

Space Launch System Ascent Aerothermal Environments Methodology

Presented By

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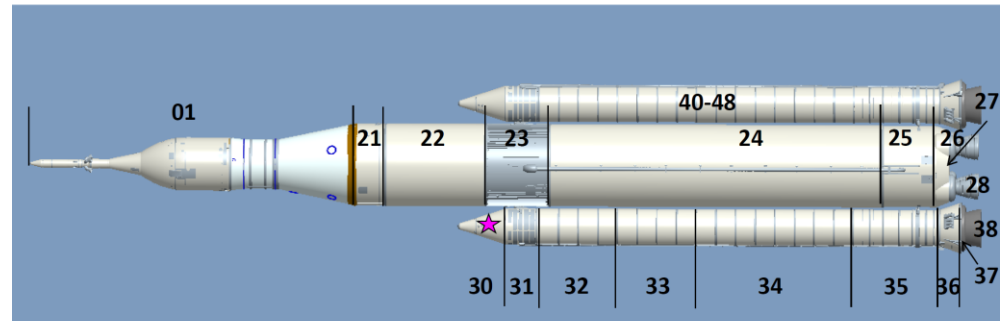
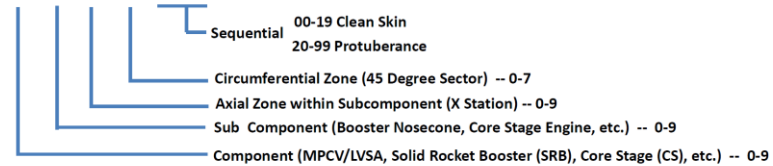
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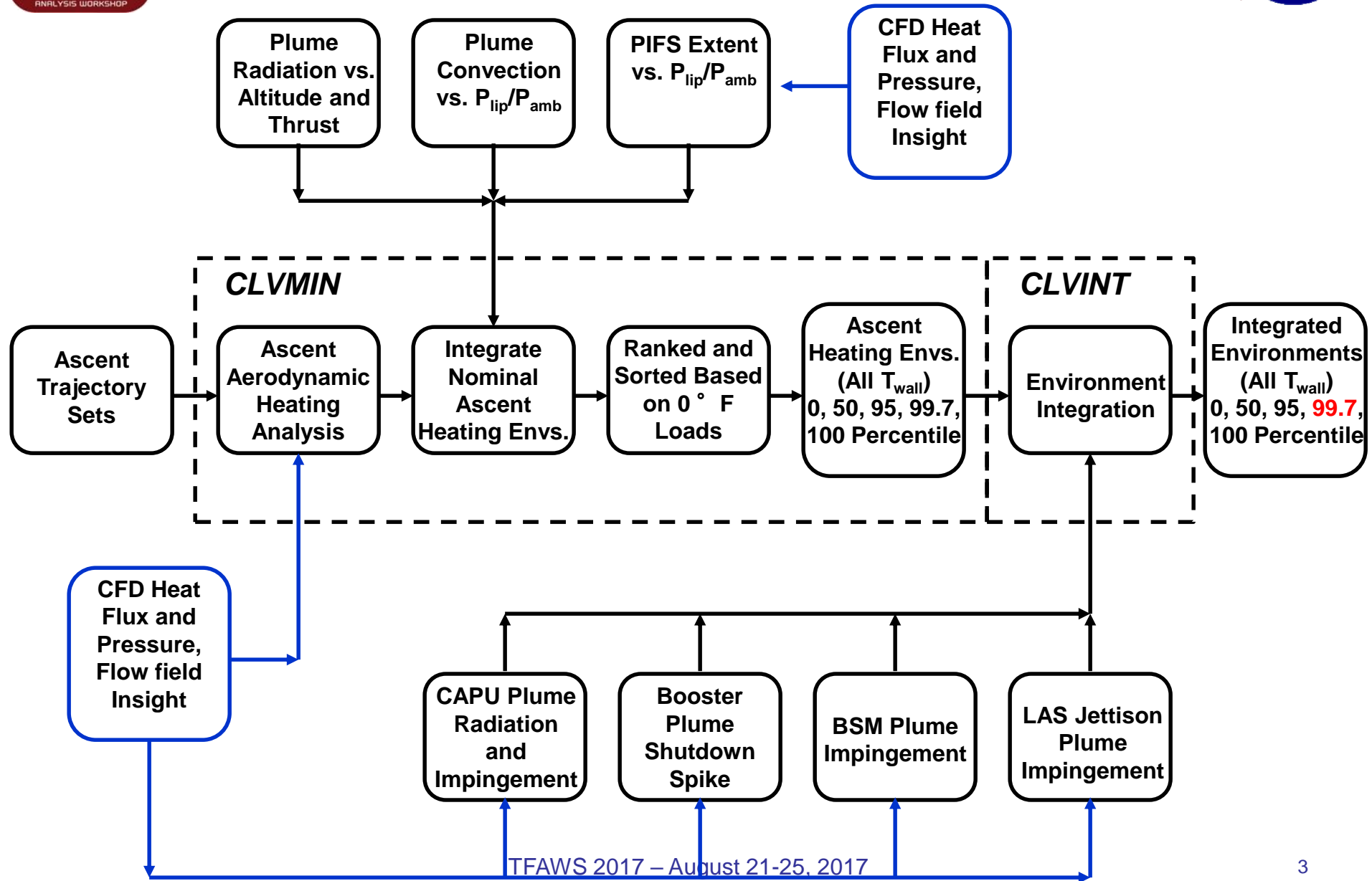
- Environments are generated at a large number of particular locations (body points) on the vehicle
- Three key inputs needed to develop aerothermal environments
 - Vehicle geometry
 - Engine / motor operating parameters
 - Trajectories

