Space Launch System Ascent Aerothermal Environments Methodology

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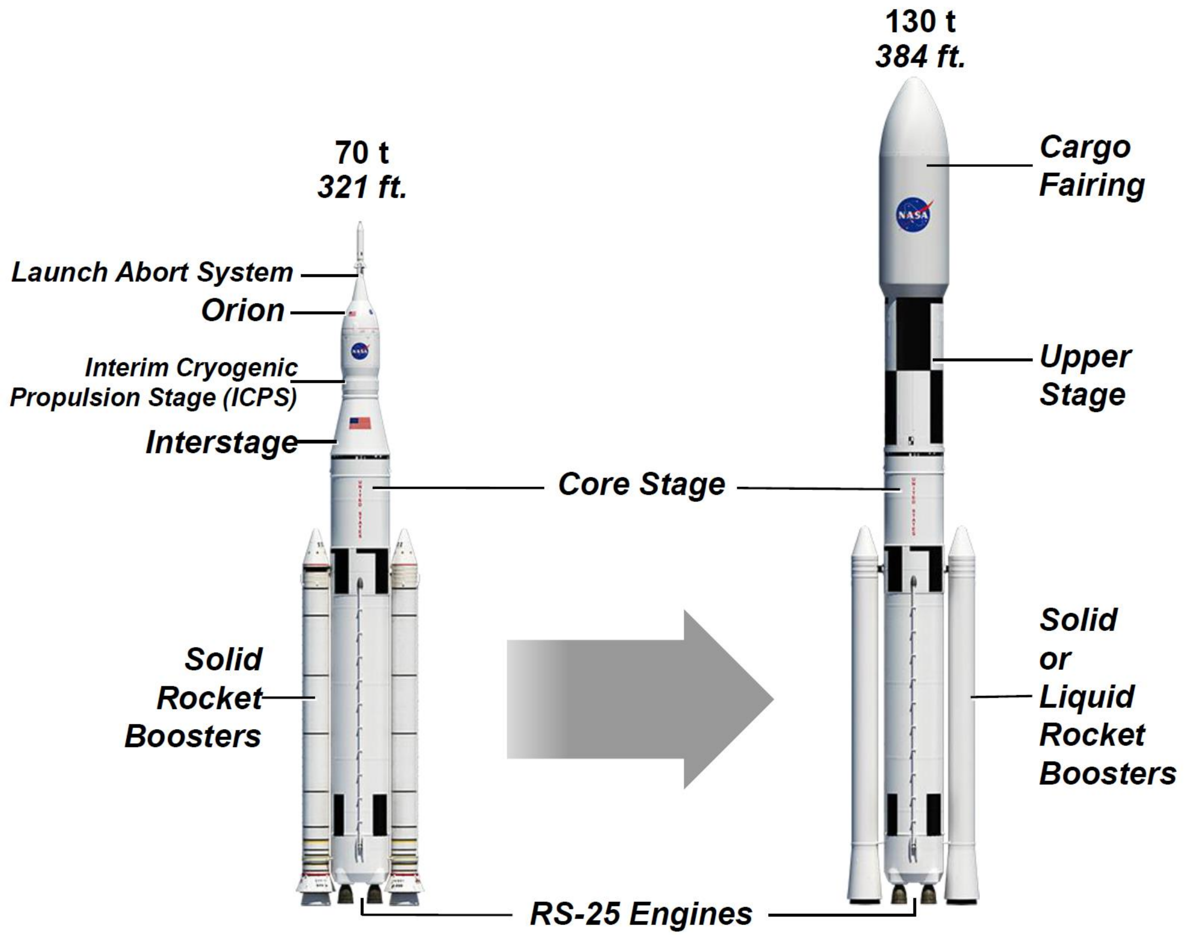
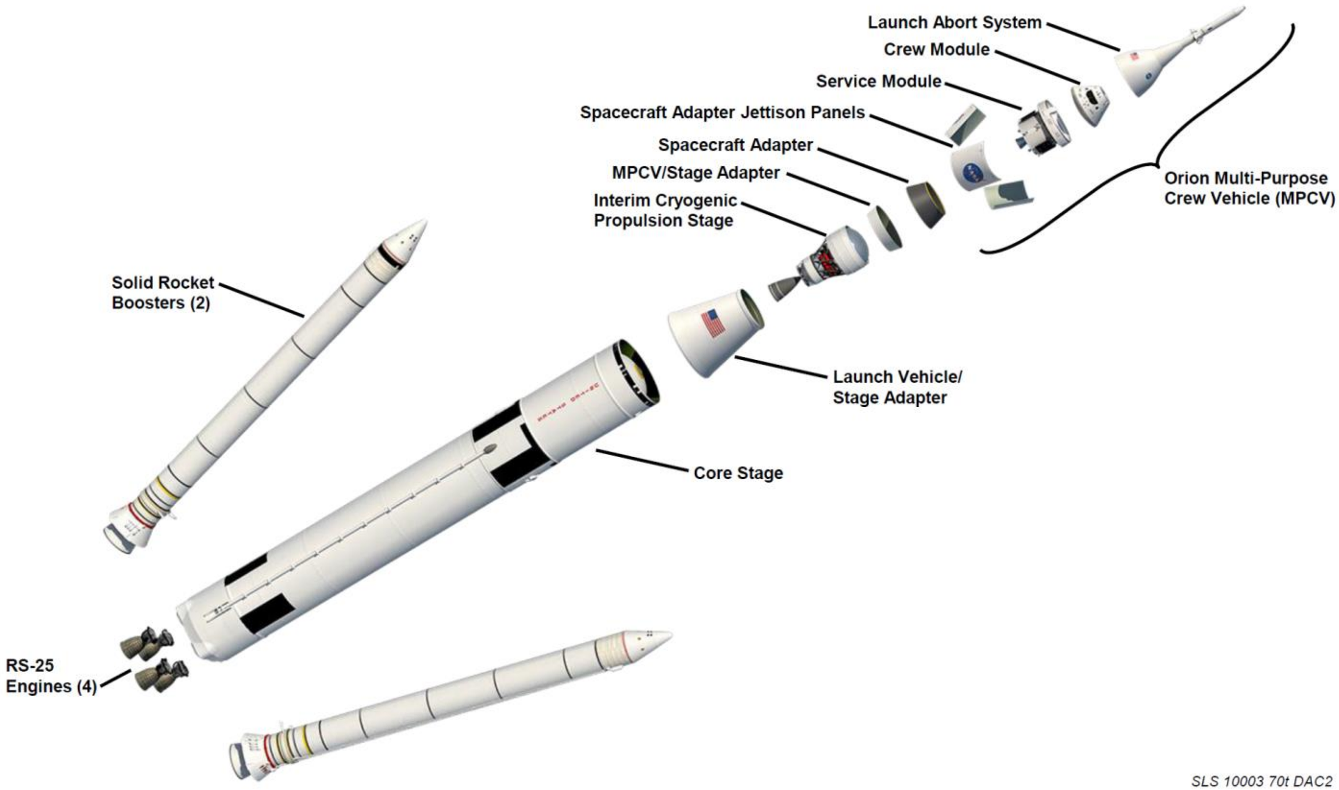
Space Launch System (SLS)



