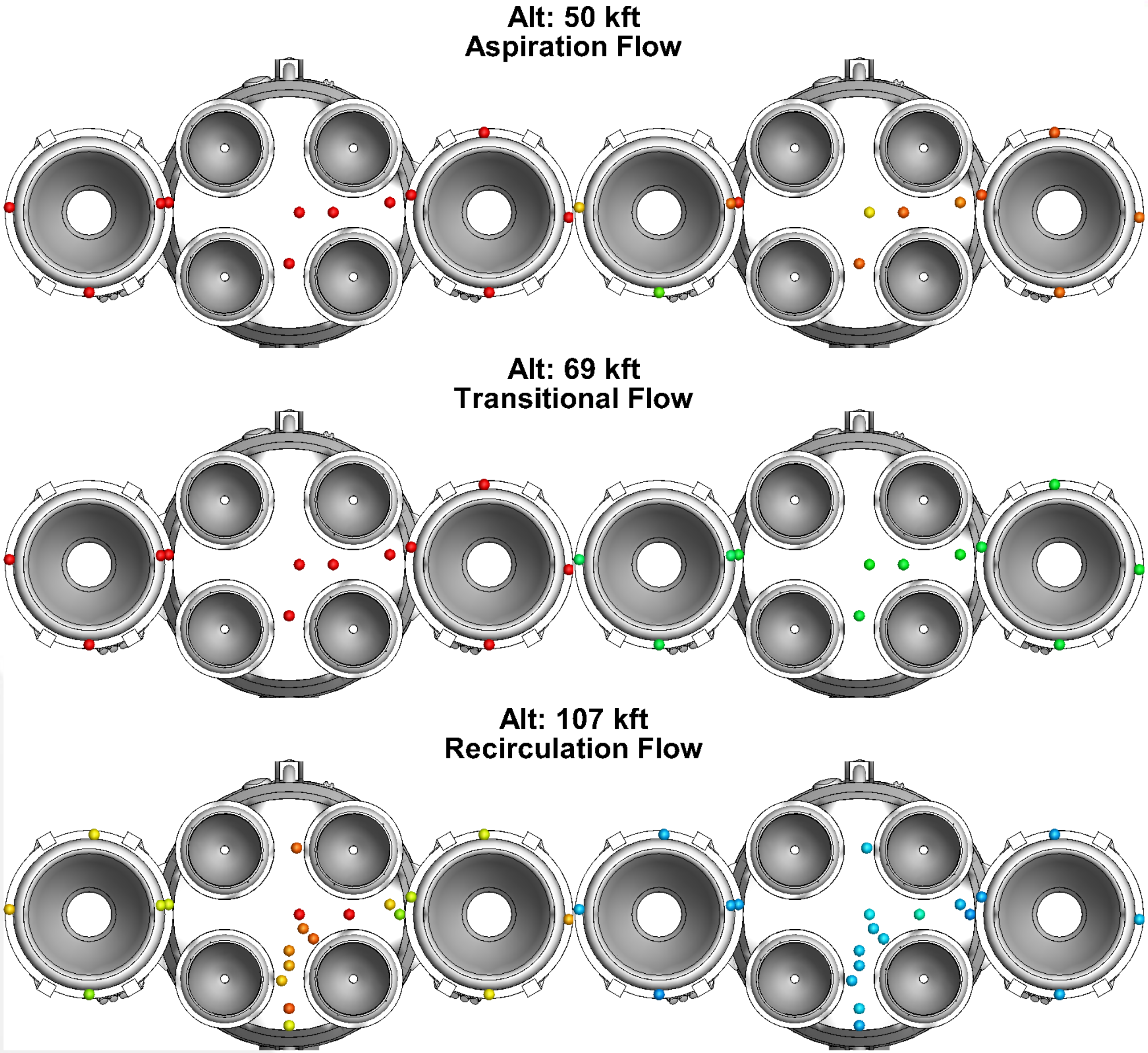


Unsteady Heat Transfer Data



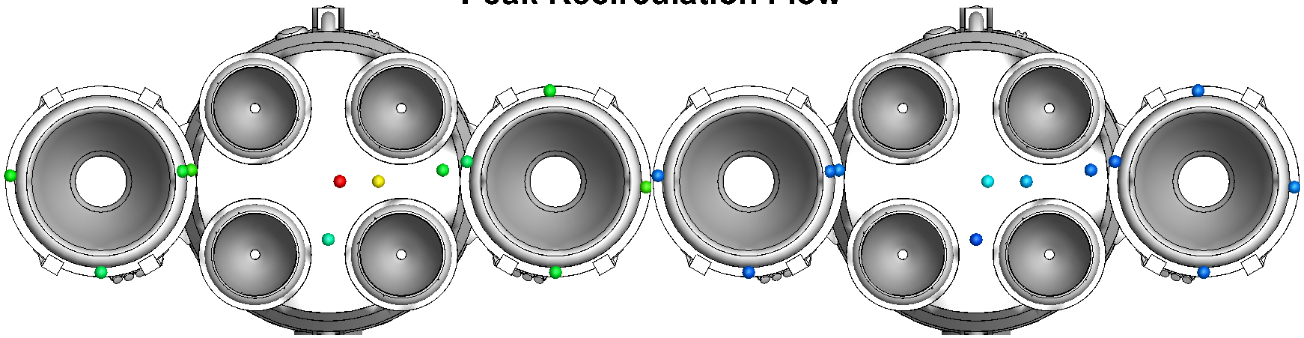


Base Heat Shield Pressure Maps

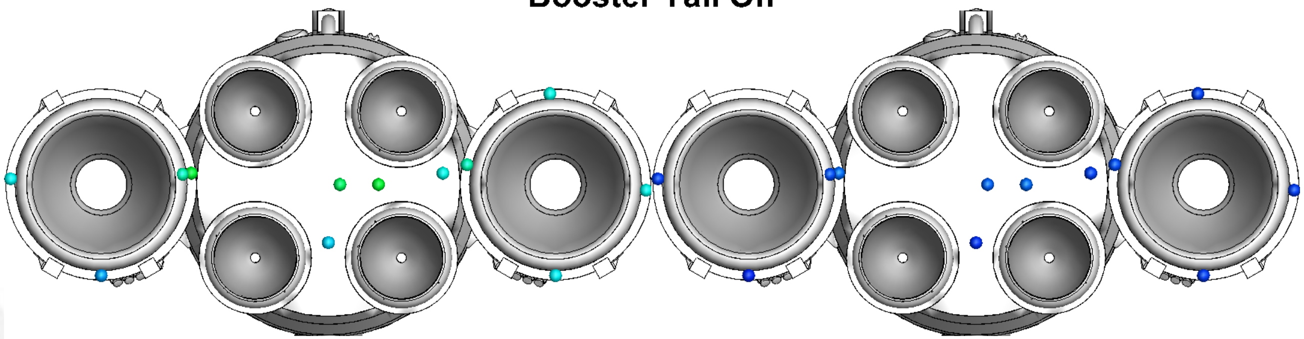


Base Heat Shield Pressure Maps

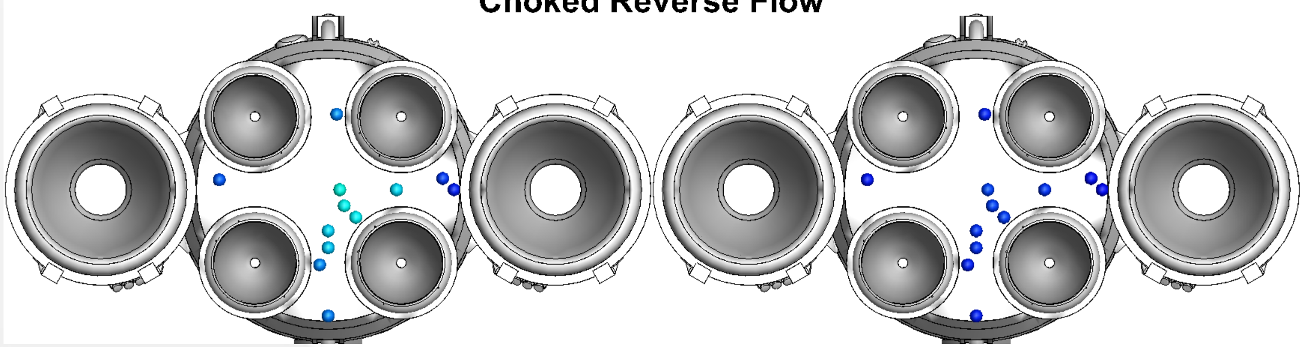
Alt: 121 kft
Peak Recirculation Flow



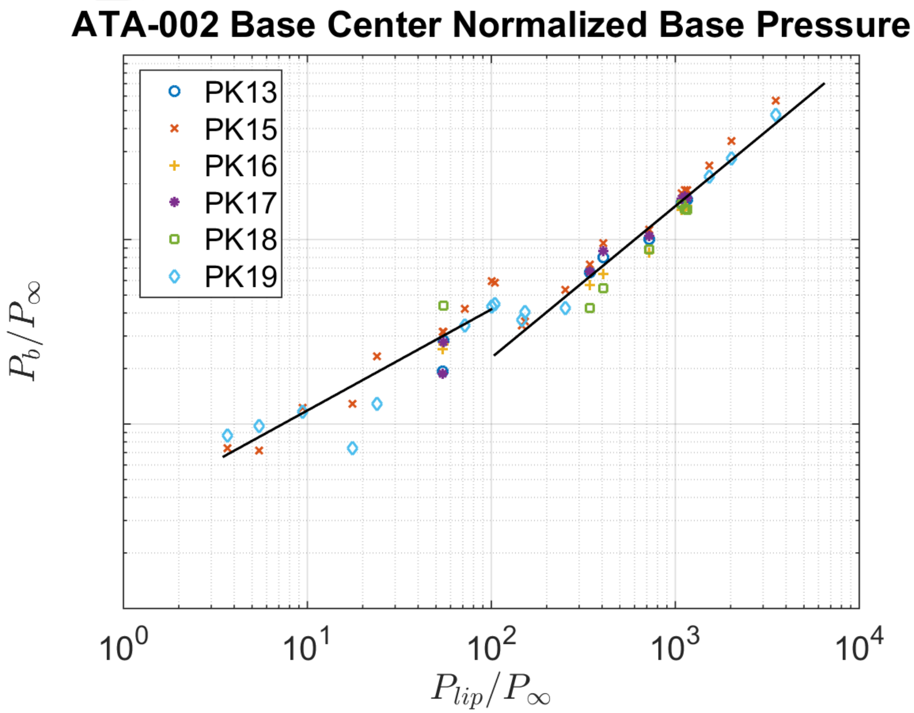
