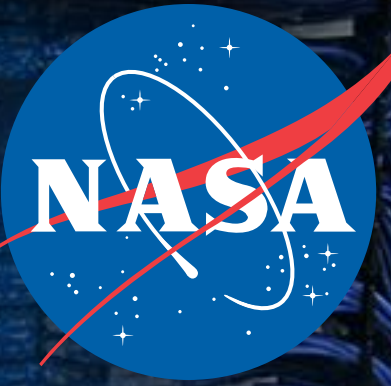


National Aeronautics and Space Administration



Building Aerodynamic Databases for the SLS Design Process

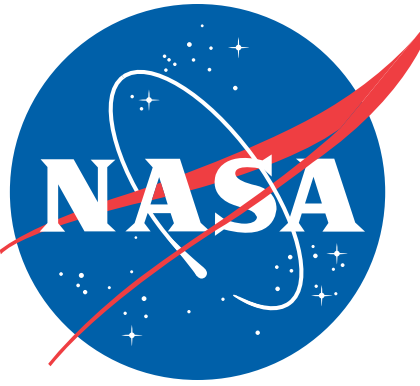
Stuart Rogers, Derek Dalle, Henry Lee, Jamie Meeroff
Jeff Onufer, William Chan, Thomas Pulliam

SLS Aerodynamics Group
Computational Aerosciences Branch
NASA Ames Research Center

Supercomputing 2017, November 12-16, 2017

www.nasa.gov

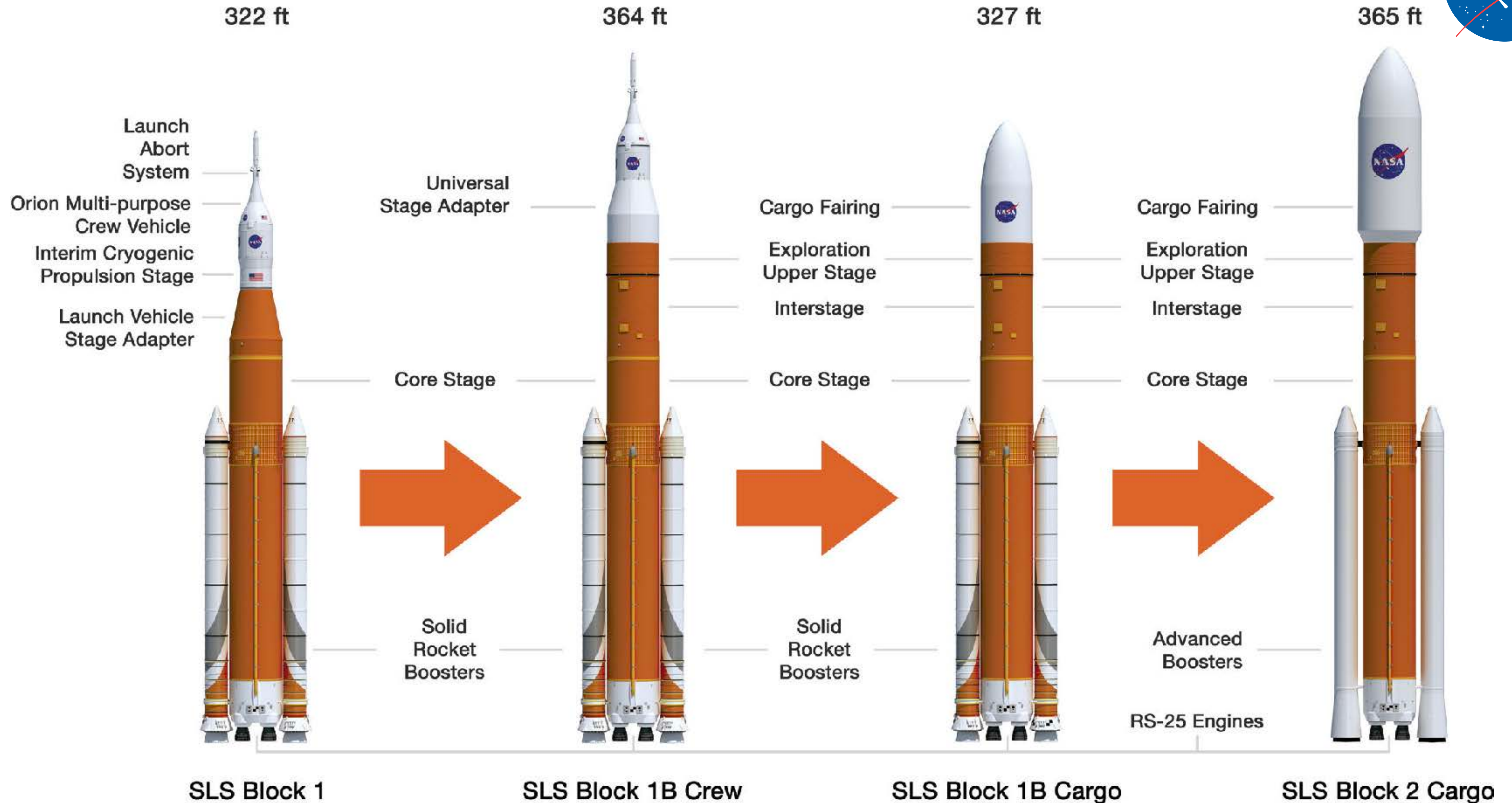
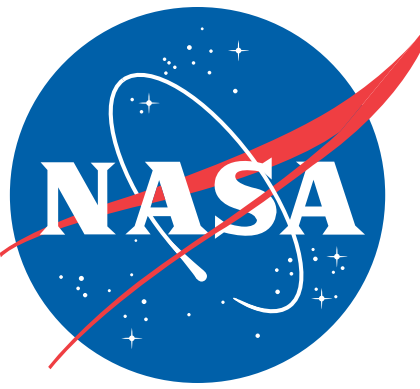
SLS: NASA Space Launch System



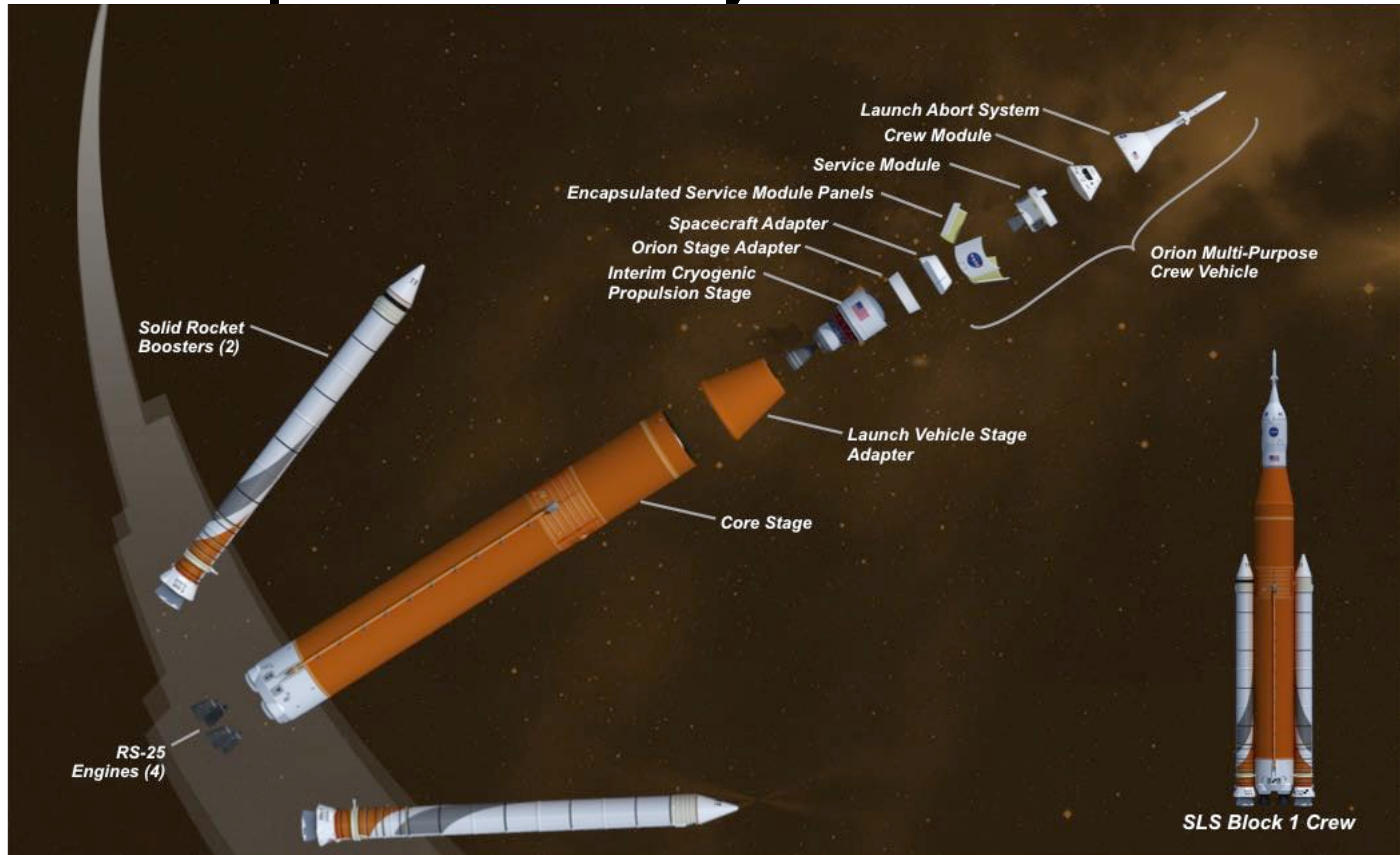
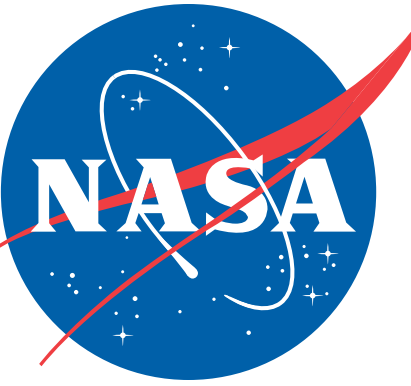
- NASA developed heavy-lift capability
- First rocket to transport astronauts beyond Earth orbit since Saturn V
- 70-metric ton payload capability
- Thrust:
 - 8.4 million pounds
 - 10% more than Saturn V
- Payload more than three times of the Space Shuttle



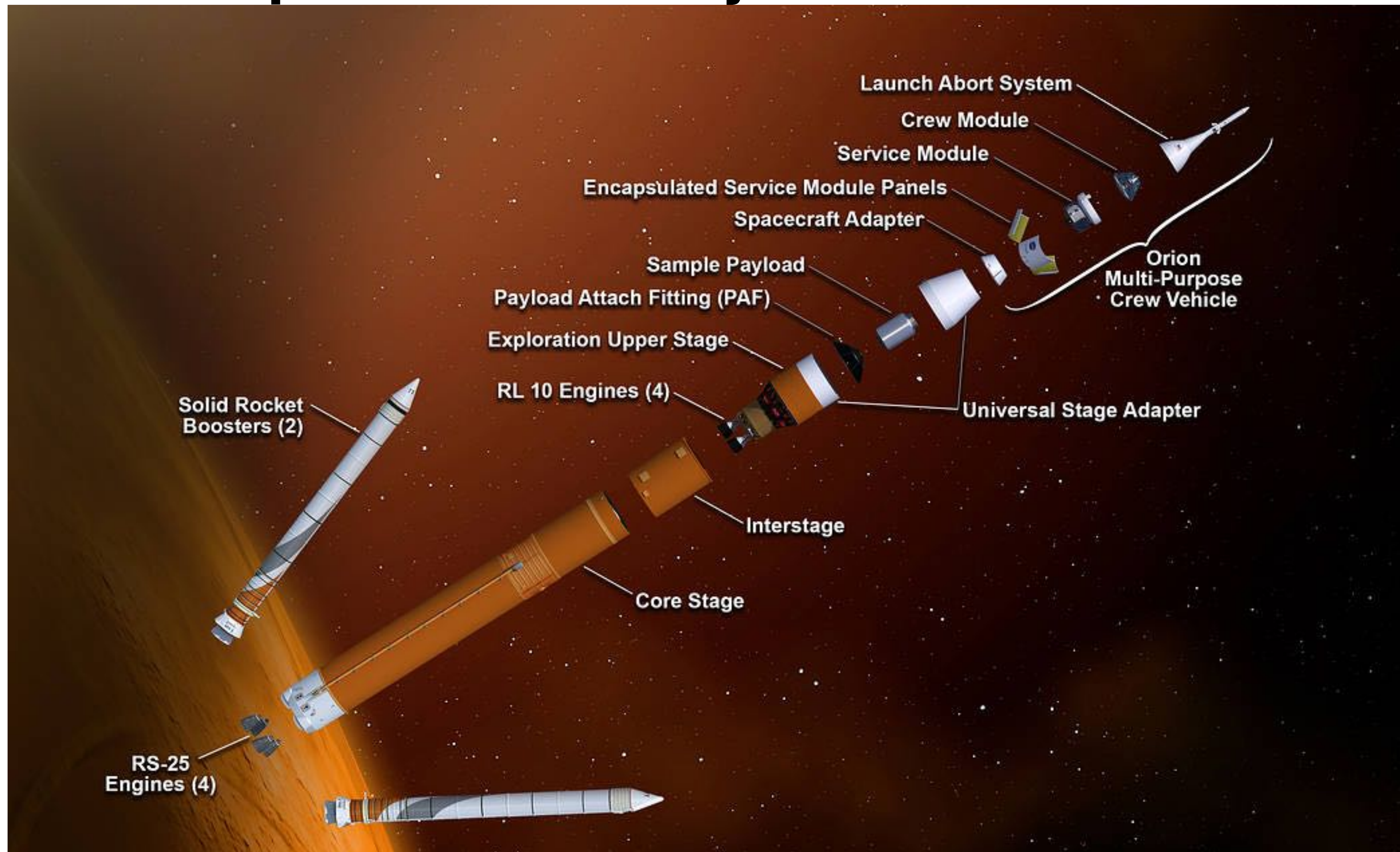
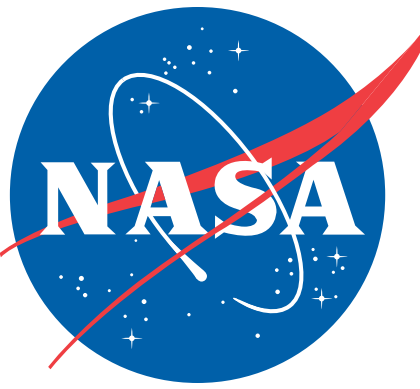
SLS: NASA Space Launch System Family



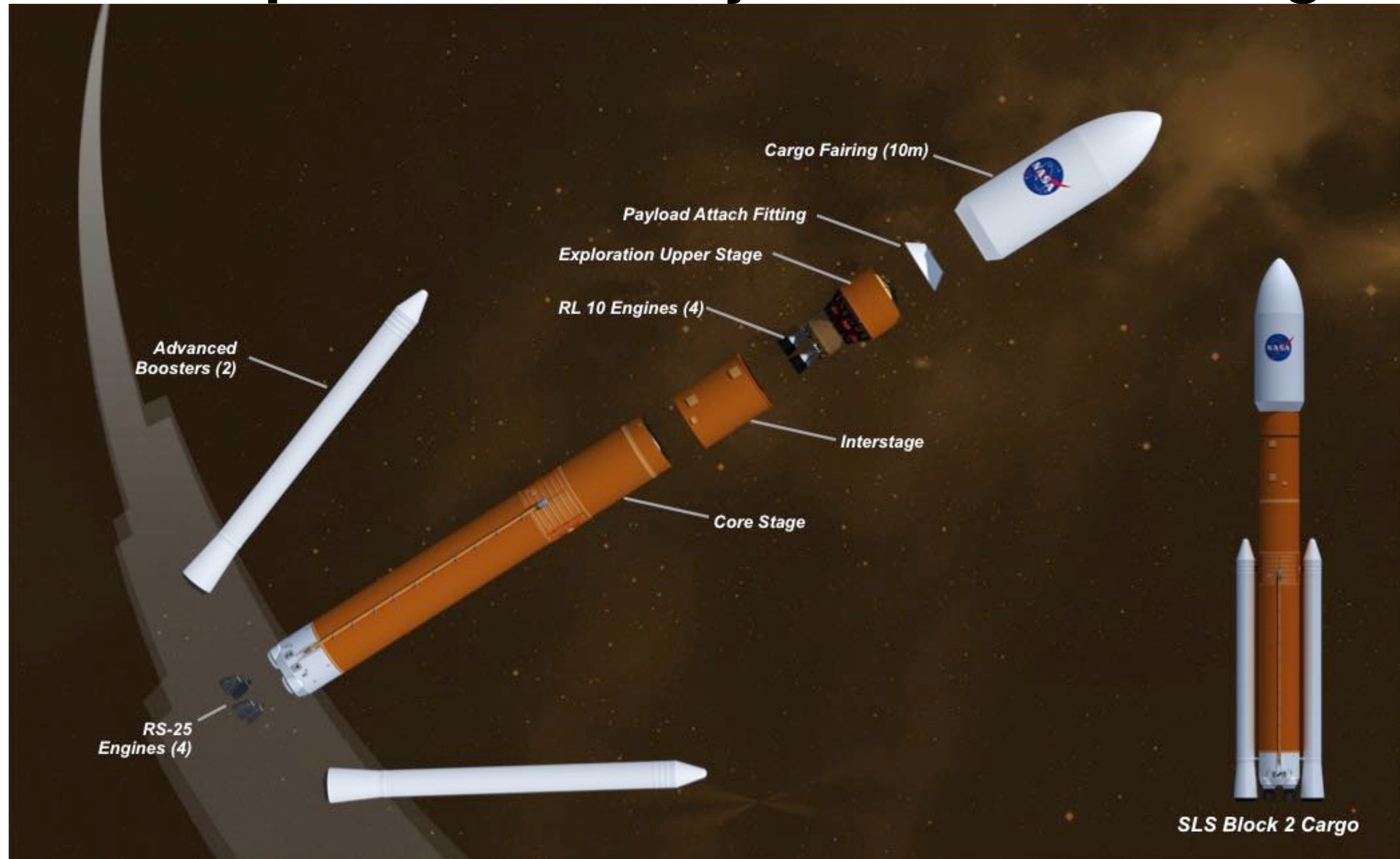
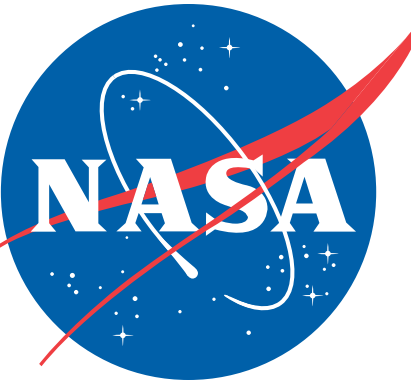
SLS: NASA Space Launch System Block 1



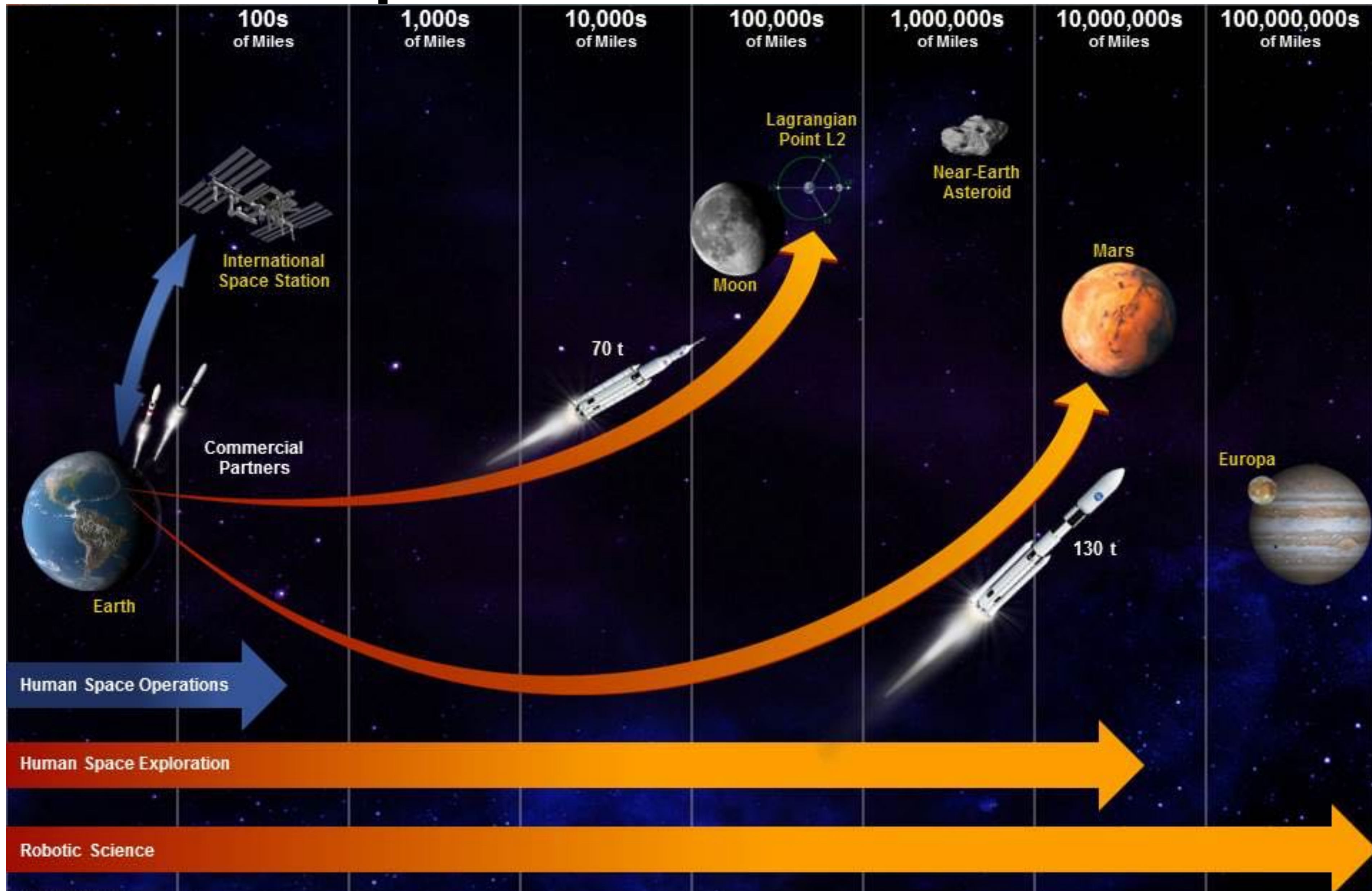
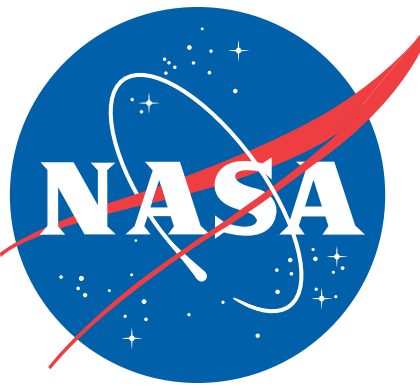
SLS: NASA Space Launch System Block 1B Crew



SLS: NASA Space Launch System Block 2 Cargo

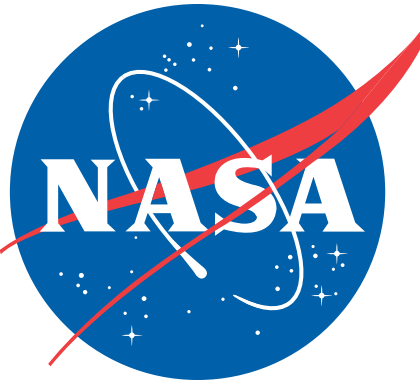


SLS: Future of Exploration

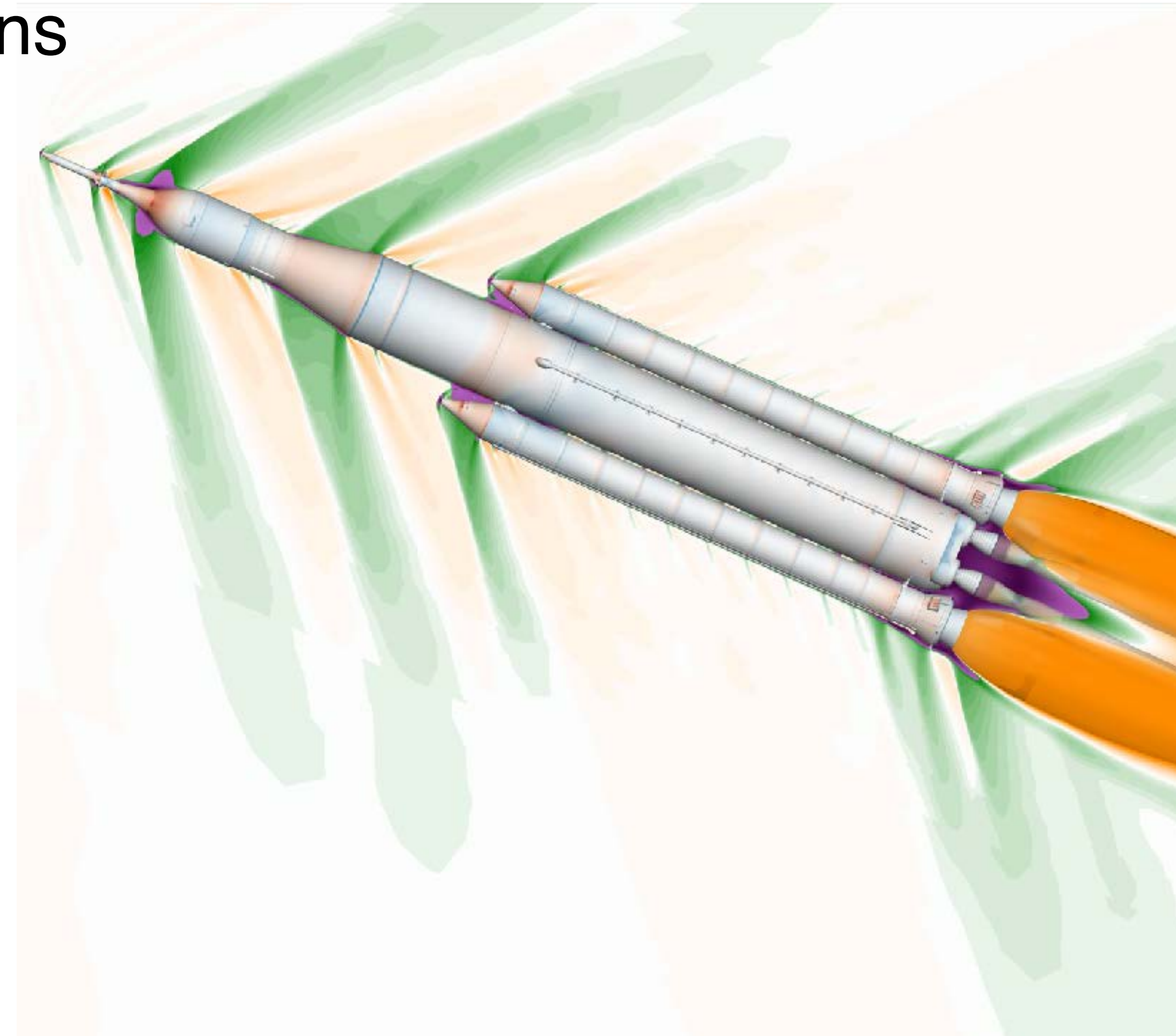




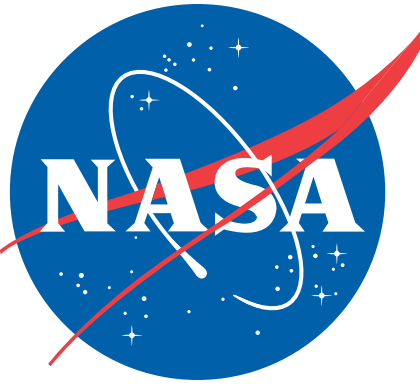
Building Aerodynamic Database: Ascent



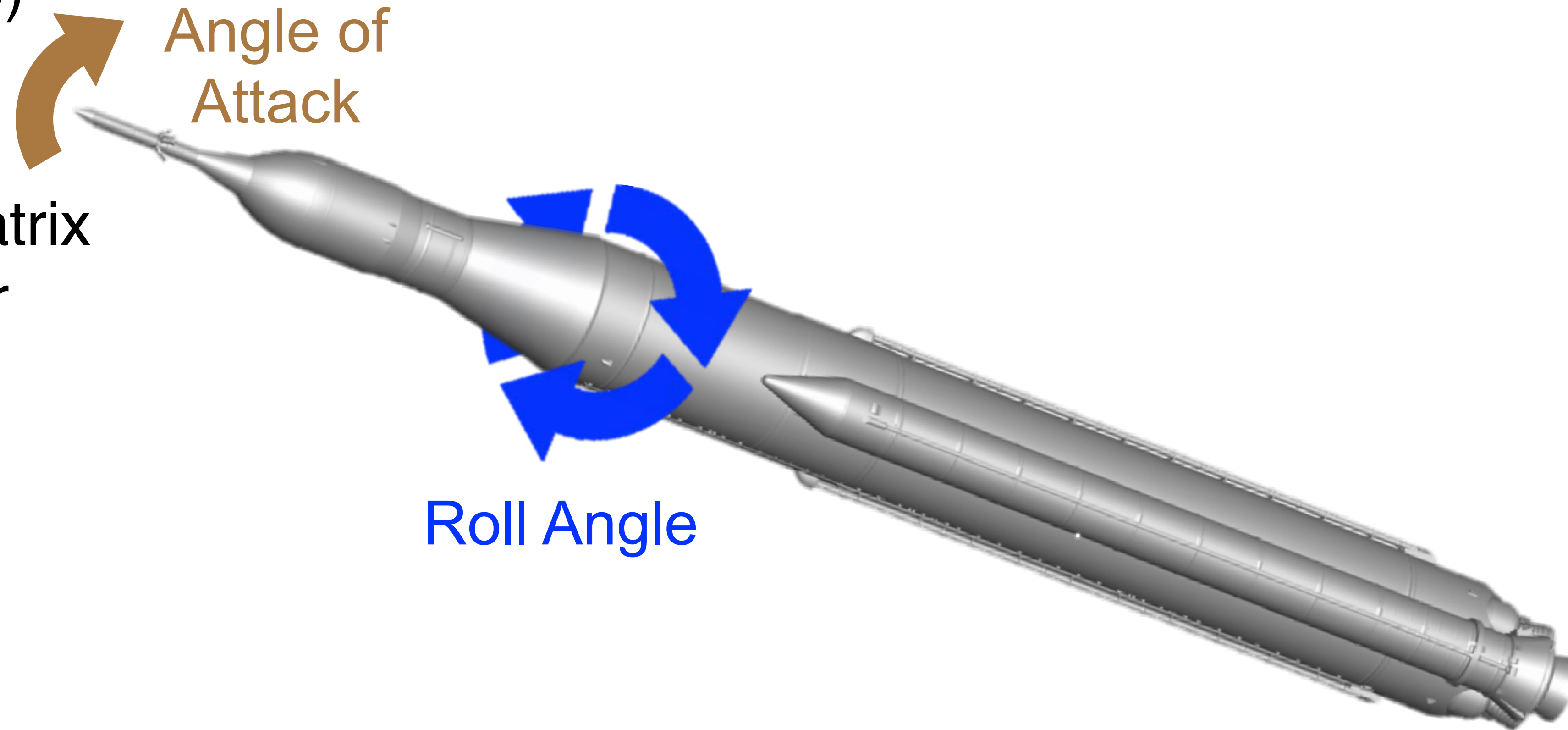
- Provide forces and moments on core and both boosters
- Complicated fluid dynamics: plume interactions
- Large data
 - Many independent parameters
 - Flight geometry & Wind-tunnel geometry
 - Static cases
- Computational Fluid Dynamics (CFD)
 - FUN3D viscous CFD solver
 - Overflow viscous CFD solver



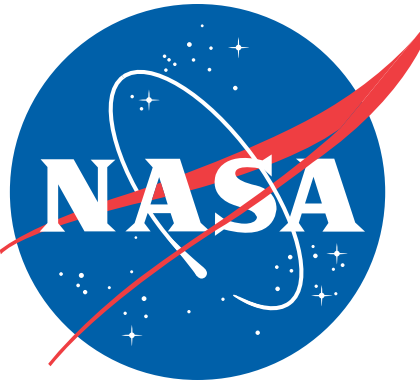
Ascent Aerodynamics Database



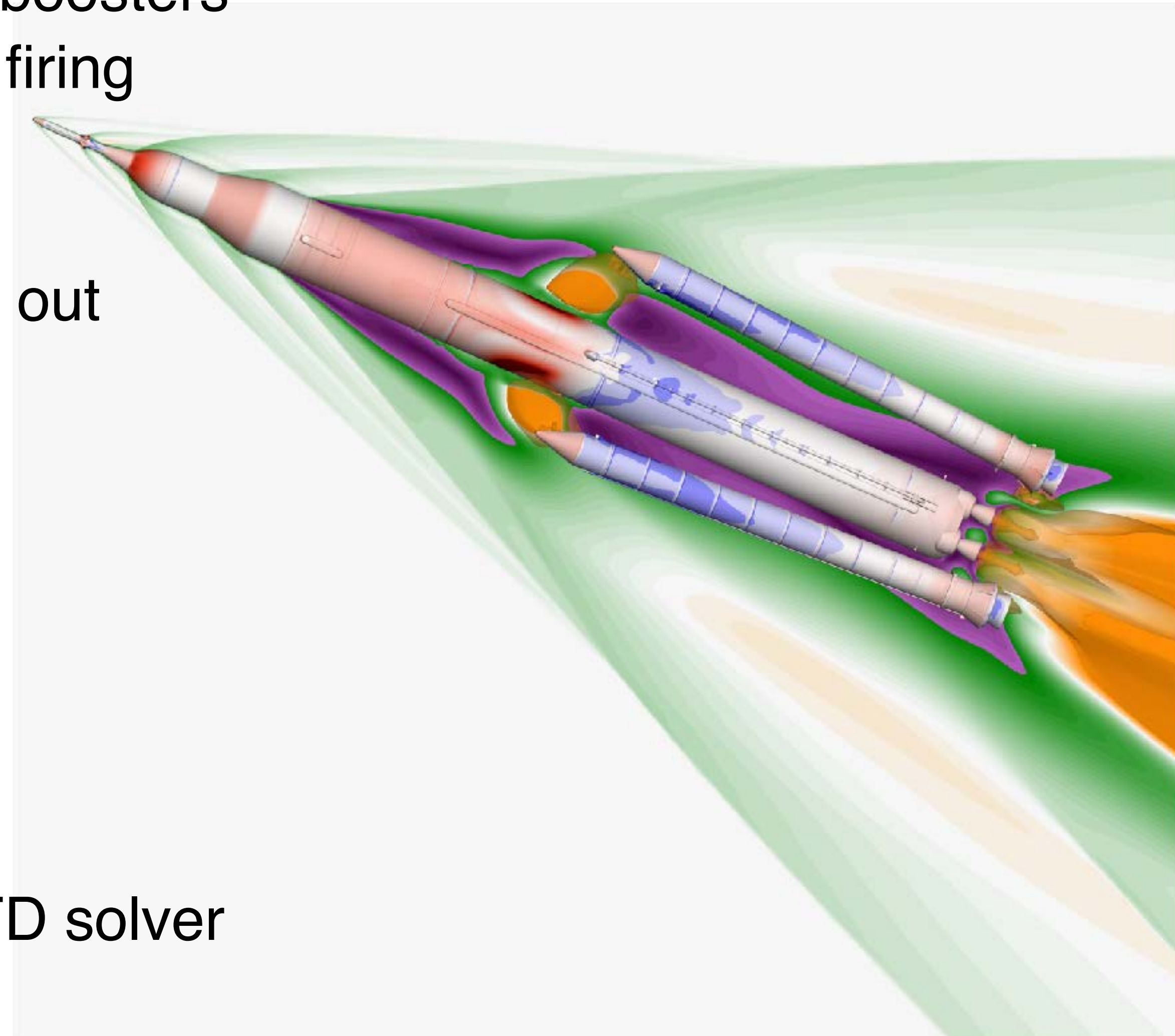
- Three-Dimensional run matrix
 - Mach number (altitude)
 - Angle of attack
 - Roll Angle
- Rectangular 2-D run matrix based on Mach number
- 1300+ cases total



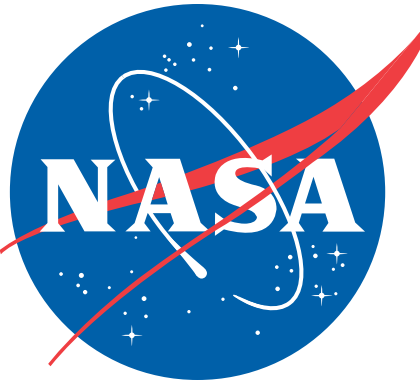
Building Aerodynamic Database: Booster Separation



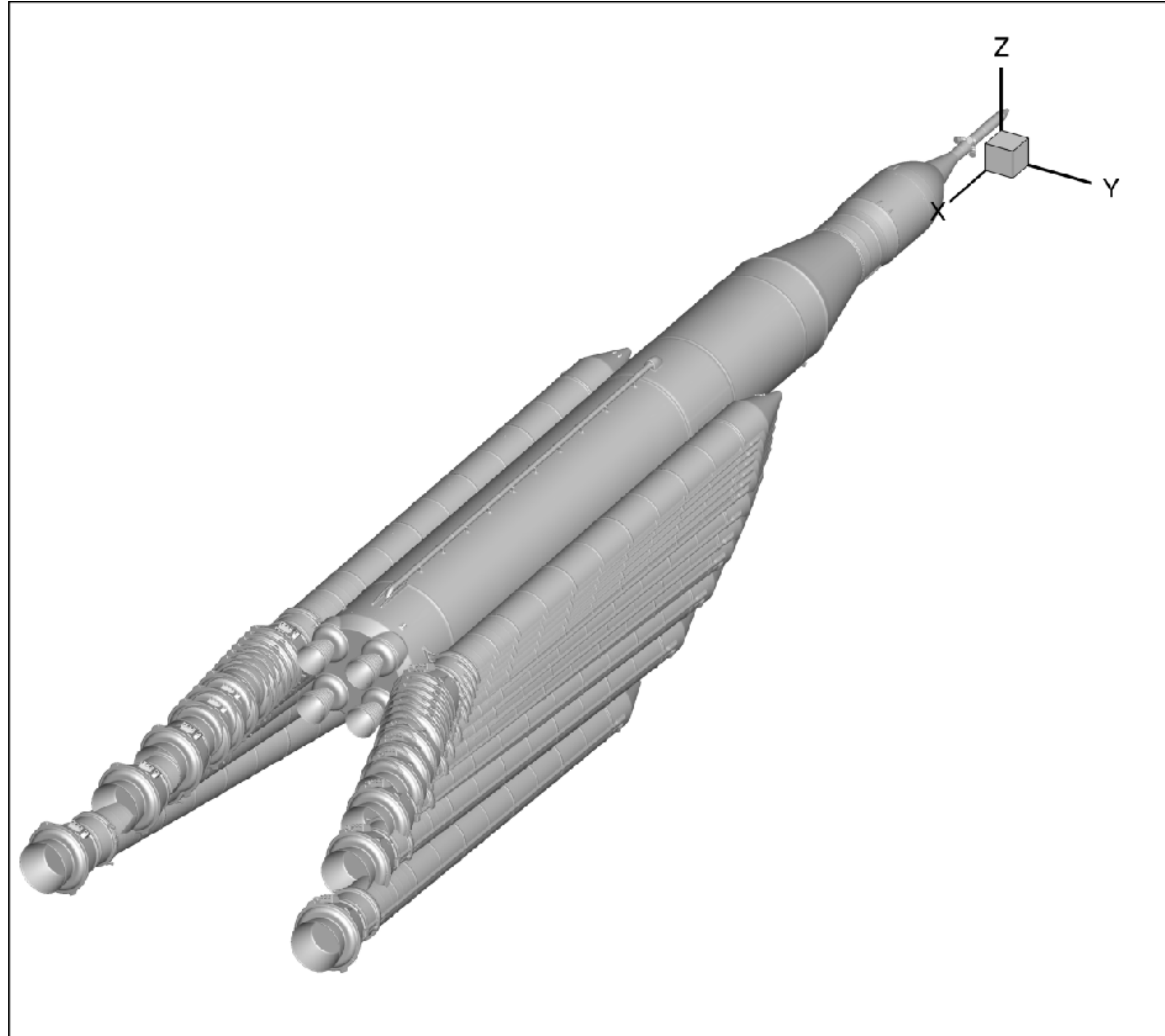
- Provide forces and moments on core and both boosters
- Complicated fluid dynamics: 14 engine plumes firing
- Large data
 - Many independent parameters
 - Off-nominal conditions: core engine out, BSM out
 - Flight geometry & Wind-tunnel geometry
 - Static and Dynamic cases
- Computational Fluid Dynamics (CFD)
 - Cart3D inviscid CFD solver
 - FUN3D viscous CFD solver
 - Overflow viscous CFD solver
 - Overflow-D viscous dynamic moving body CFD solver



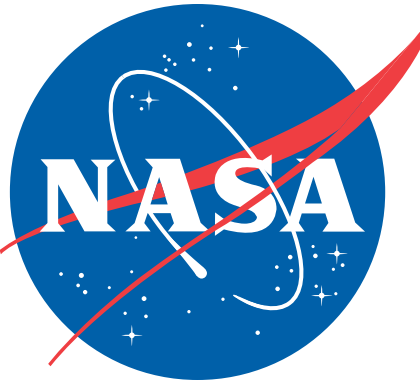
Booster Separation Aerodynamics Database



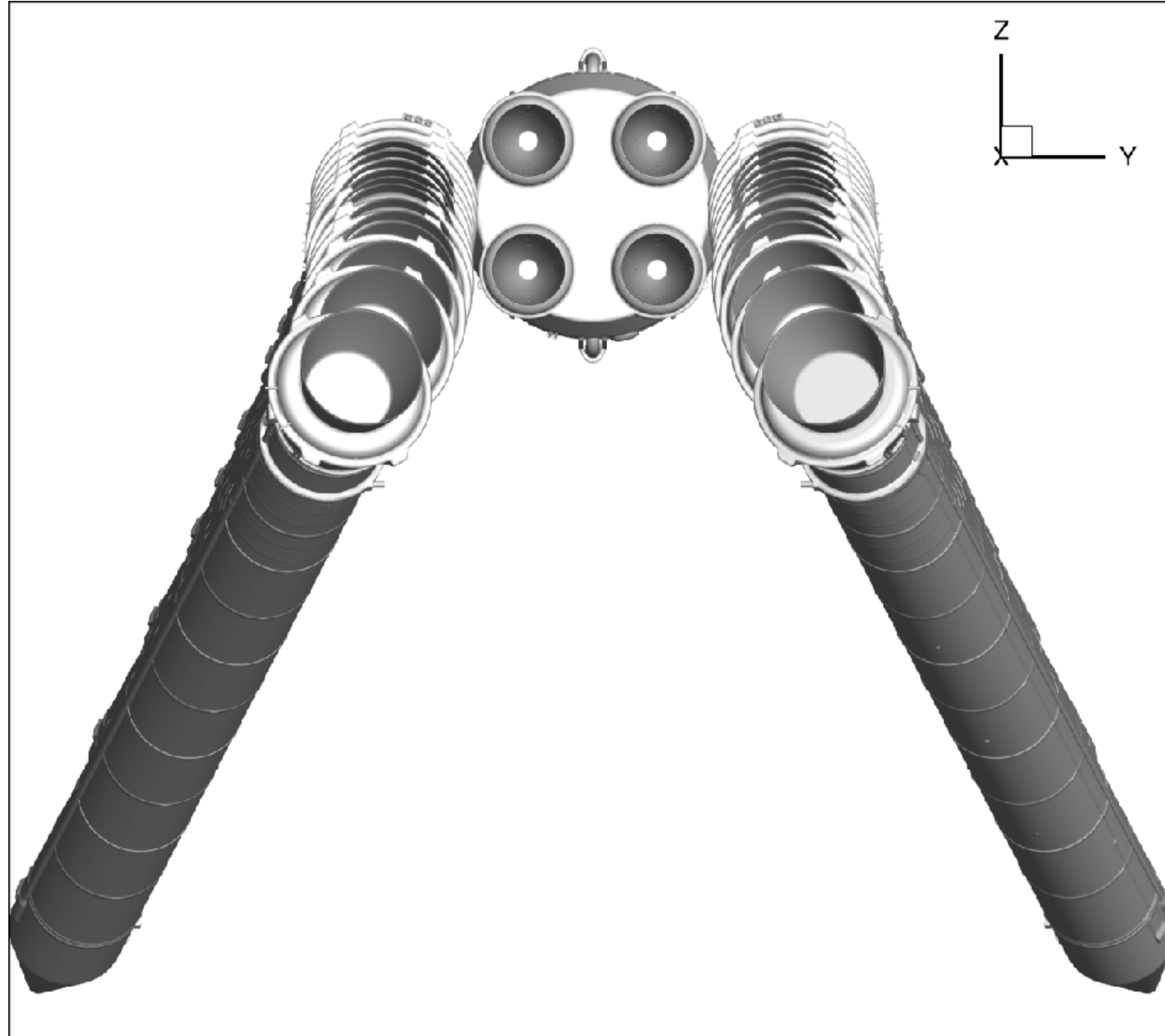
- Eight-Dimensional run matrix
 - Translational variables - 3
 - Rotational variables - 2
 - Thrust of booster separation motors -1
 - Freestream conditions - 2



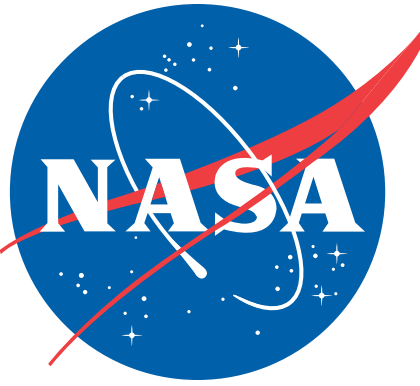
Booster Separation Aerodynamics Database



