National Aeronautics and Space Administration

Launch Vehicle Base Flows:
SLS Base Convective Environments

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marshall

Advanced Modeling & Simulation Seminar Series
NAS Division, NASA Ames Research Center

Road Map & Acknowledgement

- **Discipline Background**
- **Launch Vehicle Base Flow Physics**
- **Ground Testing**
- **SLS Base Flow Physics**
- **Development and Impact of Design Environments**

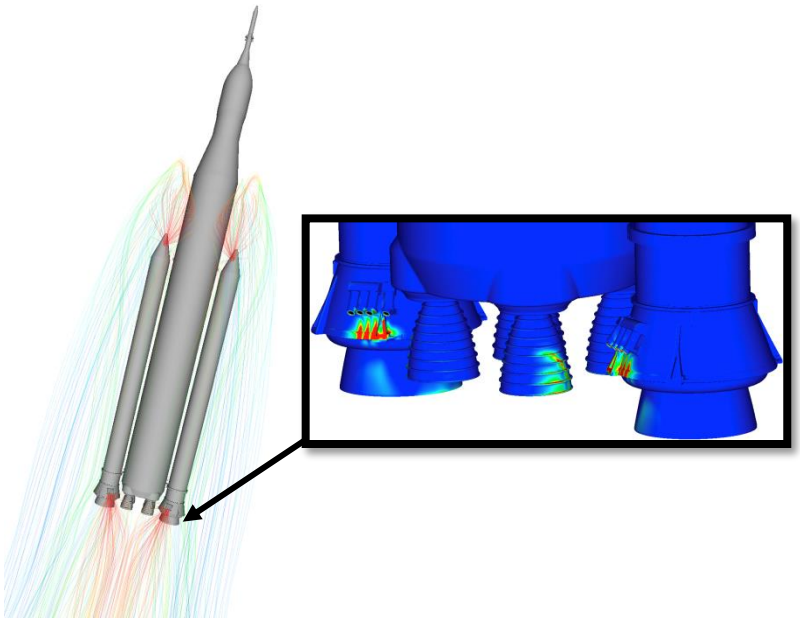
- *All the material here has been approved for public release through past AIAA and TFAWS presentations*

- Dr. Chris Morris (MSFC Aerosciences Branch Chief)
- Brandon Mobley (MSFC Aerothermodynamics Team Lead)
- Dr. Aaron Dufrene & Dr. Ron Parker (CUBRC Aerosciences)
- Dr. Mark Seaford (MSFC – retired)
- Kyle Knox (MSFC Thermal Team Lead)
- Dr. Paul Danehy (LaRC Senior Researcher)
- Dr. Francisco Canabal (MSFC Aerosciences, SME)

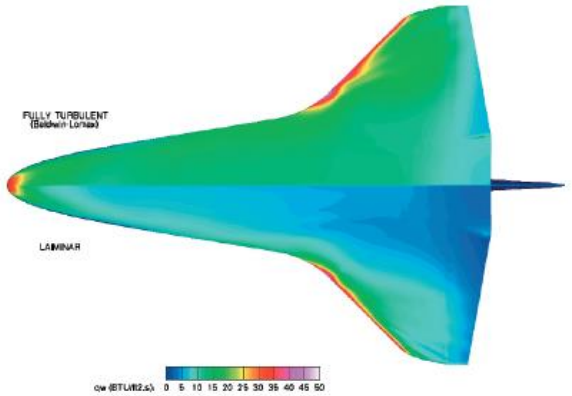
NASA Aerothermodynamics

- **Two important areas for the Agency's aerothermodynamics program**
  - Agency makes it a commitment to fully investigate the performance and environments of their vehicles

- **Rocket plume-induced environments**
  - Launch vehicle & upper-stage base flows
  - Lander base flows
  - Plume-induced flow separation (PIFS)
  - Plume impingement
    - Stage Separation Motors
    - Attitude Control Motors



- **Aerodynamic flow environments**
  - Earth crew vehicle re-entry flows
    - Shuttle Orbiter
    - Apollo
  - Fuel/oxidizer tank, booster element earth re-entry
    - External Tank, SRBs
  - Launch vehicle ascent aerodynamic flow/heating
  - Planetary spacecraft re-entry flows
    - Mars Science Laboratory (MSL)



Motivation

- **Launch vehicle base flow historically show the highest heating environments during ascent**

- **Accurate base flow predictions are critical for launch vehicle (LV) mission success.**
  - Design of thermal protection system (TPS), base heat shield, engine closeouts, base plate, engine fairing, avionics and gimbal actuators
  - Decreases design margin, decreases cost and improves LV performance
  - Decreases mission risk

- **Base flows demonstrate complex flow physics**
  - No pure analytical methods have been developed for base environment prediction

- **New base geometry, ascent sequence and performance requirements for the SLS vehicle – cannot blindly use heritage data**

Launch Vehicle Failures





10+ launch vehicle failures or major concerns from the 1950s to the modern day due to base flows **

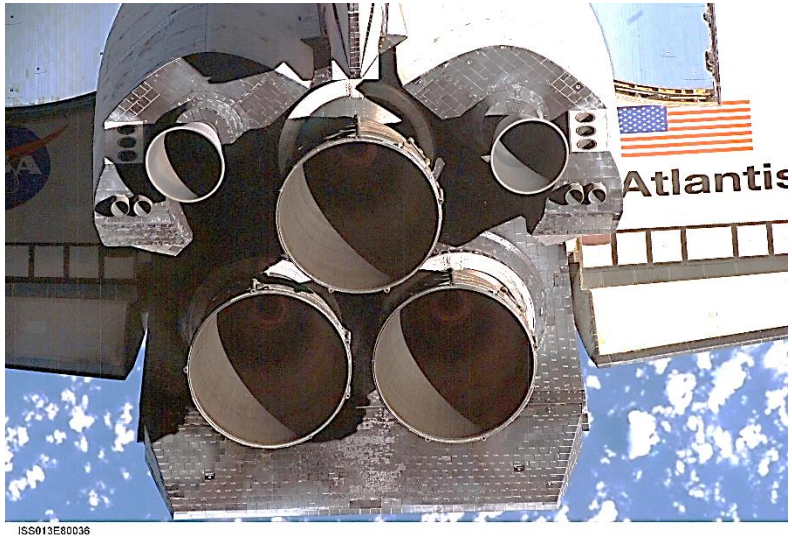
Rocket	Date	Outcome	Cause
JUPITER AM-1A	3/1/57	Failure	Base heating - Control Loss
ATLAS SM-65 A	6/11/57	Failure	Base heating - Control Loss
ATLAS SM-65 A	9/25/57	Failure	Base heating - Control Loss
THOR 114	1/1/58	Failure	Base heating - Control Loss
POLARIS A-1	12/30/58	Failure	Base heating - Control Loss
POLARIS A-1	1/9/59	Failure	Base heating - Control Loss
SATURN I	10/21/61	Concern	Base heating - Base Flow
SATURN IB	2/26/66	Concern	Base heating - Base Flow
SATURN V	11/6/67	Concern	Base heating - Base Flow
N-1 (SOVIET)	2/1/72	Failure	Base Flow - Roll Control
MAXUS (GERMAN)	5/1/91	Failure	Base heating - Control Loss
PROSPECTOR	6/19/91	Failure	Base heating - Control Loss



*** Still unresolved issues with base flow environments & TPS response to current launch vehicles*

Vandenberg AFB ICBM Failures (1960)

Launch Vehicle Base



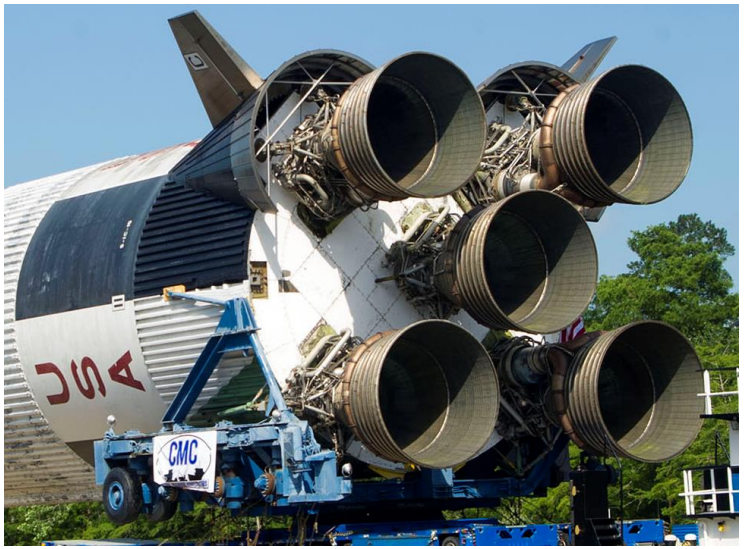
Shuttle Orbiter Base



Shuttle Base

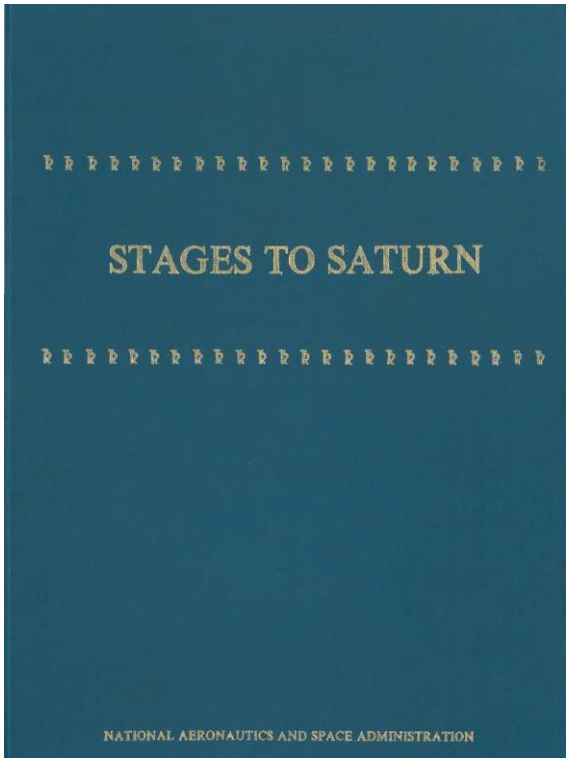


SLS Core Stage Base



Saturn V Base

Saturn IB Base Heating



More worrisome, at least in the early design stage, was the problem of base heating. Even with a rocket powered by only one engine, the flow pattern at its base proved nearly impossible to predict for the various combinations of speed and altitude. Base heating occurred when the rocket exhaust interacted with the shock waves trailing behind the vehicle. This clash created unpredictable regions of dead air and zones of turbulent mixing. Heated by the rocket exhaust, the air trapped in these areas in turn raised the heat levels at the base of the rocket to undesirable temperatures. Worse, the fuel-rich exhaust flow from the engine turbopump could get caught in these "hot-spot" regions, causing fire or explosion.

- Saturn IB had a cluster of an eight engine configuration which resembled **"Pandora's Box"** of base heating
- Saturn IB was designed to minimize "hot spots" within the base
- Four closely clustered engines minimized base heating
- Lower skirt was designed to direct high energy air towards the four central engines
- Heavy heat shield was developed between the central engines

Base Flow Field



NASA MSFC Digitized 35 mm Apollo 8

Limited & unsuccessful numerical and analytical studies have been conducted to fully characterize multi-engine plume base flows.

For the following reasons:

1. Complex flow physics

2. Unsteady turbulent/laminar flow

3. Reacting flow

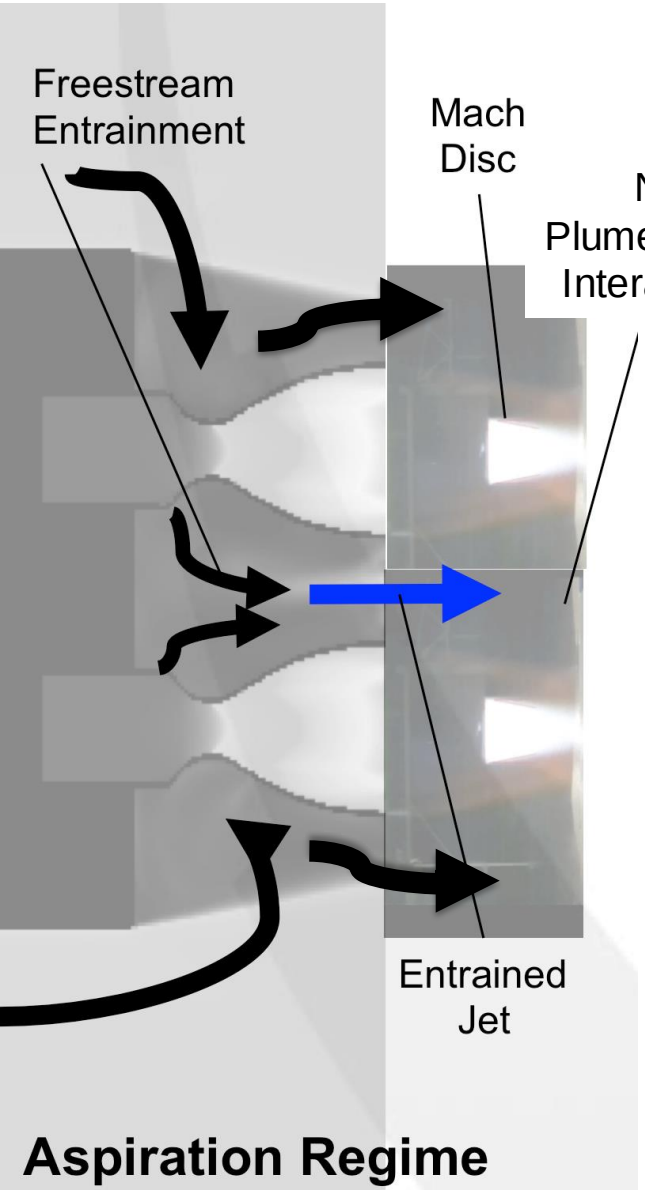
4. Many interacting flow features & species

5. Sensitive to engine performance, combustion chemistry, base configuration and ascent trajectory

6. Different flow physics and flow regimes dependent on altitude (e.g. continuum, rarefied, etc.)

Base Flow Physics

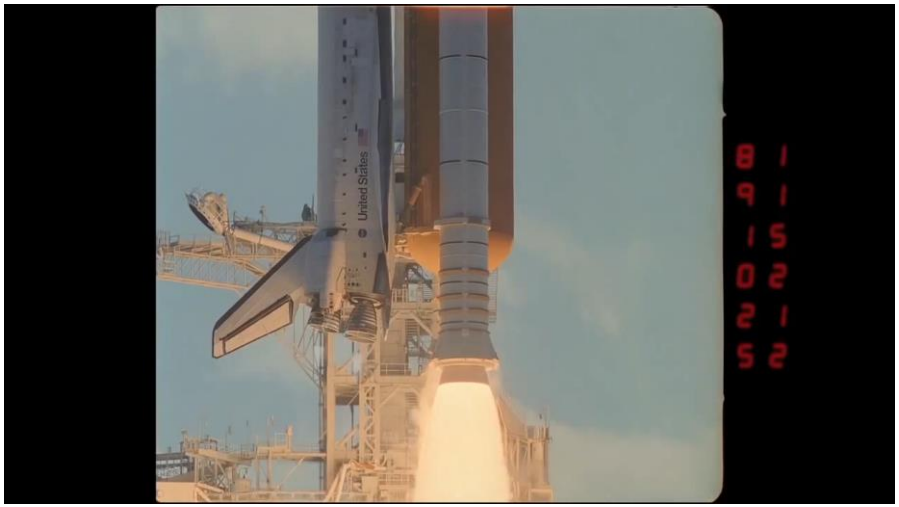
Highly Over-Expanded Rocket Plumes



NASA MSFC Digitized 35 mm Apollo 8

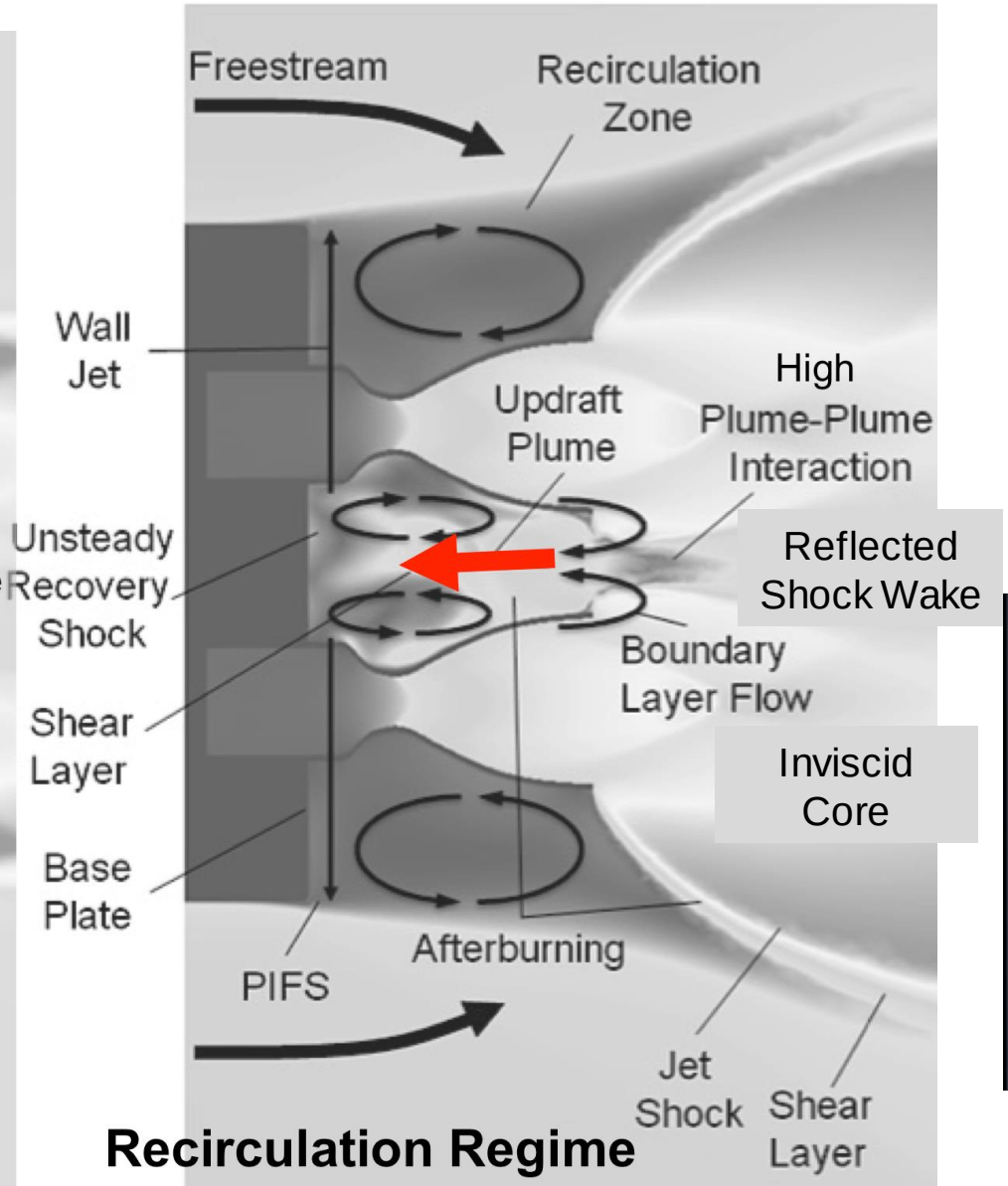


NASA "Best of the Best Shuttle Clips"



