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SPACE LAUNCH SYSTEM

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Base Heating Test: Environments and Base Flow Physics

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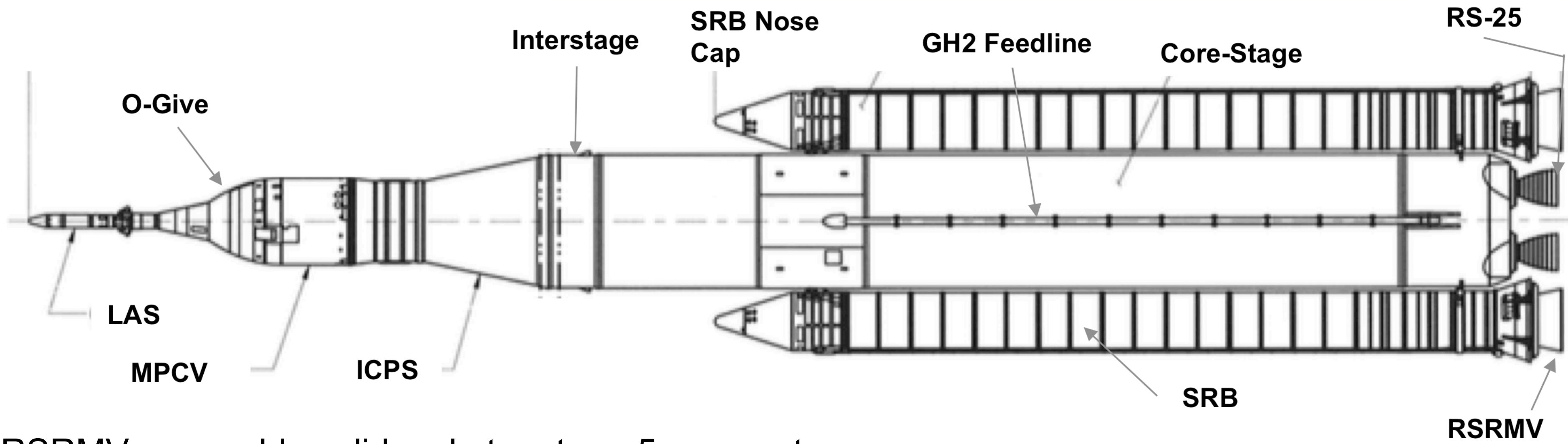
Motivation and Focus

- **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

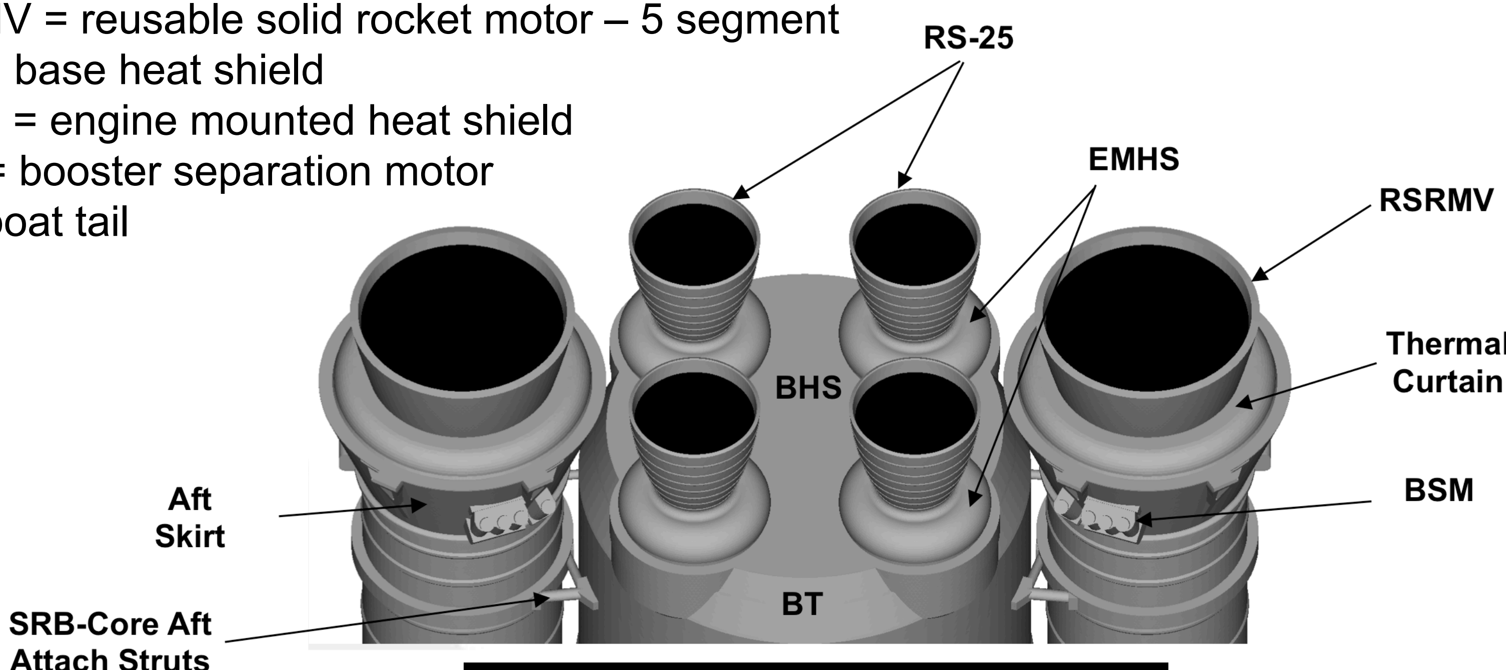
- **NASA MSFC and CUBRC developed a 2% scale SLS propulsive wind tunnel test program[1,2] to obtain base heating test data during ascent.**
  - Such a test program has not been conducted in 40+ years since the Shuttle Program
  - Dufrene et al paper[3] described the operation, instrumentation type and 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).**

SLS Vehicle and Base Region



RSRMV = reusable solid rocket motor – 5 segment
BHS = base heat shield
EMHS = engine mounted heat shield
BSM = booster separation motor
BT = boat tail



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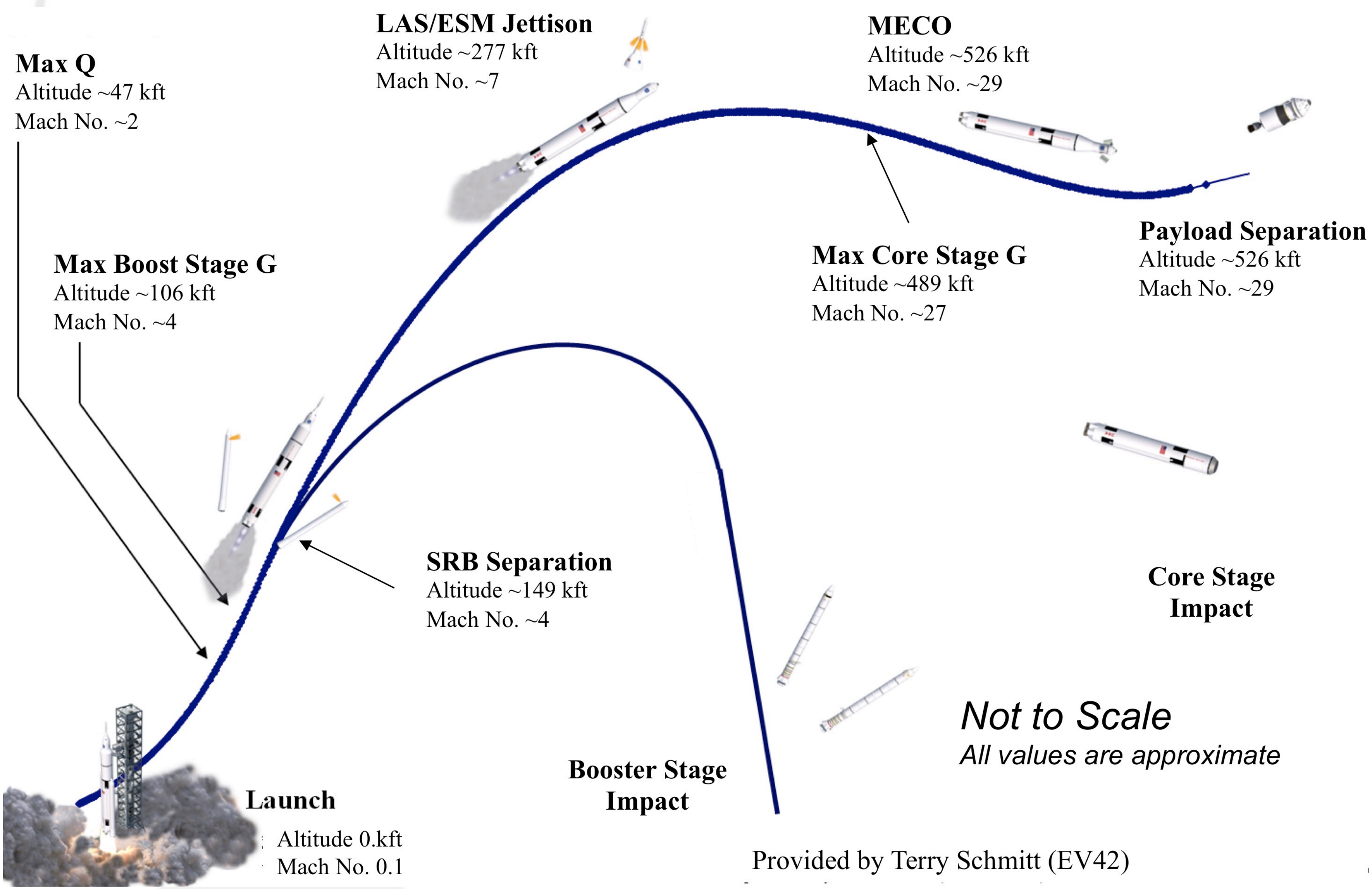
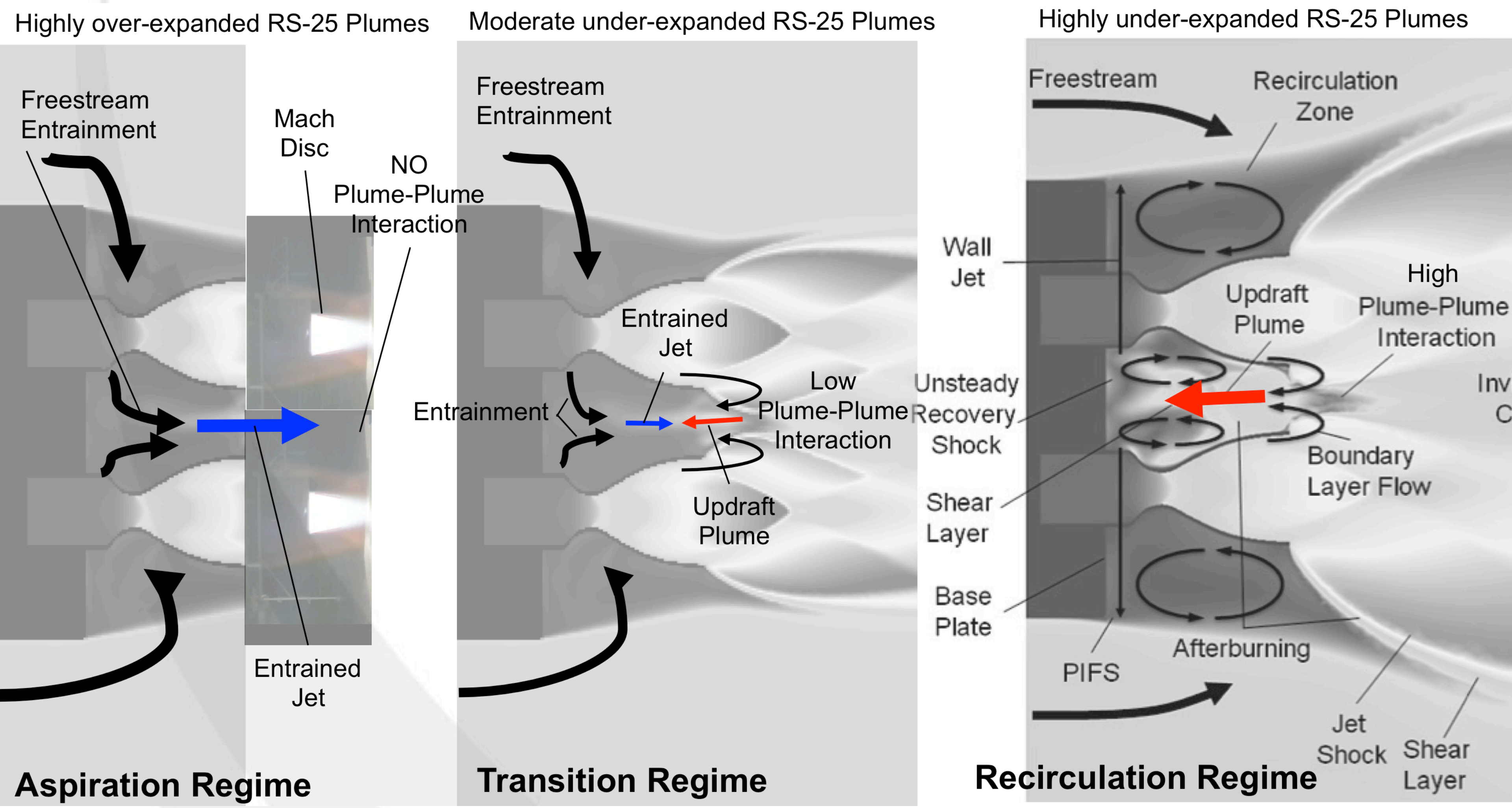
SLS Mission Profile