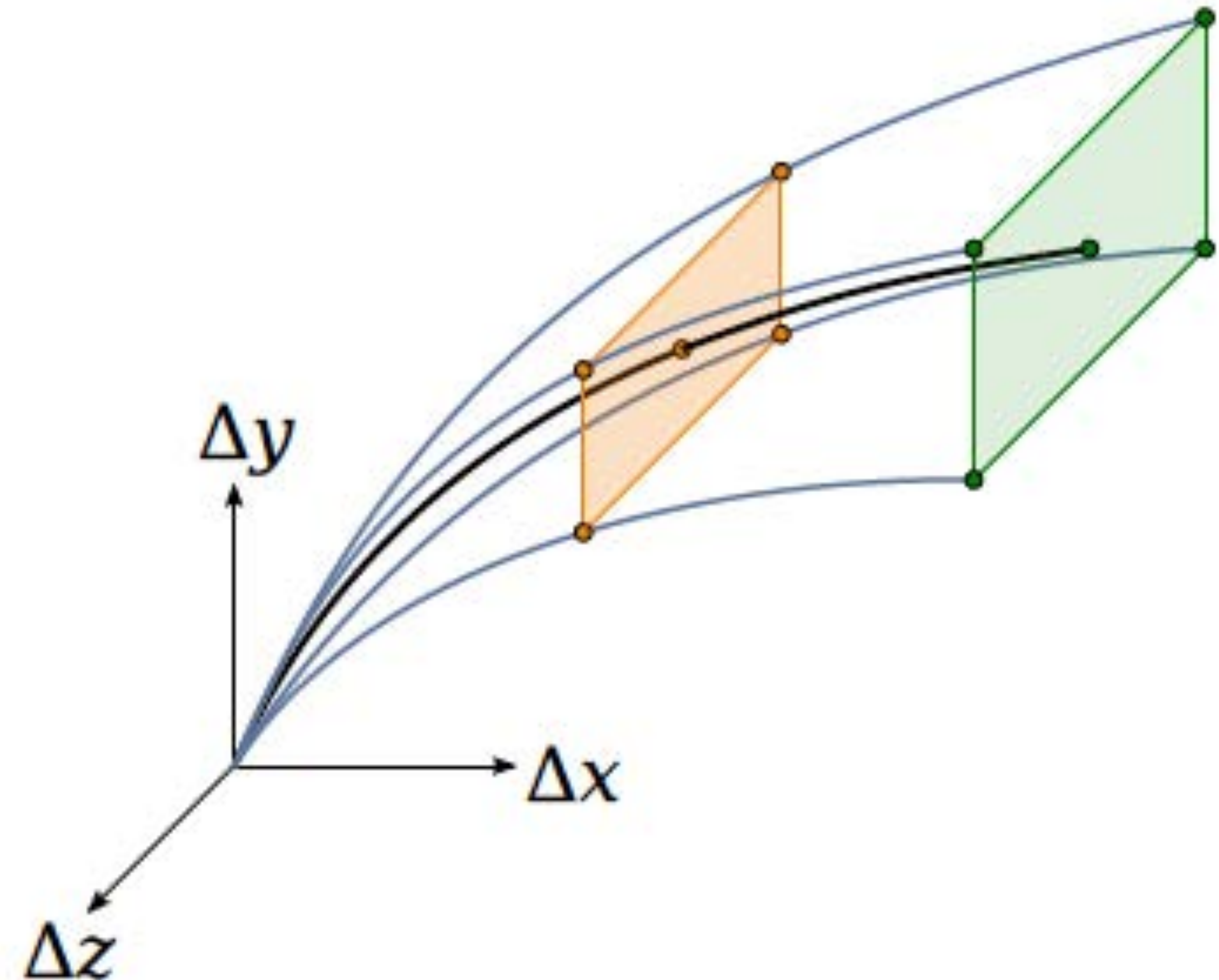
- Eight-Dimensional run matrix
 - Translational variables - 3
 - Rotational variables - 2
 - Thrust of booster separation motors - 1
 - Freestream conditions - 2
- 7-dimensional rectangular run matrix for each dx value



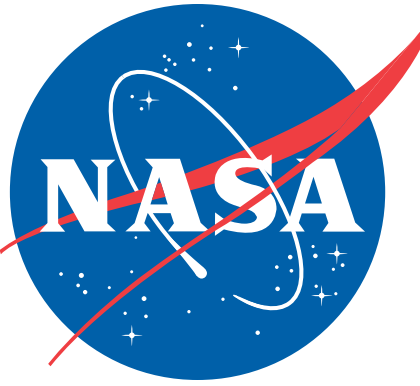
Booster Separation Aerodynamics Database



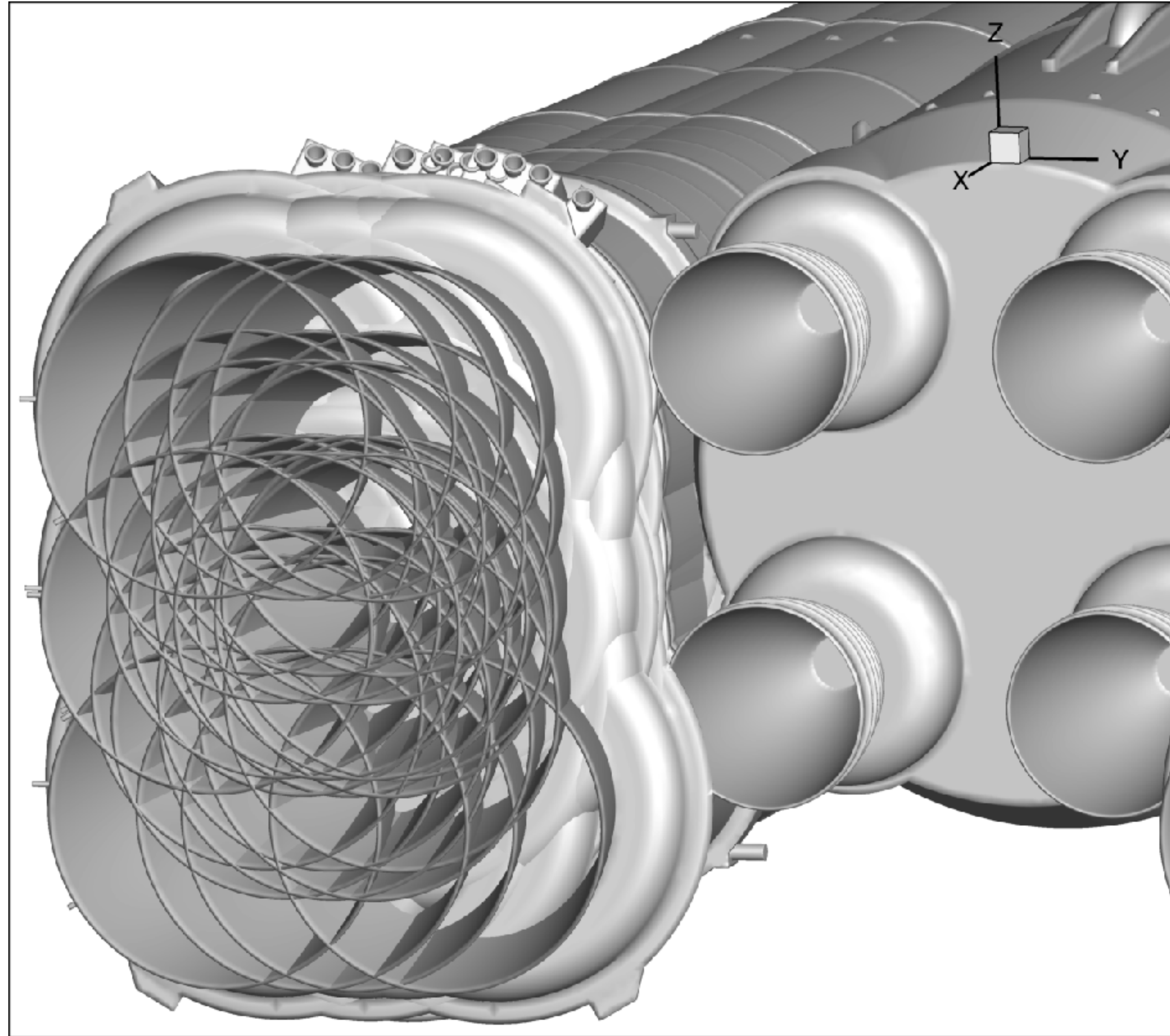
- Eight-Dimensional run matrix
 - Translational variables - 3
 - Rotational variables - 2
 - Thrust of booster separation motors -1
 - Freestream conditions - 2
- 7-dimensional rectangular run matrix for each dx value
- Pyramid-shaped run matrix



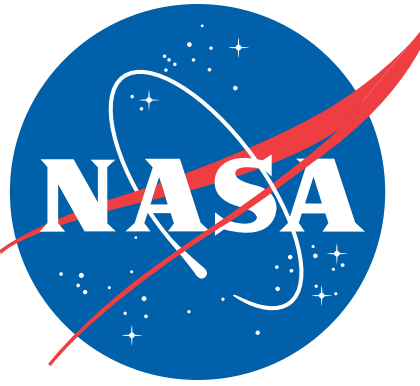
Booster Separation Aerodynamics Database



- Eight-Dimensional run matrix
 - Translational variables - 3
 - Rotational variables - 2
 - Thrust of booster separation motors - 1
 - Freestream conditions - 2
- 7-dimensional rectangular run matrix for each dx value
- Pyramid-shaped run matrix
- 22,000+ runs required



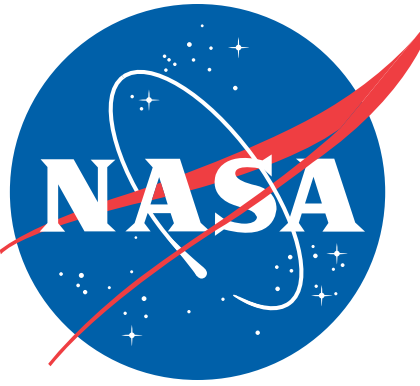
NAS Pleiades & Electra Supercomputer



- SGI Ice cluster with Intel Xeon processors
- InfiniBand in a dual-plane hypercube technology
- Pleiades
 - 7.24 Pflop/s peak cluster
 - 11,440 nodes; 246,048 cores
 - 935 TB Memory
 - Broadwell, Haswell, Ivy Bridge, & Sandy Bridge Nodes
- Electra
 - 4.79 Pflops/ peak cluster
 - 2,304 nodes; 78,336 cores
 - 368 TB Memory
 - Skylake and Broadwell Nodes



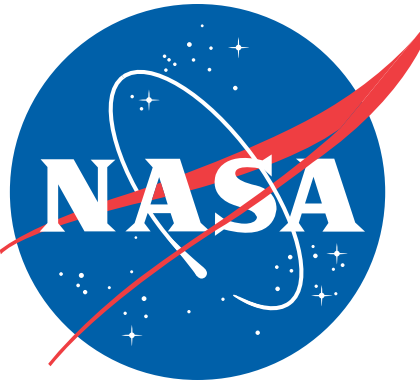
Computational Resources Consumed 2017



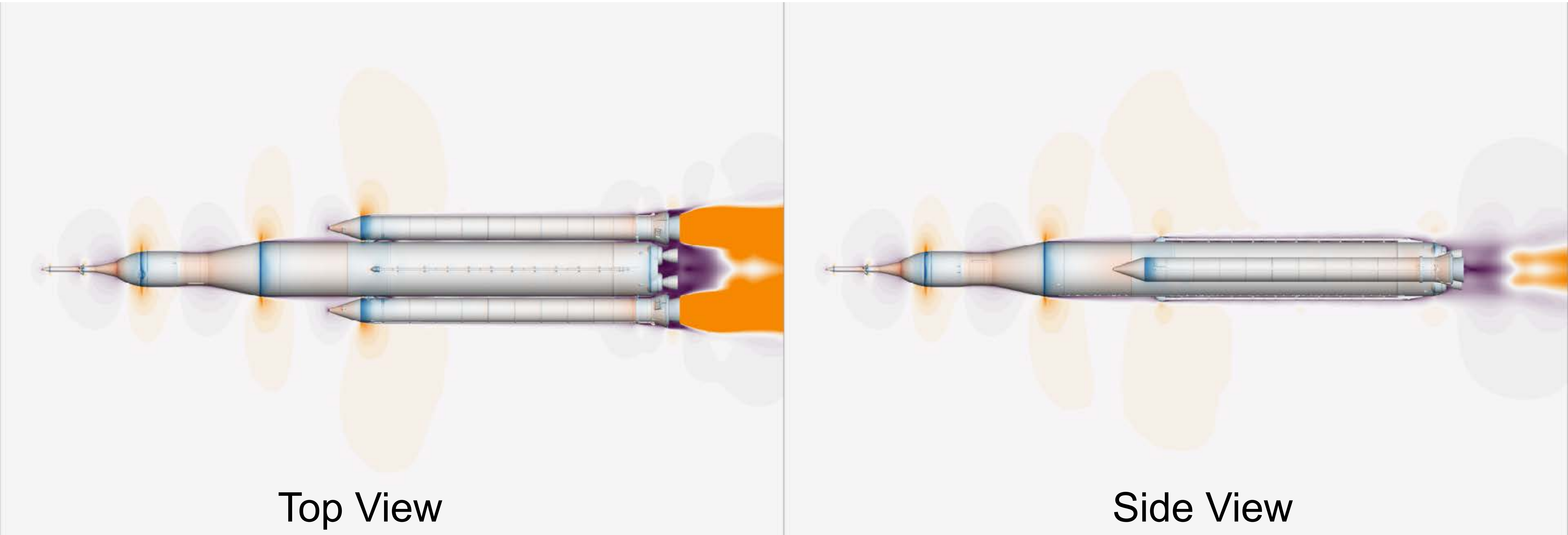
- Over 71 million core hours
- Over 500 terabytes of storage used

- Block 1 Crew Ascent
 - *3000+* cases
 - 36 million core hours
- Block 1B Crew Ascent & Booster Separation
 - *~1,300 + ~3000* cases
 - 25 million core hours
- Block 1B Cargo Ascent Database
 - *~1,300* cases
 - 5 million core hours

SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High

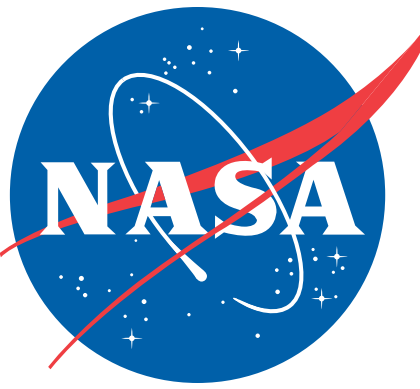


Top View

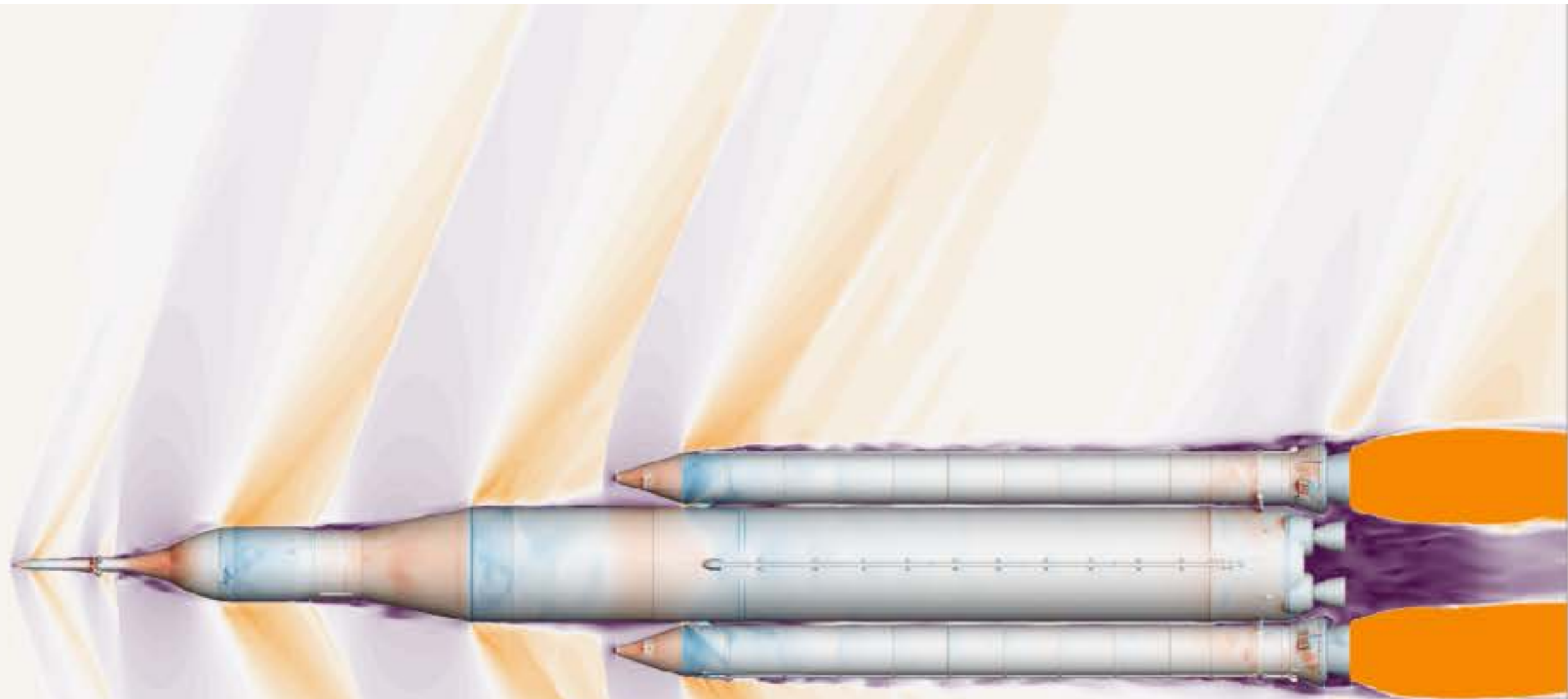
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

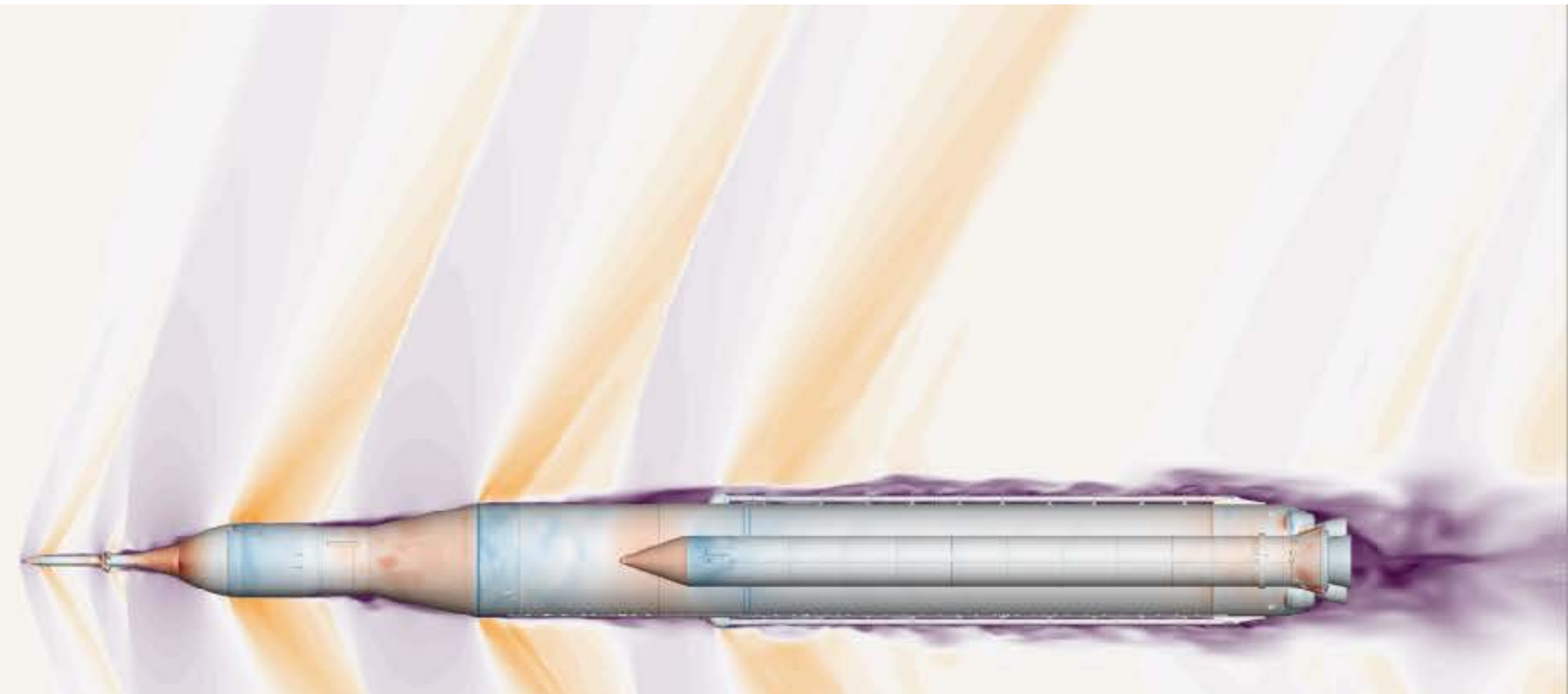
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



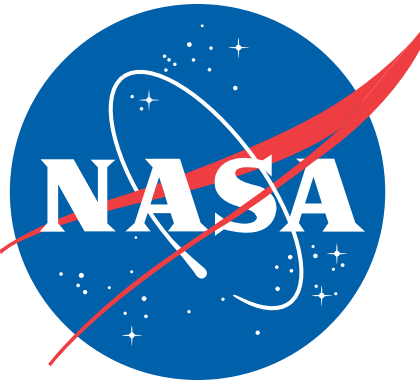
Top View



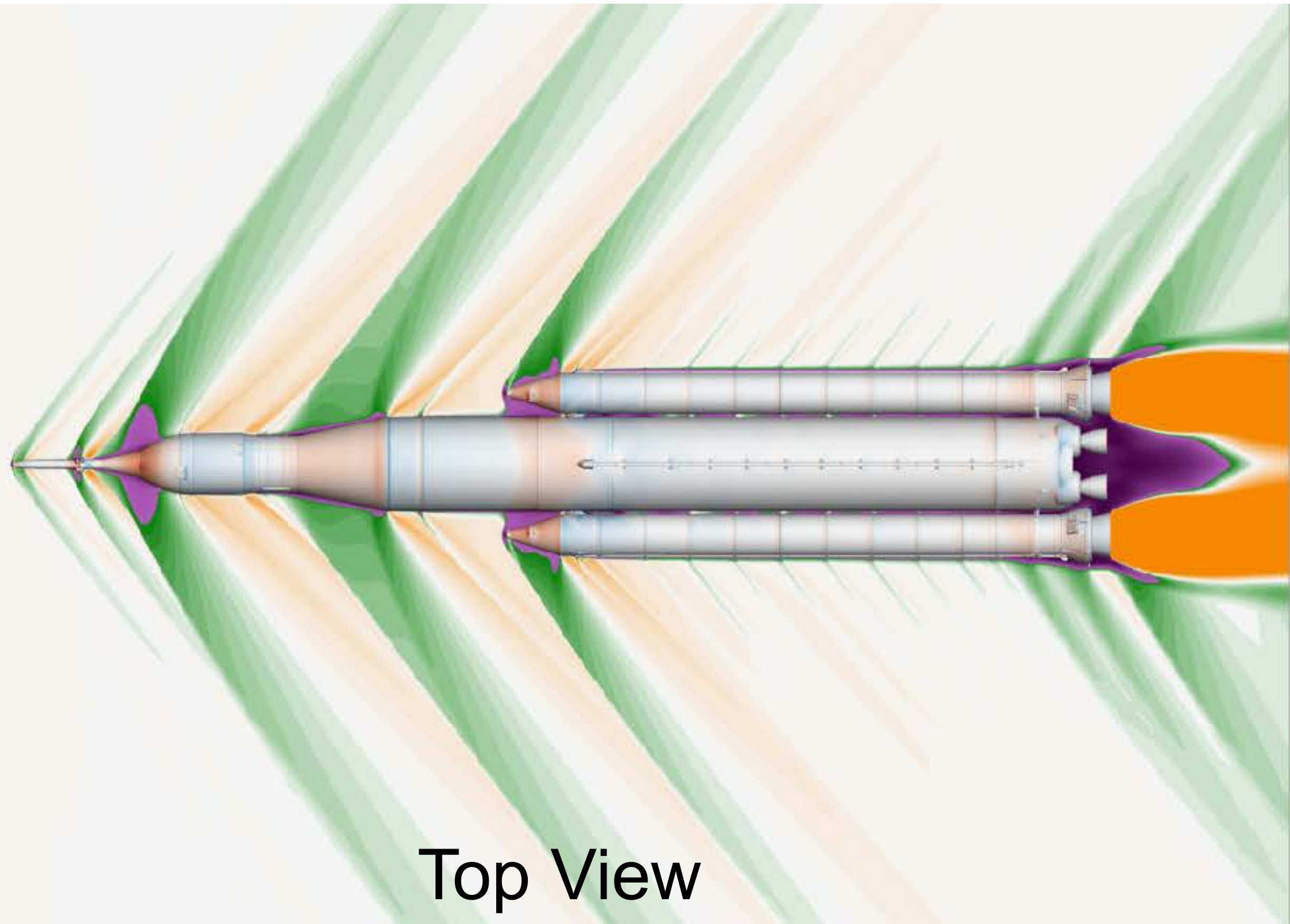
Side View

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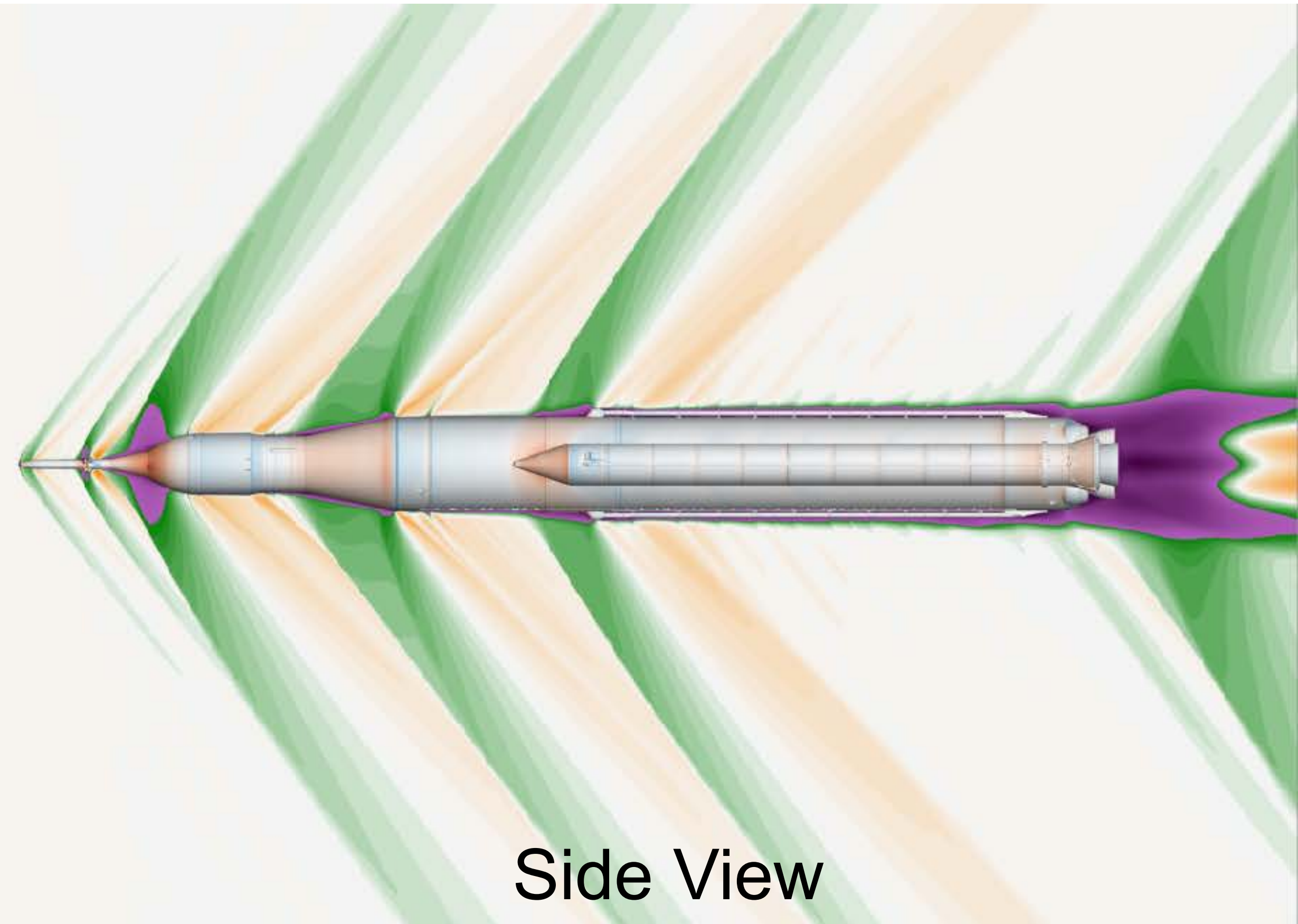
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



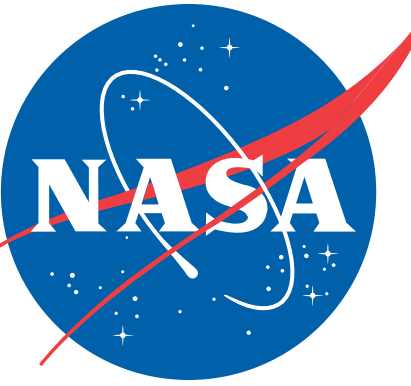
Top View



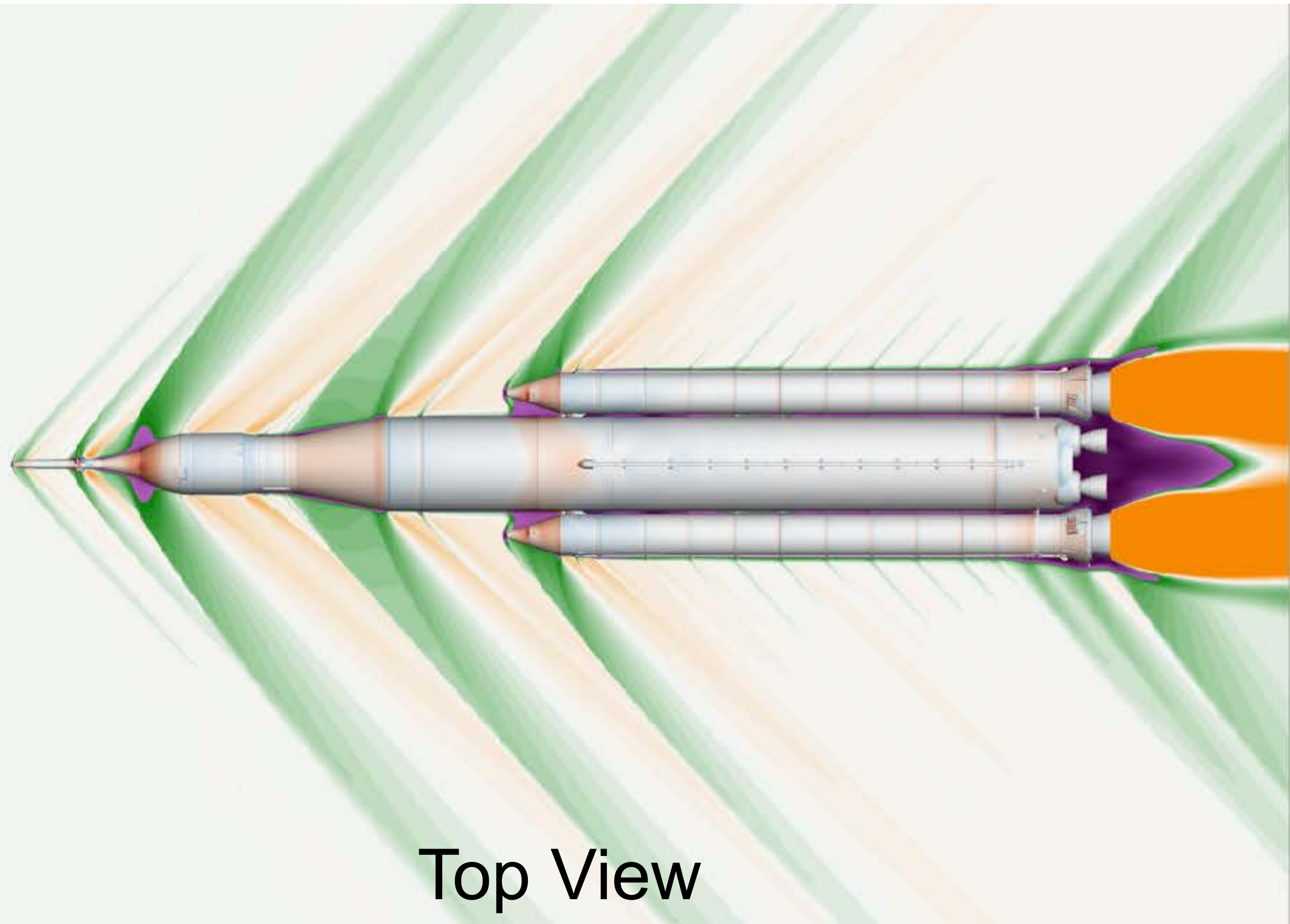
Side View

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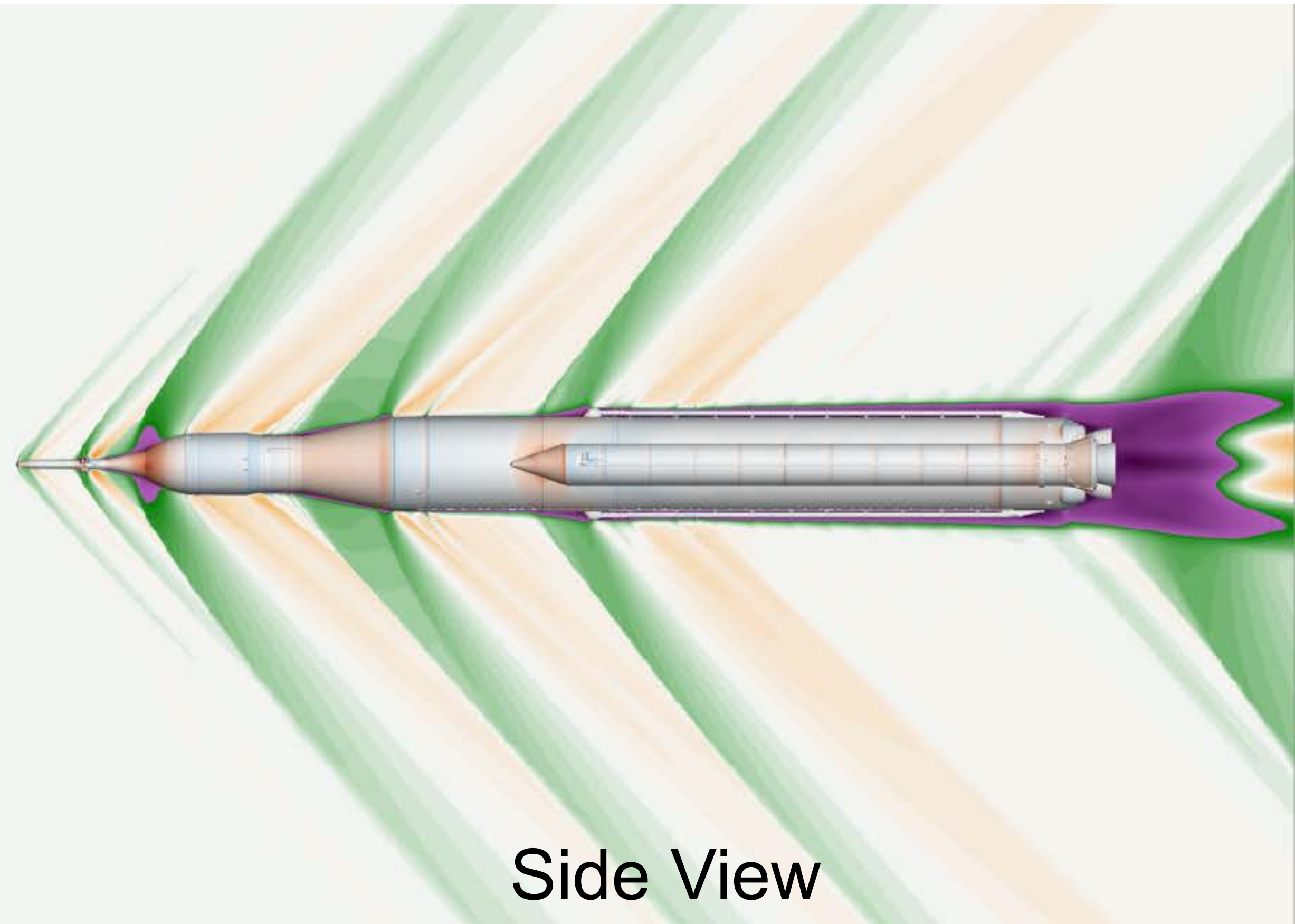
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



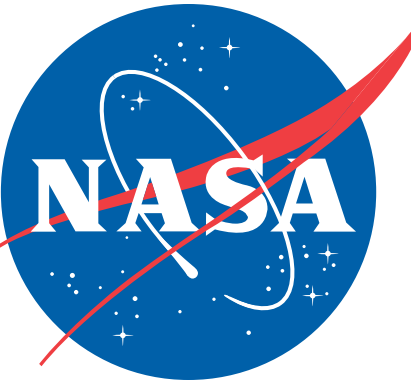
Top View



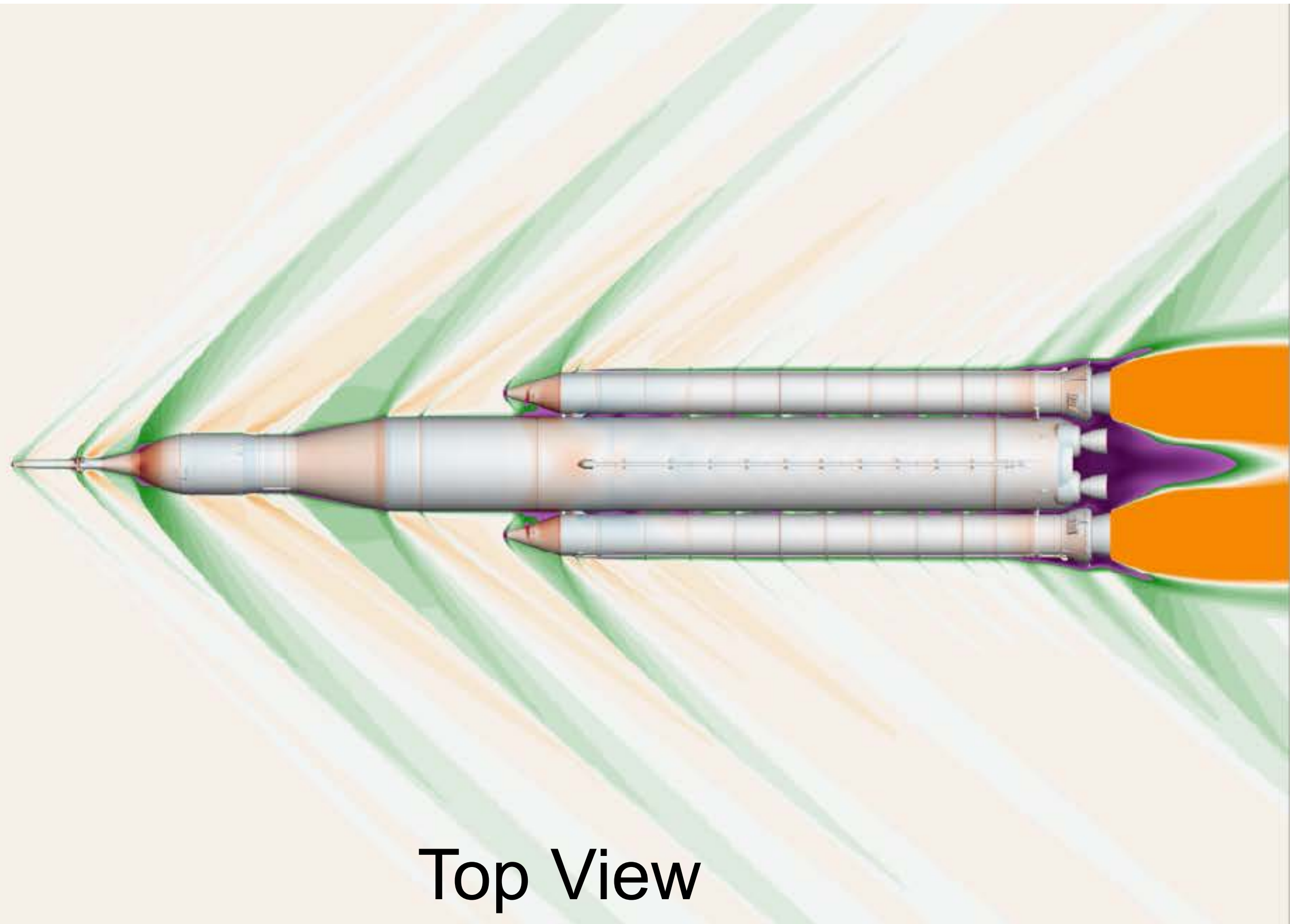
Side View

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Vehicle surface blue-white-red color contours represent low to high pressures

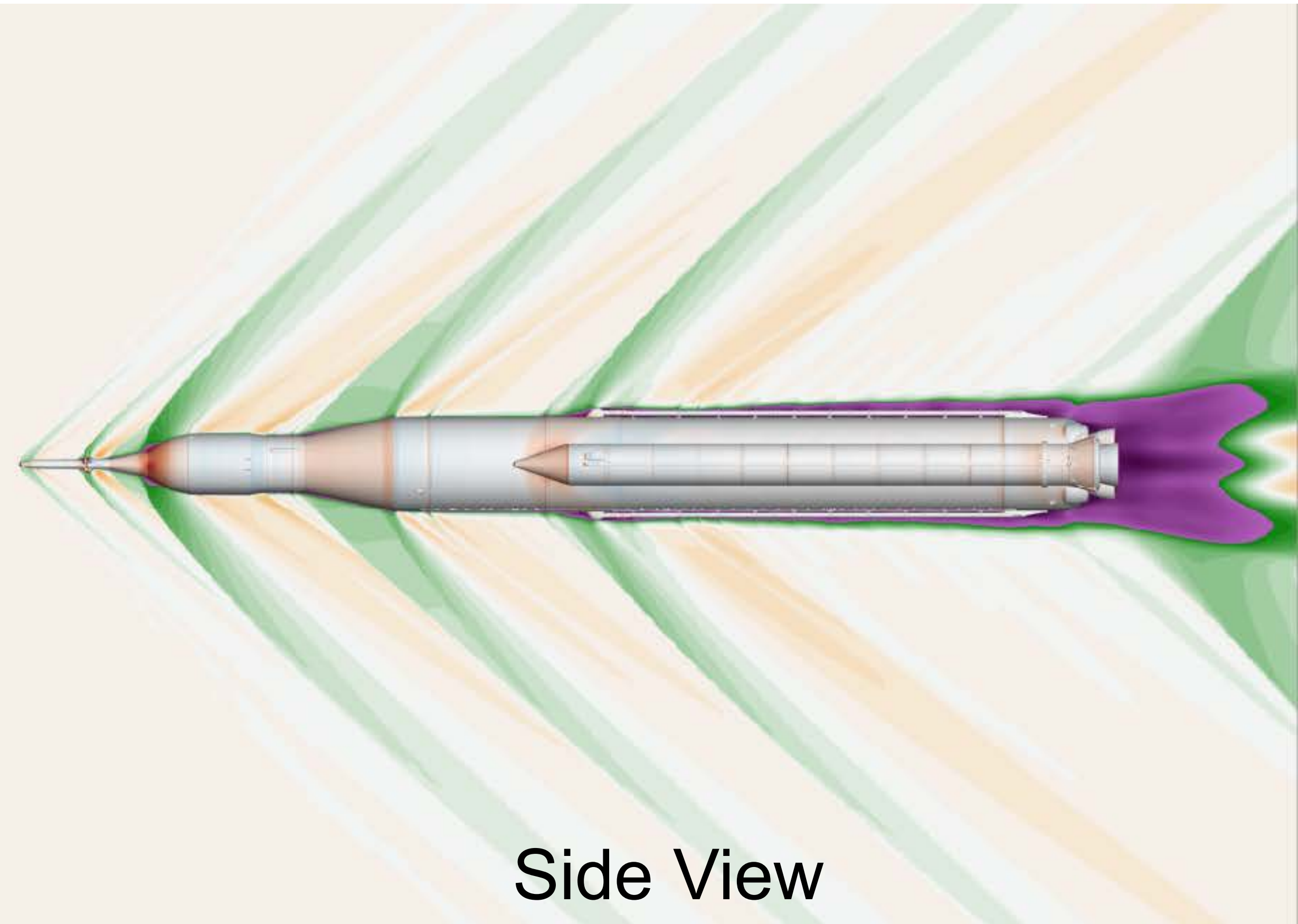
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



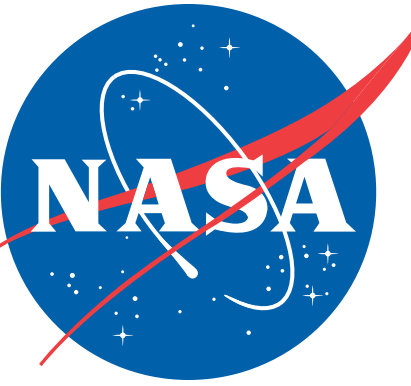
Top View



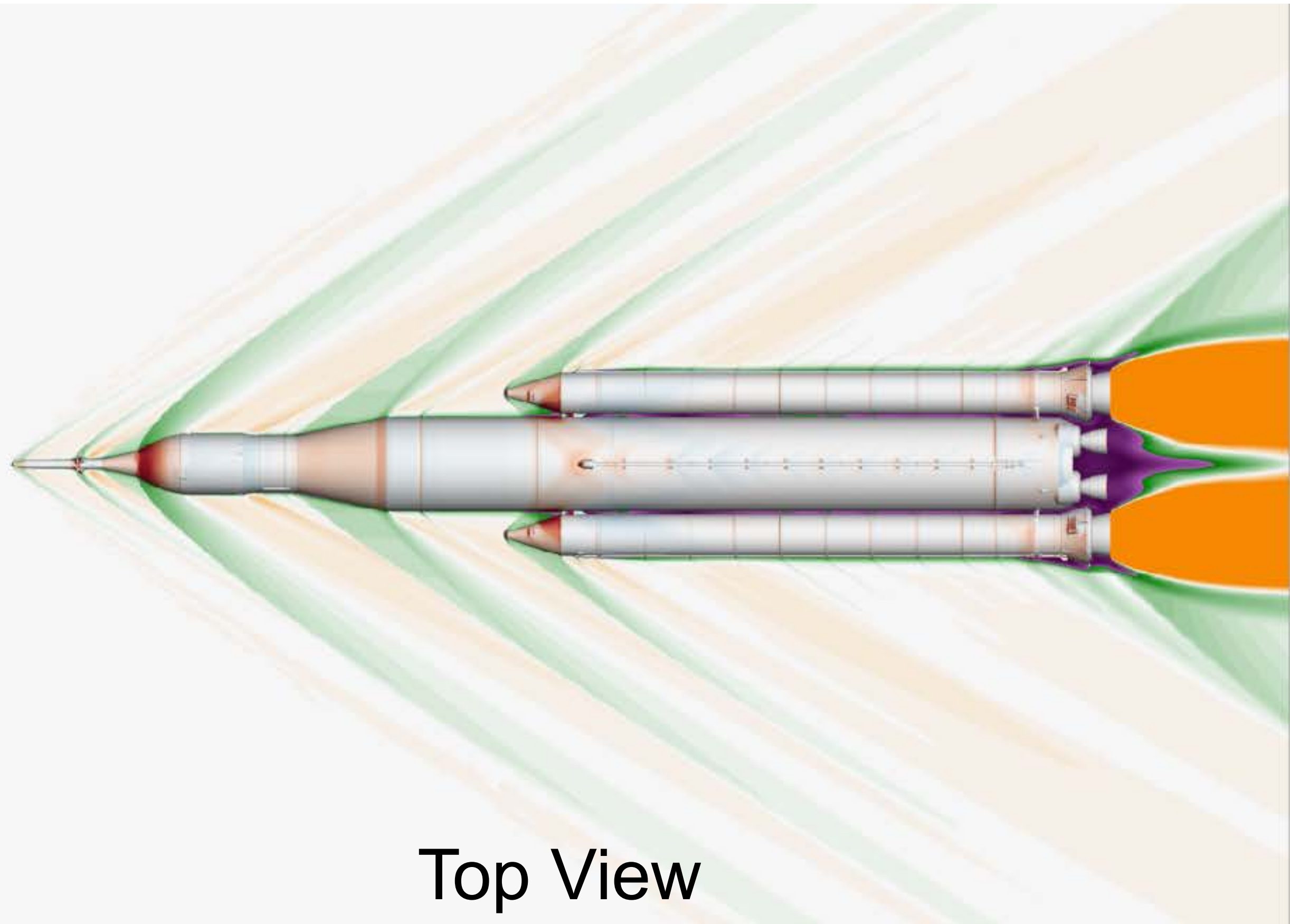
Side View

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Vehicle surface blue-white-red color contours represent low to high pressures