Base Flow Physics

Highly Under-expanded Rocket Plumes

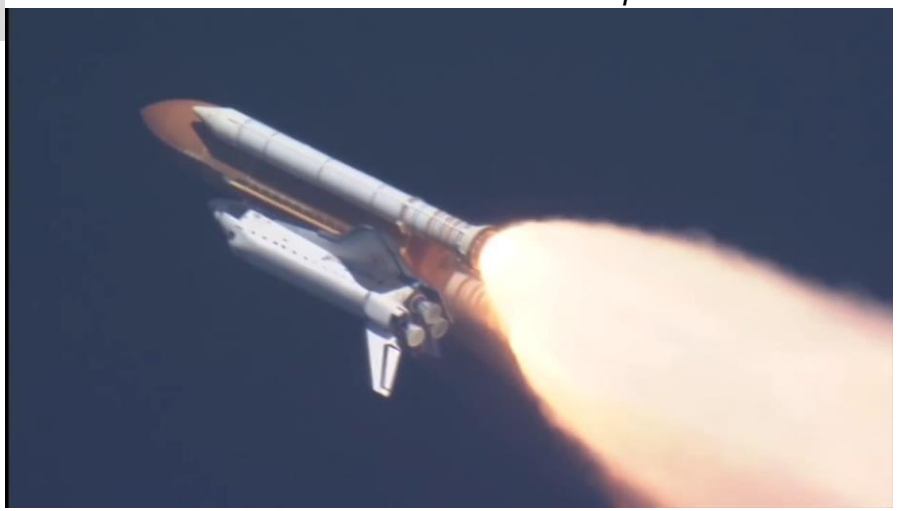


Recirculation Regime

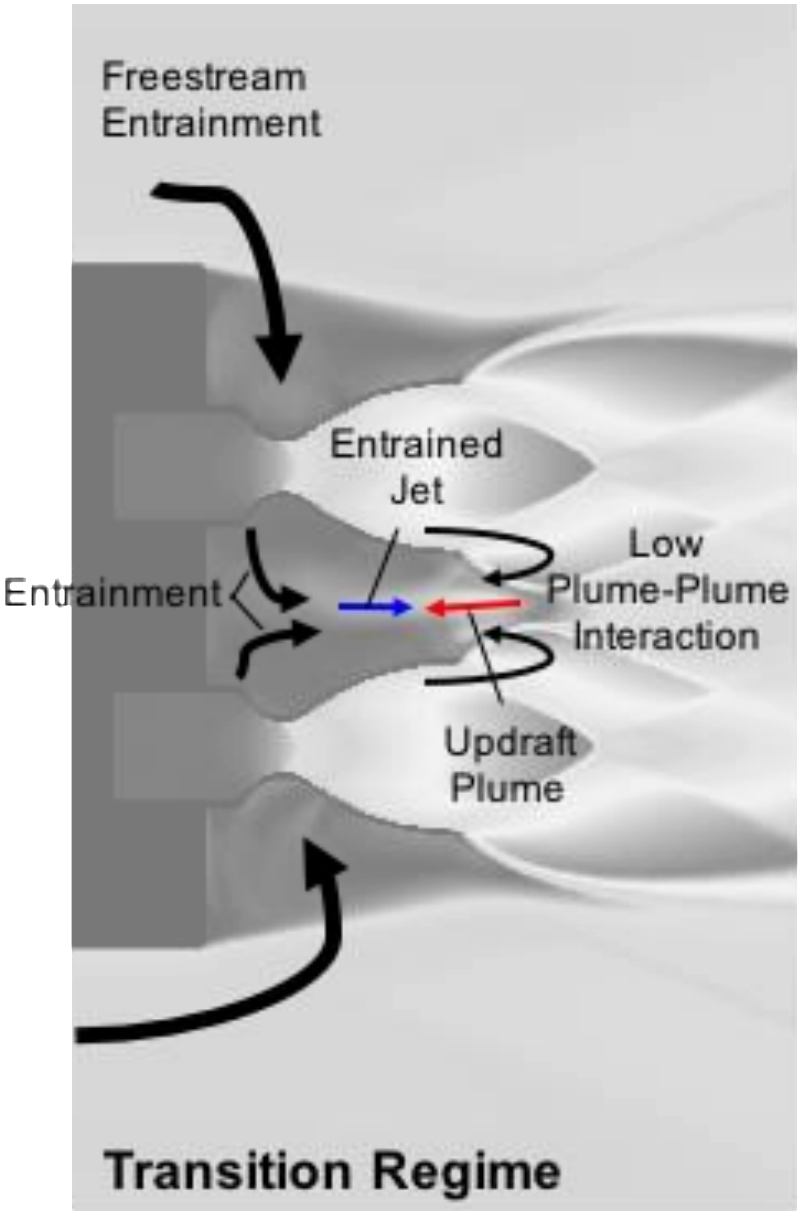
NASA MSFC Digitized 35 mm Apollo 8



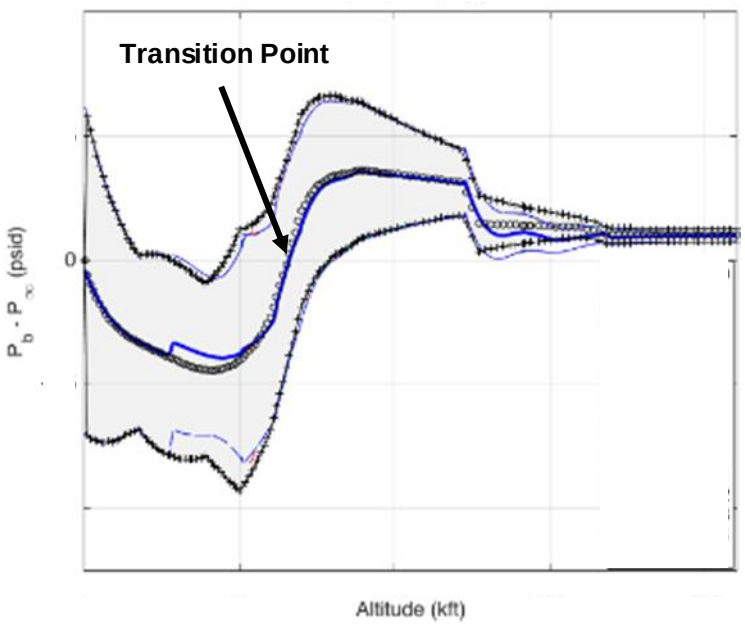
NASA "Best of the Best Shuttle Clips"



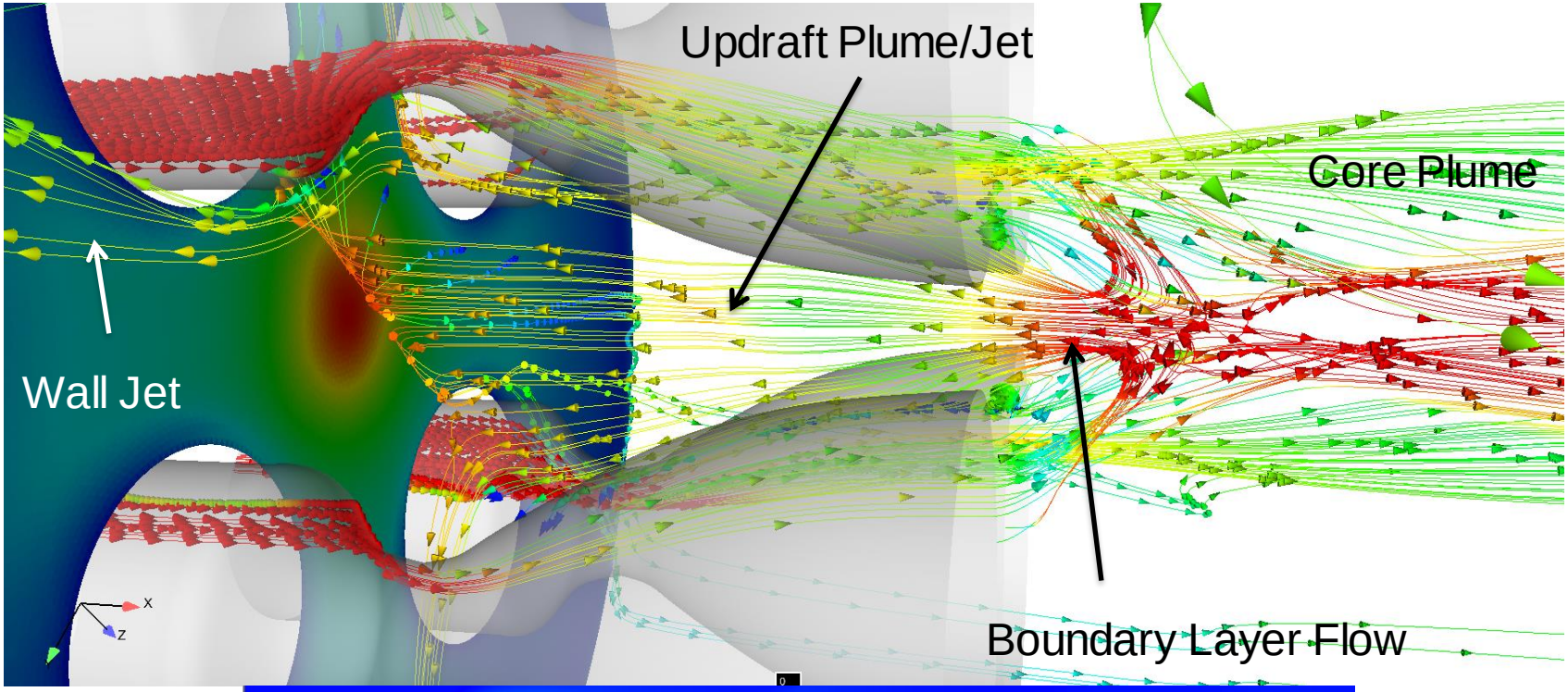
Base Flow Physics

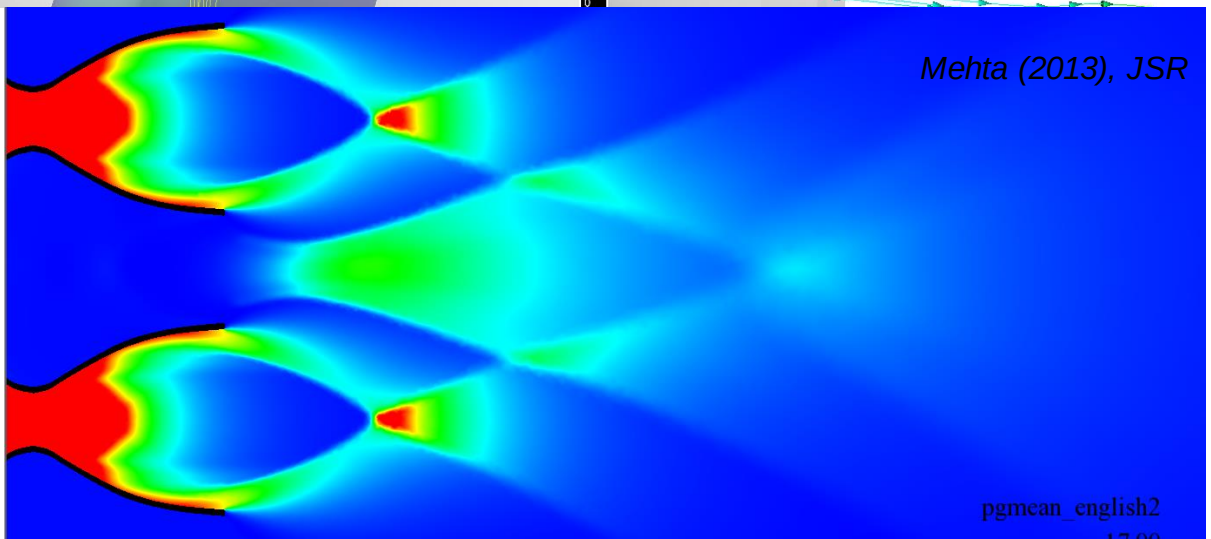


- Transition occurs when entrained air jet balances the updraft rocket plume (reverse jet)
- Nulls the differential base pressure and convective heating rates
- Defines when positive heat load is observed



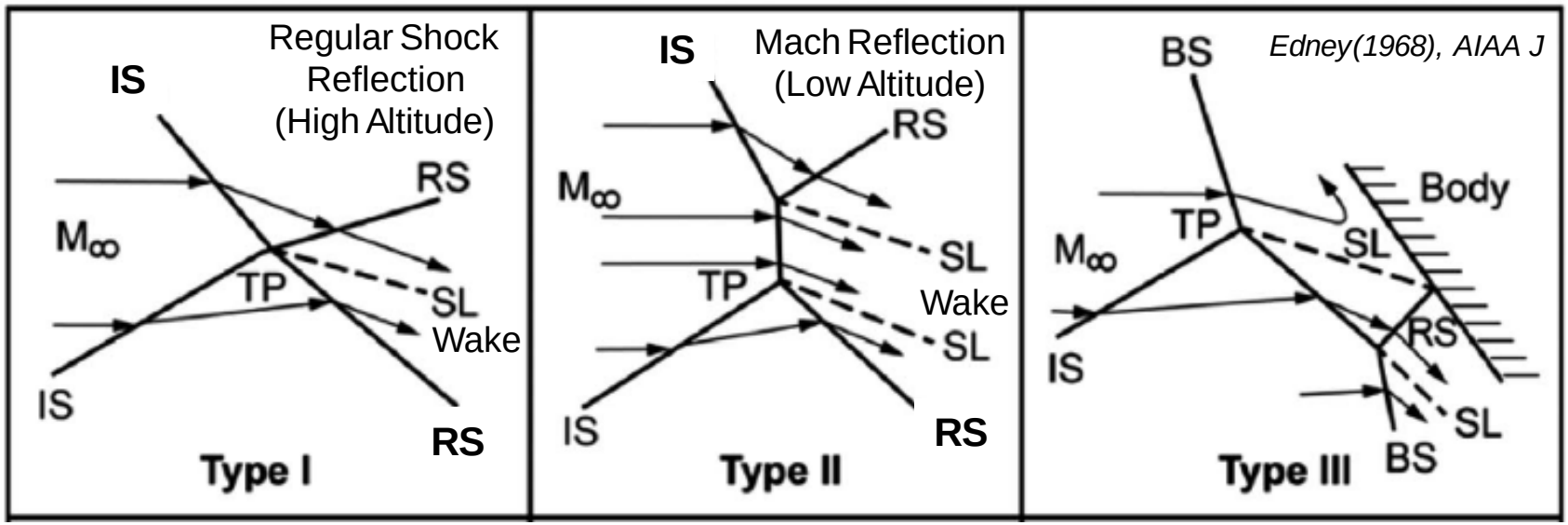
Viscous Flow



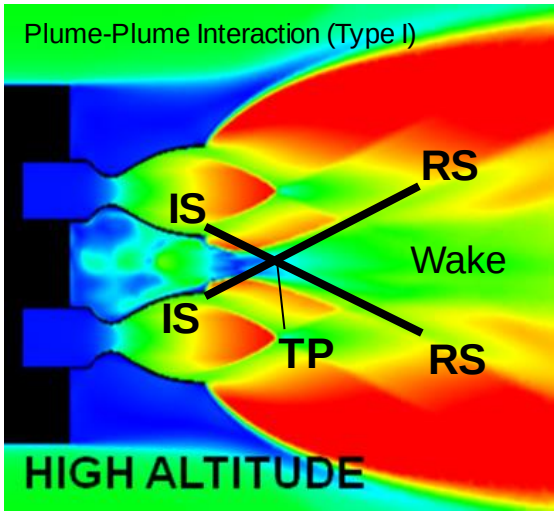


Inviscid Flow

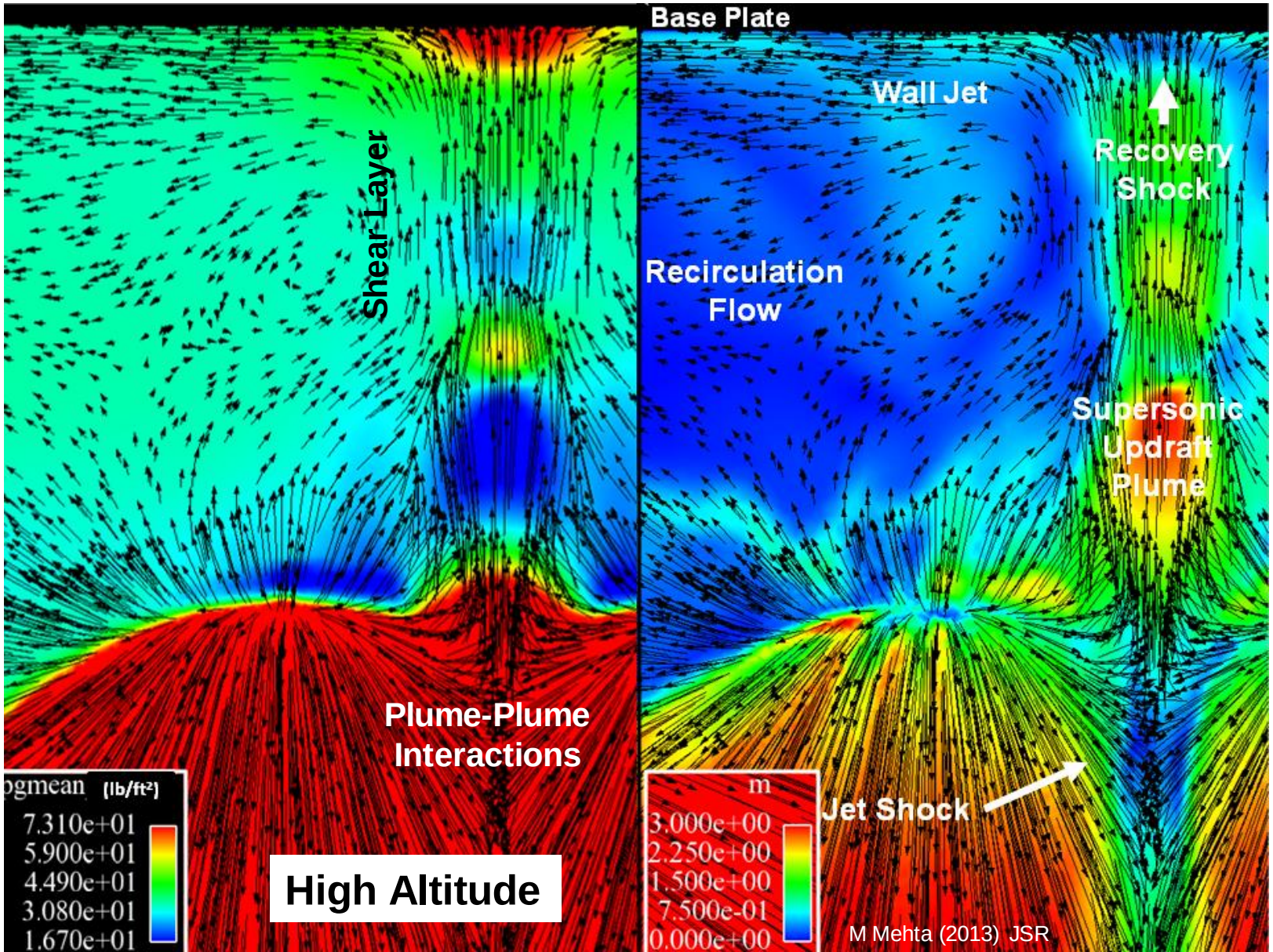
IS = incident shock, BS = bow shock, RS = reflected shock, EF = expansion fan,
TP = triple point, SL = shear layer, M_∞ = freestream Mach number