- SLS will enable human exploration beyond low Earth orbit (LEO)
- Block I vehicle will initially lift 70 metric tons (mT) to LEO, will evolve to 130 mT to LEO (Block II)

Block I SLS Vehicle



- **Liquid H_2/O_2 Core Stage, supplying four RS-25 engines**
- **Five segment Solid Rocket Boosters**
- **Integrated Spacecraft and Payload Element (ISPE)**
- **Orion Multi-Purpose Crew Vehicle (MPCV)**

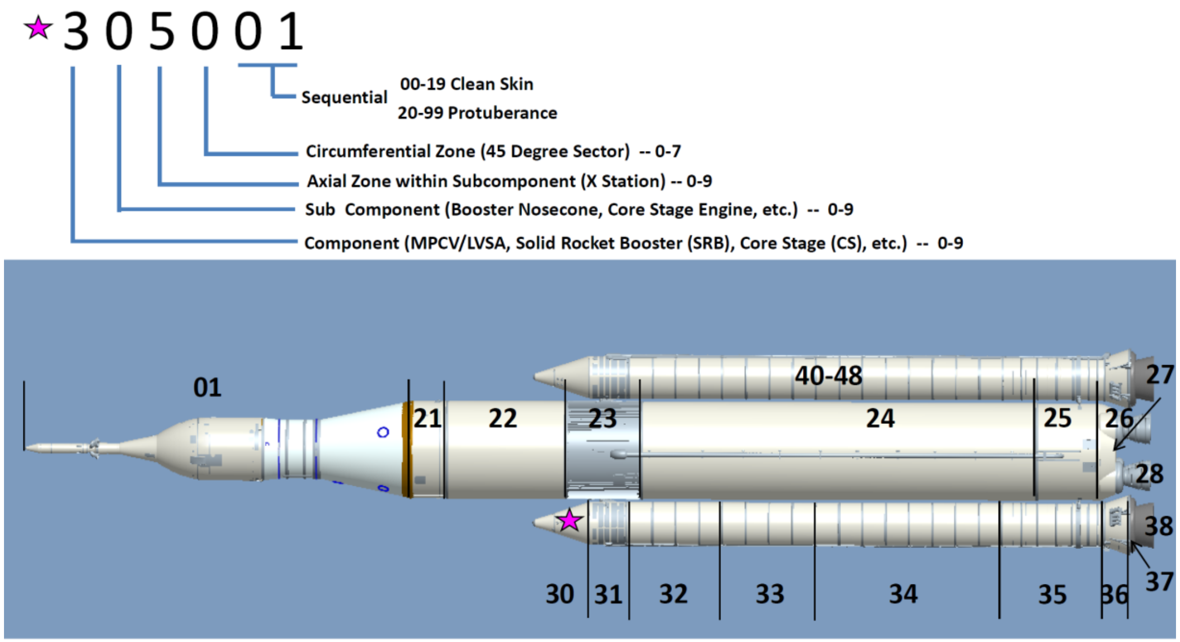
SLS External Thermal Analysis Status and Plans

- **SLS Program passed Preliminary Design Review (PDR) in July, 2013**
  - Design Analysis Cycles (DAC) 1 and 2 were completed and informed the vehicle design before PDR
  - Vehicle external thermal environments were generated for 2080 body point locations on the vehicle in DAC2
  - Delivered as engineering data and also documented in official SLS program documentation

- **SLS Program Critical Design Review (CDR) scheduled for May, 2015**
  - DAC3 and DAC3R were completed in the past year
  - Vehicle external thermal environments were generated for 2737 body point locations on the vehicle in DAC3R
  - Final revisions to official SLS program design documents are underway in preparation for the vehicle CDR