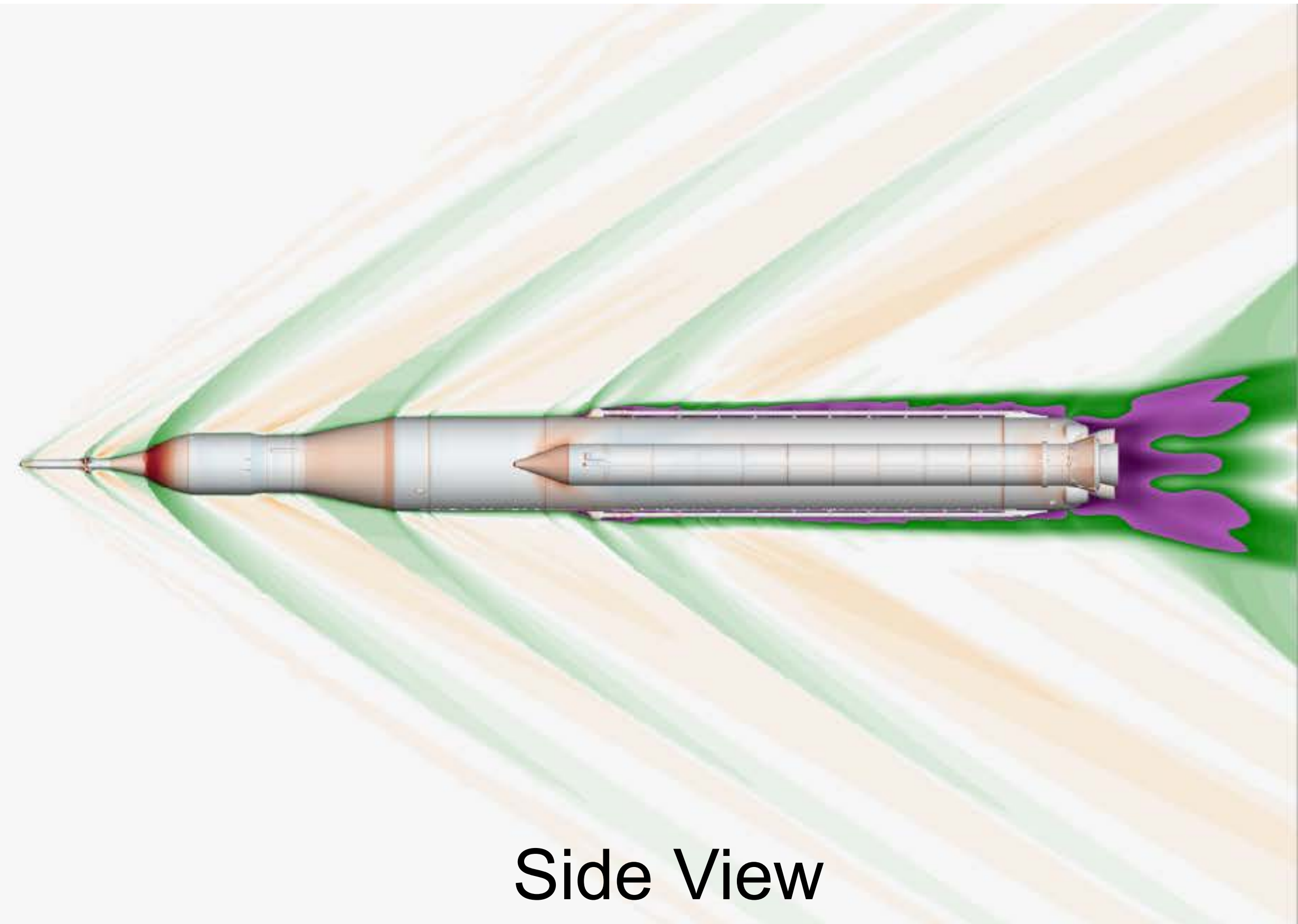
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



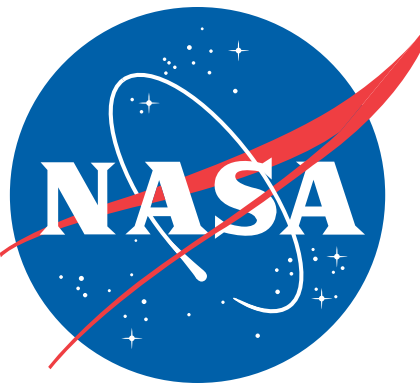
Top View



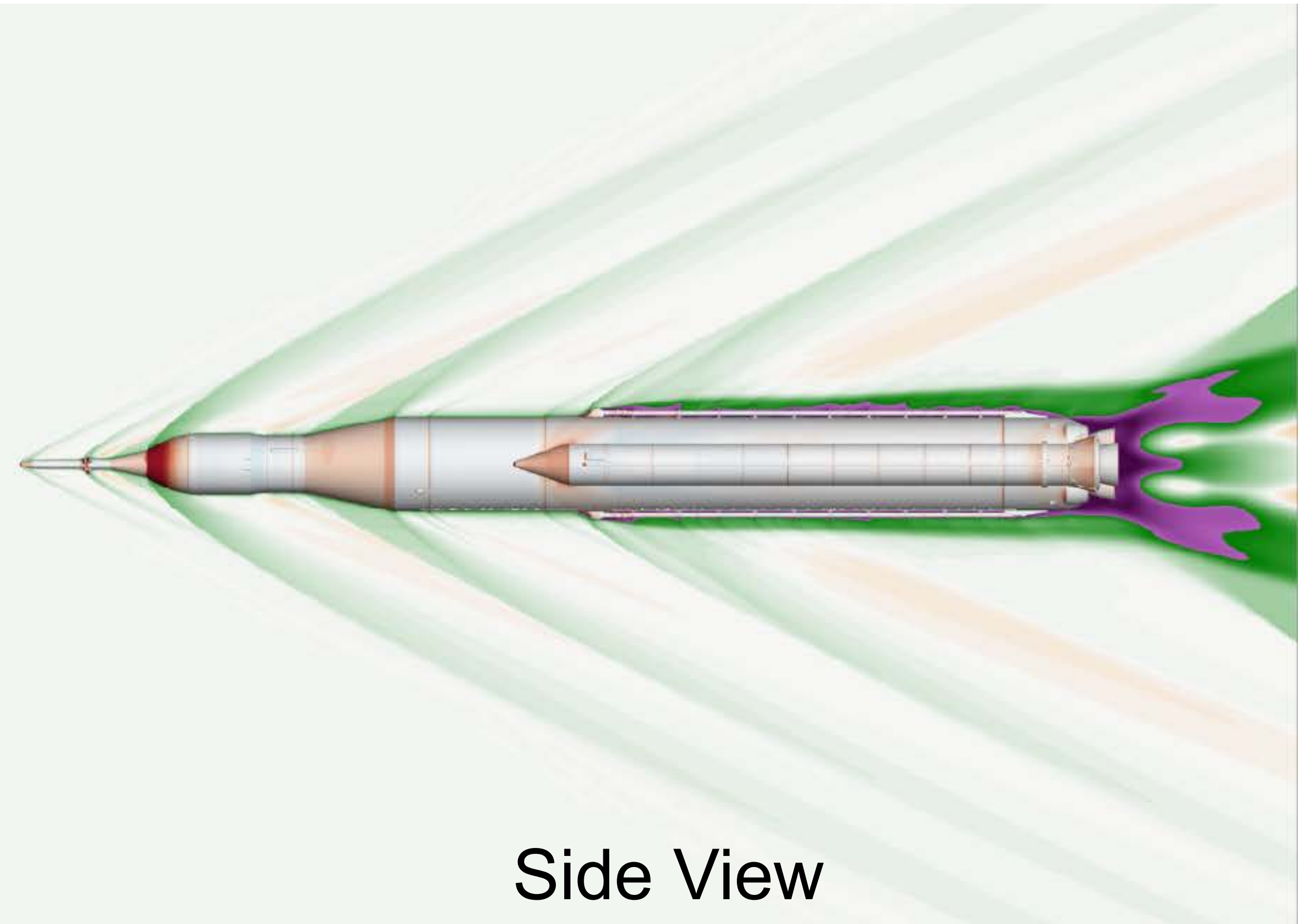
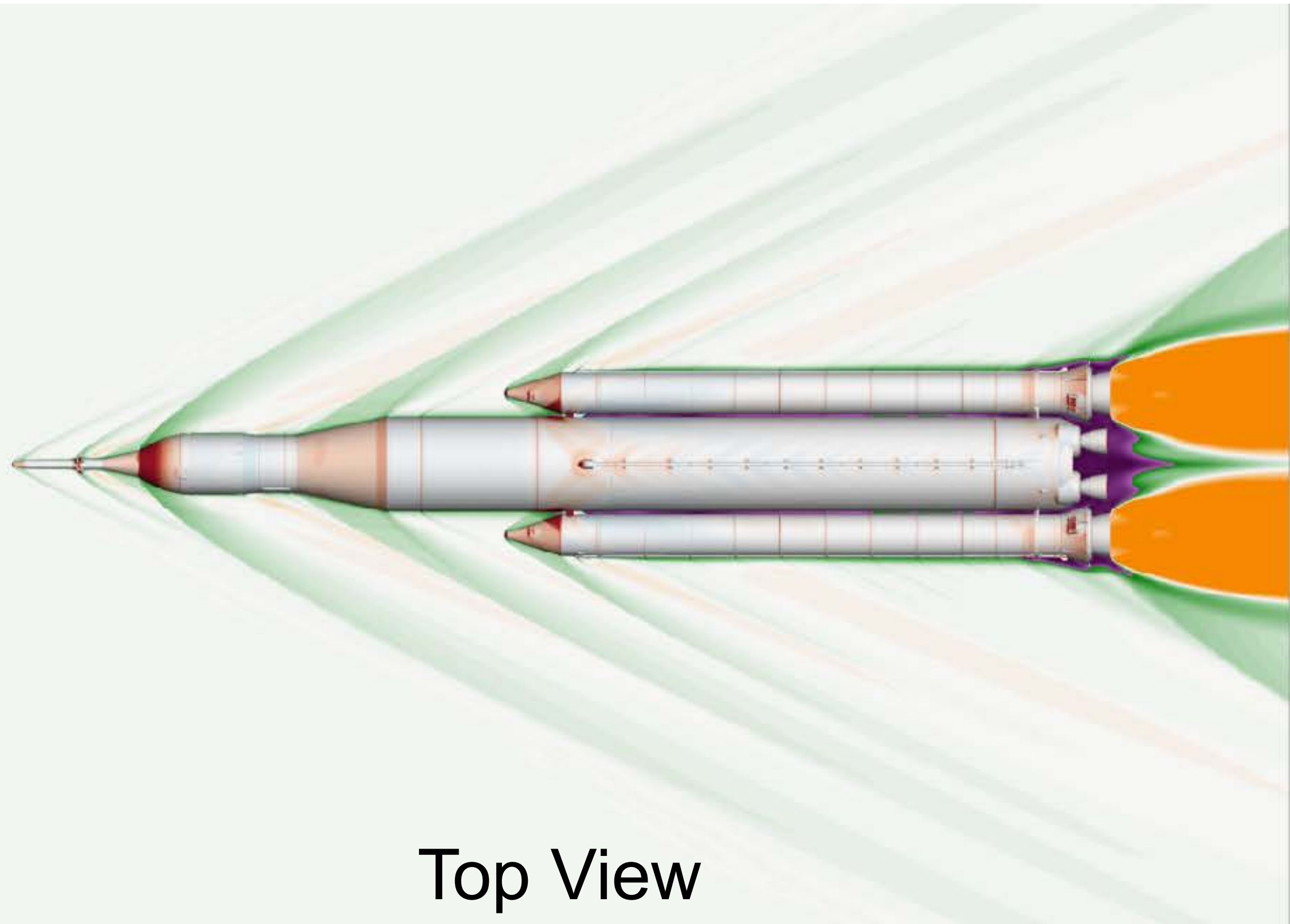
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1 Crew Ascent

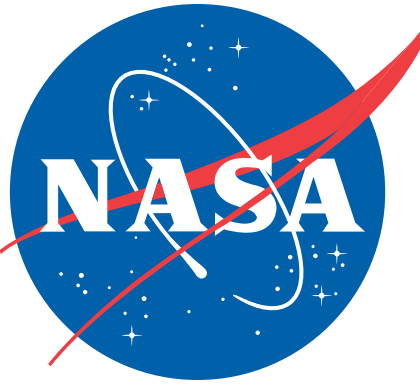


Altitude: Low • • • • • • • • • • High

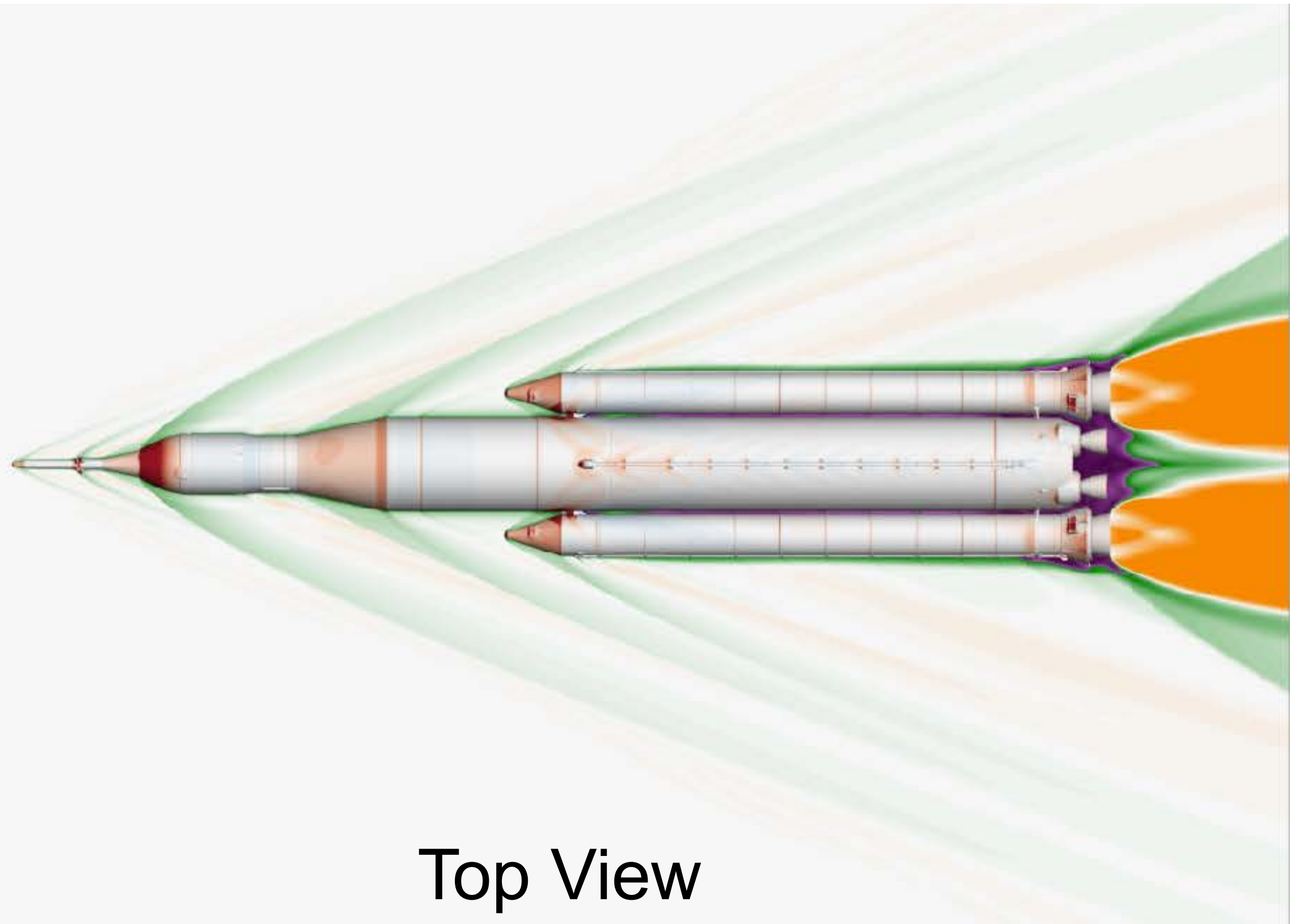


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

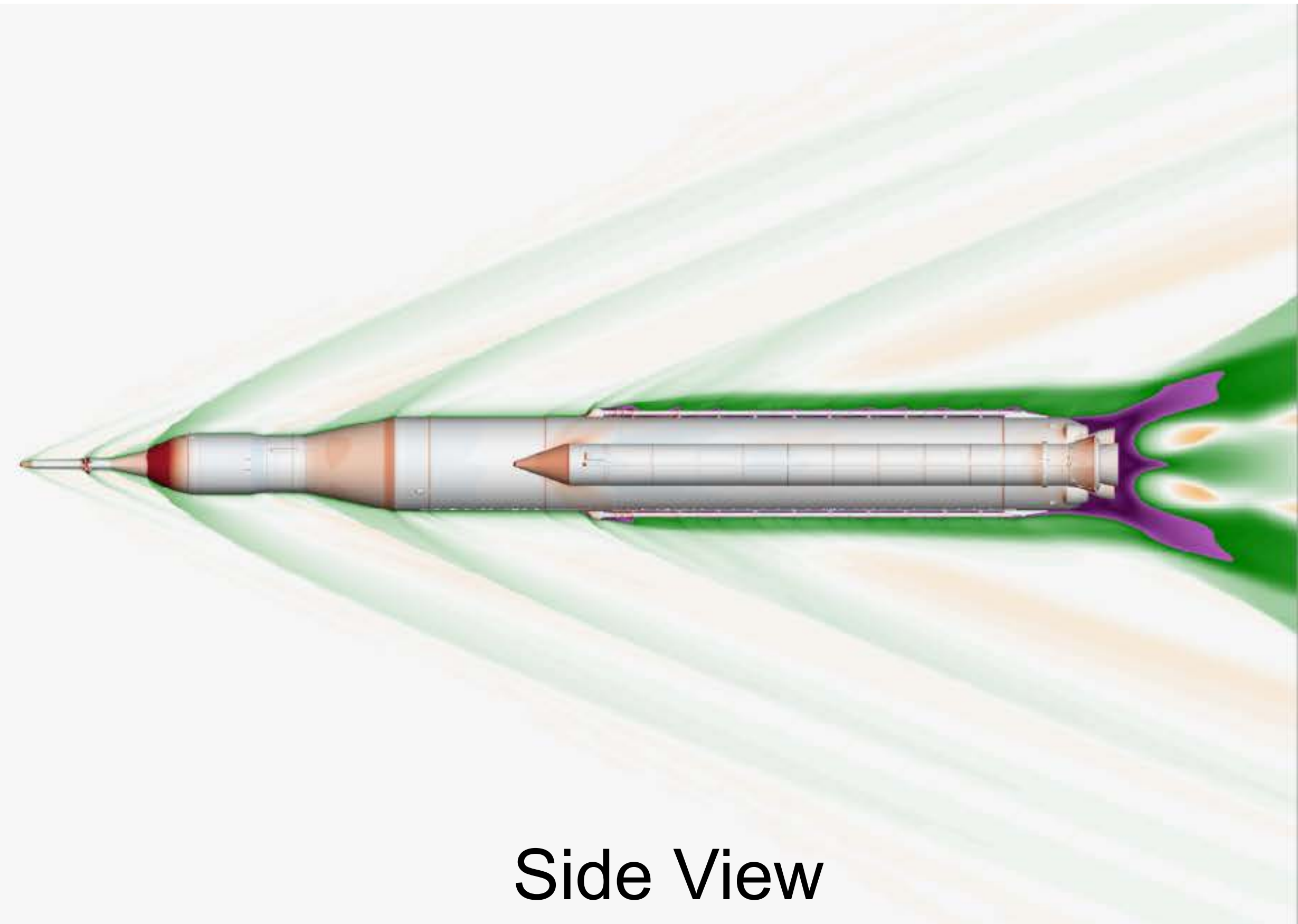
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



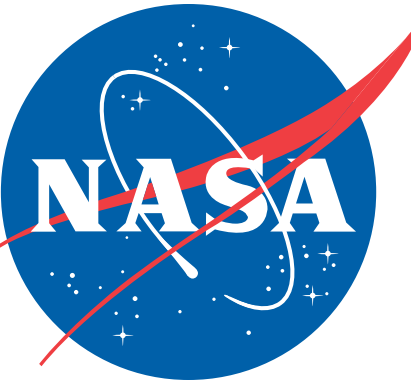
Top View



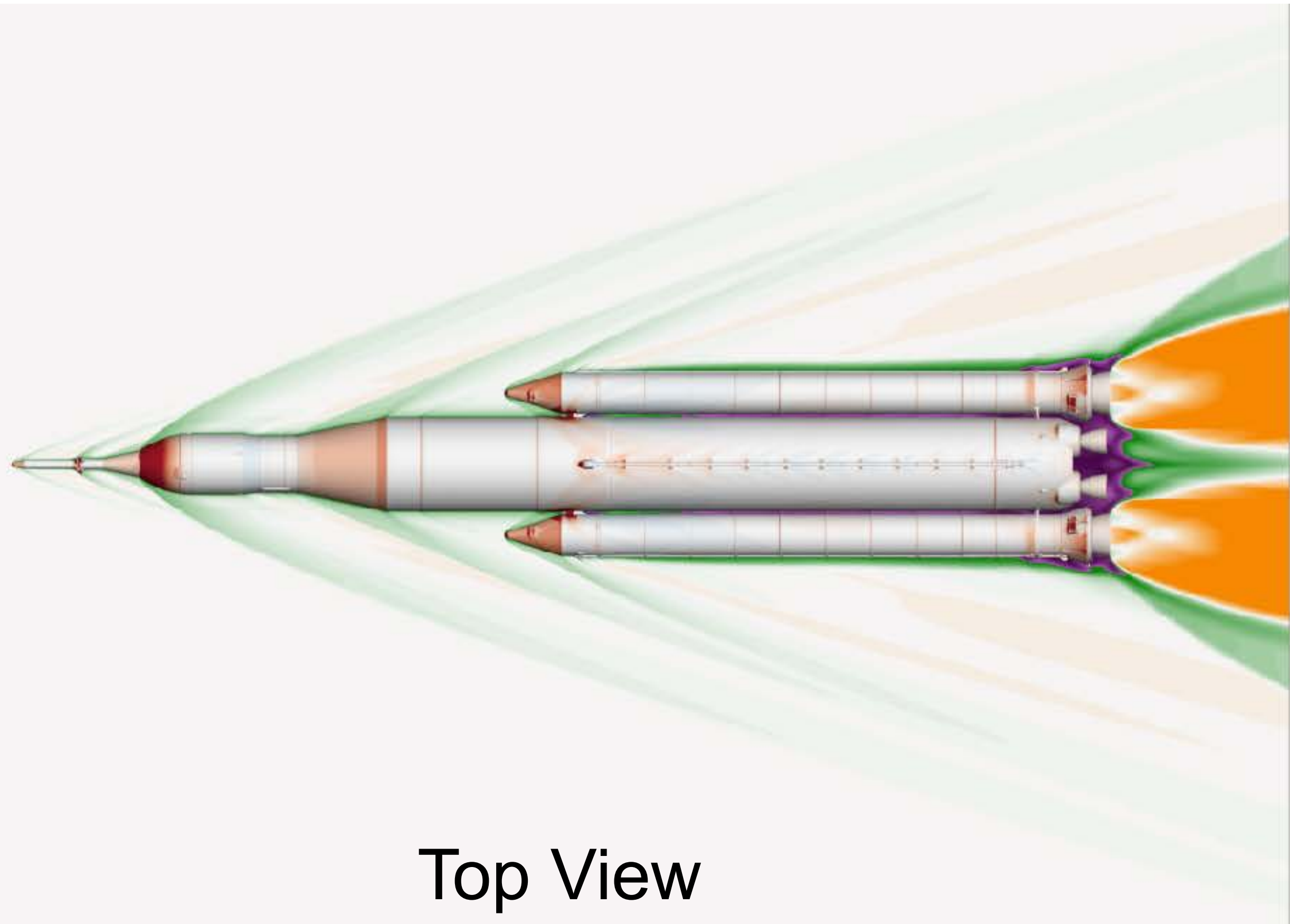
Side View

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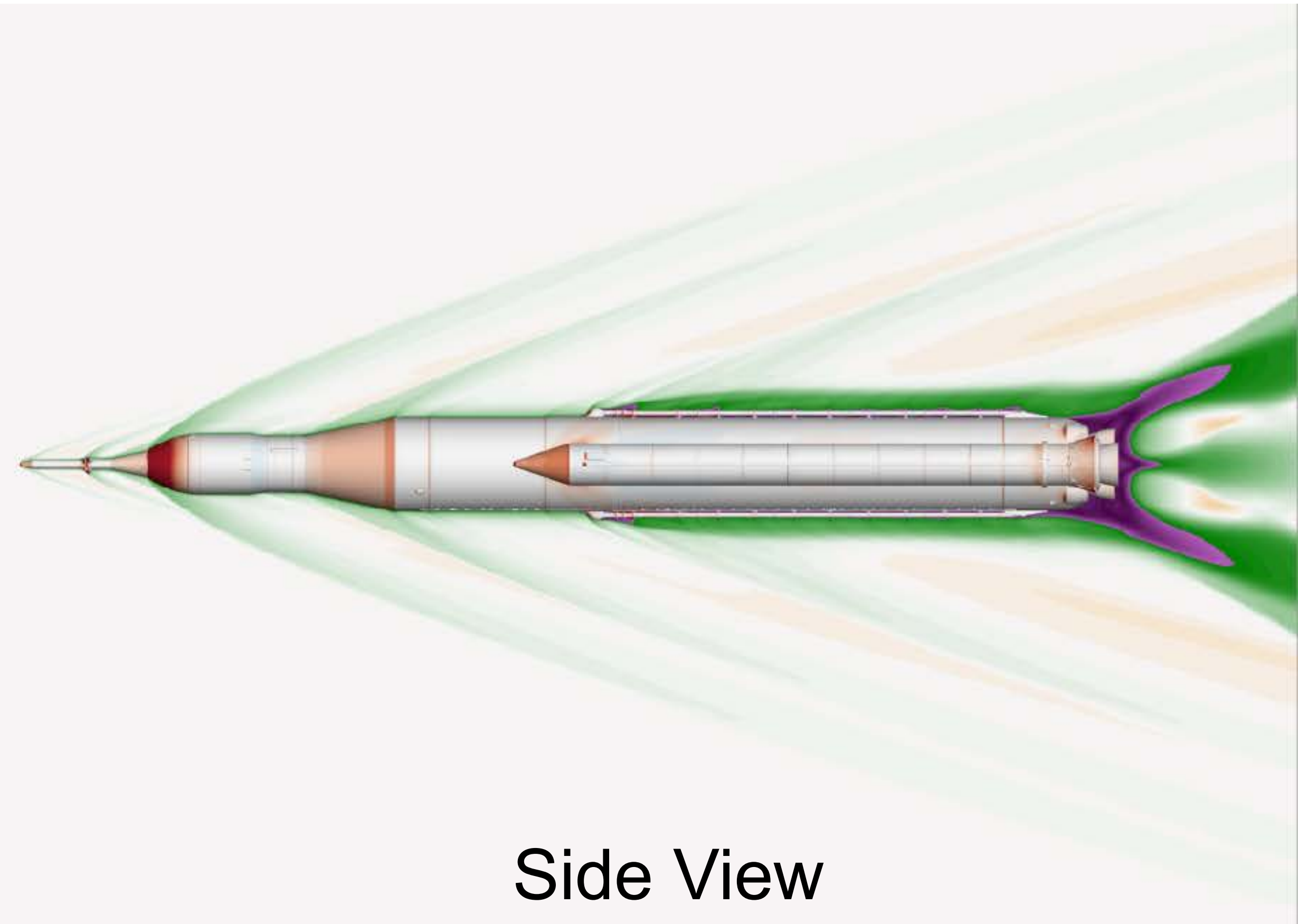
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



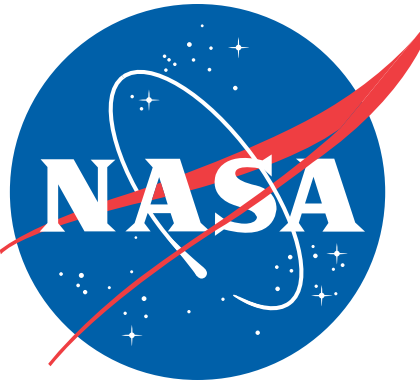
Top View



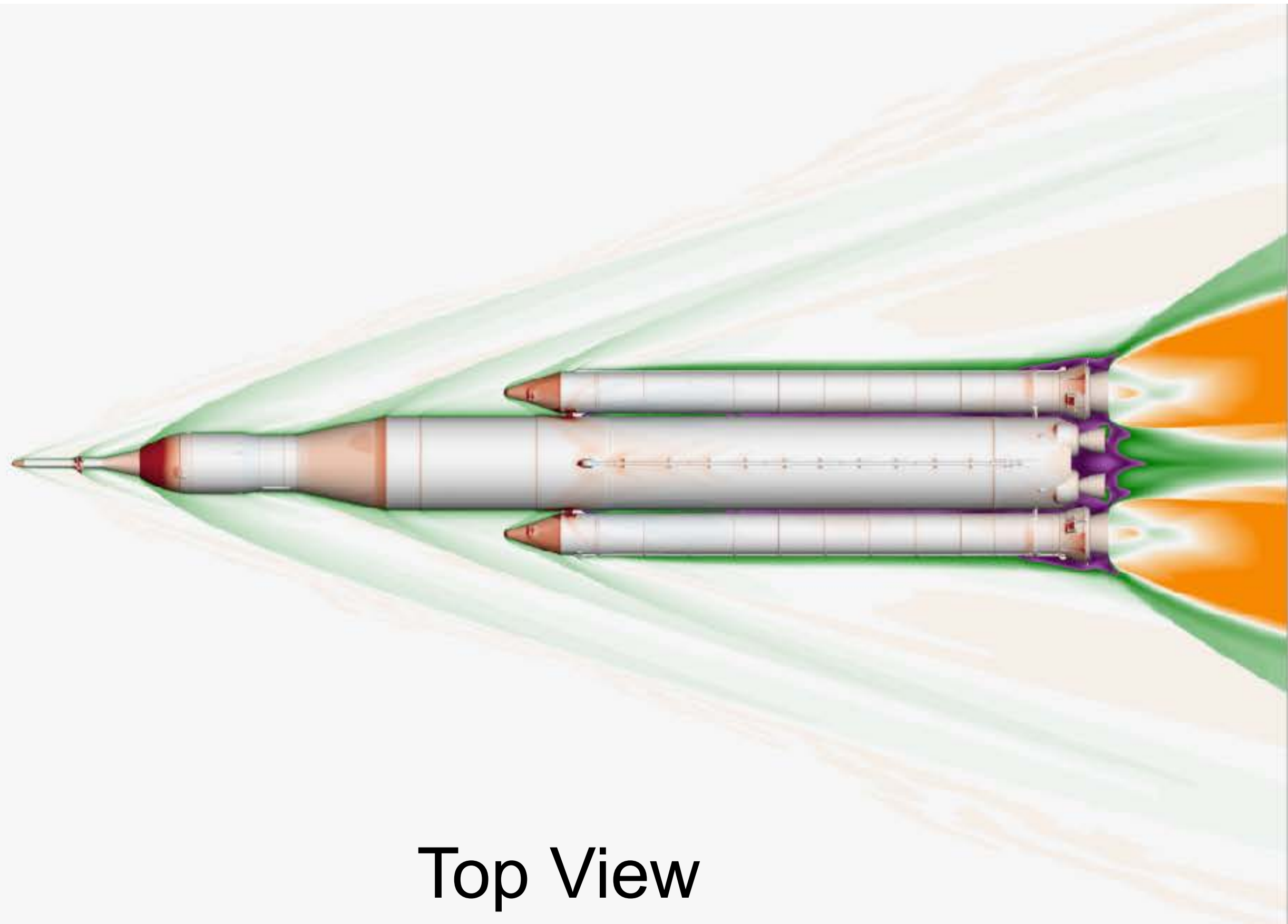
Side View

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Vehicle surface blue-white-red color contours represent low to high pressures

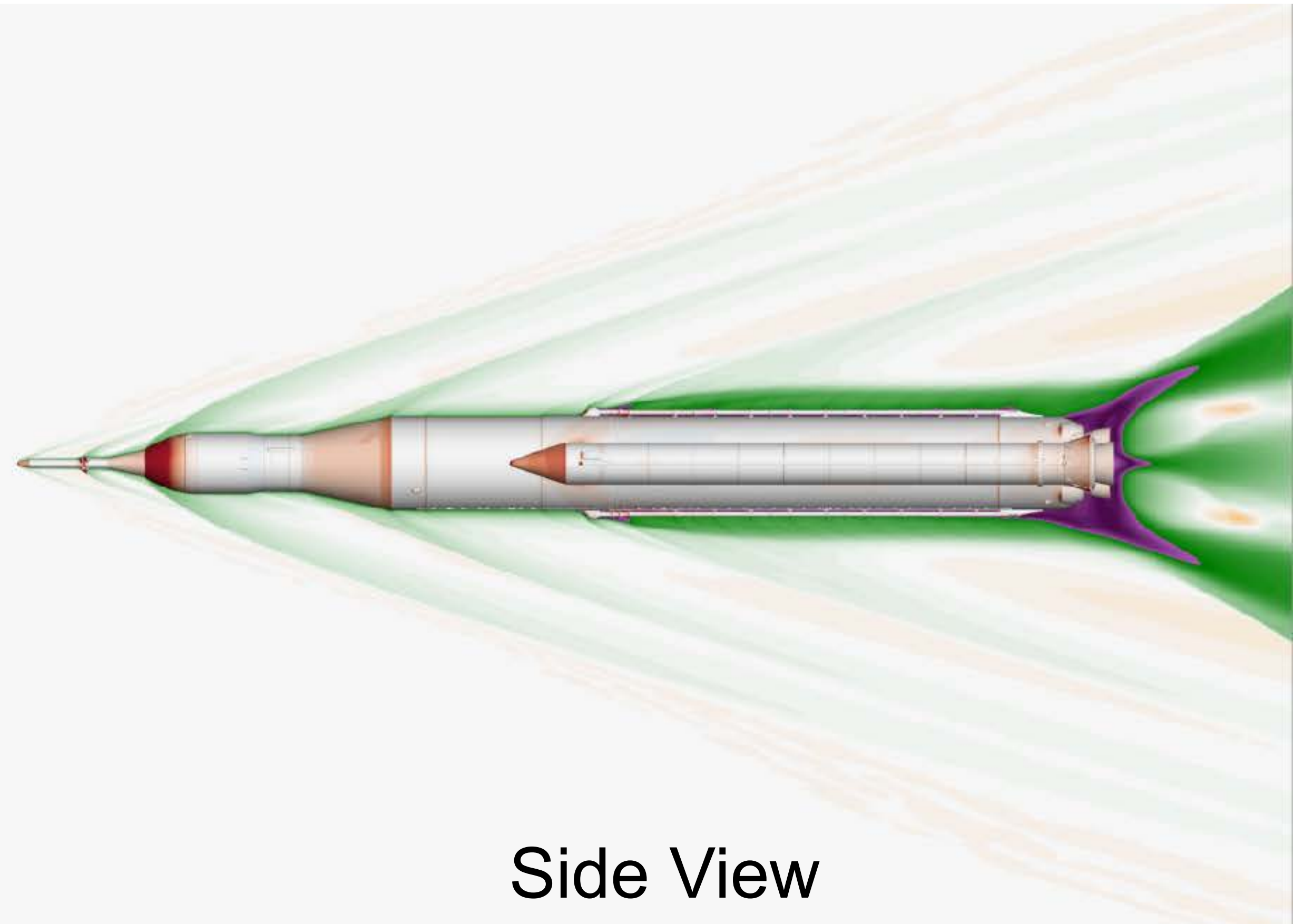
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



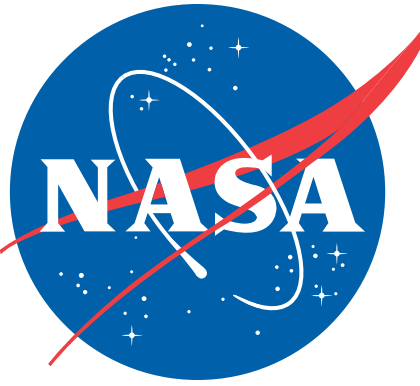
Top View



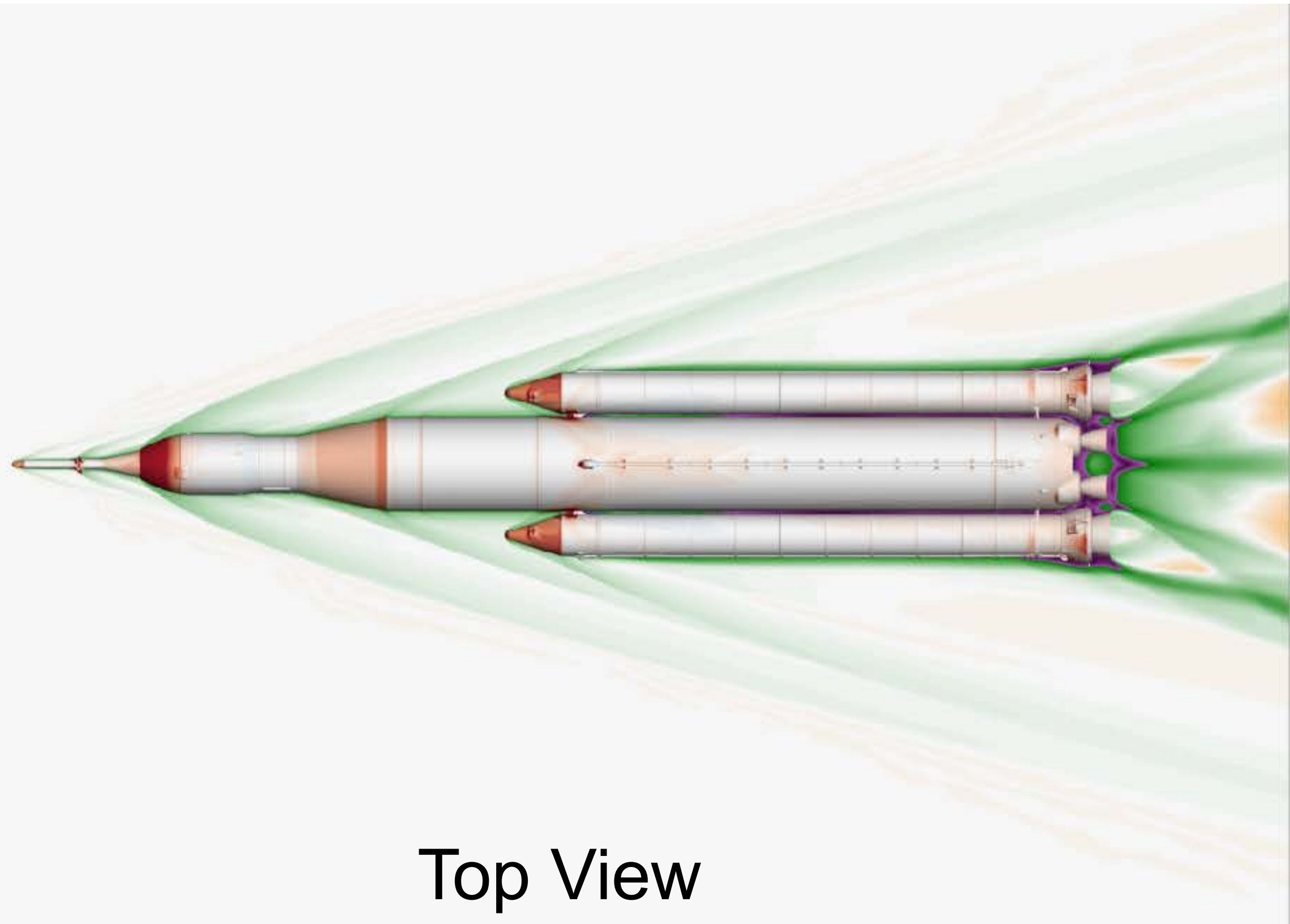
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

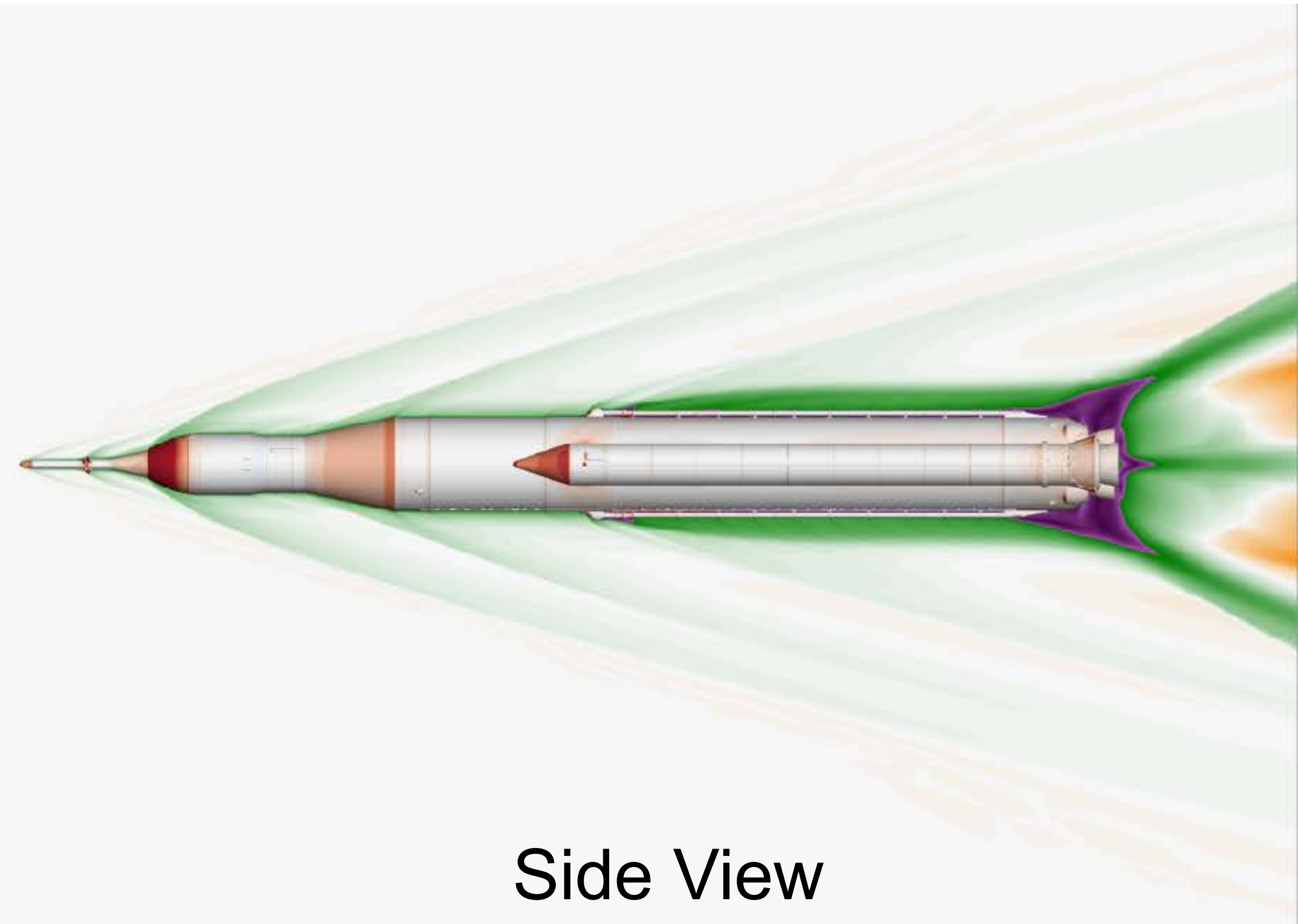
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