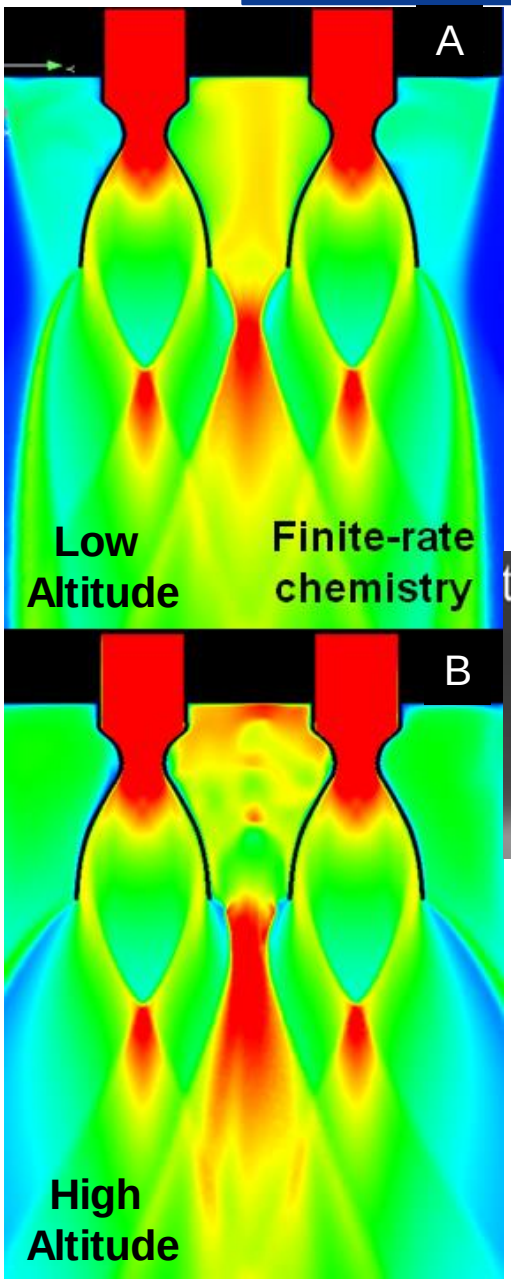


Recovery Shock & Recirculation Zone

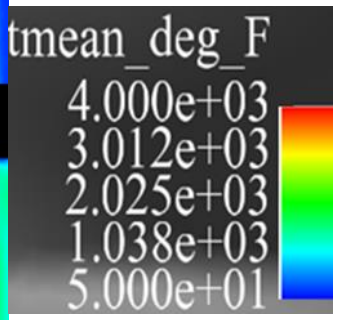


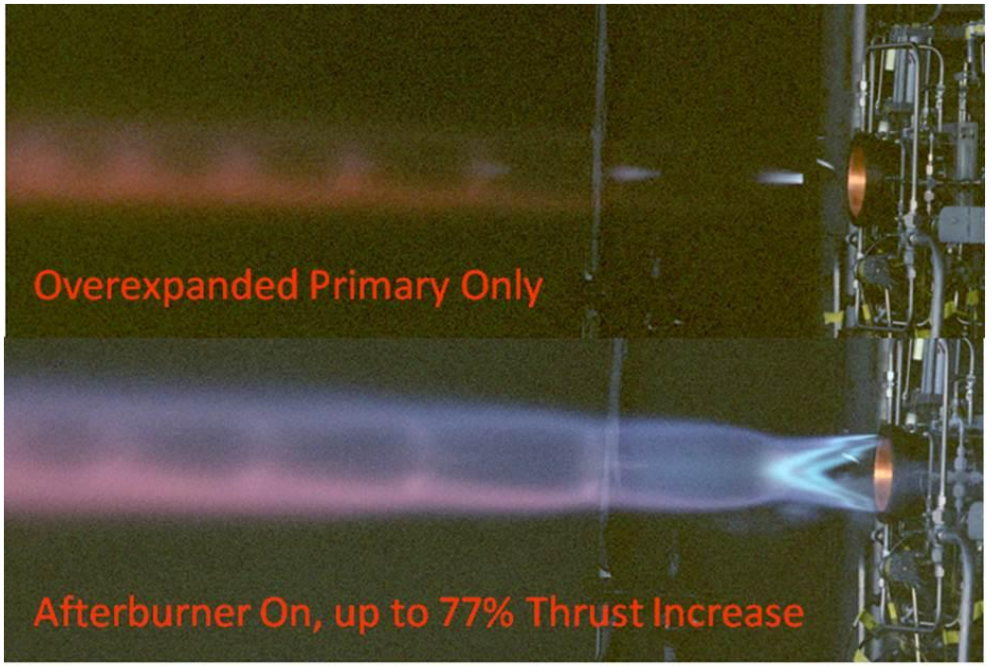
M Mehta (2013) JSR

Afterburning





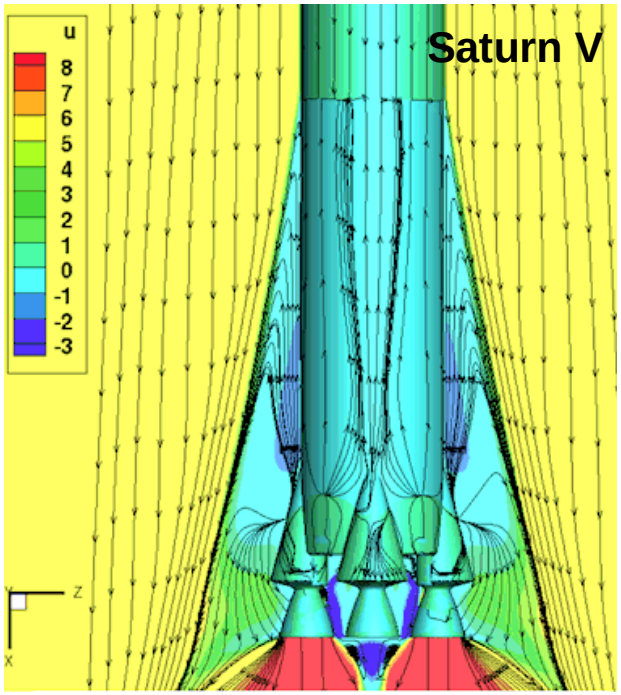




Mehta (2013) JSR, 201

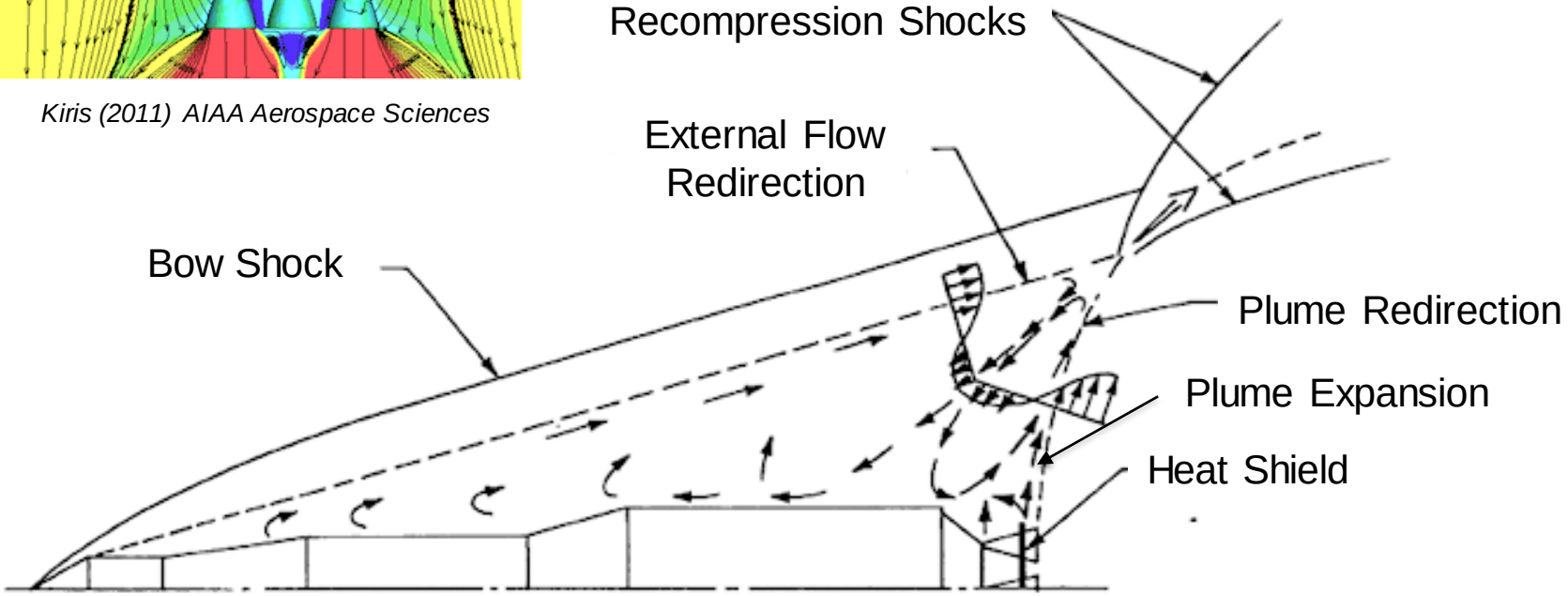
Bullman (2013) NASA Tech Briefs

Plume-Induced Flow Separation (PIFS)