Body Point Numbering Convention

★ 3 0 5 0 0 1

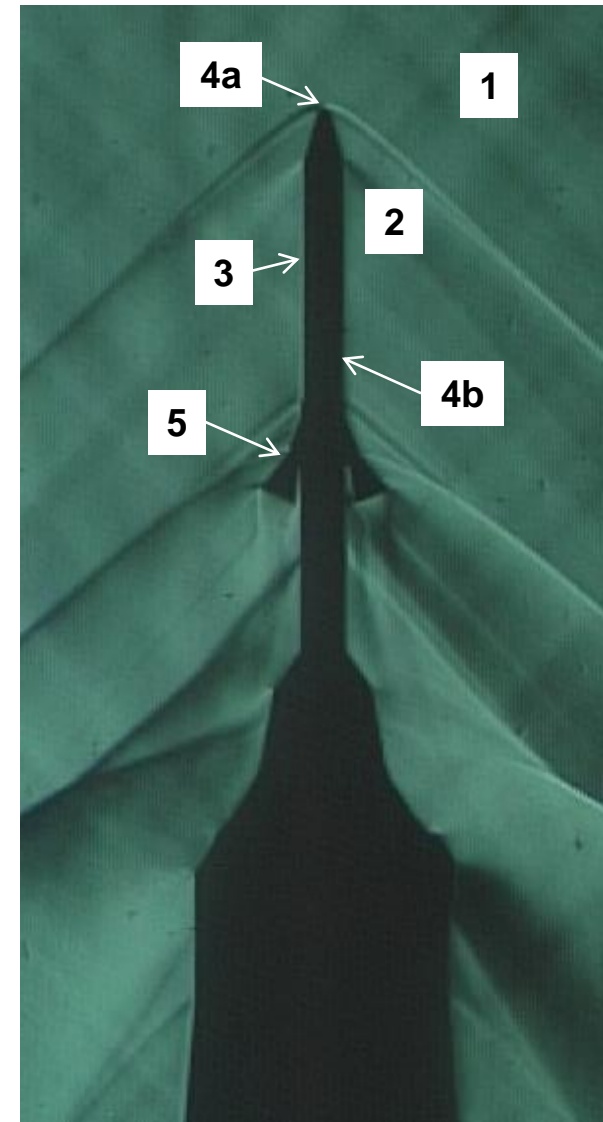


- Current environments are statistical (99.7% highest at each location)
- Block 1 SLS aerothermal environments are documented in SLS-SPEC-044-02