Alt: 131 kft
Booster Tail Off

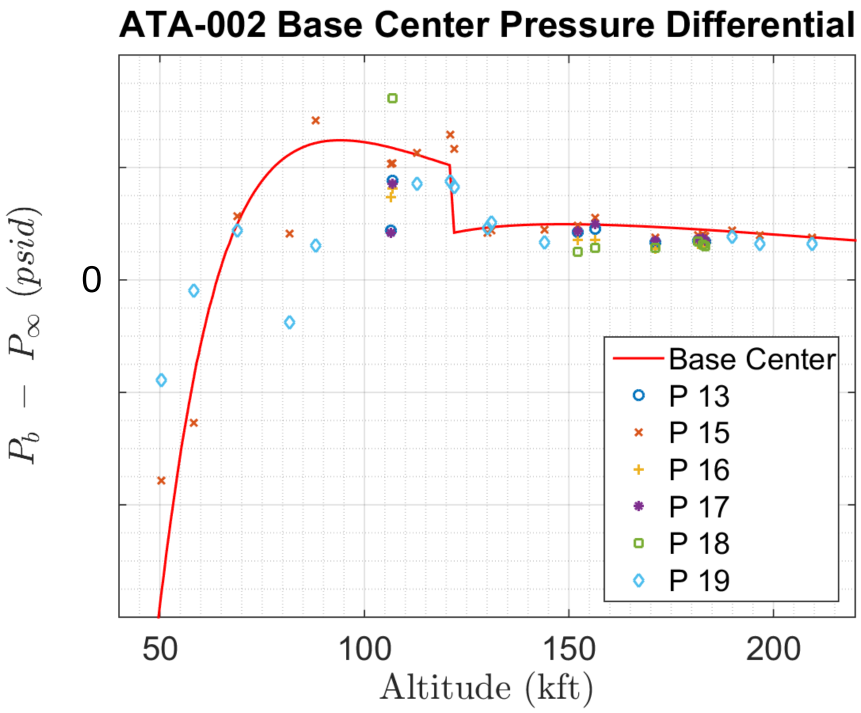


Alt: 171 kft
Choked Reverse Flow

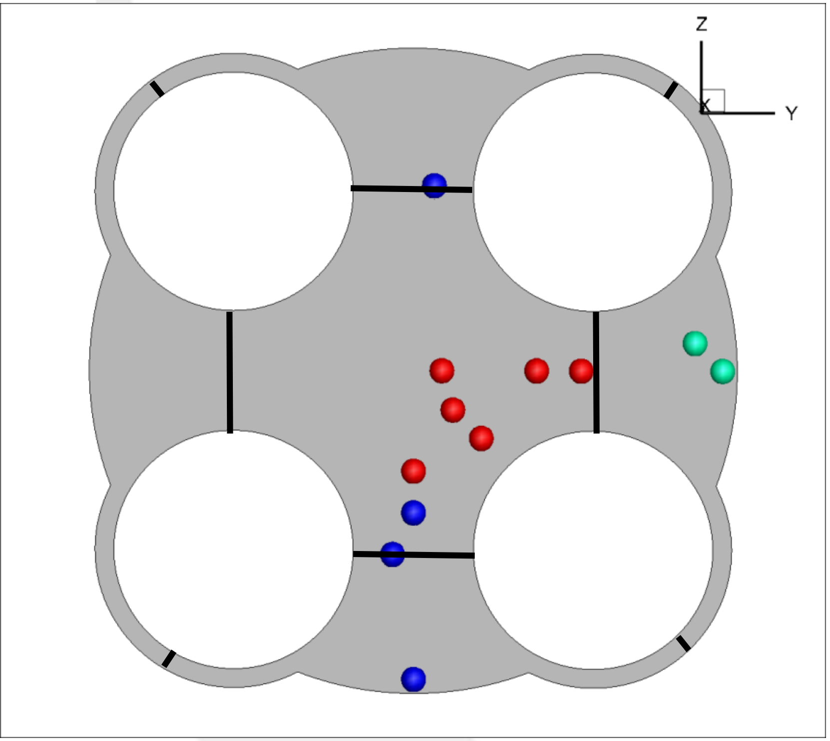


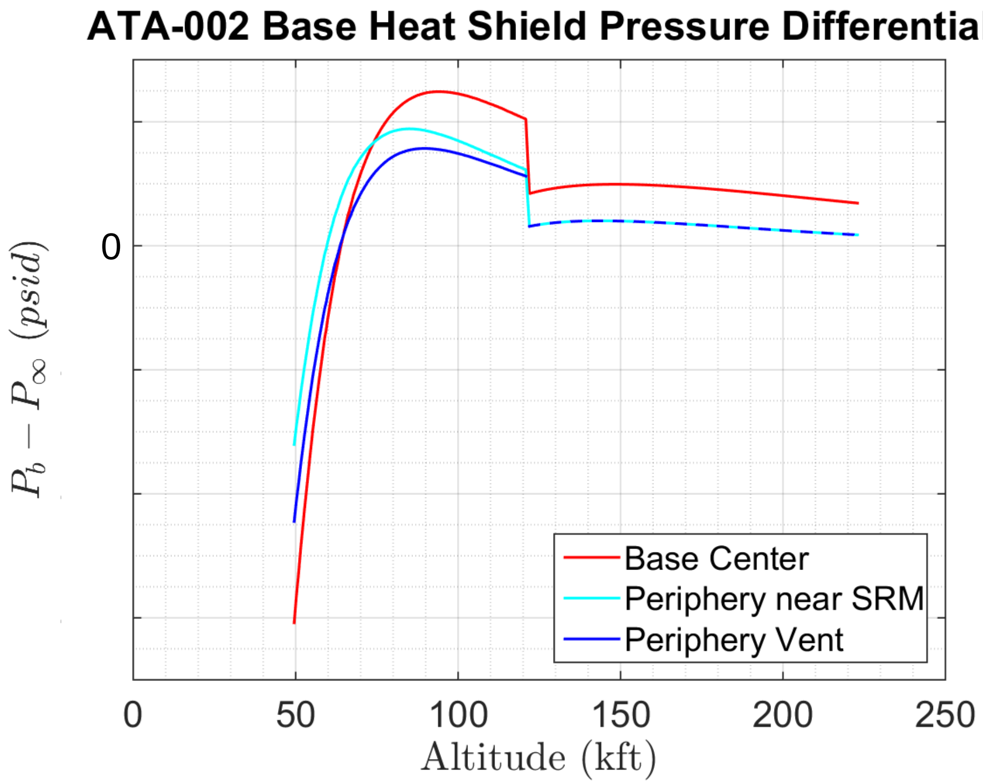
Base Center Pressure Differential





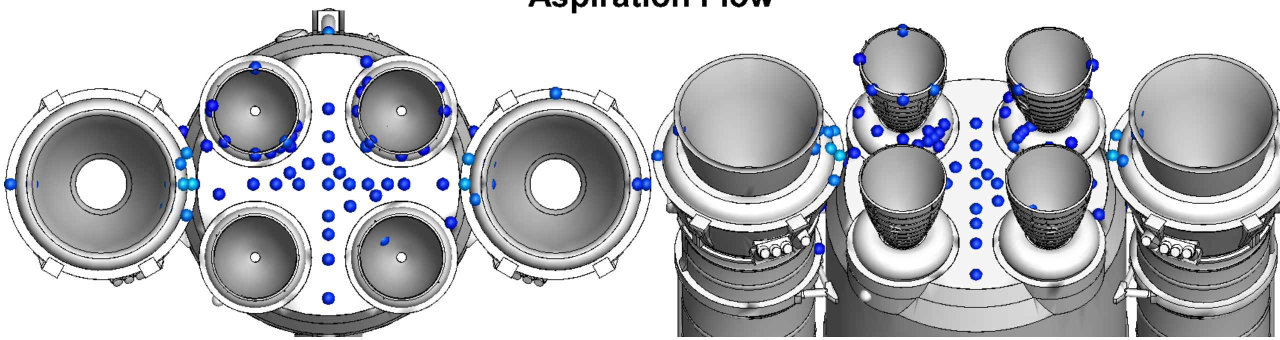
Base Heat Shield Pressure Differential



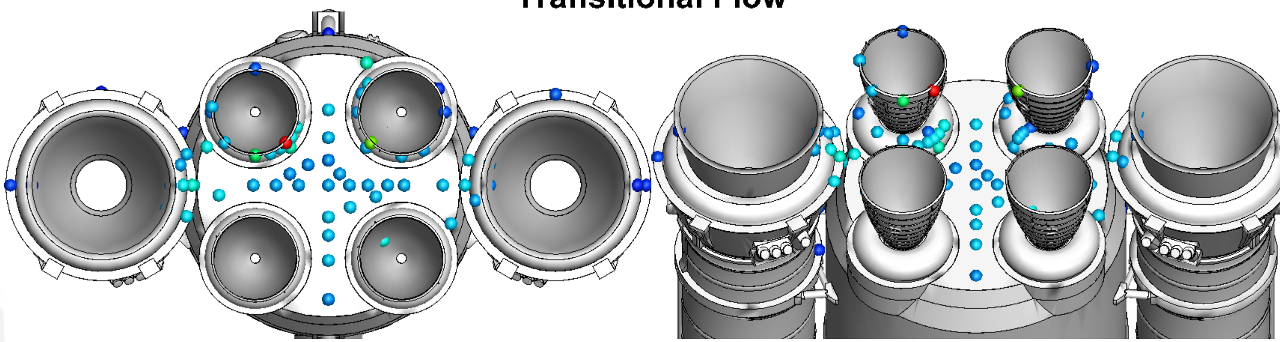