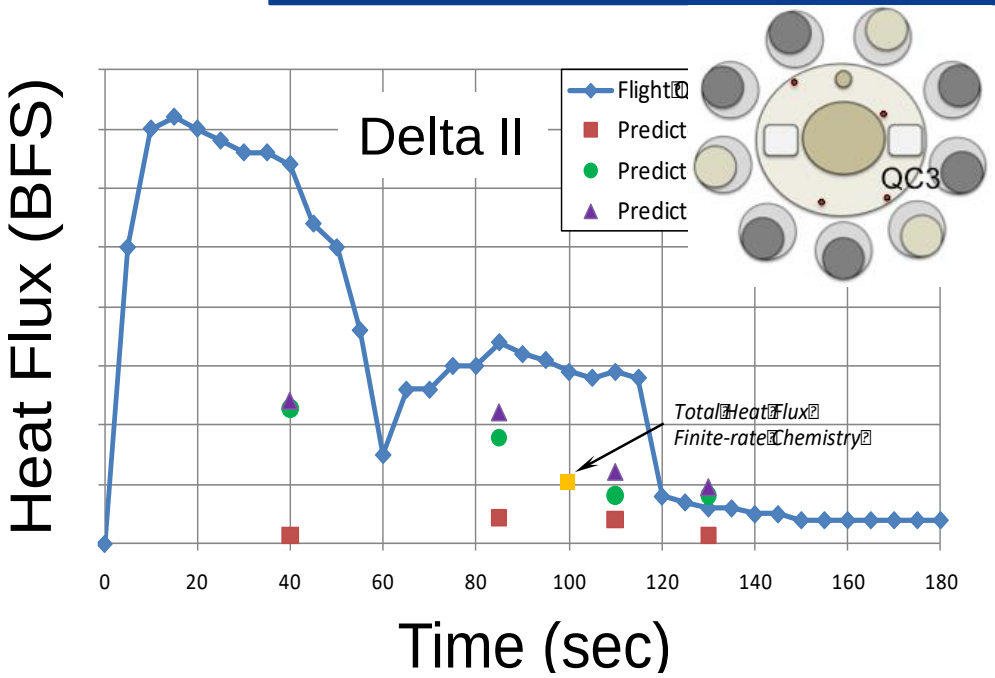


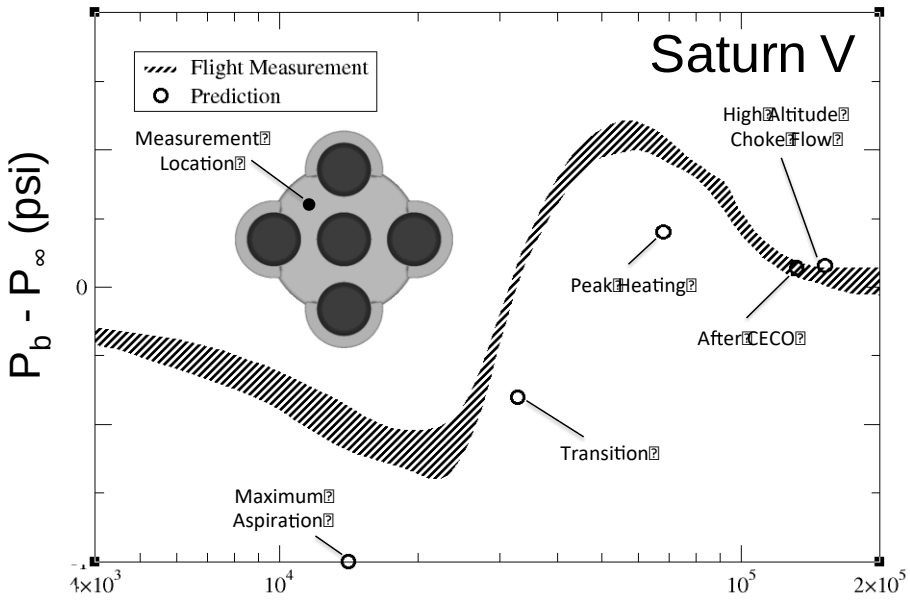
Kiris (2011) AIAA Aerospace Sciences

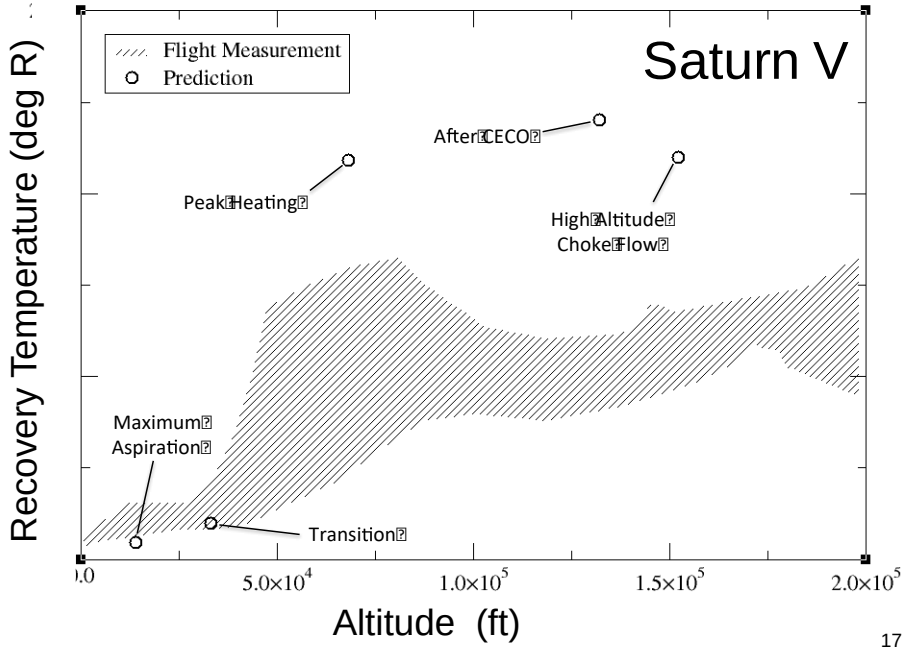




Base Flight Predictions





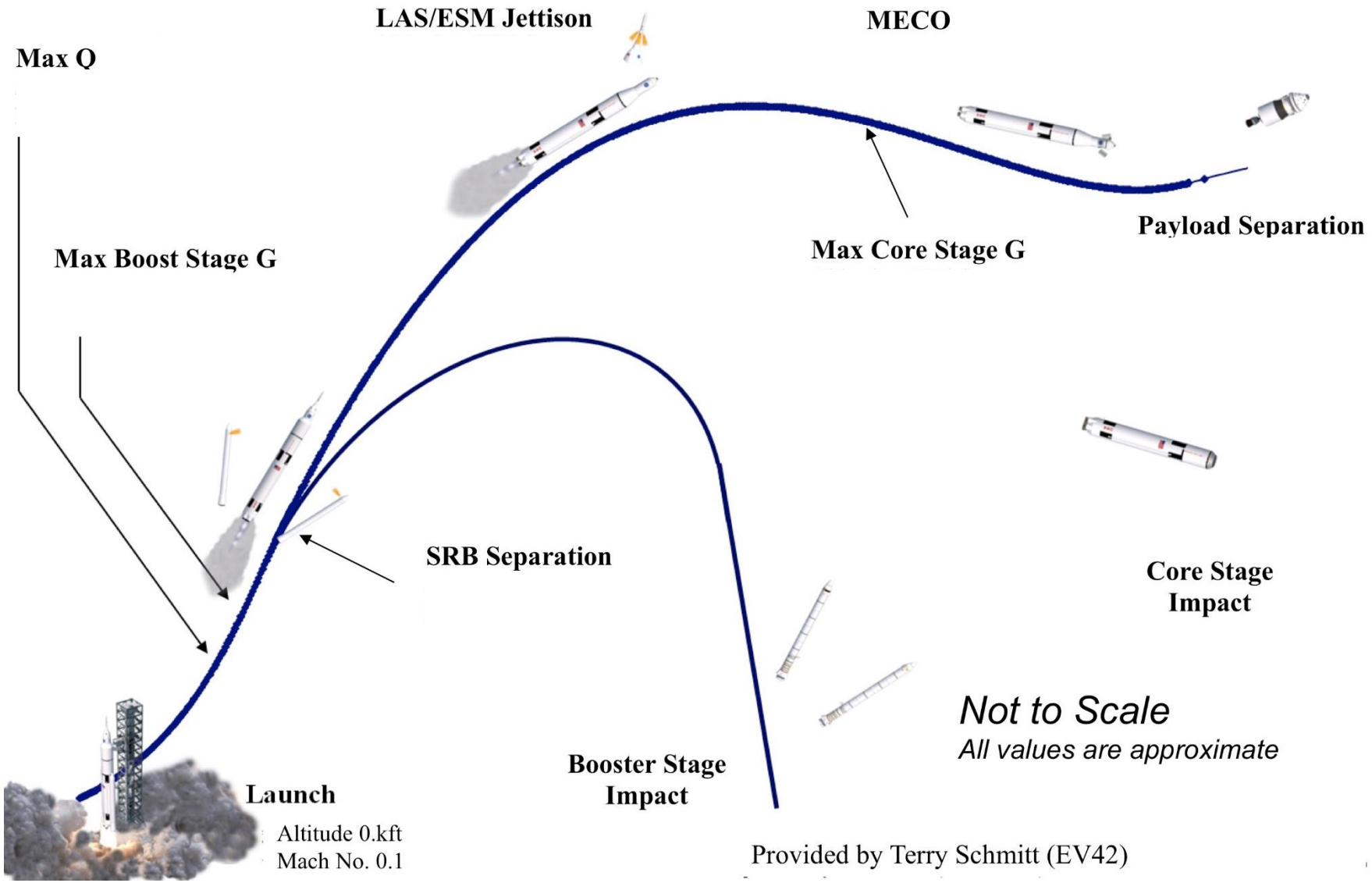


- **Computational approaches do not adequately capture:**
  - Flow physics
  - Peaks
  - Trends

Test Motivation and Requirements

- **Lack of accurate environments leads to inefficient/inadequate thermal protection system (TPS) design which results in reduction in payload mass and/or mission failure**
- **General Pathfinder goals and requirements**
  - 2% scale model, same propellants, nozzle profiles
  - Obtain similar model prop performance to flight RS-25 and RSRMV
- **Main Base Heating Test requirements**
  - Simulated altitude: Sea-level, 45,000 ft to 210,000 ft
  - Flow field: no flow, Mach 2.5 - 5.5
  - Configuration: full-stack and core-stage only
  - Steady-state data collection times >30 msec
  - Additional Configurations: RS-25 engine-out, Angle of Attack, RS25 gimbaling
  - Additional Tests: Reynolds-Scaling, Heated Base Plate
- **Developed a sub-scale SLS propulsive wind tunnel test program to obtain base heating and pressure test data and flow visualization during ascent.**
  - Such a test program of this complexity has not been conducted in 40+ years since the Shuttle Program

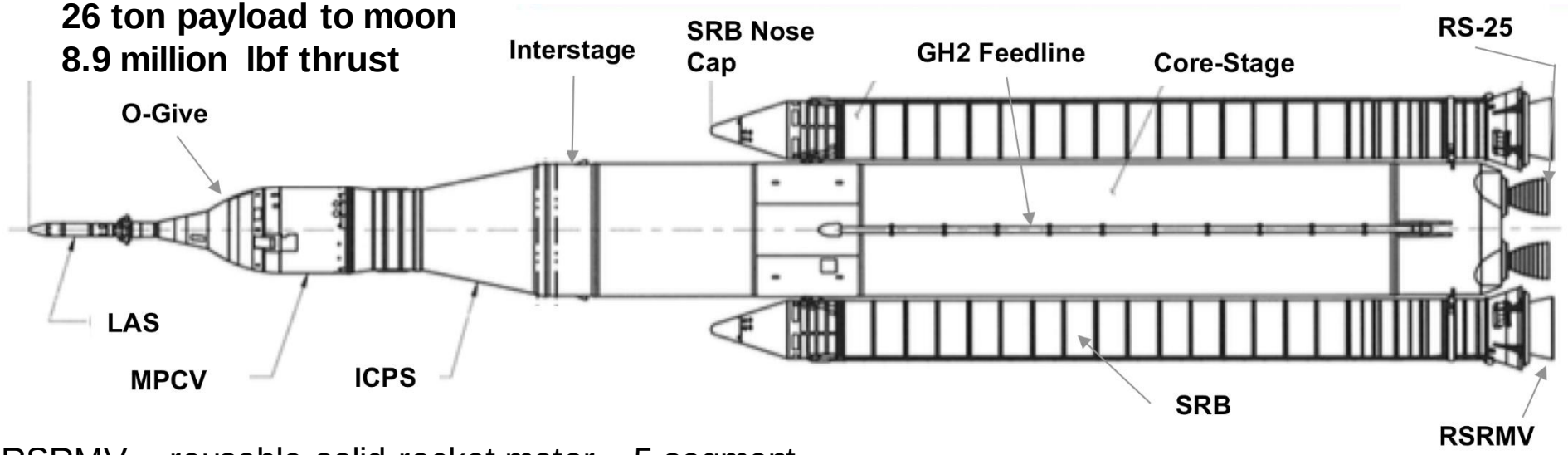
SLS Mission Profile



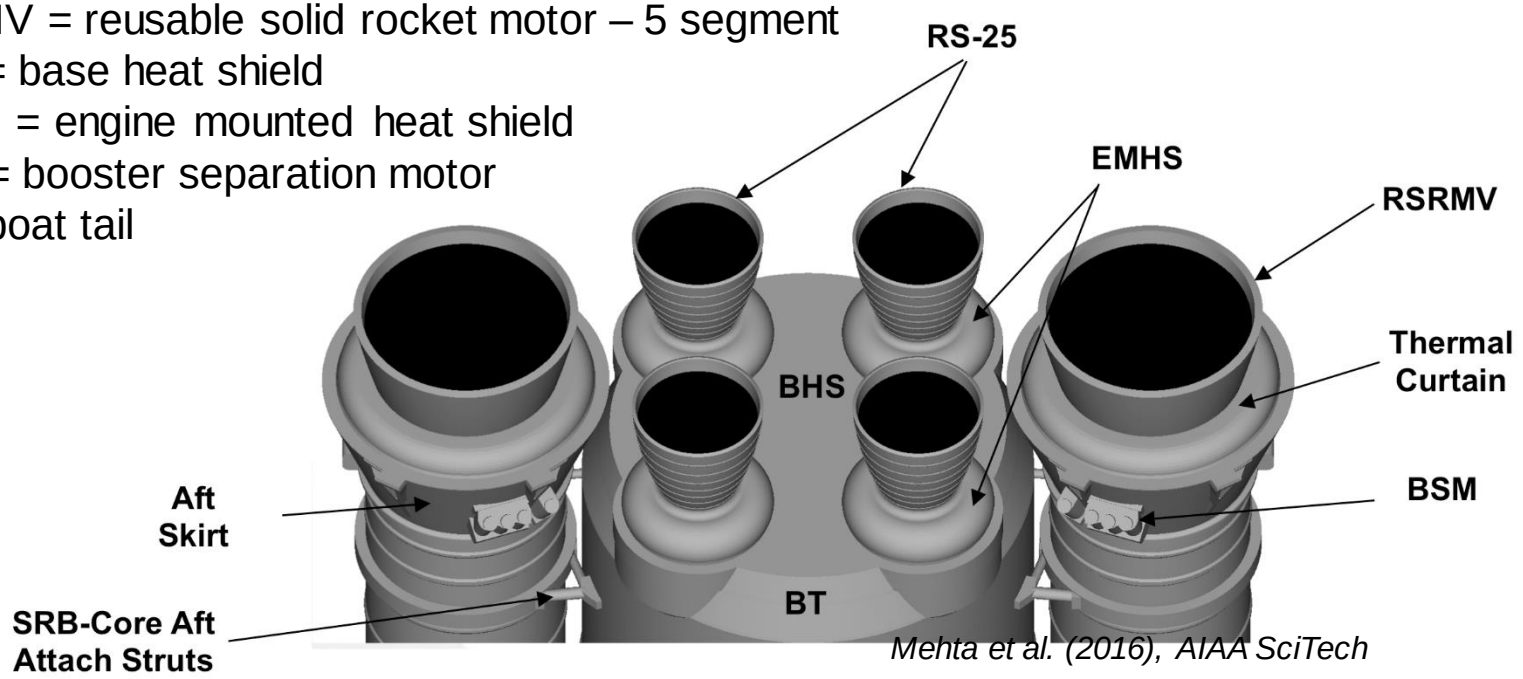
Morris (2015), AIAA SciTech

SLS Vehicle and Base Region

321 ft long
26 ton payload to moon
8.9 million lbf thrust



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



Mehta et al. (2016), AIAA SciTech

CUBRC LENS

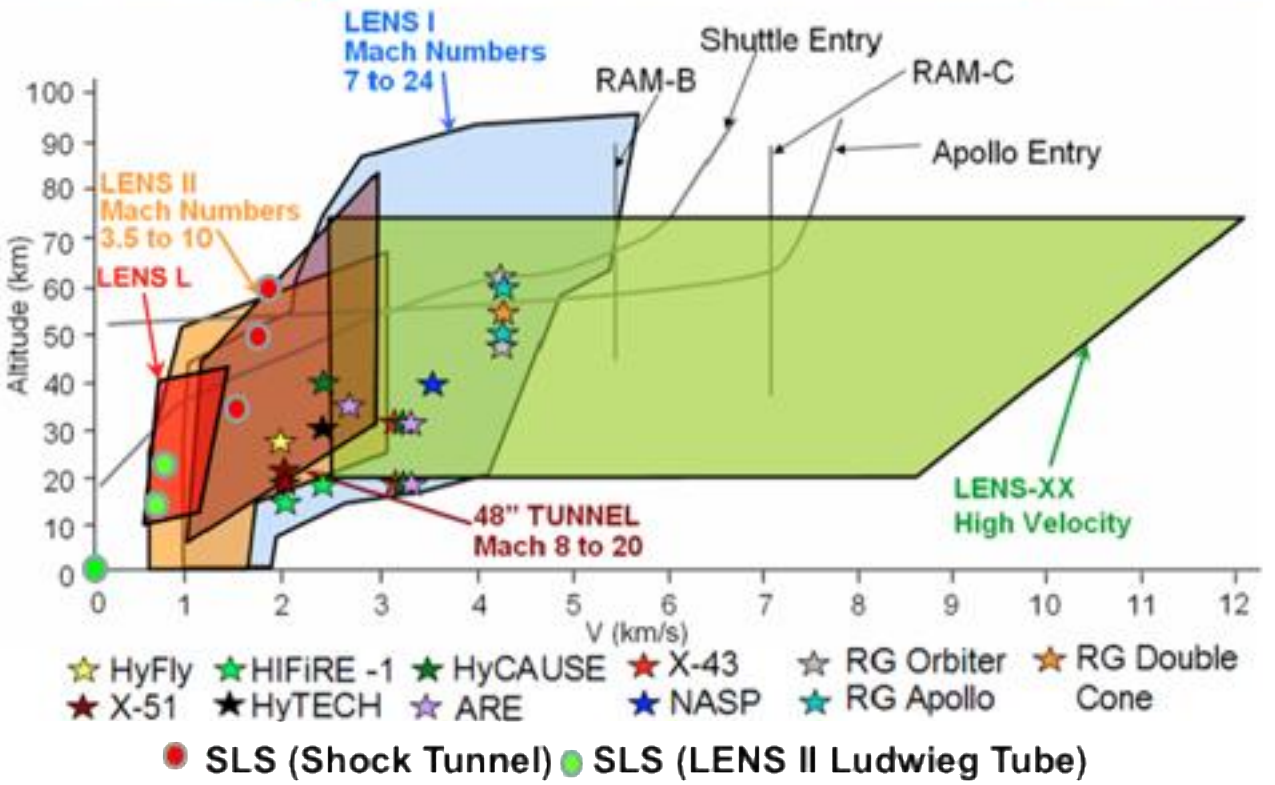






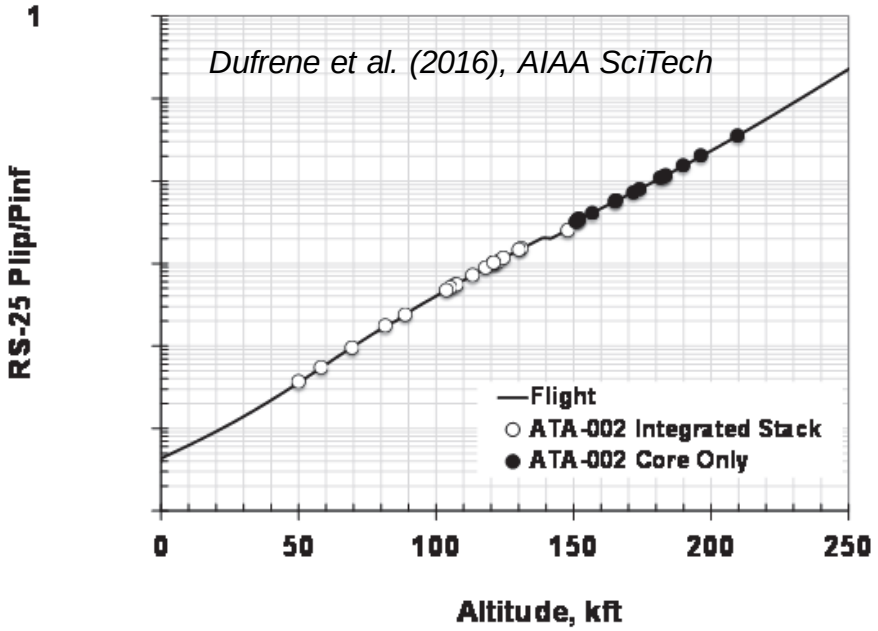


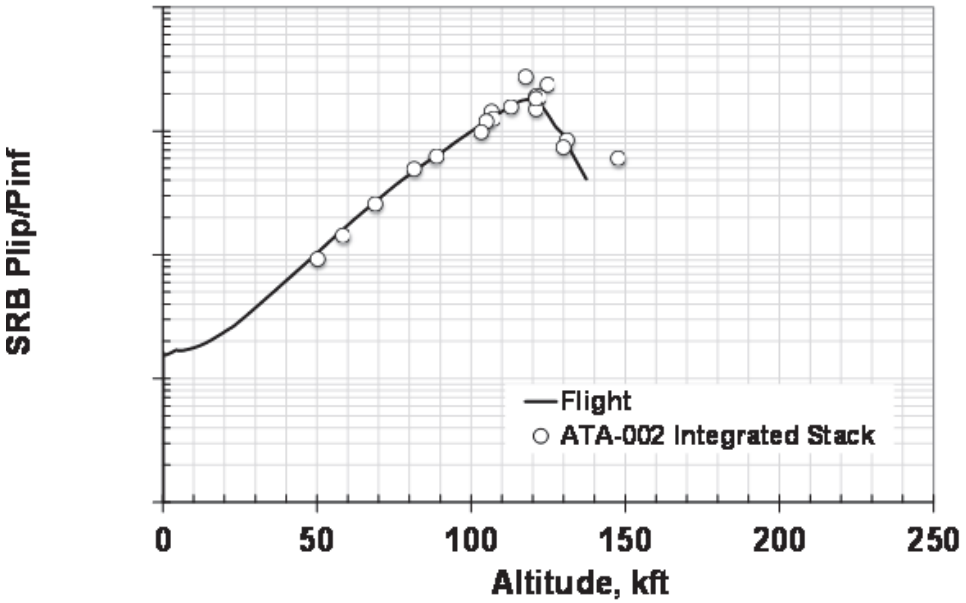
- **Test Section Geometry**
  - Test Section Diameter – 8 feet
  - Test Section Length – 30 feet
- **Option to run the facility as a shock tunnel or a Ludwieg Tube**
  - Test time for Ludweig Tube 200 to 165 msec
  - Test time for shock tunnel ~ 75 to 29 msec