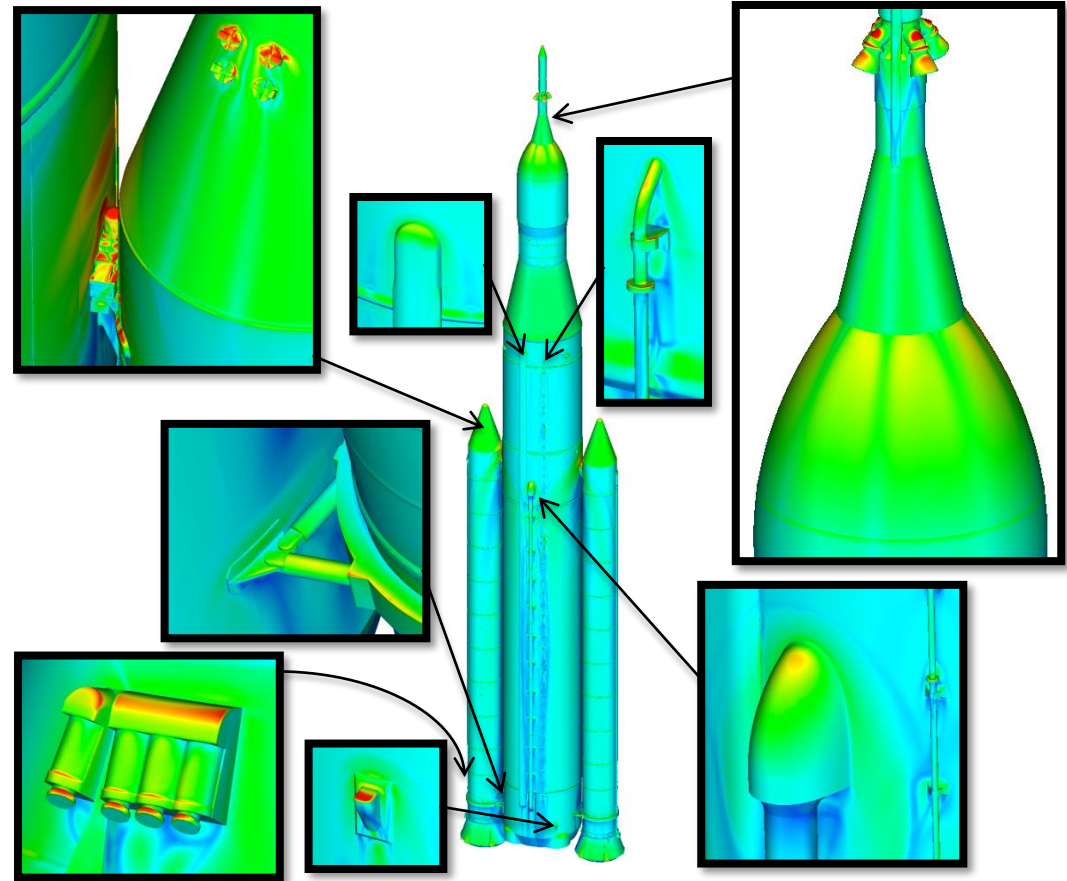


- CLVMIN is an enhanced version of the MINIVER code
 - Improved local condition determination
 - Modified to generate statistical environments from trajectory sets
1. Flow field: Free stream trajectory conditions (P, T, Mach, etc.) are processed through appropriate shock(s) using compressible flow equations
 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)

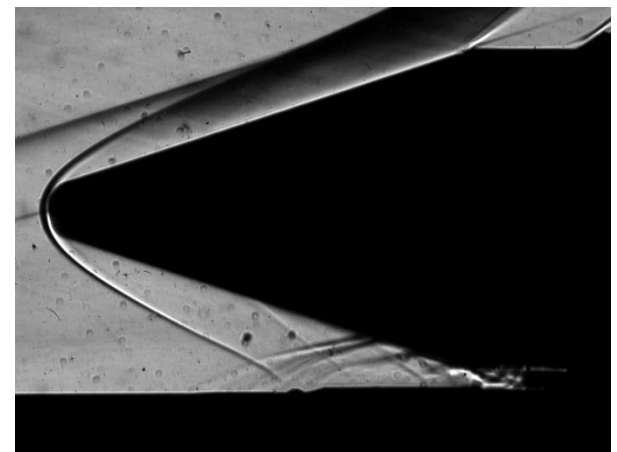
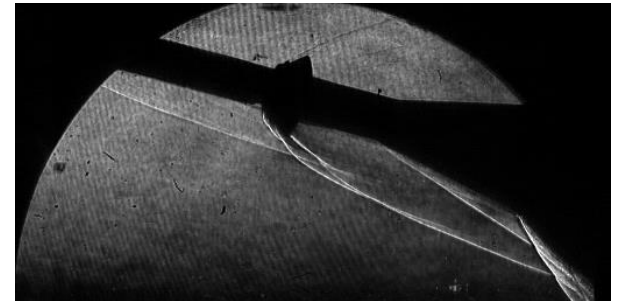
*Significant use of empirical amplification factors for core stage and booster geometry with extensive flight/wind tunnel testing history



- Many similarities, but also some key differences, compared with Shuttle
- Much of current Block 1 design informed by CFD cases run in DAC-3R
 - SLS-10005 OML
 - TD3 6-DOF trajectory sets
 - Altitudes from 50-160 kft
 - Mach numbers from 2.0-4.5
- 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
- Verification phase for Block 1 vehicle (VAC-1) is currently being informed by CFD using an updated SLS-10008 OML