Base Heat Shield Heating Maps

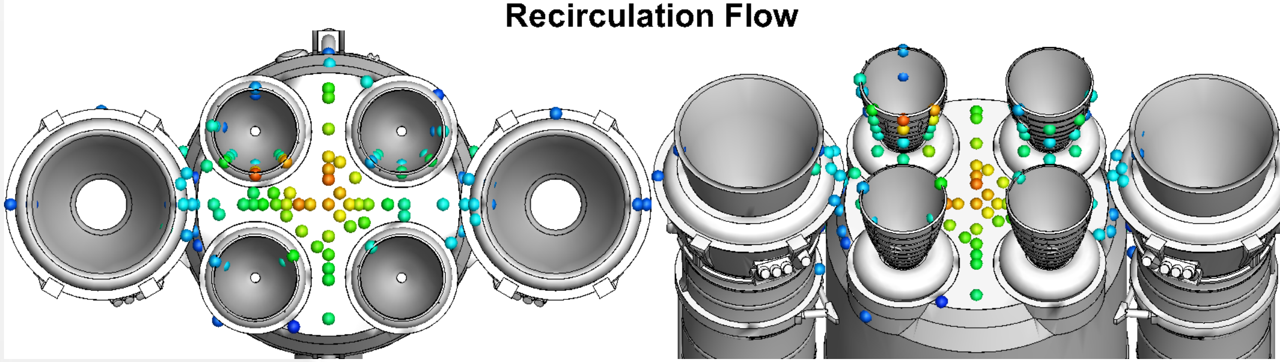
Alt: 50 kft
Aspiration Flow



Alt: 69 kft
Transitional Flow

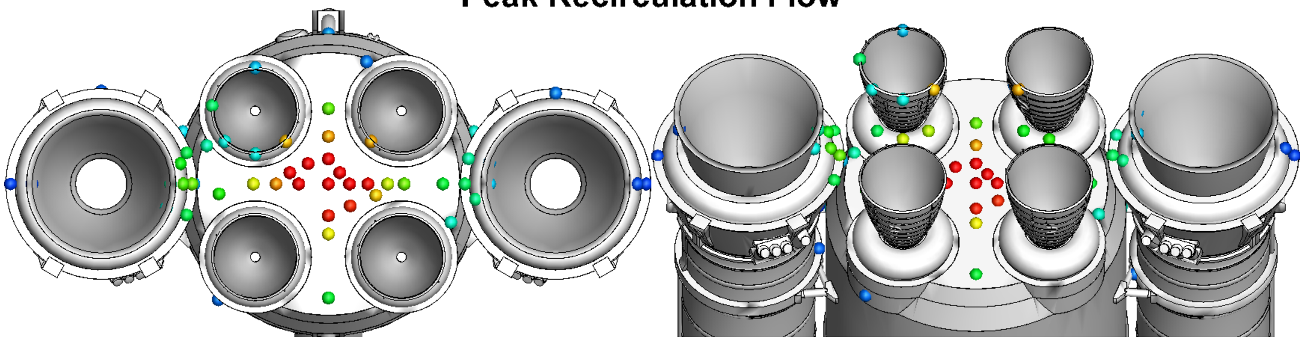


Alt: 107 kft
Recirculation Flow

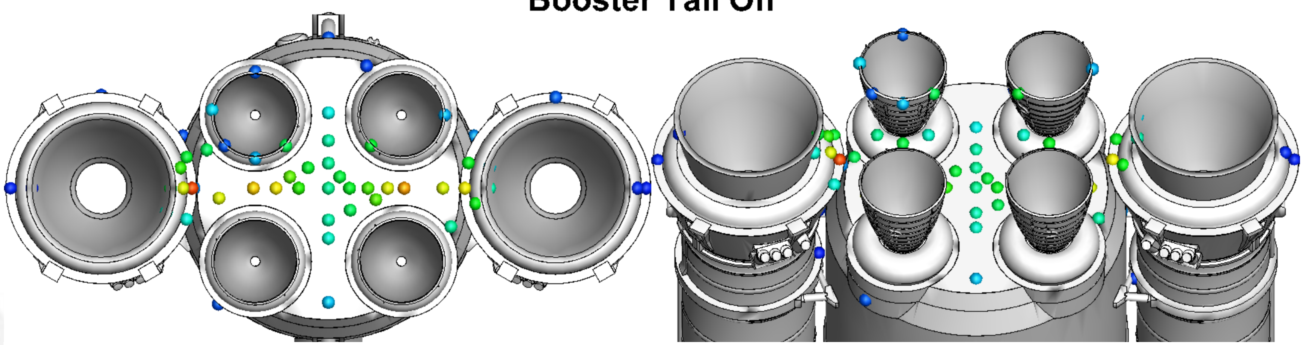


Base Heat Shield Heating Maps

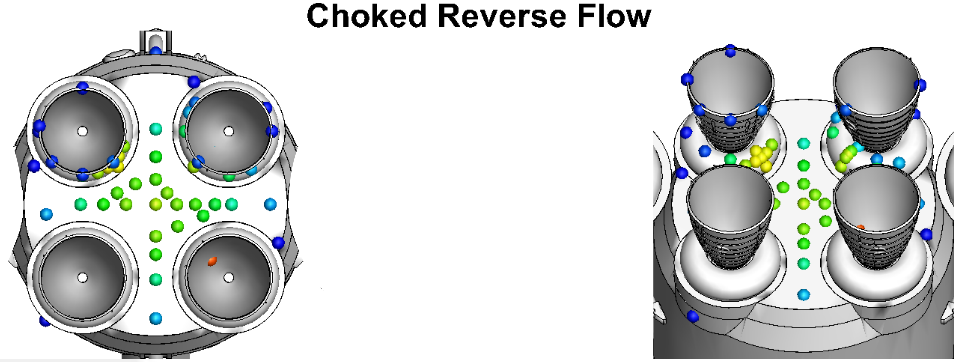
Alt: 121 kft