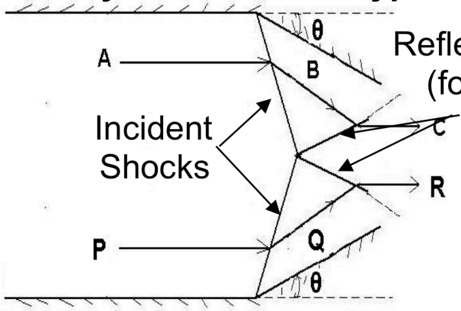
Base Flow Physics

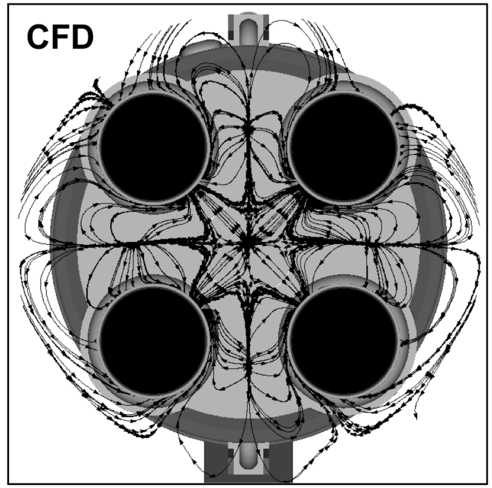


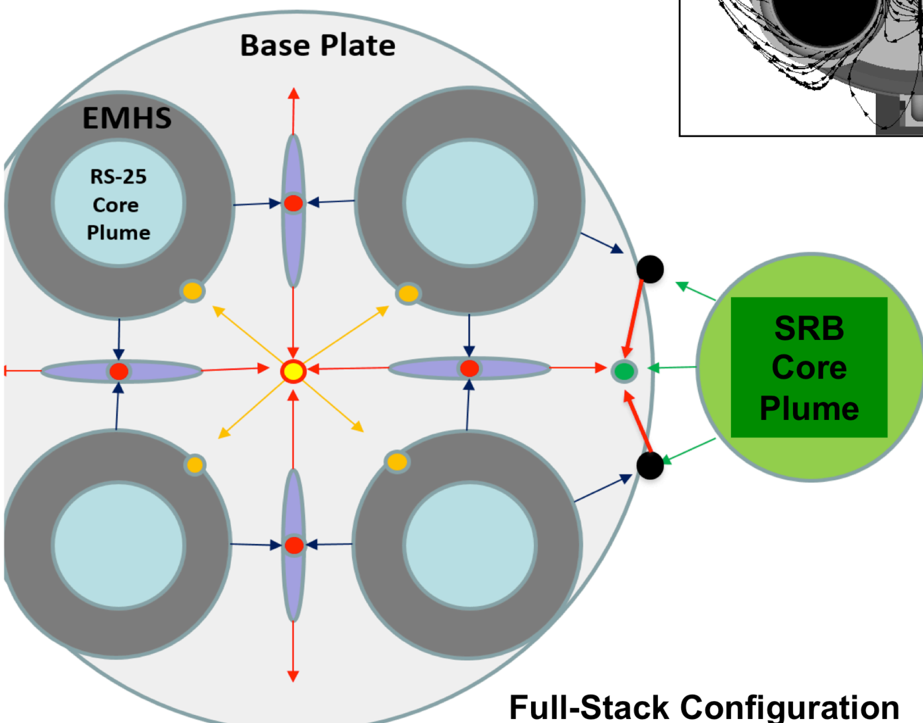
Mehta et al (2013)[5]