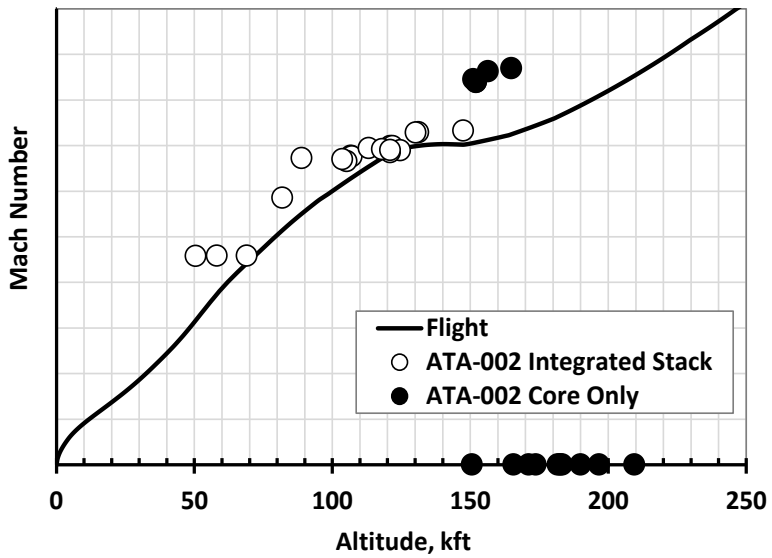


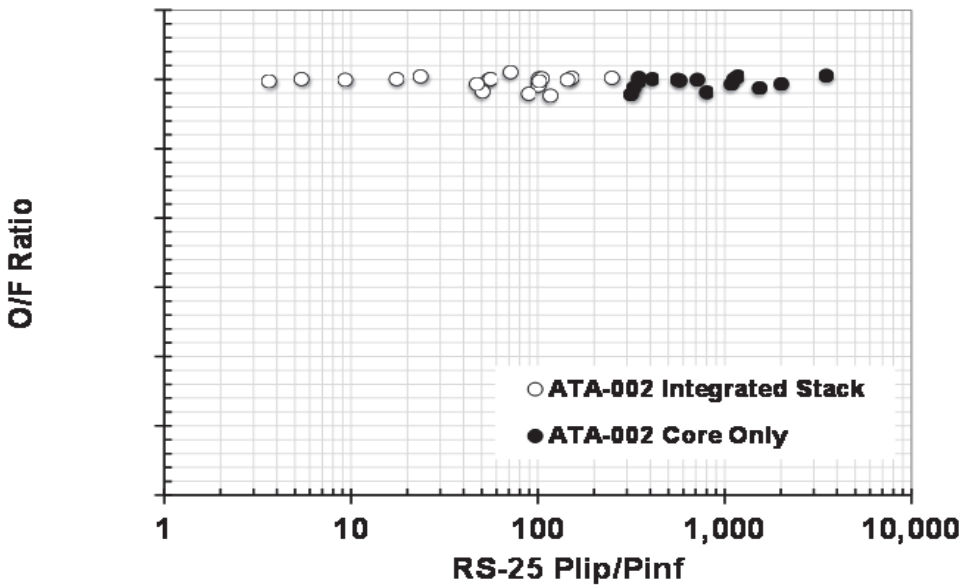
Dufrene et al. (2016), AIAA SciTech

ATA-002 Propulsion System Performance



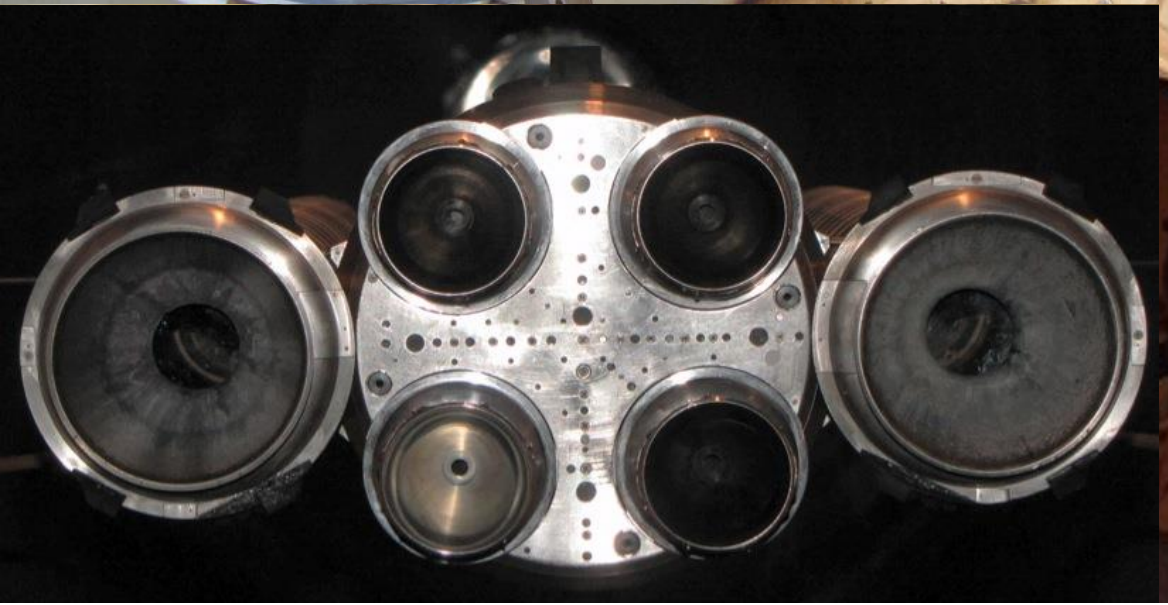






ATA-002 SLS Propulsion Model



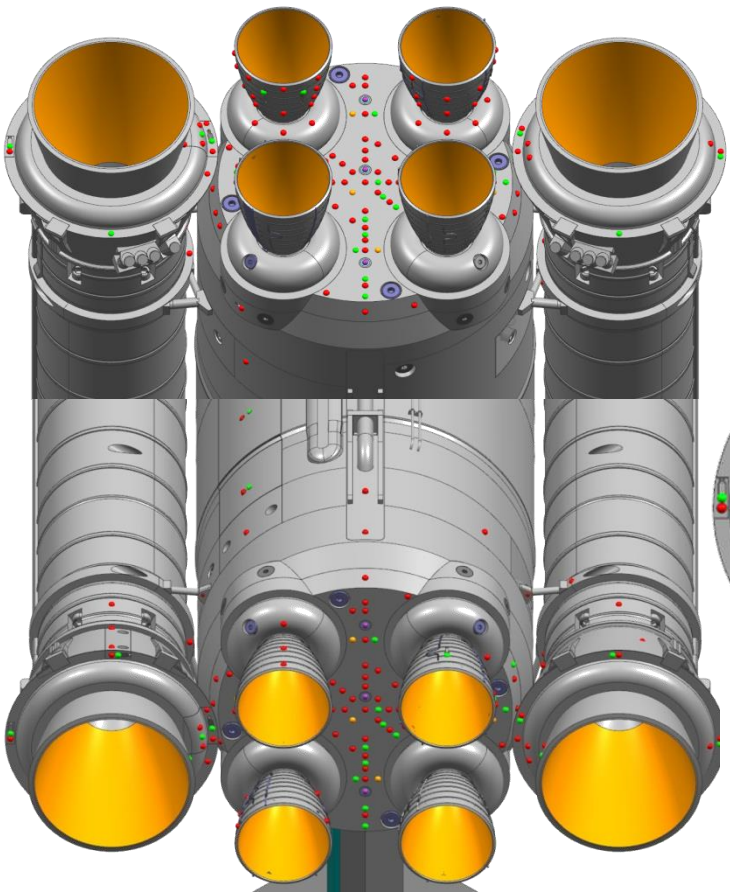


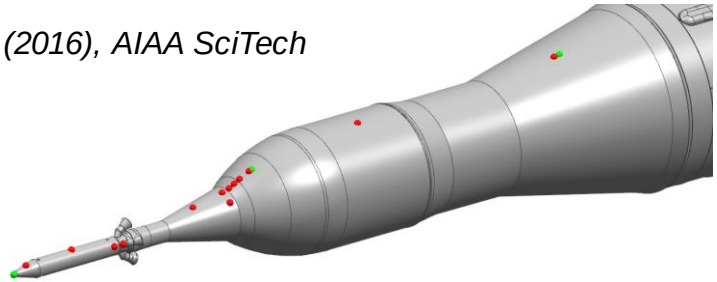


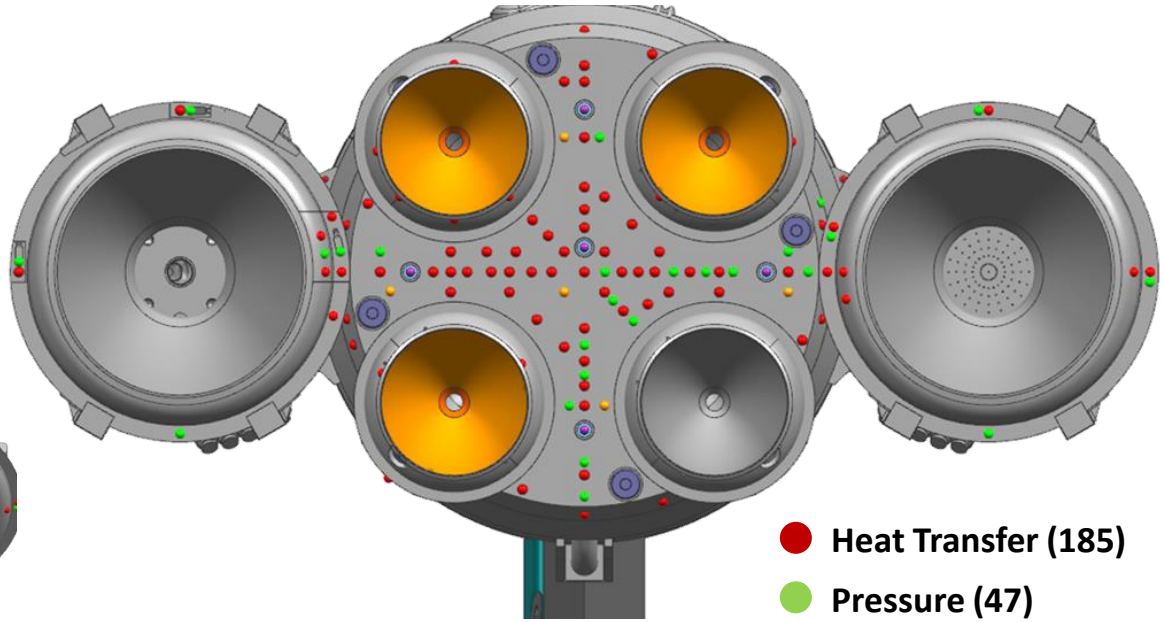
Instrumentation Layout

- Installed (not shown) multiple pressure and temperature sensors within both the Core Stage and SRB internal propulsion components to monitor performance

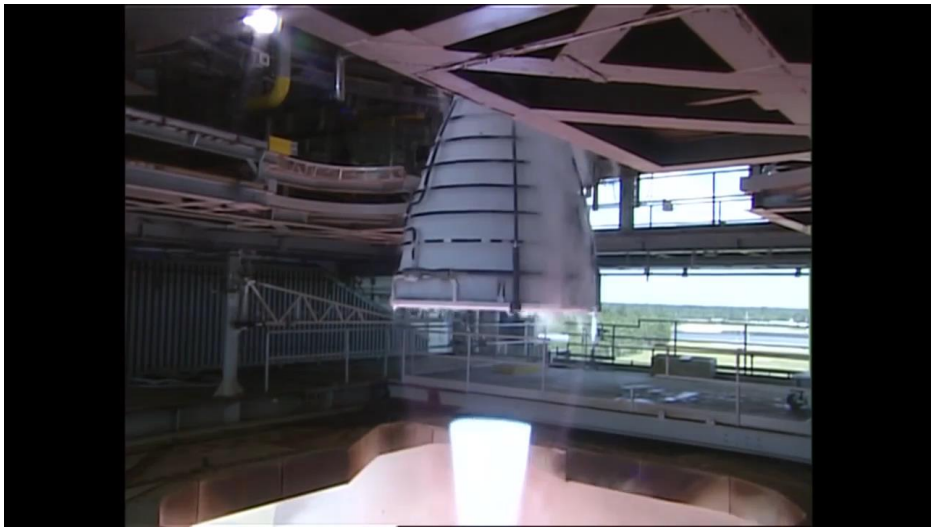
Dufrene et al. (2016), AIAA SciTech







Flight and Model SLS Propulsion Components



All Sea-Level Videos



Mehta et al. (2016), AIAA SciTech
NASA MSFC (2016), HDR Video of QM-2

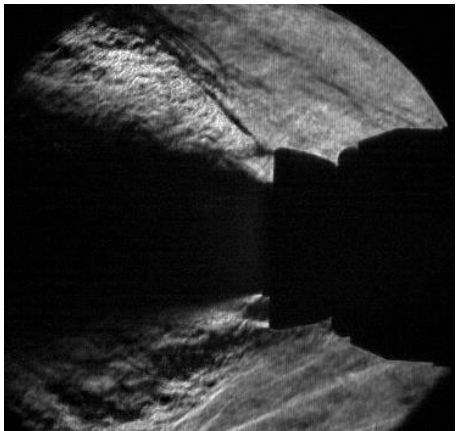




VIS Imaging



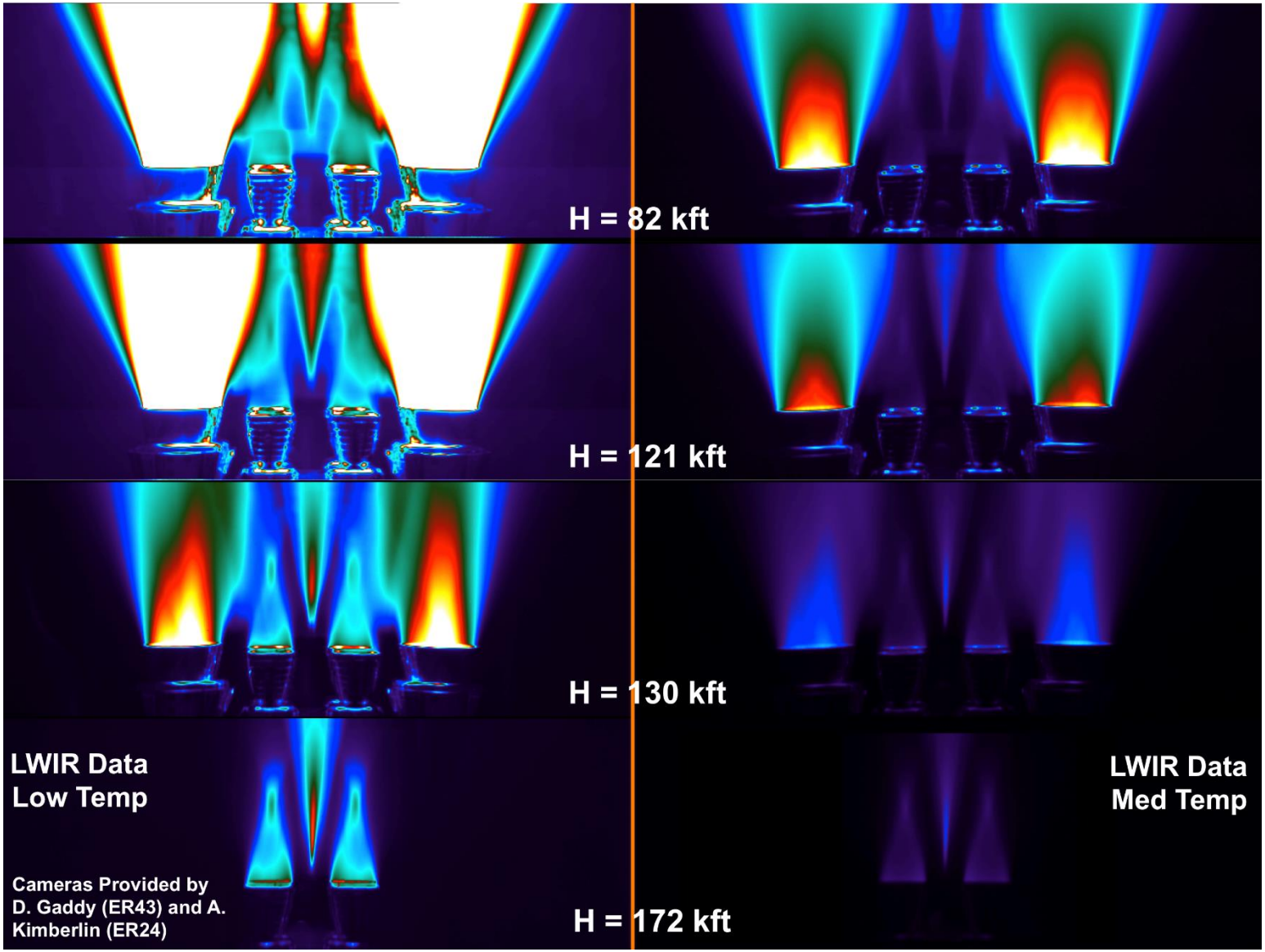
Visible high-speed camera side view, sea-level, full-stack



