National Aeronautics and Space Administration

Space Launch System: moving beyond low-Earth orbit

Plume-induced and aerothermal environments

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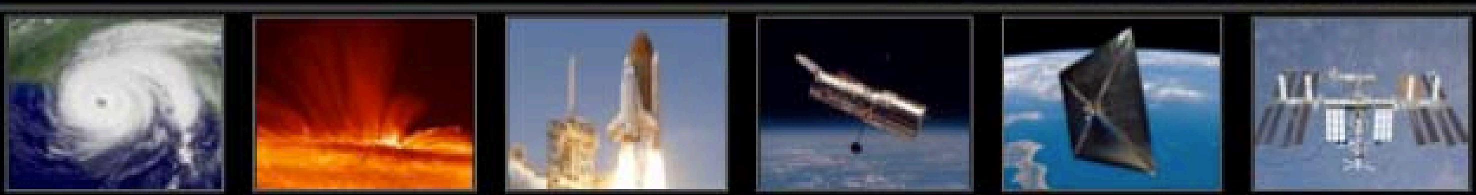

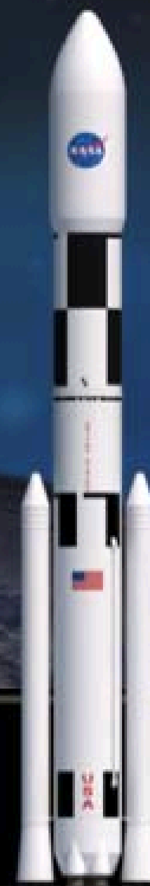

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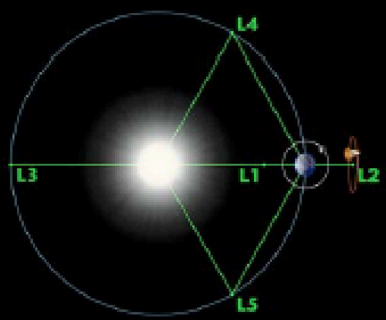
April 25th 2013

Road Map

- Space Launch System (SLS) Architecture
- Plume-Induced & Aerothermal Environments
- Cutting Edge Research and Development (R&D)
- Conclusions

Space Launch System (SLS): National Asset

SLS Destination



Mars and Its Moons Phobos and Deimos:
- A premier destination for discovery: Is there life beyond Earth? How did Mars evolve?
- True possibility for extended, even permanent, stays
- Significant opportunities for international collaboration
- Technological driver for space systems

High-Earth Orbit (HEO)/Geosynchronous-Earth Orbit (GEO)/Lagrange Points:
- Microgravity destinations beyond LEO
- Opportunities for construction, fueling, and repair of complex in-space systems
- Excellent locations for advanced space telescopes and Earth observatories

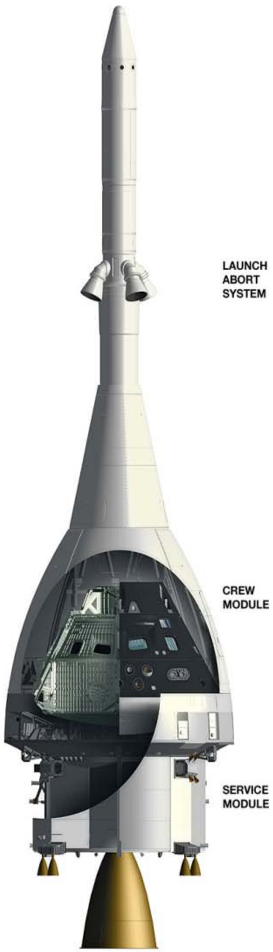
Earth’s Moon:
- Witness to the birth of the Earth and inner planets
- Has critical resources to sustain humans
- Significant opportunities for commercial and international collaboration

Near-Earth Asteroids:
- Compelling science questions: How did the Solar System form? Where did Earth’s water and organics come from?
- Planetary defense: Understanding and mitigating the threat of impact
- Potential for valuable space resources
- Excellent stepping stone for Mars

SLS Is Evolvable and Flexible

SLS Destination

2014 Orion-Delta IV Flight (EFT-1)

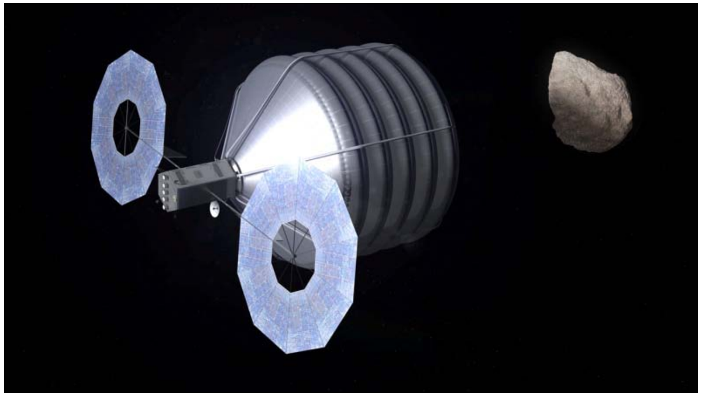


Multi-Purpose
Crew Vehicle
(MPCV – Orion)