SLS Base Flow Physics

Edney Shock-Shock Type I Interaction



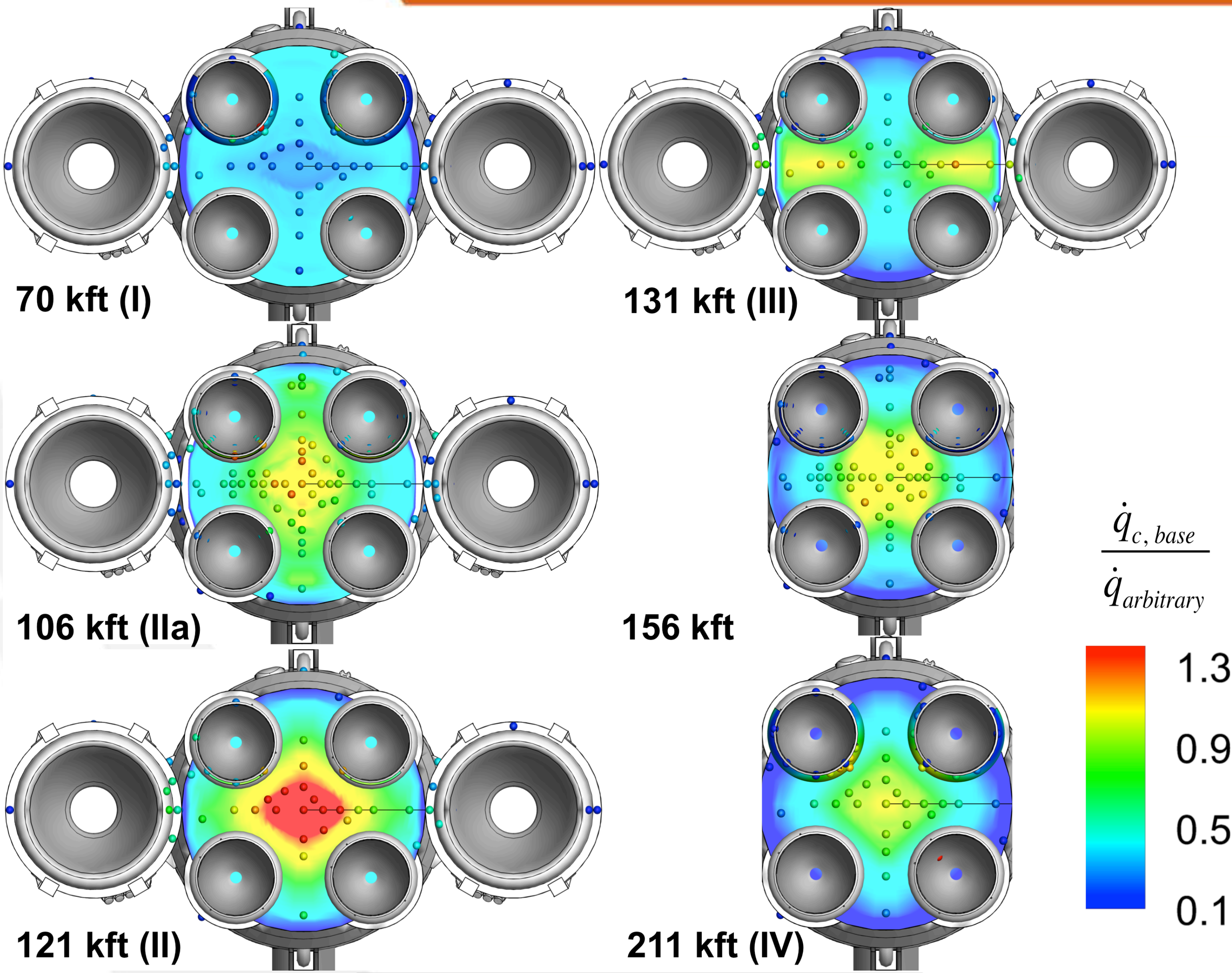




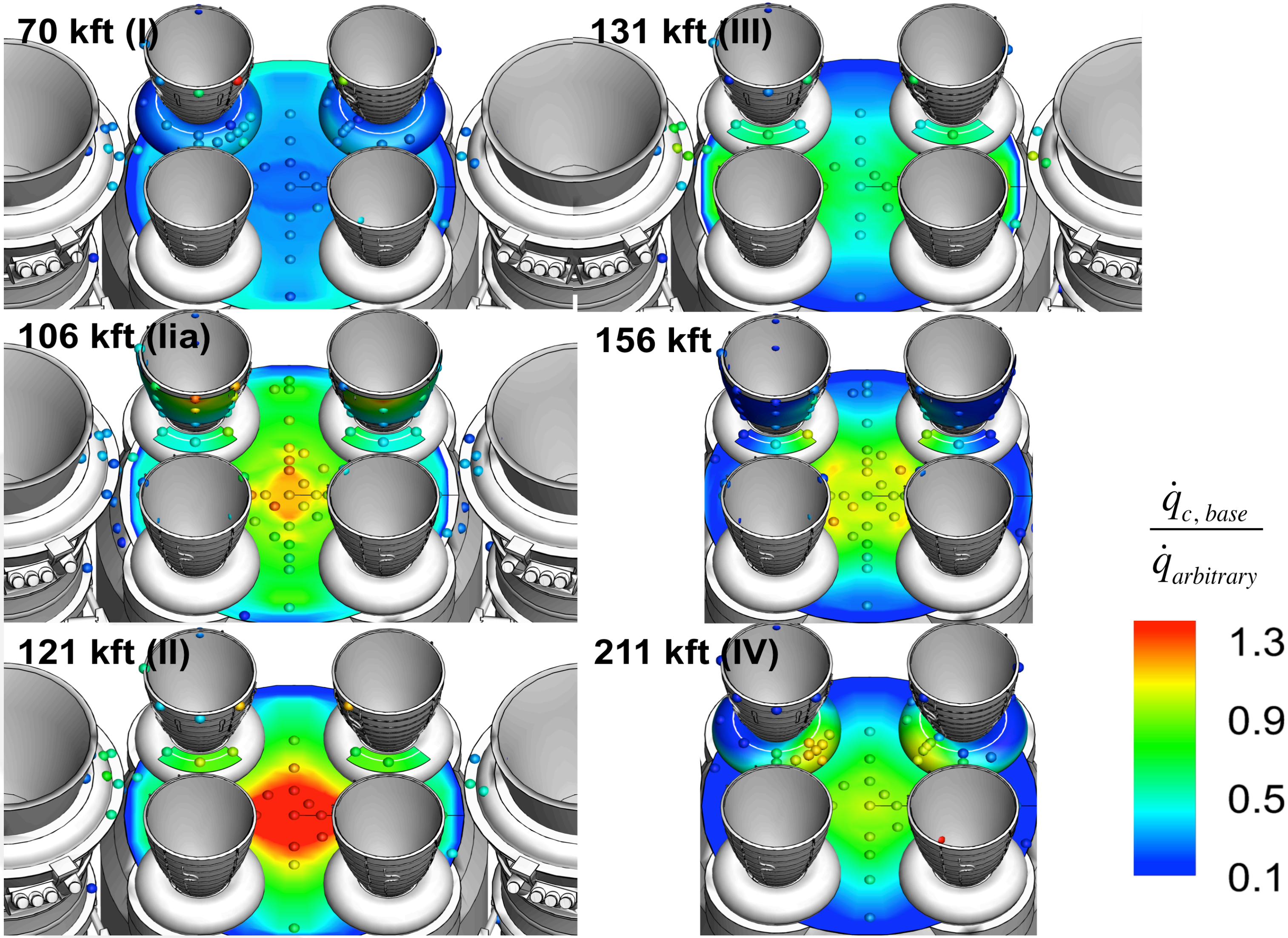
Full-Stack Configuration

- 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

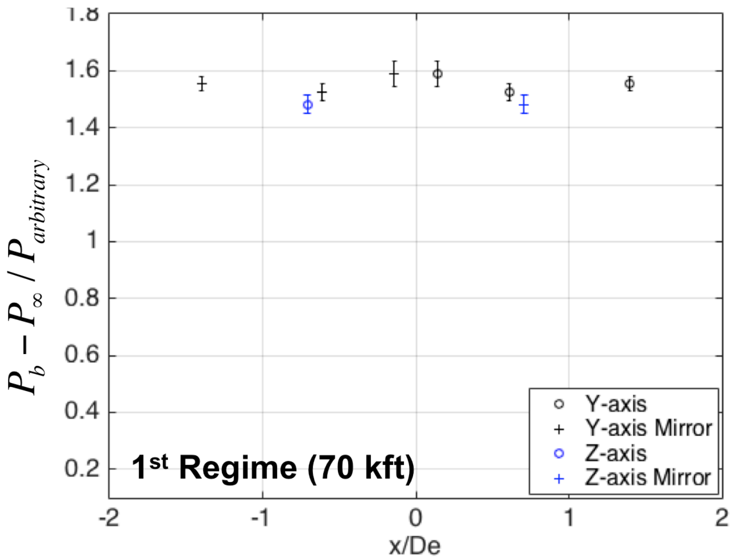
BHS Heating Contour Plots

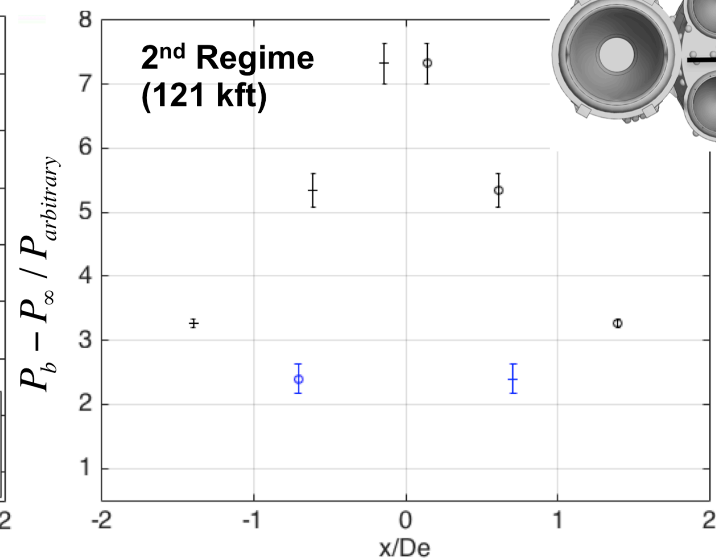


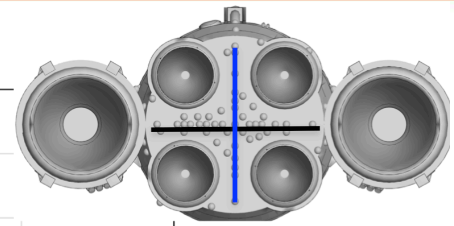
EMHS Heating Contour Plots

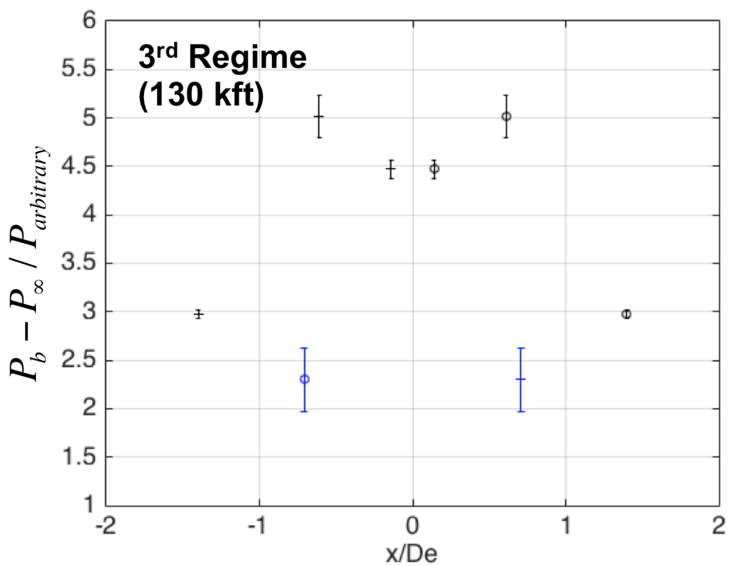