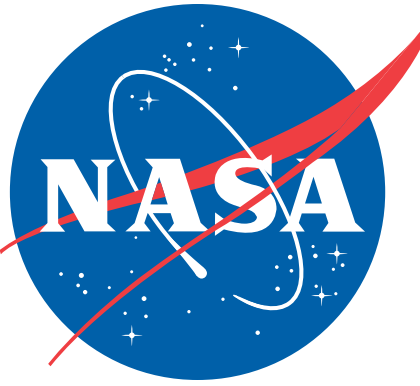
Top View



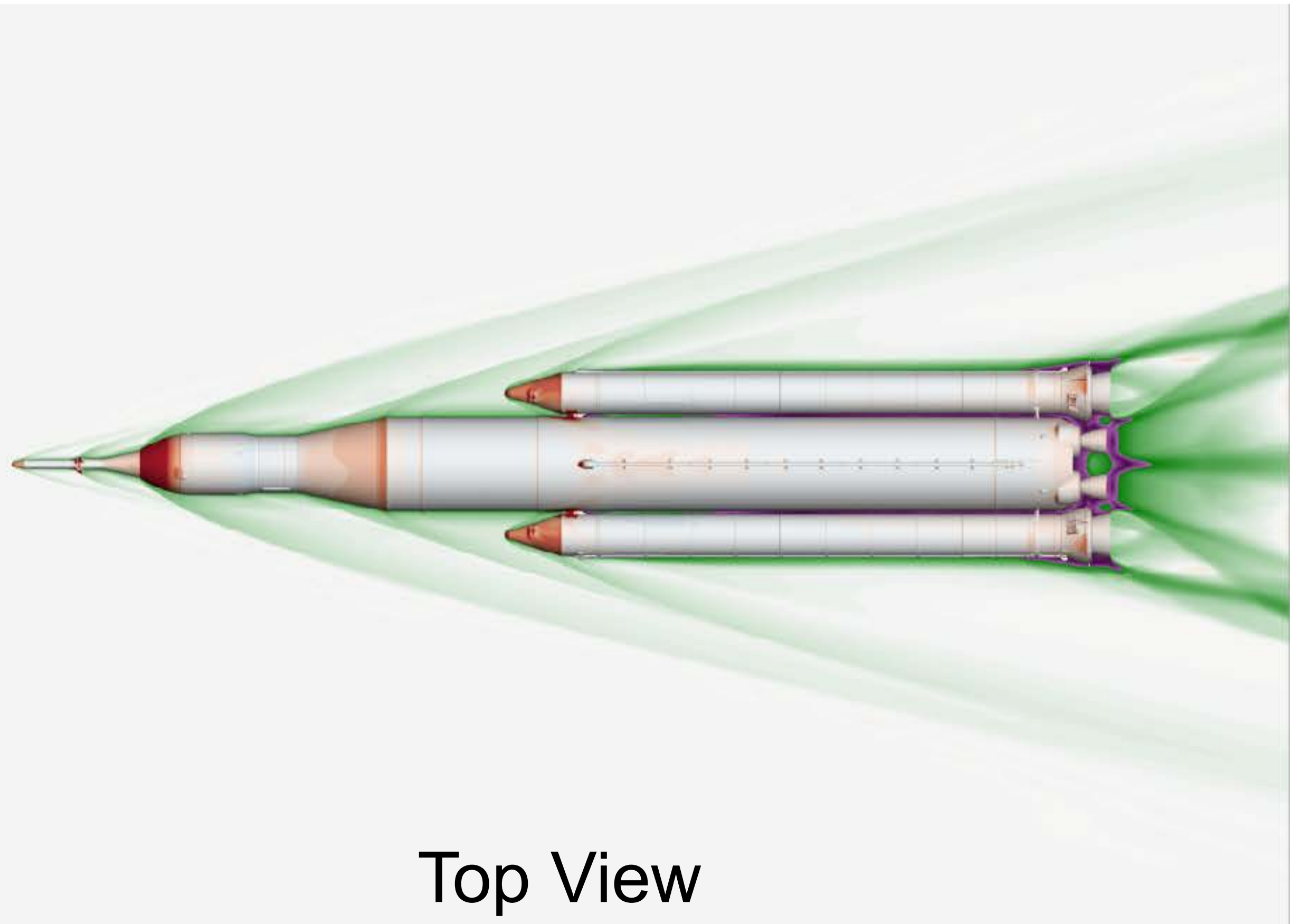
Side View

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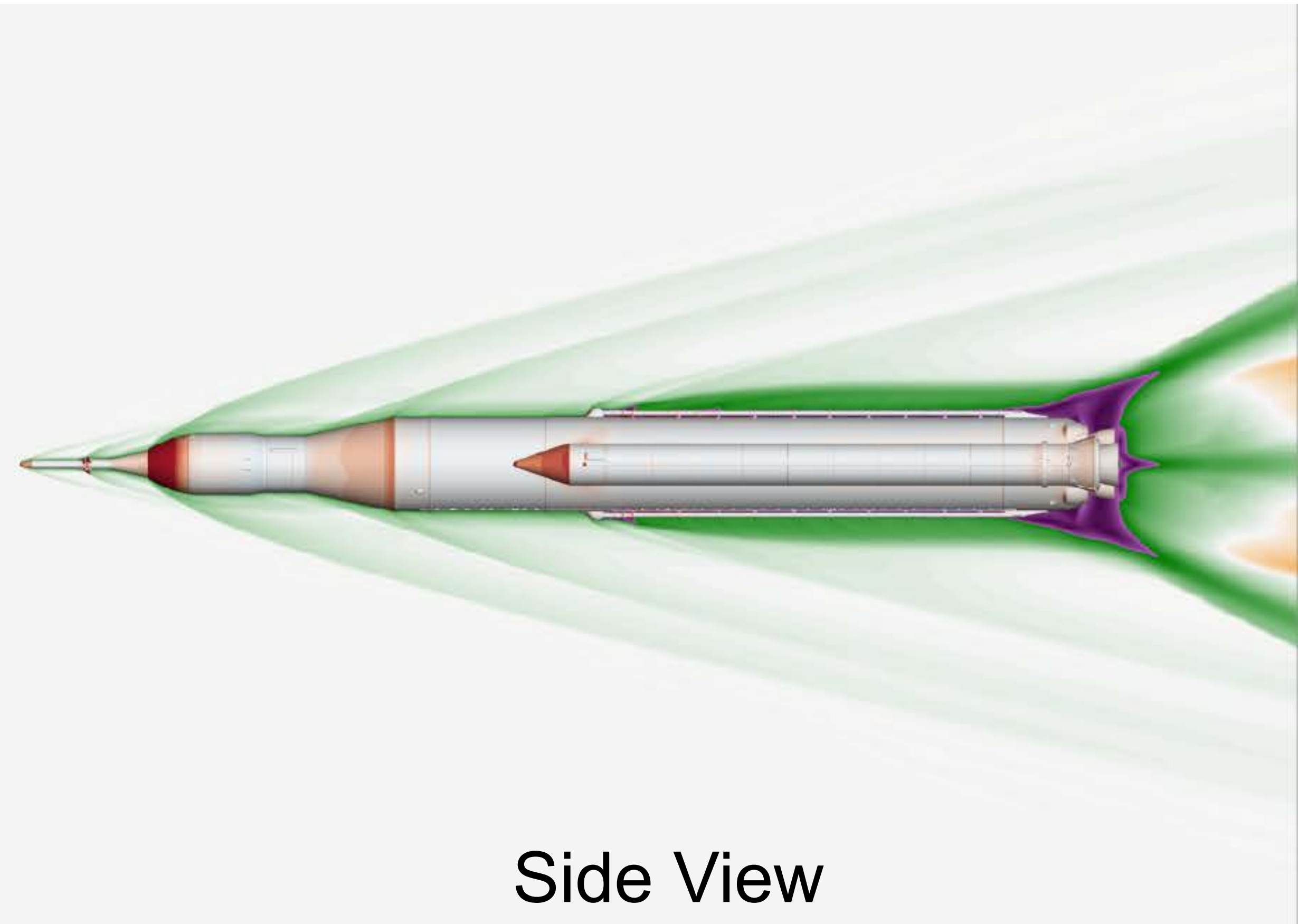
SLS Block 1 Crew Ascent



Altitude: Low • • • • • • • • • • High



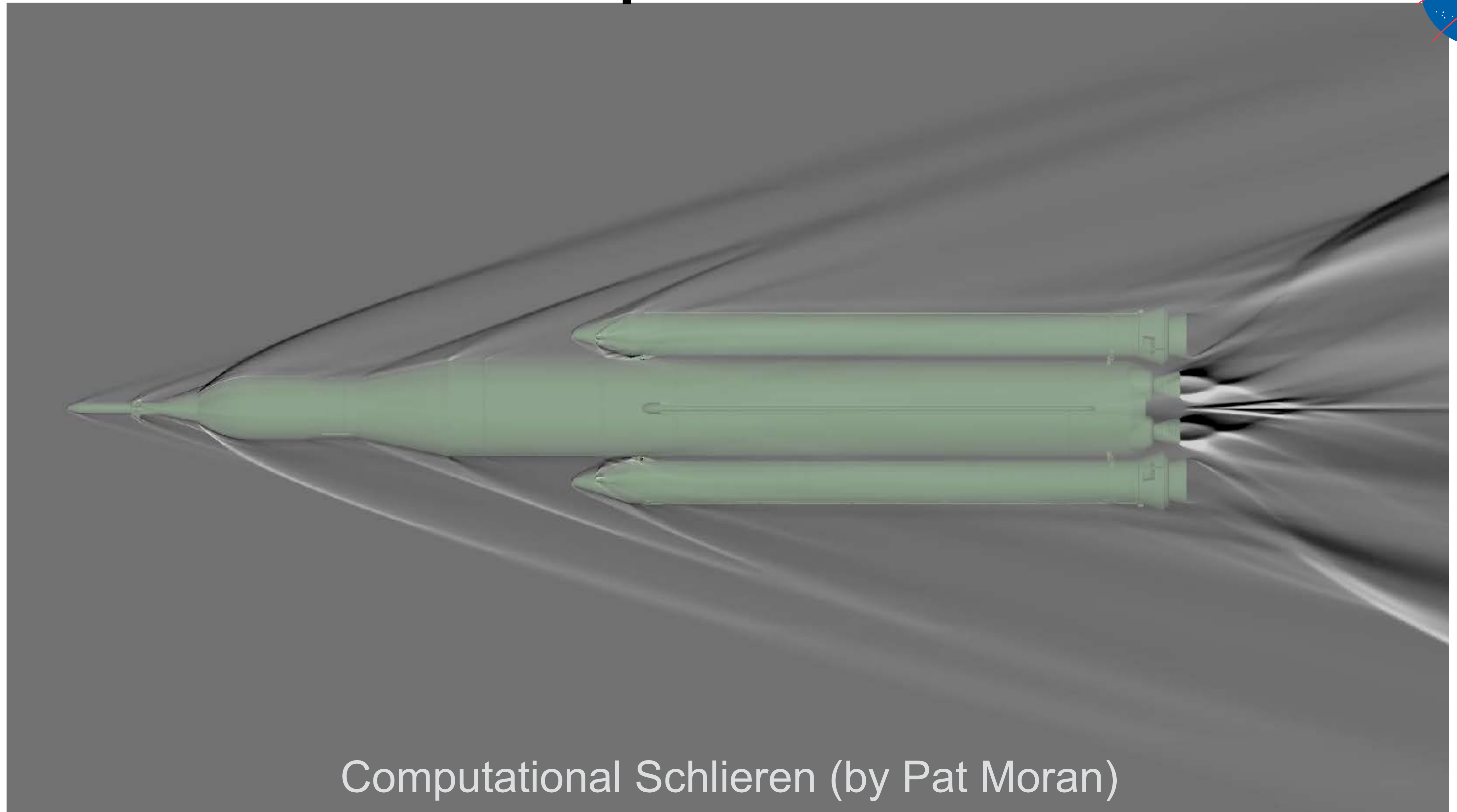
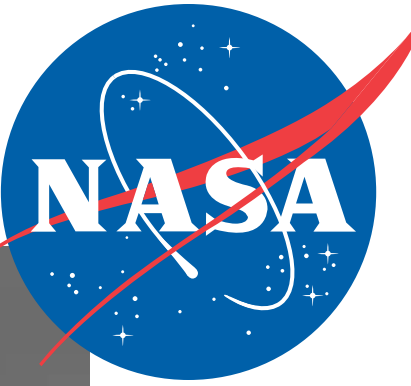
Top View



Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

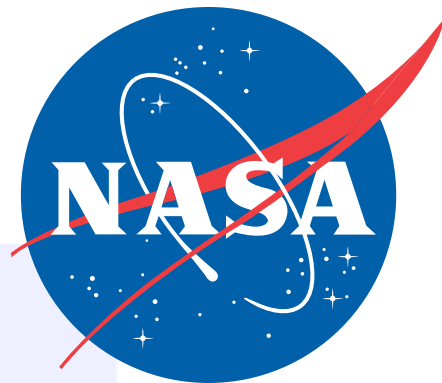
SLS Block 1 Booster Separation



Computational Schlieren (by Pat Moran)

SLS Block 1 Booster Separation

Particles Colored by BSM Nozzle
(Pat Moran, Tim Sandstrom)

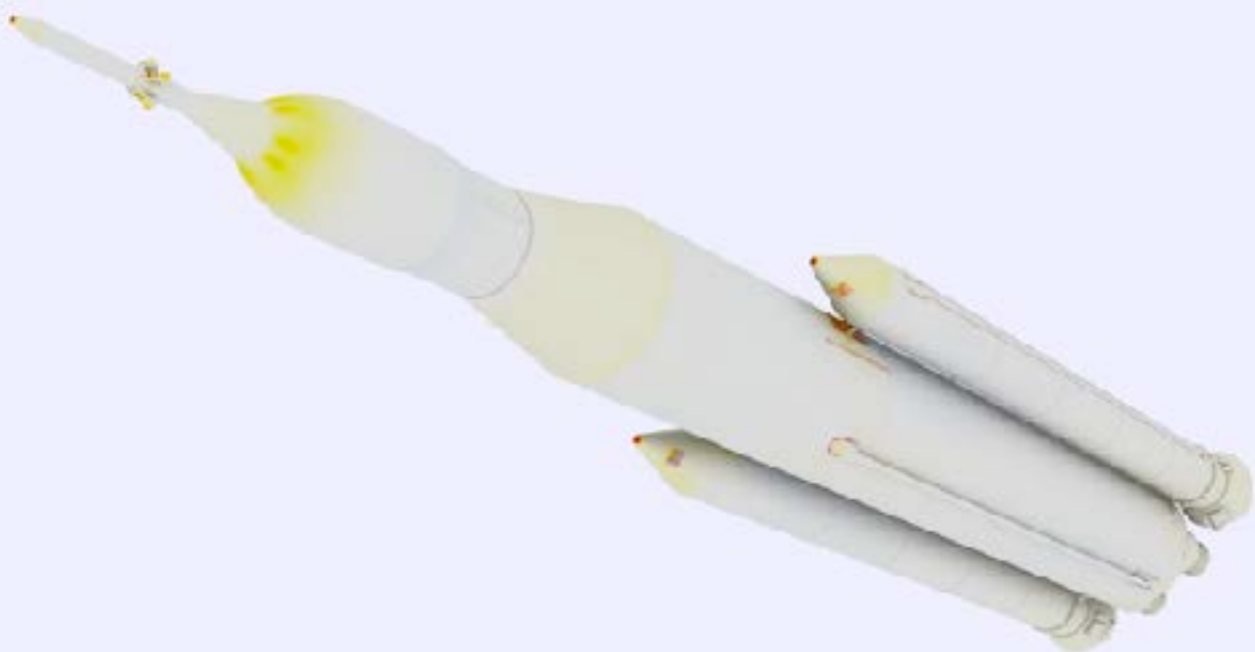


Top View



0' 0"

Iso View



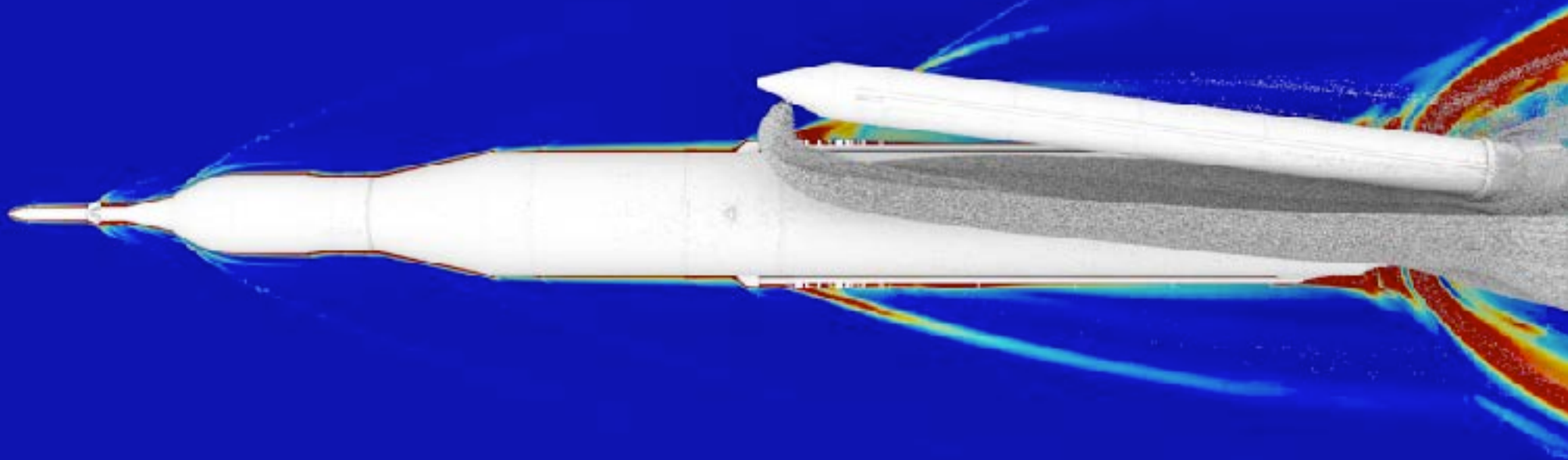
0' 0"

Side View



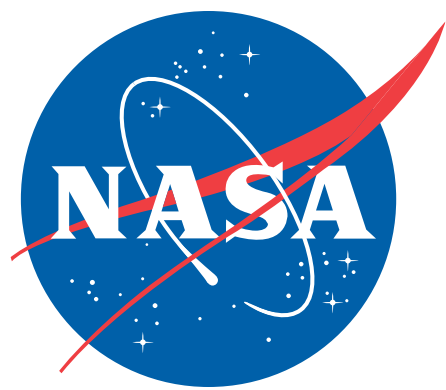
0' 0"

Side Slice (vorticity)

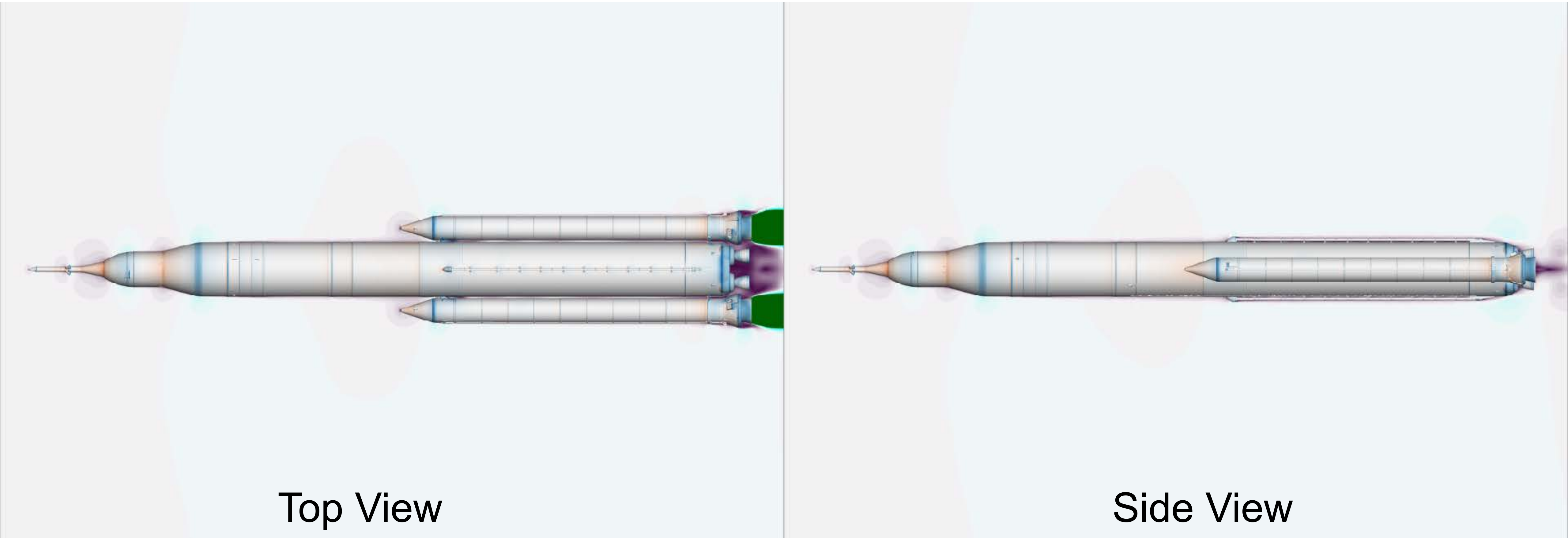


23' 11"

SLS Block 1B Crew Ascent



Altitude: Low • • • • • • • • • • • • • • • • High

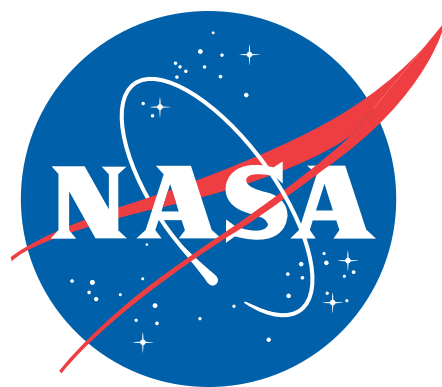


Top View

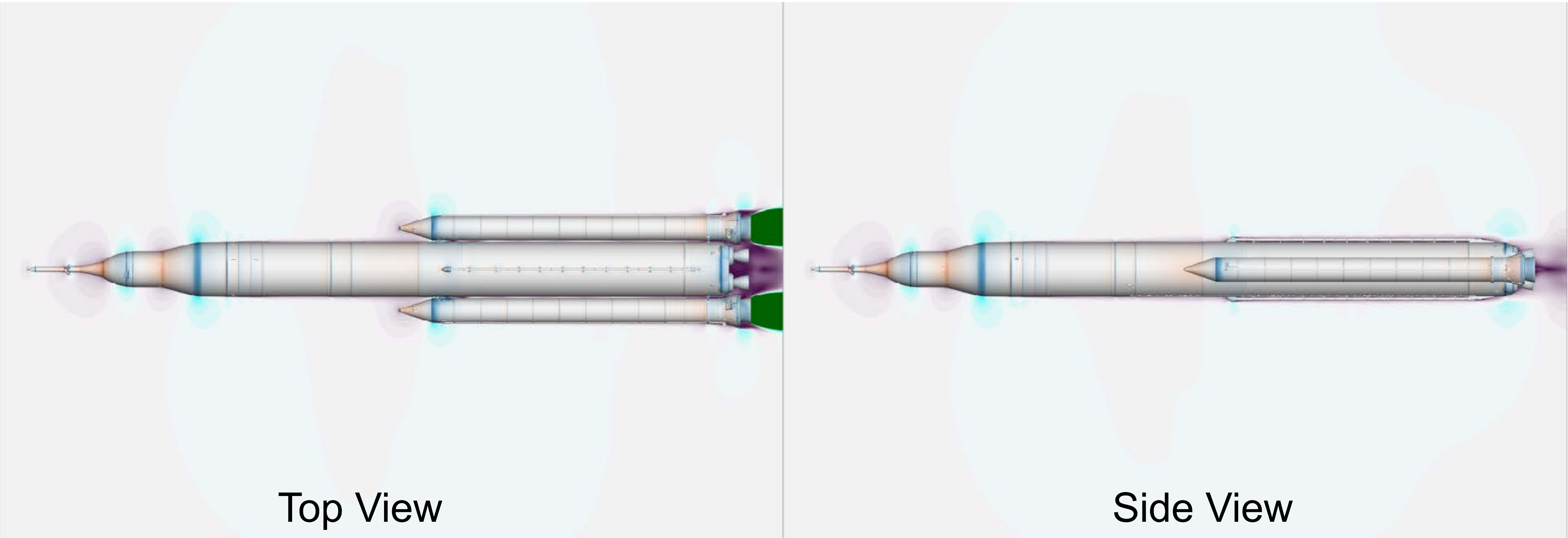
Side View

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Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

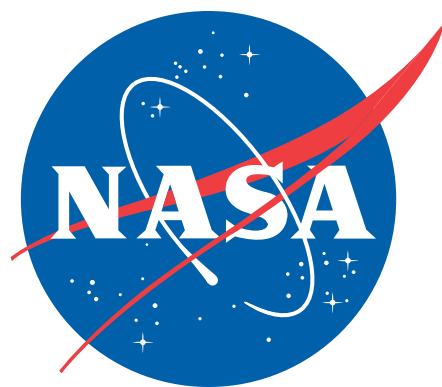


Altitude: Low • • • • • • • • • • • • • • High

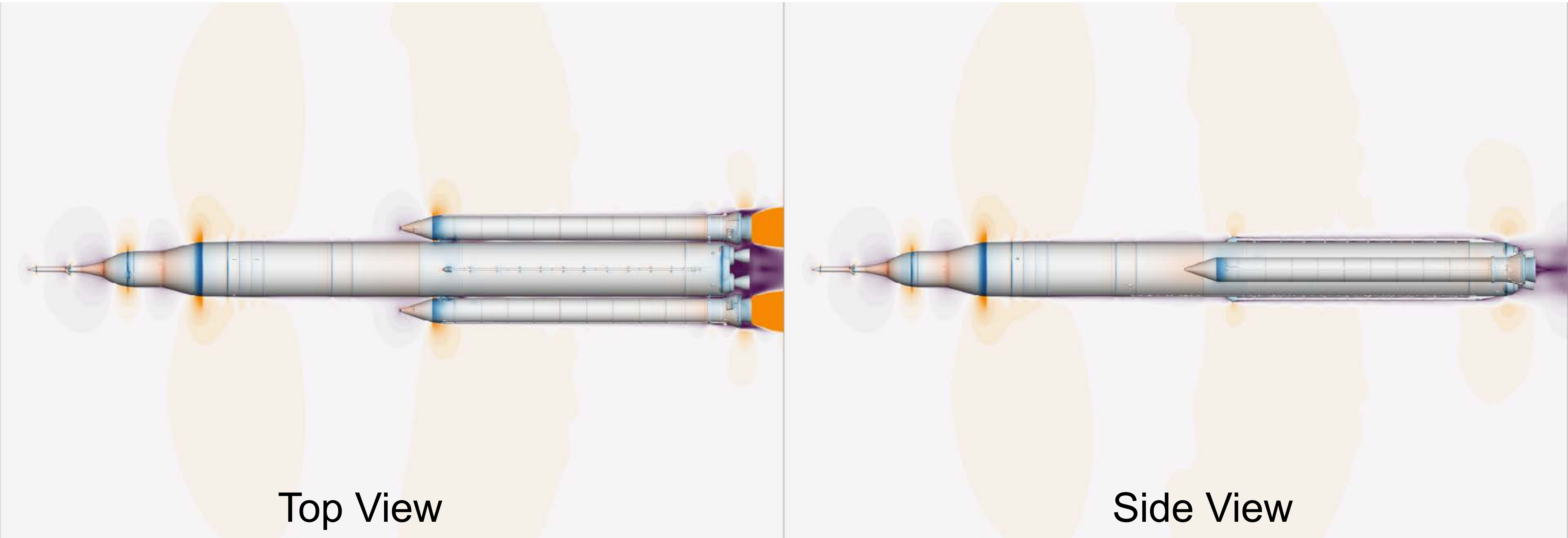


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

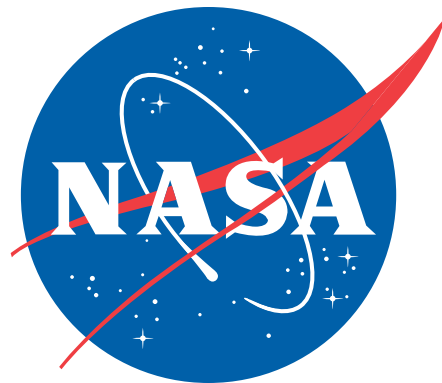


Altitude: Low • • • • • • • • • • • • • • • • High

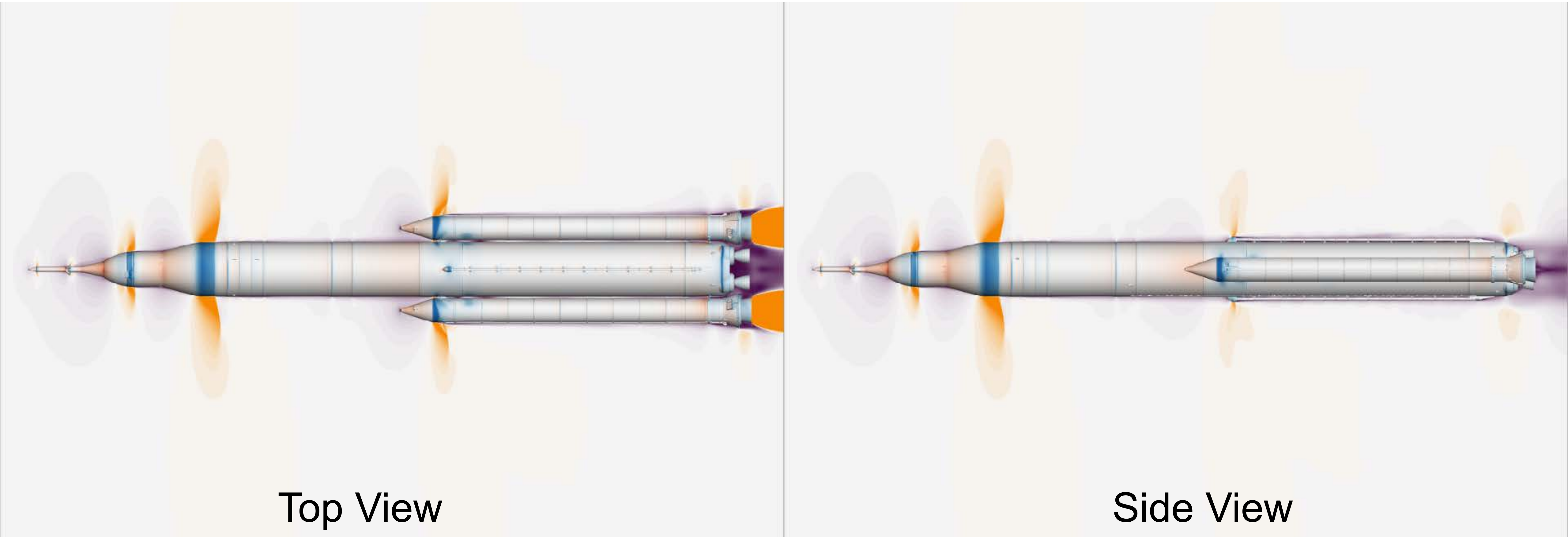


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

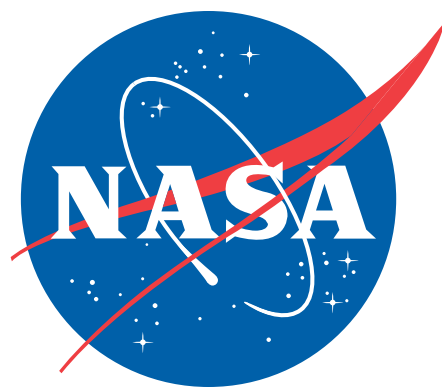


Altitude: Low • • • • • • • • • • • • • • High

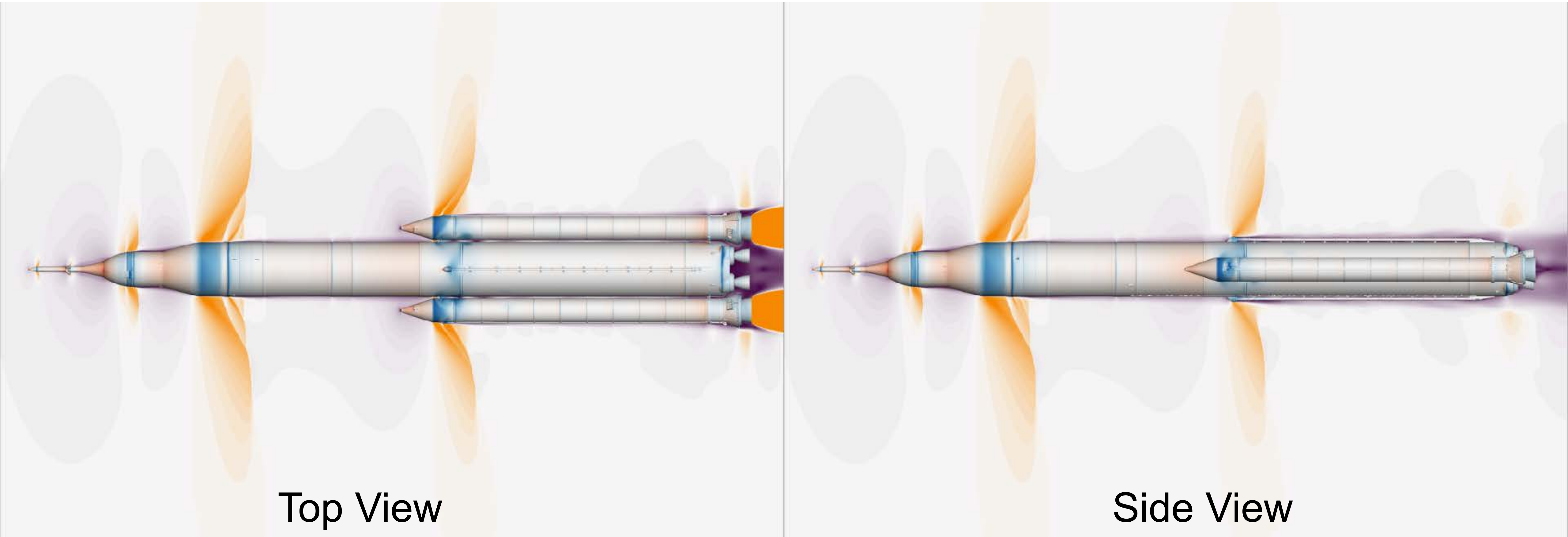


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

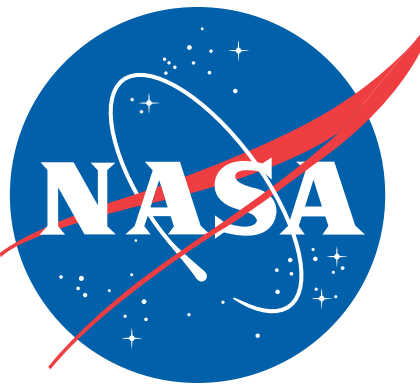


Altitude: Low • • • • • • • • • • • • • • • • High

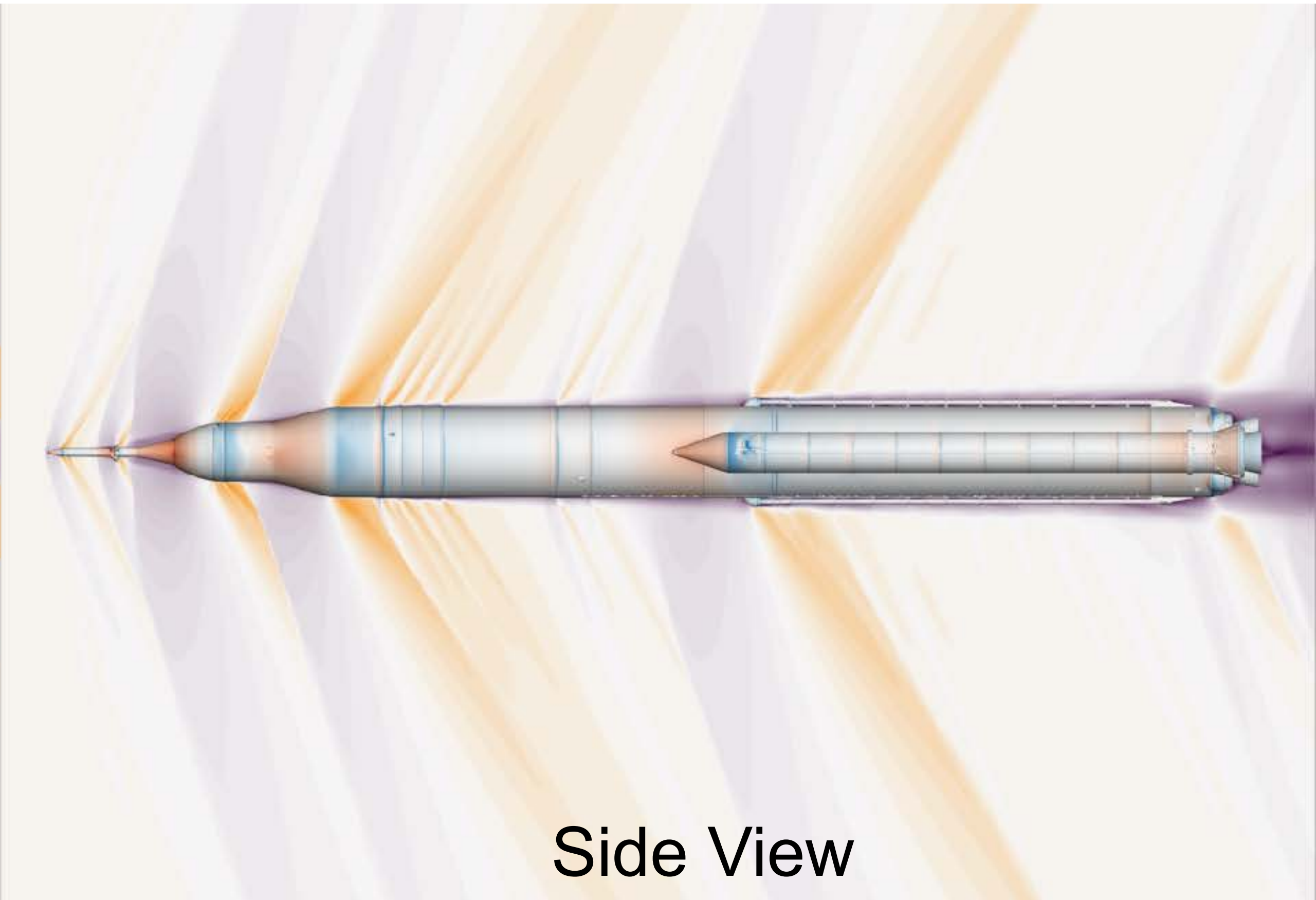
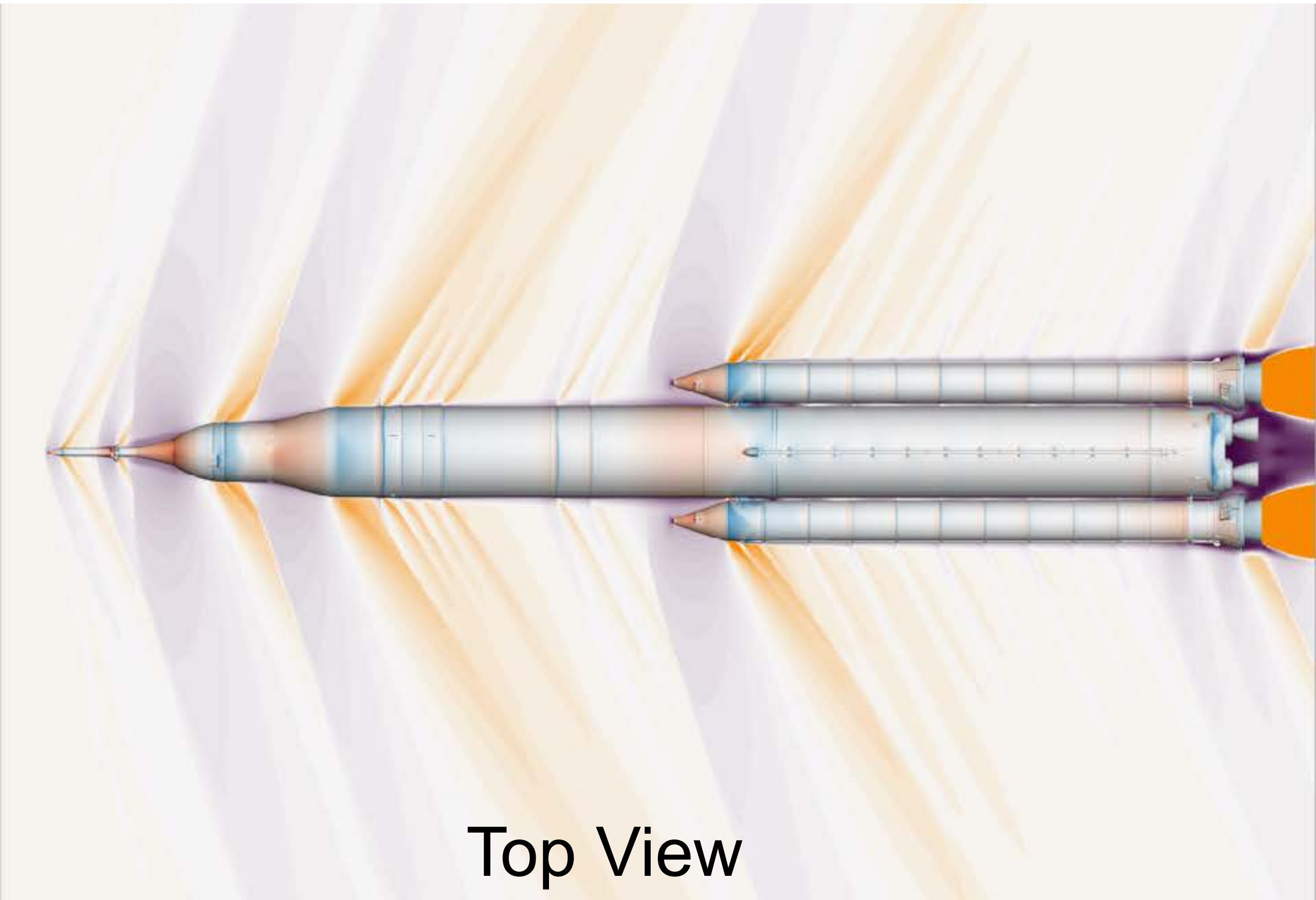


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

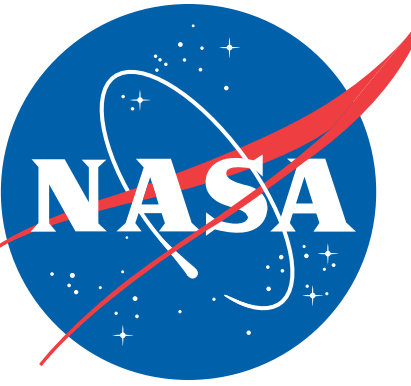


Altitude: Low • • • • • • • • • • • • • • • • High

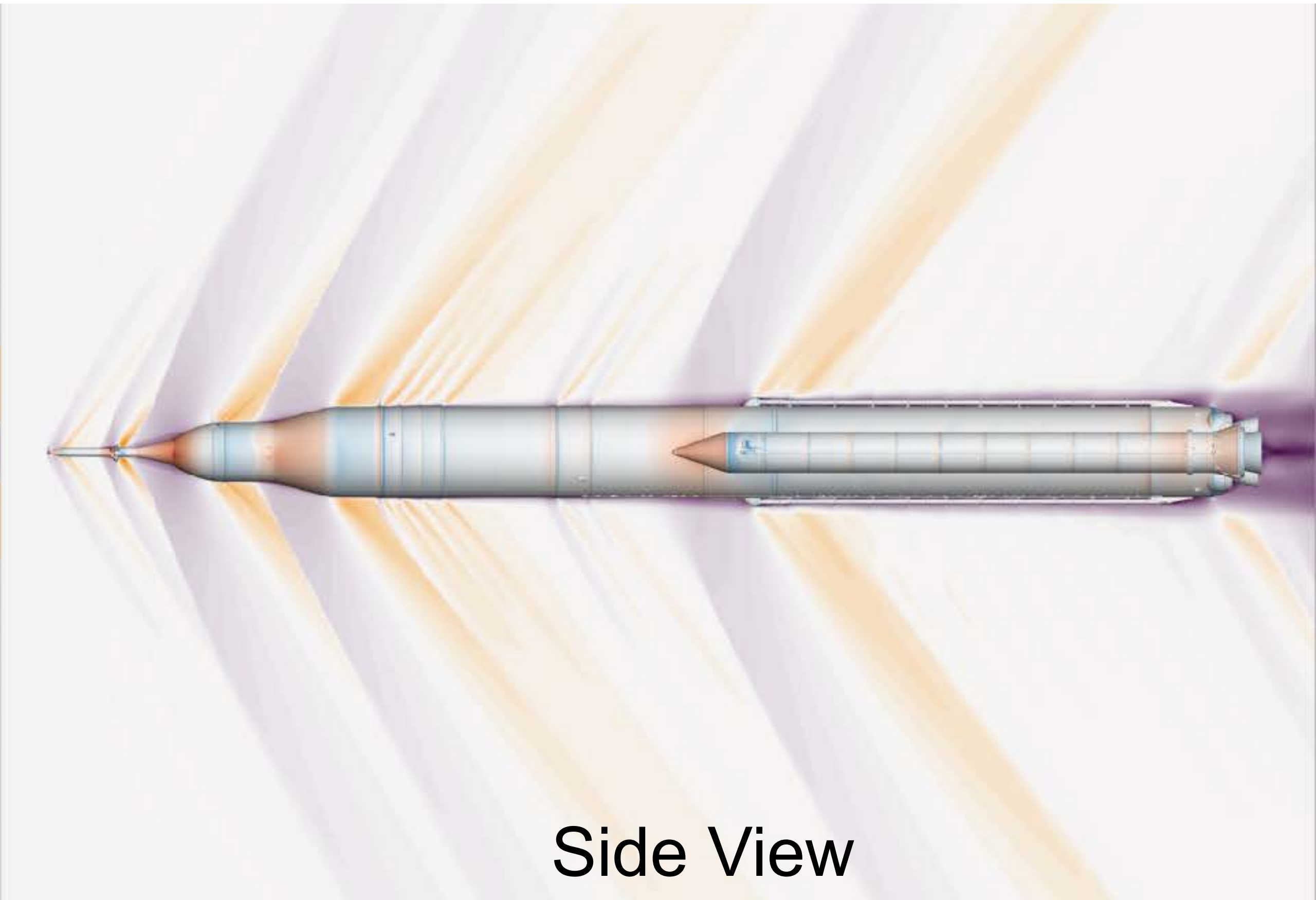
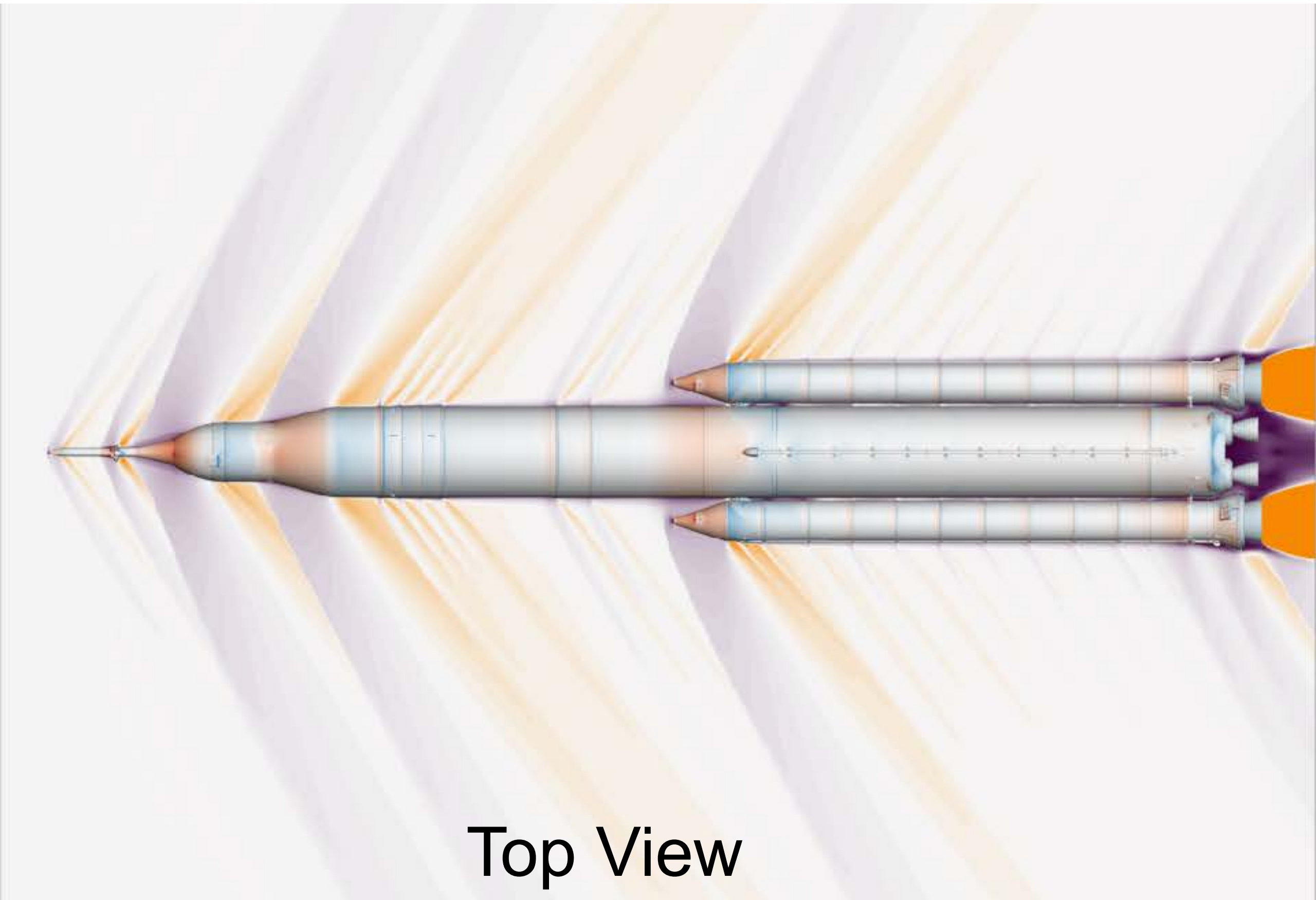