Human Exploration of an Asteroid

http://www.nasa.gov/multimedia/videogallery/index.html

Human Exploration of Mars

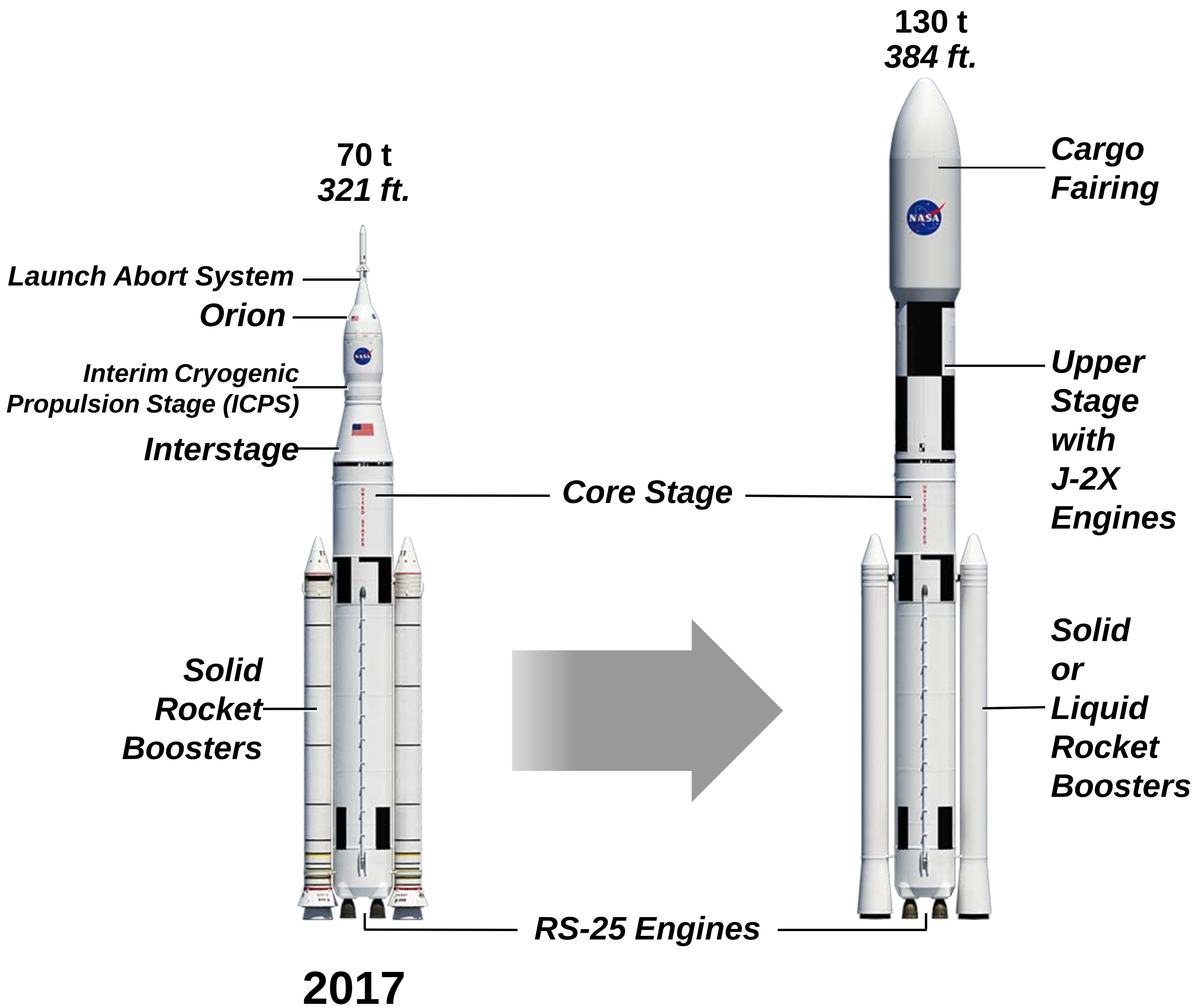


Asteroid Capturing Mission

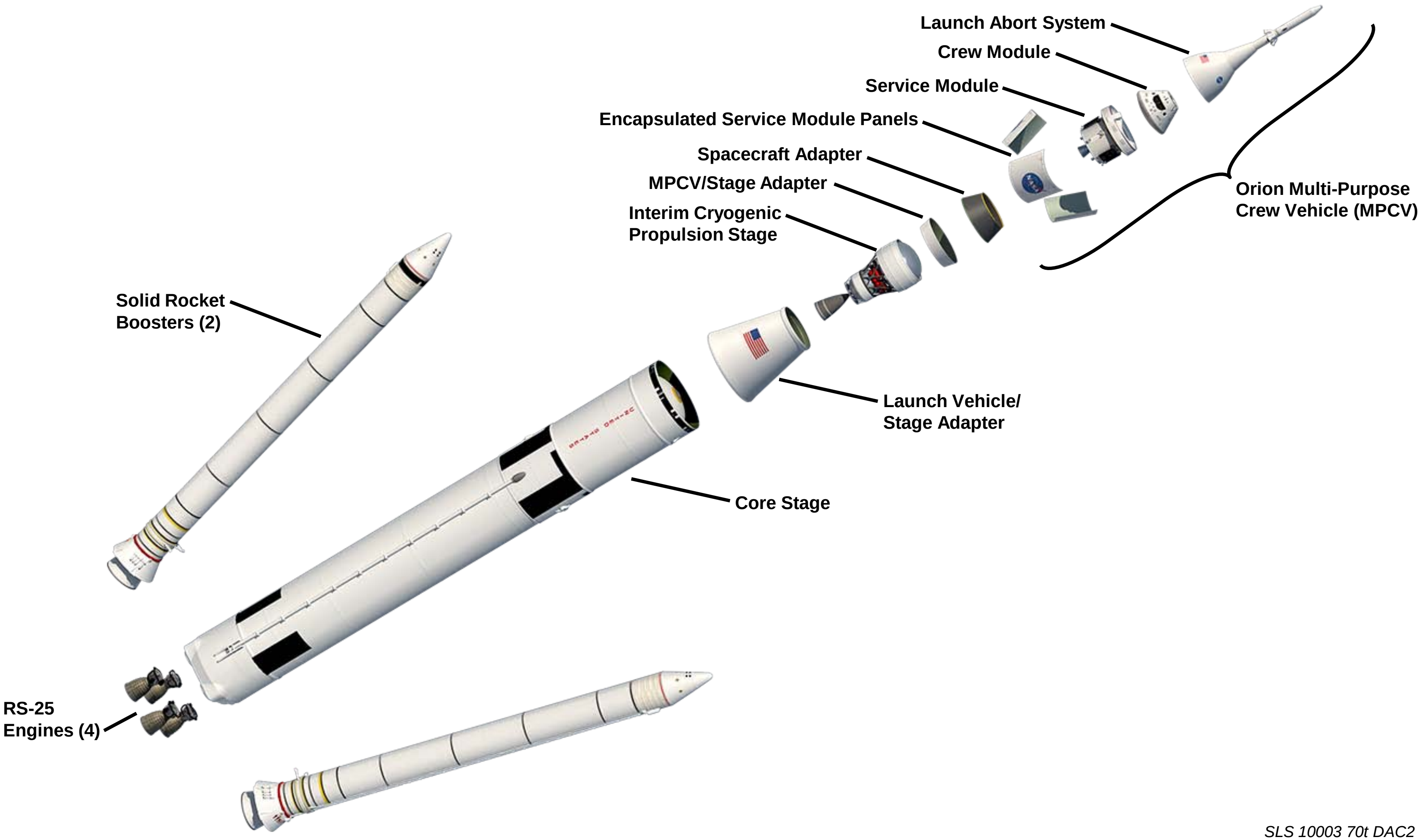
SLS Animation Video

http://www.nasa.gov/multimedia/videogallery/index.html?collection_id=73621

SLS Architecture



SLS 70t Expanded View



SLS 10003 70t DAC2

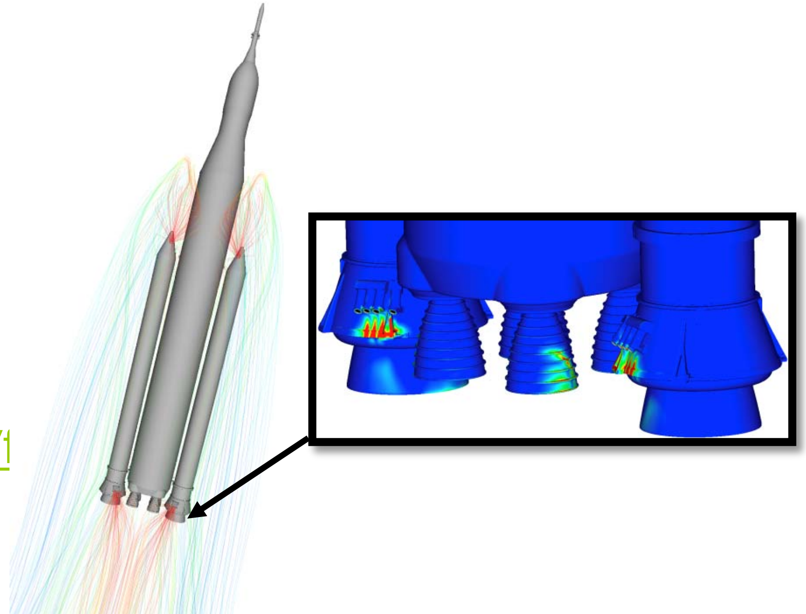
Motivation

- **Accurate base heating, plume impingement and aerodynamic heating predictions are critical for launch vehicle (LV) mission success.**
  - Design of Thermal Protection System (TPS), base plate, base fairing, and base instrumentation
  - Decreases design margin, decreases cost and improves LV performance
  - Decreases mission risk
- **Current prediction tool: semi-empirical methodology**

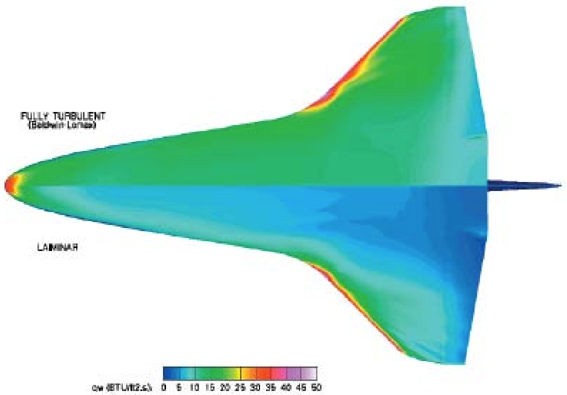
  Drawbacks:
  - Envelopes environments over broad zones
  - Dependent on the limitation of the data base
  - Cannot provide physics, surface and volumetric distributions
- **Future prediction tool: computational fluid dynamics (CFD)**
  - Due to changes in LV configuration and rocket motors, a physically-based approach is necessary for design of the next-generation LVs
- **CFD and semi-empirical methodologies show poor comparisons for plume-induced environments**
  - CFD solutions underpredict the semi-empirical results all base heat shield body points
- **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**

Plume-Induced and Aerothermal Environments

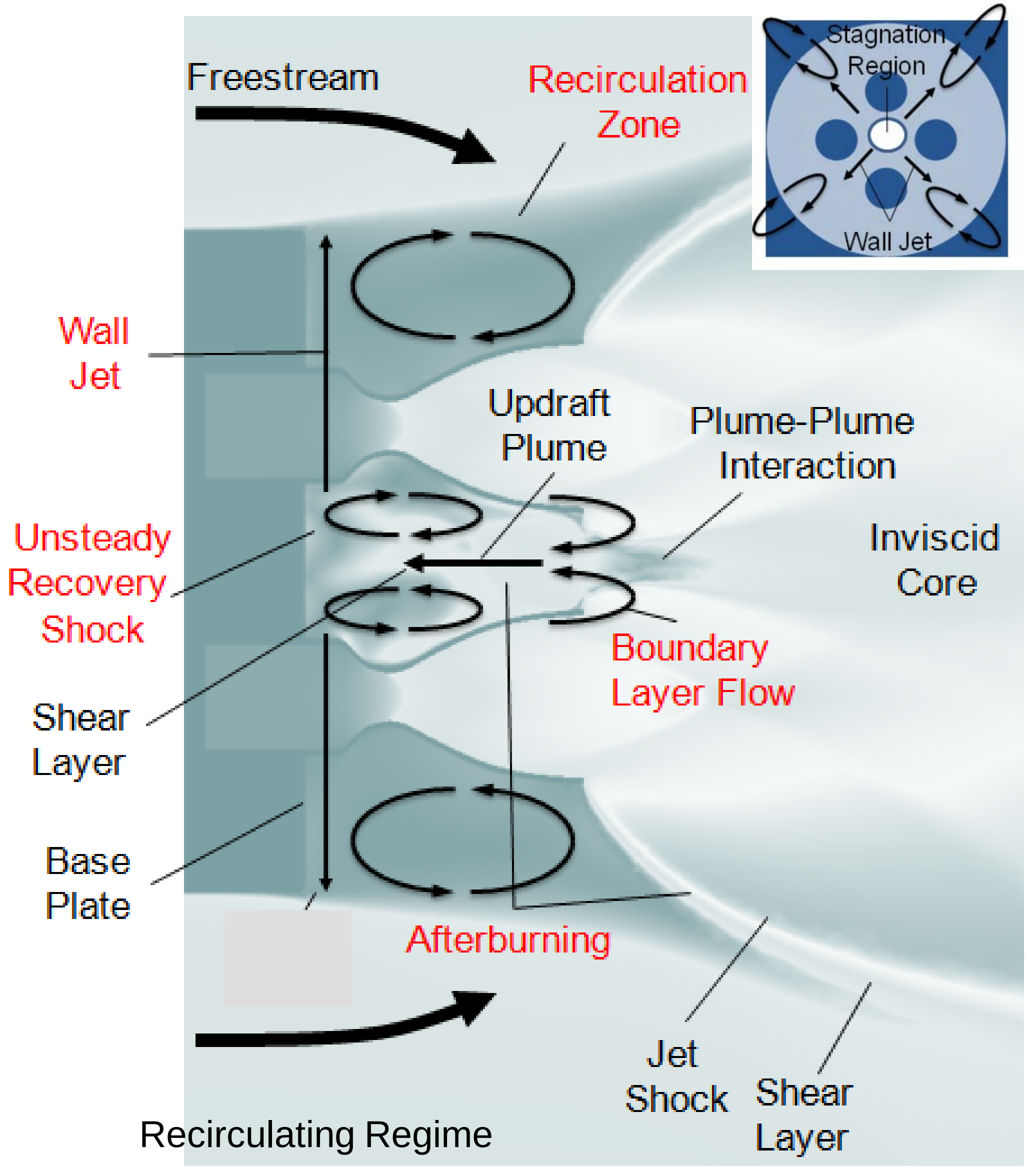
- **Two general external vehicle environments of importance for launch vehicle mission success**
- **Plume-induced environment**
  - Base Heating
  - Plume-Induced Flow Separation (PIFS)
  - Plume Impingement
    - Stage Separation Motors
    - Attitude Control Motors
  - http://www.youtube.com/watch?v=FzCsDVf



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



Base Flow Field



Recirculating Regime

Limited numerical and analytical studies have been conducted to fully characterize multi-plume base heating.

For the following reasons:
1. Complex
2. Unsteady
3.Finite-rate chemistry
4. Many interacting flow features/species
5. Sensitive to engine performance
5. Leads to many different trends, distributions and deltas

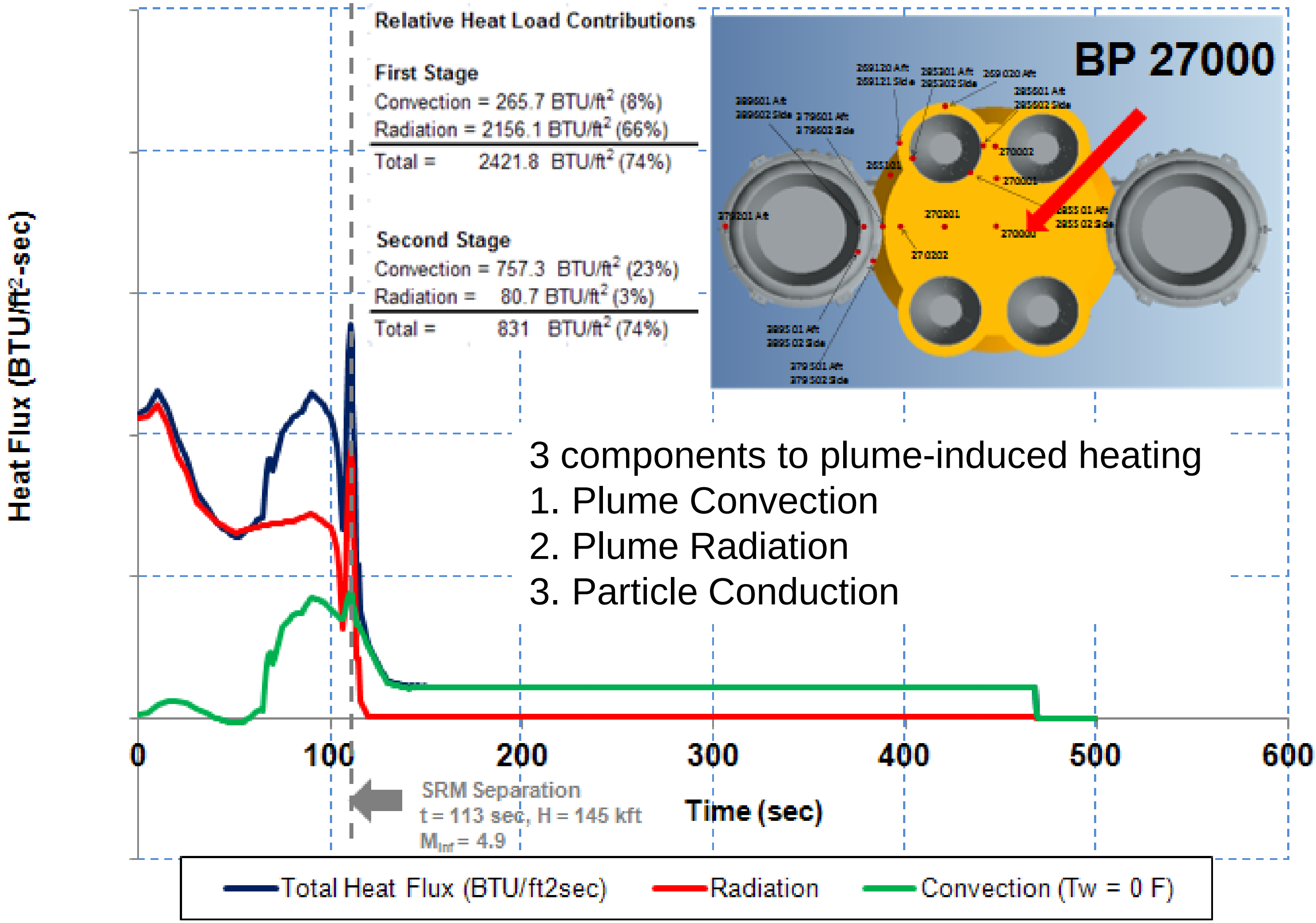
Base Flow Regimes:
Aspirating – Freestream air is entrained by the non-interacting rocket plumes (cooling)