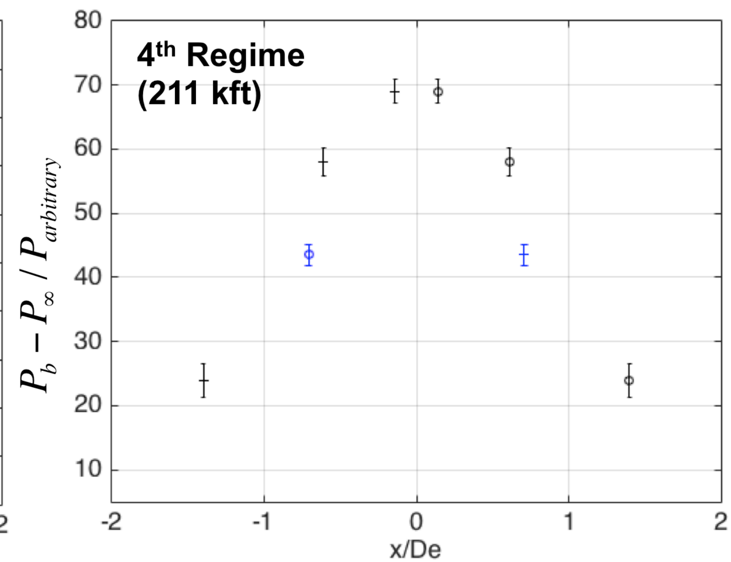
Base Pressure Spatial Profiles



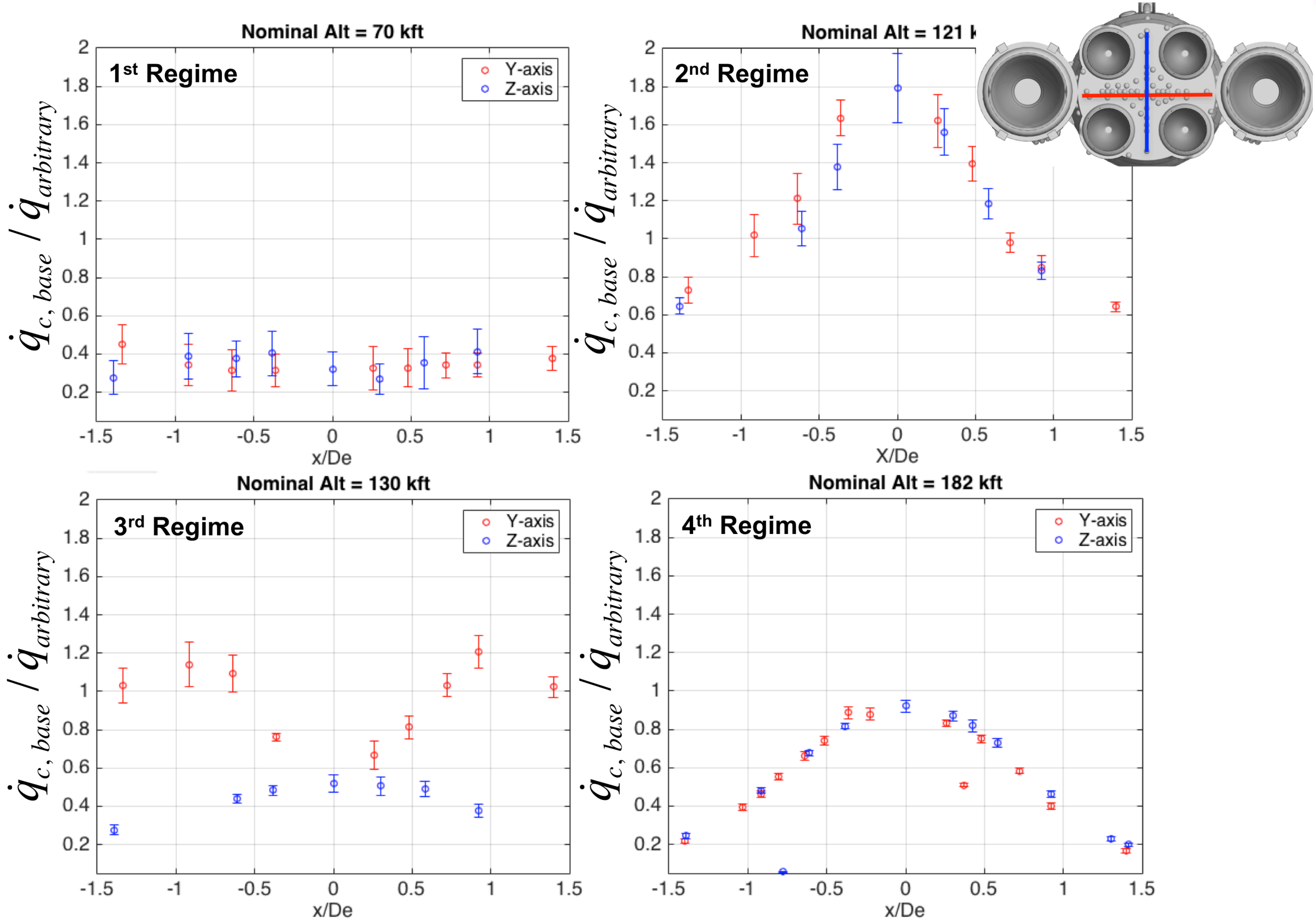




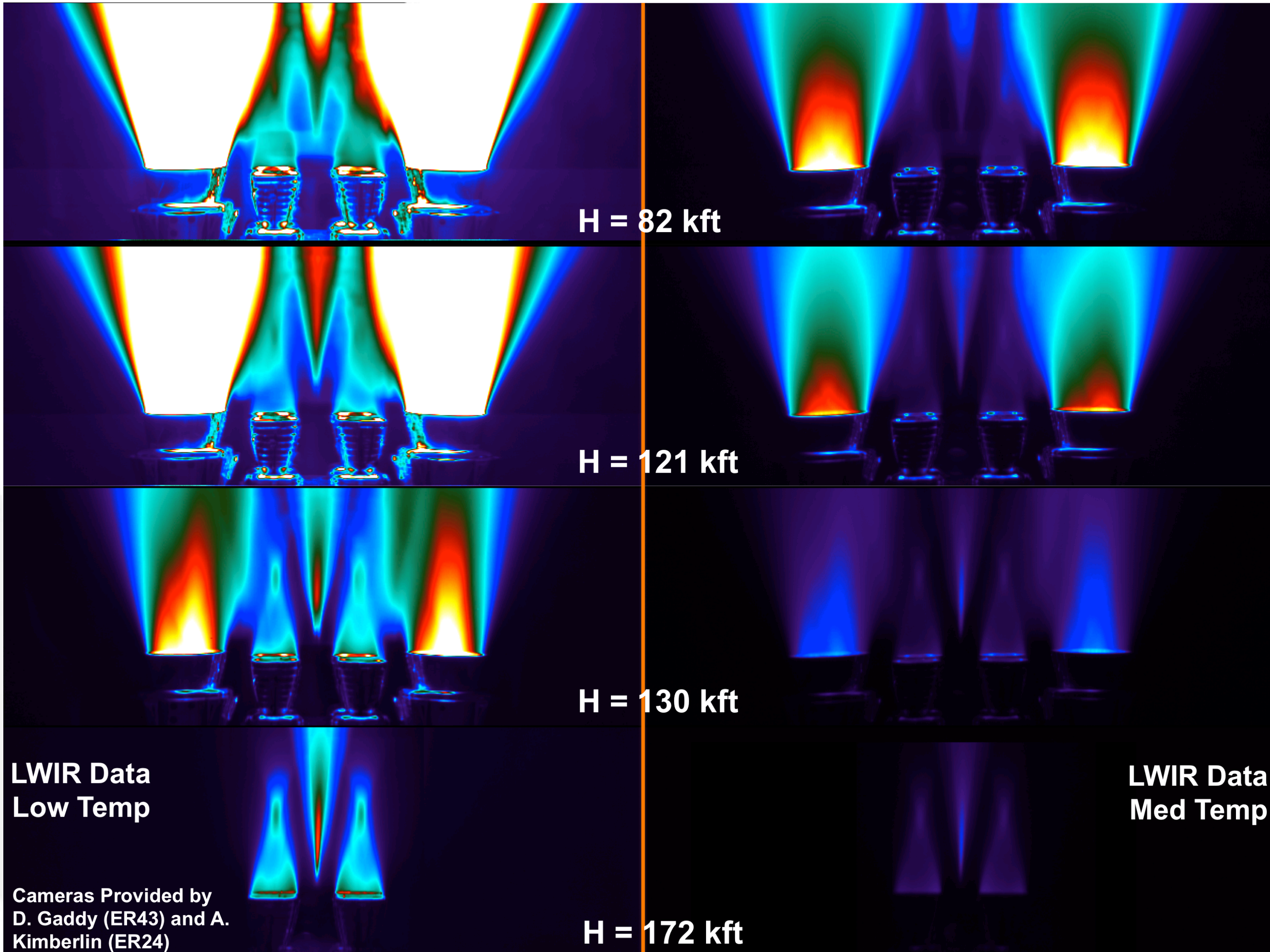




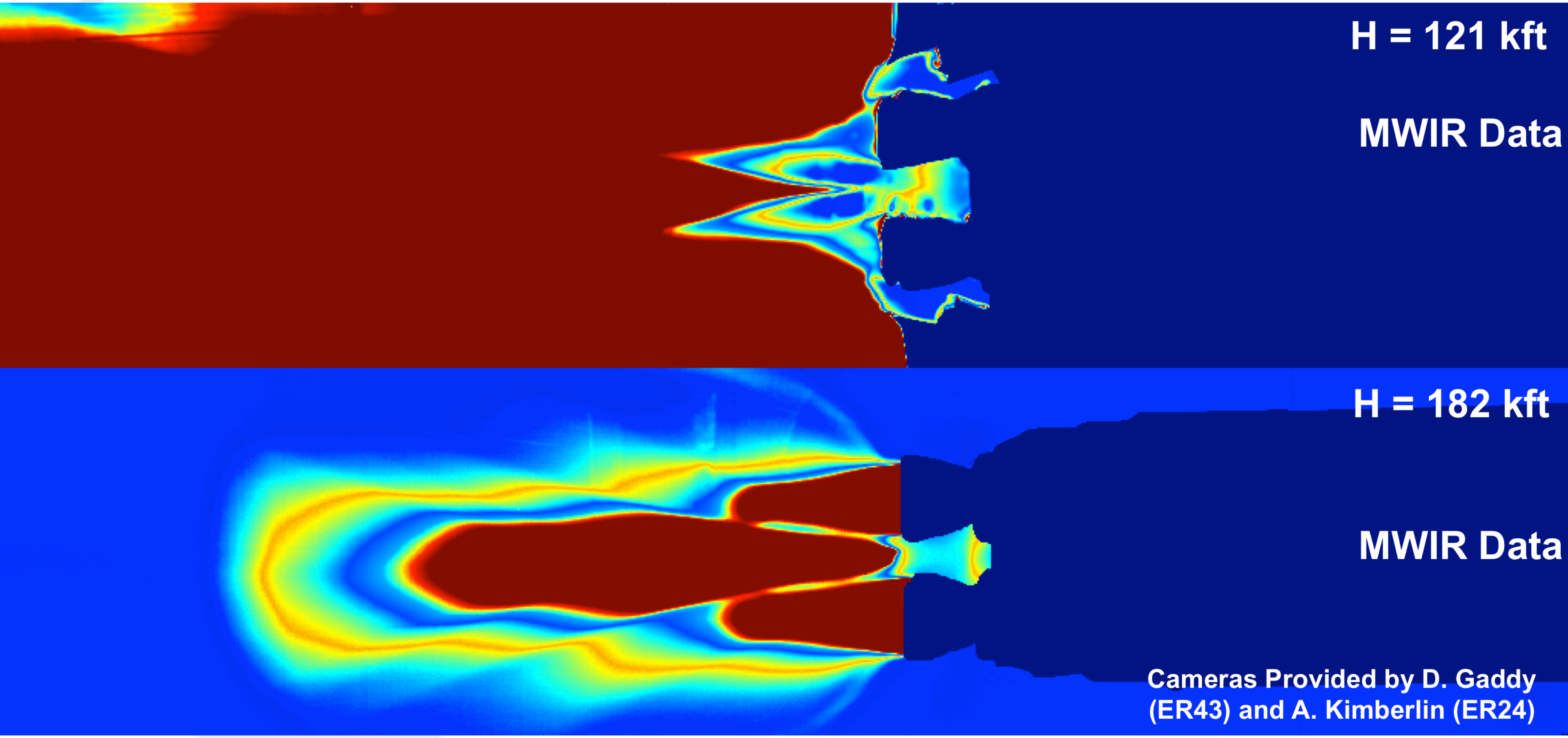
Base Heating Spatial Profiles



LWIR Imaging

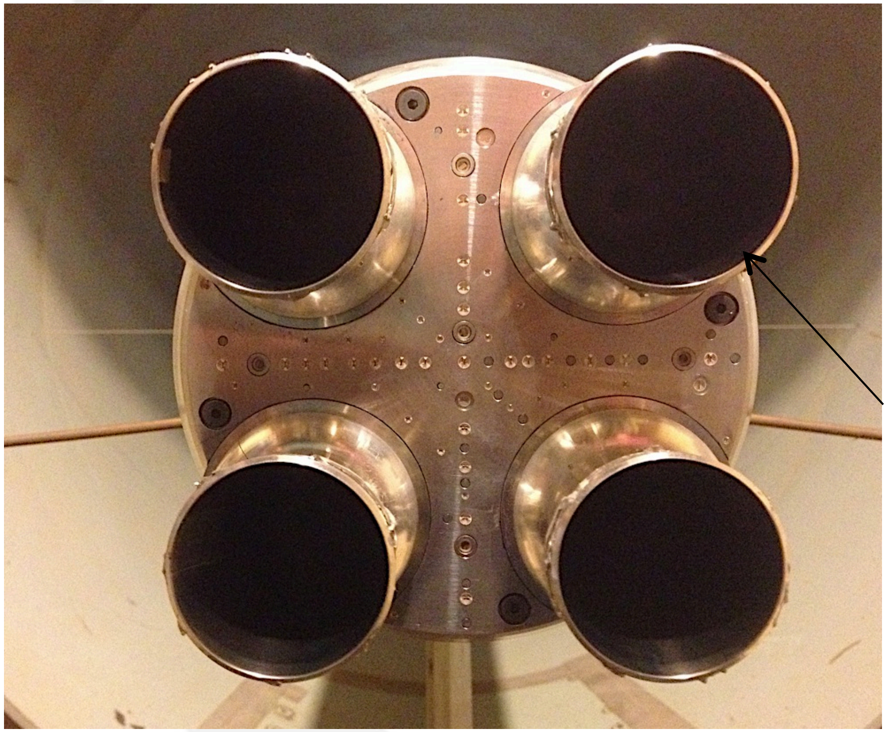


MWIR Imaging

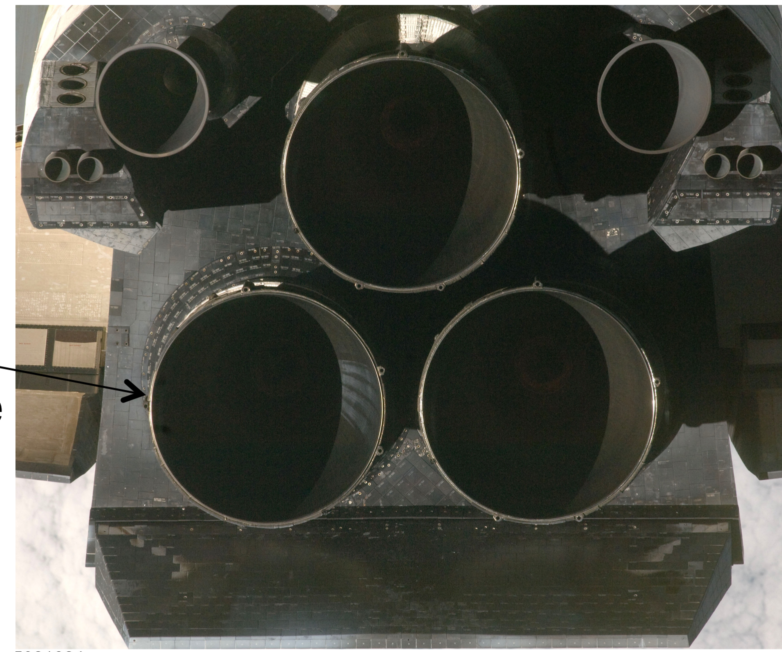


SLS and Shuttle Orbiter Base Configurations

- **ATA-002 SLS Core Base (Wind Tunnel)**
- **Space Shuttle Orbiter Base (STS-124)**