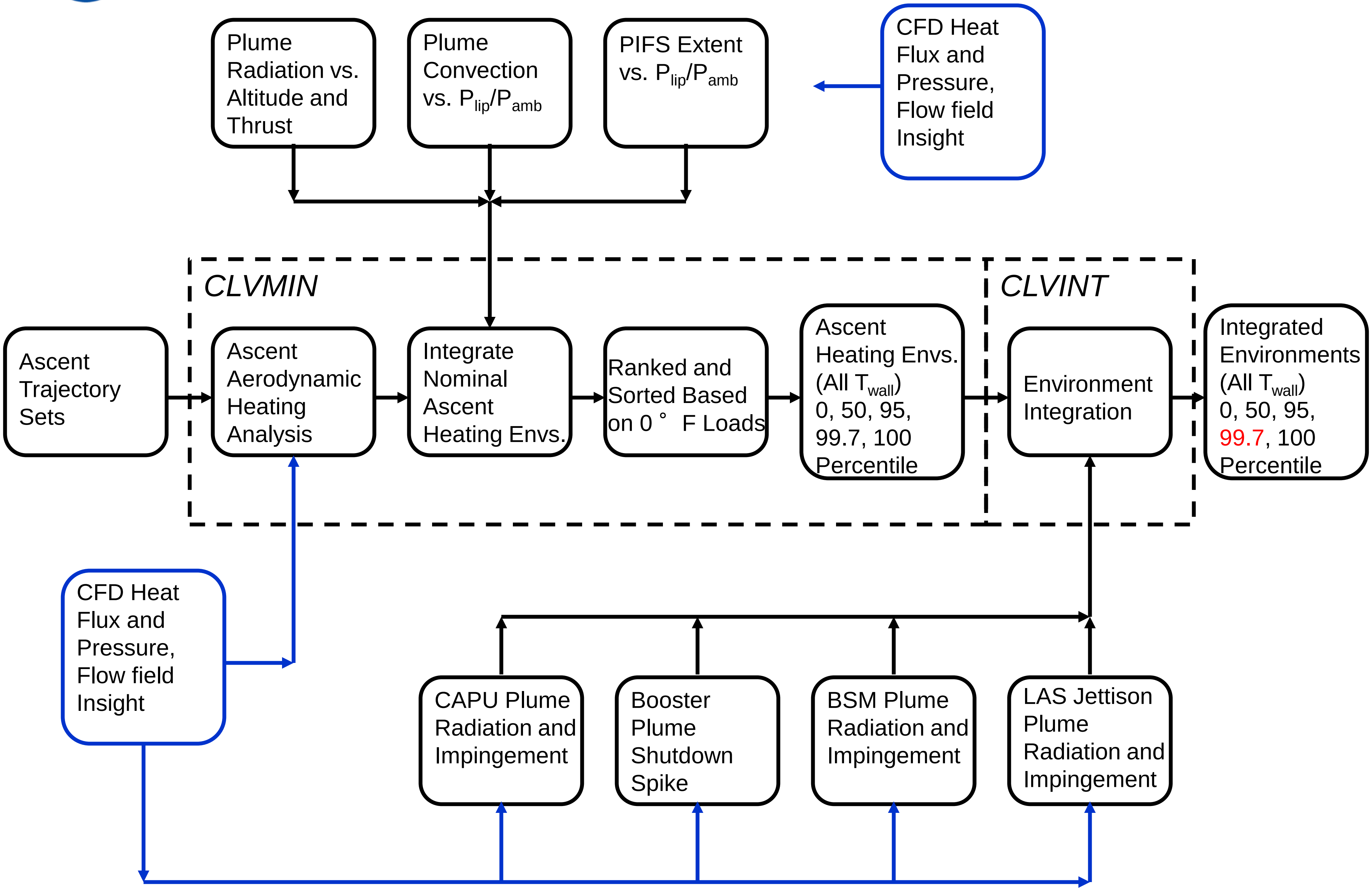
Overall External Thermal Analysis Approach

Body Point Numbering Convention



- **Environments are generated at a large number of particular locations (body points) on the vehicle**
- **Three key inputs needed to develop aerothermal environments**
  - Vehicle geometry
  - Engine/motor operating parameters
  - Trajectories
- **Current environments are statistical (99.7% highest at each location)**

SLS External Thermal Environments Processes and Codes



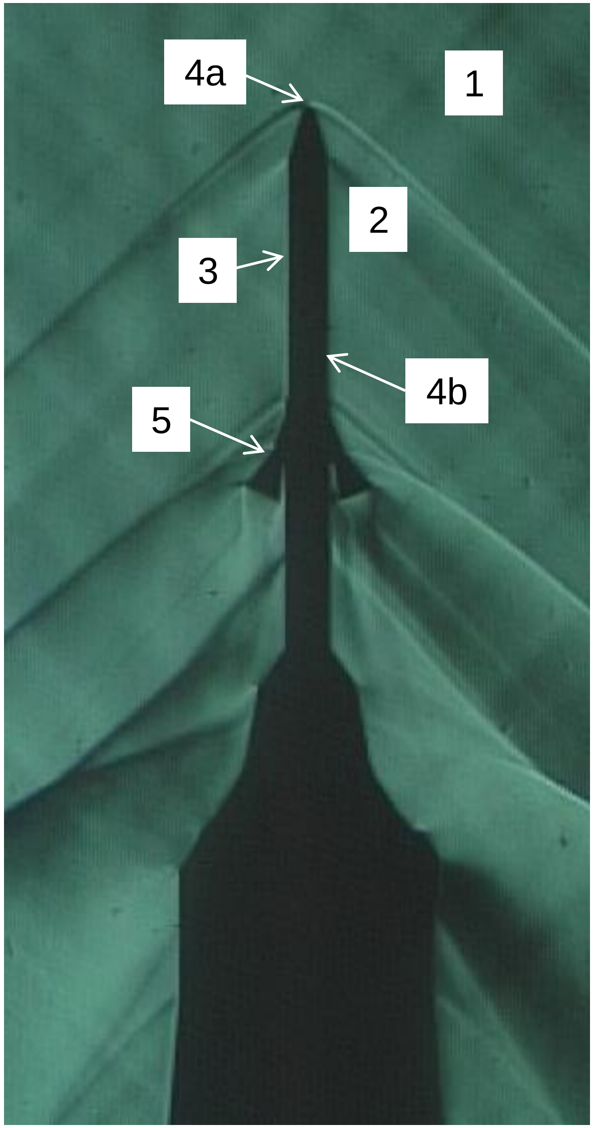
SLS External Thermal Environment Prediction
Aerodynamic Heating