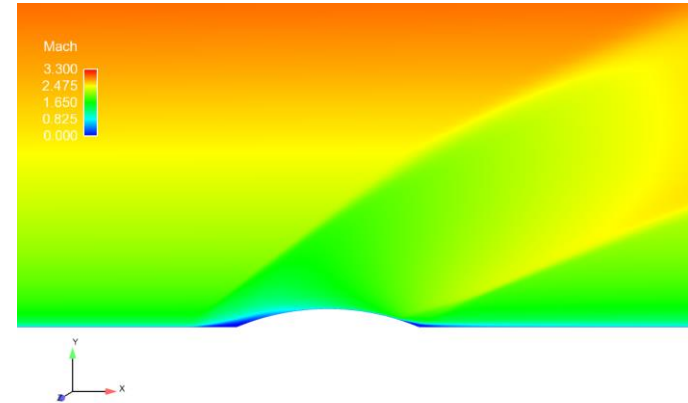


- Block 1 SLS aerodynamic heating environments for clean skin and protuberances were recently validated using measurements from the ATA-003 Phase 1 aerodynamic heating test conducted at CUBRC in 2016
 - 3% model scale
 - 176 heat flux gauges and 28 pressure gauges
 - 21 test runs at Mach 3.5-5.0
 - Schlieren and temperature sensitive paint imaging
- Heat flux measurements indicate that vast majority of SLS aerodynamic heating design environments are either accurate or conservative
- Some exceedances noted on Core Stage / Booster forward and aft attach struts – both of which are very complex flow fields. Updated aft attach environments have been sent to Booster.
- CFD comparisons with test data inform best practices
- Block 1B SLS configurations with additional sensors were tested in ATA-003 Phase 2 conducted in 2016-2017 – will inform Block 1B DAC-2 currently underway

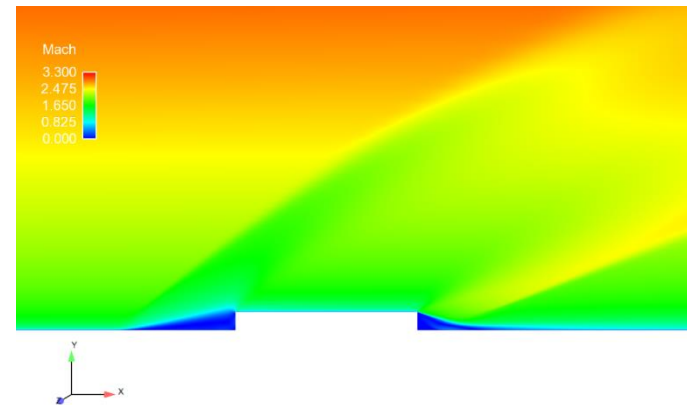


- SLS small protuberance methodology is based on results from several hundred Loci/CHEM 2-D RANS CFD cases
- Intended to provide simple estimate of enhanced heating for small (< 0.5 inch) protuberances significantly smaller than the local boundary layer thickness
- Results for relatively smooth protuberances 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