Transitional – slight interactions by adjacent plumes leads to updraft plume component and downward aspirating jet

Recirculating – large interactions by highly expansive plumes leads to predominantly an updraft plume (heating)

Ref: M Mehta et al., AIAA JSR, 2013 (in press)

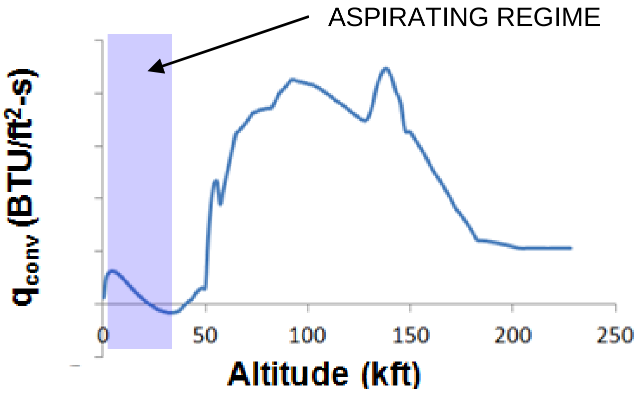
Plume-Induced Heating

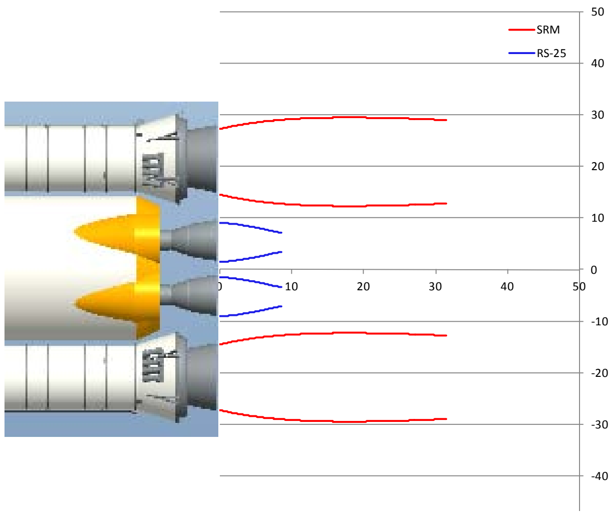


3 components to plume-induced heating
1. Plume Convection
2. Plume Radiation
3. Particle Conduction

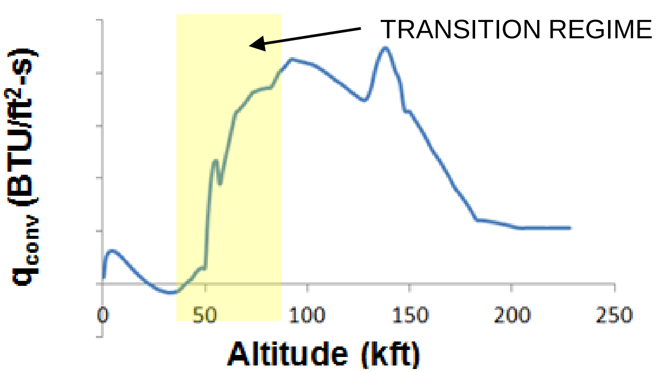
Base Convection

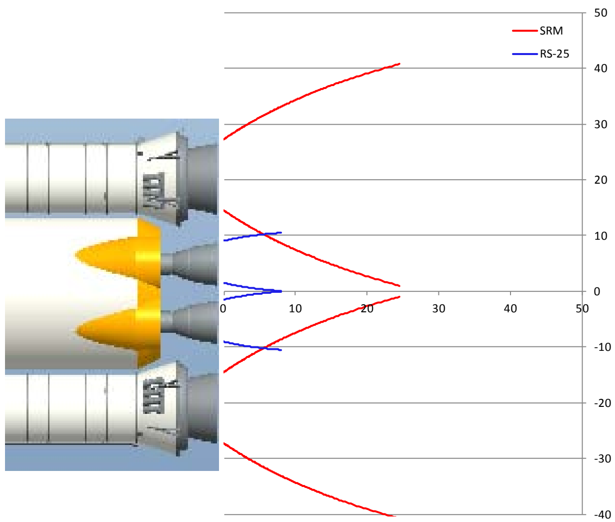
- Plume Boundaries and Regime Definition
- Aspirating Flow, 10Kft





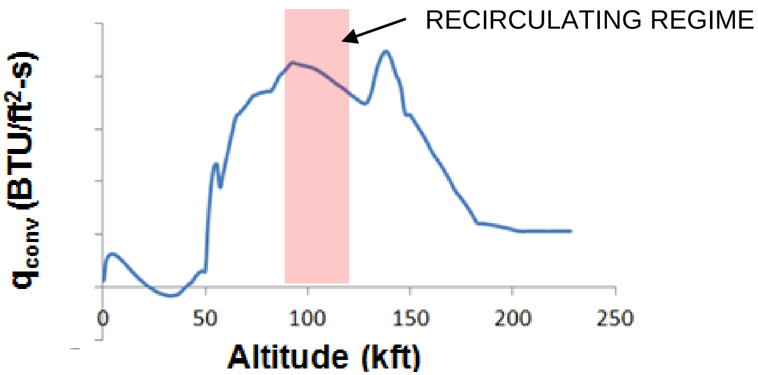
- Core Transition, 48-50Kft

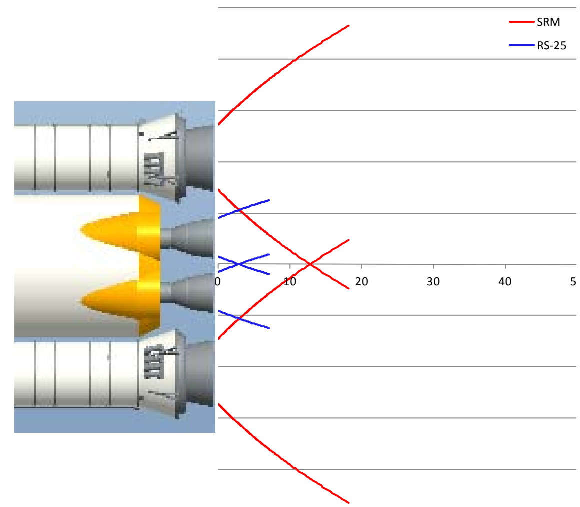




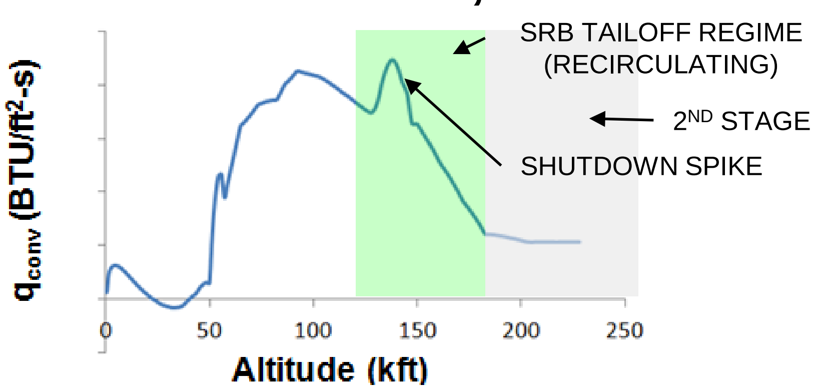
Base Convection

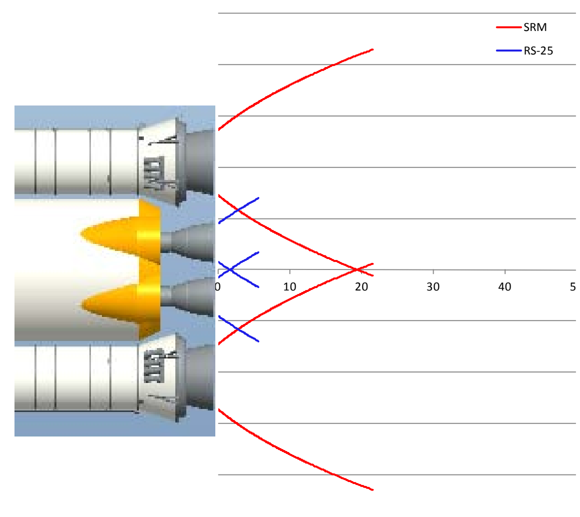
- **Plume Boundaries and Regime Definition**
- **Peak Heating, 85Kft**





- **Pre-SRB Shutdown, 115Kft**

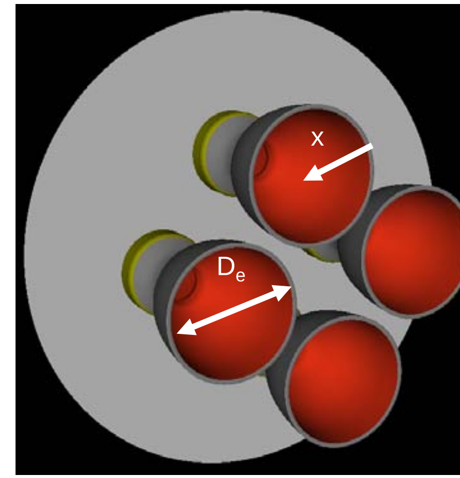


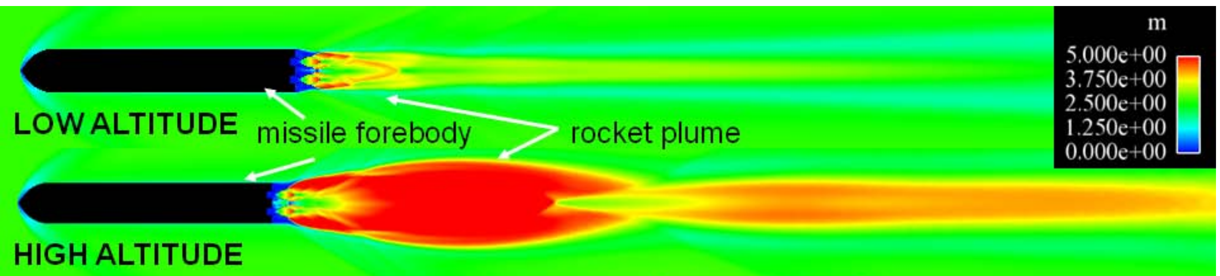


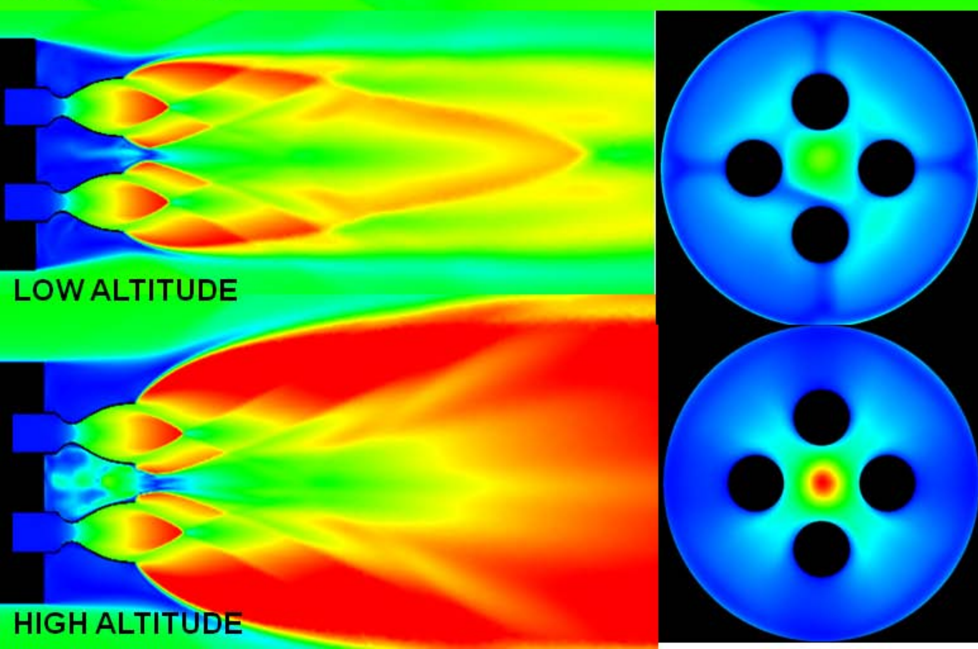
Rocket Plume Flow Field

Plume structures are different between two altitude regimes because this is a function of the freestream shear stress and pressure on the shock layer.