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

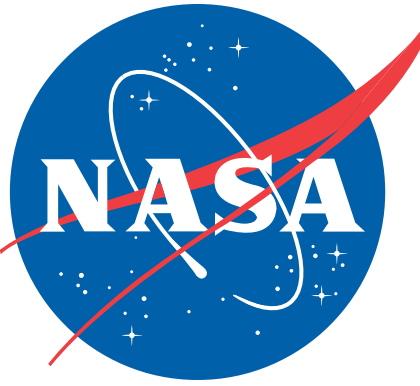


Altitude: Low • • • • • • • • • • • • • • • • High

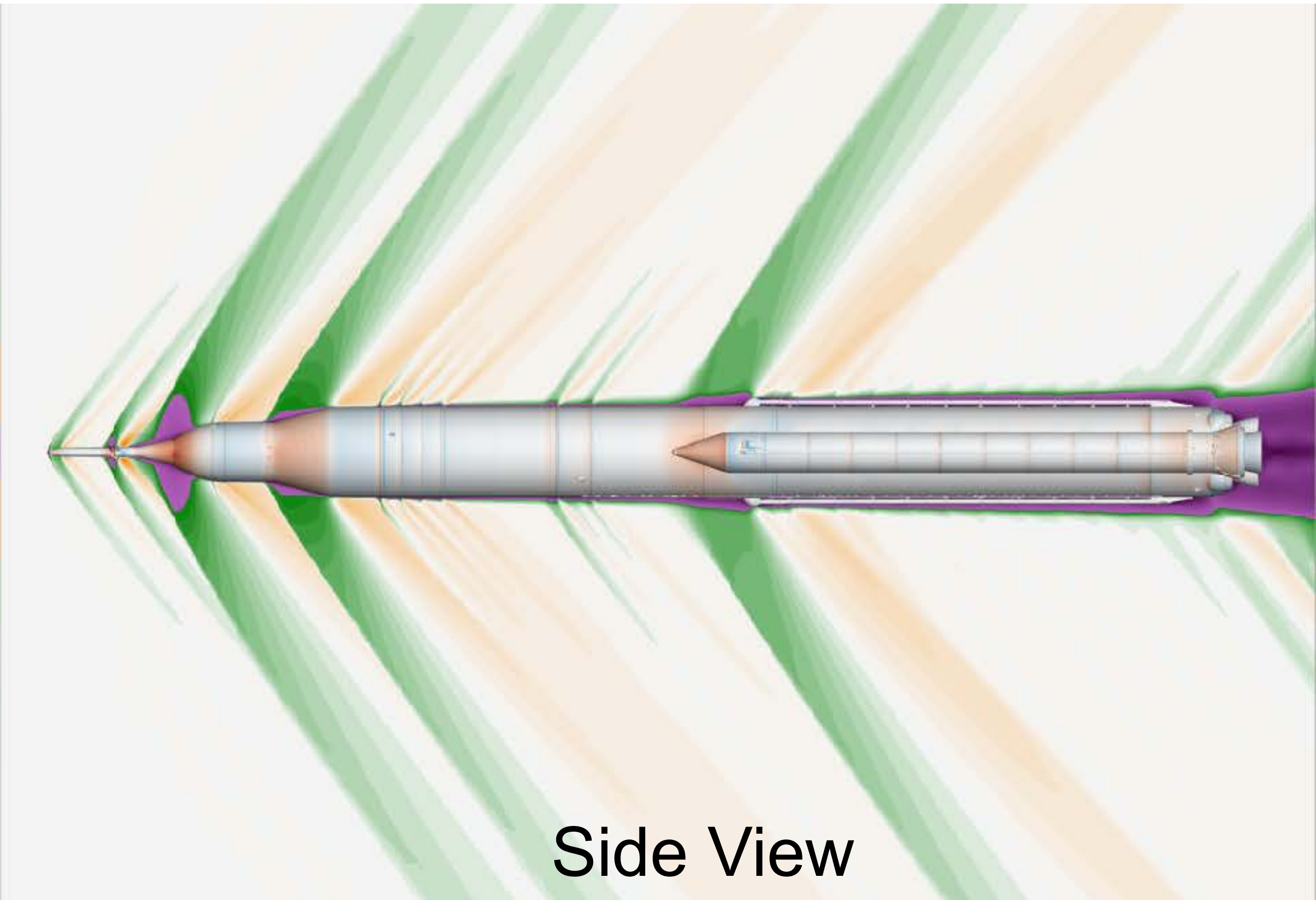
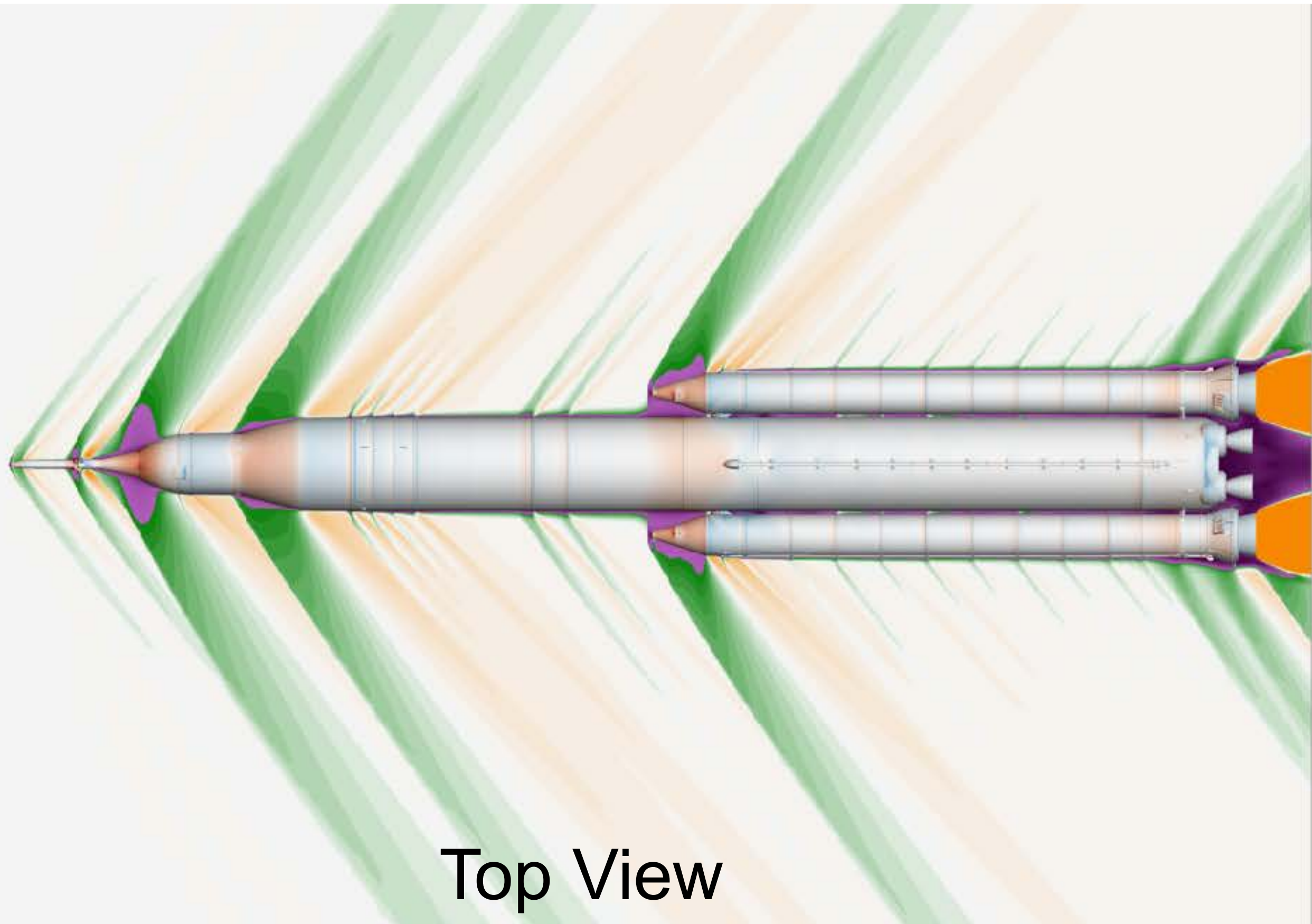


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

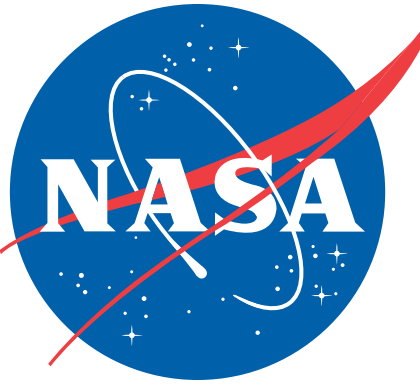


Altitude: Low • • • • • • ● • • • • • • • High

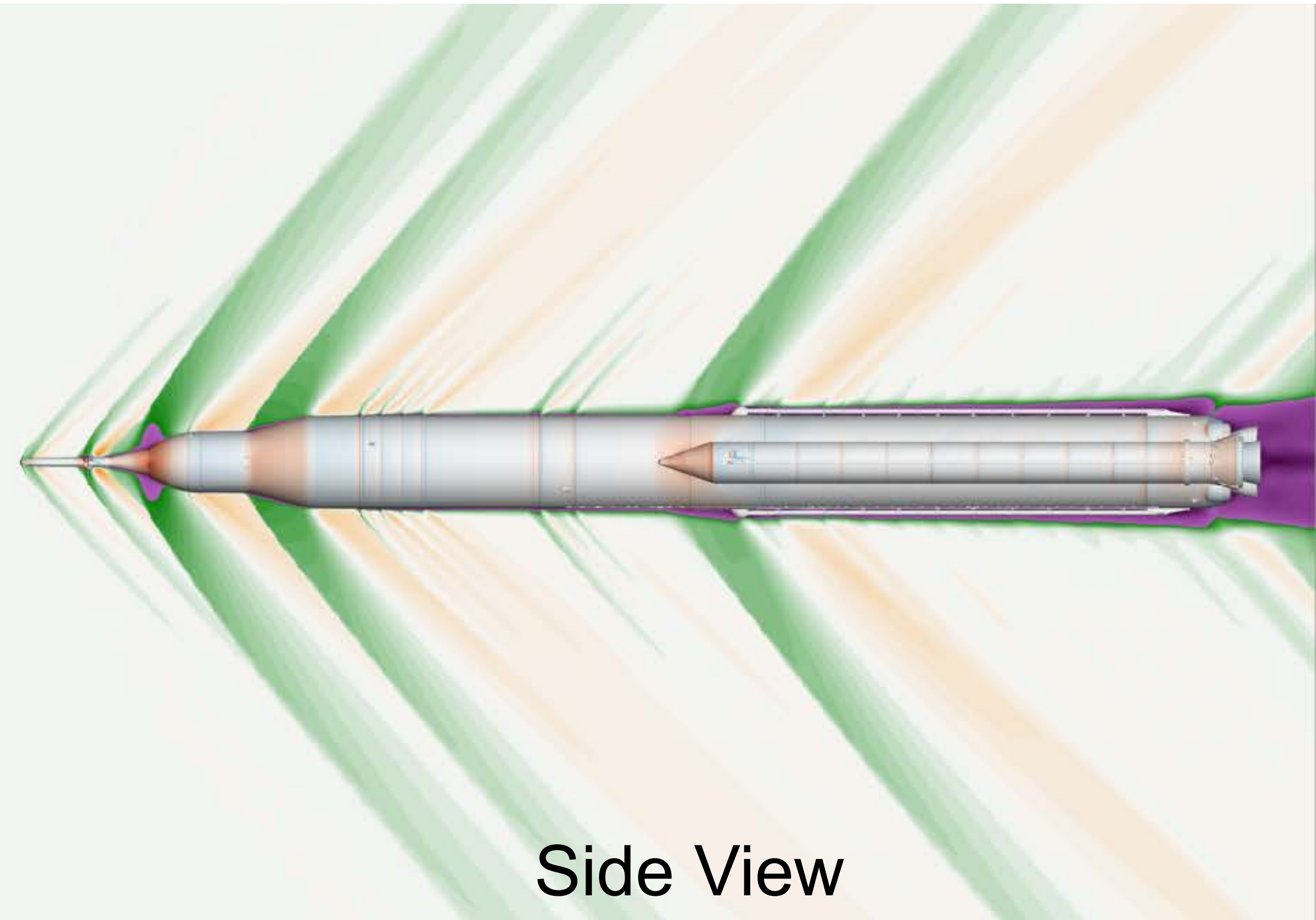
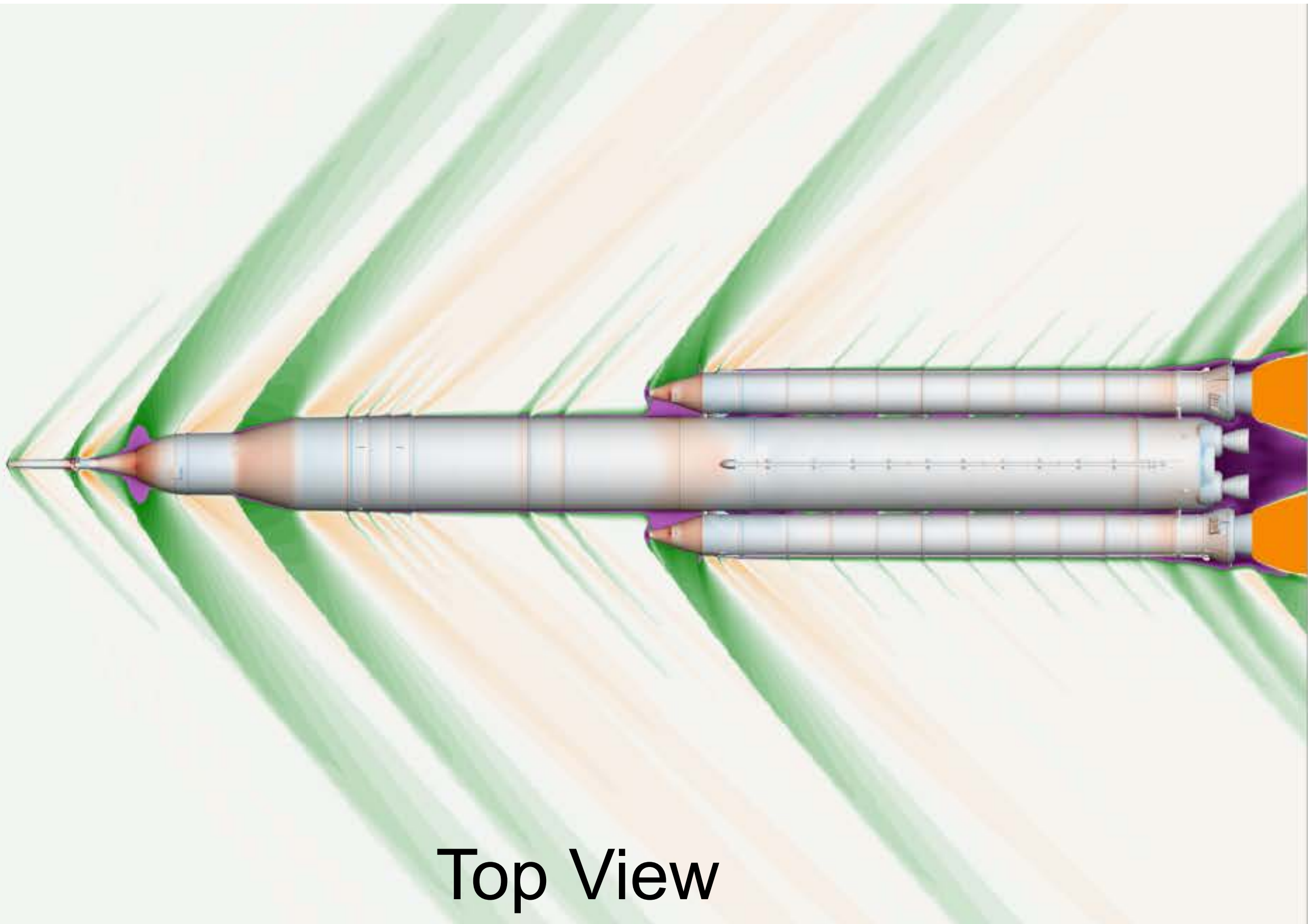


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

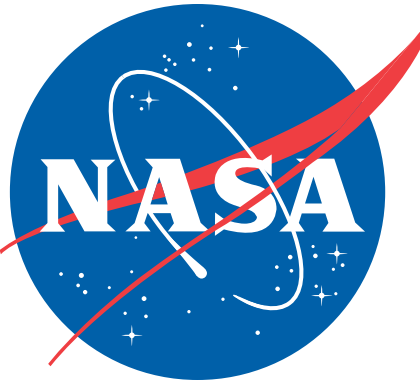
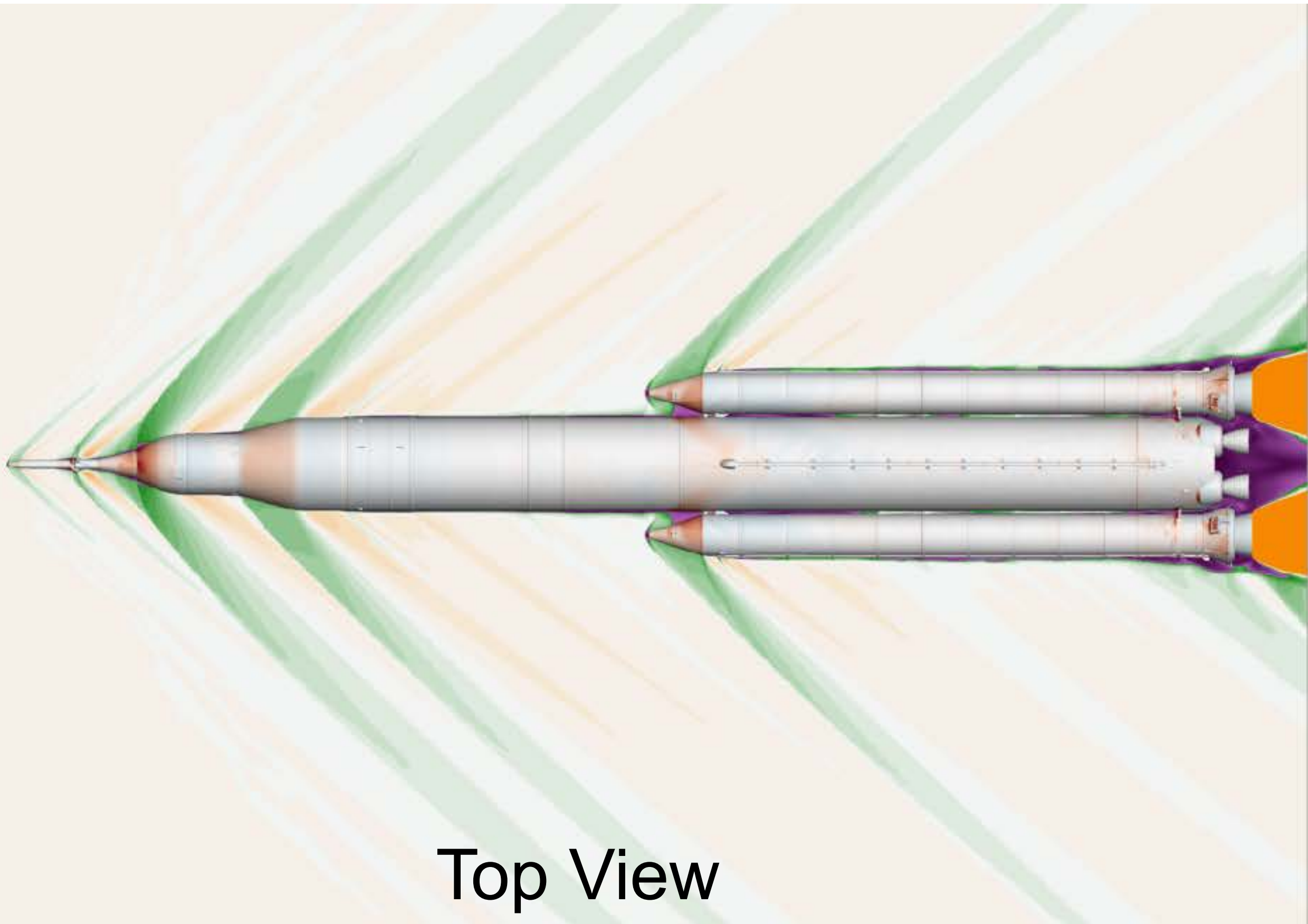


Altitude: Low
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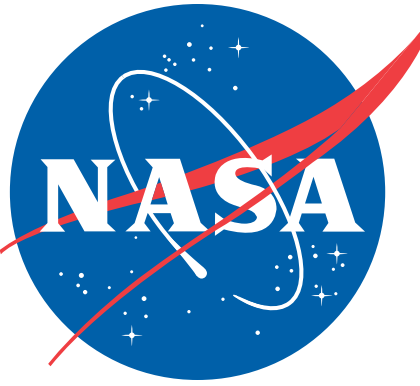
Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

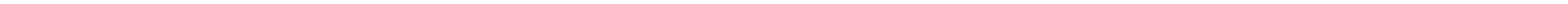
SLS Block 1B Crew Ascent

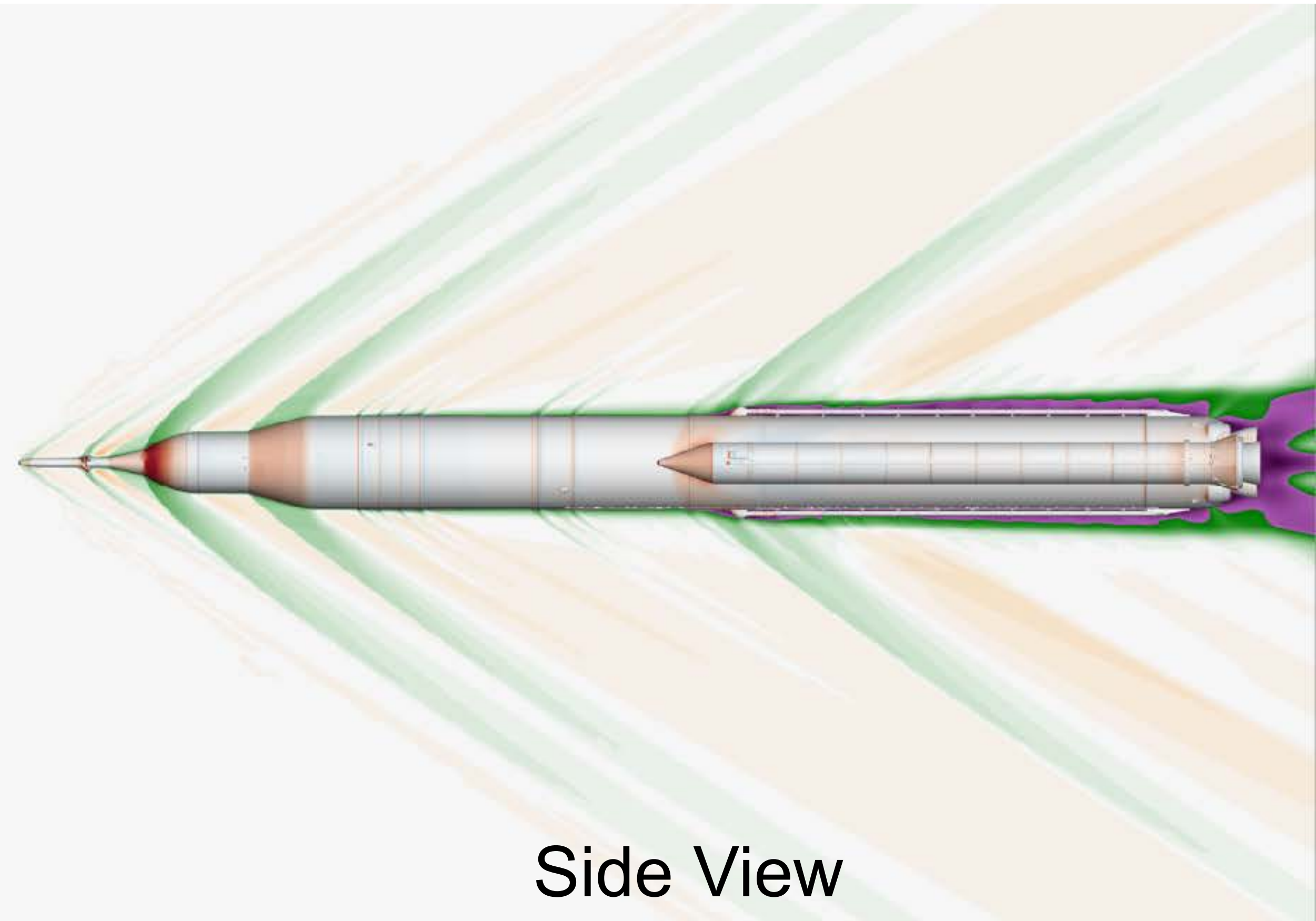
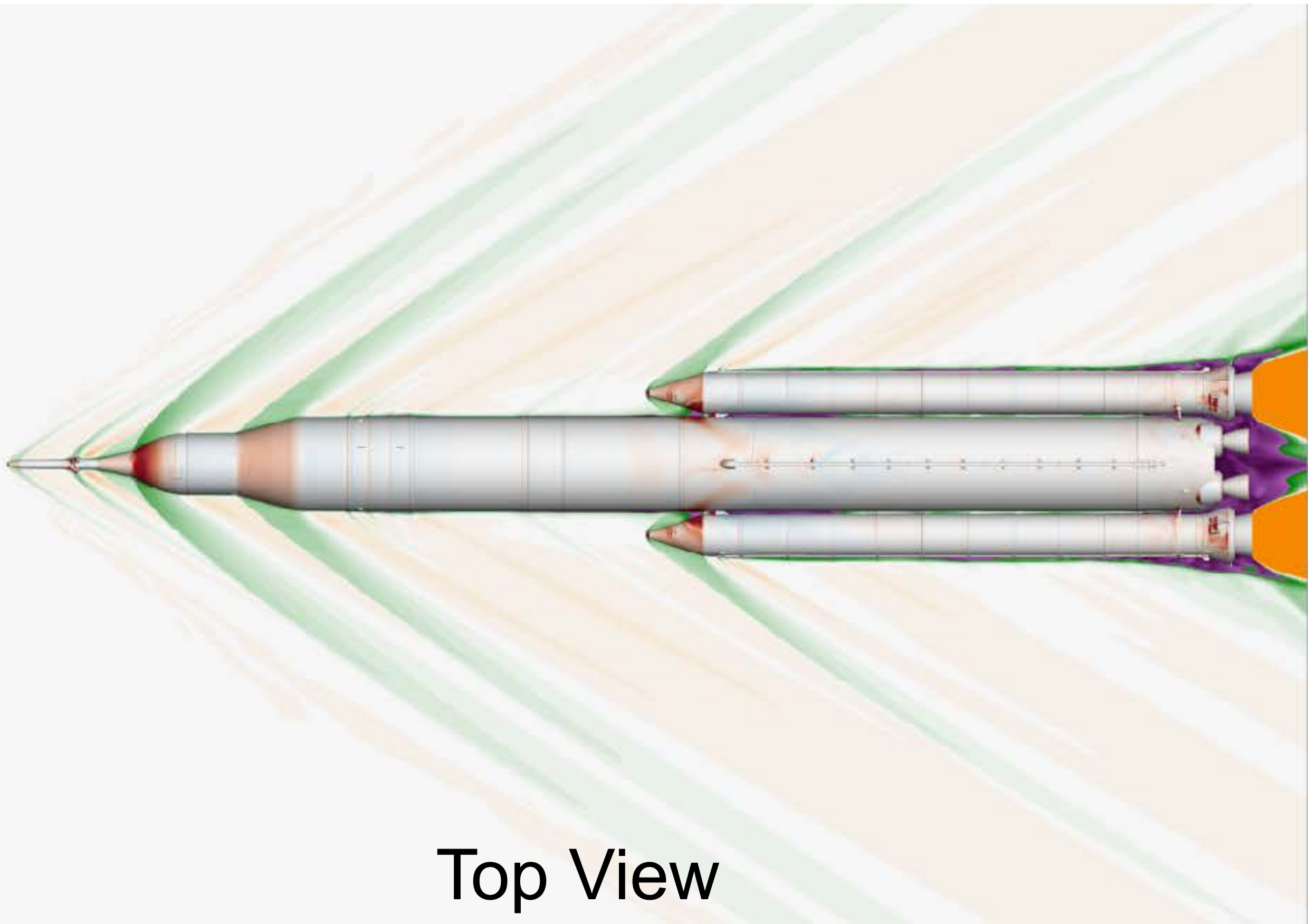
[illegible]

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

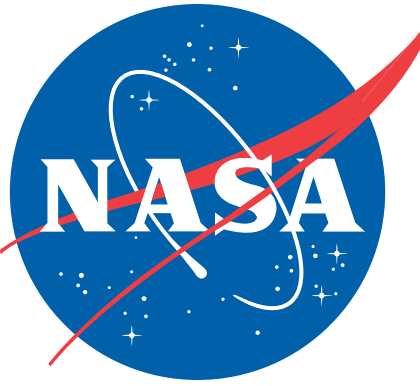


Altitude: Low  High

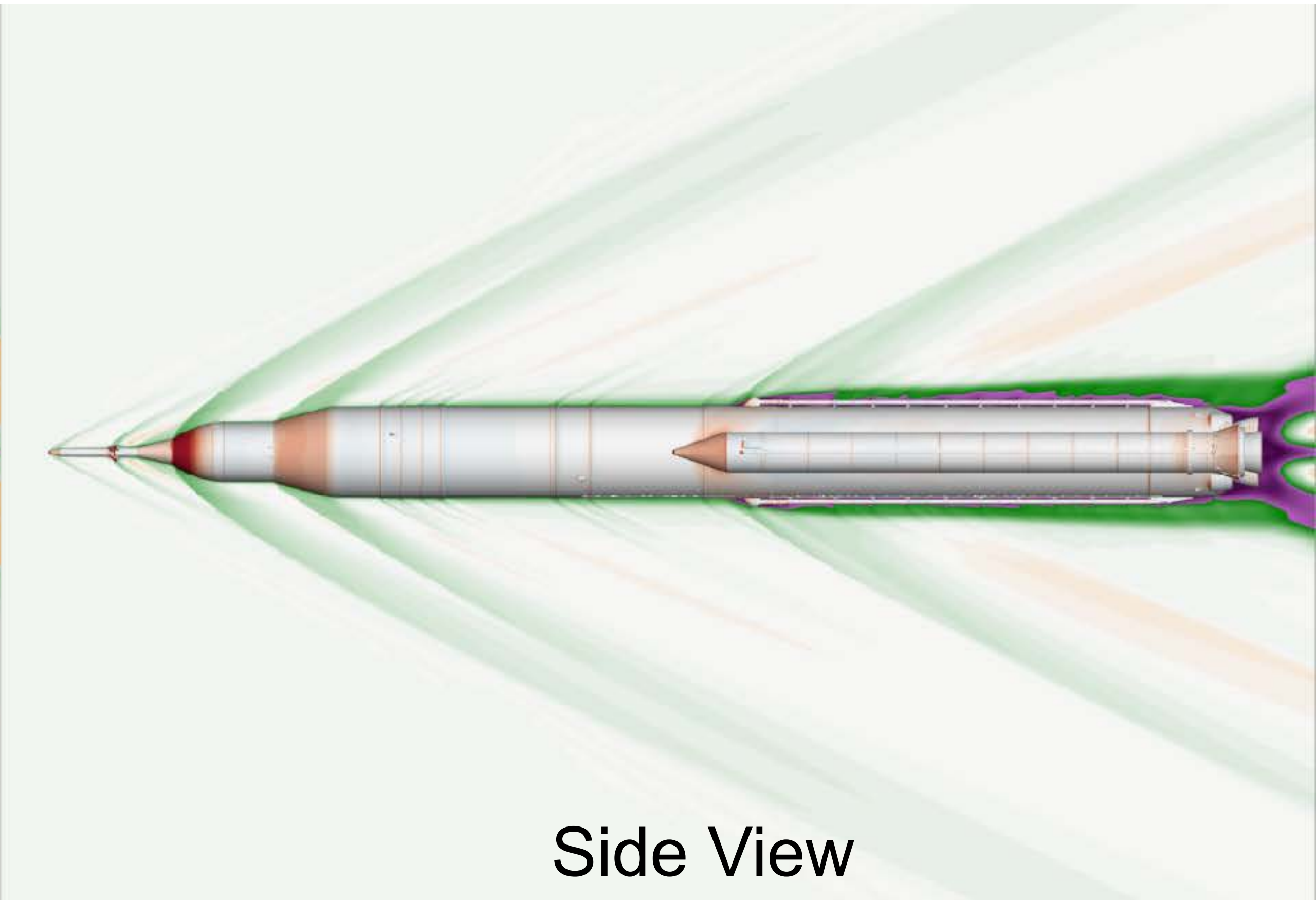


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

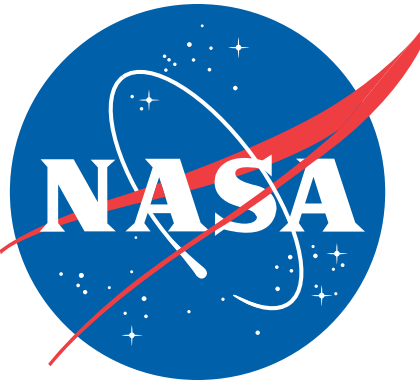
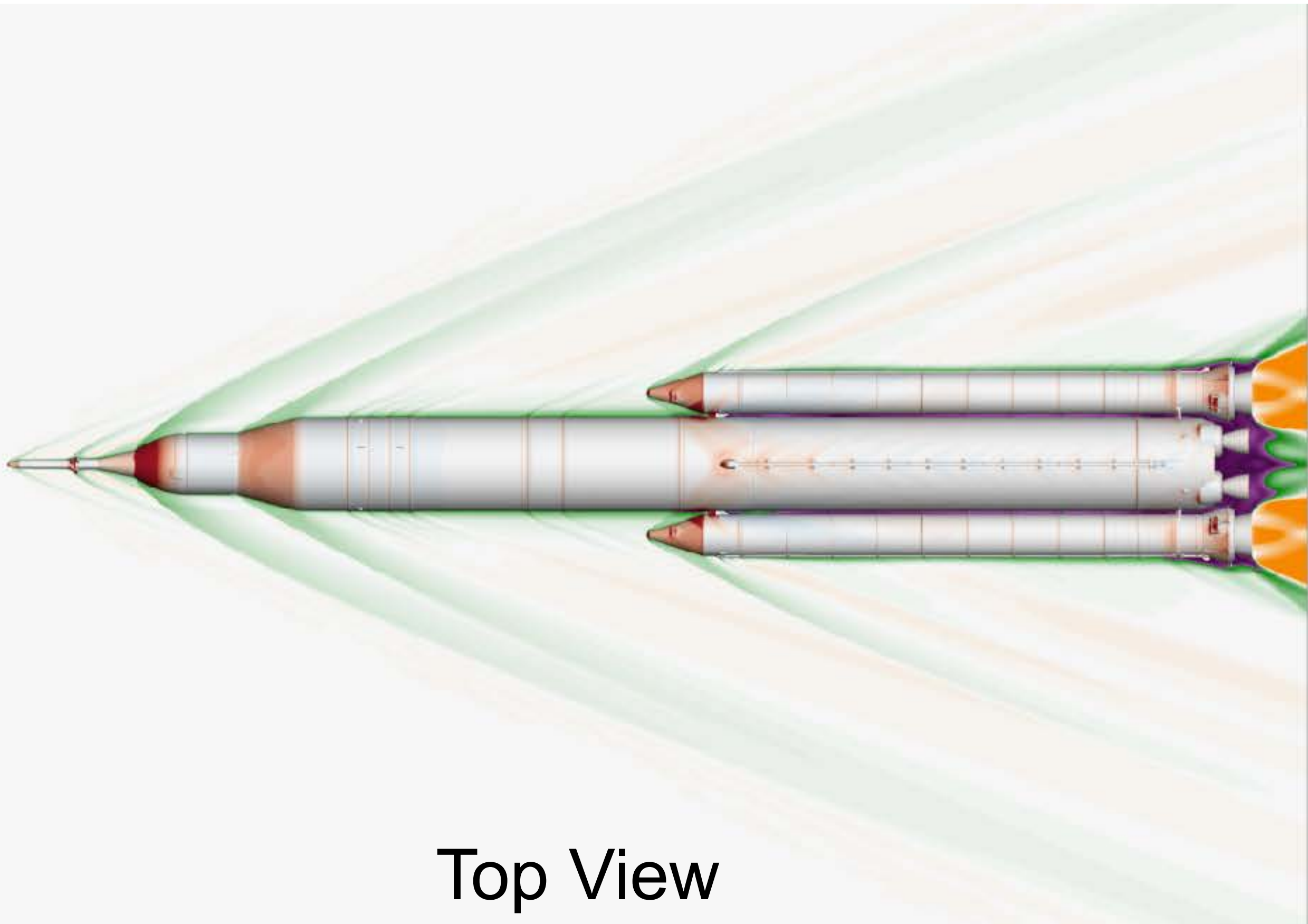


Altitude: Low High

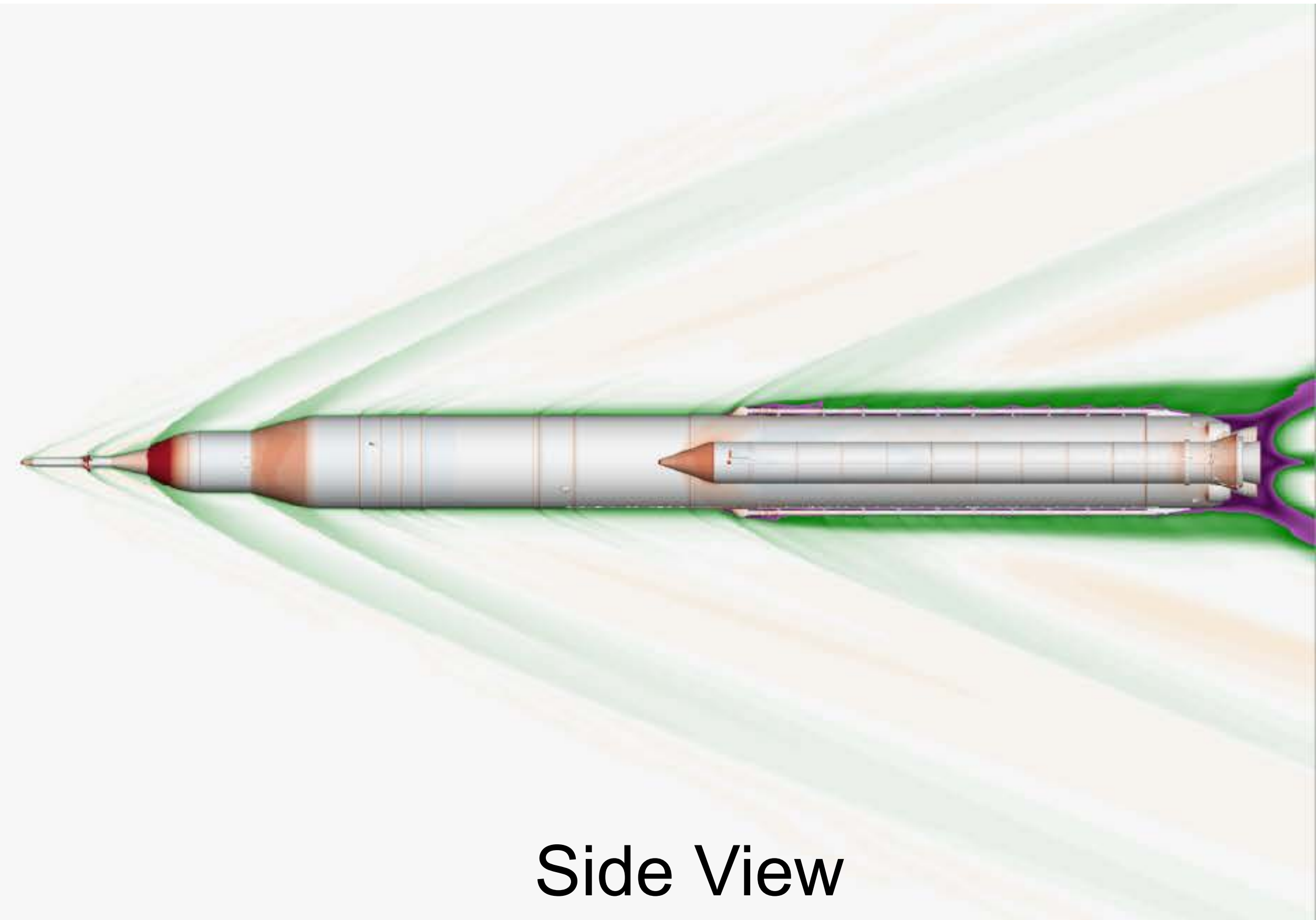


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

[illegible]

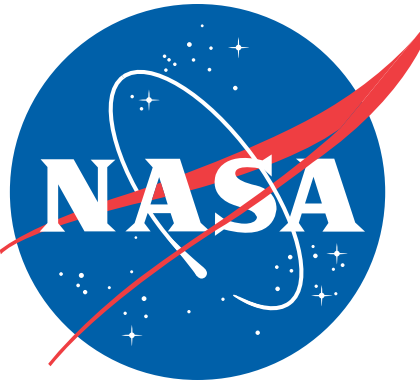
Top View



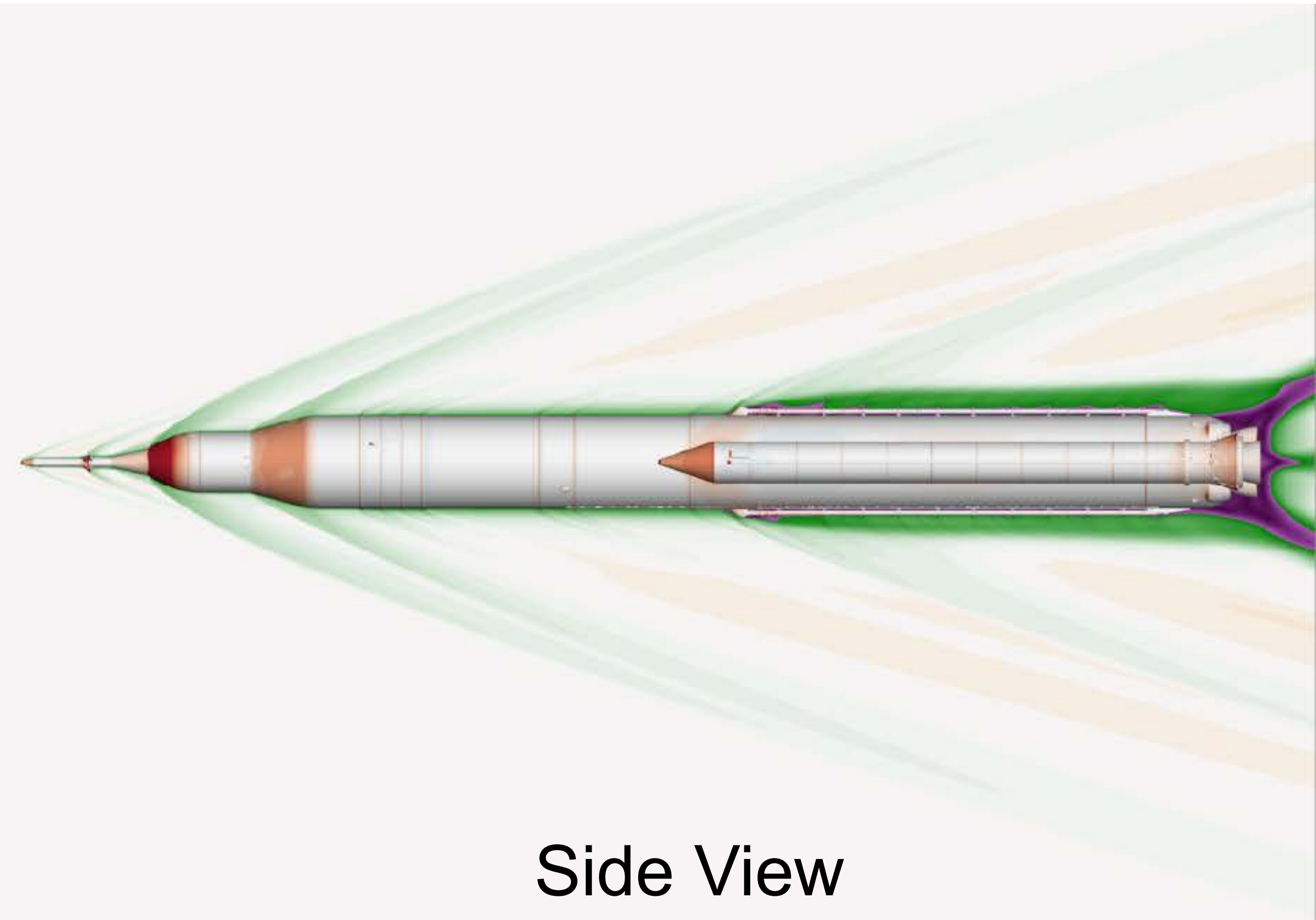
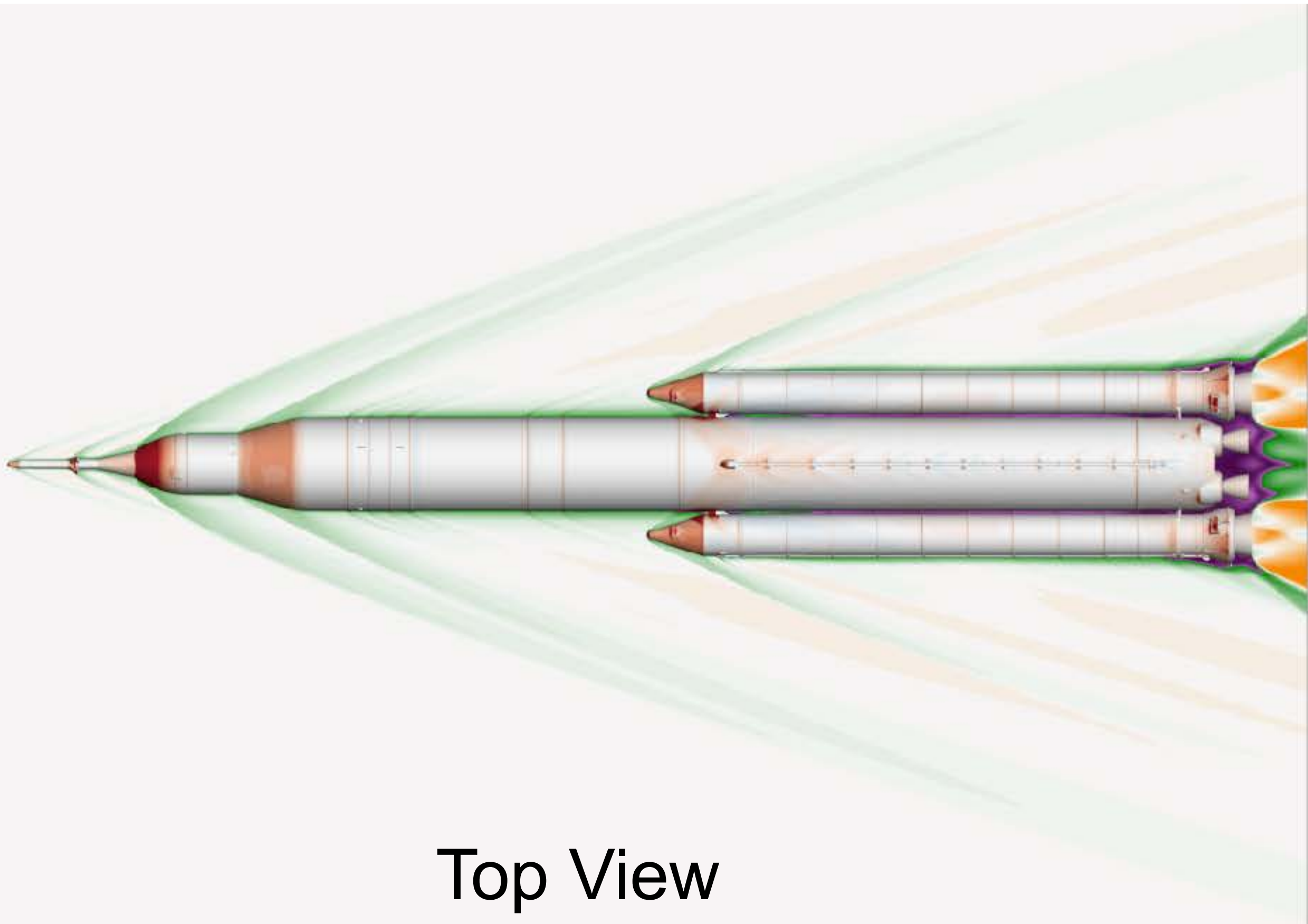
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent

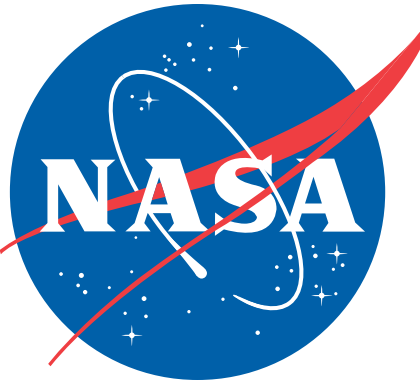


Altitude: Low ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● High

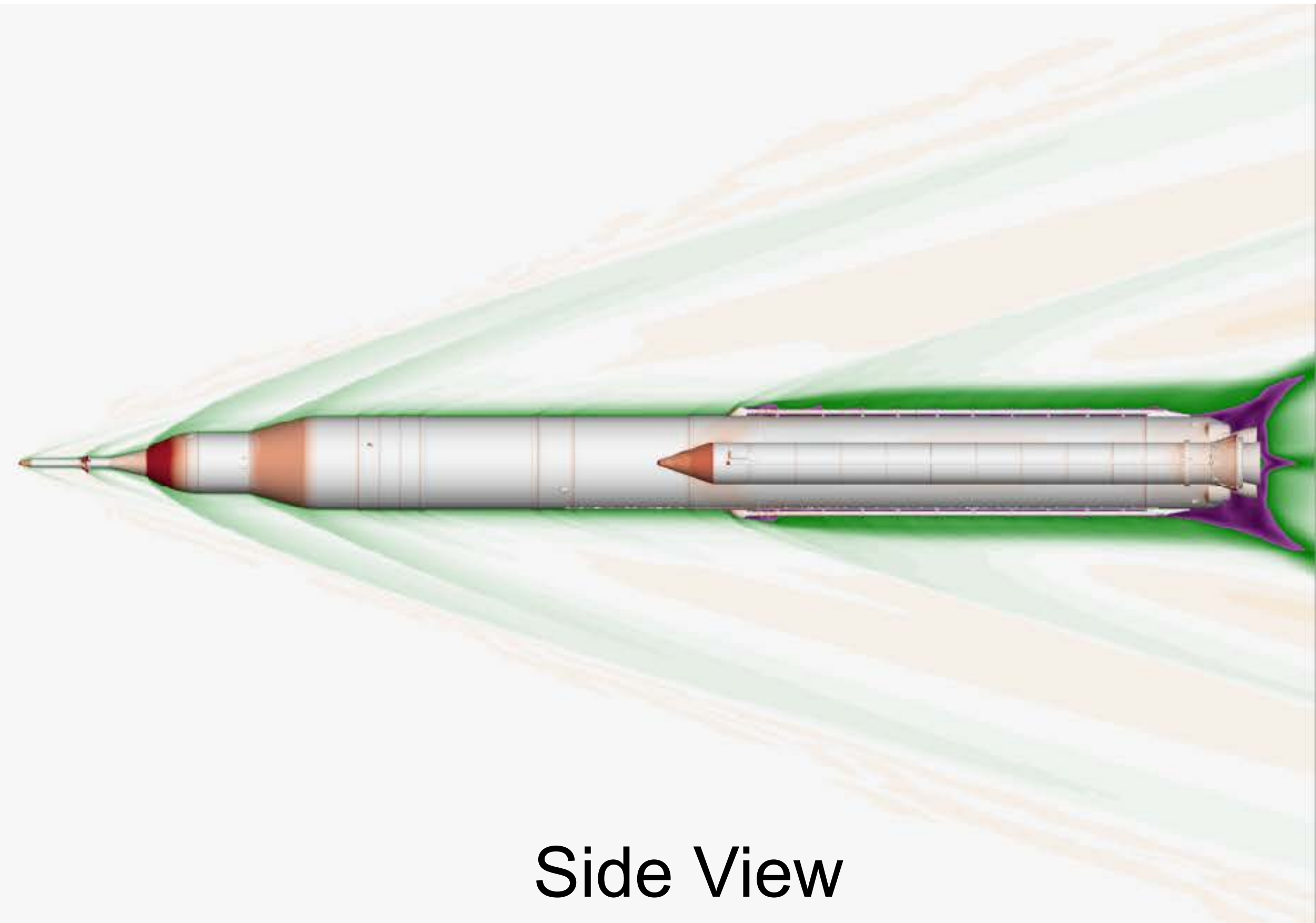
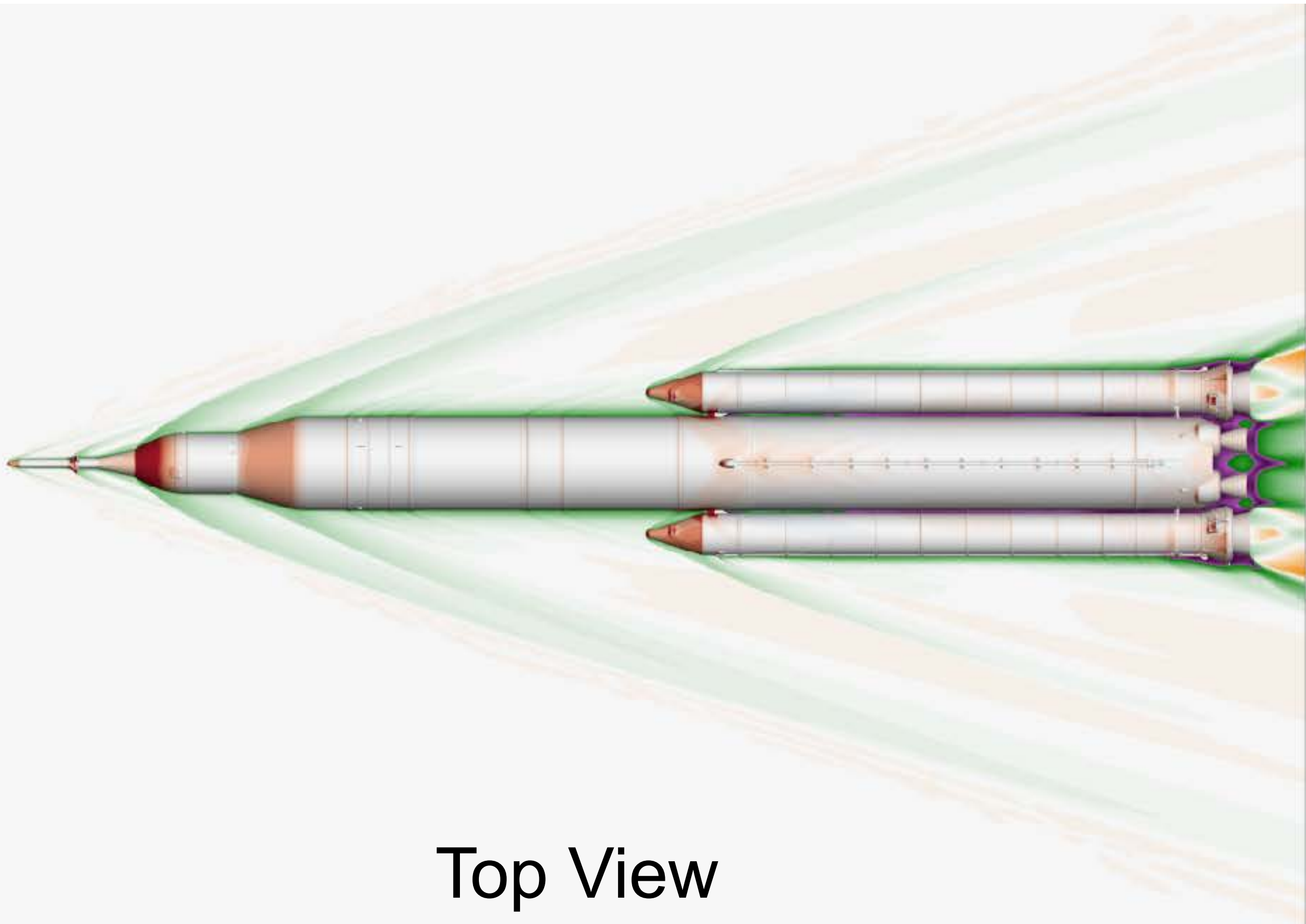


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Crew Ascent



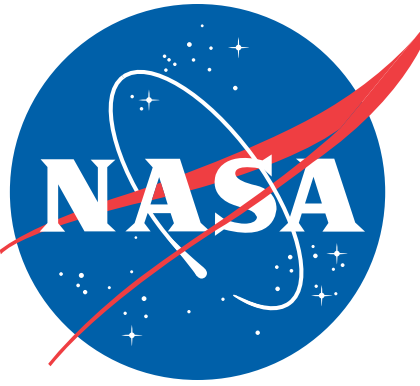
Altitude: Low ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● High



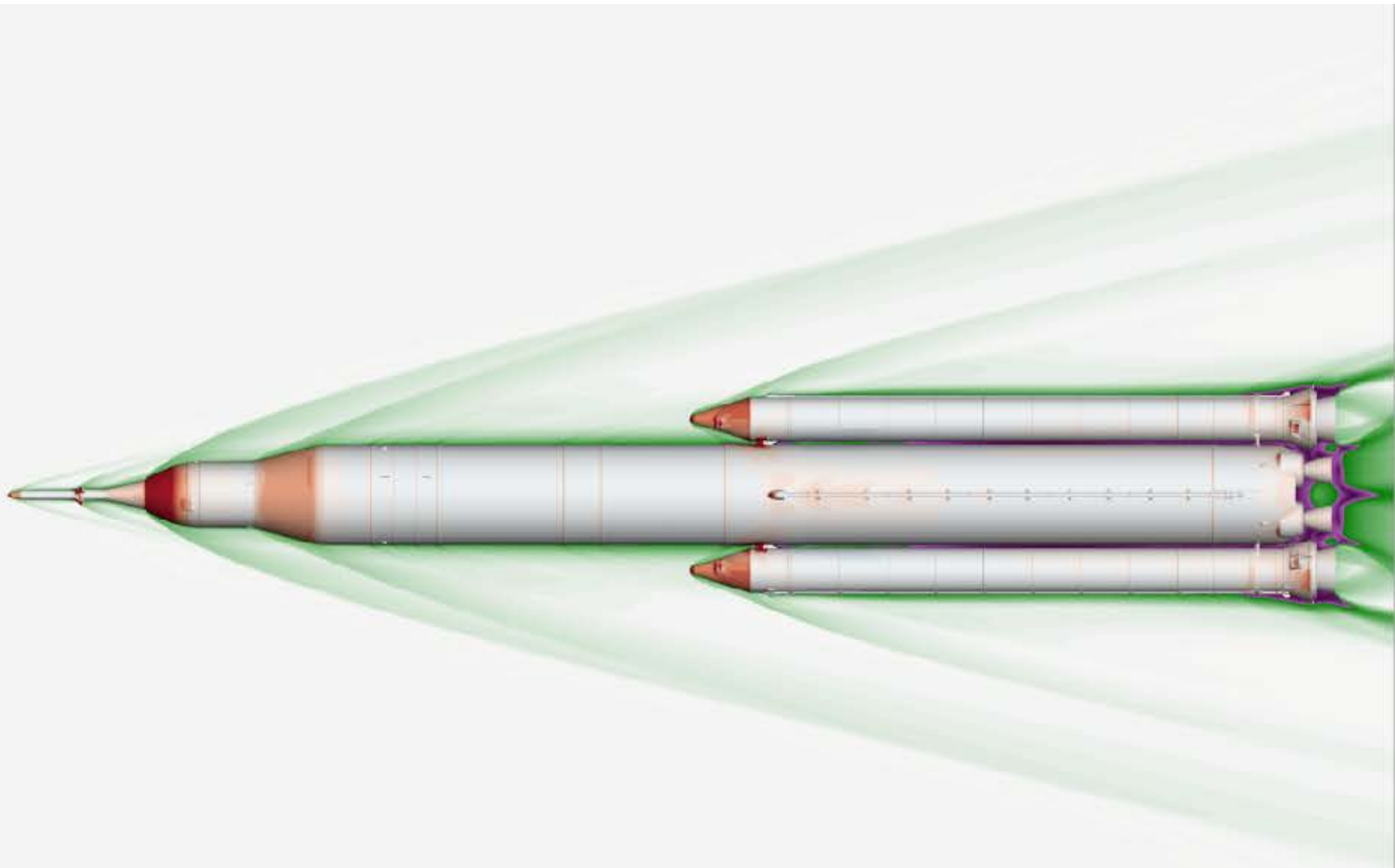
Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

The figure consists of two side-by-side plots showing the flow field around a three-stage rocket. The left plot is labeled 'Top View' and the right plot is labeled 'Side View'. Both plots show streamlines and color-coded regions representing different flow properties. The rocket is oriented horizontally, with the nose pointing to the left. The flow field is characterized by a large, elongated, and slightly curved region of high velocity (yellow/orange) surrounding the rocket, and a smaller, more compact region of high pressure (green) near the base. The streamlines are shown as thin, curved lines that follow the contour of the rocket and the flow field. The color-coded regions are used to represent different flow properties, such as velocity, pressure, or density, with yellow/orange indicating high values and green indicating lower values.

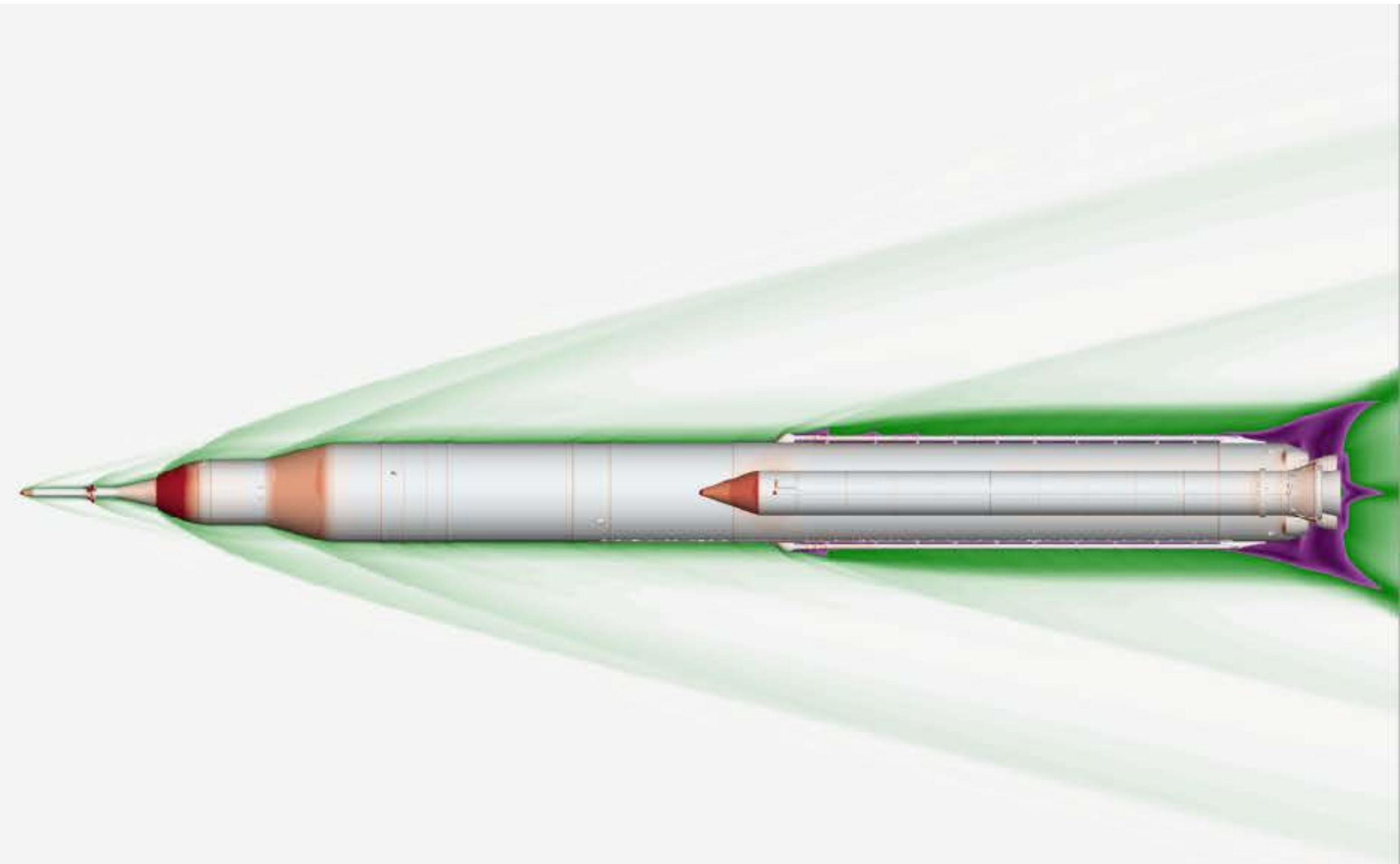
SLS Block 1B Crew Ascent



Altitude: Low • • • • • • • • • • • • • • • • • • High



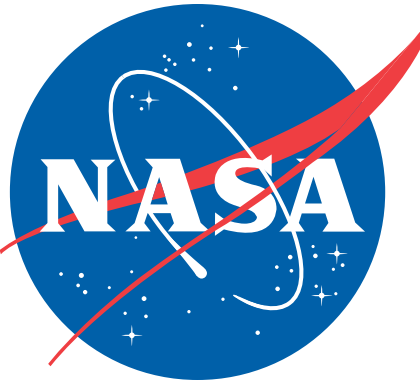
Top View



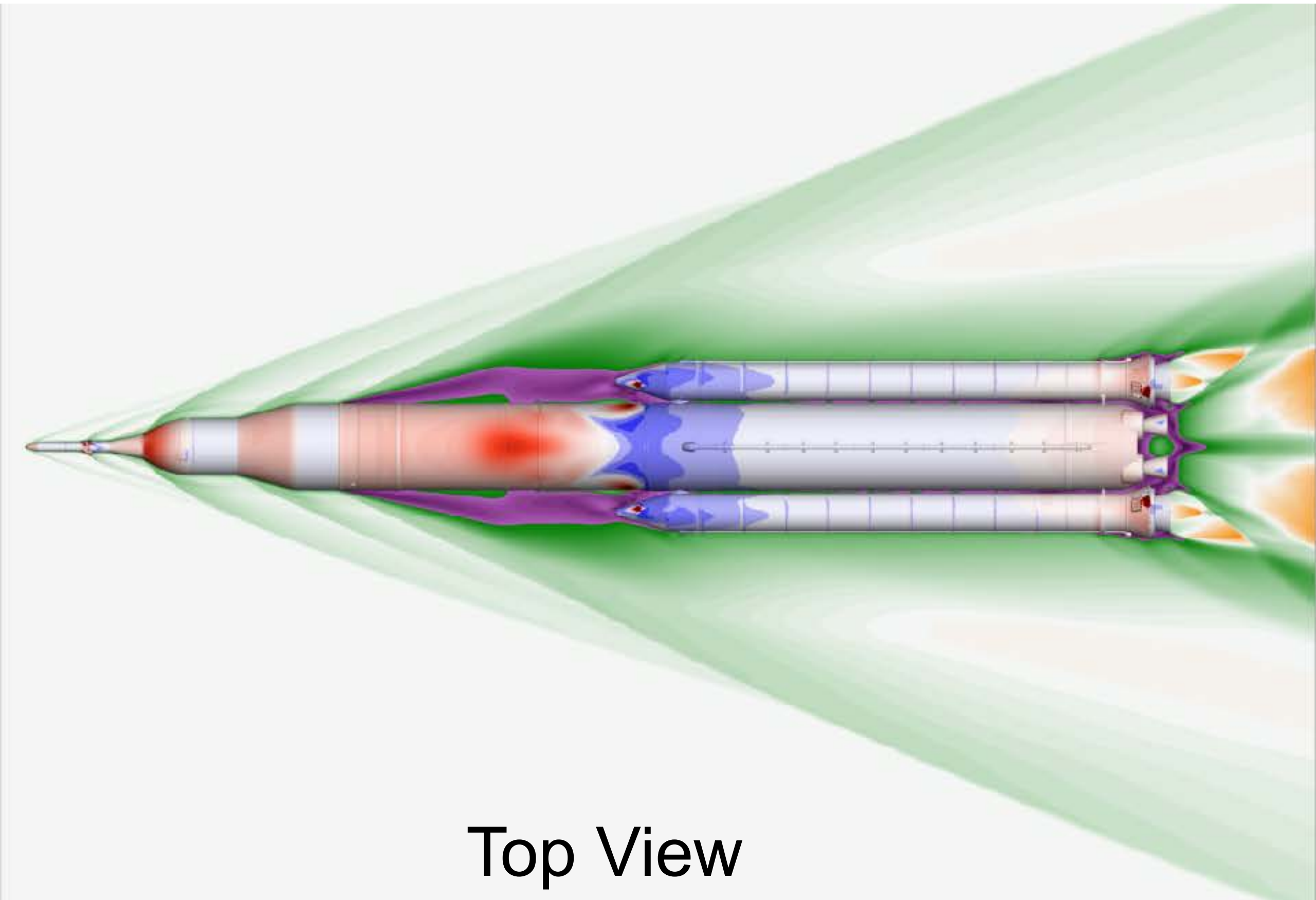
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

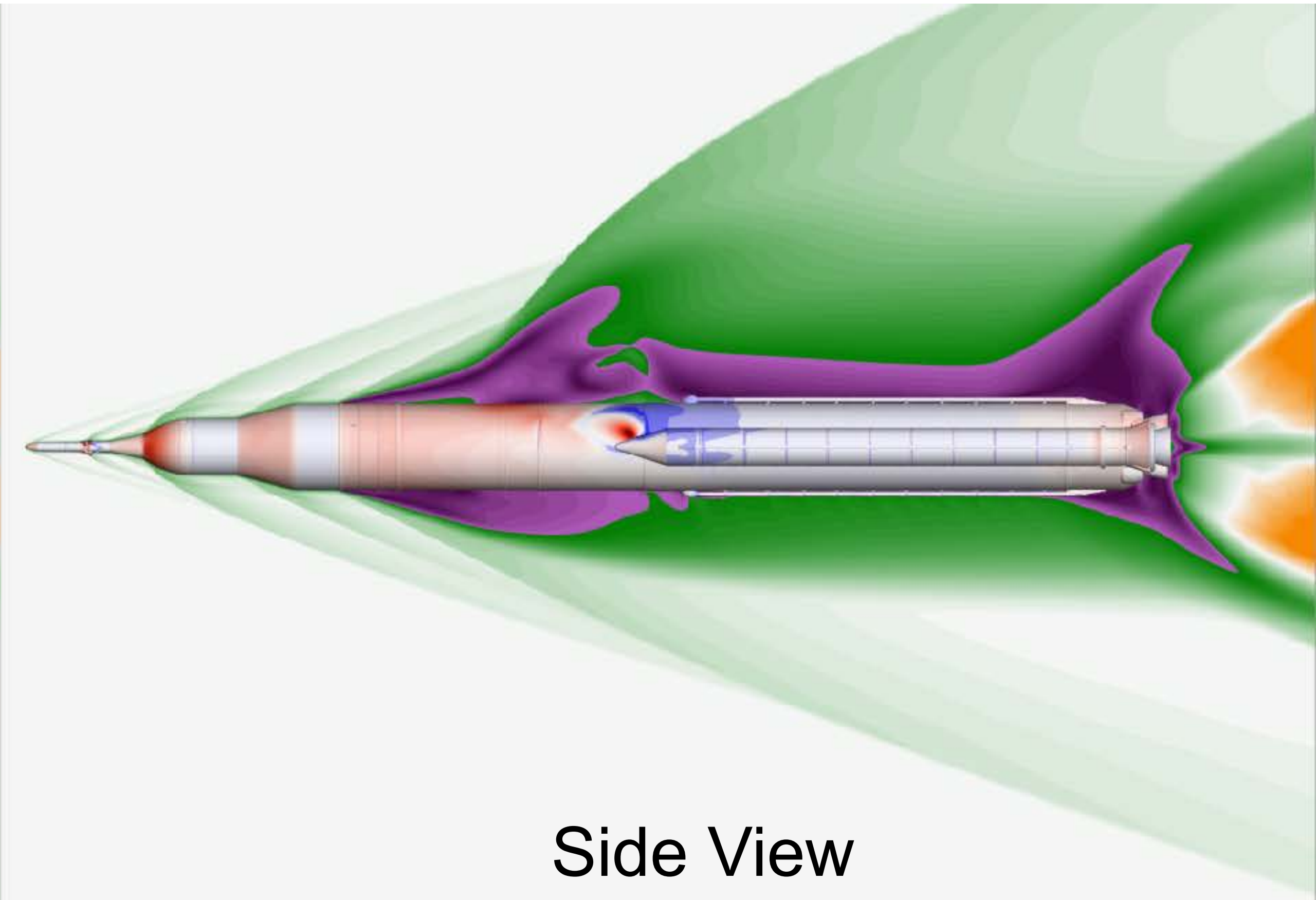
SLS Block 1B Crew Booster Separation



Booster Proximity: Attached • • • • • Separated



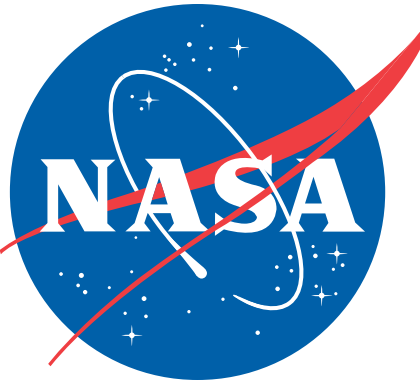
Top View



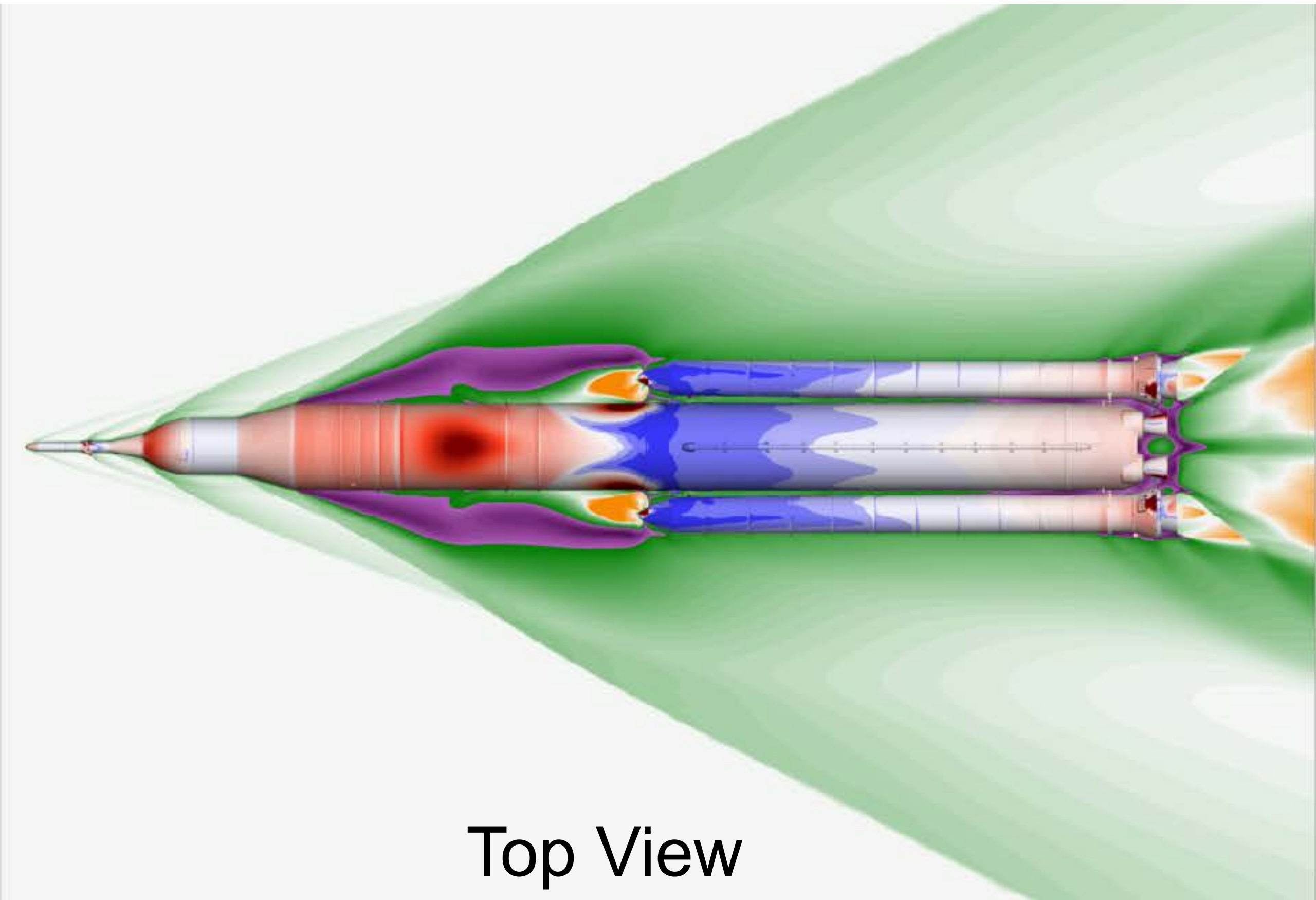
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

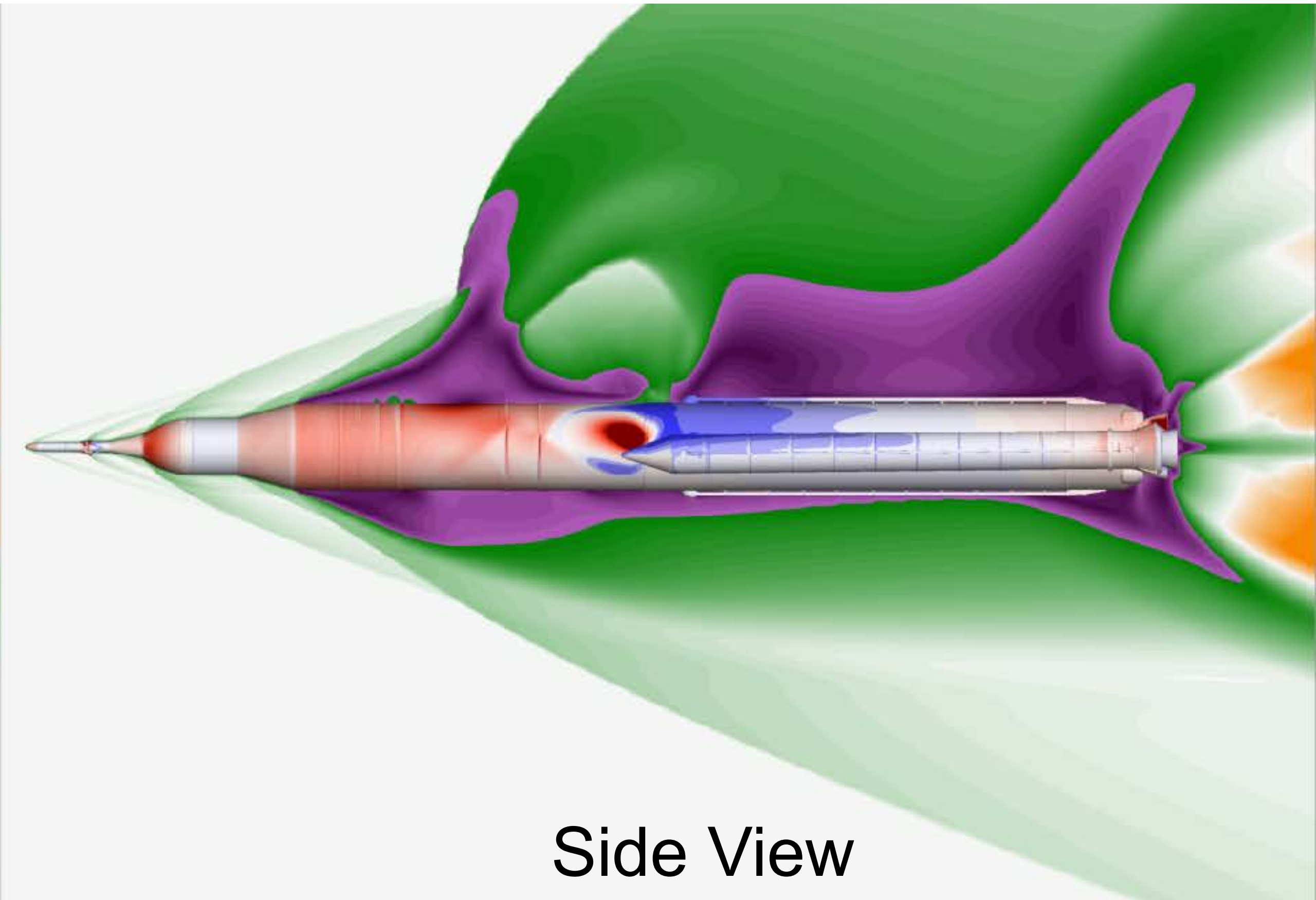
SLS Block 1B Crew Booster Separation



Booster Proximity: Attached • • • • • Separated



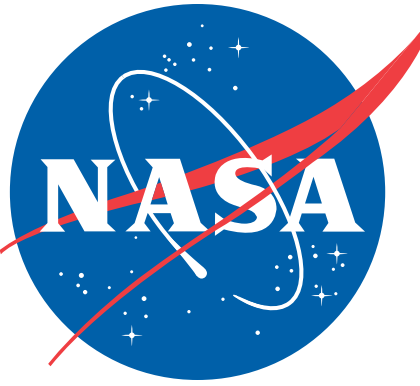
Top View



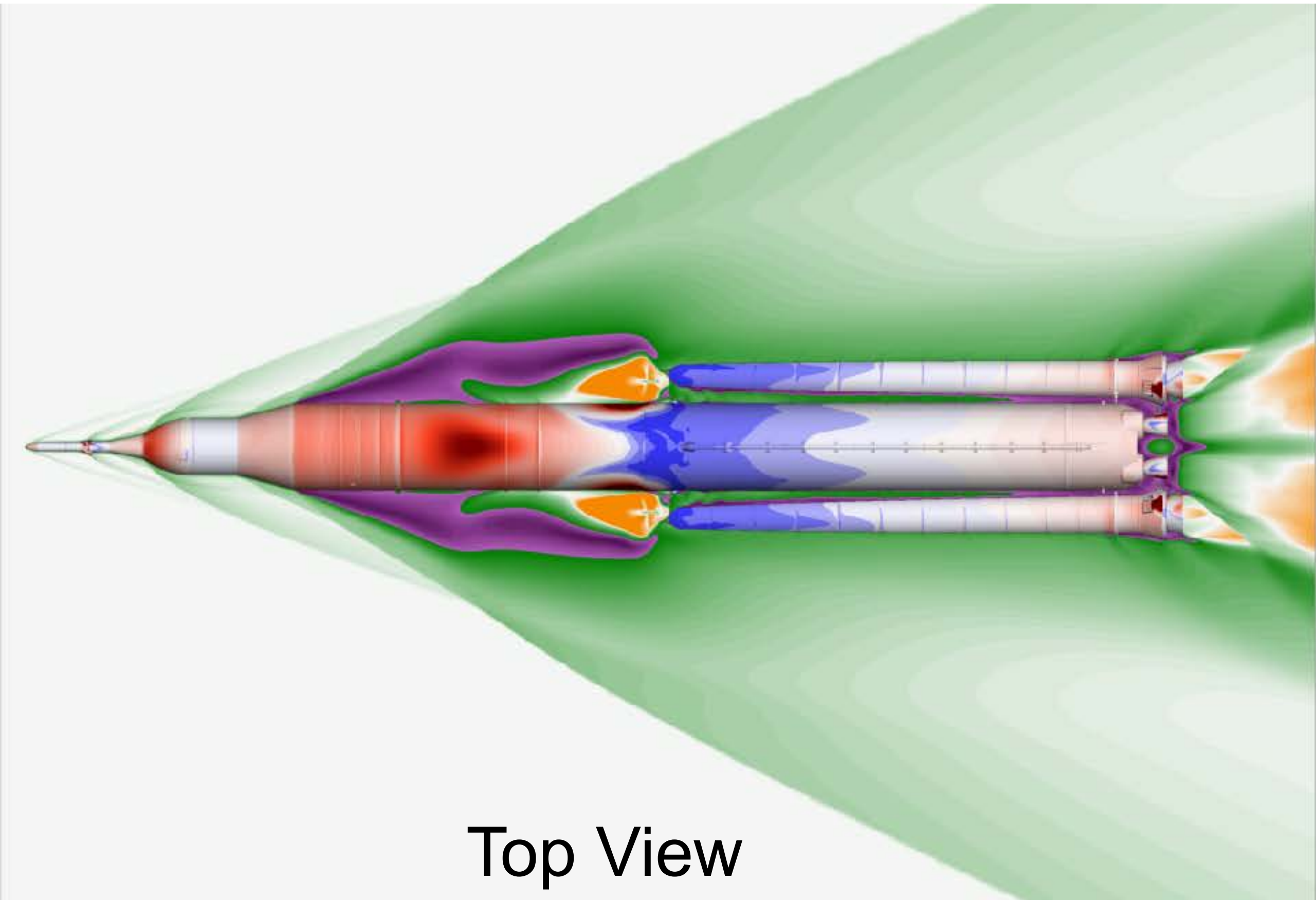
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

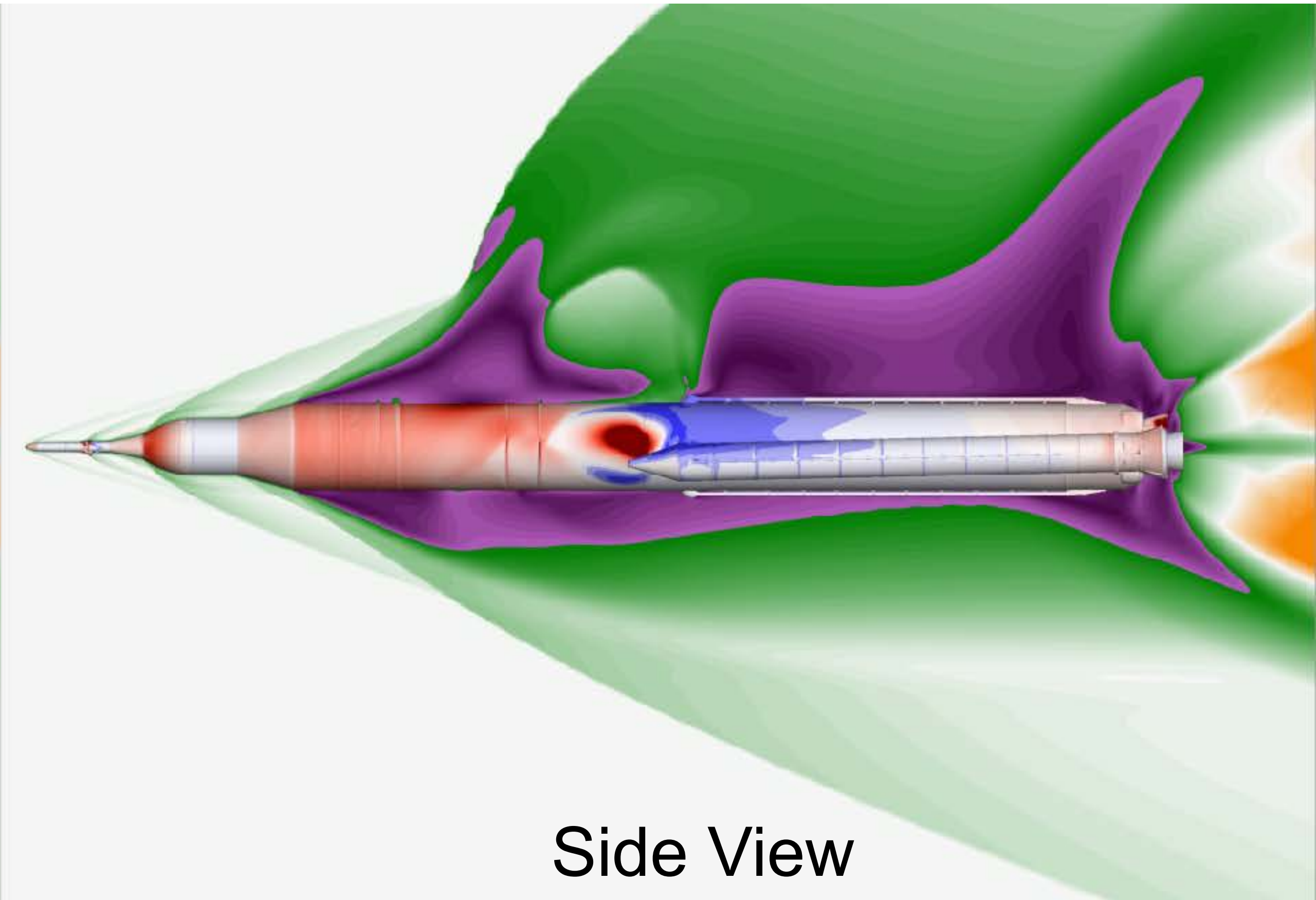
SLS Block 1B Crew Booster Separation



Booster Proximity: Attached • • • • • Separated



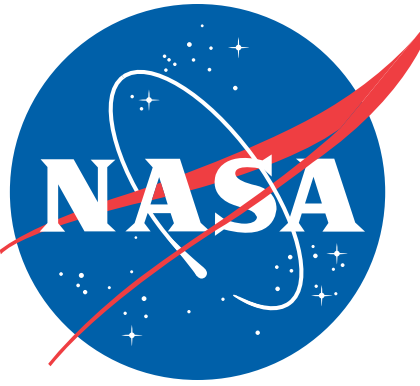
Top View



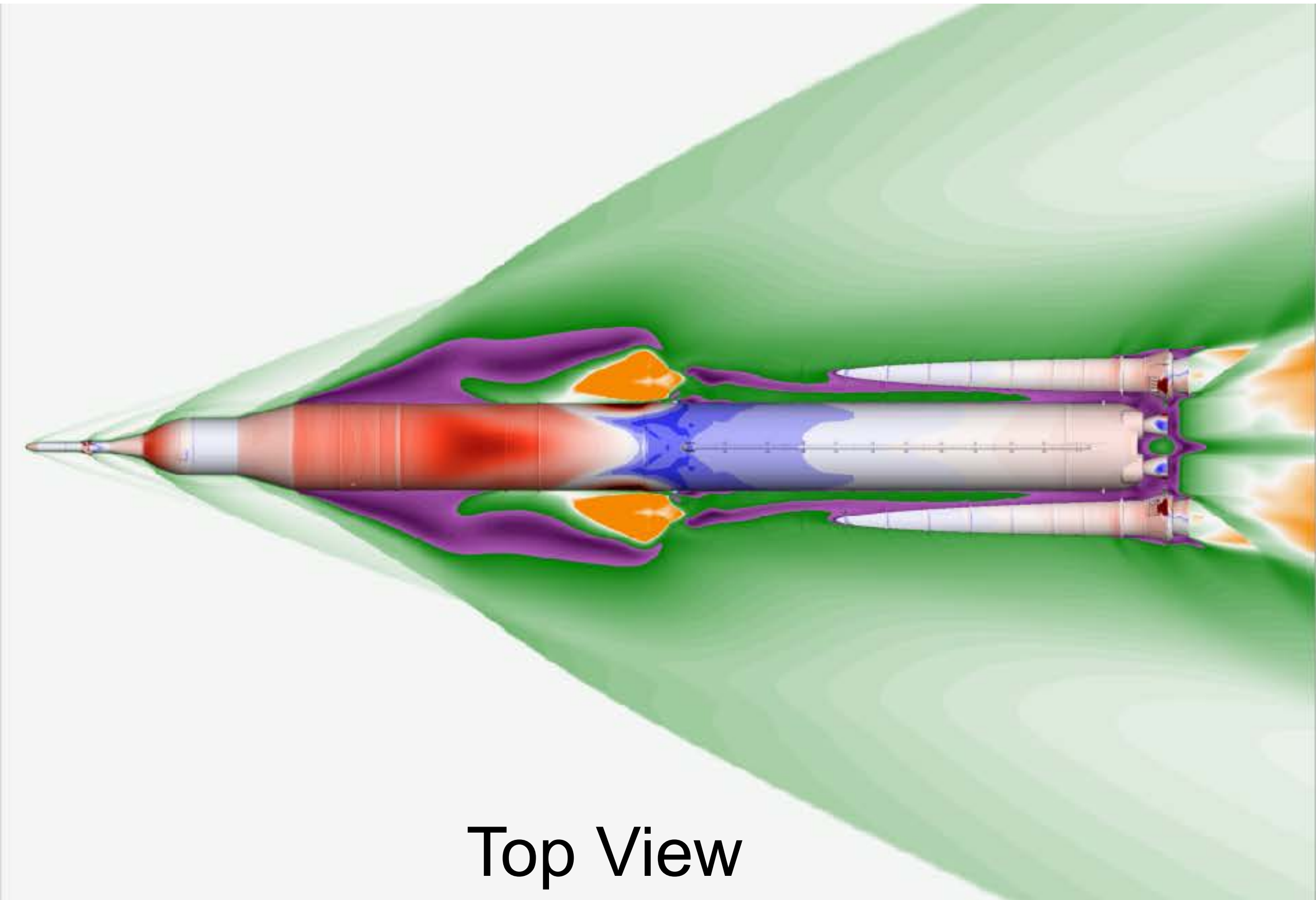
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