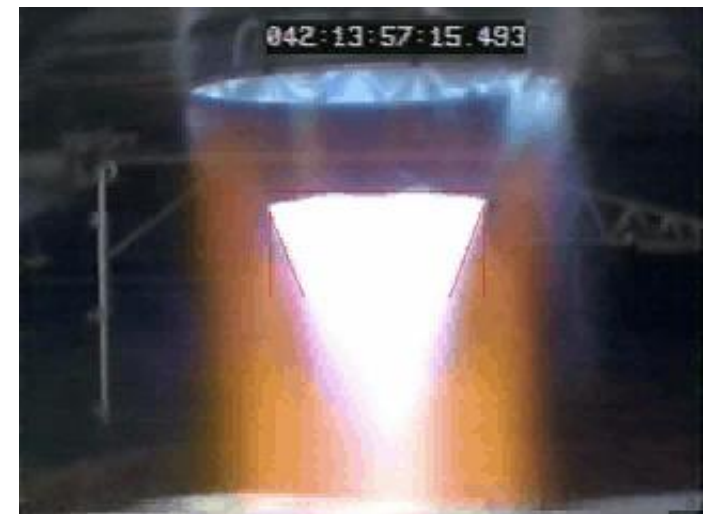
Circular Arc Protuberance



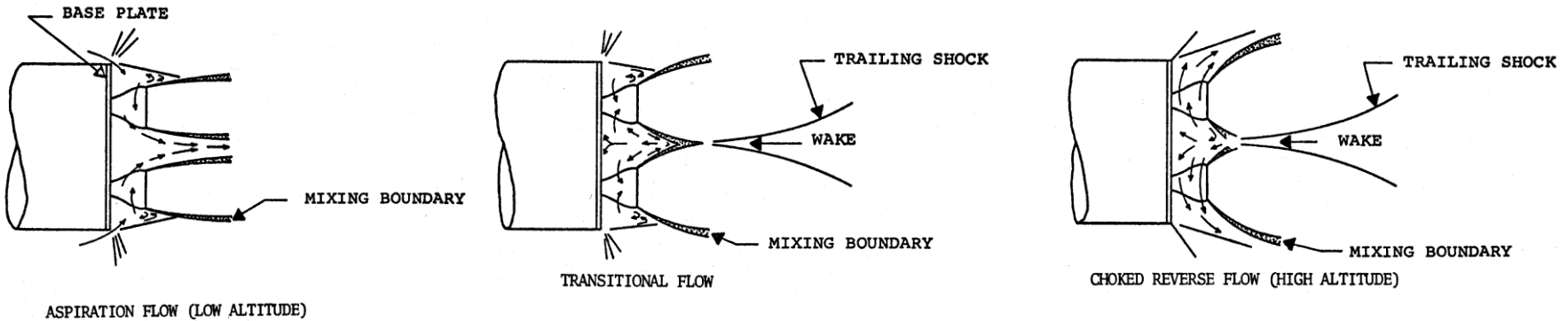
Step Protuberance



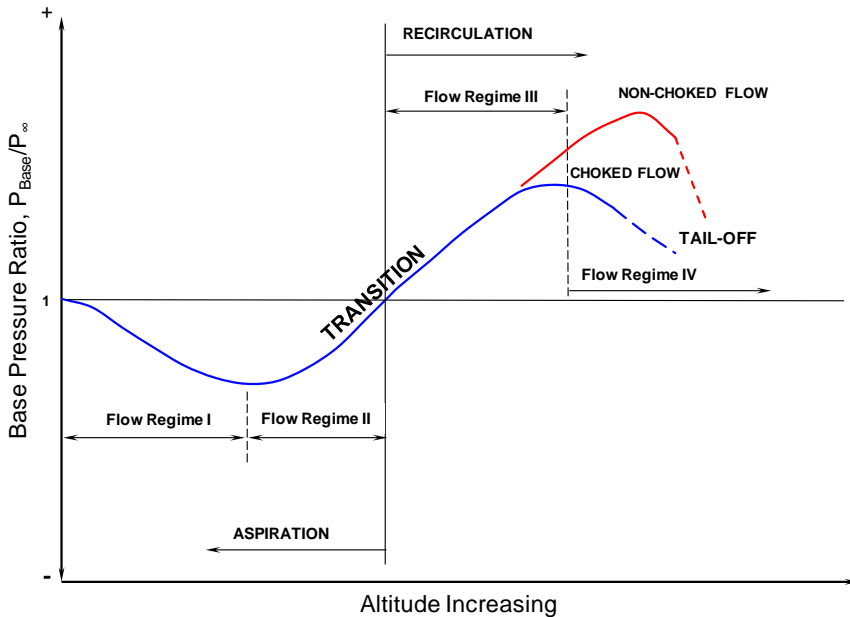
- Though both the RS-25 engines and the five segment solid rocket Boosters are derived from Shuttle, the engines and Boosters are now in much closer proximity
- Plume radiation heating primarily driven by H_2O in RS-25 plume Mach discs and Al_2O_3 particles in booster exhaust – most significant early in flight
- Significant 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/SPF3, 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



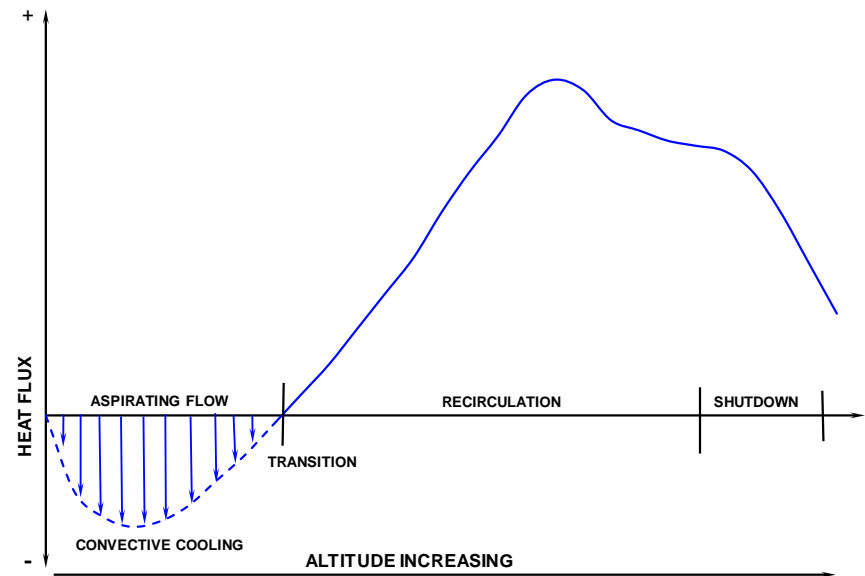
- Base pressure and convection change with altitude and Mach number