♦ Status

- CLVMIN is an enhanced version of the MINIVER code
  - – Improved local condition determination
  - – Modified to generate statistical environments from trajectory sets

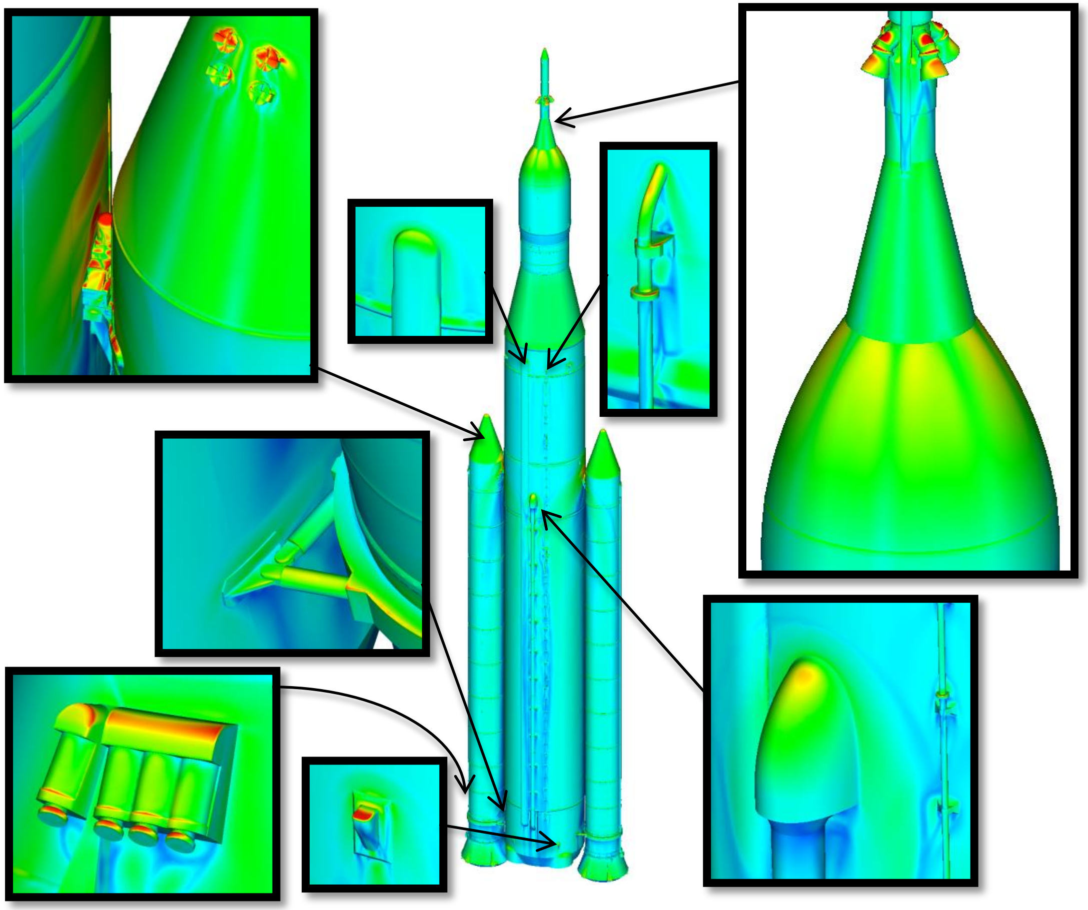
1. Flow field: Free stream trajectory conditions (P, T, Mach, etc.) are processed through appropriate shock(s) using compressible flow equations
2. Flow regime: Determine if continuum / transitional / rarefied / free molecular based on Mach, Reynolds #
3. Boundary layer: If continuum flow, determine if turbulent or laminar boundary layer conditions based on Mach, Reynolds #
4. Heating Model: Apply depending on geometry, examples: spherical – 4a (i.e. Fay & Riddell), flat plate – 4b (Spalding-Chi w/ Mangler transformation)
5. Protuberance Factor: If needed, apply empirical or analytical amplification factor (h_i/h_u)

*Significant use of empirical amplification factors for core stage and booster geometry with extensive flight/wind tunnel testing history



SLS External Thermal Environment Prediction Protuberances

- **Status**
  - Eight CFD cases completed
    - SLS-10005 OML
    - TD3 6-DOF trajectory sets
    - Altitudes from 50 to 160 kft
    - Mach numbers from 2.0 to 4.5
  - Loci/CHEM CFD code
    - ~360M Cells (unstructured)
    - RANS turbulence modeling
  - h_i/h_u factors developed from solutions using protuberance heating and local "clean-skin" heating

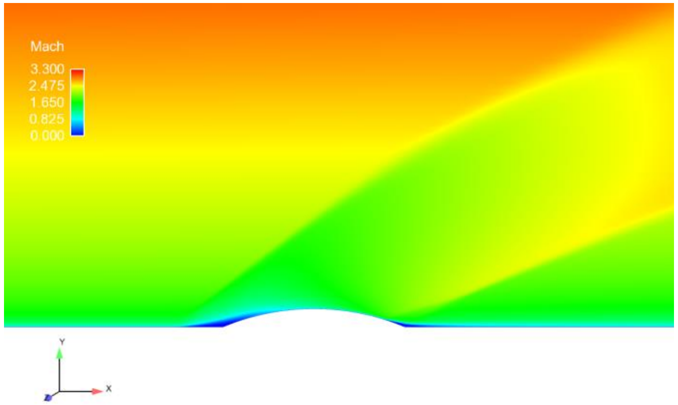


- **Future Work**
  - Compare predictions with ATA-003 aerodynamic heating test
  - Re-run using updated VAC1 vehicle geometry