Schlieren side view, 100 kft, full-stack

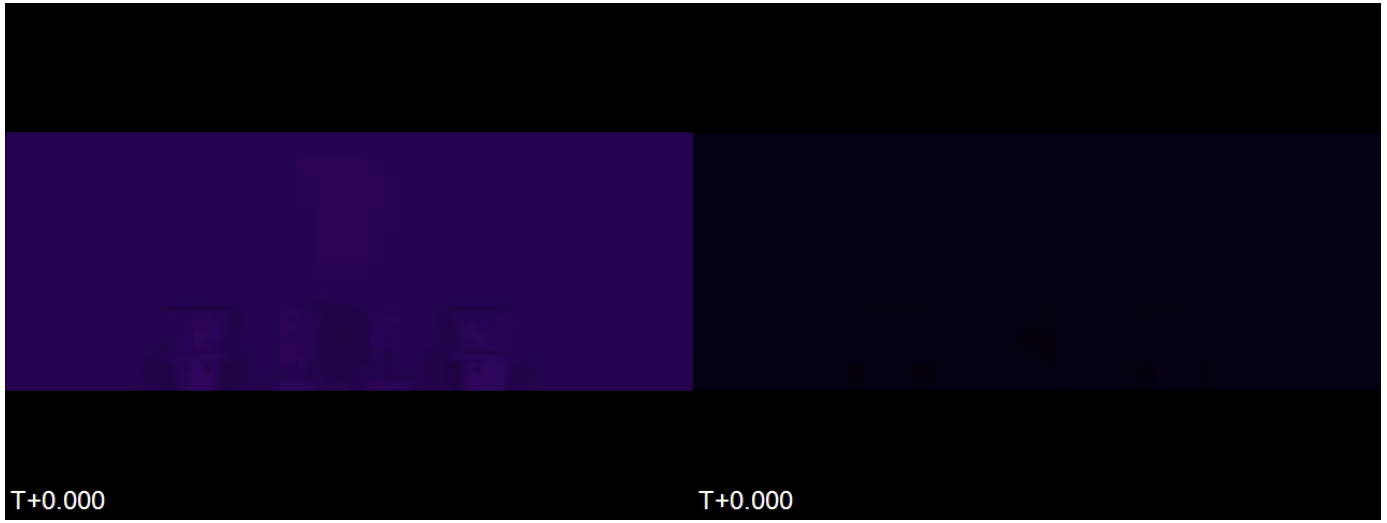
Mehta et al. (2016), AIAA SciTech

LWIR Imaging



Mehta et al. (2016), AIAA SciTech

LWIR Imaging



H = 121 kft

Mehta et al. (2016), AIAA SciTech

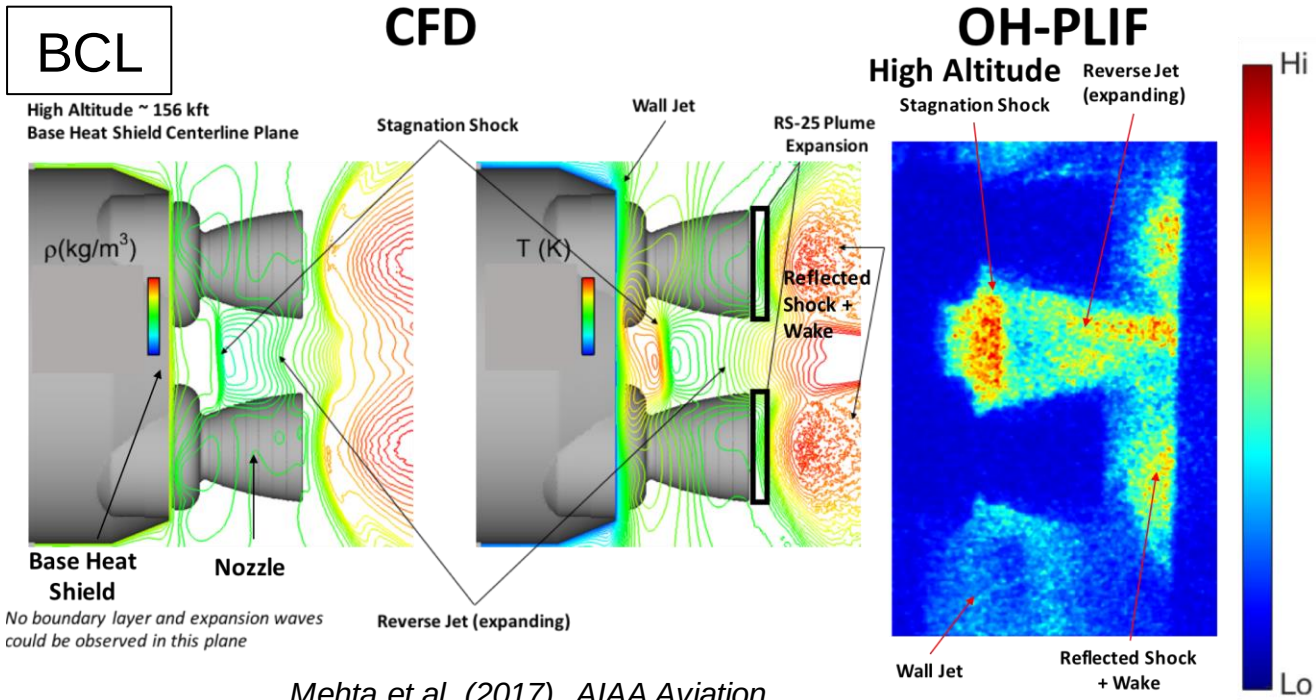


H = 172 kft

PLIF Diagnostics

- Base flow structures were successfully visualized using OH-PLIF
  - Shows OH emission intensity
  - Assuming constant mole fraction, frozen flow, extract qualitative gas temperature map
- Observe good qualitative agreement between test data and computational results
- Complex base flow structures
  - Stagnation shock
  - Reverse jet
  - Reflected shocks
  - Wall jet
  - Shock impingement

- Tunable Diode Laser Absorption Spectroscopy (TDLAS) was used to develop an integrated path length measurement of the base gas recovery temperature
  - This was provided over the altitude regime tested
- PLIF thermometry was also conducted to develop a spatial gas temperature map of a few high-altitude test points

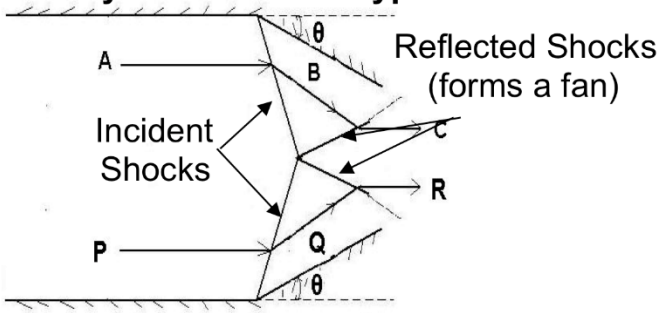


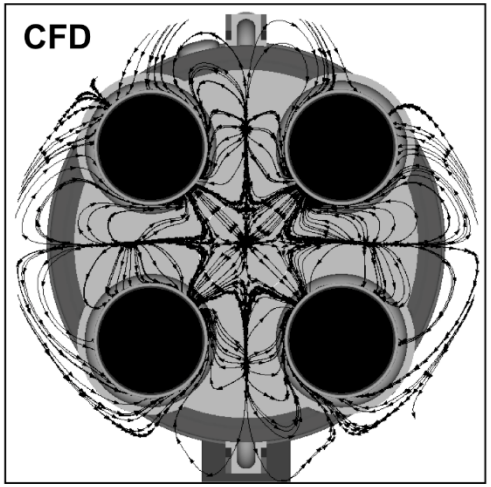
Mehta et al. (2017), AIAA Aviation

PLIF Imagery provided by P. Danehy and J. Inman (LARC)
CFD solutions provided by F. Canabal (MSFC-EV33)

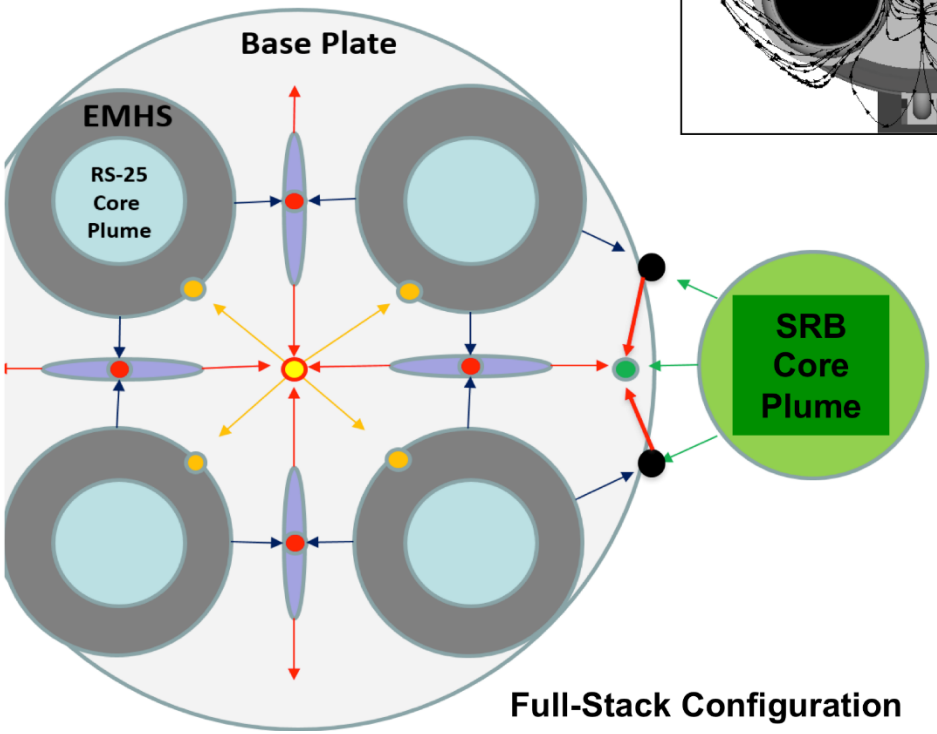
SLS Base Flow Physics

Edney Shock-Shock Type I Interaction





- 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

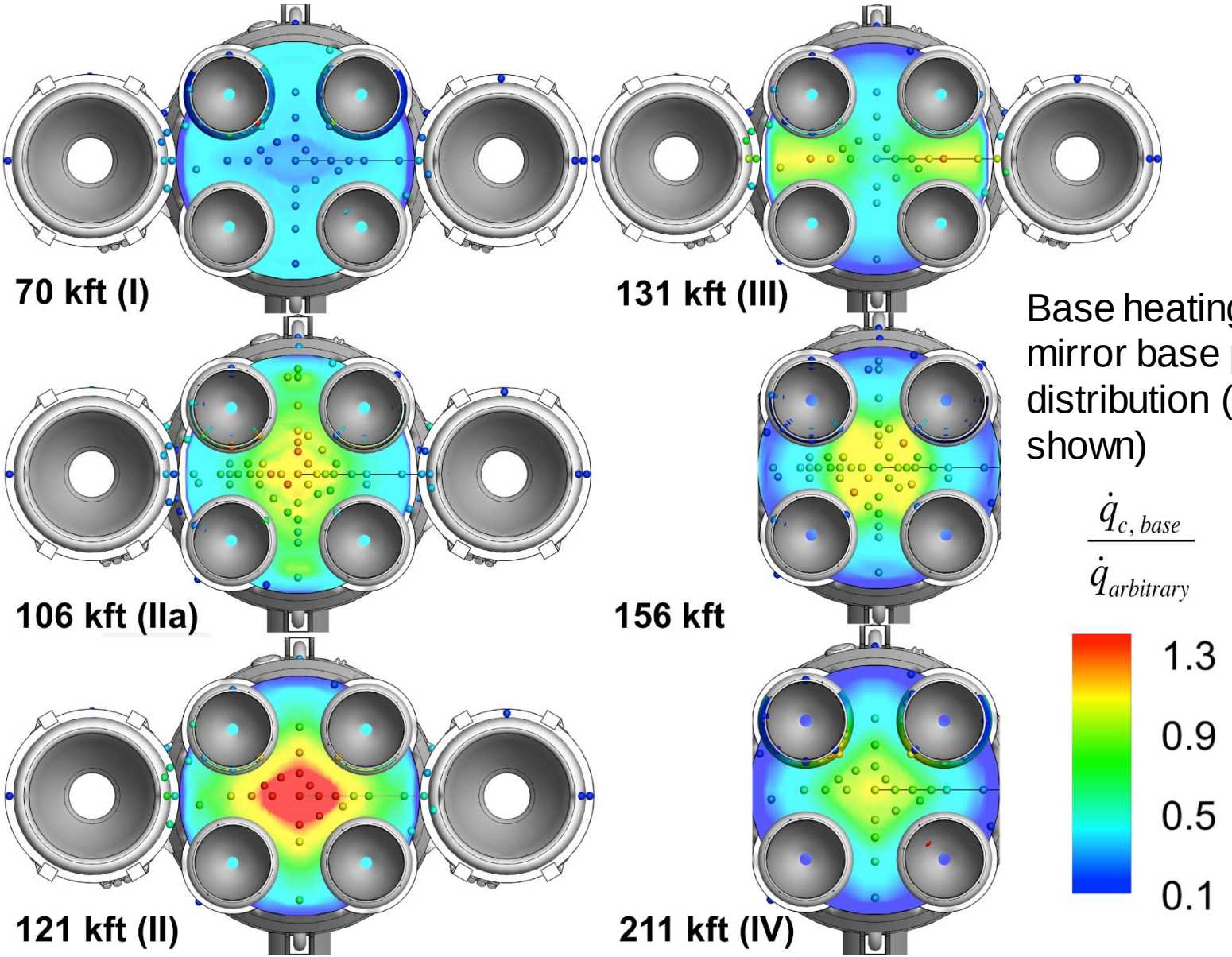


Full-Stack Configuration

- Base Flow
- Core Plume Flow
- Wall Jet
- SRB Plume Flow

Mehta et al. (2016), AIAA SciTech

BHS Heating Contour Plots



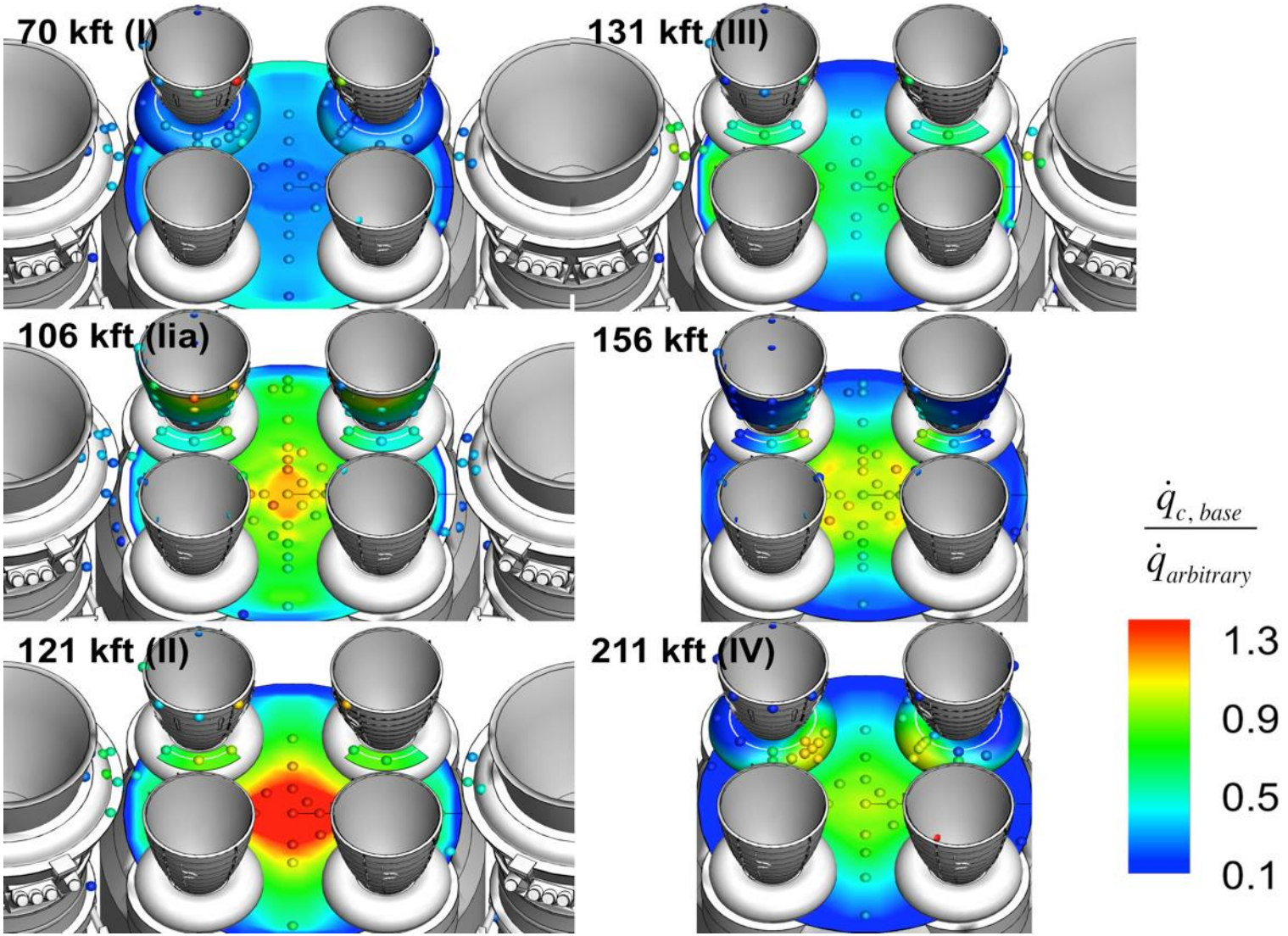
Base heating profiles mirror base pressure distribution (not shown)