http://www.youtube.com/watch?v=mbtvFIEBJdA

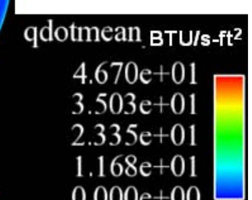






BASE PLATE

Moderately expansive plumes (limited plume-plume interactions) lead to transitional base flow regime and low base heat flux



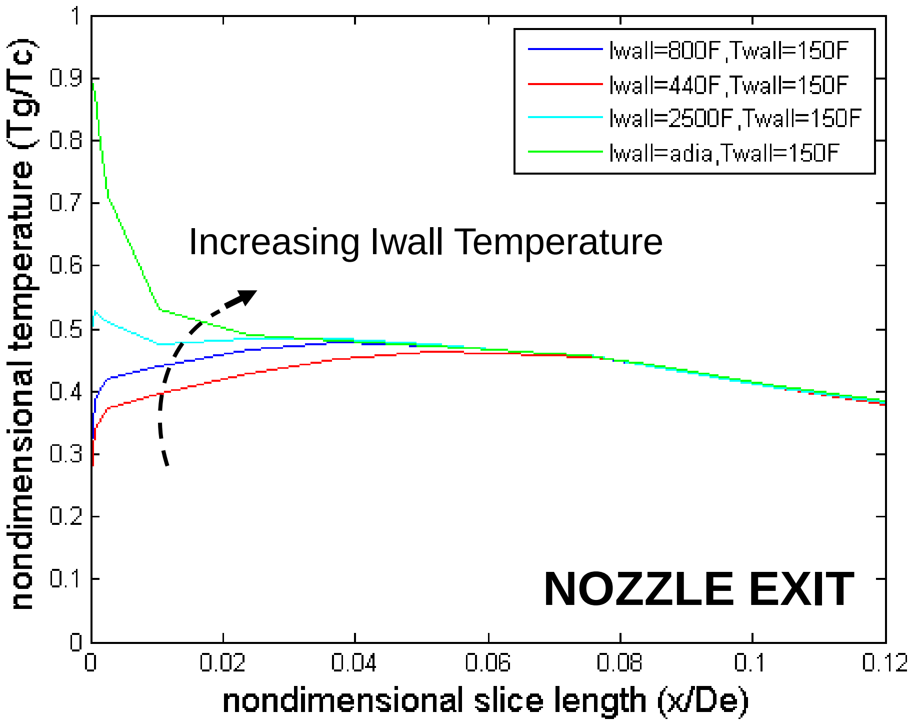
Highly expansive plumes (significant plume-plume interactions) lead to choked-recirculating base flow regime and high base heat flux

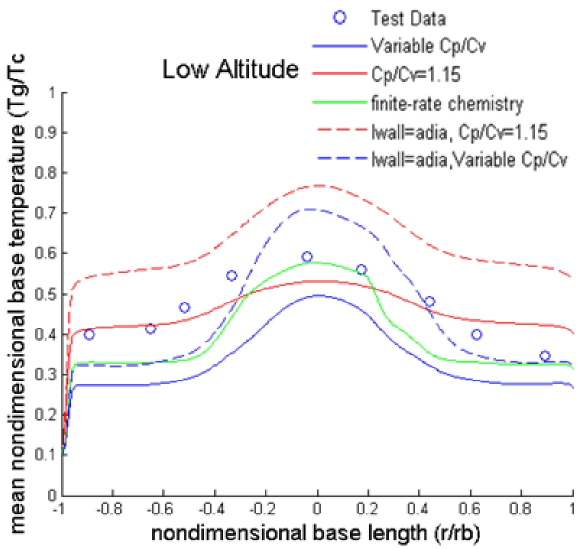
Ref: M Mehta et al., AIAA JSR, 2013 (in press)

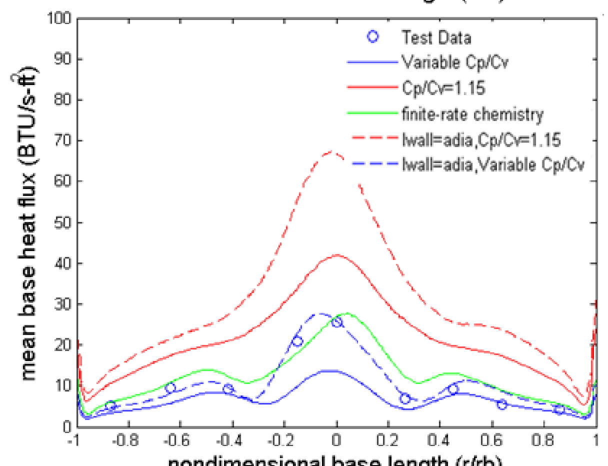
Iwall Temperature Sensitivity

20% increase in the thermal boundary layer area profile between the Iwall 800 deg F (blue curve) and adiabatic wall (green curve) boundary condition leads to an average increase of 70% in the base heat flux and 45% in the base gas temperature.

Adiabatic wall assumes no heat escape and results in artificially higher boundary layer temperatures and thermal energy for regenerative-cooled liquid rocket engines



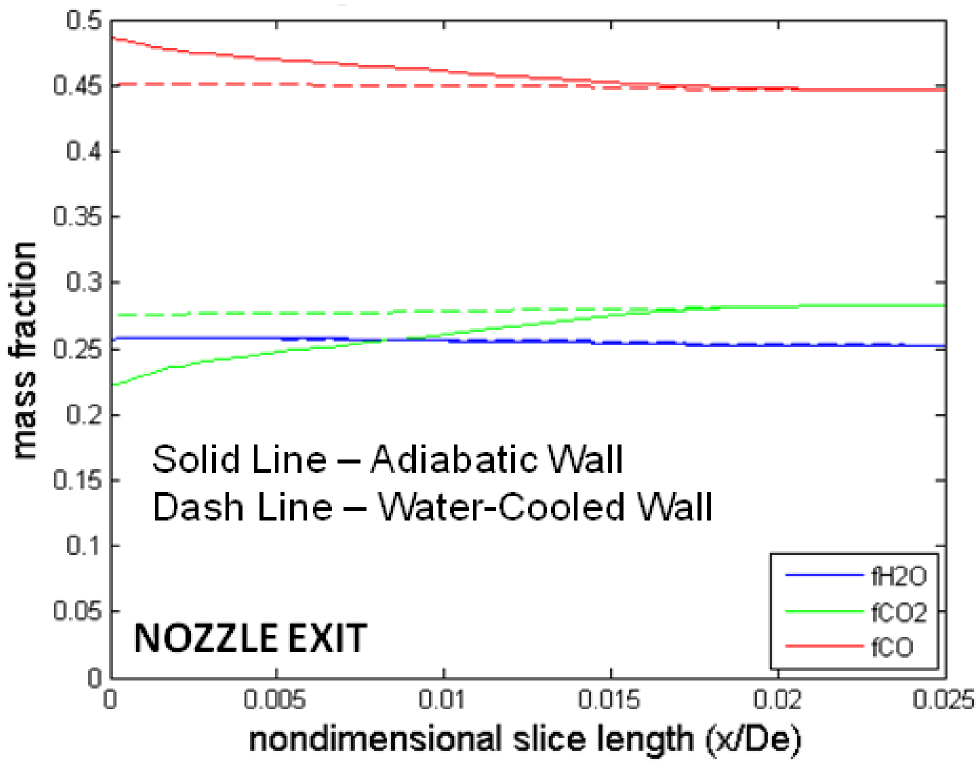




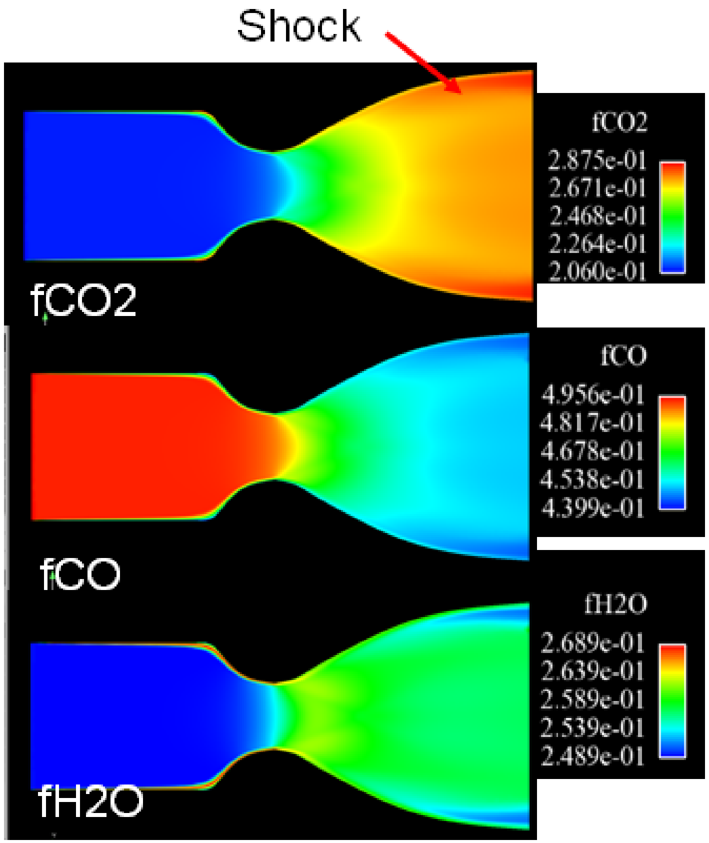
Ref: M Mehta et al., AIAA JSR, 2013 (in press)

Boundary Layer Chemical Reactions

Iwall boundary conditions (A) and shocks (B) change the plume chemical composition within the boundary layer – leads to a change in the thermal boundary layer profile and base heating characteristics