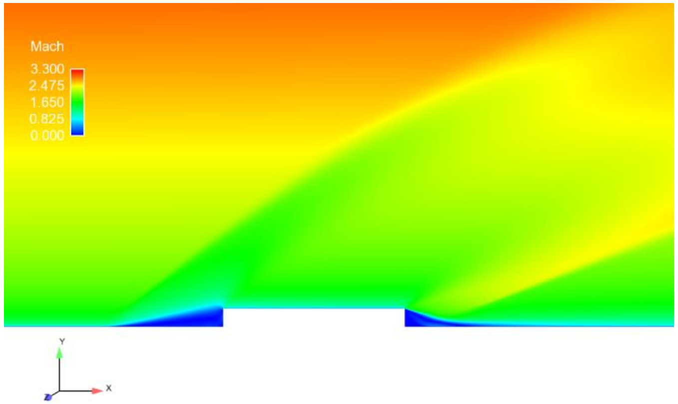
SLS External Thermal Environment Prediction
Small Protuberance Methodology

- **Status**
  - Recently-completed SLS small protuberance methodology is based on results from several hundred Loci/CHEM 2-D RANS CFD cases
  - Intended to provide simple estimate of enhanced heating for small (< 0.5 inch) protuberances significantly smaller than the local boundary layer thickness
  - Results for relatively smooth protuberances show good agreement with the semi-empirical formula reported by Jaeck, 1966 in flow scenarios the formula was intended for, but important differences in scenarios it was not
- **Ongoing Work**
  - Evaluate wider range of turbulence models based on separate Loci/CHEM RANS flow separation study
  - Compare with small-protuberance heating data from 103-AH and ATA-001 tests