$$\frac{\dot{q}_{c,\,base}}{\dot{q}_{arbitrary}}$$

1.3
0.9
0.5
0.1

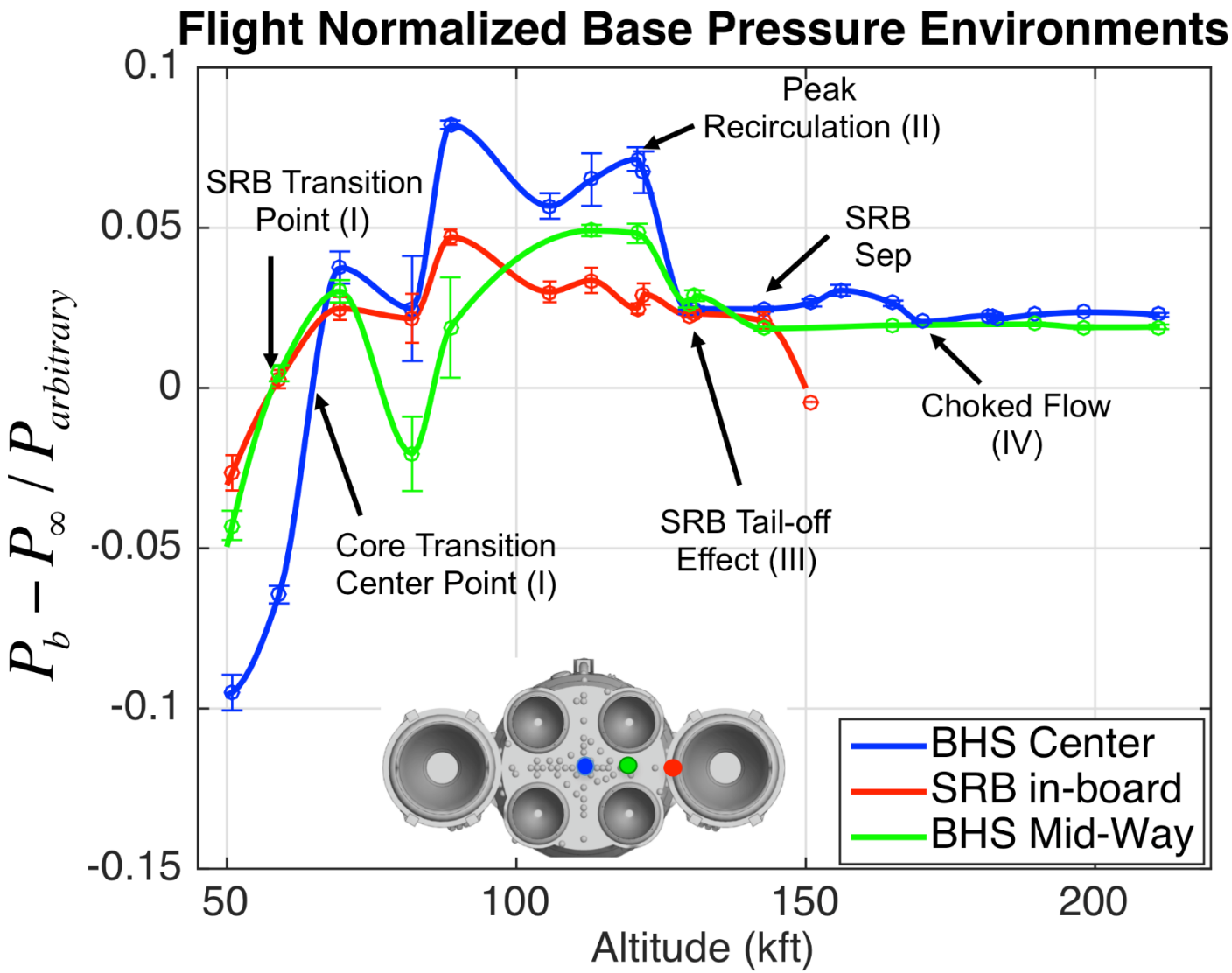
Mehta et al. (2016), AIAA SciTech

EMHS Heating Contour Plots



Mehta et al. (2016), AIAA SciTech

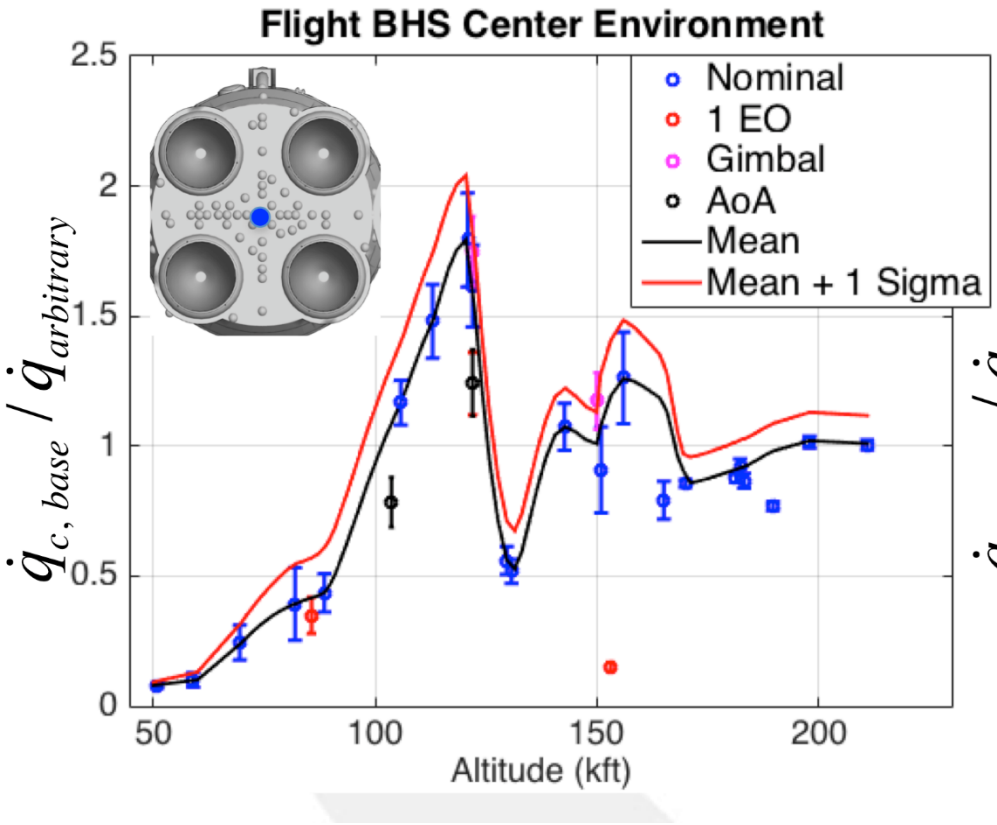
Base Pressure – Altitude Profile



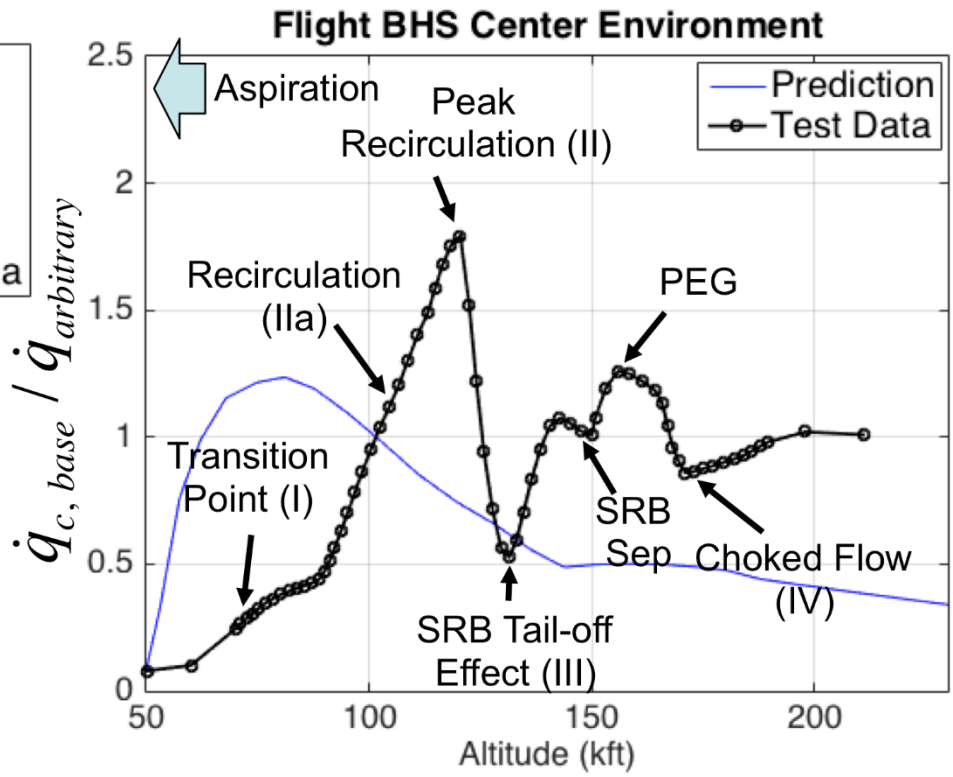
Mehta et al. (2016), AIAA SciTech

Base Heating – Altitude Profile: BHS Center

- **Scaled test data, mean and mean + 1 sigma data profiles**



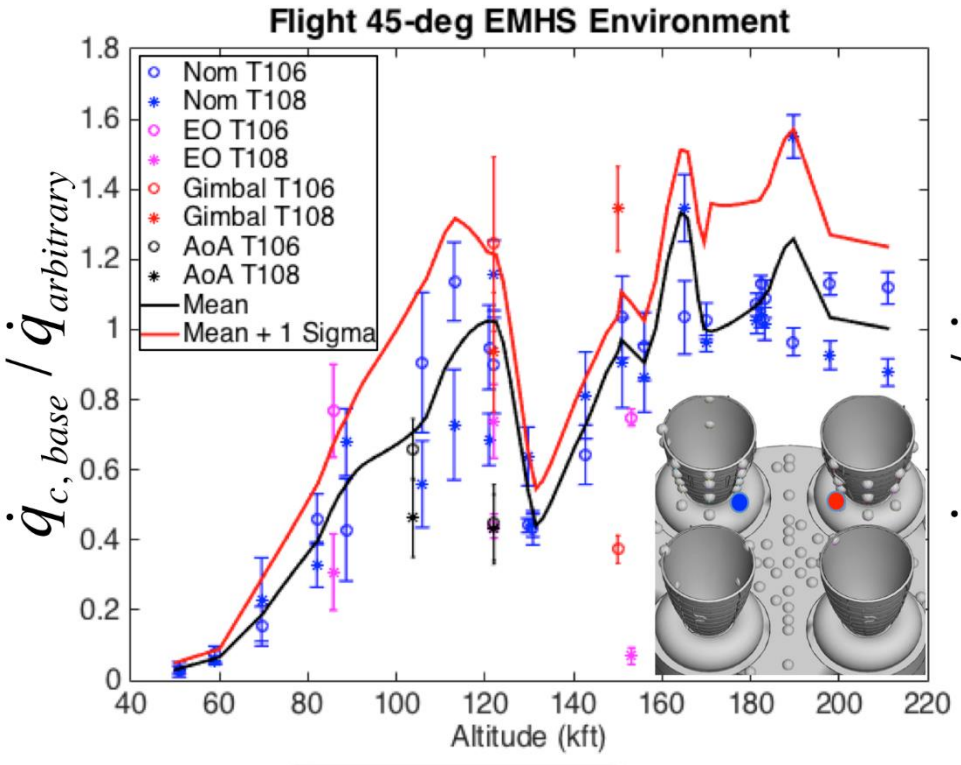
- **Mean data and prediction profiles (prediction based on shuttle configuration)**

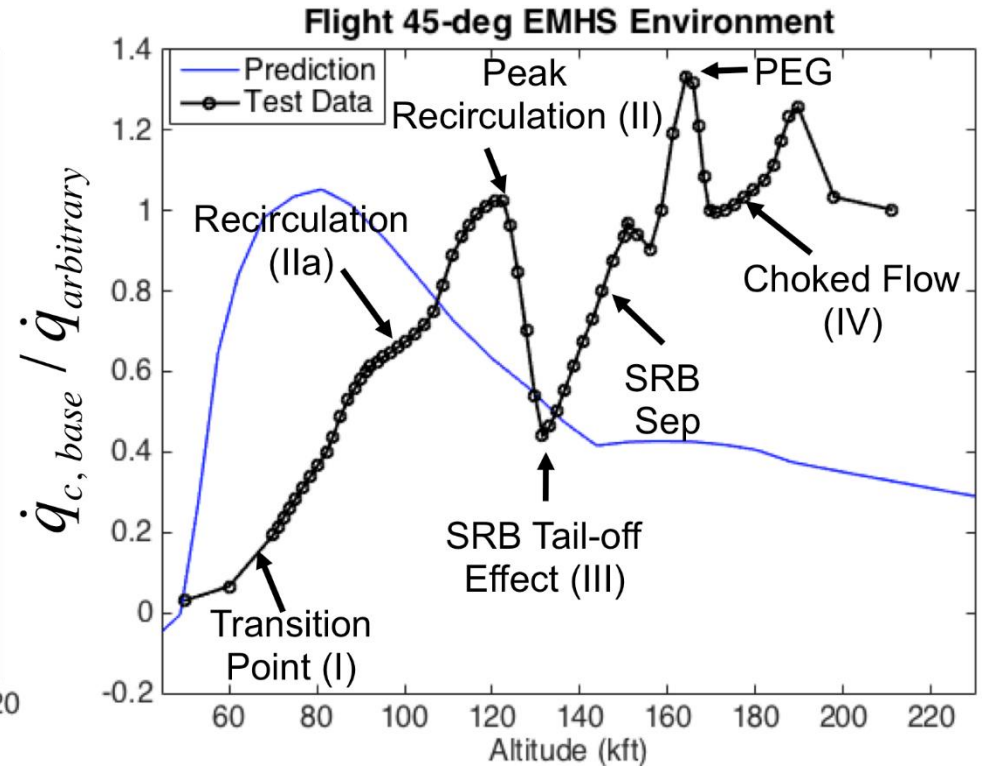


Mehta et al. (2016), AIAA SciTech

Base Heating – Altitude Profile: EMHS

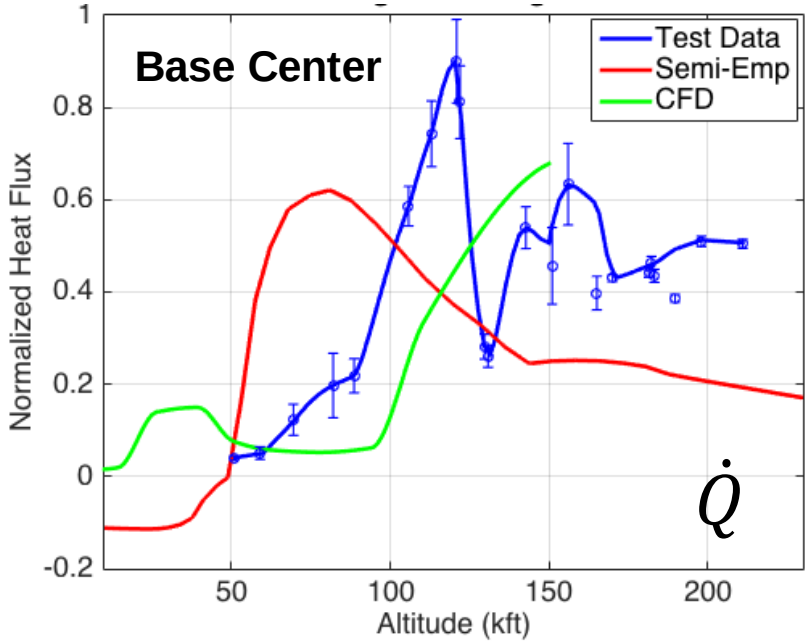
- **Scaled test data, mean and mean + 1 sigma data profiles**
- **Mean data and prediction profiles**

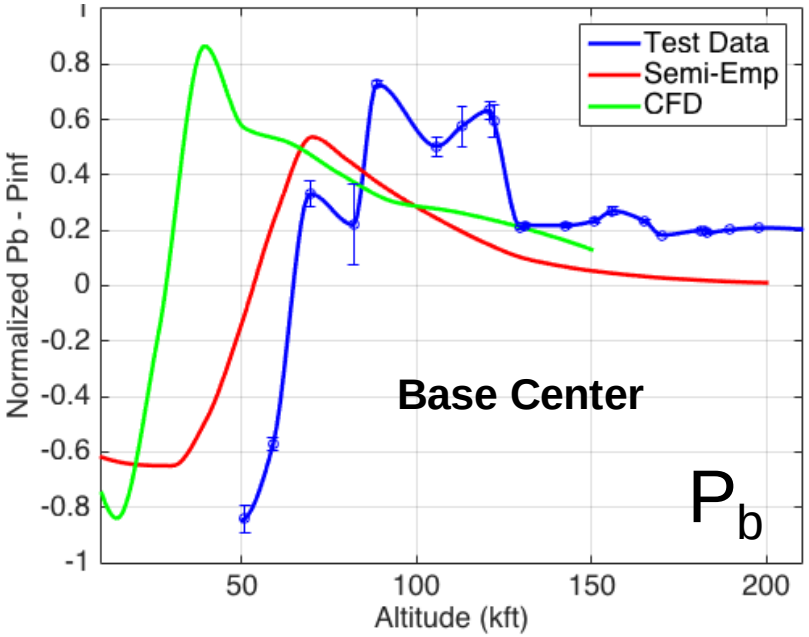




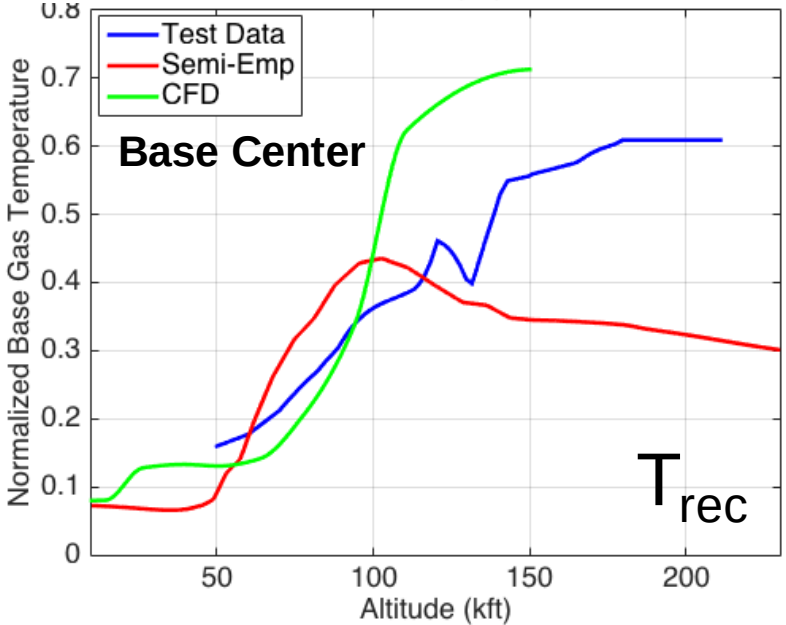
Mehta et al. (2016), AIAA SciTech

SLS Base Flow Predictions



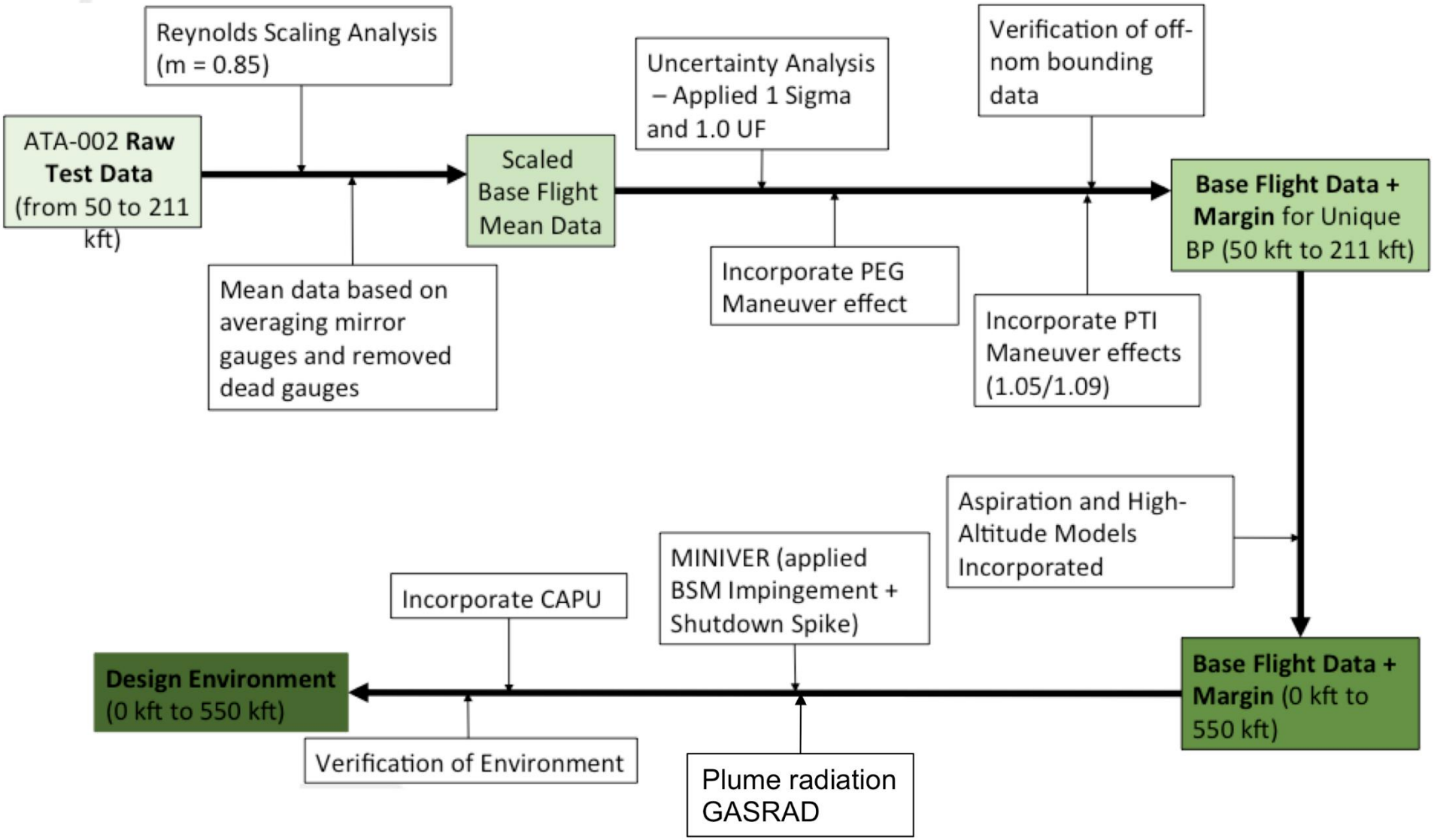


- **Semi-empirical & computational approaches do not adequately capture:**
  - Flow physics
  - Peaks
  - Trends