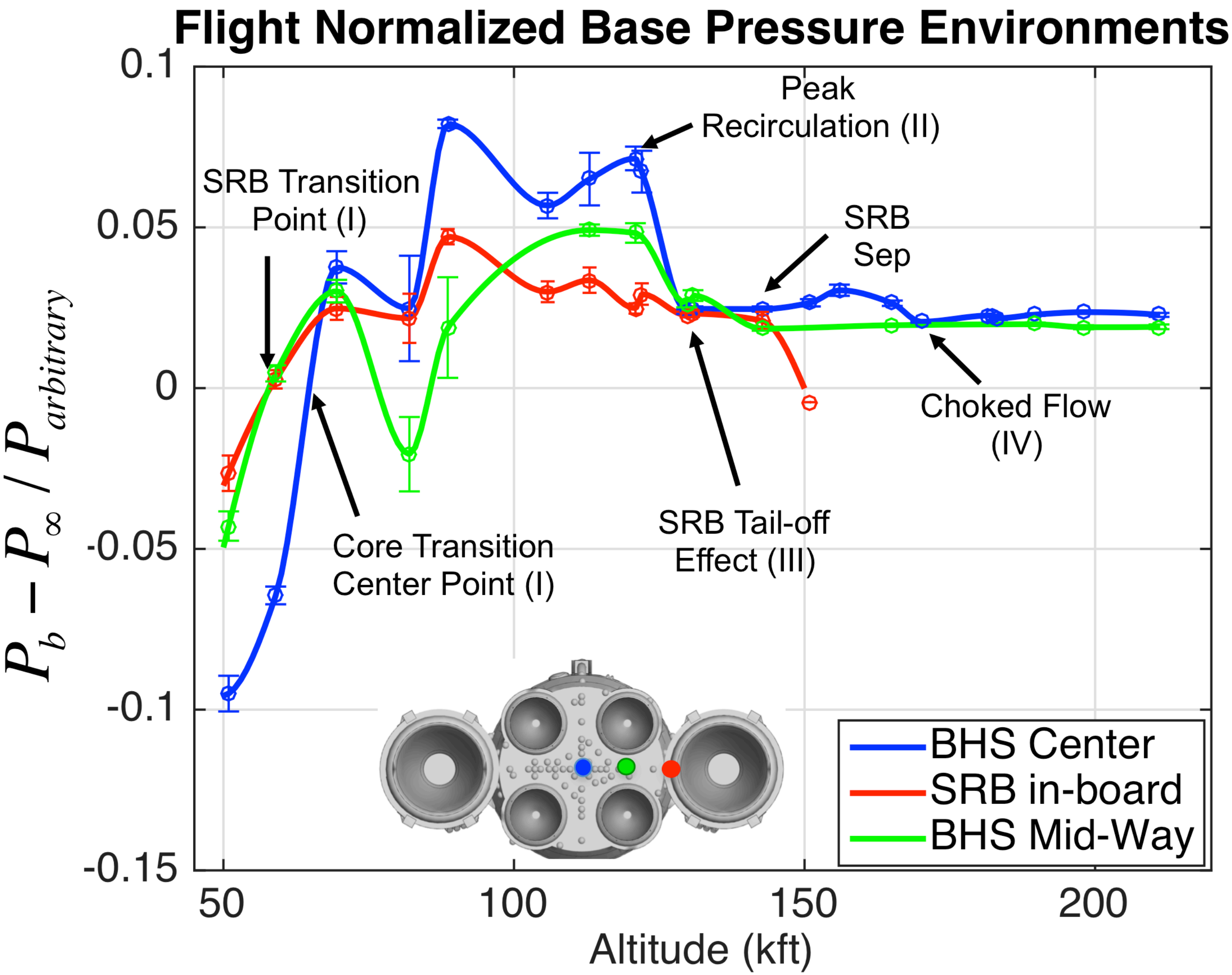
RS-25 Nozzle



BOTH IMAGES ARE TO SCALE

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

Base Pressure – Altitude Profile



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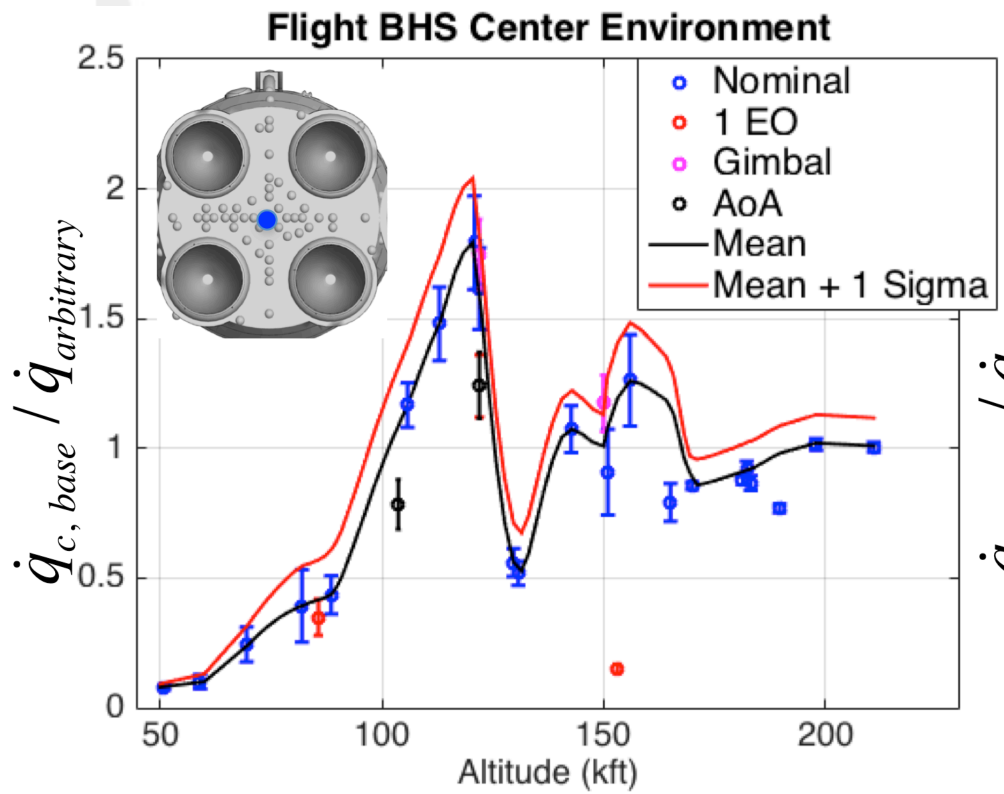
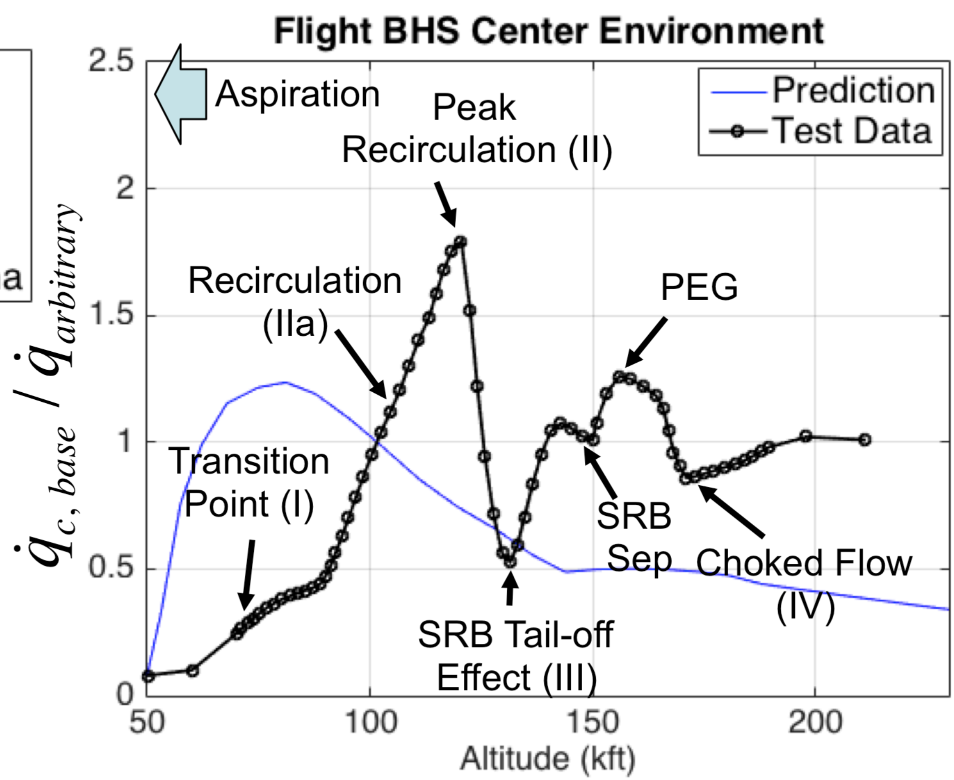
Base Heating – Altitude Profile: BHS Center

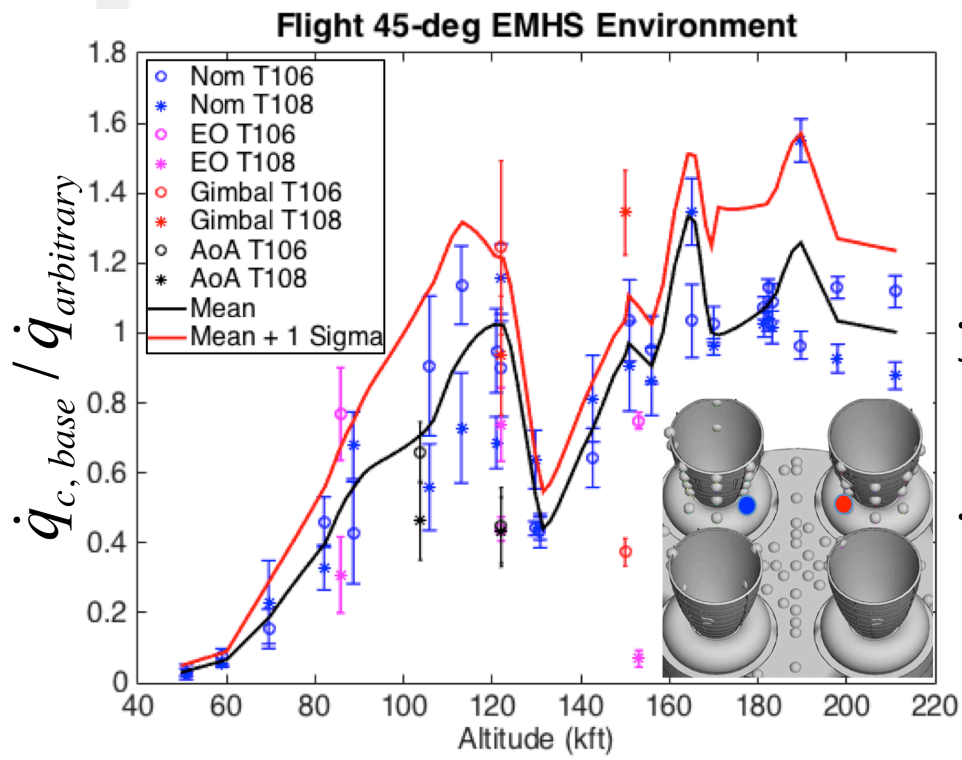
- Scaled test data, mean and mean + 1 sigma data profiles
- Mean data and prediction profiles

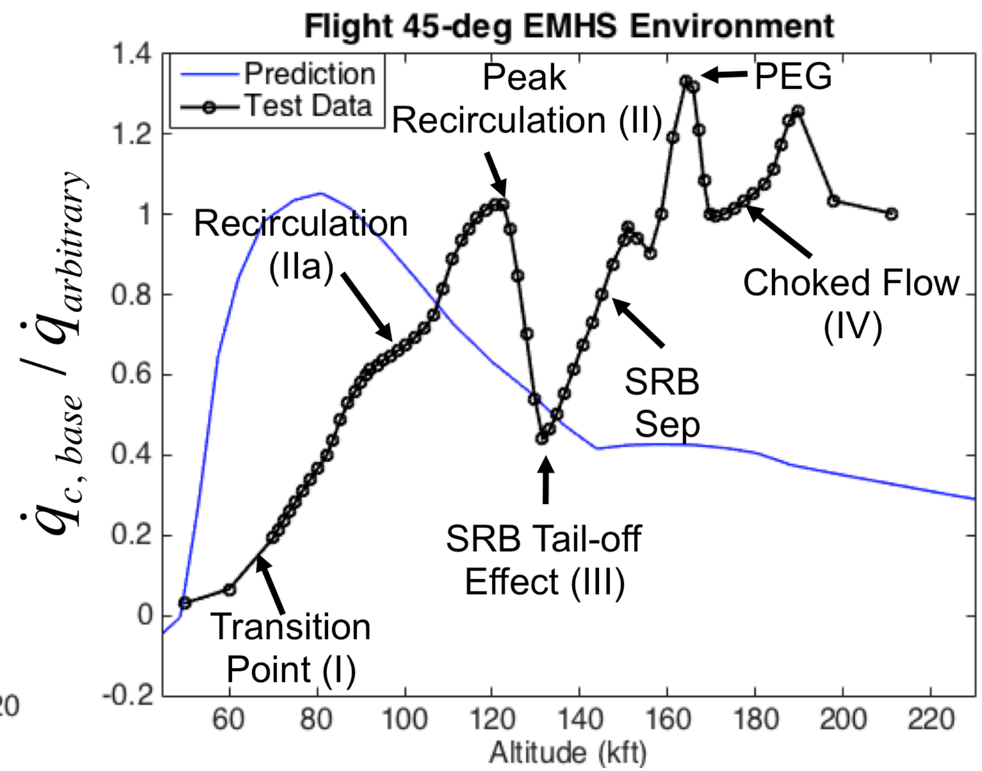




Base Heating – Altitude Profile: EMHS

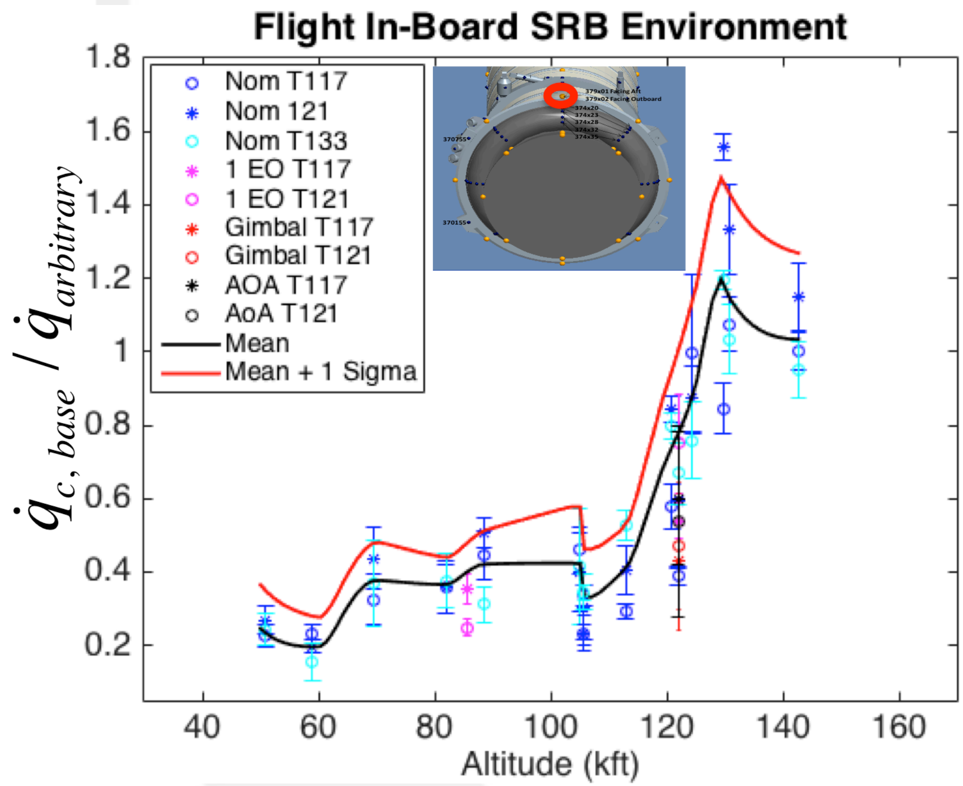
- Scaled test data, mean and mean + 1 sigma data profiles
- Mean data and prediction profiles