Peak Recirculation Flow



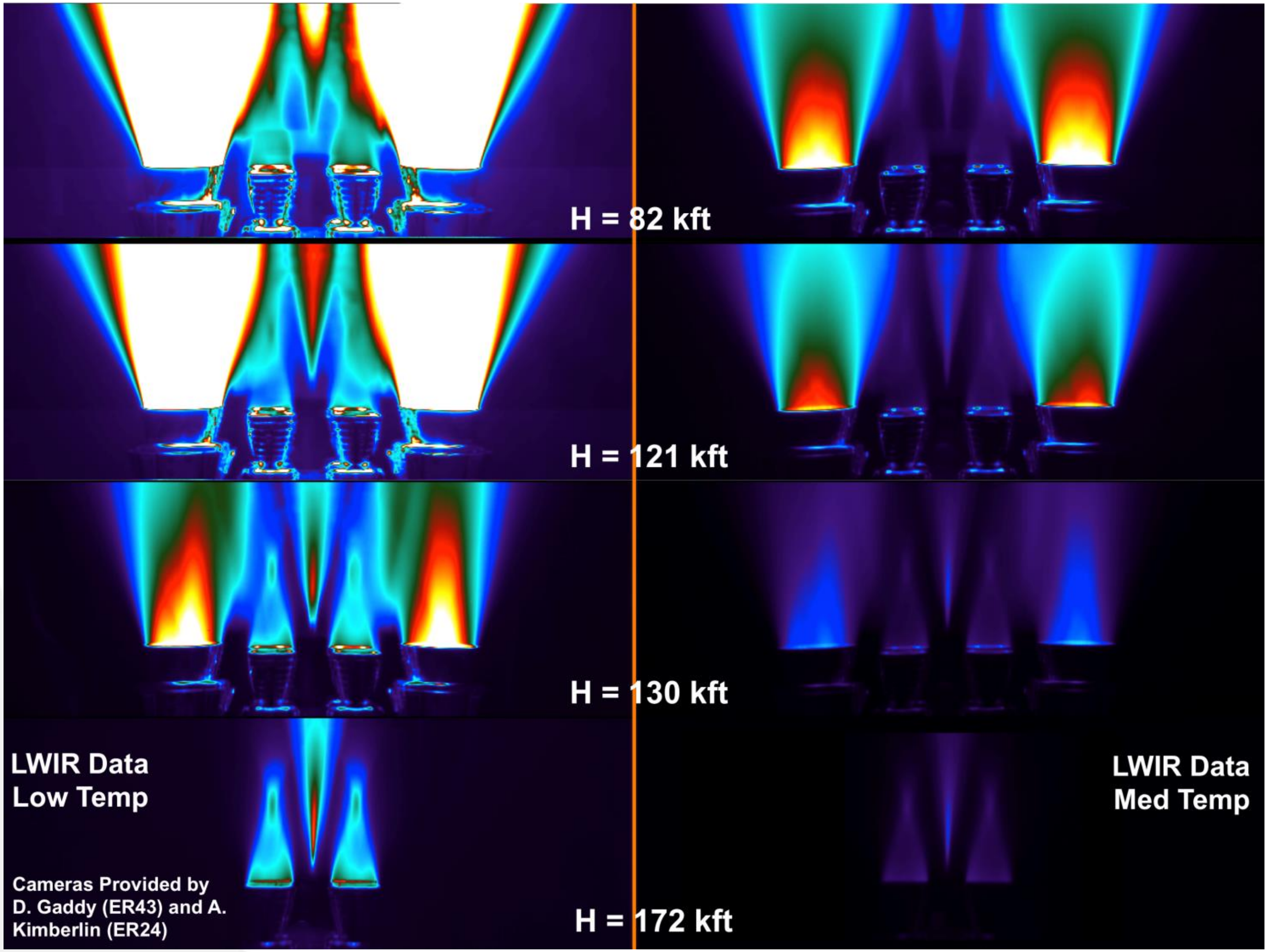
Alt: 131 kft
Booster Tail Off



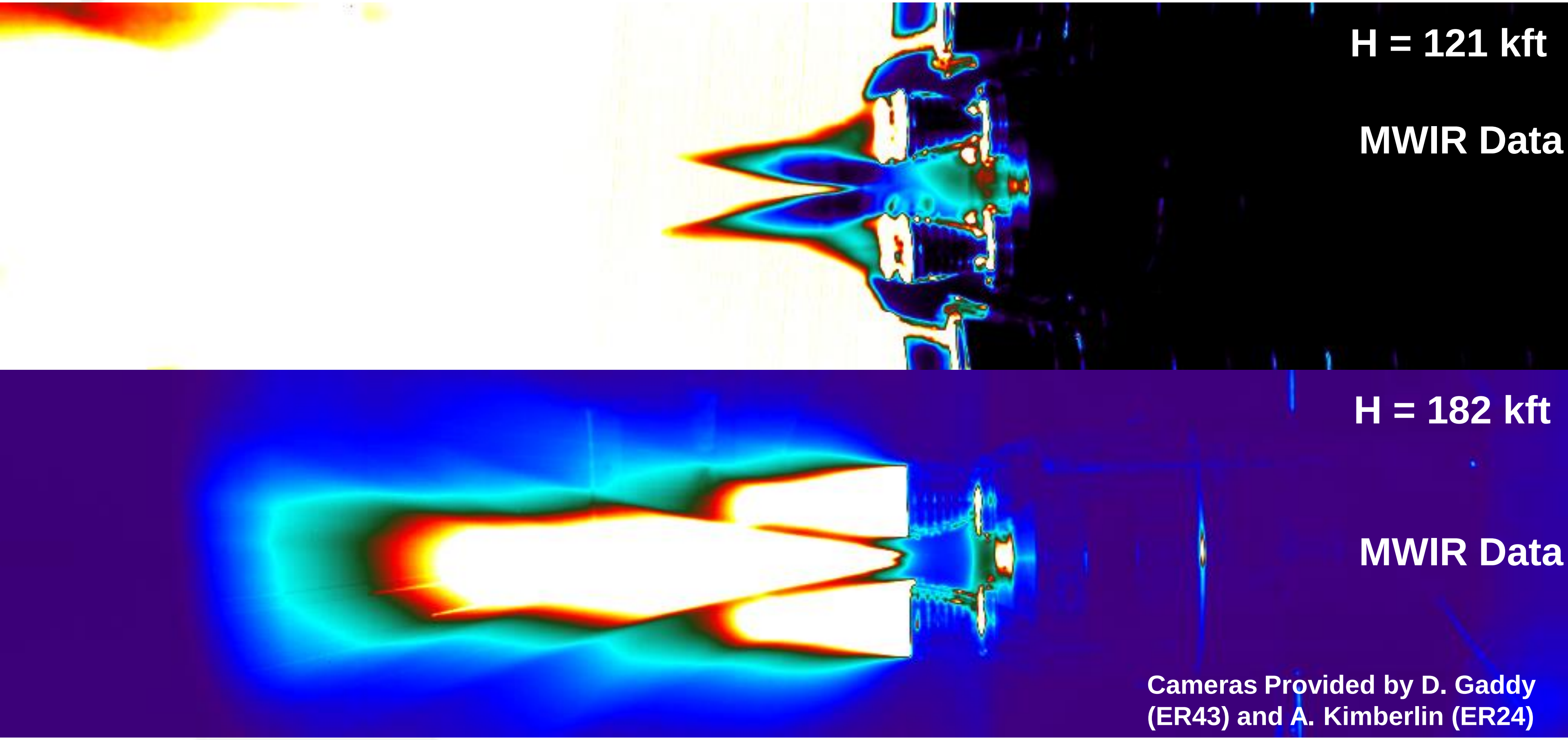
Alt: 209 kft
Choked Reverse Flow



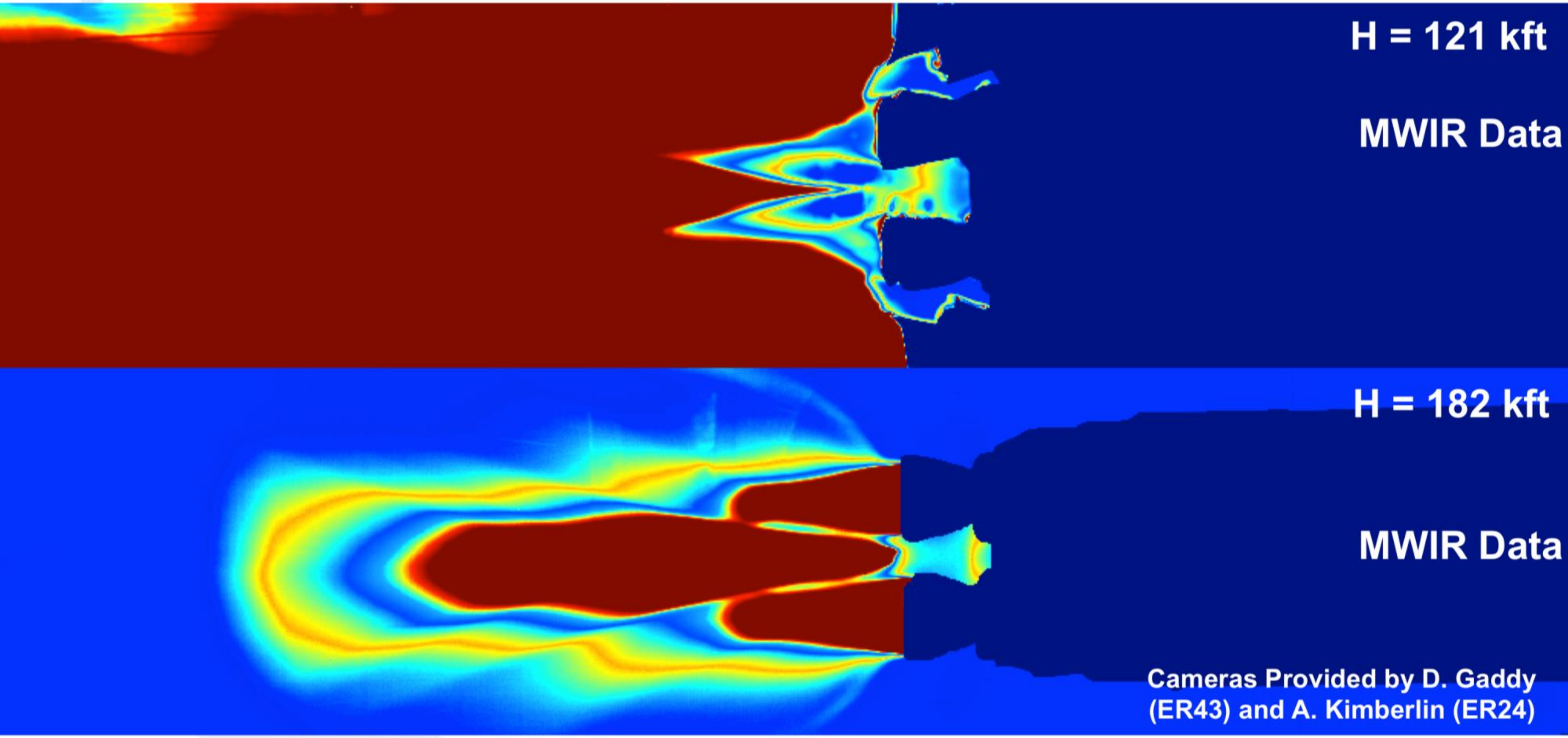
Long Wave Infrared Imaging



Mid Wave Infrared Imaging

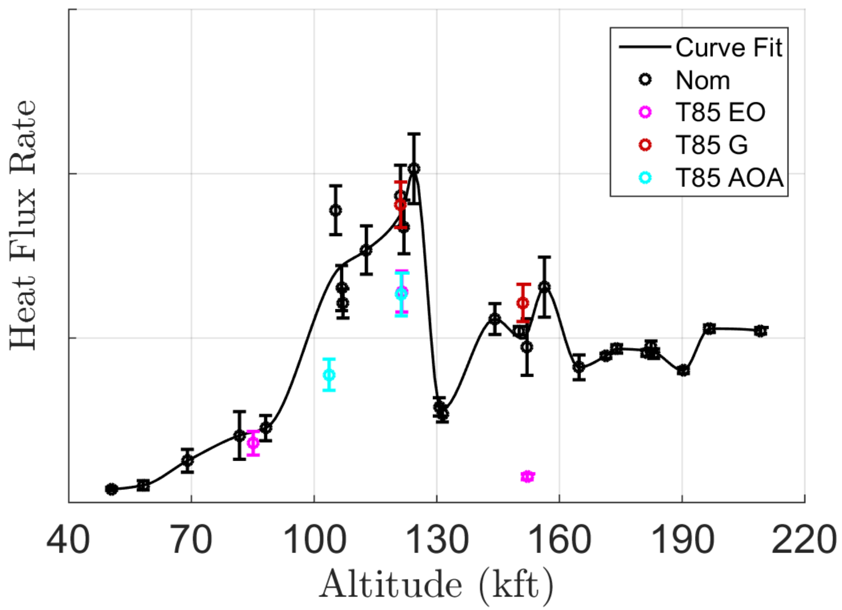


MWIR Masked Imaging