Circular arc protuberance



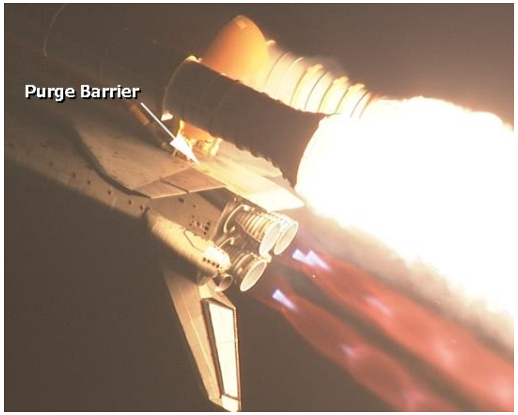
Step protuberance

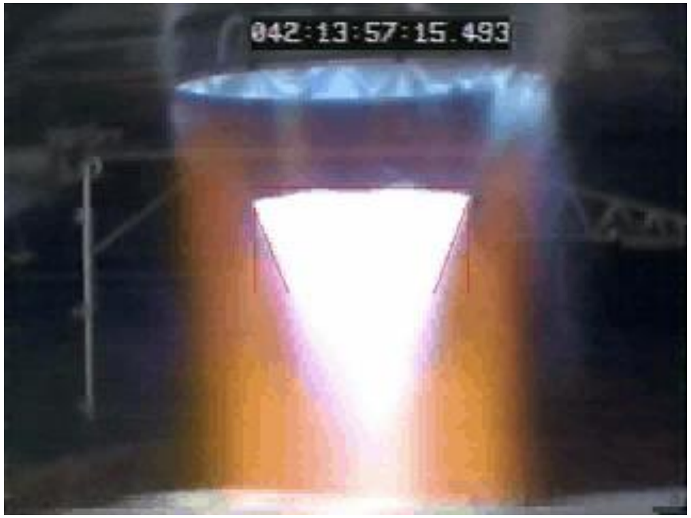


SLS External Thermal Environment Prediction
Plume Radiation Heating

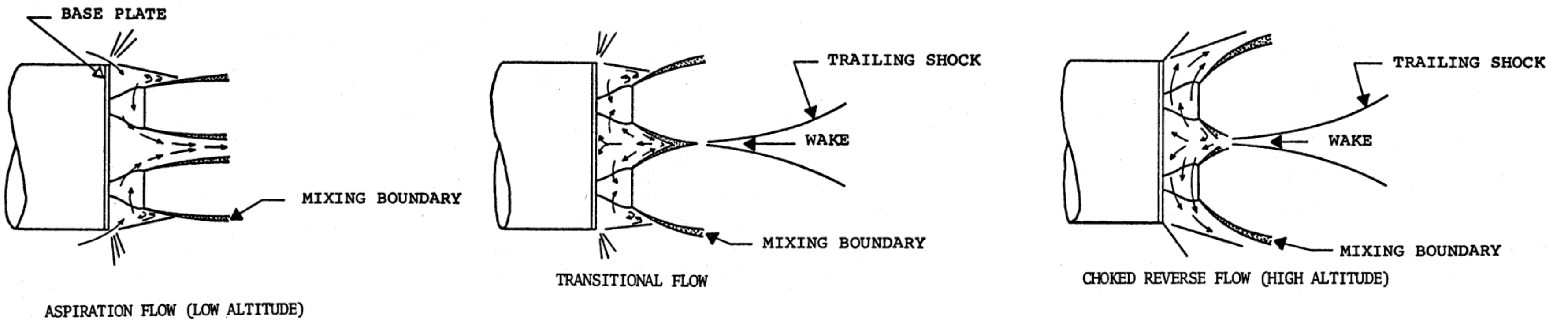
♦ Status

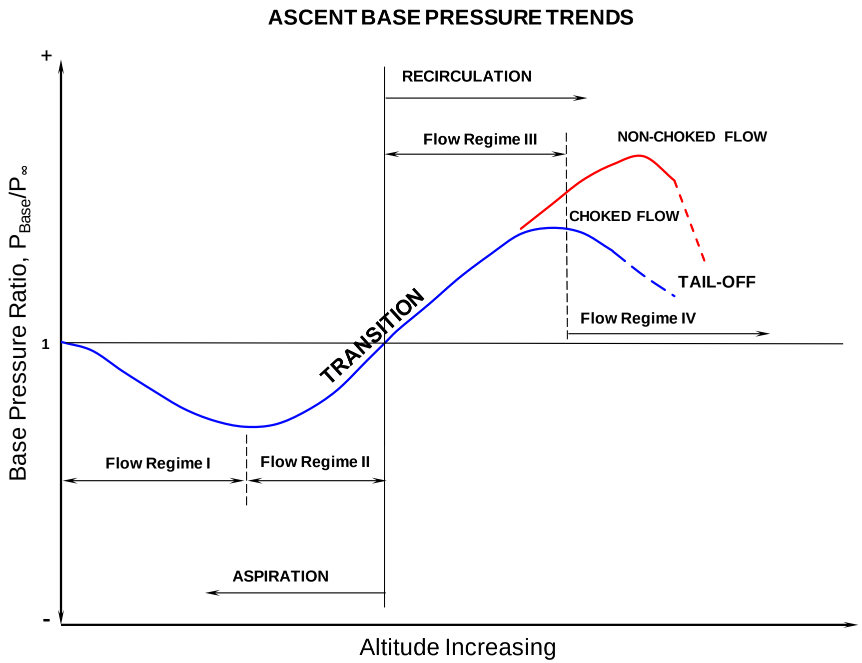
- Plume radiation heating primarily driven by H_2O in RS-25 plume Mach discs and Al_2O_3 particles in booster exhaust – most significant early in flight
- Dominant heat load for areas of the vehicle base which have a clear view of the Booster and RS-25 plumes
- Typically calculated using two step process - calculate plume using CEC/RAMP2/SPF, then model radiation:
  - Reverse Monte-Carlo (RMC) code for multi-phase (Booster) plumes
  - Gaseous Radiation (GRAD) code for gas-only (RS-25) plumes
- Radiation calculated at various altitudes for SLS ascent
- “Shutdown spike” is captured