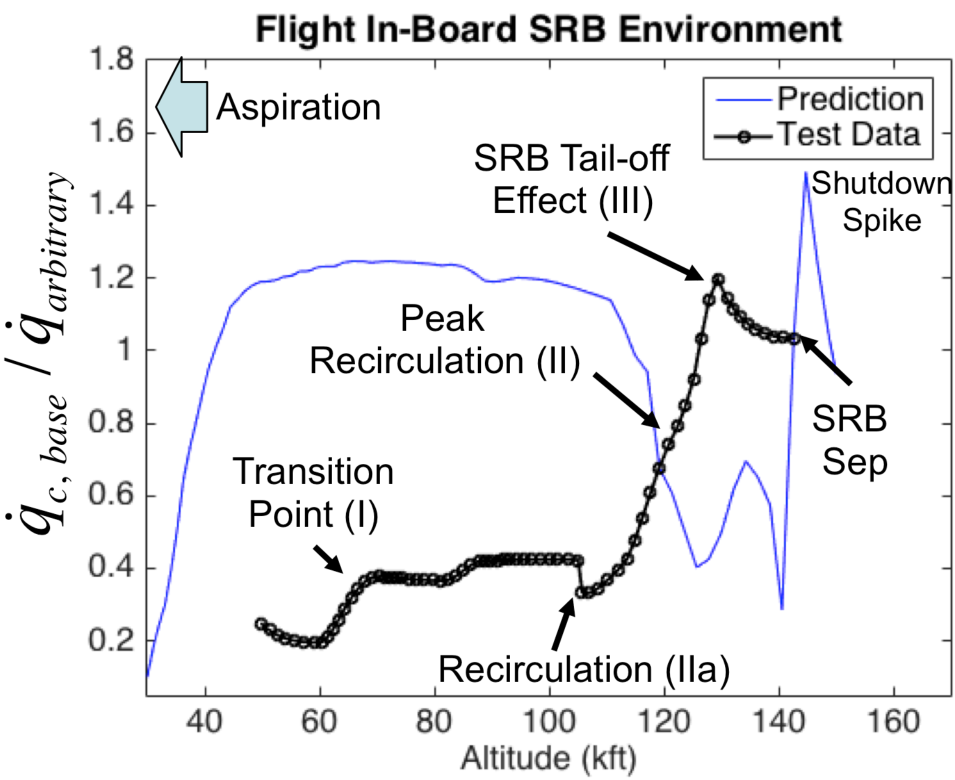




Base Heating – Altitude Profile: SRB Base

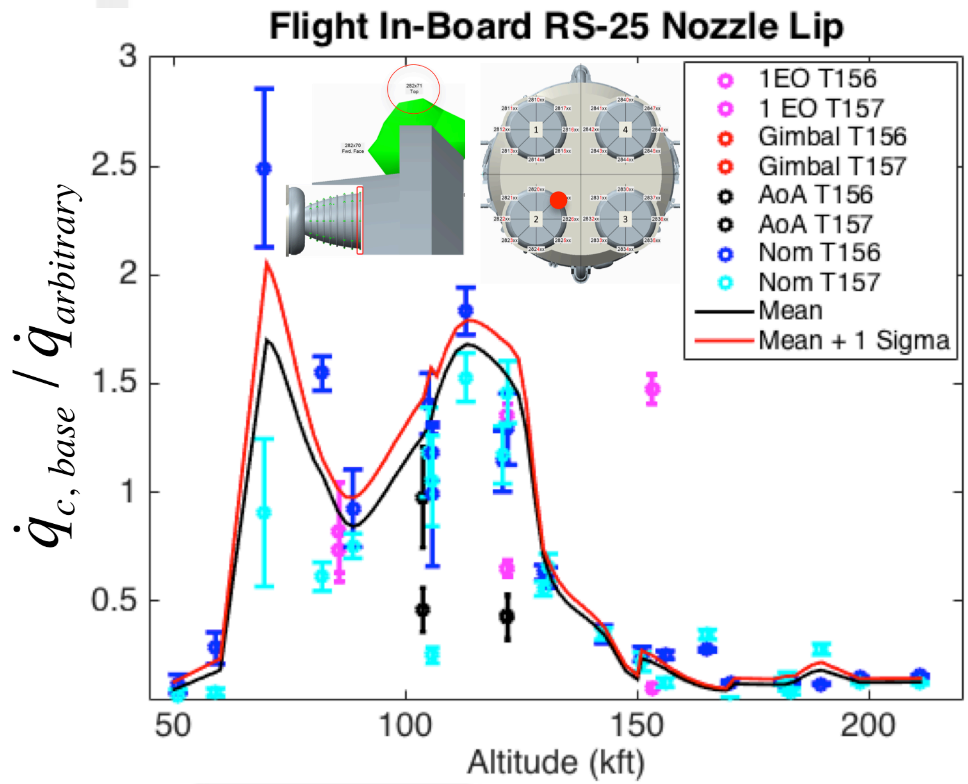
- Scaled test data, mean and mean + 1 sigma data profiles
- Mean data and prediction profiles

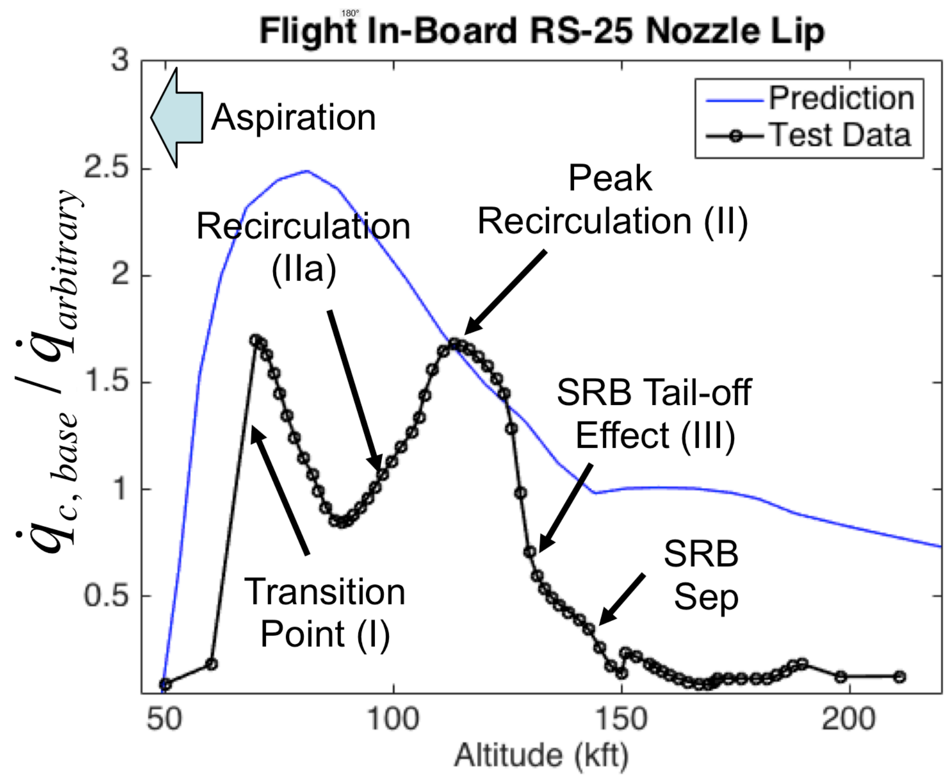




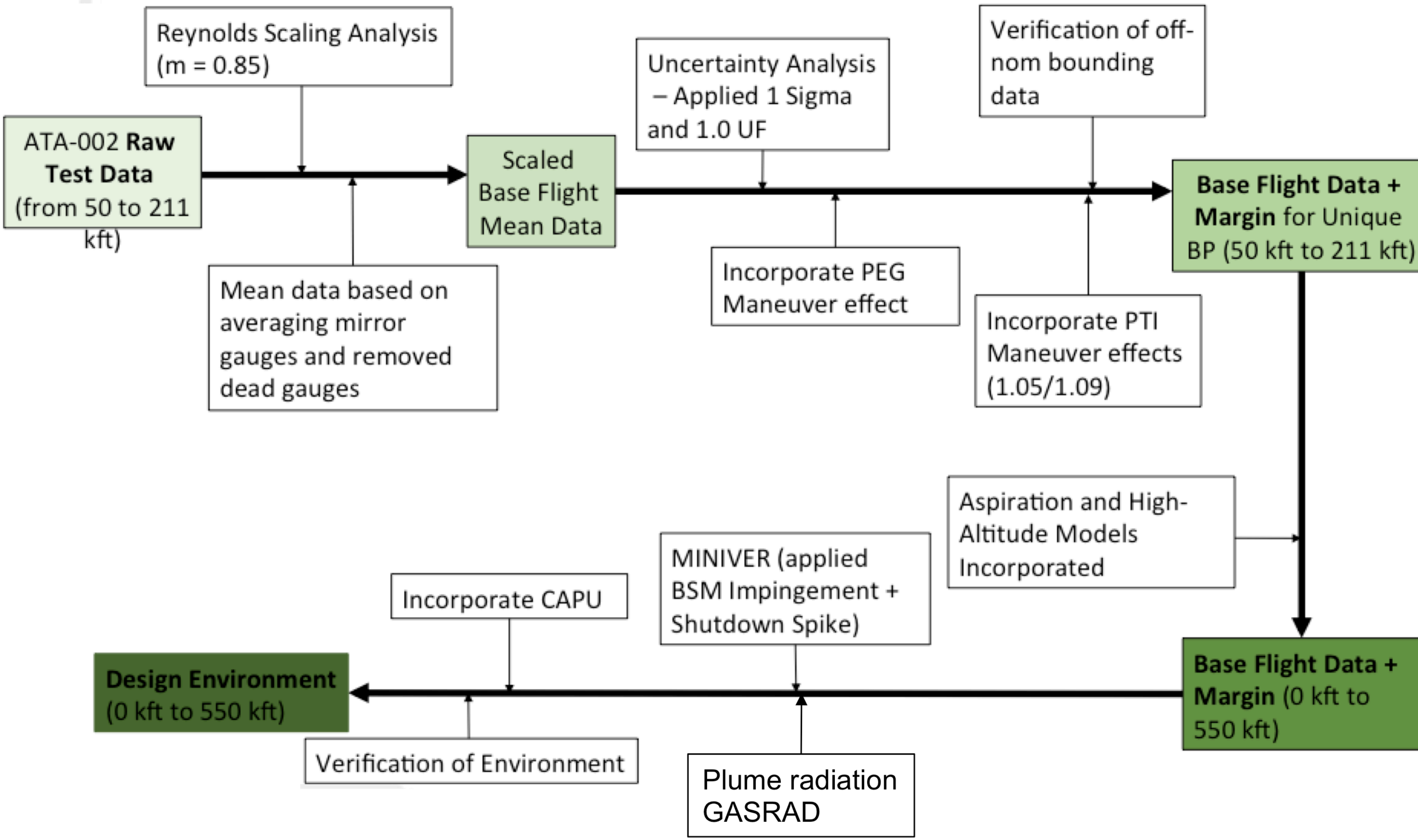
Base Heating – Altitude Profile: RS-25 Nozzle

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





SLS Base Design Environment Methodology



Base Heating Scaling Methodology

$Nu_b = C\,\mathrm{Re}_b^m \mathrm{Pr}_b^n$

Assuming: (1) $\mathrm{Pr}_{test} = \mathrm{Pr}_{flight}$ (O/F ratio matched)

(2) $T_{g-test} = T_{g-flight}$ (O/F ratio matched)

(3) $\left(\dfrac{P_{lip}}{P_\infty}\right)_{test} \approx \left(\dfrac{P_{lip}}{P_\infty}\right)_{flight}$

(4) $P_{base} = k_2 P_c$ (Valid based on theory)

$\dot{q} \propto k_1 P_b^m D^{m-1} = k_1 k_2 P_c^m D^{m-1}$ (assuming $P_b = k_2 P_c^1$)

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

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

$T_{r,flight} \sim T_{r,test} \longrightarrow$ TDLAS - Parker et al Paper[6]

$h_{flight},\ T_{r,flight},\ \left(\dfrac{P_{lip}}{P_\infty}\right)_{flight}$

$+$ Trajectory Information $\Rightarrow \dot{q}_{conv,flight}$

- ATA-002 data scaled to flight conditions using classic Colburn scaling methodologies [7]