A

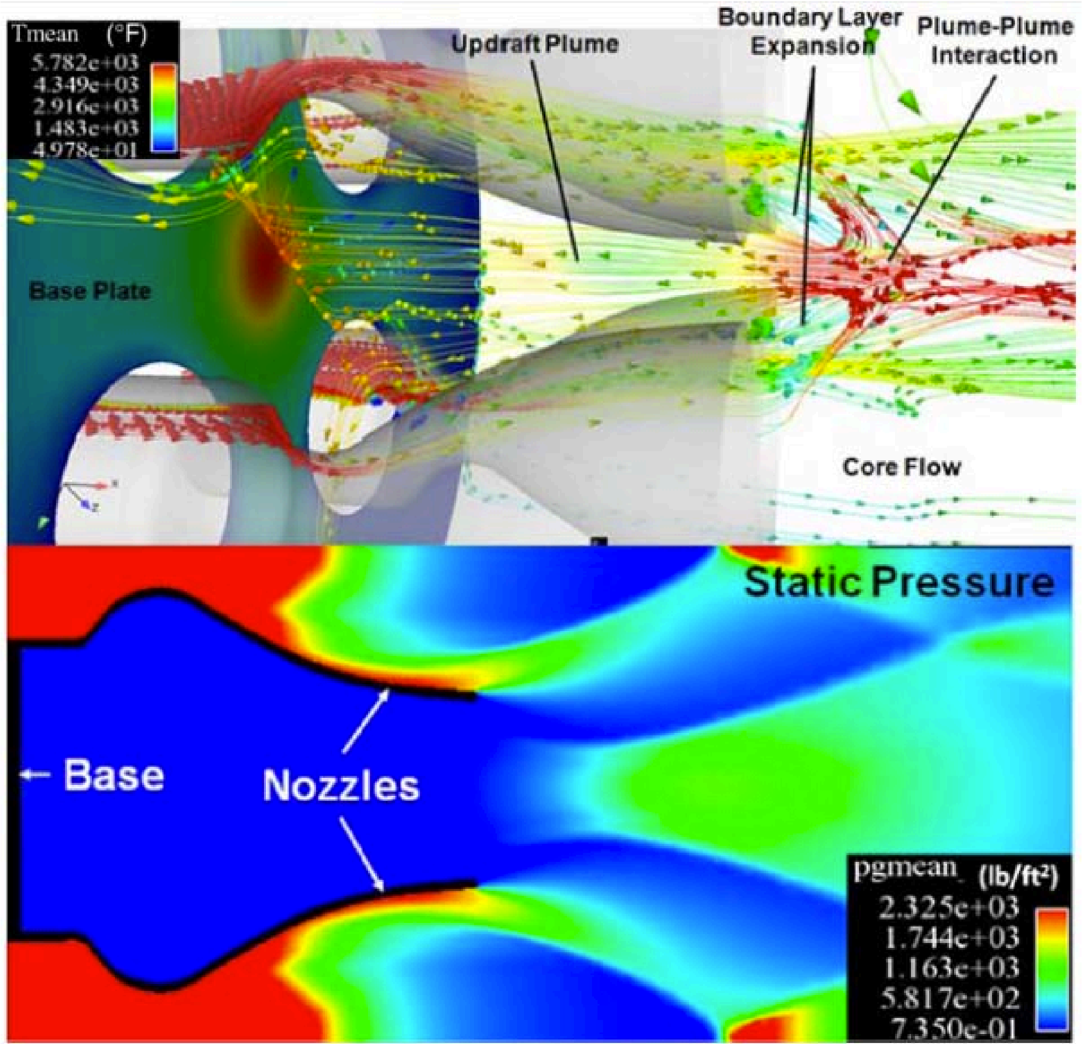


B

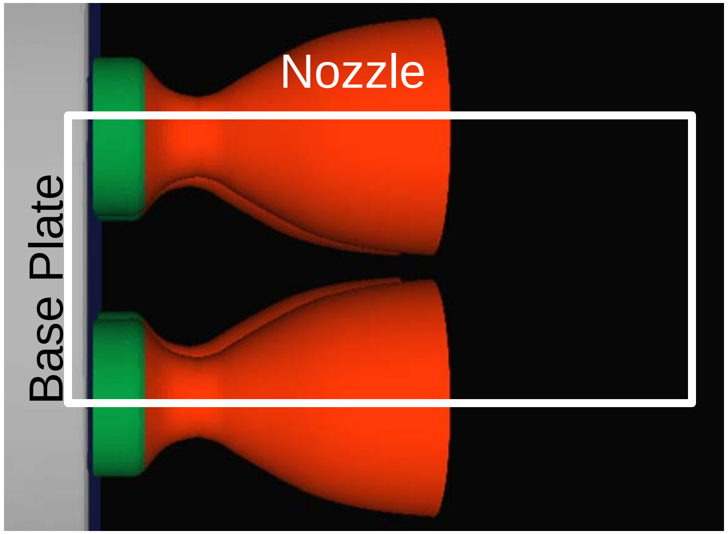
Ref: M Mehta et al., AIAA JSR, 2013 (in press)

Boundary Layer Flow

Low kinetic energy nozzle inner wall boundary layer rebounds off the Type I shock-shock induced pressure gradient and flows upstream toward the base plate – main driver in base heating.



High Altitude



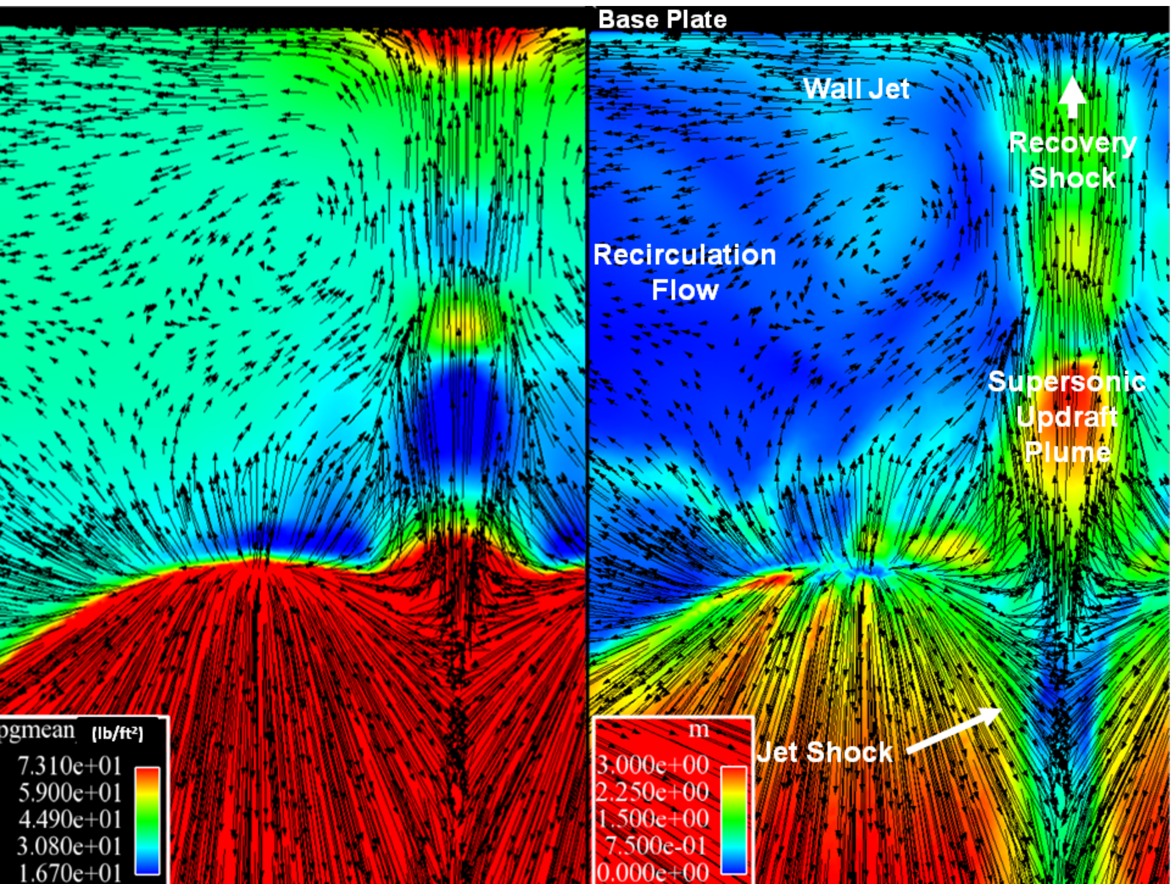
Cut plane through nozzle centerline

Ref: M Mehta et al., AIAA JSR, 2013 (in press)

Recovery Shock & Recirculation Zone

Supersonic updraft plume develops an unstable recovery shock at the base center and low-pressure recirculation zones - leads to maximum peaks and large perturbations in heat flux and pressure at the base plate center for high altitude case

High Altitude



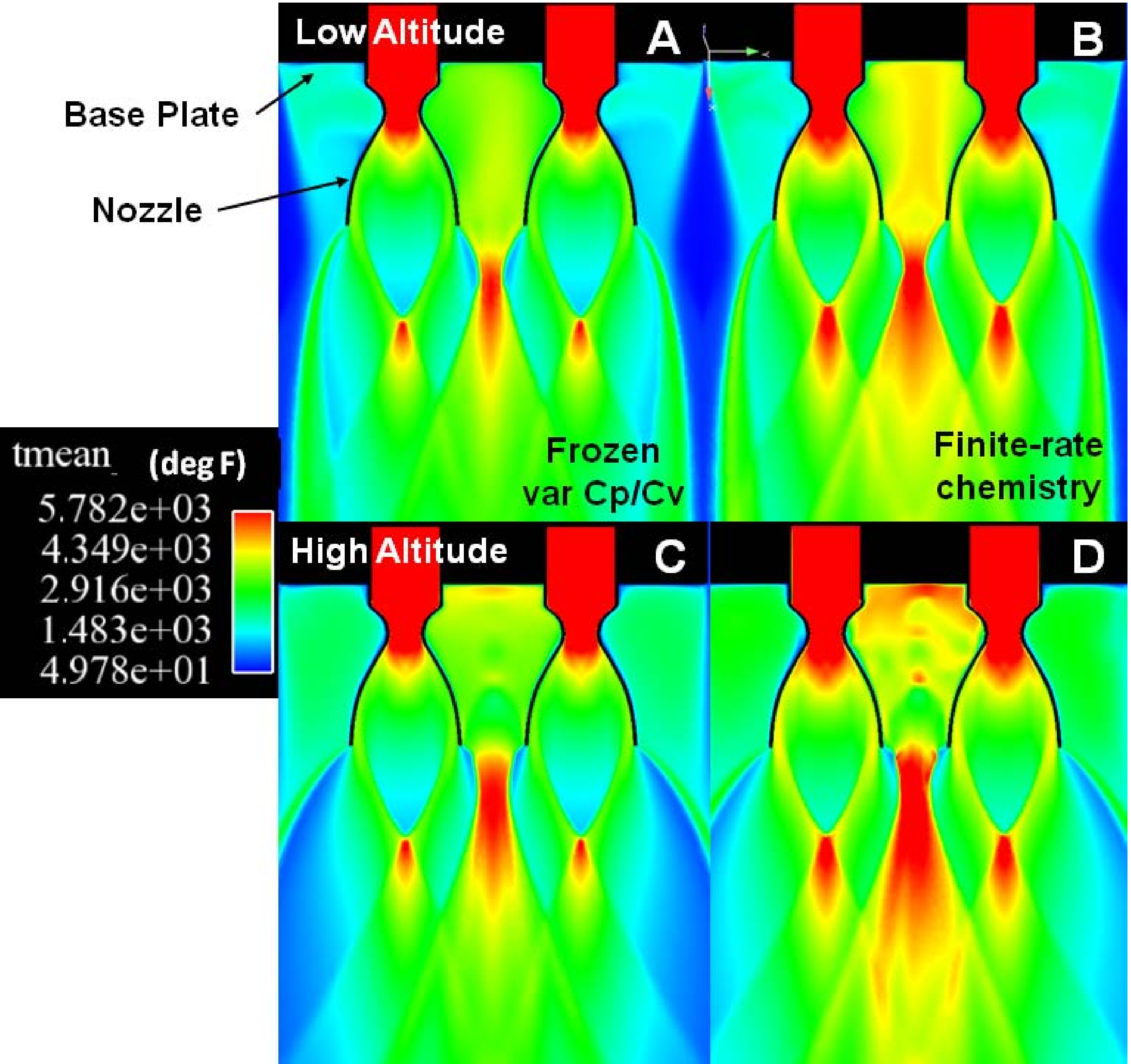
Momentum imbalance between the two structures – leads to unsteady recovery shock dynamics

These responses are dampened by the higher number density freestream for the low altitude case.