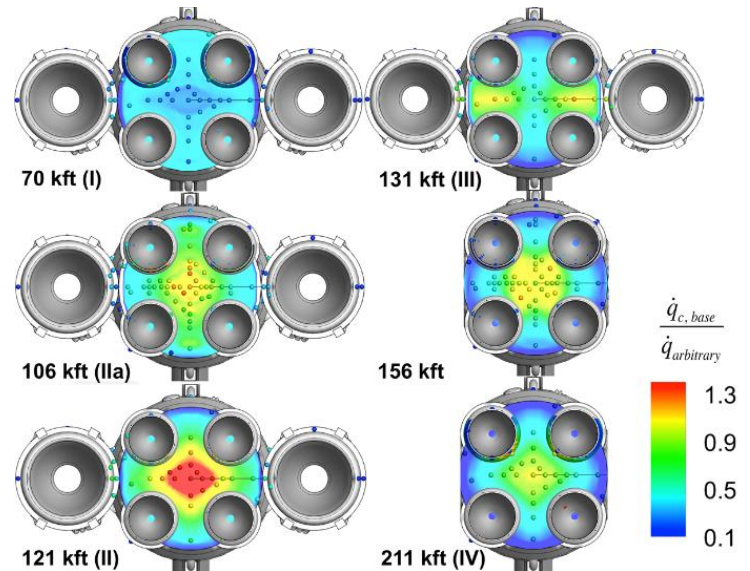
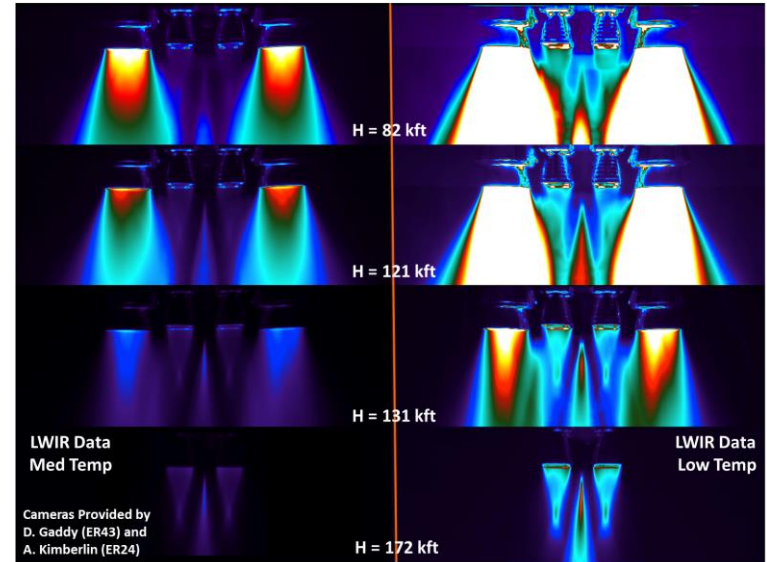
ASCENT BASE PRESSURE TRENDS



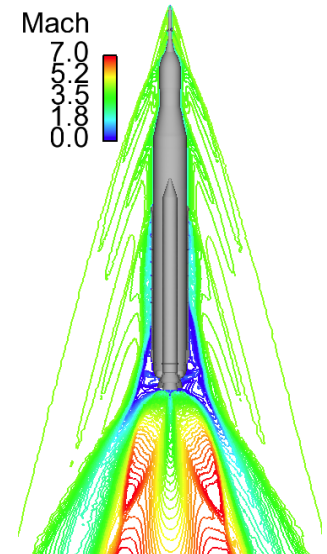
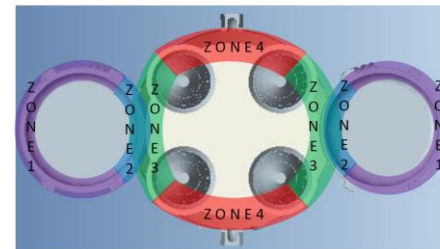
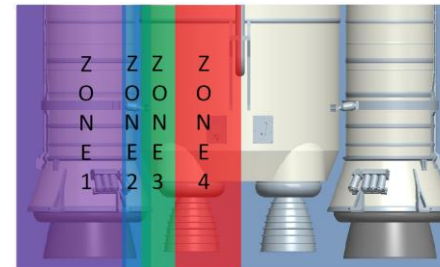
ASCENT BASE CONVECTION TRENDS