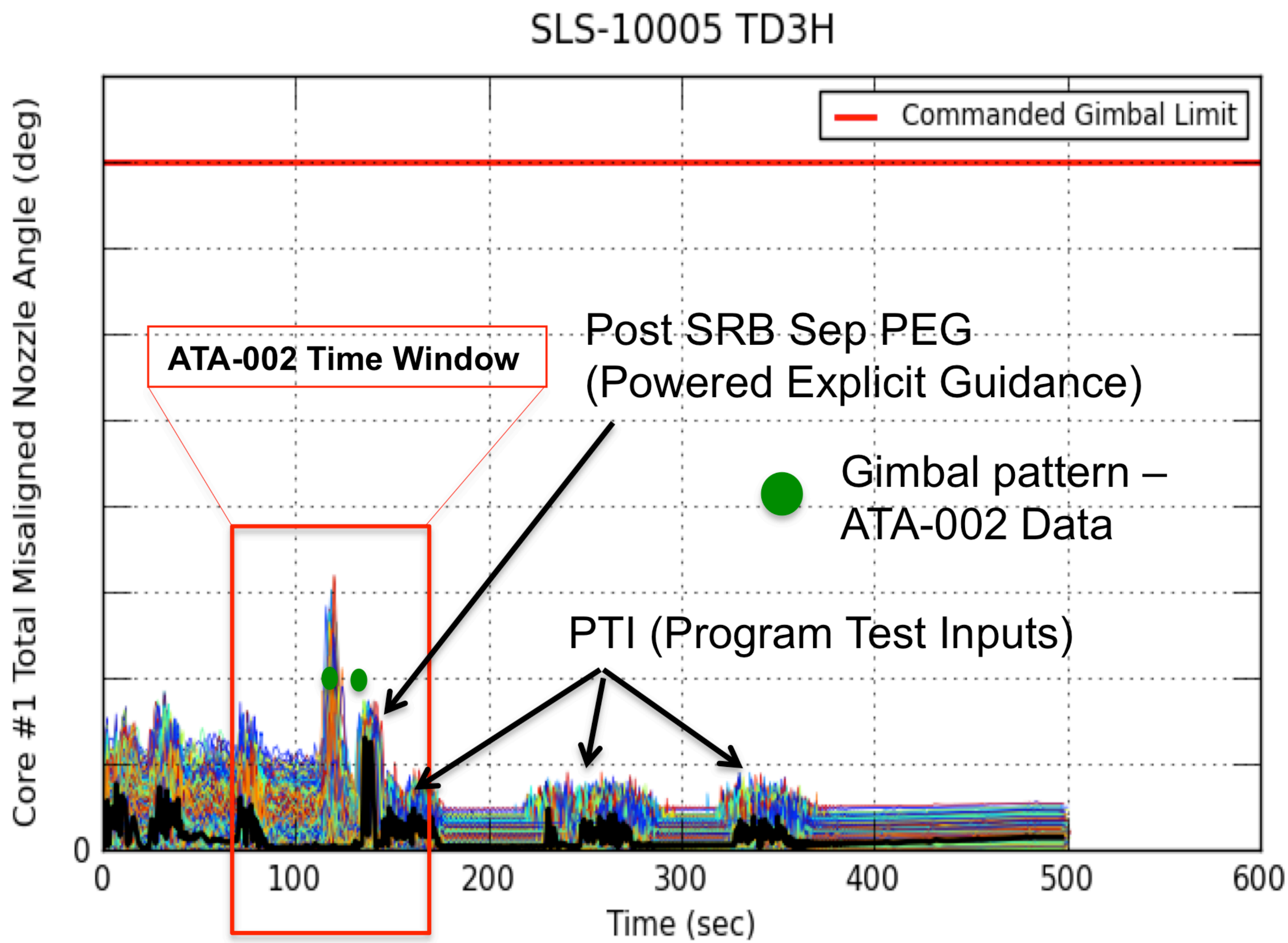
Reynolds exponent is within a narrow band of values of 0.88 and 0.82

Flow	m exponent	Re
Incompressible*	0.844	1E5 – 1E9
Compressible**	0.883	1E5 – 1E9
Incompressible*	0.822	1E5 – 1E7
Compressible**	0.861	1E5 – 1E7
Re Scale Tests***	0.820	4E3 – 1E4

***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**

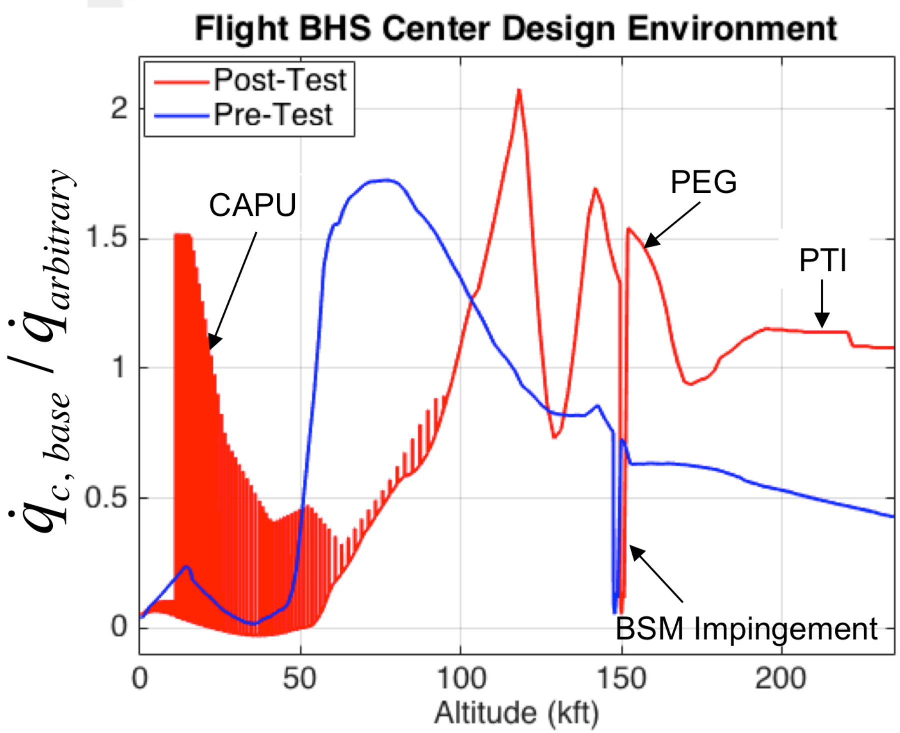
Recommend a mean Reynolds exponent (m) of 0.85 – most representative exponent for expected Re range