Cut plane between two nozzles

Ref: M Mehta et al., AIAA JSR, 2013 (in press)

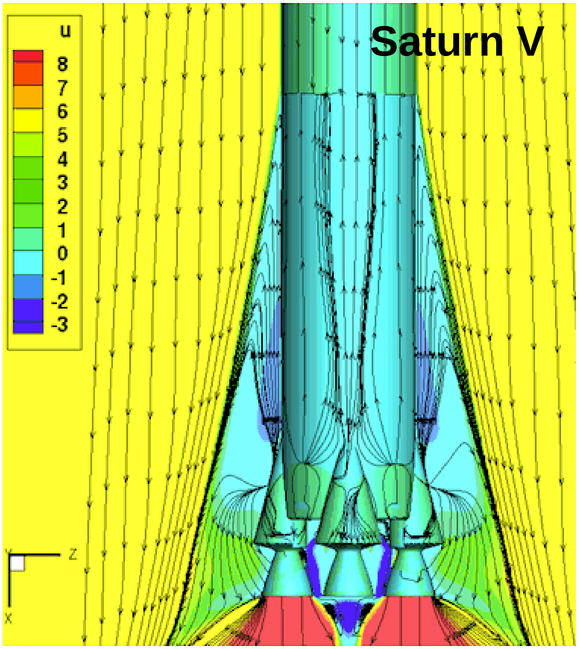
Afterburning



- **Mixing of the carbon residual-exhaust species within the boundary layer and the freestream oxygen in the base region results in combustion and release of chemical energy within the updraft plume – leading to a rise in static temperature and base heat flux**

Ref: M Mehta et al., AIAA JSR, 2013 (in press)

PIFS



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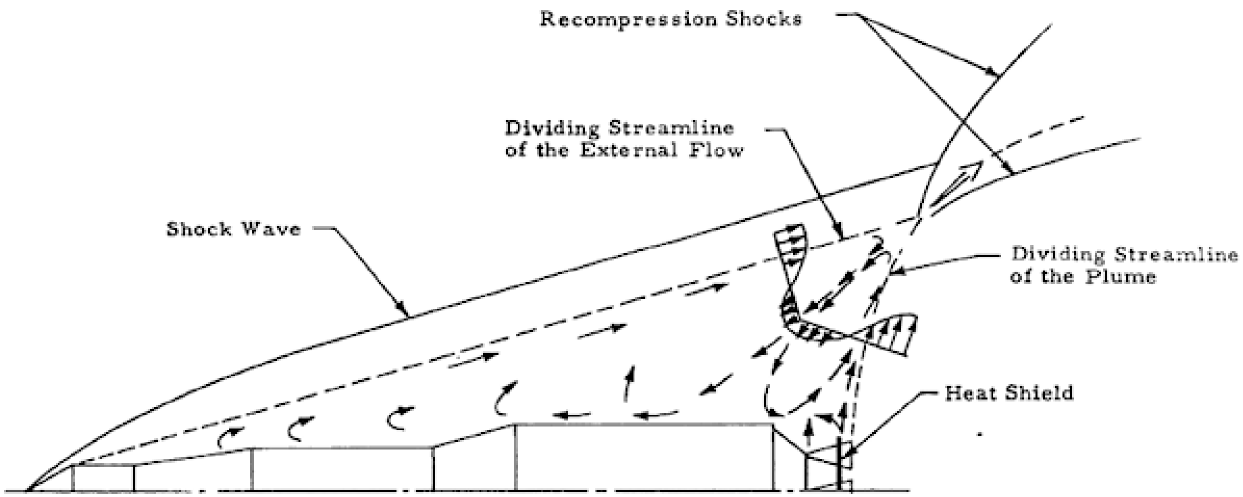
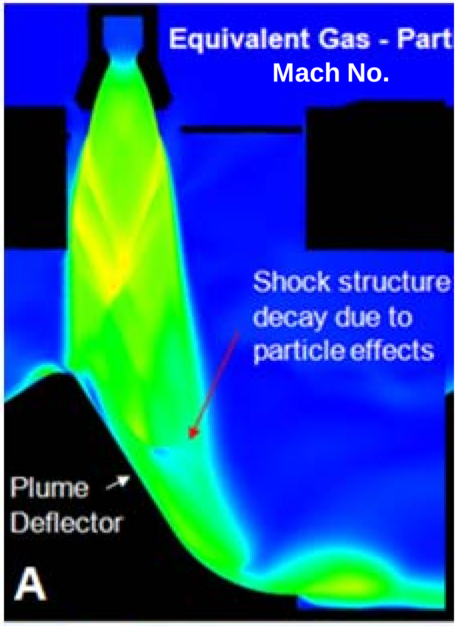
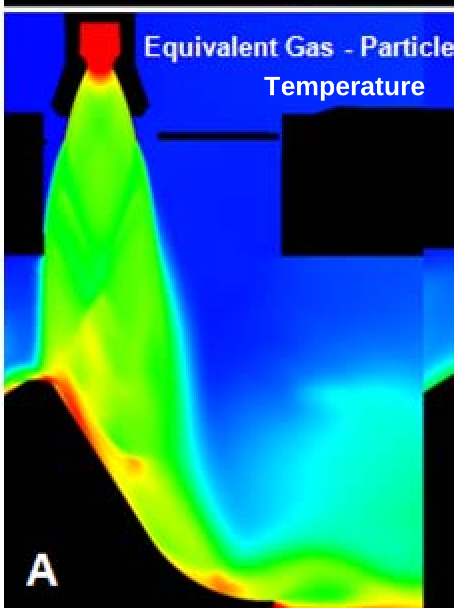
Saturn V



Recompression Shocks
Dividing Streamline of the External Flow
Shock Wave
Dividing Streamline of the Plume
Heat Shield

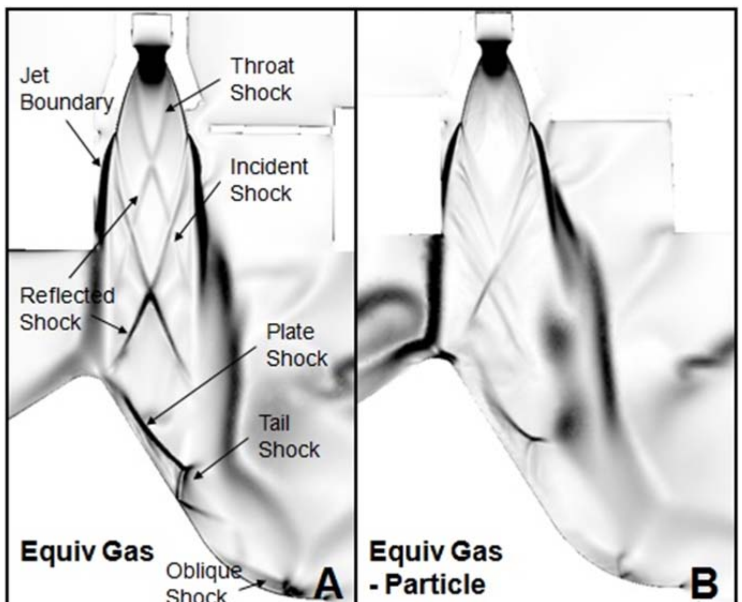
Plume Impingement

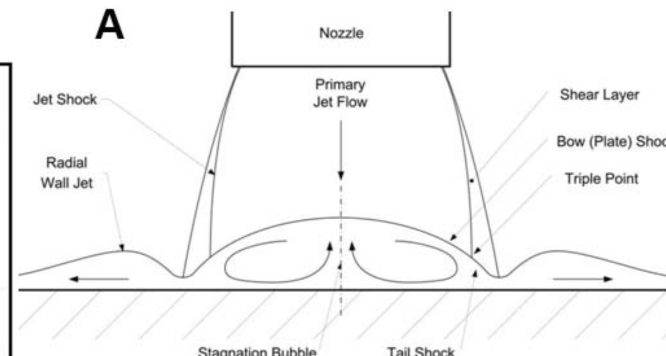


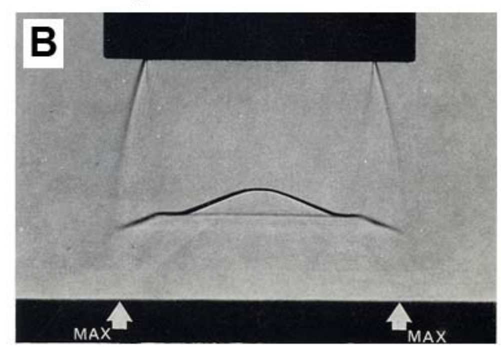


- **Booster separation and deceleration motor plumes interact with launch vehicle structures**

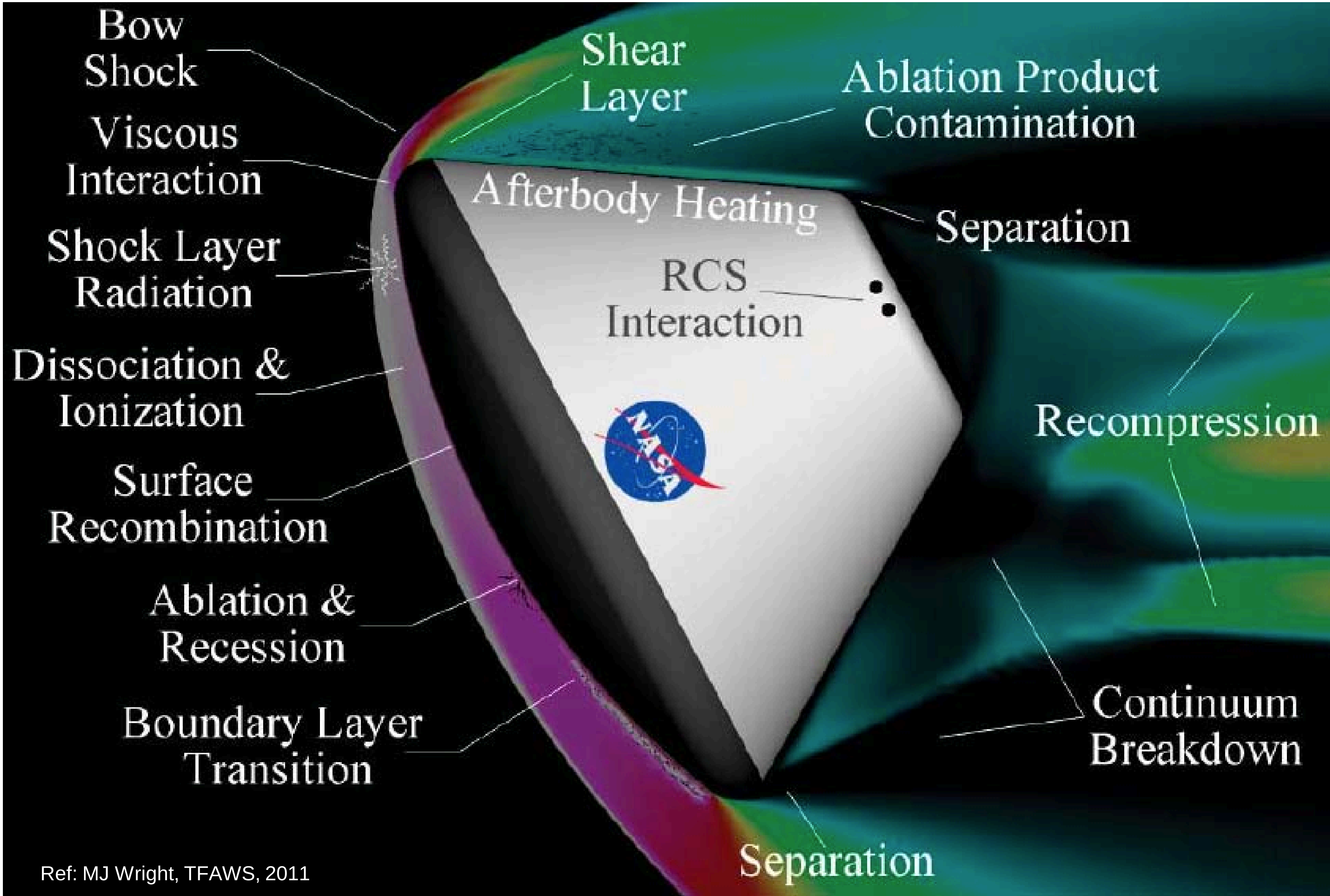
- **Rocket plume – launch pad interactions**