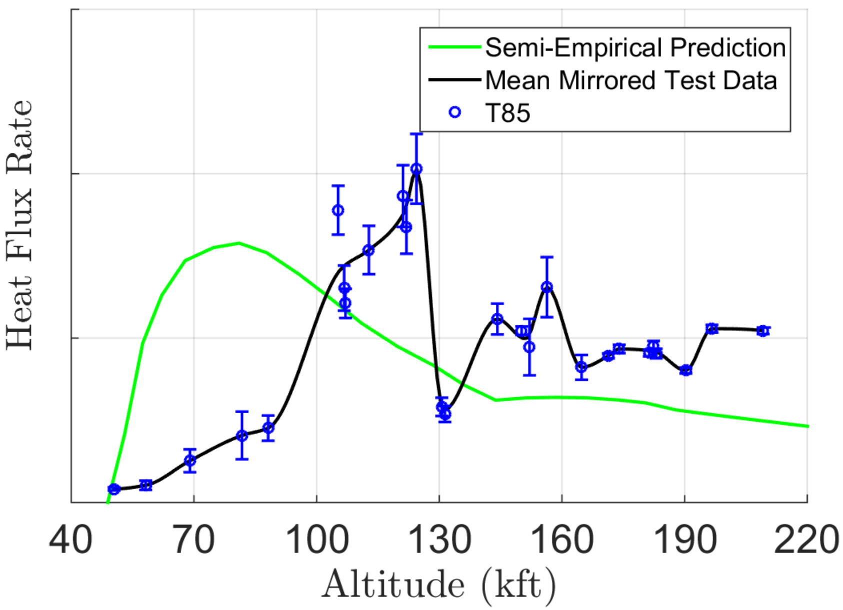


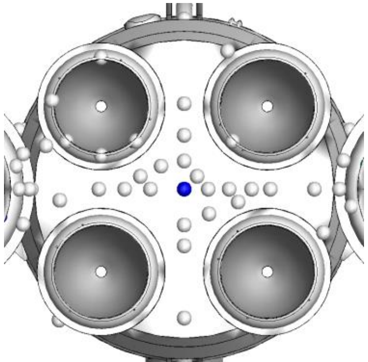
Base Heating – Altitude Profile: BHS Center

Base Heat Shield Off-Nominal



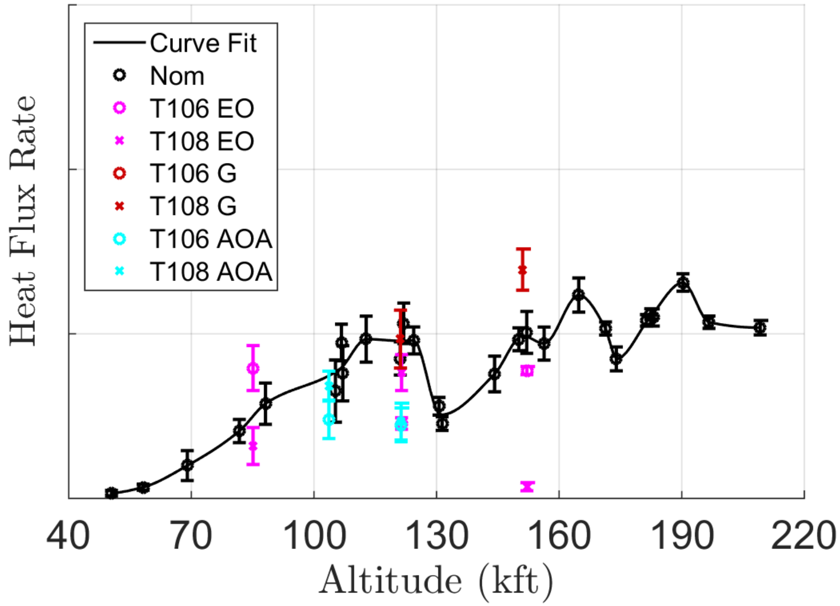
Base Heat Shield Nominal



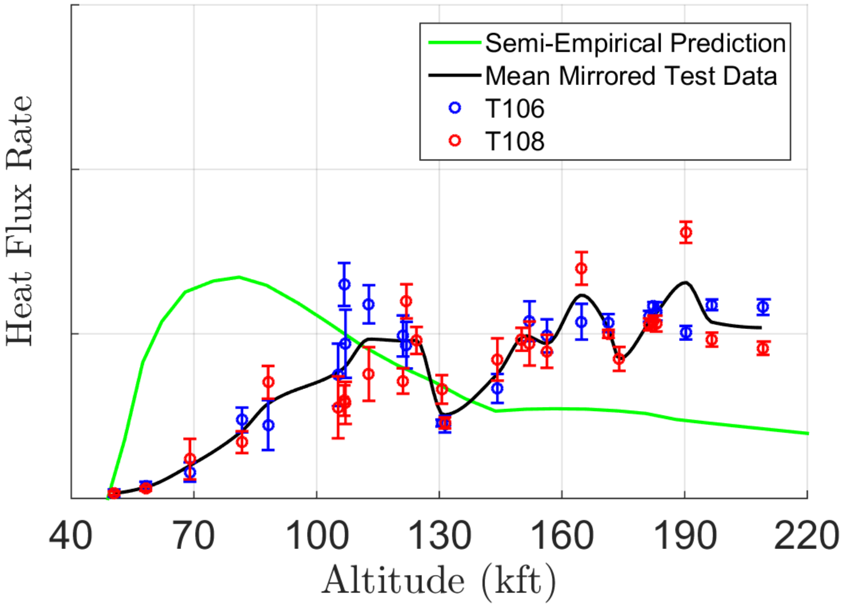


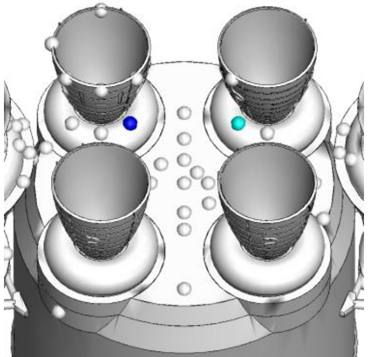
Base Heating – Altitude Profile: Inboard EMHS