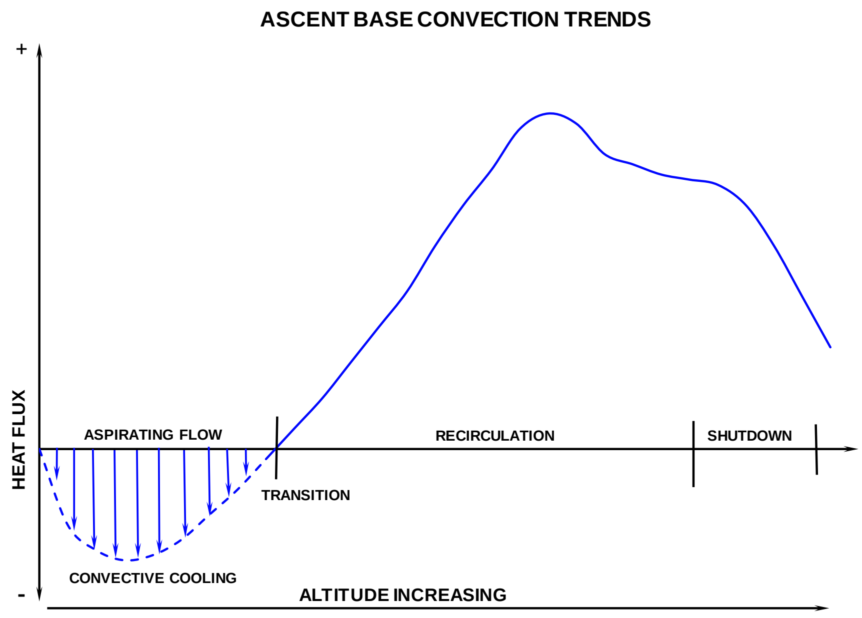




♦ Base convection and pressure change w/ altitude and Mach number

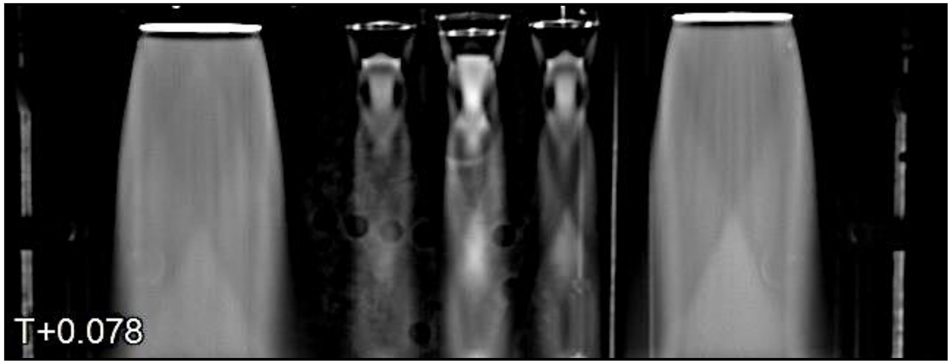




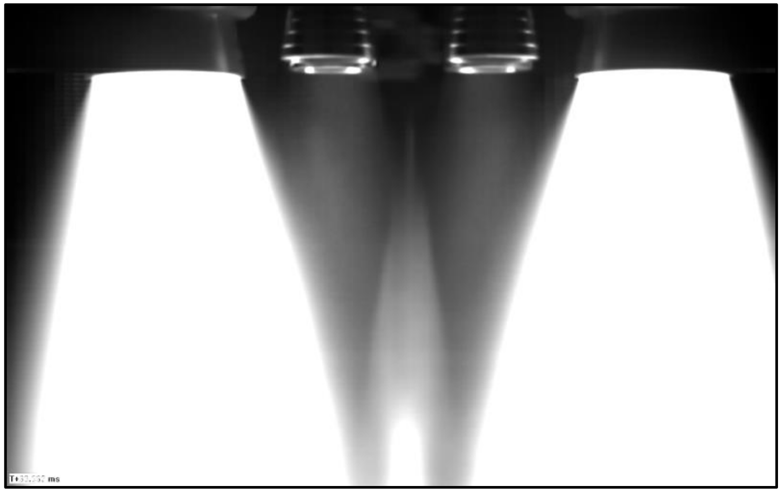


SLS External Thermal Environment Prediction
Base Convective Heating

- **Status**
  - Current methodology predicts base convective heating using semi-empirical approach (P_{lip}/P_{amb} ratio) derived from Saturn V, Shuttle and wind tunnel data
  - CFD predictions of base convective heating differ from semi-empirical method
  - ATA-002 test is assessing conservatism in existing design environments and will lead to improved models
    - Pathfinder developed 2% scale model propulsion system
    - Main base heating test is currently underway at CUBRC



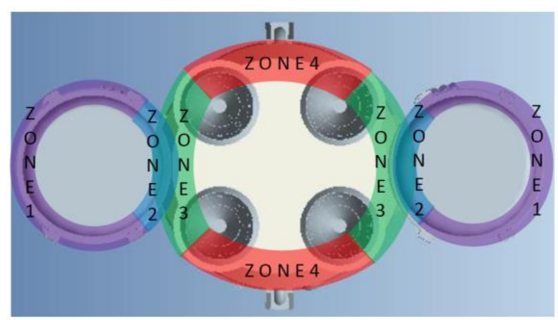
Long-wave infrared image of 2% scale propulsion system plumes firing at sea-level. Note that the 2% scale Core Stage RS-25 engine nozzles are rotated 45 degrees from their normal orientation.

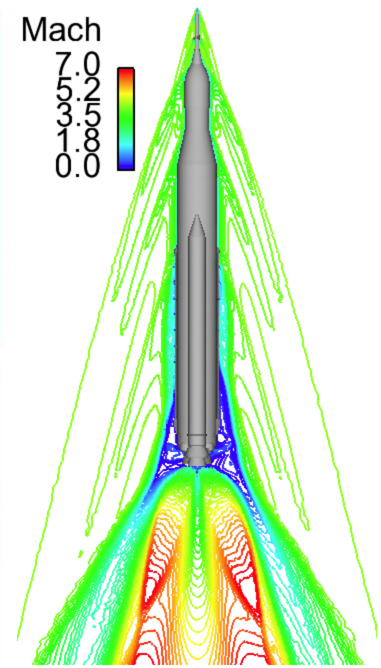


Integrated visible wavelength image of 2% scale propulsion system firing at a freestream condition consistent with 100,000 ft altitude.

SLS External Thermal Environment Prediction
Plume Induced Flow Separation (PIFS) Heating

- **Status**
  - Current methodology predicts PIFS heating based on Shuttle and Saturn V data and P_{lip}/P_{amb} ratio
  - PIFS heating on the Core stage and Booster is applied by circumferential zones