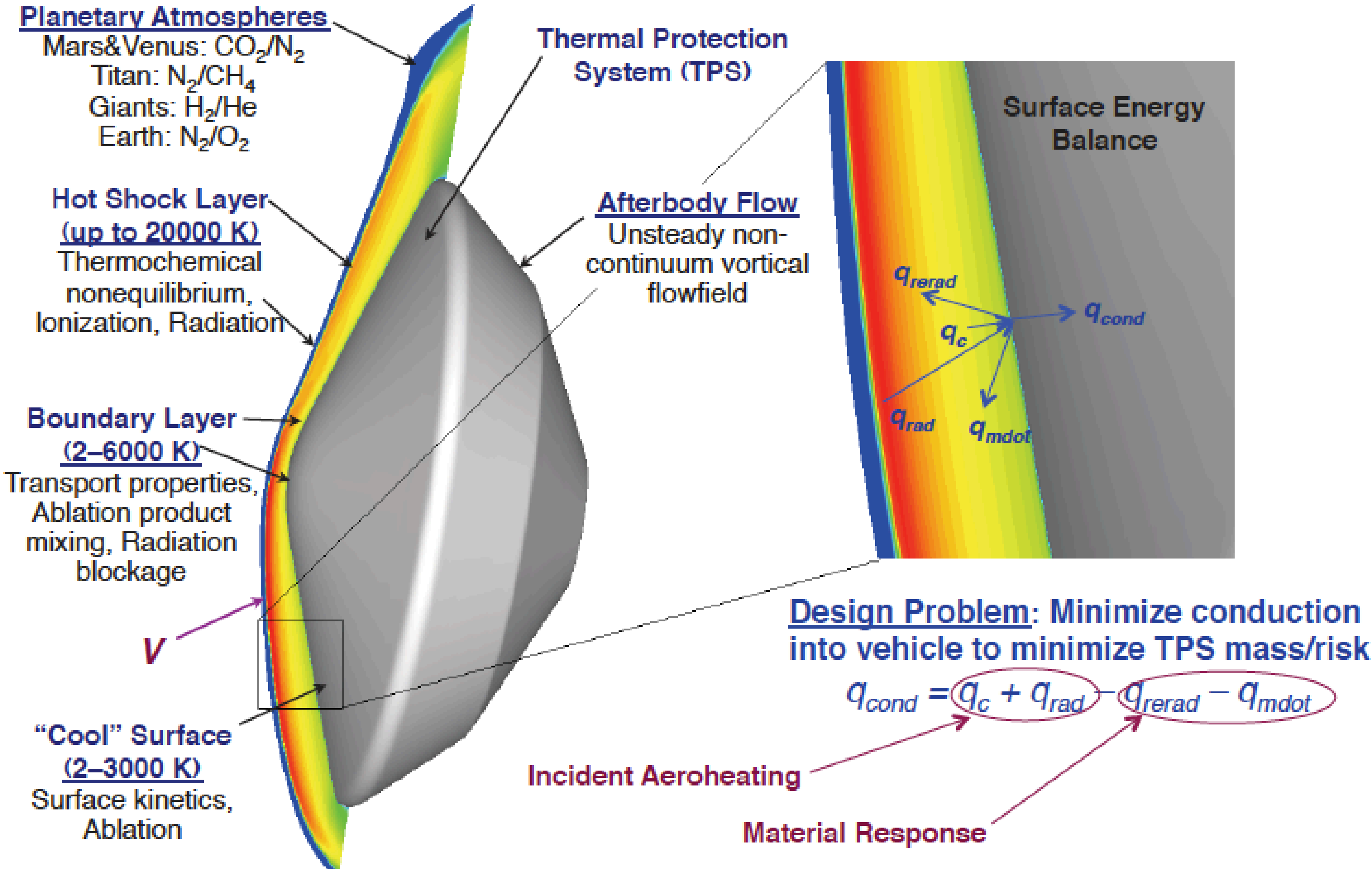


Aerothermal Environment: Flow Field



Ref: MJ Wright, TFAWS, 2011

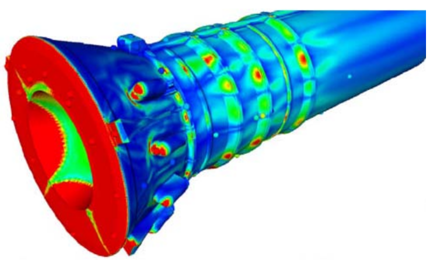
Aerothermal Environment



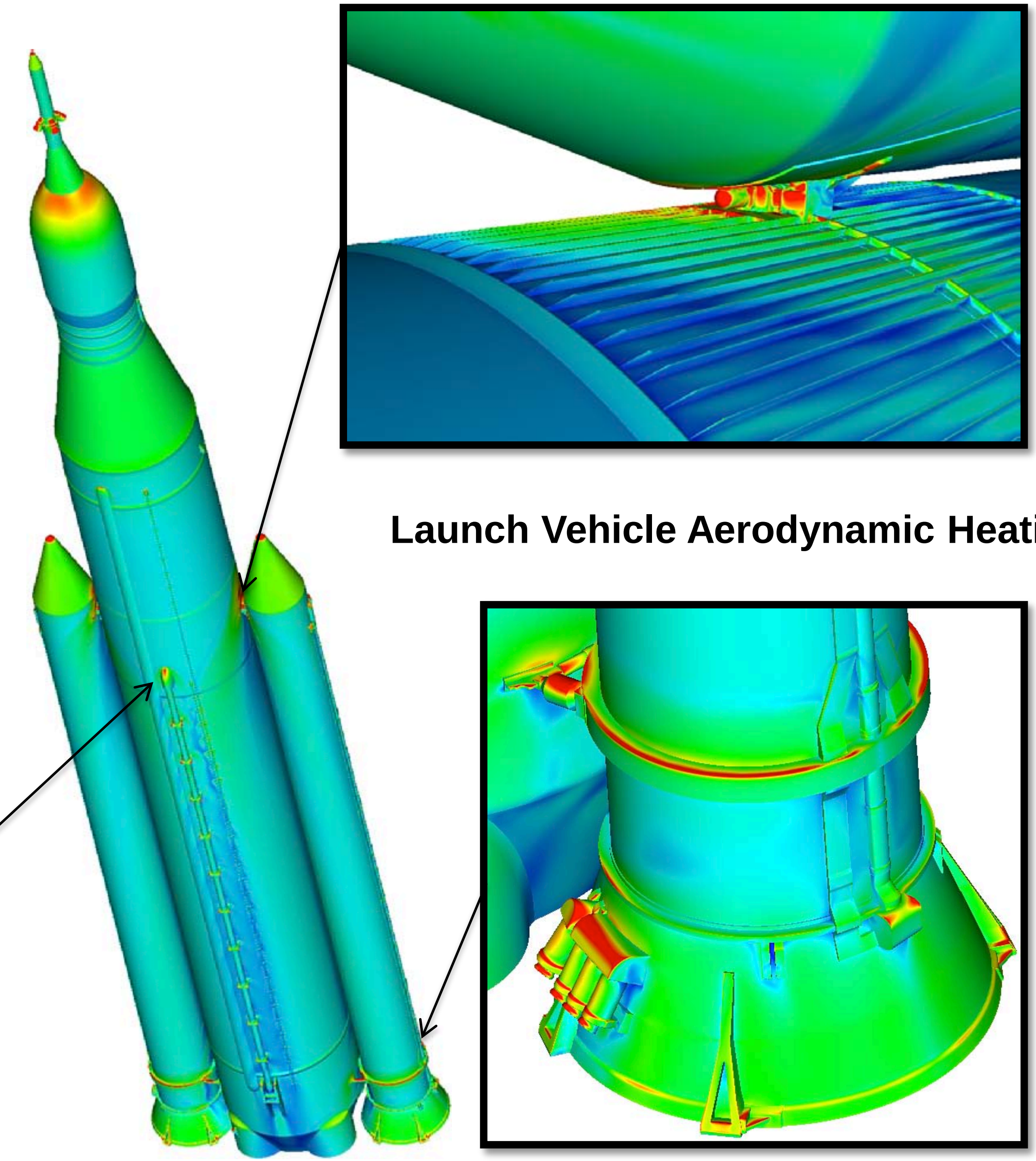
Ref: MJ Wright, TFAWS, 2011

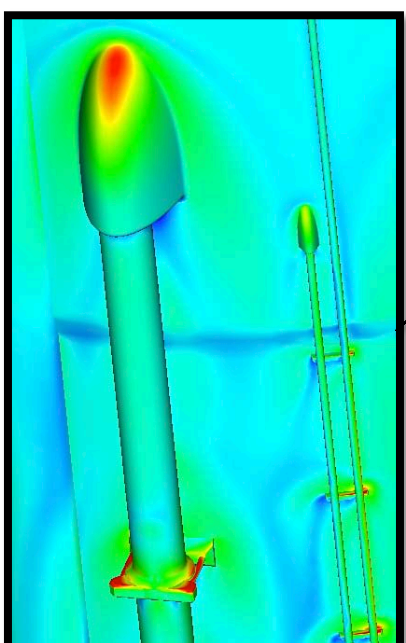
Aerothermal Environment

Booster Re-entry



Launch Vehicle Aerodynamic Heating

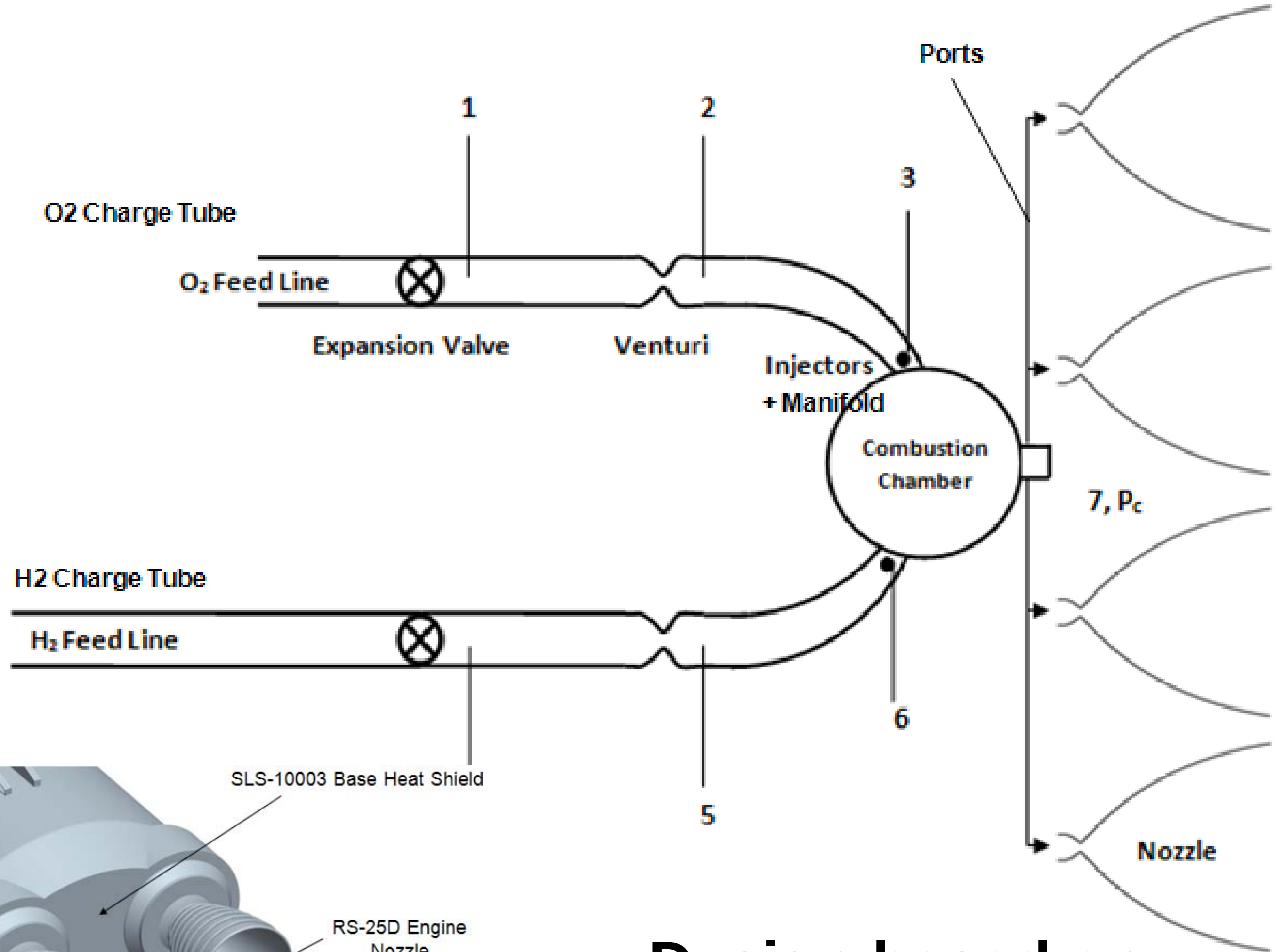


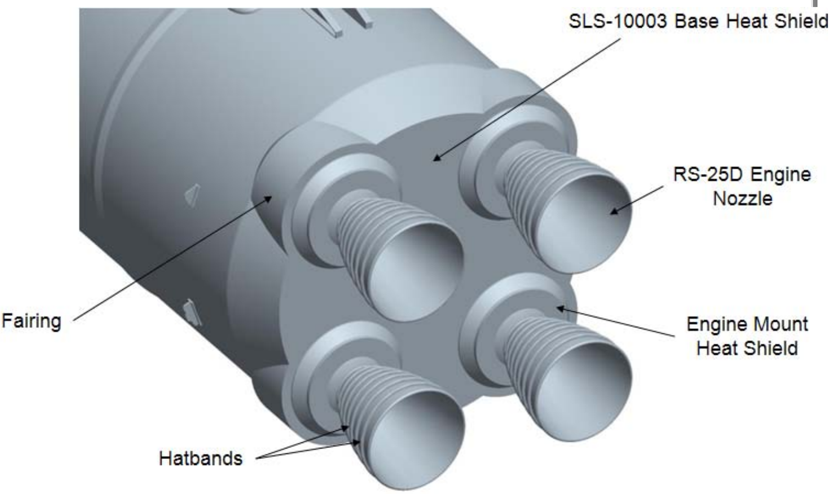


Cutting Edge Research and Development

- **Designing and developing a subscale hot-fire propulsion test model of the SLS vehicle (Pathfinder Test Program)**
  - Computational combustion modeling of core-stage engine
  - Develop a subscale gaseous hydrogen and oxygen combustion RS-25D engine for the core-stage
  - Develop a subscale RSRM-analog solid propellant motor for the booster stage
- **Conduct wind tunnel base convective heating tests at various altitudes to simulate SLS flight (Main Test Program)**
  - Altitude range from 45 Kft to 200 Kft
  - Freestream Mach number range from M = 2.5 – 5.5
  - Test full-stack stage and core-only stage flights
  - Goal of test to identify convective base heating and PIFS and predict base heating trends for the flight vehicle
  - Similar tests have not been done for a NASA vehicle in 40 years