Engine Mounted Heat Shield Off-Nominal



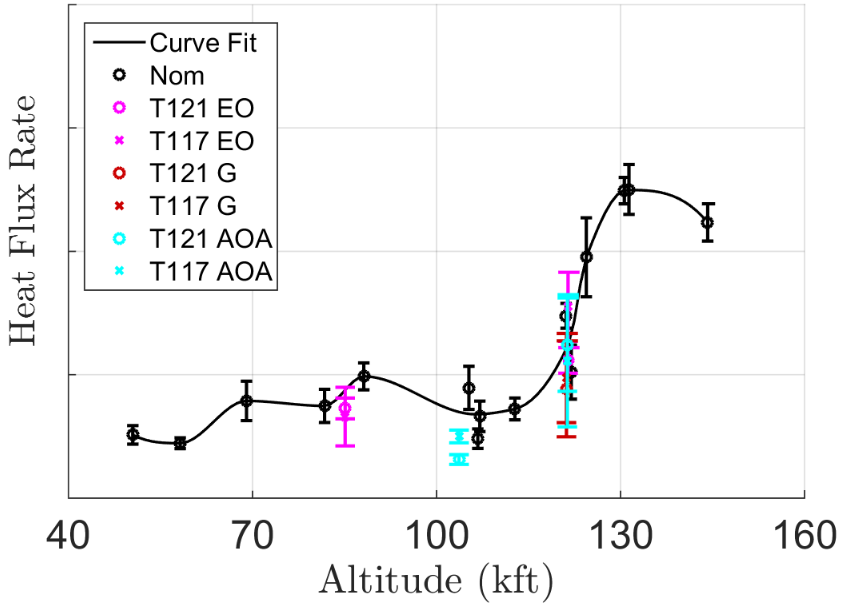
Engine Mounted Heat Shield Nominal



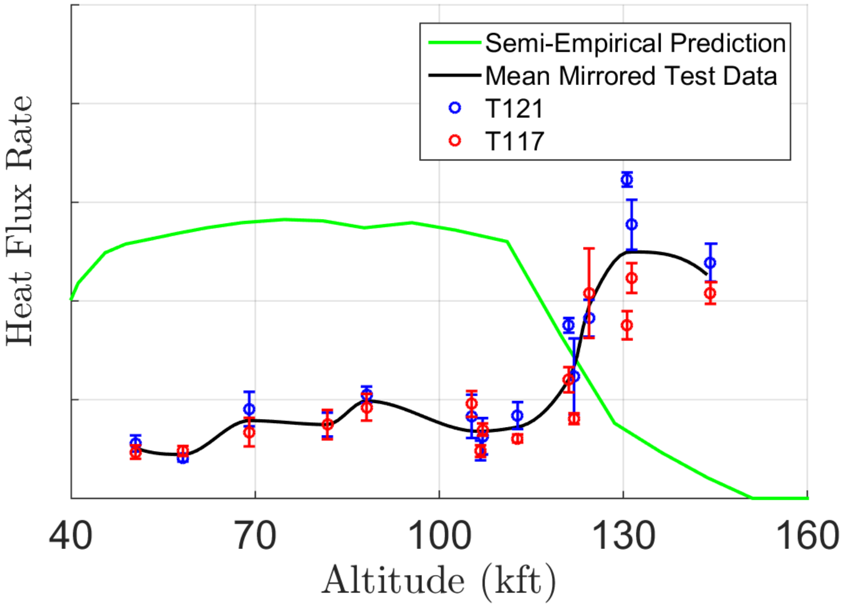


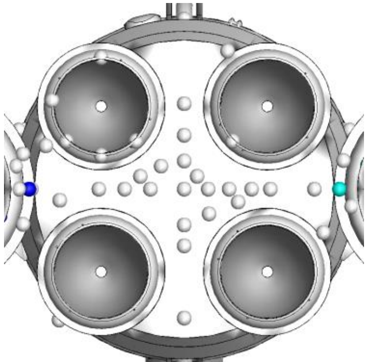
Base Heating – Altitude Profile: Inboard SRB

Booster Aft Skirt Lip Aft Face Off-Nominal



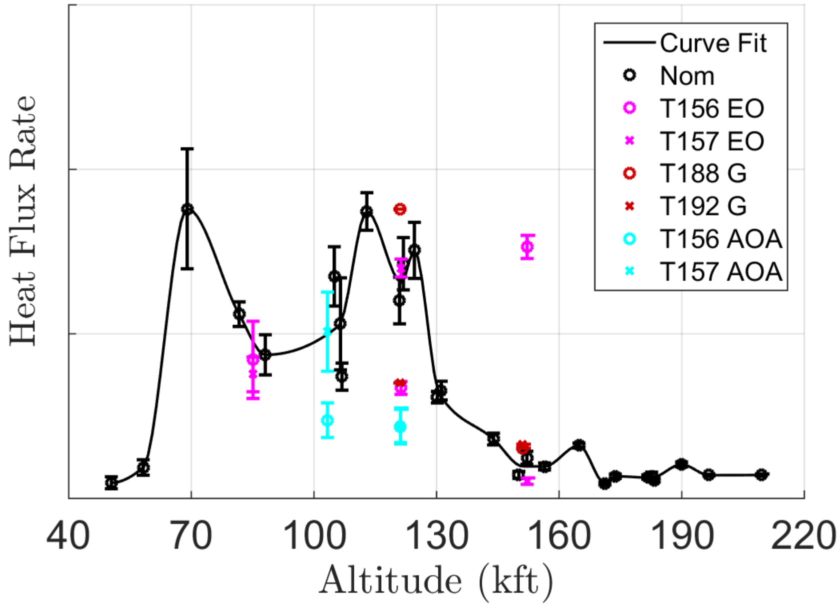
Booster Aft Skirt Lip Aft Face Nominal



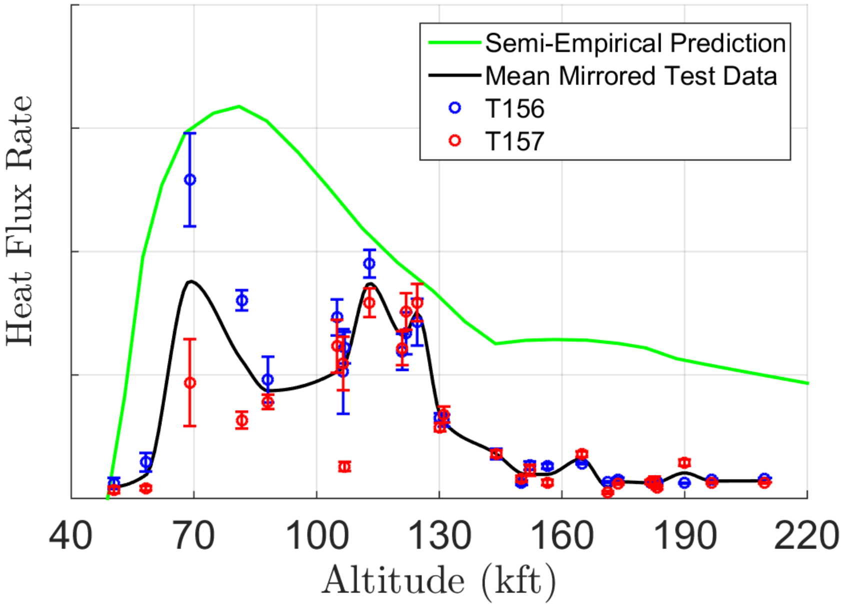


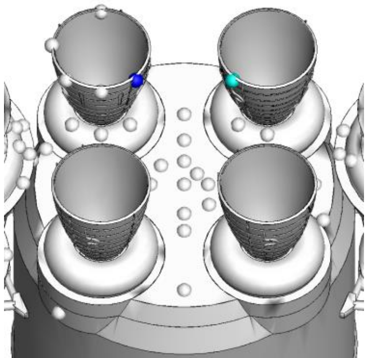
Base Heating – Altitude Profile: RS-25 Nozzle