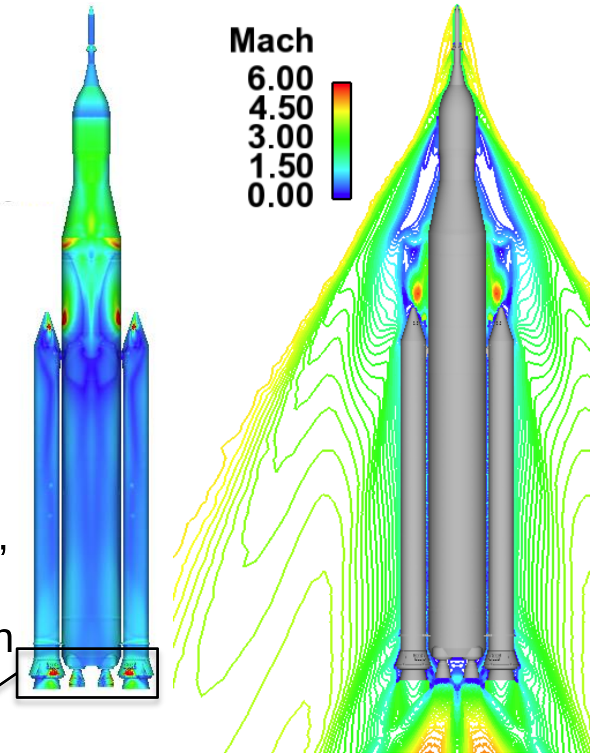


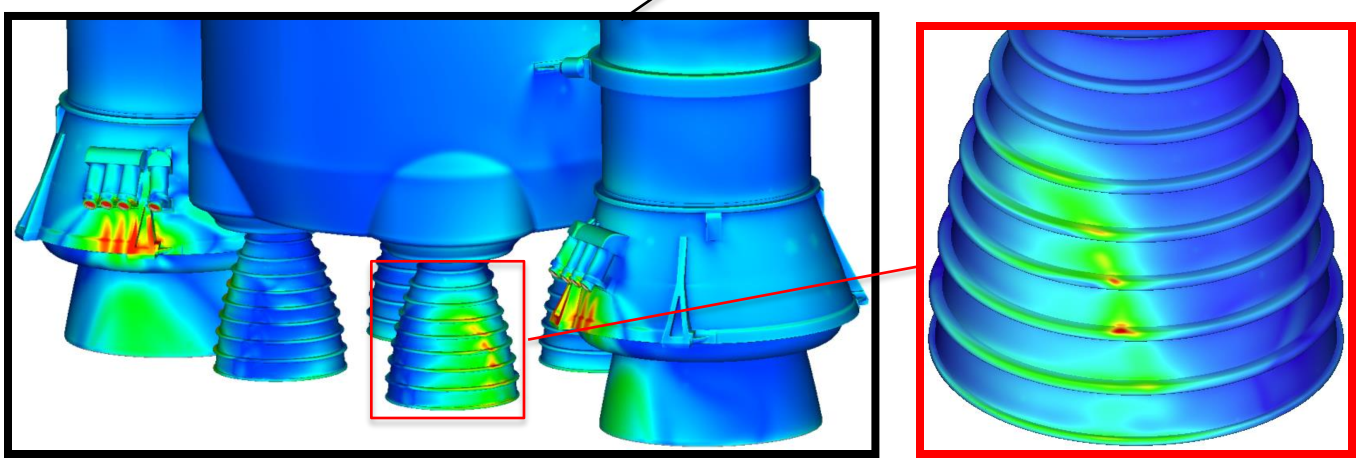
- **Ongoing Work**
  - Three CFD cases completed for camera contamination study
  - Loci/CHEM CFD solutions
    - Altitudes from 94 to 147 kft
    - Mach numbers from 3.5 to 4.5
  - Will compare with baseline semi-empirical methodology

SLS External Thermal Environment Prediction
Booster Separation Motor (BSM) Plume Impingement Heating

♦ Status

- Total of four cases completed at 0.02, 0.2, 0.4, and 0.6 seconds after initiation of booster separation
- Loci/CHEM unstructured CFD code
  - ~120M cell grid assumes flow field symmetry
  - RANS turbulence modeling and frozen chemistry
  - Plume gases modeled as a single equivalent gas
- High confidence in direct plume impingement heating prediction from CFD, based on Constellation-era tests and Ares I-X flight data
- Updates to these BSM simulations are currently underway, as well as comparisons to new Shuttle BSM CFD models
- Recently completed updated CFD simulations for the Orion MPCV Launch Abort System (LAS) Jettison Motor (JM) plume impingement environments



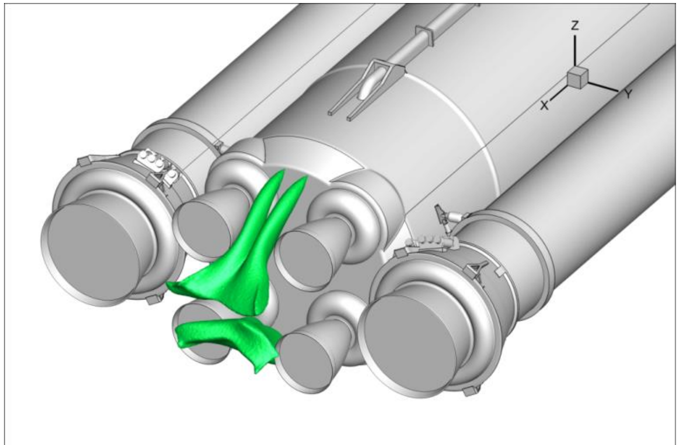


SLS External Thermal Environment Prediction
Core Auxiliary Power Unit (CAPU) Plume Heating

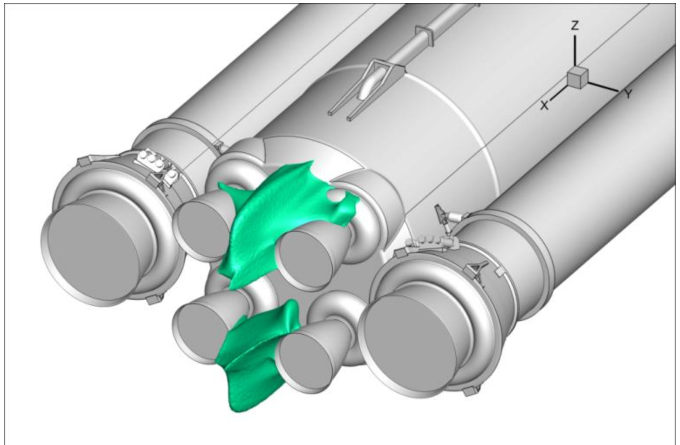
♦ Status

- CAPU system drives hydraulic fluid used for RS-25 gimballing and throttling
- Powered in flight by H_2 gas tapped off from main propulsion system
- Loci/CHEM CFD solutions
  - ~200M cell grid
  - 6 species (O_2, N_2, H_2, H_2O + 2 equivalent plume gas species)
  - Fast $2H_2 + O_2 \rightarrow 2H_2O$ chemistry assumed
  - Solutions throughout Boost Stage flight completed
- Convective heating environments developed from analysis and simplification of these solutions
- Updated CFD simulations with revised CAPU duty cycle inputs are currently underway
- Radiative heating initially developed from simplified plume models, but full consistency with CFD models is planned

Iso-surfaces of 10% H_2O Mass Fraction RS-25 and Booster Plume Exhaust Not Shown for Clarity



Mach 0.1, 600 ft



Mach 2, 51,000 ft

Summary and Status

- **The third DAC cycle for SLS is complete and the program is moving toward its Critical Design Review**
- **External Thermal environments for the vehicle are integrated from several different sources of heating:**
  - Aerodynamic heating
  - Plume radiation heating
  - Plume base convection/recirculation heating
  - Plume induced flow separation heating
  - Plume impingement heating
  - CAPU plume/flame heating
- **Moving forward, many of these models will be further refined with additional CFD simulations and wind tunnel testing**