  - Goal is to provide much higher fidelity testing than previous tests done in the the 60s/70s
  - To use new non-intrusive diagnostics
- **Technical Partners**
  - NASA Marshall Space Flight Center Aerosciences Branch (Lead) including SLU's very own **Mr. Brian Kovarik**
  - Calspan-University of Buffalo Research Center Aerosciences
  - NASA Glenn Research Center Propulsion and Propellants Branch
  - $4M Test Program

Core-Stage Engine Test Article

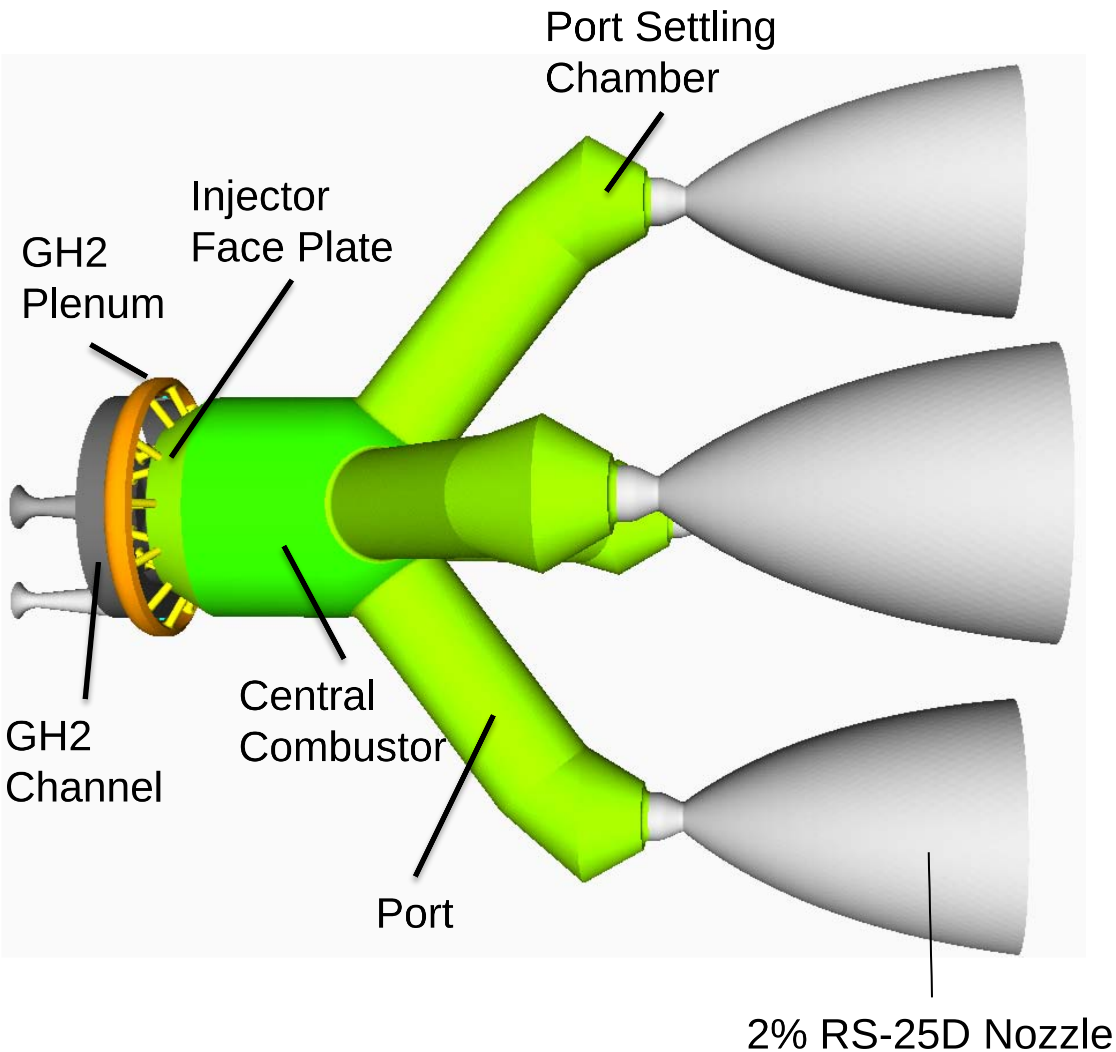


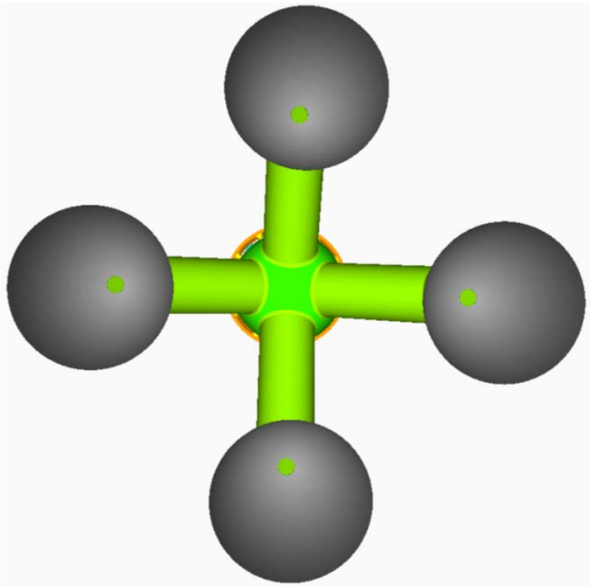


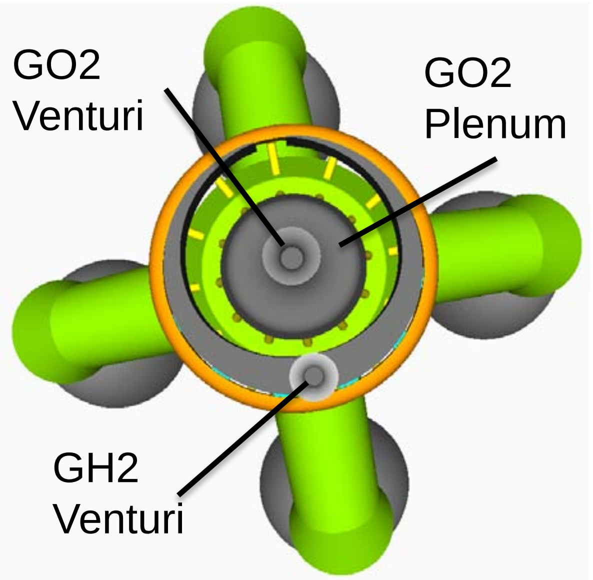
Design based on:

1. Engineering Codes
2. Computational Modeling
3. Semi-Empirical/Heritage

Core Stage Engine Test Article





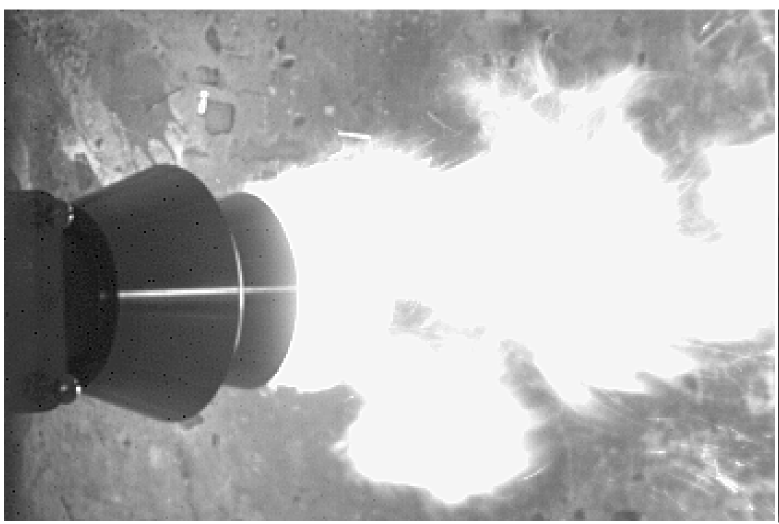


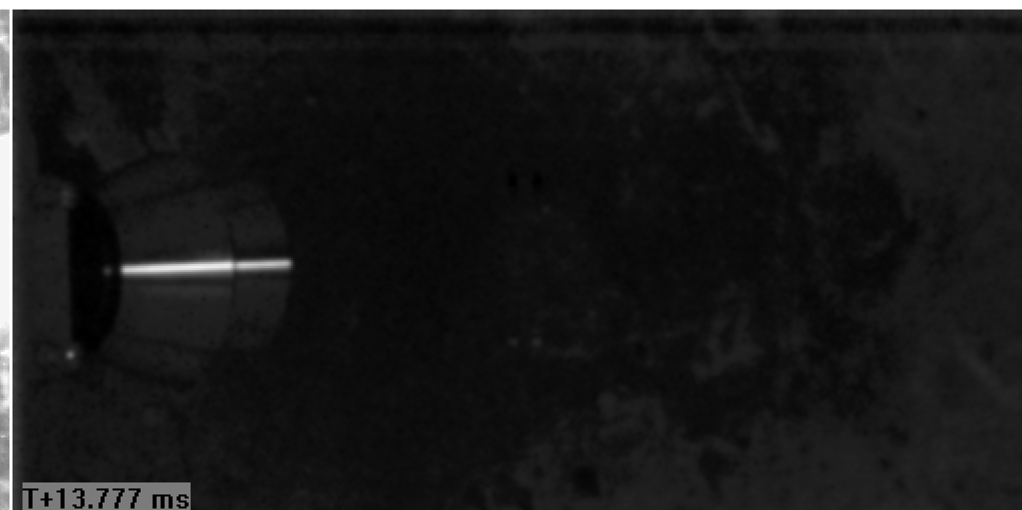
Completed Preliminary Design Review in December 2012
Currently in Final Design Phase

Booster Stage Solid Rocket Motor Test Article

Completed Preliminary Design Review in December 2012

Currently in Final Design Phase





Conclusions

- **To accurately predict the aerophysics associated with various environments during launch vehicle ascent, the following areas are needed:**
  - Thorough understanding of the flow physics/flow field
  - Semi-empirical/heritage base modeling
  - Computational modeling
  - Ground/wind tunnel testing
  - Scaling Analyses
  - Flight Tests

Questions