Core Stage Engine Nozzle Off-Nominal



Core Stage Engine Nozzle Nominal



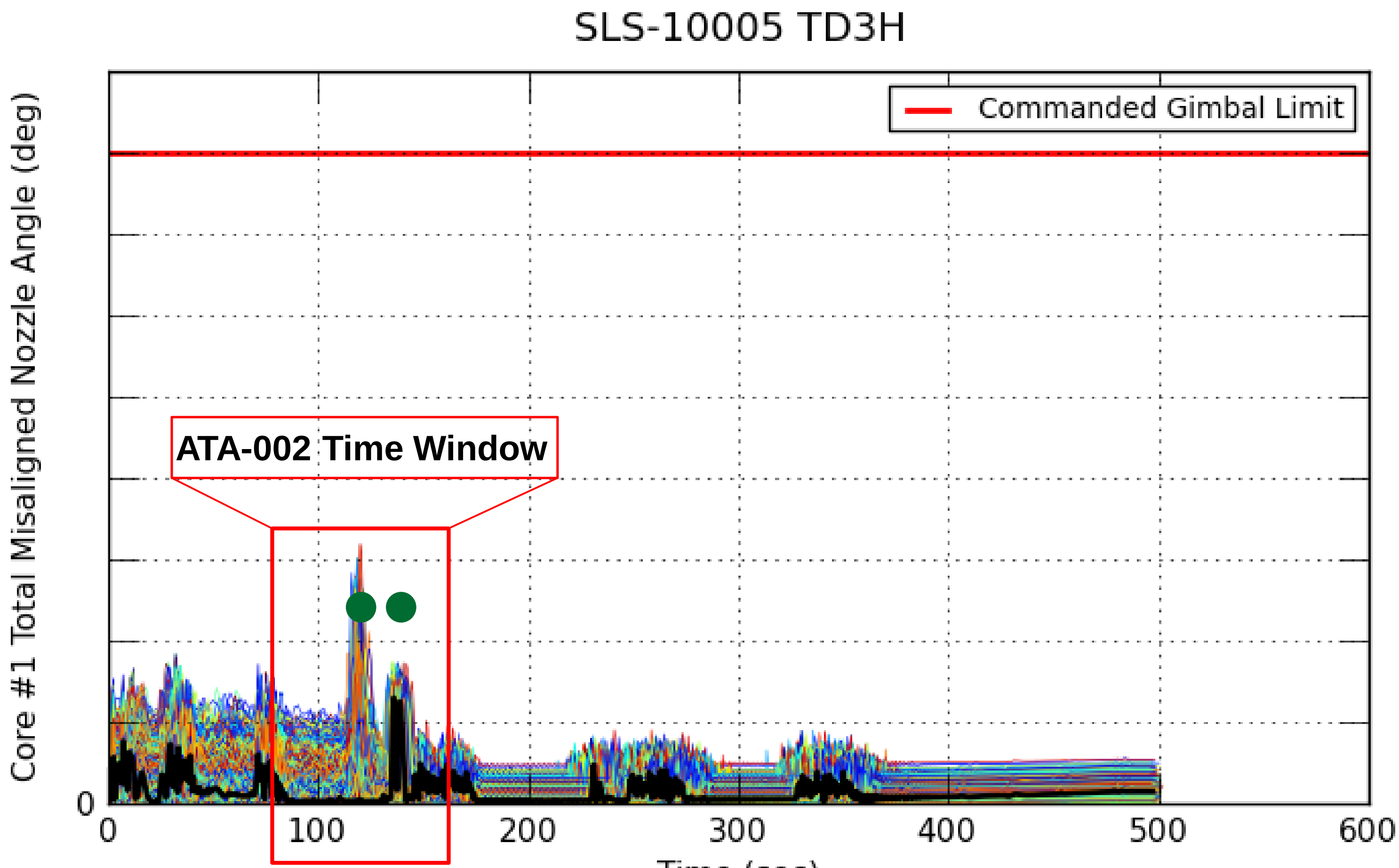


Base Heating Scaling Method

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

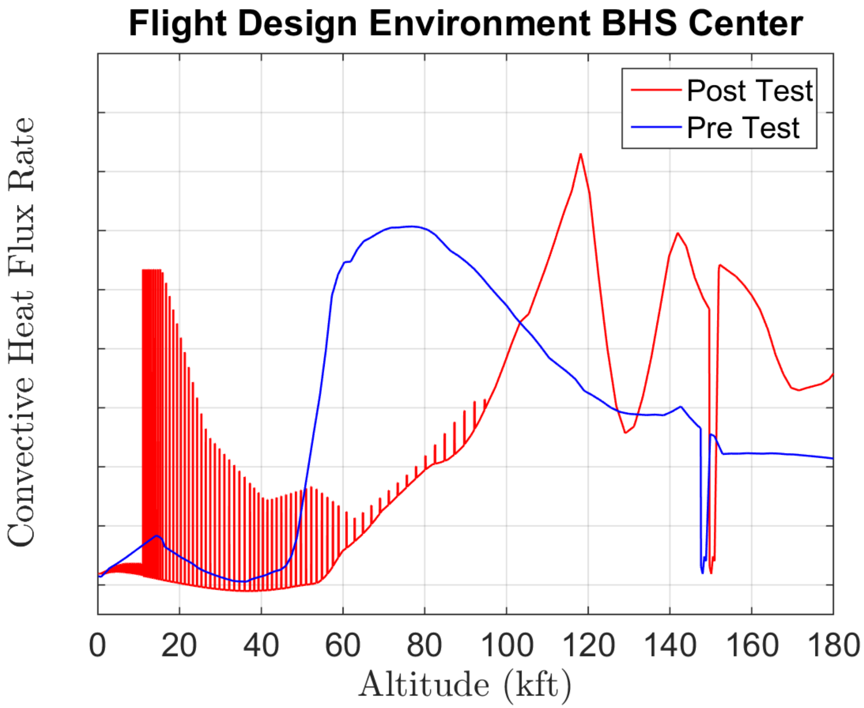
- $Nu = C\, Re^m Pr^n$
- $Nu = \frac{hL}{k}$
- $\frac{hL}{k} \propto Re^m Pr^n$
- $Re = f(P, L)$
- $h \propto P_c^m\, L^{m-1}$
- $h_F = h_T \left(\frac{P_{c,F}}{P_{c,T}}\right)^m \left(\frac{L_F}{L_T}\right)^{m-1}$
- $\dot{q}_F = \dot{q}_T \left(\frac{P_{c,F}}{P_{c,T}}\right)^m \left(\frac{L_F}{L_T}\right)^{m-1}$