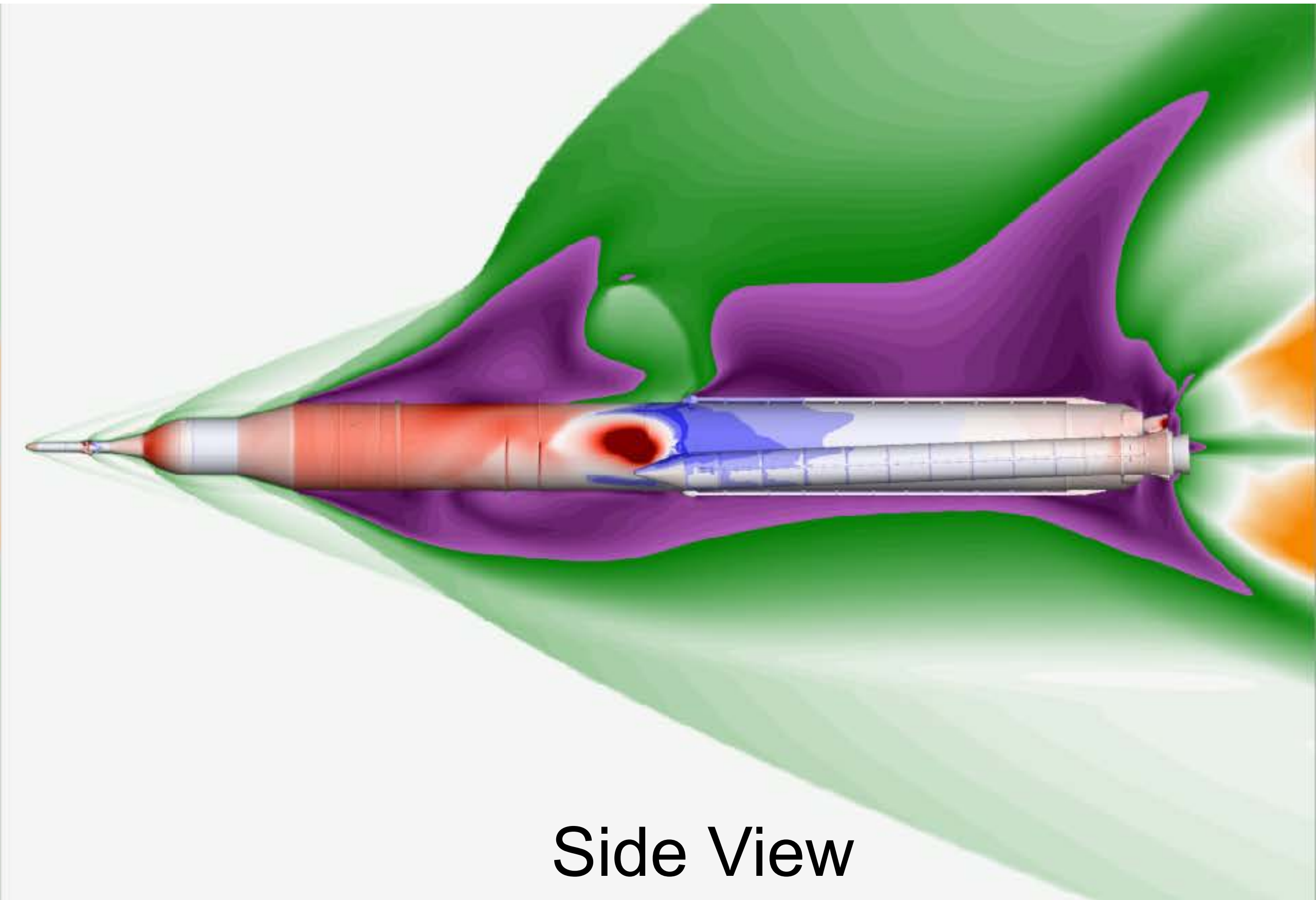
SLS Block 1B Crew Booster Separation



Booster Proximity: Attached • • • • • Separated



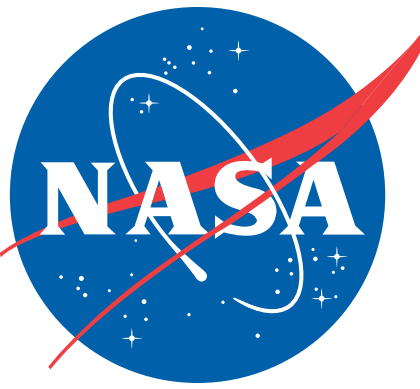
Top View



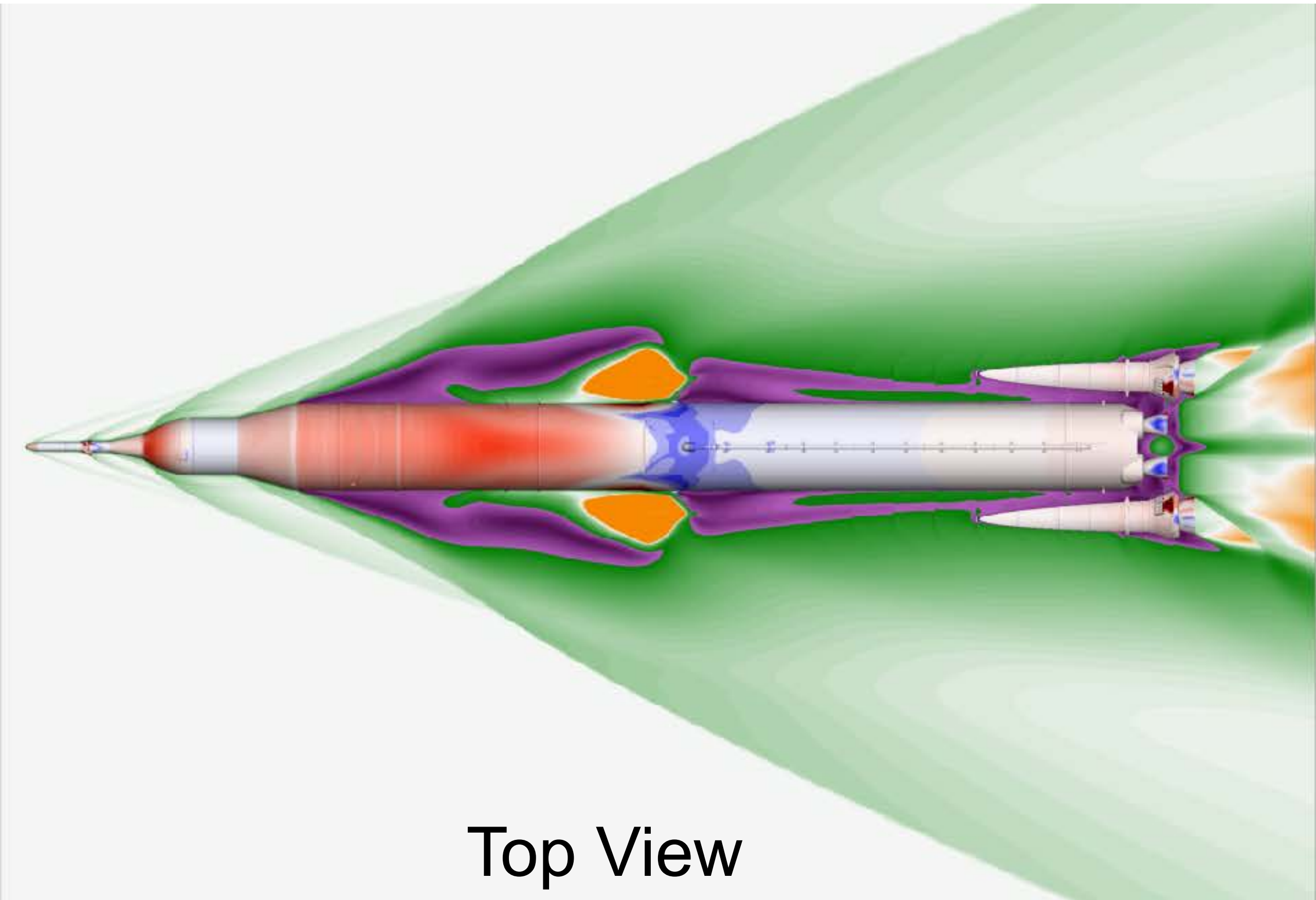
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

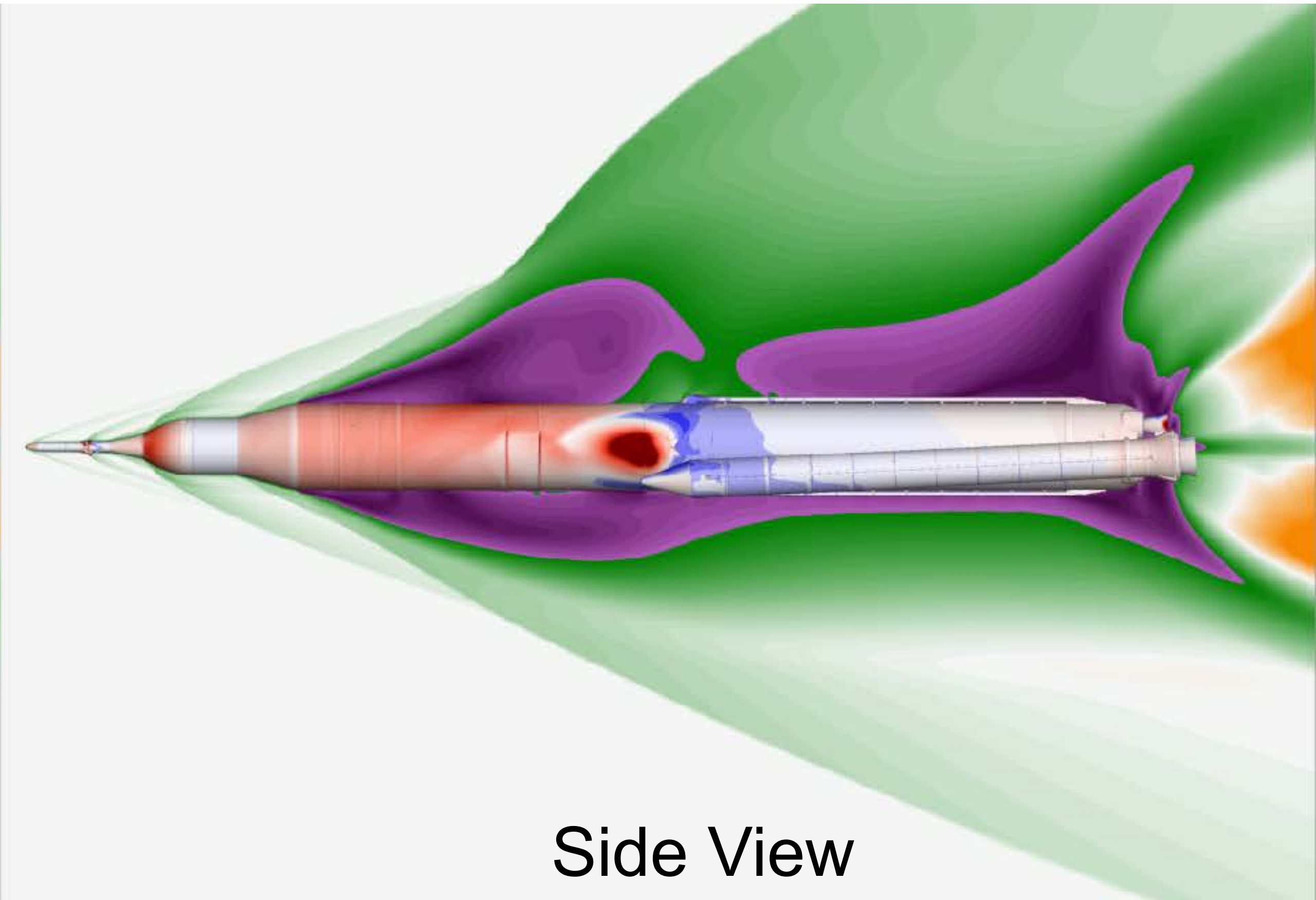
SLS Block 1B Crew Booster Separation



Booster Proximity: Attached Separated



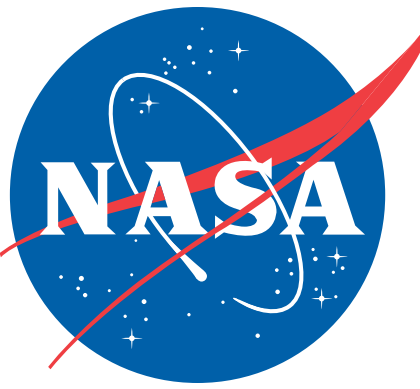
Top View



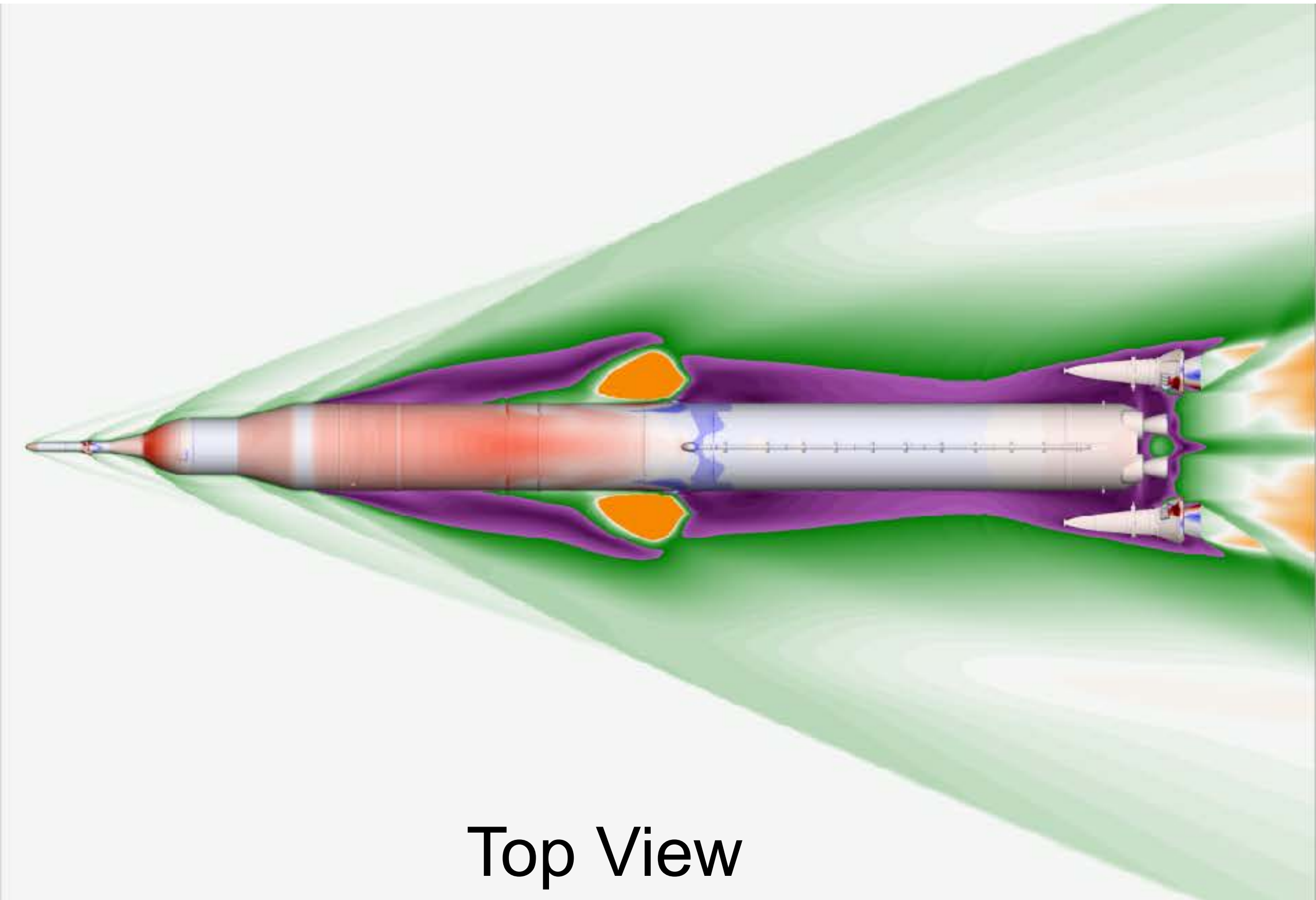
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

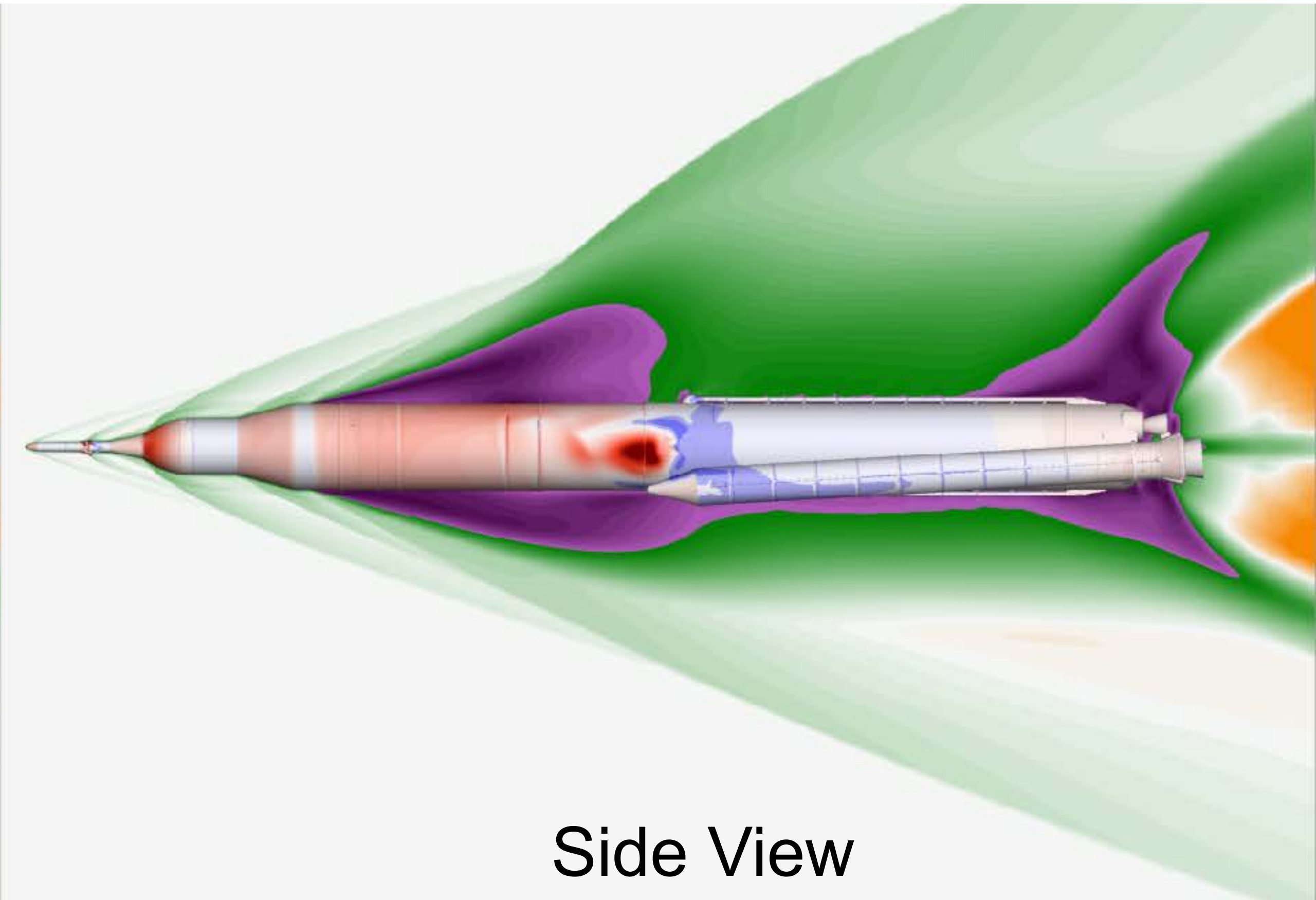
SLS Block 1B Crew Booster Separation



Booster Proximity: Attached Separated



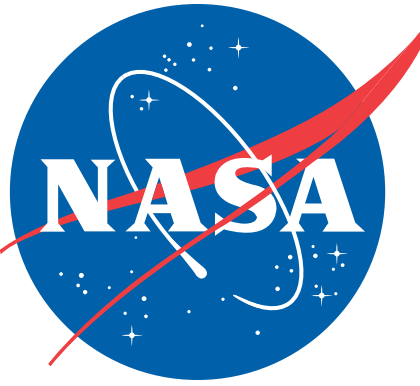
Top View



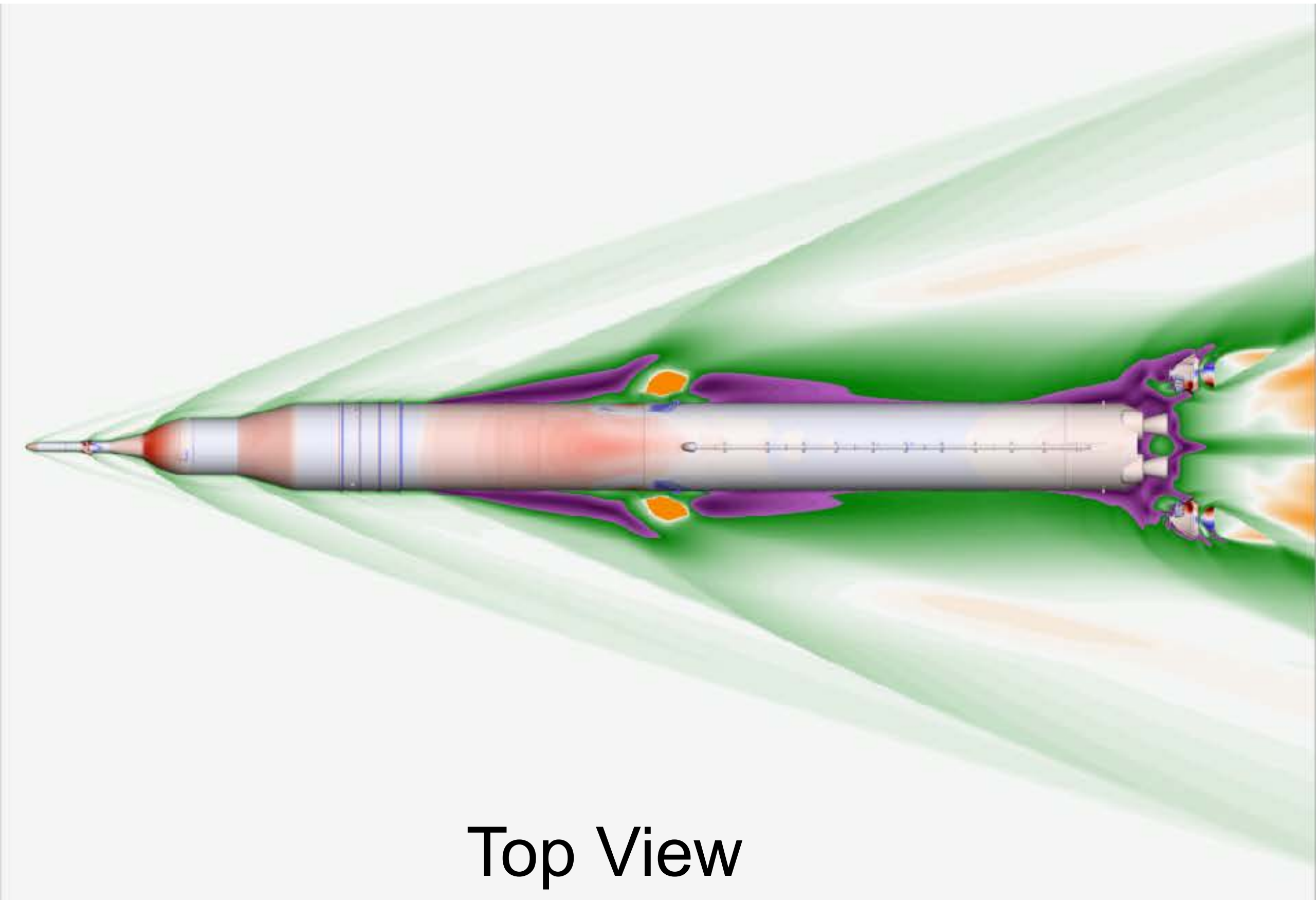
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

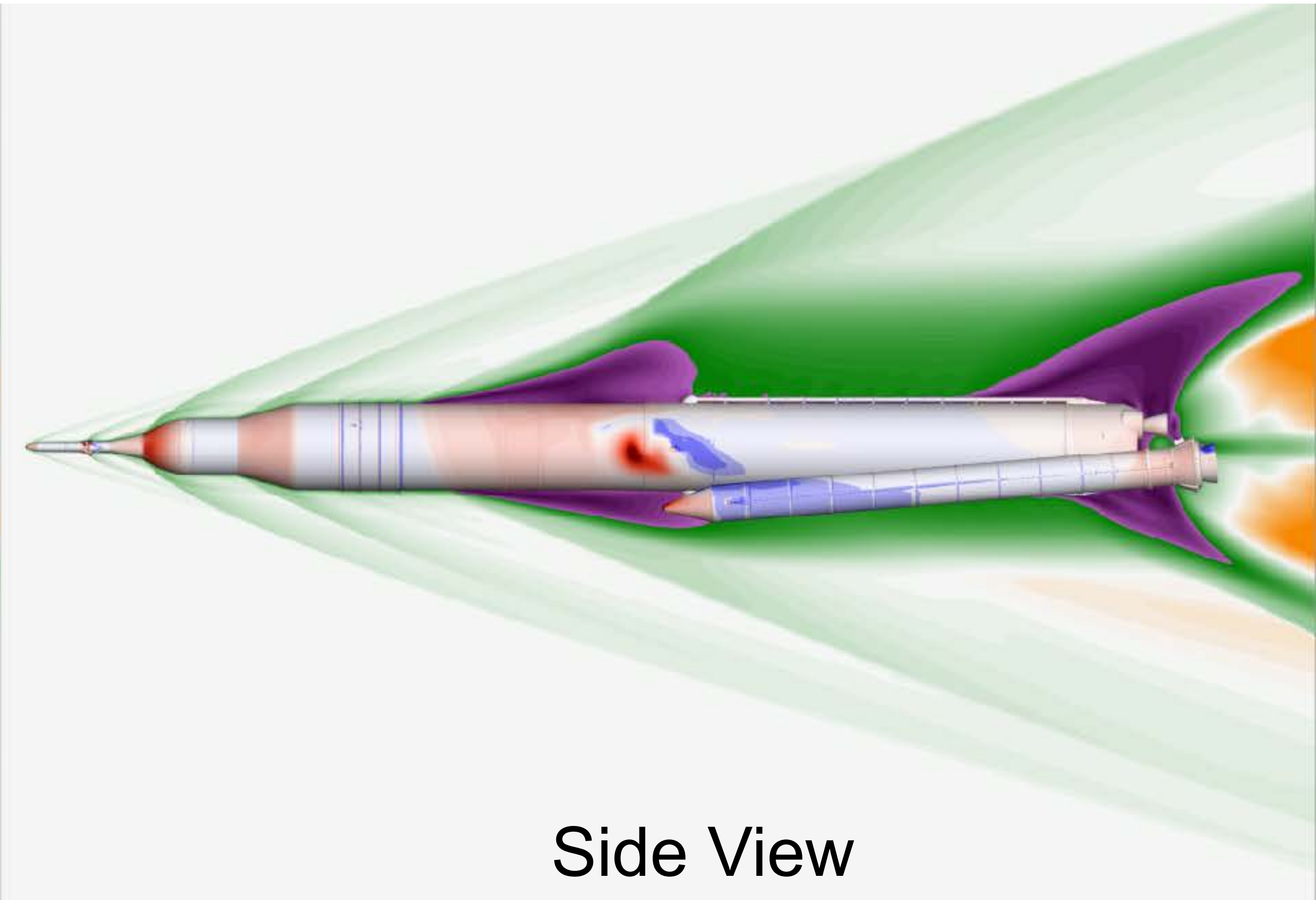
SLS Block 1B Crew Booster Separation



Booster Proximity: Attached Separated



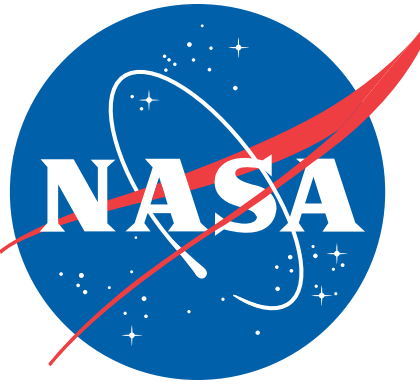
Top View



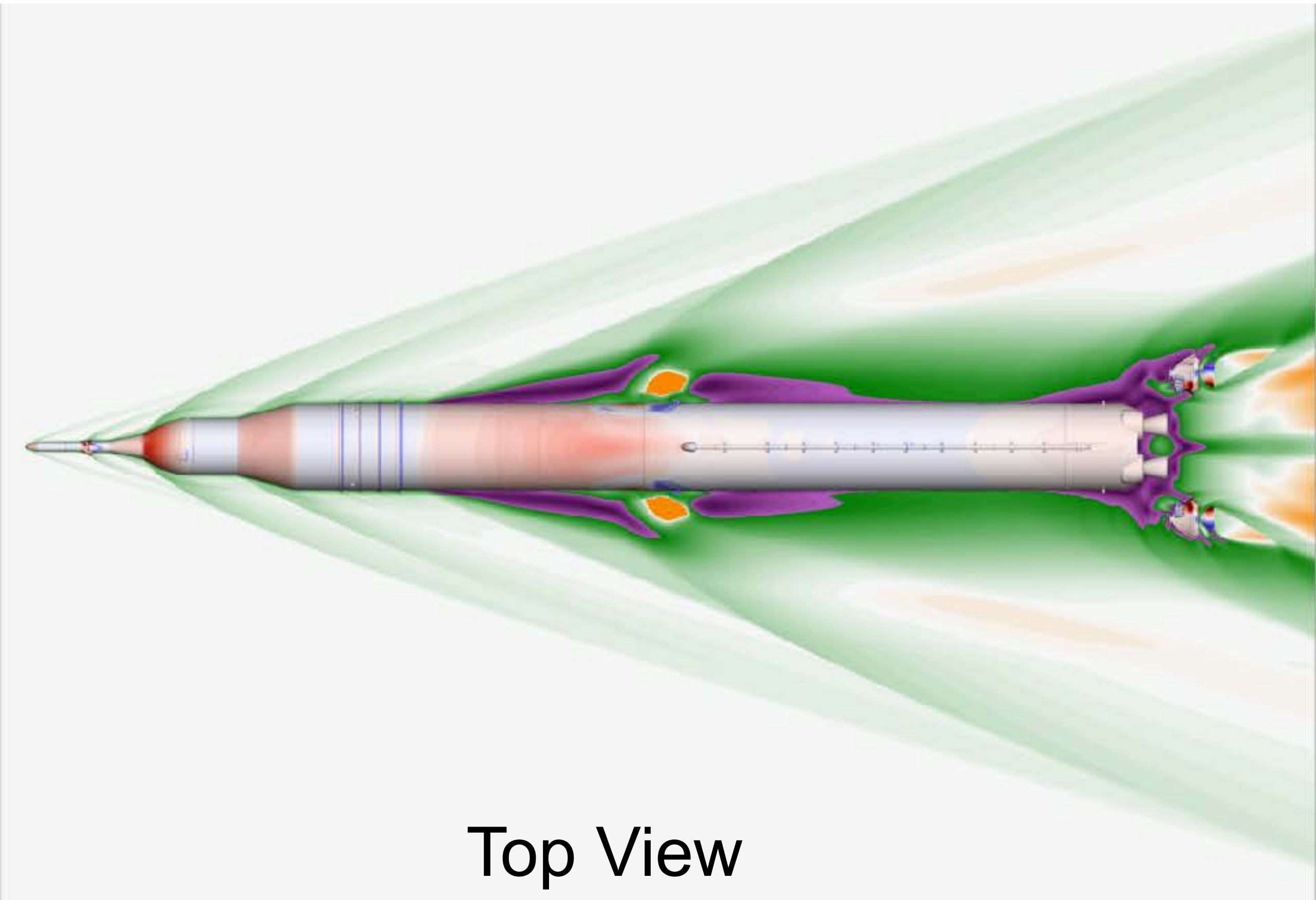
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

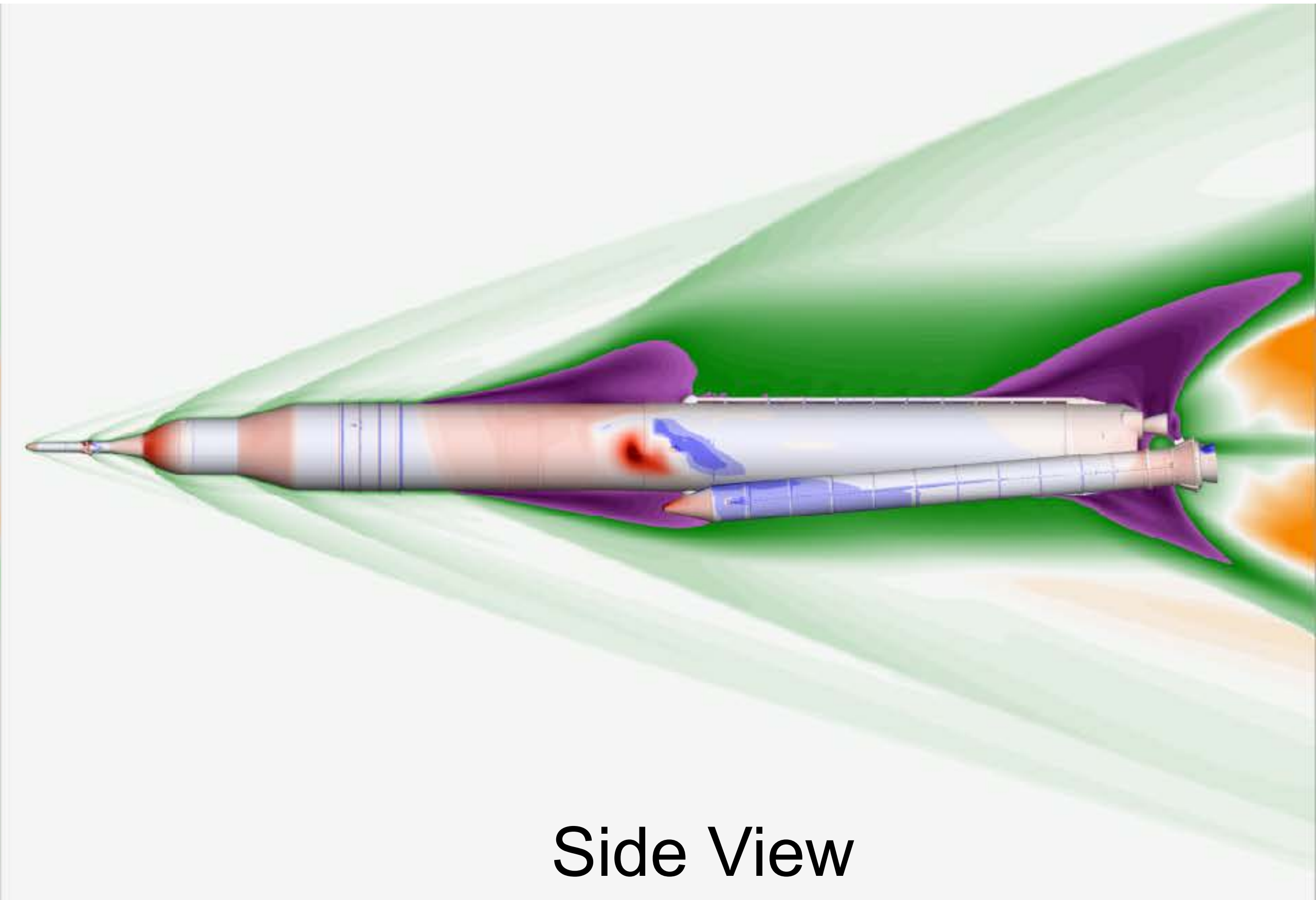
SLS Block 1B Crew Booster Separation



Booster Proximity: Attached • • • • • • • Separated



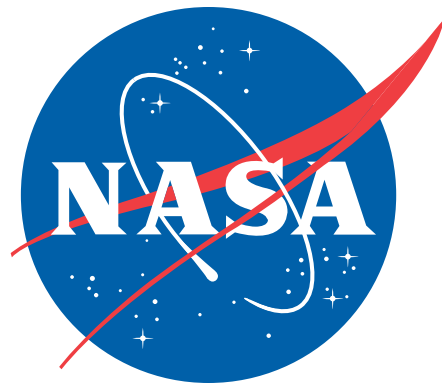
Top View



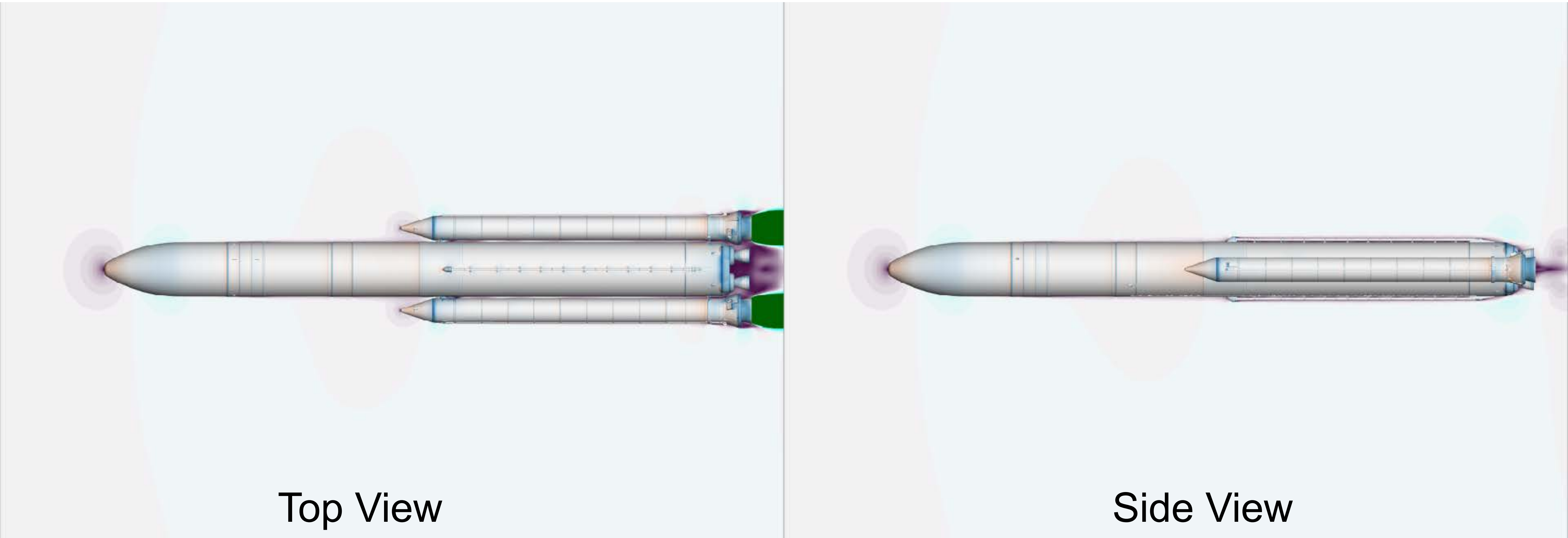
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Cargo Ascent