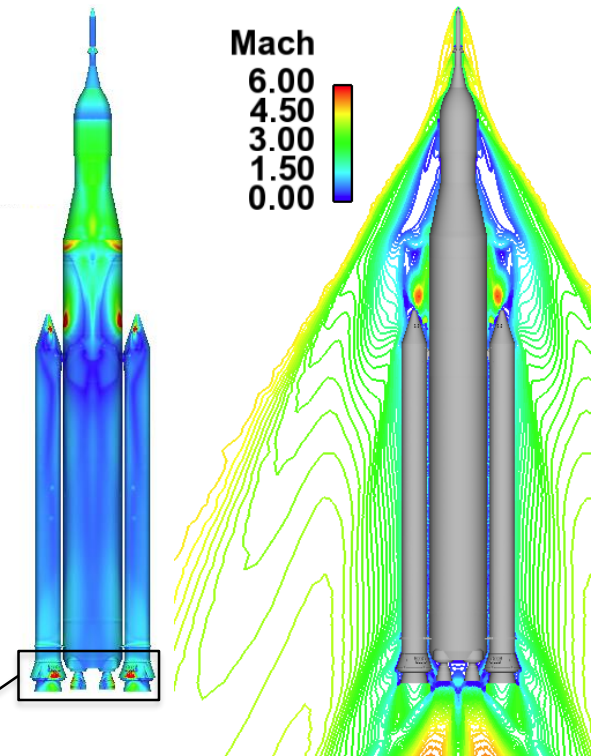
- Due to completely different base and engine configuration for SLS, compared to Shuttle or Saturn V, a subscale ATA-002 plume convective heating wind tunnel test was conducted at CUBRC as part of SLS development in 2013-2015
 - 2% model scale
 - 169 heat flux gauges and 37 pressure gauges
 - 76 tests were run at simulated altitudes of 50-211 kft, and Mach 2.7-5.0
- To reduce risk, a pathfinder subscale engine / motor development effort was conducted before the main plume convection heating test was run
- Updated plume convection environments were derived from test data and baselined in SLS-SPEC-044-02 documentation in late 2015
- Test data exhibited significant differences from Shuttle (e.g. base heat shield, engine thermal blankets, engine nozzles)
- CFD comparisons with test data inform best practices for these types of environments



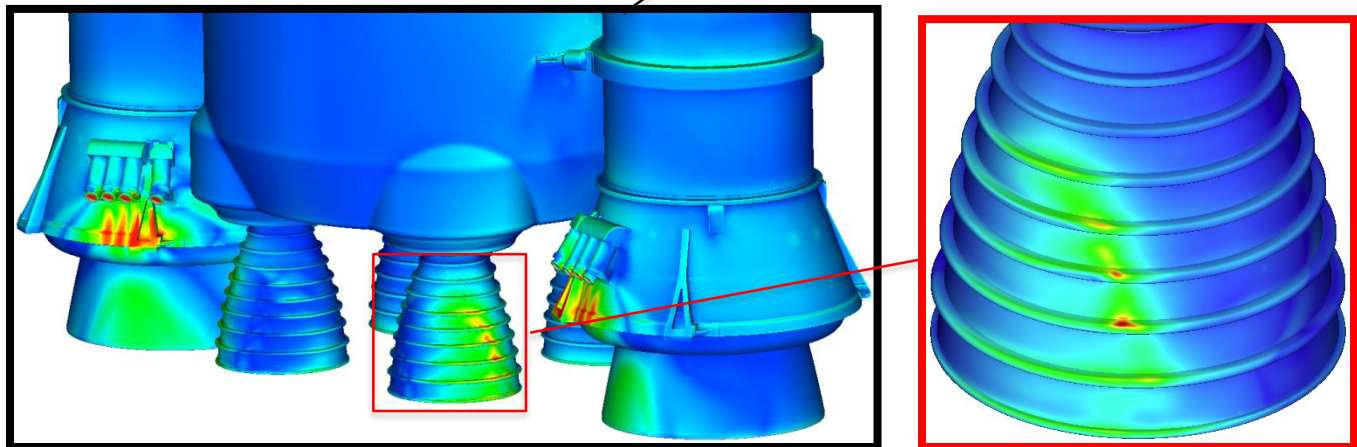
- PIFS is closely related to plume convection heating, and occurs as the recirculating plume gases cause boundary layer separation on the vehicle at high altitude
- Classic example is Saturn V
- Current SLS PIFS heating methodology predicts heating based on Shuttle and Saturn data
- PIFS heating is applied to the Core Stage and Booster by circumferential zones using RS-25 engine and Booster P_{lip} / P_{amb} ratio
- The phenomenon is also observed in Loci/CHEM CFD solutions – comparisons will be made moving forward