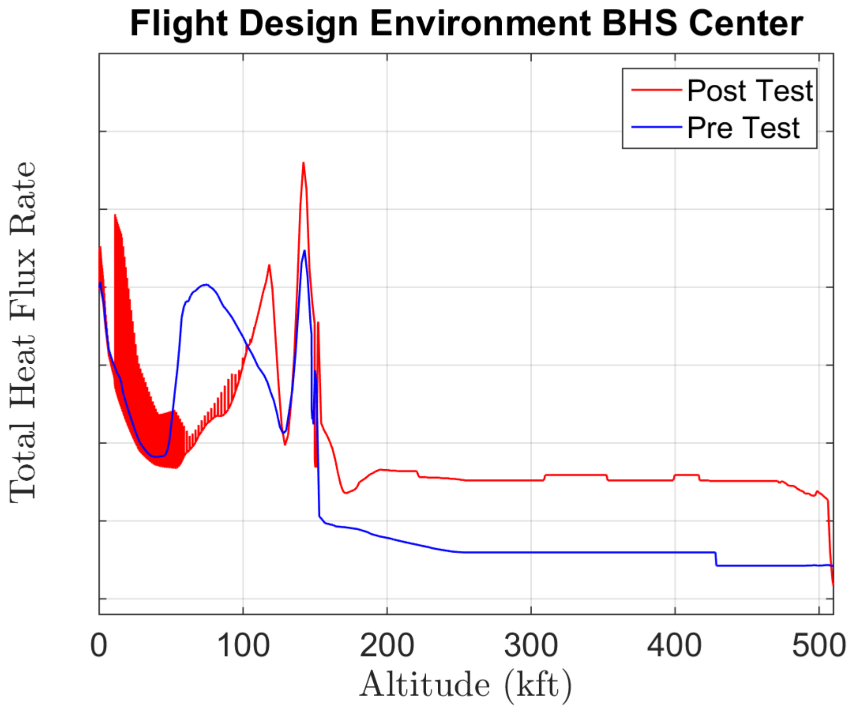
SLS Vehicle Maneuvers

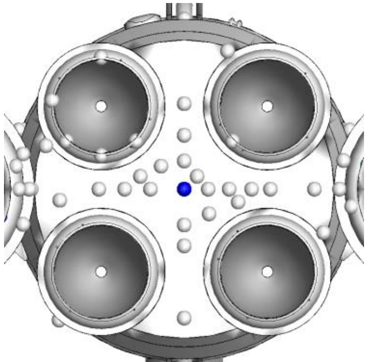


● ATA-002 Gimbal Test Runs

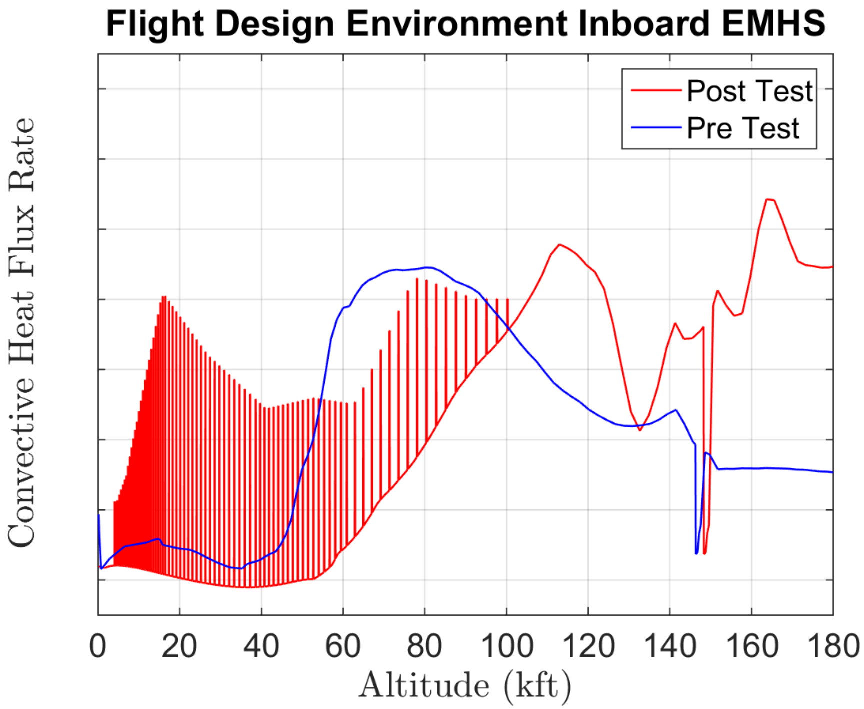
Design Environment: BHS Center

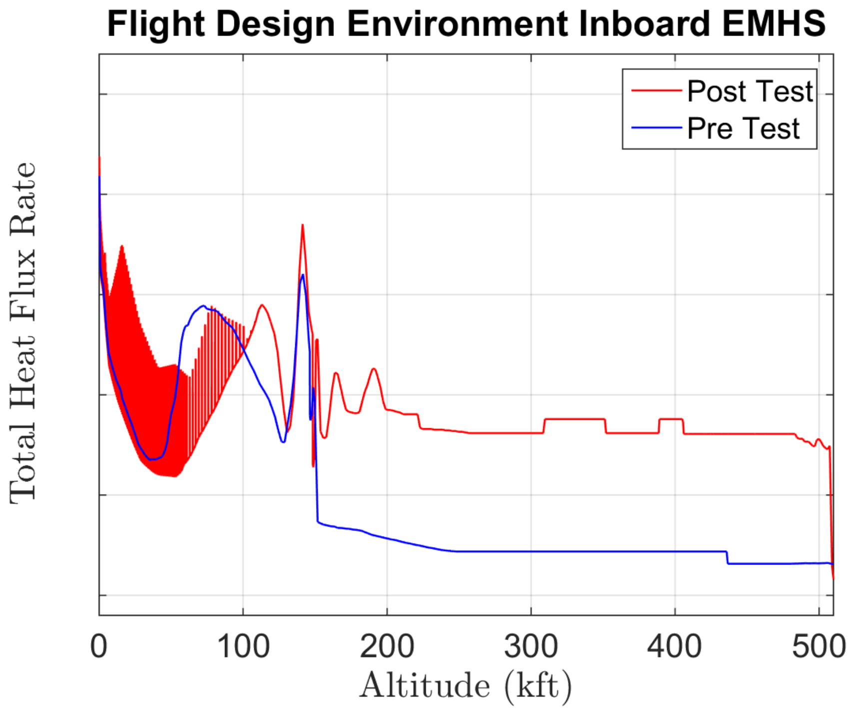


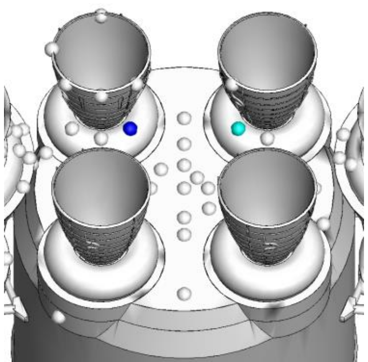




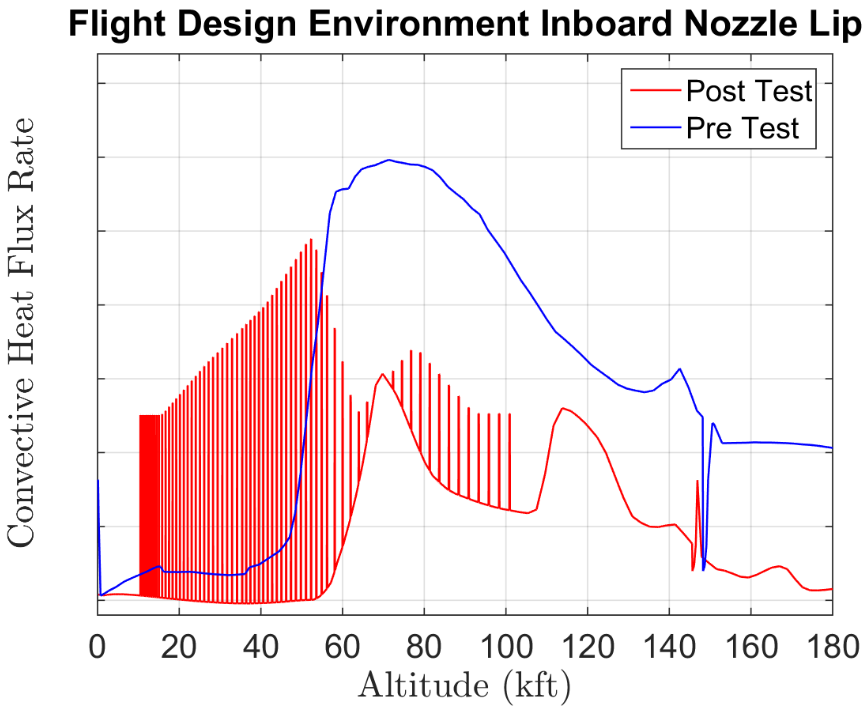
Design Environment: Inboard EMHS

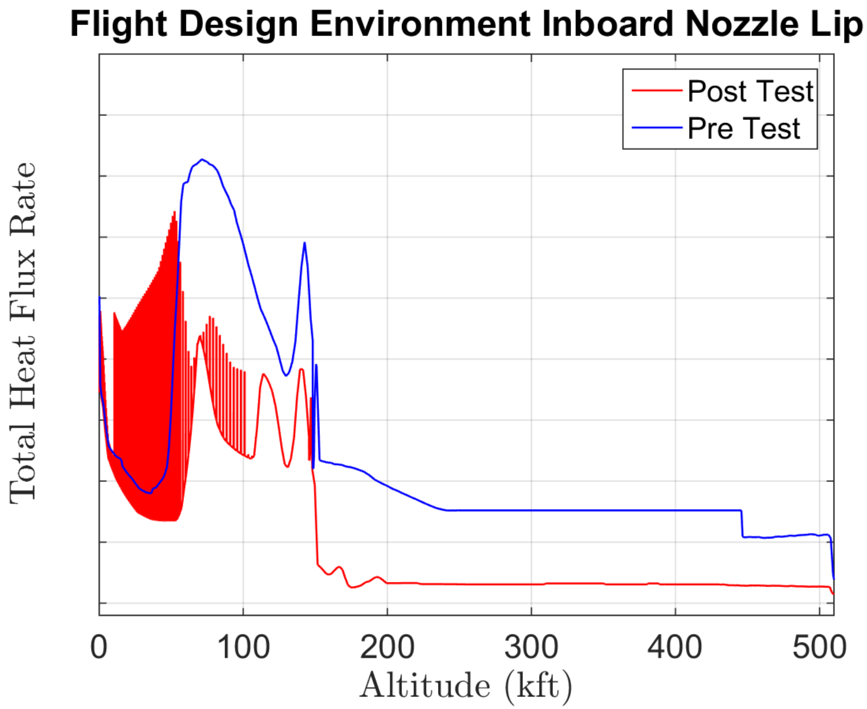


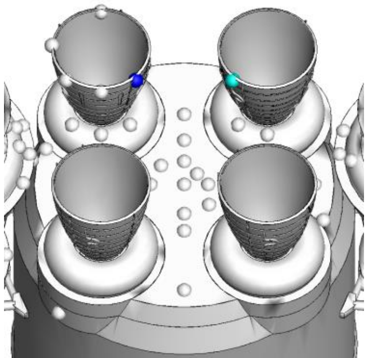




Design Environment: Inboard Nozzle Lip







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

References

- [1]Mehta, M. et al (2014), Space Launch System (SLS) Pathfinder Test Program: Sub-scale booster solid rocket motor development for short-duration testing, NASA MSFC Spacecraft & Vehicle Systems Department EV33 Tech. Memo 14-024, Aerosciences Branch (EV33), Huntsville, AL, December 2014.
- [2]Mehta, M. et al (2014), Space Launch System (SLS) Pathfinder Test Program: Sub-scale core-stage rocket engine development for short-duration testing, NASA MSFC Spacecraft & Vehicle Systems Department EV33 Tech. Memo 14-023, Aerosciences Branch (EV33), Huntsville, AL, October 2014.
- [3]Dufrene, A.T. et al (2016), Space Launch System Base Heating Test: Experimental Operations and Results, AIAA 2016-0546, 2016 AIAA SciTech Conference, San Diego, CA.
- [4]Morris, C.I. (2015), Space Launch System Ascent Aerothermal Environments Methodology, AIAA 2015-0561, 2015 AIAA SciTech Conference, Kissimmee, FL.
- [5]Mehta et al (2013), Numerical Base Heating Sensitivity Study for a Four-Rocket Engine Core Configuration, *JSR*, Vol. 50, No. 3.
- [6]Parker, R. et al (2016), Space Launch System Base Heating Test: Tunable Diode Laser Absorption Spectroscopy, AIAA 2016-0548, 2016 AIAA SciTech Conference, San Diego, CA.
- [7]Bergman, T.L., A.S. Lavine, F.P. Incropera and D.P. DeWitt (2015), Fundamentals of Heat and Mass Transfer, John Wiley & Sons, Inc., Hoboken, NJ.
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Acknowledgements

- NASA MSFC Aerosciences Aerothermodynamics Team
- NASA MSFC Propulsion Thermal Analysis Branch
- CUBRC Aerosciences/LENS Team
- NASA SLS Project Office
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