Mehta et al. (2016), TFAWS

SLS Base Design Environment Methodology



Mehta et al. (2016), AIAA SciTech

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

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

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

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

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

$$T_{r,flight} \sim T_{r,test} \longrightarrow$$

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

+ 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

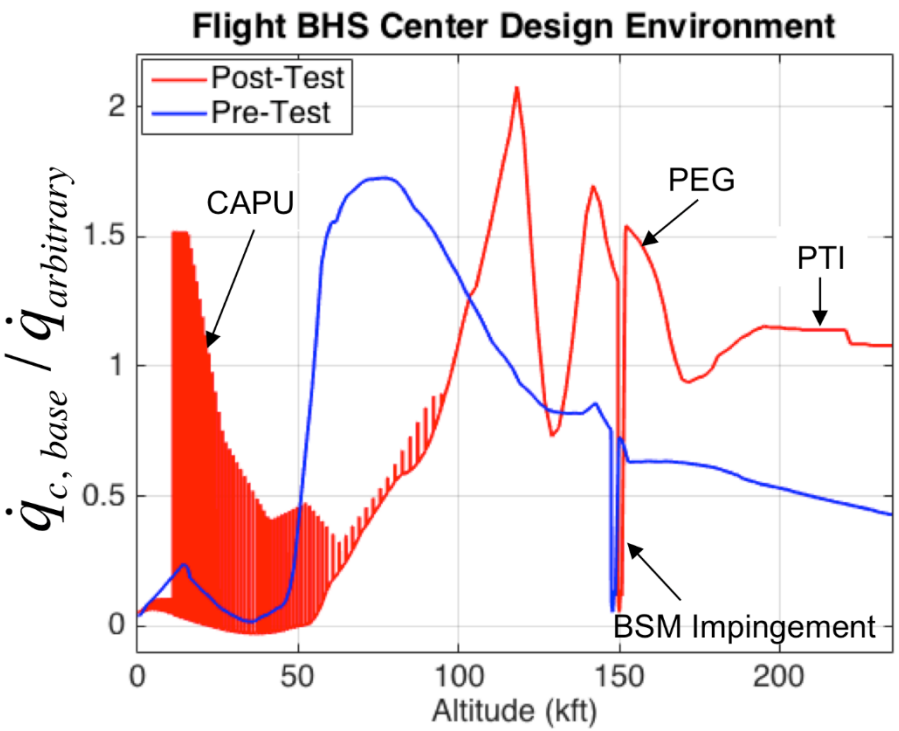
***Mean Value**
****Karman-Schoenherr Skin Friction Law with Spalding and Chi Compressibility Correction**
***** Difficult to estimate edge conditions and flow potentially tripped due to complex plume interactions**

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

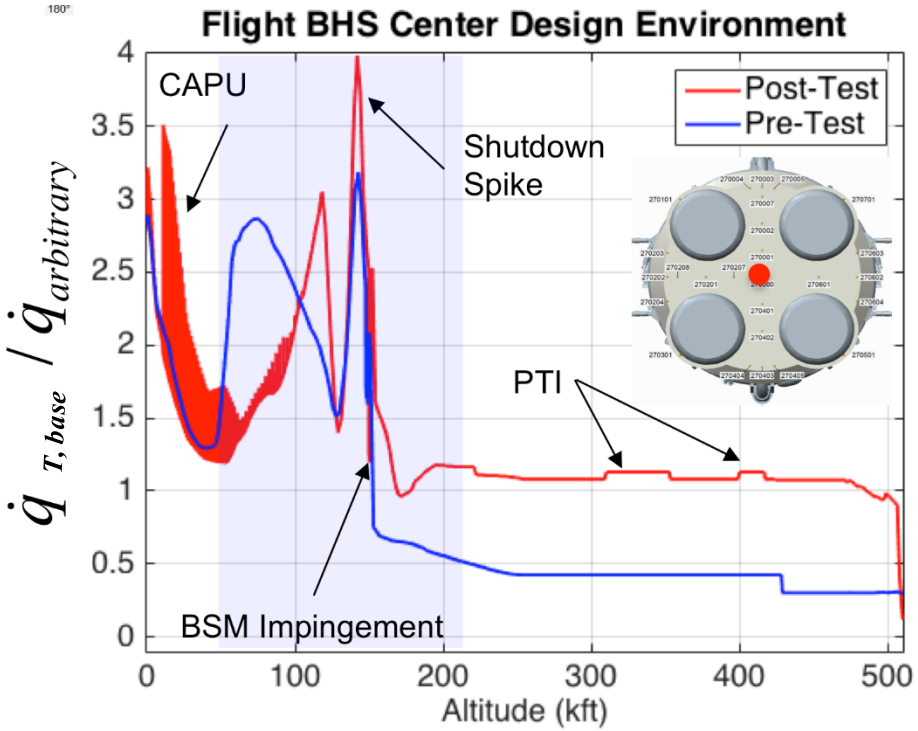
Mehta et al. (2016), AIAA SciTech

Design Environment: BHS Center

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



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



Total heating = convection + radiation + particle heating

Mehta et al. (2016), AIAA SciTech

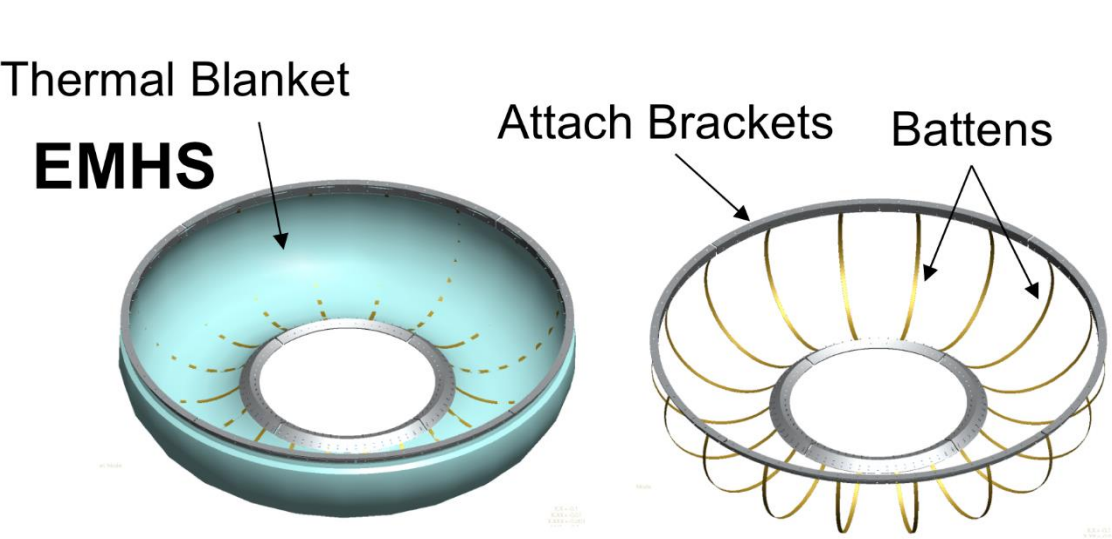
Design Environment: Base Heat Load

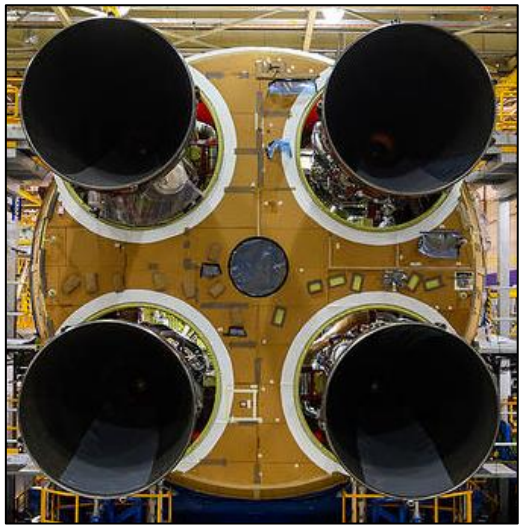
- **Heat load drives the TPS thickness and heating rate drives TPS type**
- **Highest heat load deviation from the semi-empirical (pre-test) approach are: BHS, EMHS in-board and RS-25 nozzle HB #3**

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

Mehta et al. (2016), AIAA SciTech

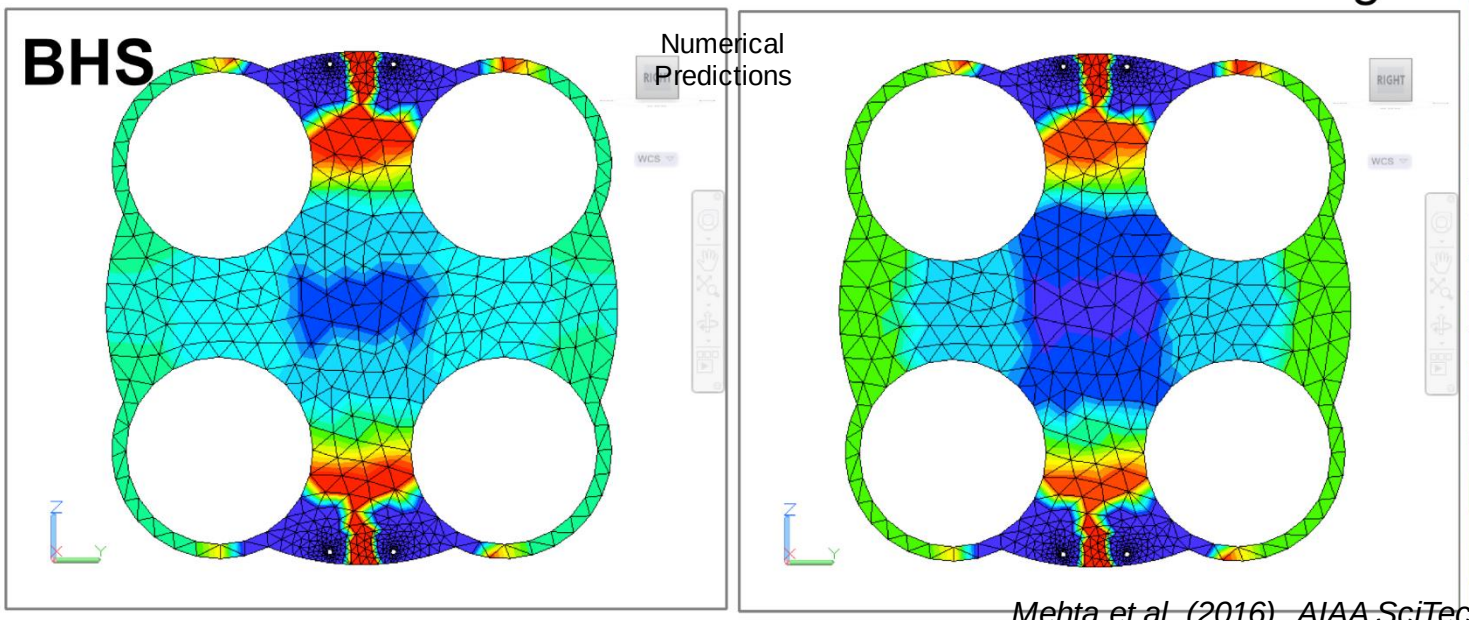
Thermal Analysis: BHS and EMHS





Pre-Test Heating

Post-Test Heating



Mehta et al. (2016), AIAA SciTech

Conclusions

- **Established general physics associated with LV base flows**
- **Described some prediction methods with focus on testing**
- **Investigated SLS base flow physics and environments**
- **Design environments show highest heating rate and heat loads at the:**
  - BHS
  - EMHS in-board
  - RS-25 nozzle base
- **Artemis I post-flight assessment will substantiate these environment predictions**
  - Enable improvement in computational modeling
  - Enable deep-dive into scaling methodologies

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.

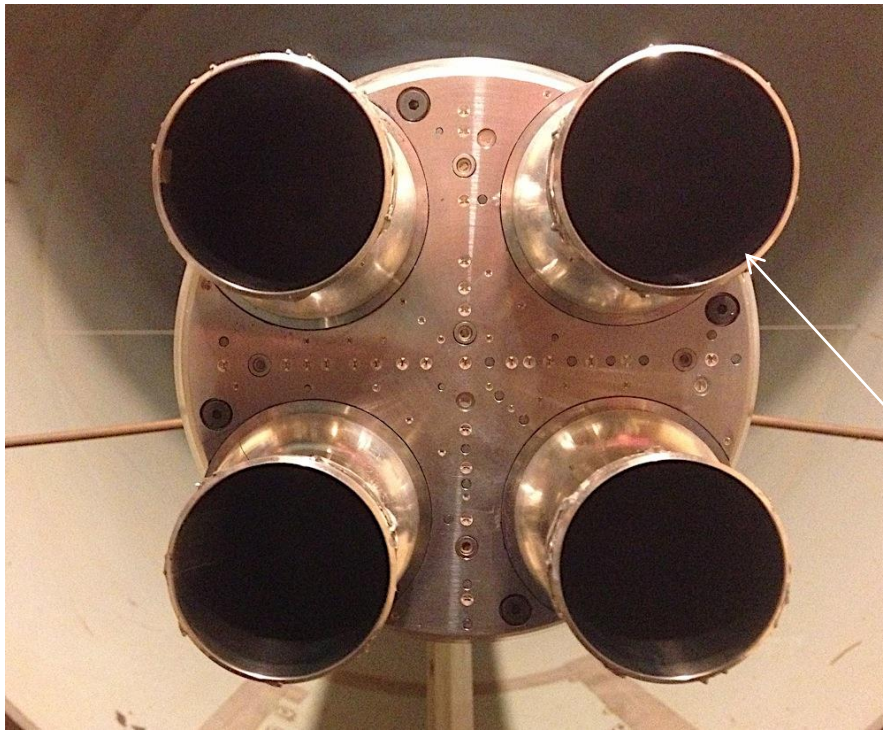
- [3]Dufrene, A.T. et al (2016), Space Launch System Base Heating Test: Experimental Operations and Results, AIAA 2016-0546, 2016 AIAA SciTech Conference, San Diego, CA.

- [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.

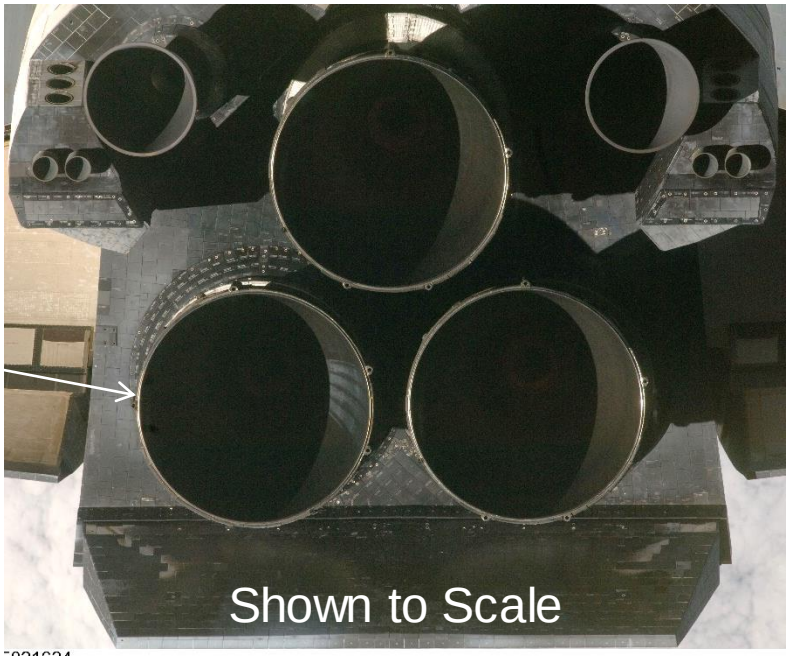
SLS and Shuttle Orbiter Base Configurations

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



RS-25 Nozzle

- **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**

Mehta et al. (2016), AIAA SciTech