- Forward BSM plume impingement environment is similar to Shuttle scenario, but aft BSM environment is completely new for SLS
- 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
 - Four cases completed at 0.02, 0.2, 0.4, and 0.6 seconds after initiation of booster separation
- High confidence in direct plume impingement heating prediction from CFD, based on Constellation-era tests and Ares I-X flight data
- Recent CFD analysis has analyzed aft BSM rotation options to enhance separation clearance

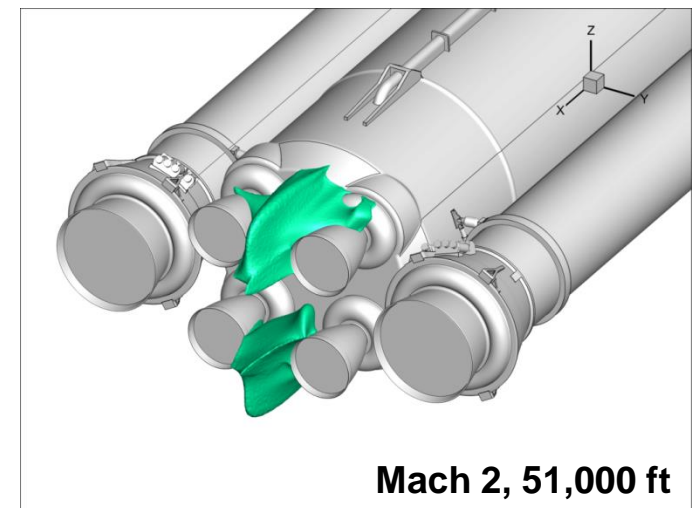
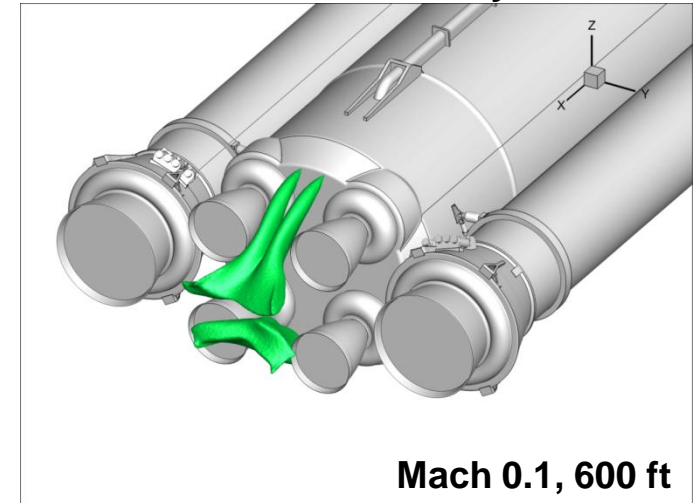


*Orion MPCV Launch Abort System (LAS) Jettison Motor (JM) plume impingement environments also derived from CFD



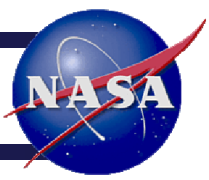
- New environment for SLS - CAPU system drives hydraulic fluid used for RS-25 gimbaling and throttling
- System is powered in flight by H_2 gas tapped off from main propulsion system
- Four exhaust ports in Core Stage base emit the H_2 gas in a “low” flow state for most of the time, but also periodically pulse into a “high” flow state
- 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 through Boost Stage flight completed in 2015
- Convective heating environments developed from analysis and simplification of these solutions
- Radiative heating environments developed from these solutions and GASRAD code
- Combined convective and radiative environments integrated into the final design environments

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





Summary



- Aerothermal 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
- Experience and test data obtained during Block 1 SLS development is aiding work on Block 1B vehicle