SLS Vehicle Maneuvers

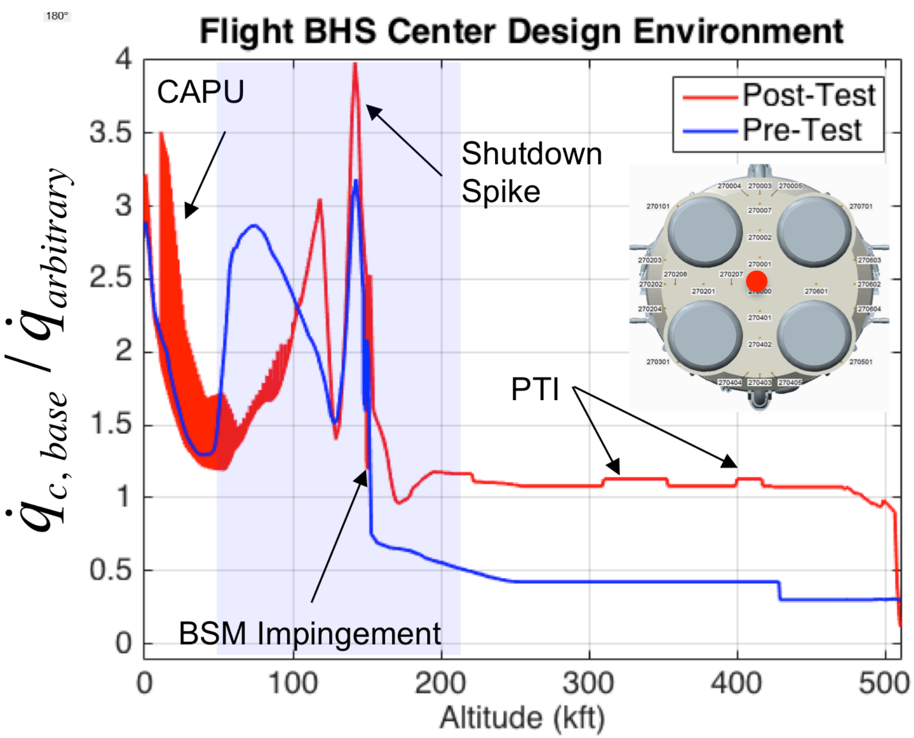


Design Environment: BHS Center

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

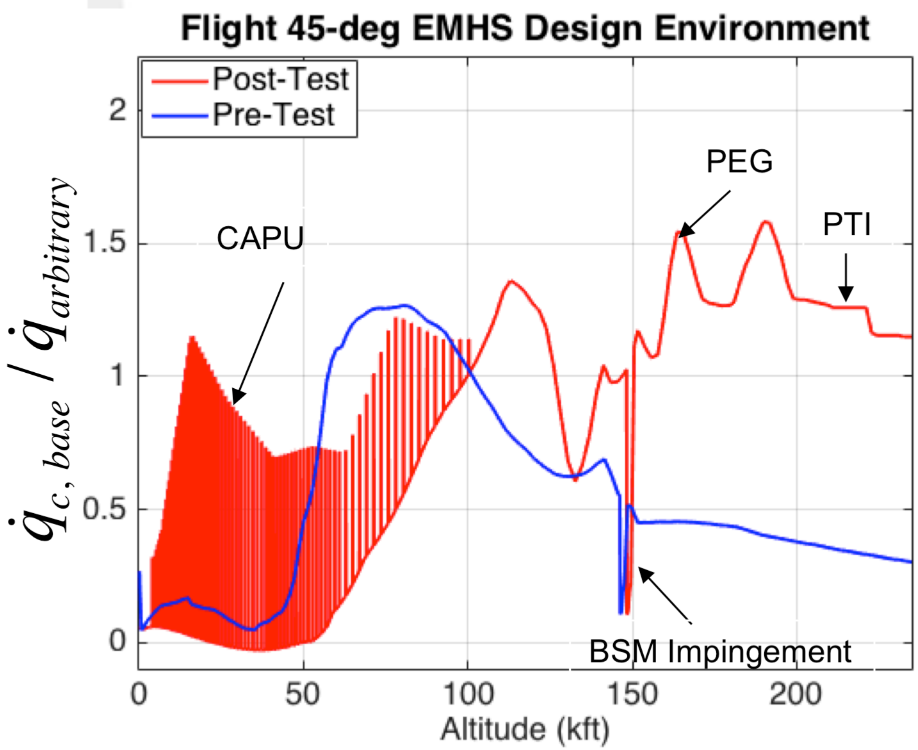


- Post-test and pre-test total heating design environments

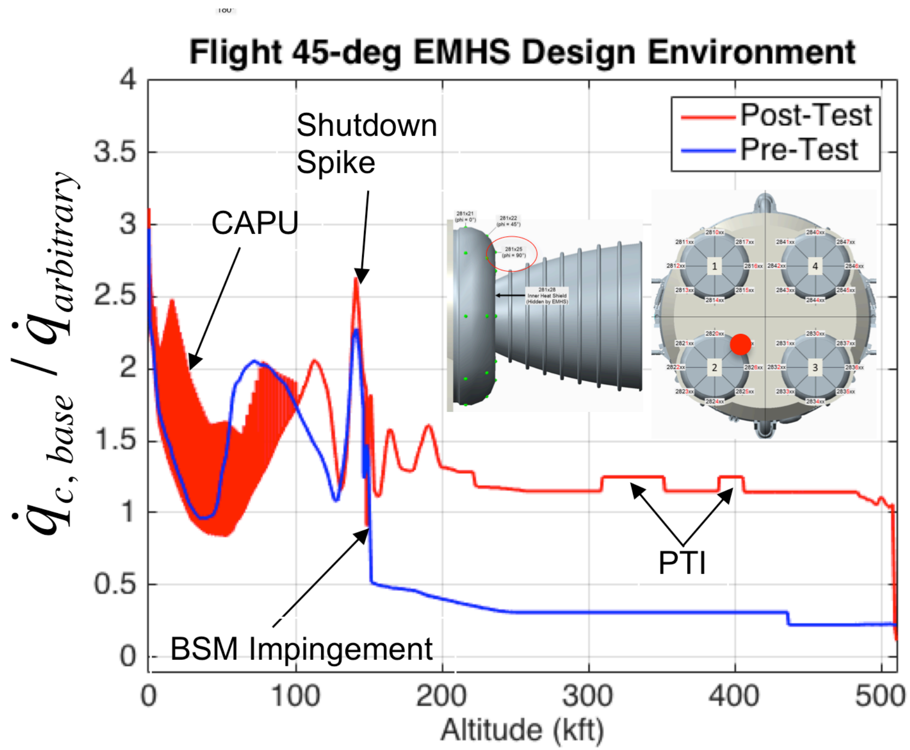


Design Environment: EMHS

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

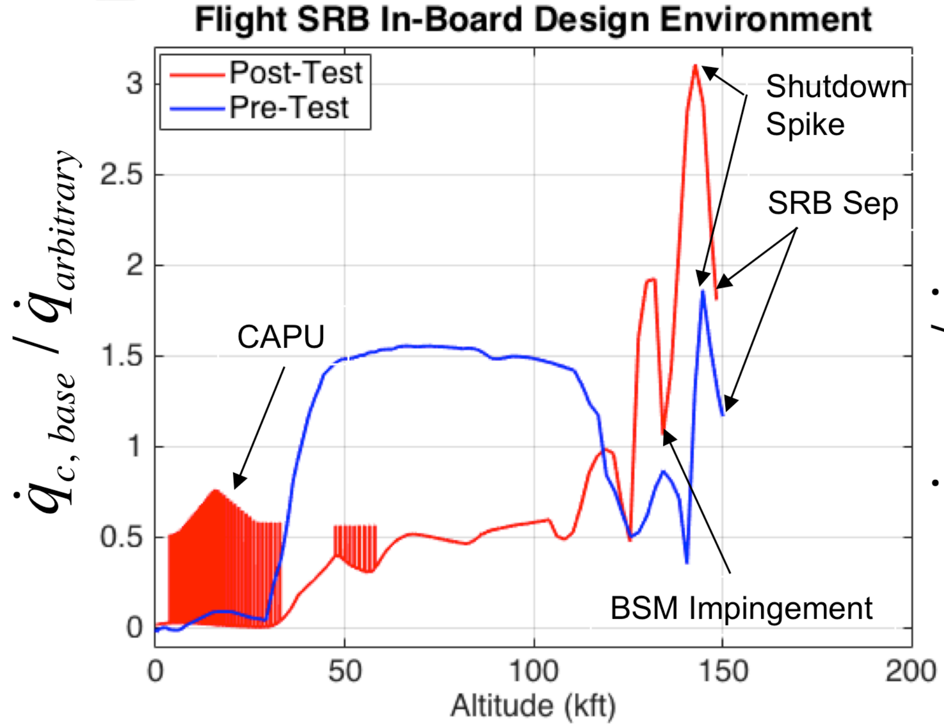


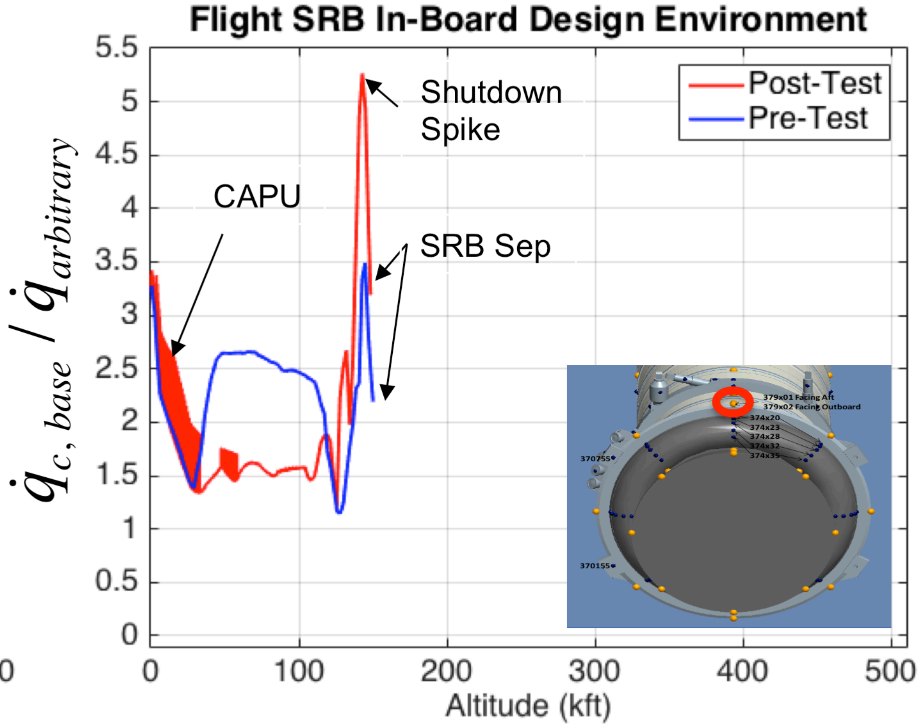
- Post-test and pre-test total heating design environments



Design Environment: SRB Base

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

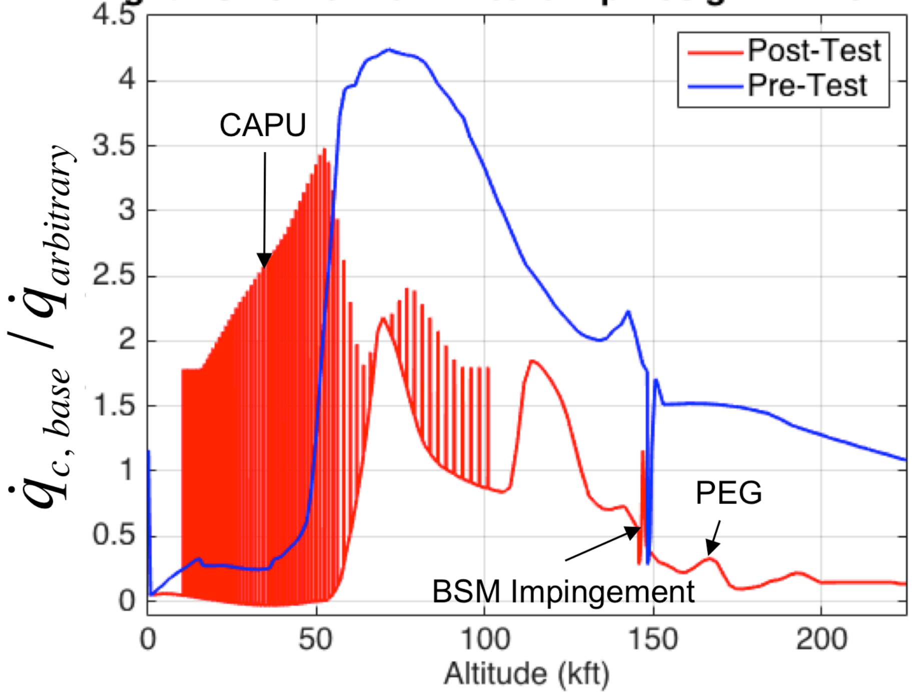




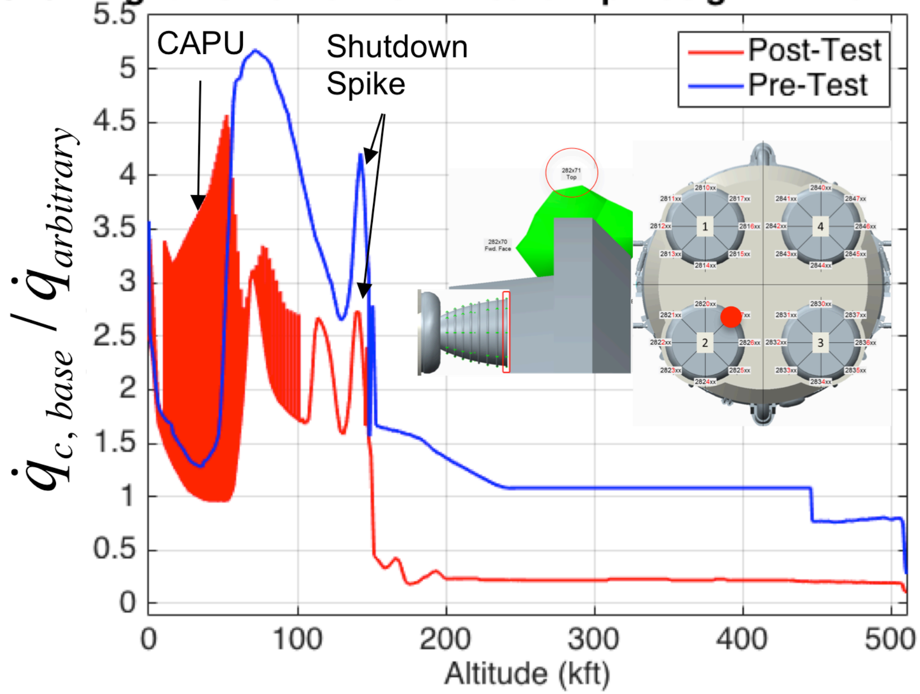
Design Environment: RS-25 Nozzle

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

Flight RS-25 Nozzle In-Board Lip Design Environment



Flight RS-25 Nozzle In-Board Lip Design Environment

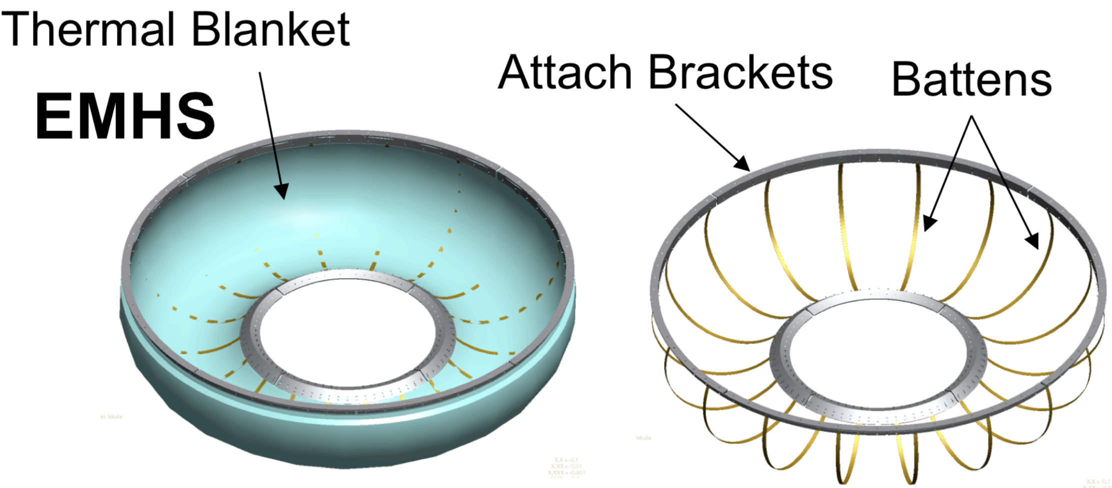


Design Environment: Base Heat Load

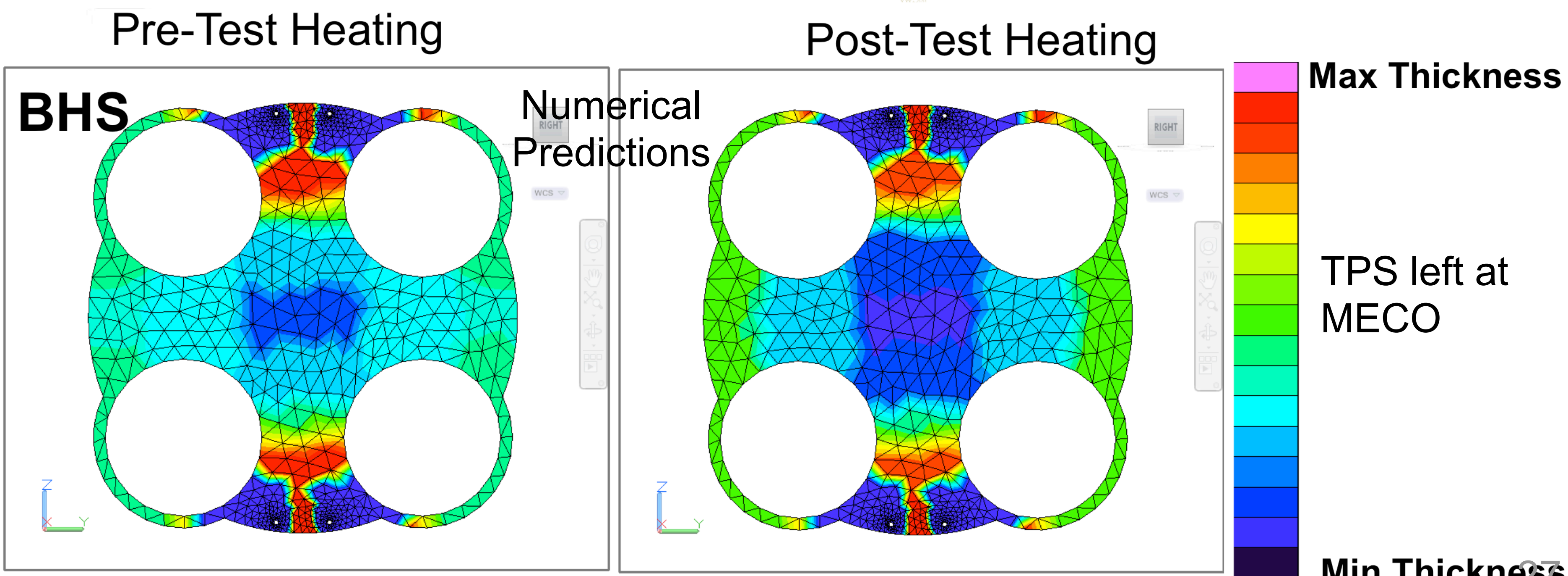
- Heat load drives the TPS thickness and heating rate drives TPS type
- Highest heat load deviation from the pre-test environments are: BHS, EMHS in-board and RS-25 nozzle HB #3

Base Regions	Normalized Values		
	Post-Test Heat Load	Pre-Test Heat Load	Post/Pre Heat Load Ratio
BHS Center	9.9	6.6	1.5
EMHS 45-deg In-Board (phi = 45 deg)	9.4	5.0	1.9
EMHS 45-deg In-Board (phi = 0 deg)	8.2	2.4	3.5
SRB In-Board Base	4.1	4.7	0.9
RS-25 In-Board Nozzle Lip	4.9	11.2	0.4
RS-25 In-Board Nozzle Hat-Band 3	10.0	5.1	2.0

Thermal Analysis: BHS and EMHS



- 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



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

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), <u>Fundamentals of Heat and Mass Transfer</u>, John Wiley & Sons, Inc., Hoboken, NJ.

Acknowledgements

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