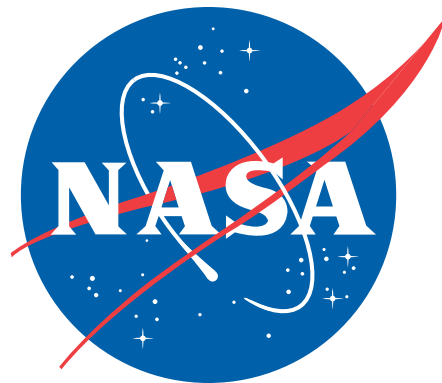


Altitude: Low • • • • • • • • • • • • • • • • High

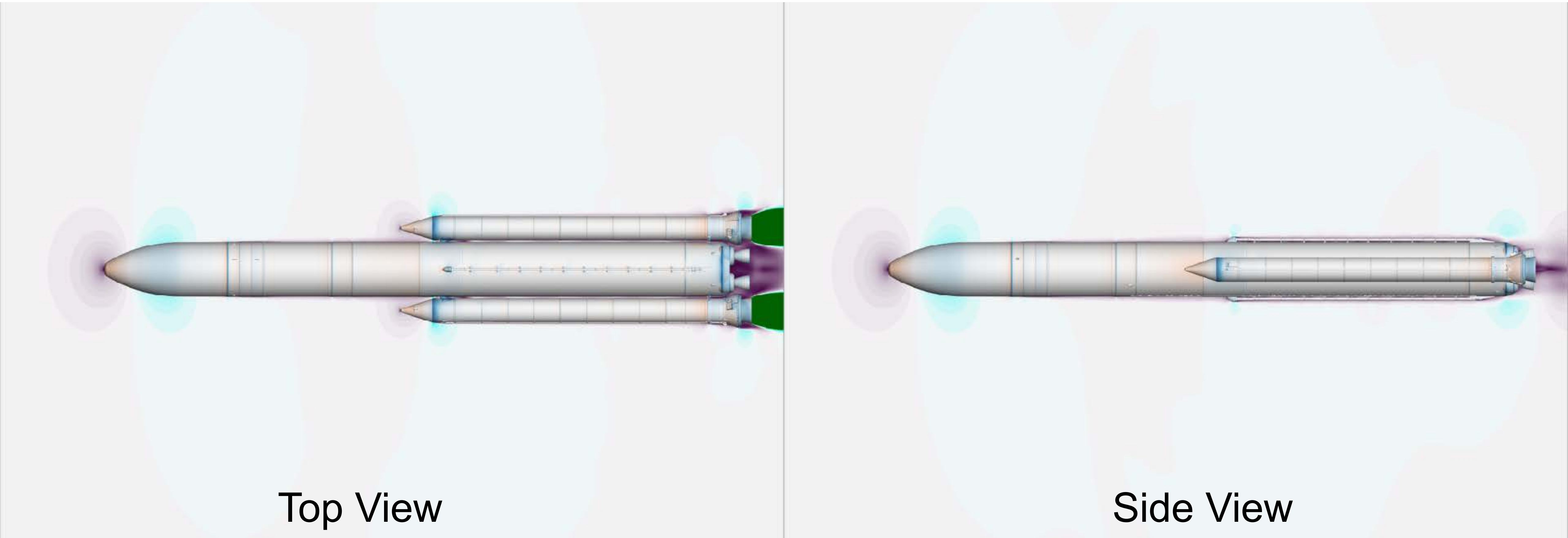


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Cargo Ascent

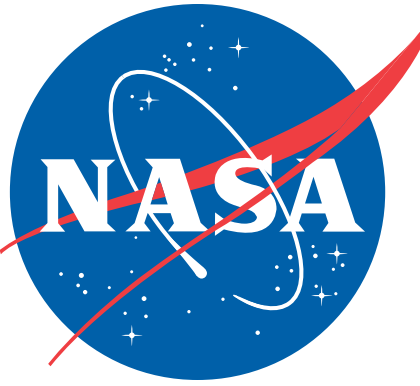


Altitude: Low • • • • • • • • • • • • • • High

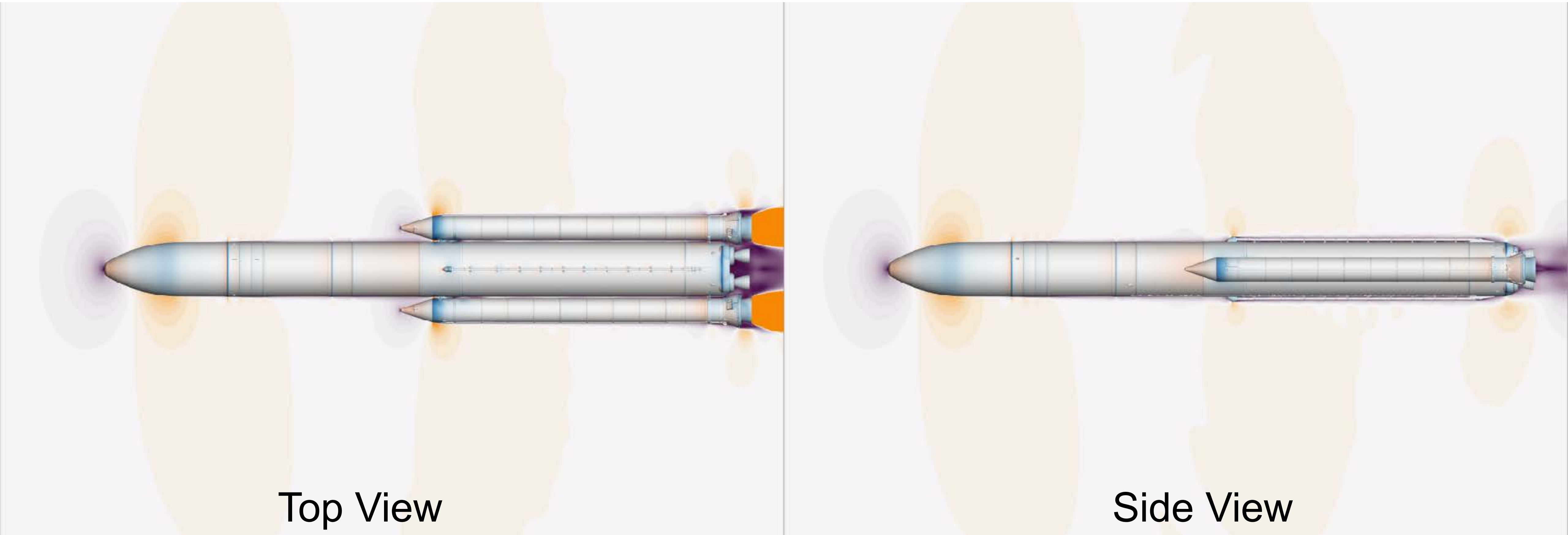


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Cargo Ascent

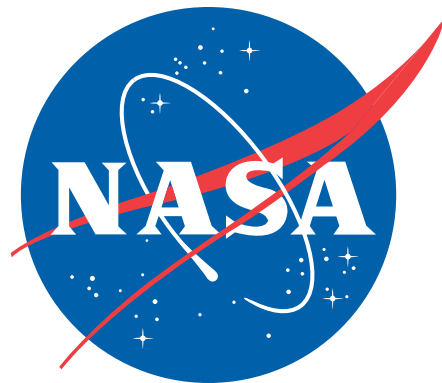


Altitude: Low • • ● • • • • • • • • • • • High

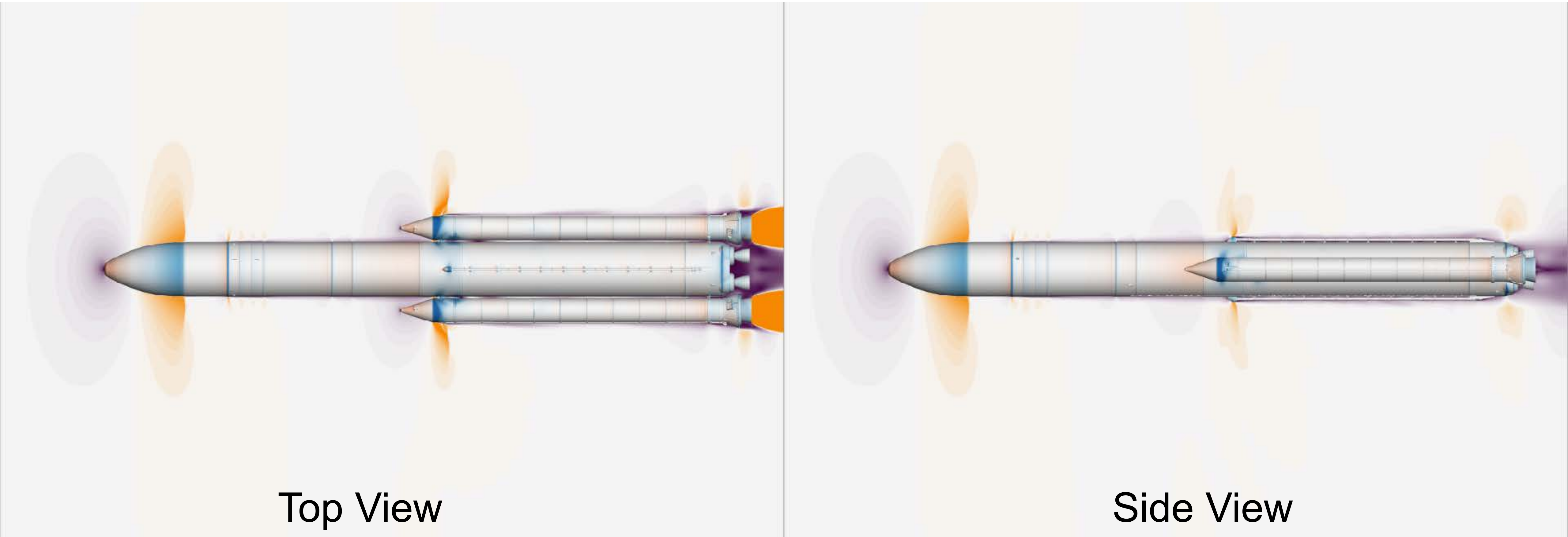


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Cargo Ascent

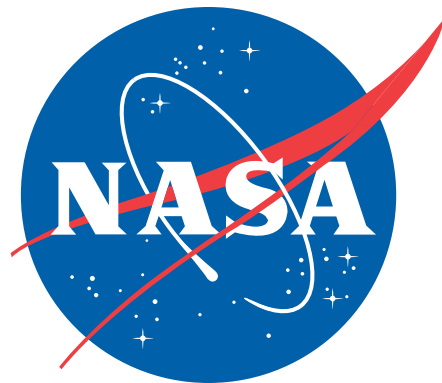


Altitude: Low • • • • • • • • • • • • • • High

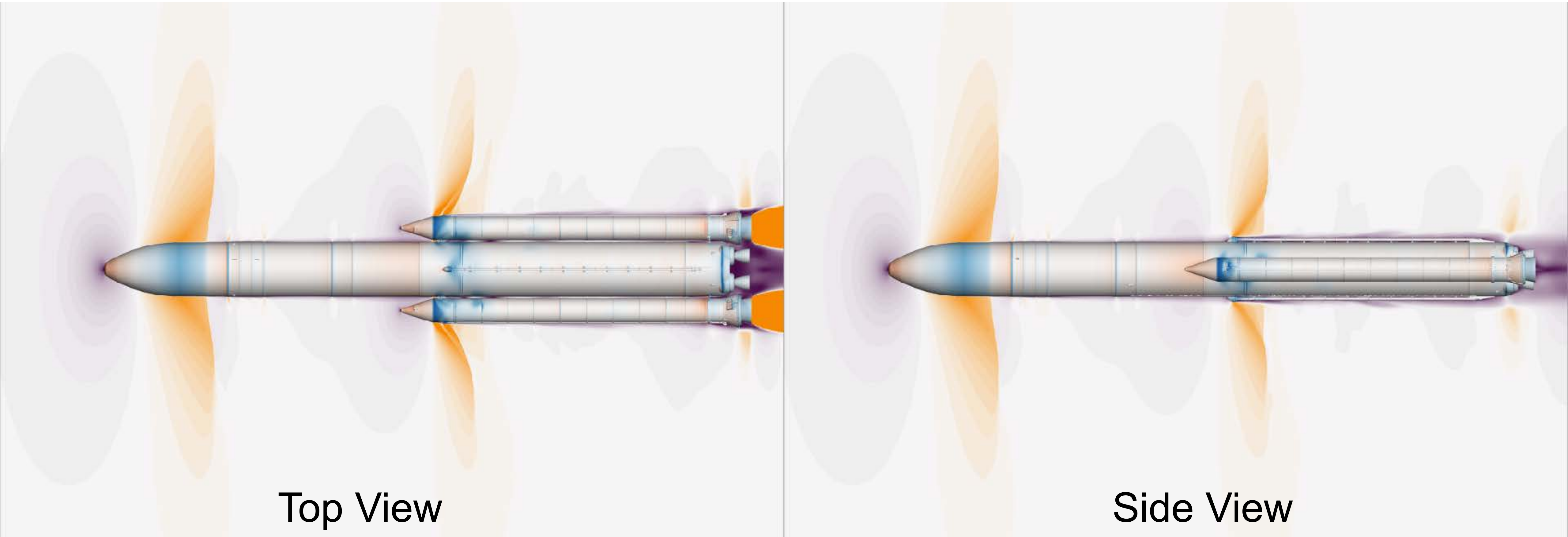


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Cargo Ascent

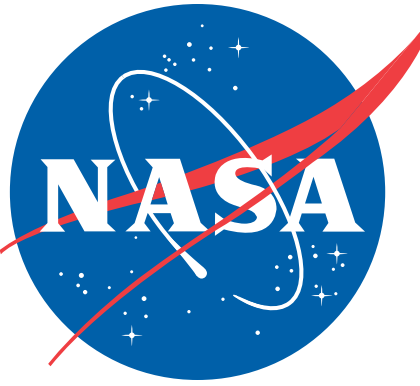


Altitude: Low High

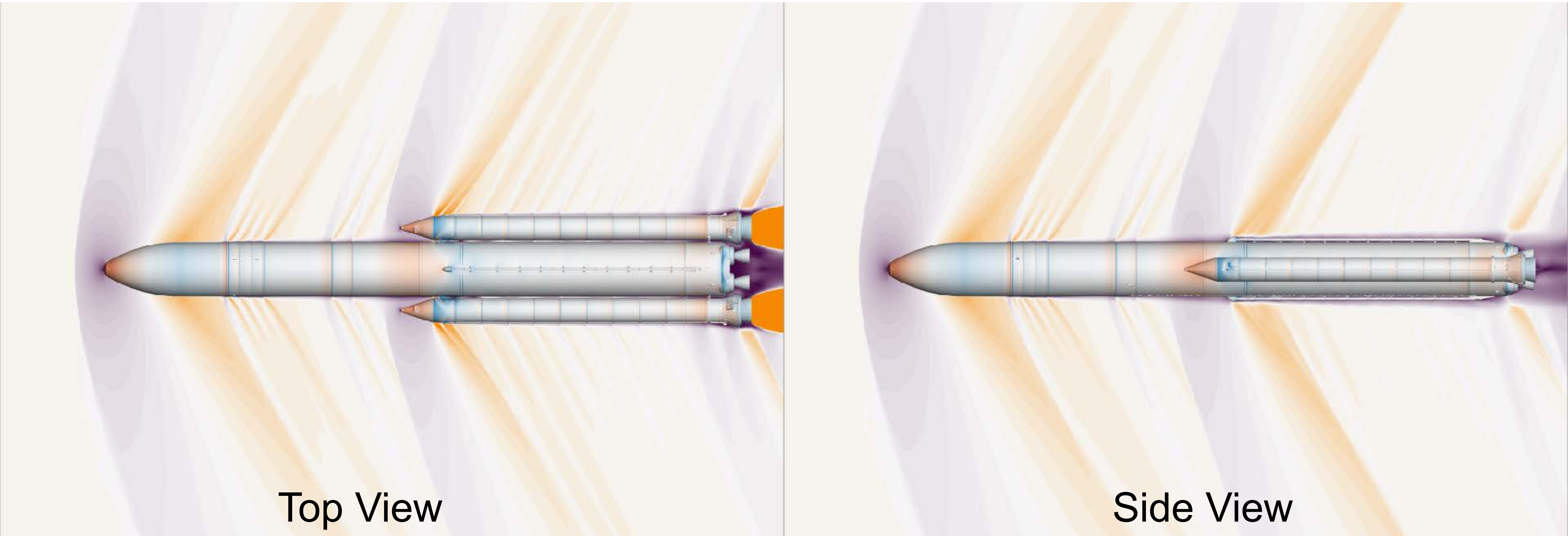


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Cargo Ascent



Altitude: Low • • • • • • • • • • • • • • High

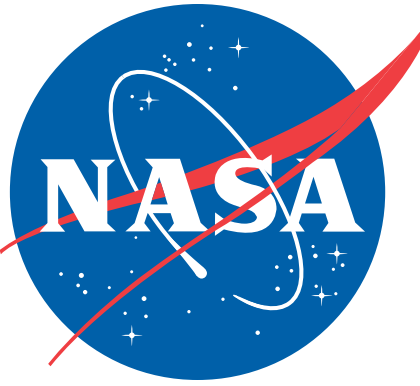


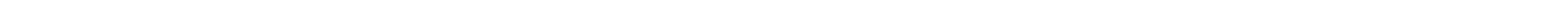
Top View

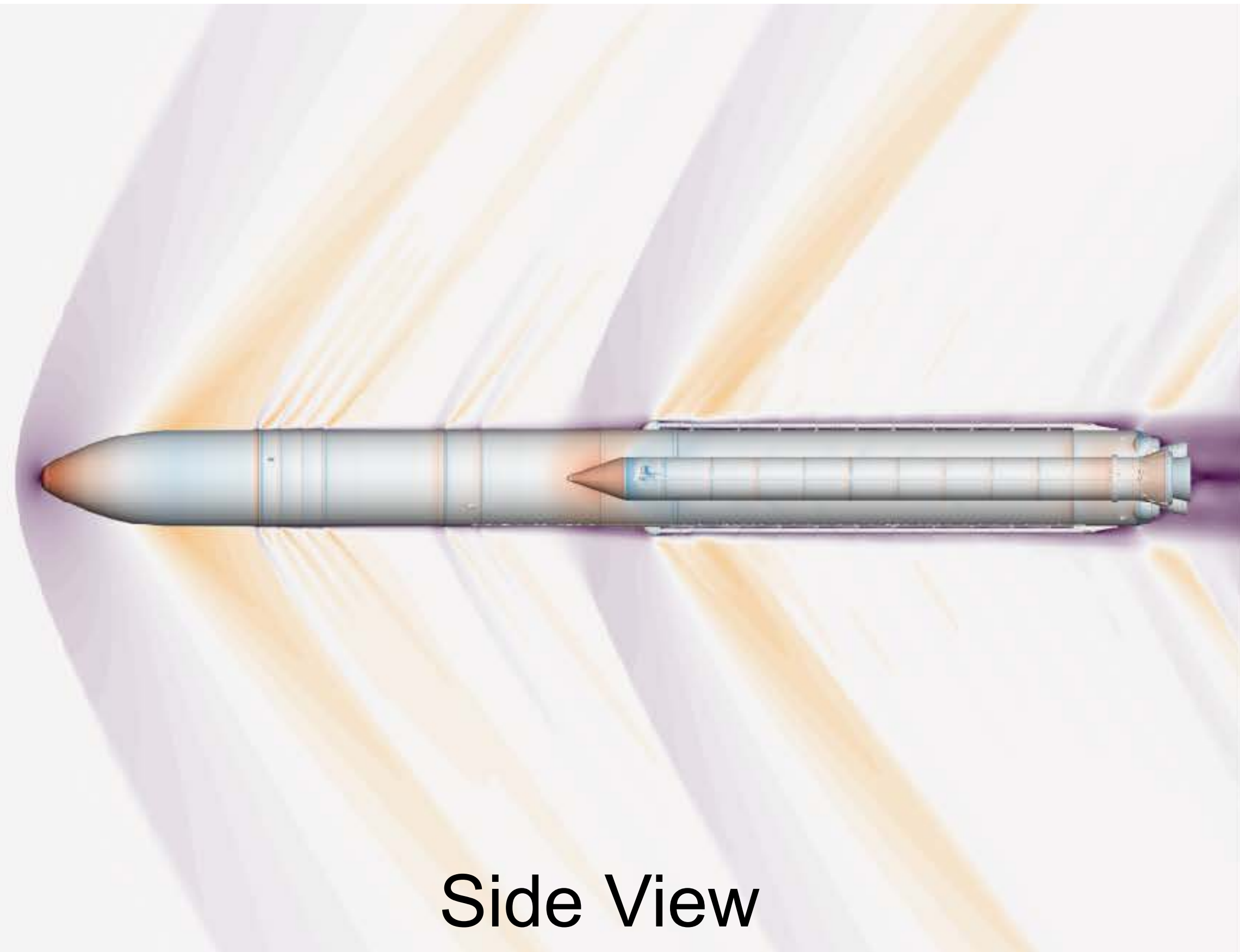
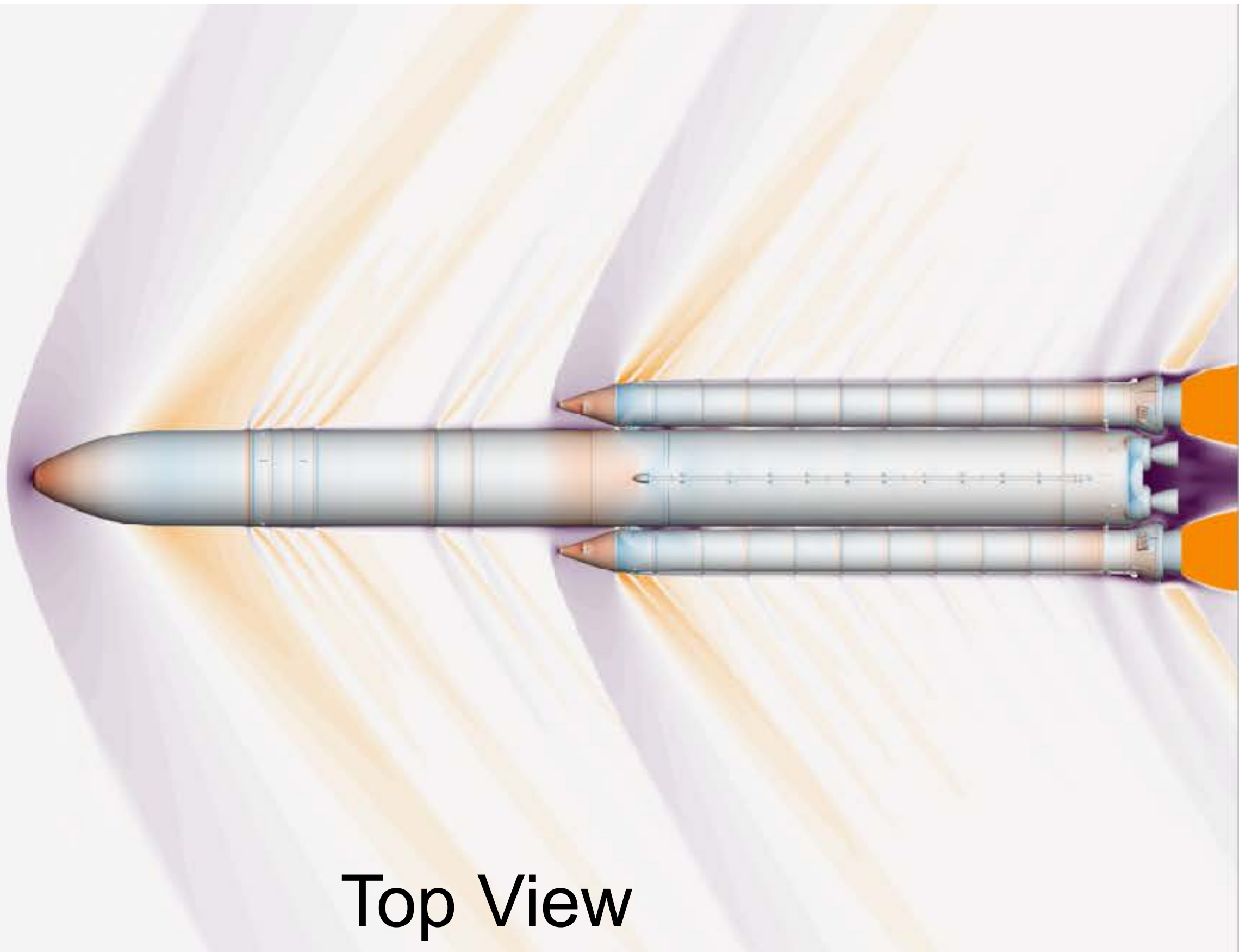
Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Cargo Ascent

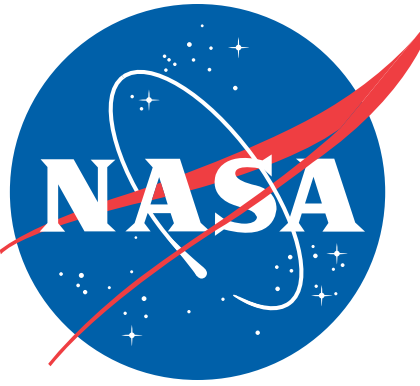


Altitude: Low  High

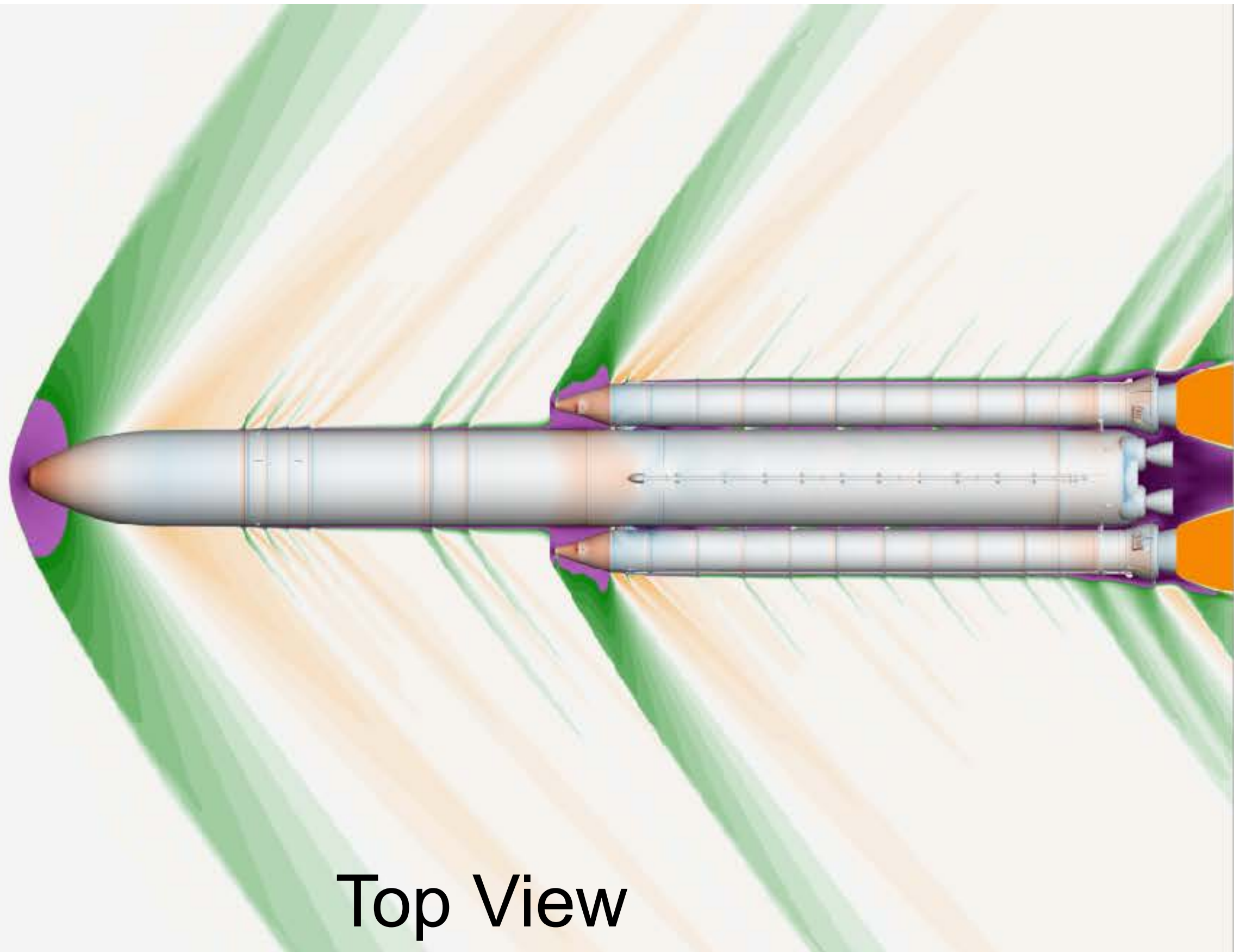


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

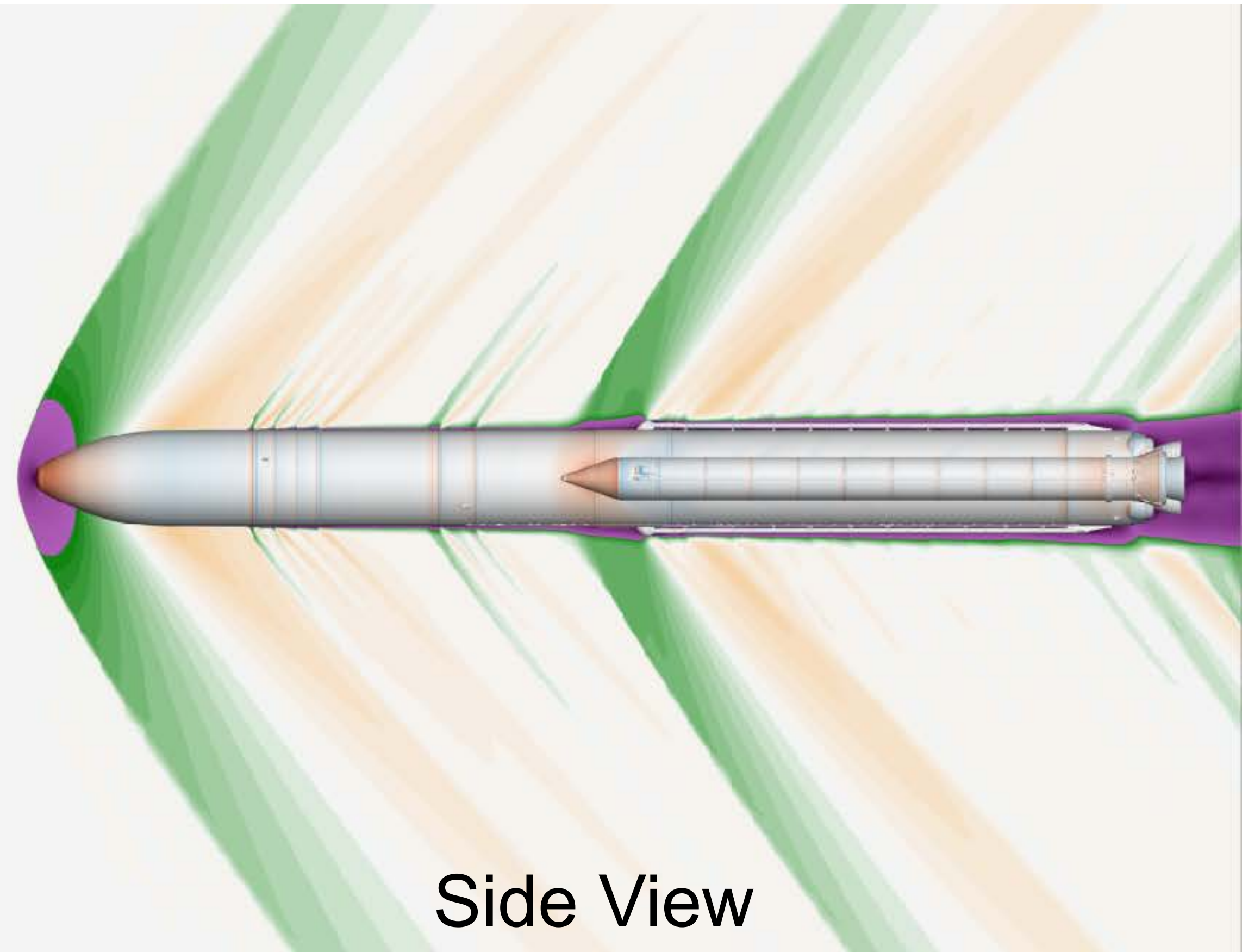
SLS Block 1B Cargo Ascent



Altitude: Low • • • • • • • • • • • • • • • • High



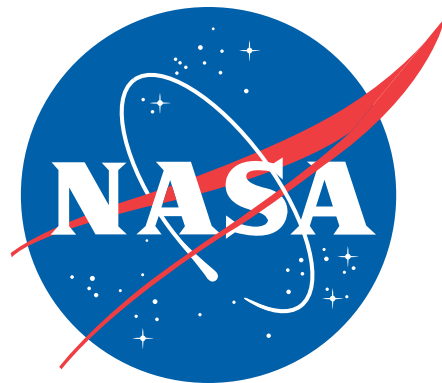
Top View



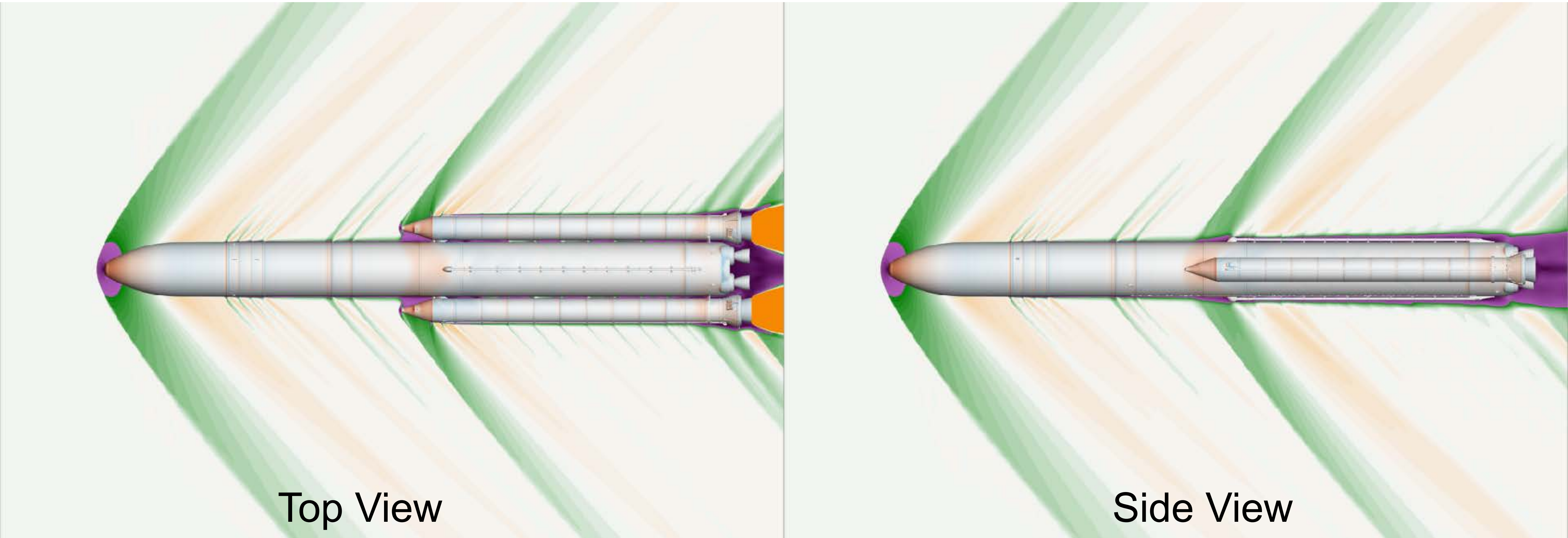
Side View

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SLS Block 1B Cargo Ascent



Altitude: Low • • • • • • • • • • • • • • • High

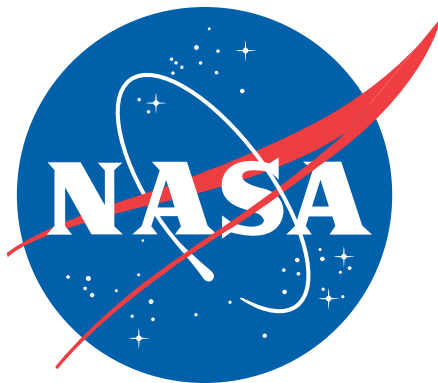


Top View

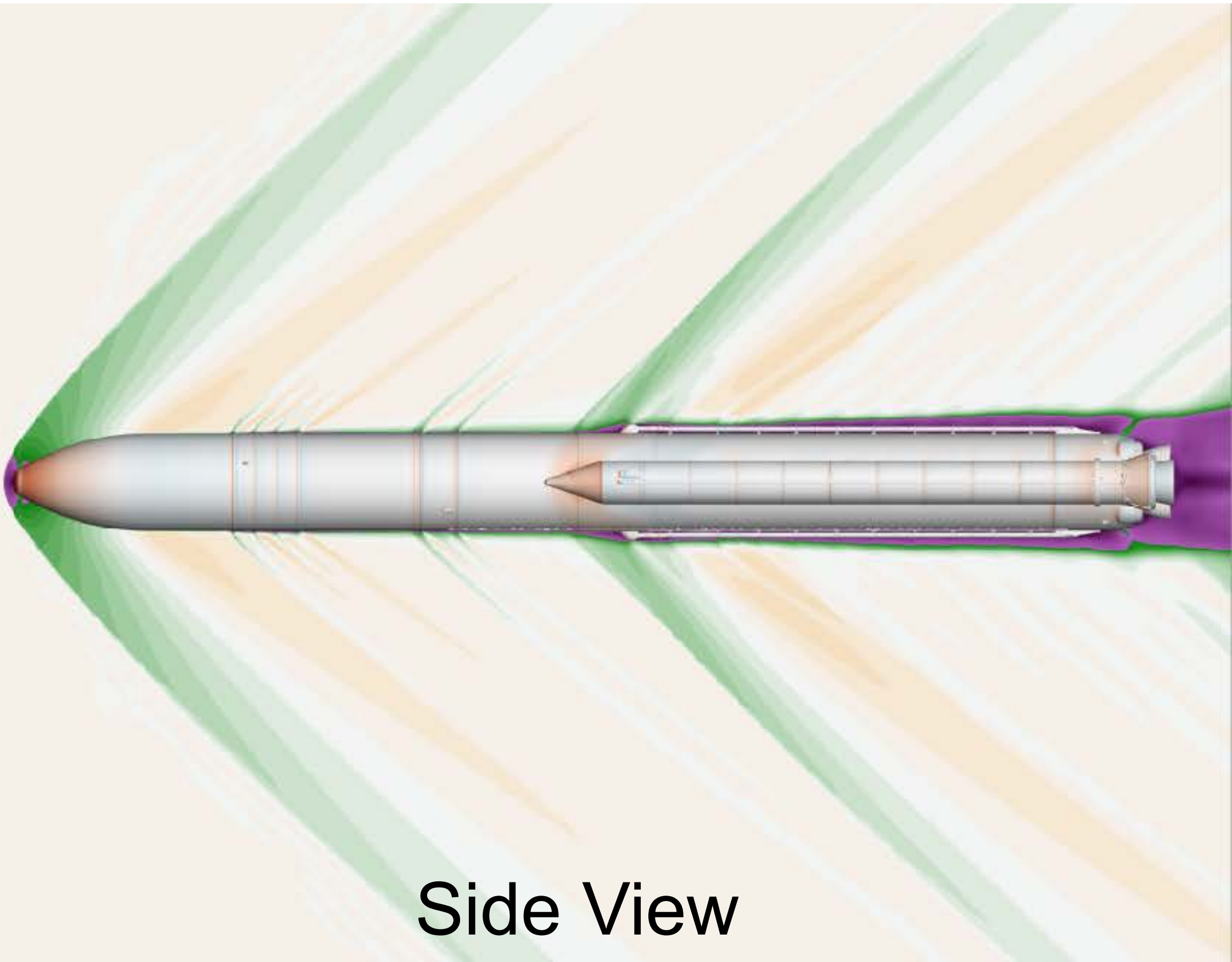
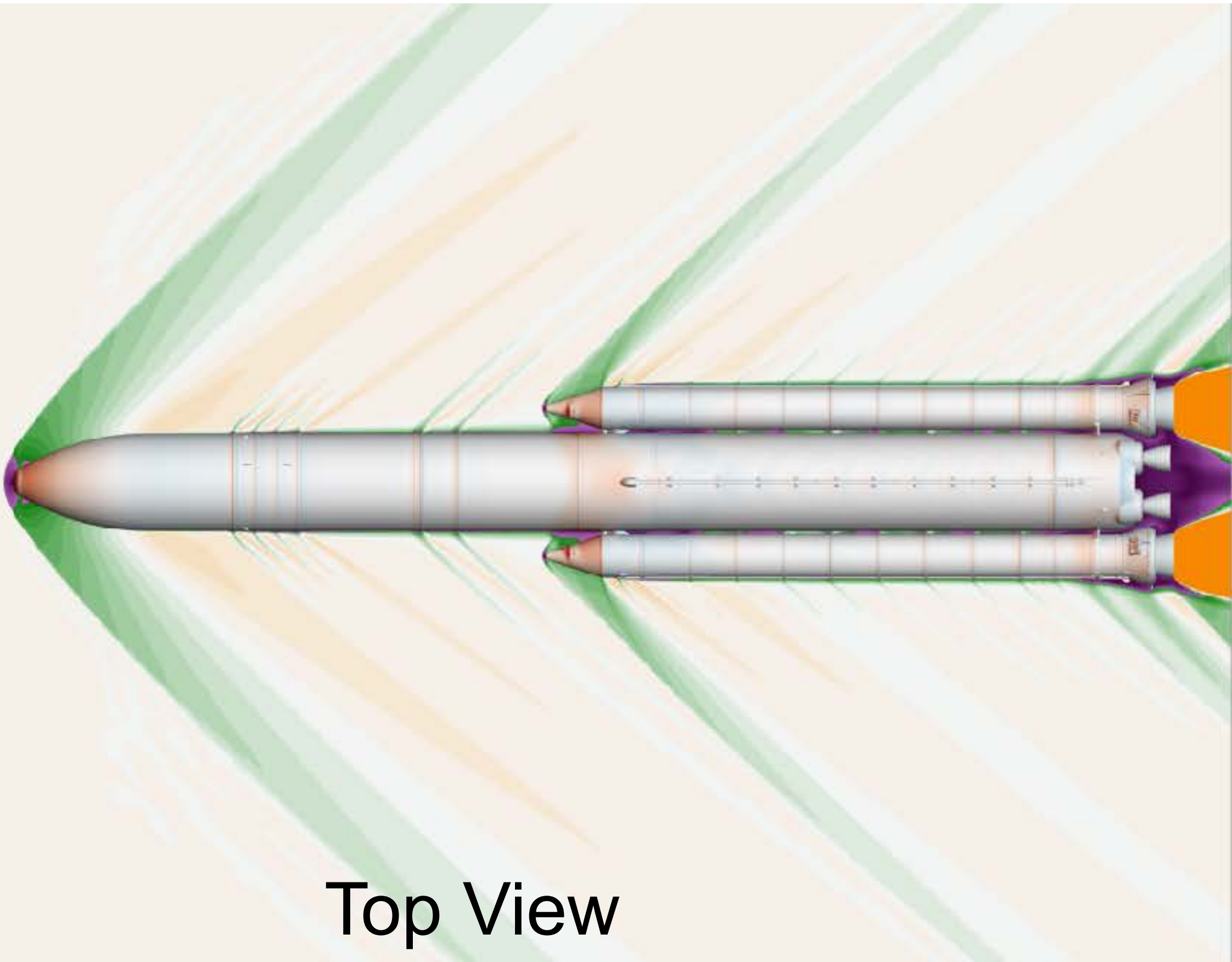
Side View

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Vehicle surface blue-white-red color contours represent low to high pressures

SLS Block 1B Cargo Ascent

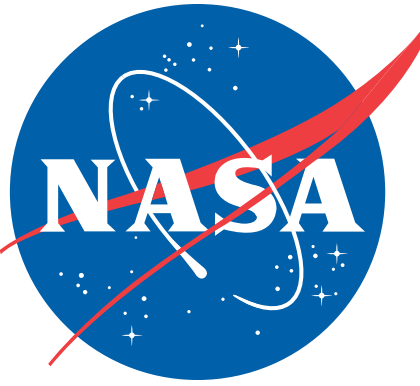


Altitude: Low • • • • • • • • • • • • • • High

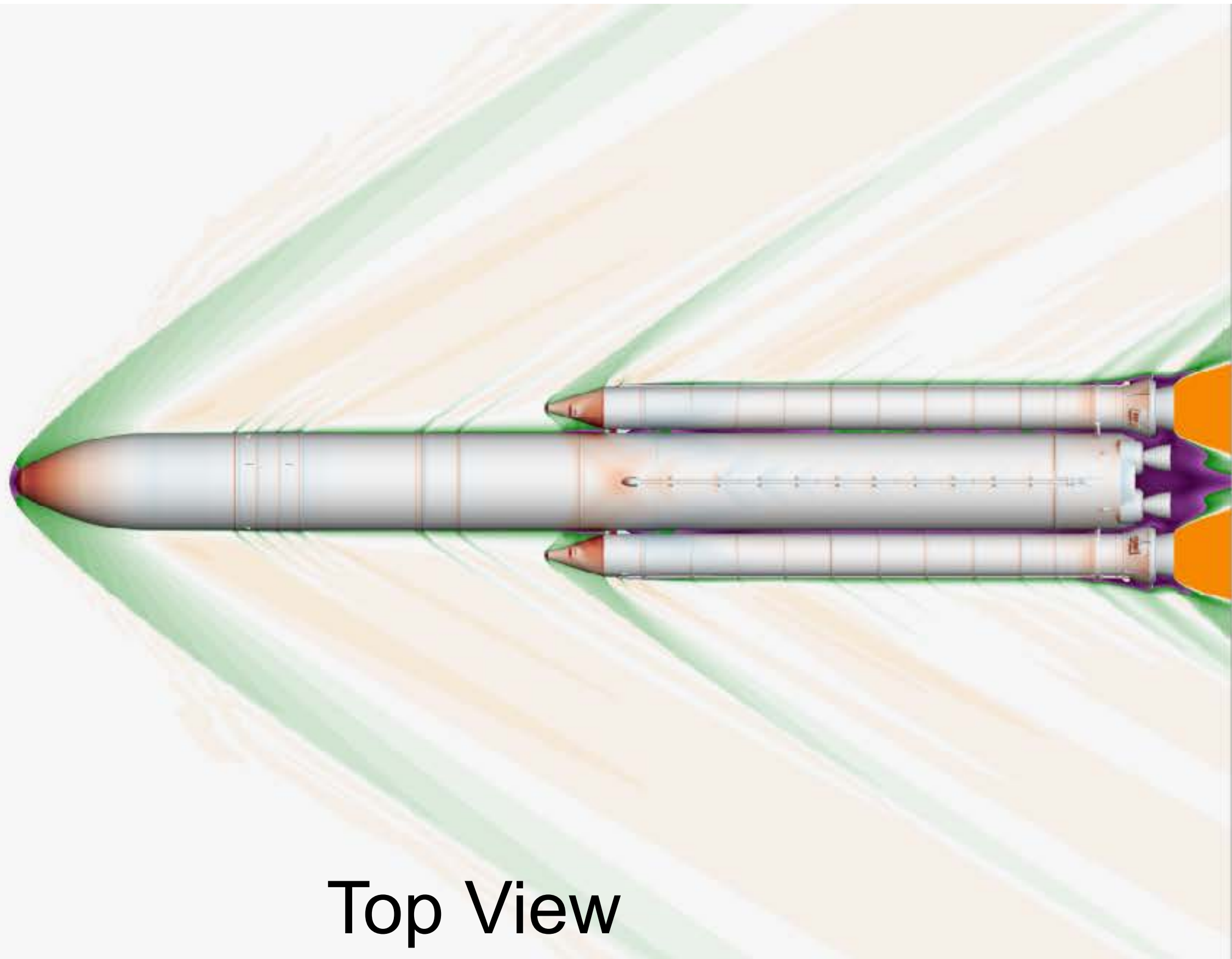


Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

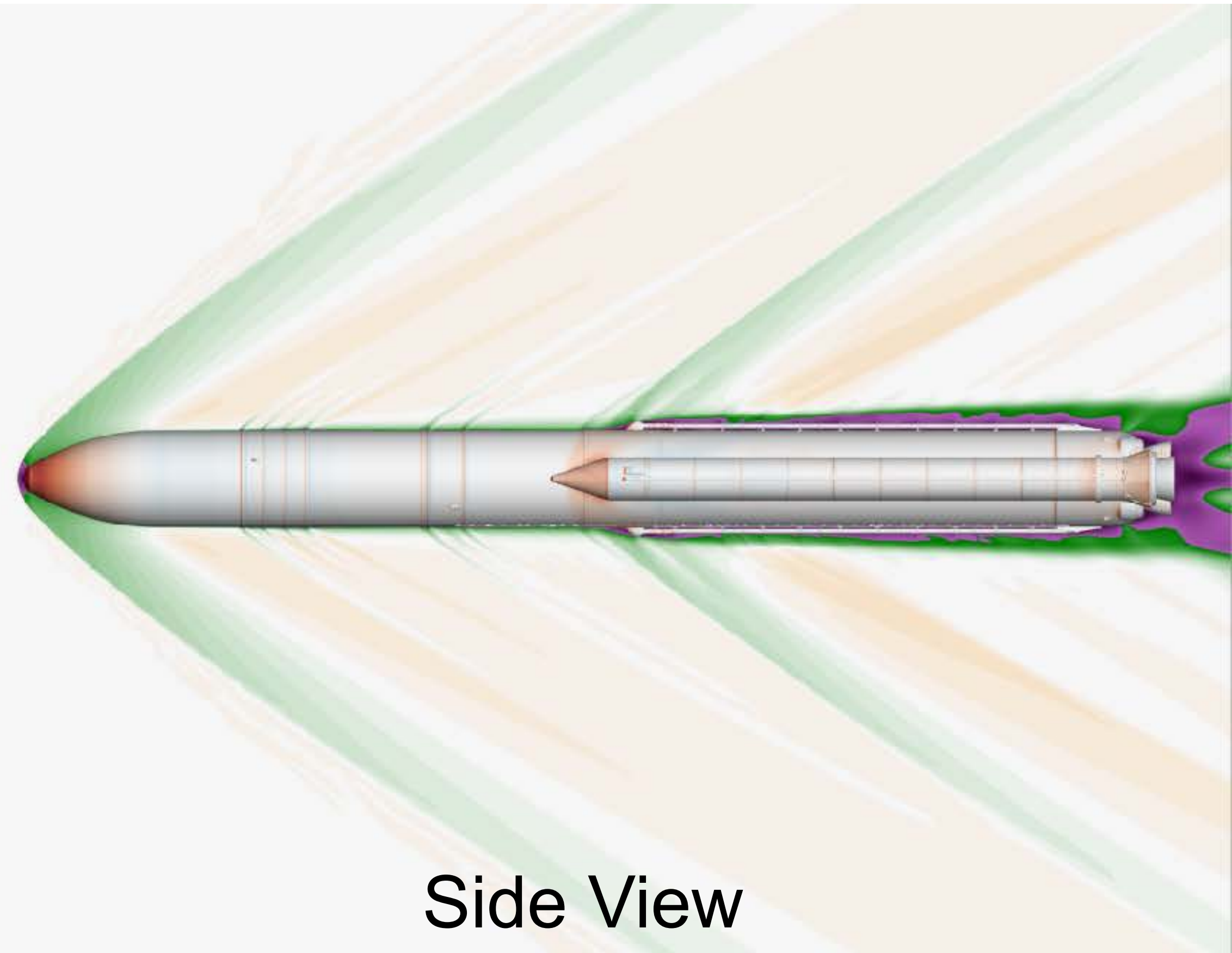
SLS Block 1B Cargo Ascent



Altitude: Low • • • • • • • • • • • • • • • • High



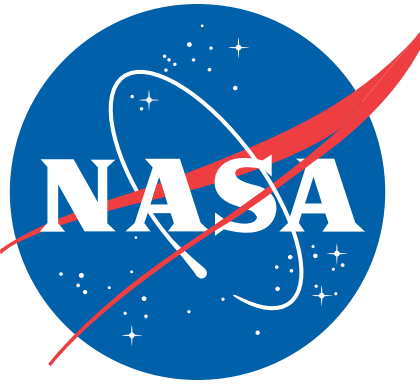
Top View



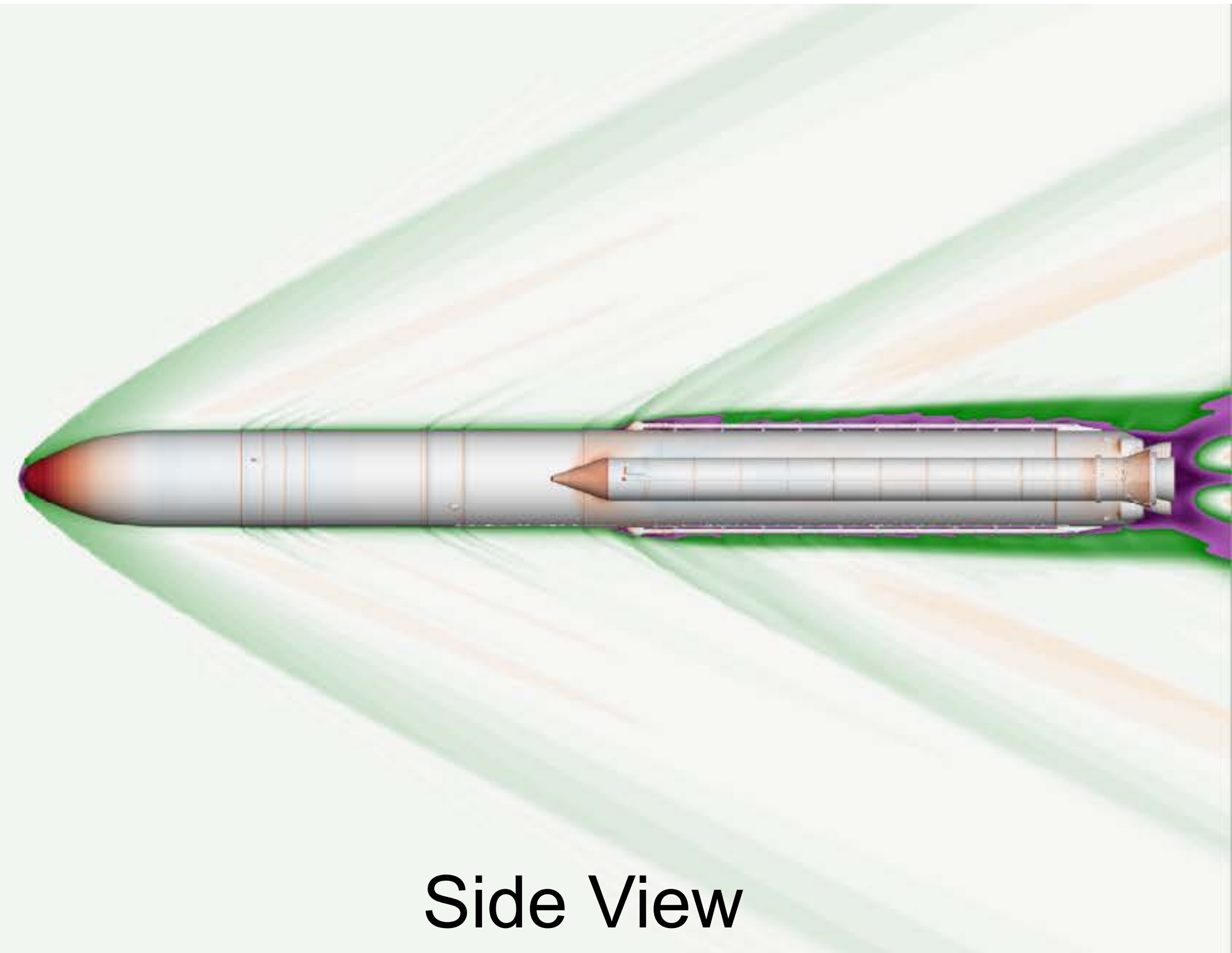
Side View

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SLS Block 1B Cargo Ascent

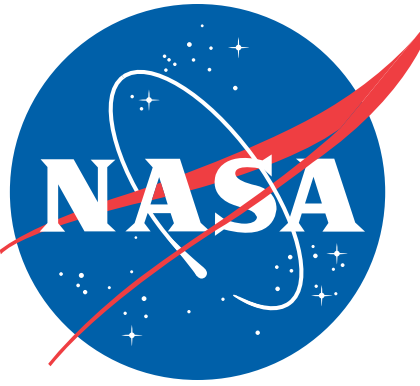


Altitude: Low • • • • • • • • • • • • • • • • High



Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

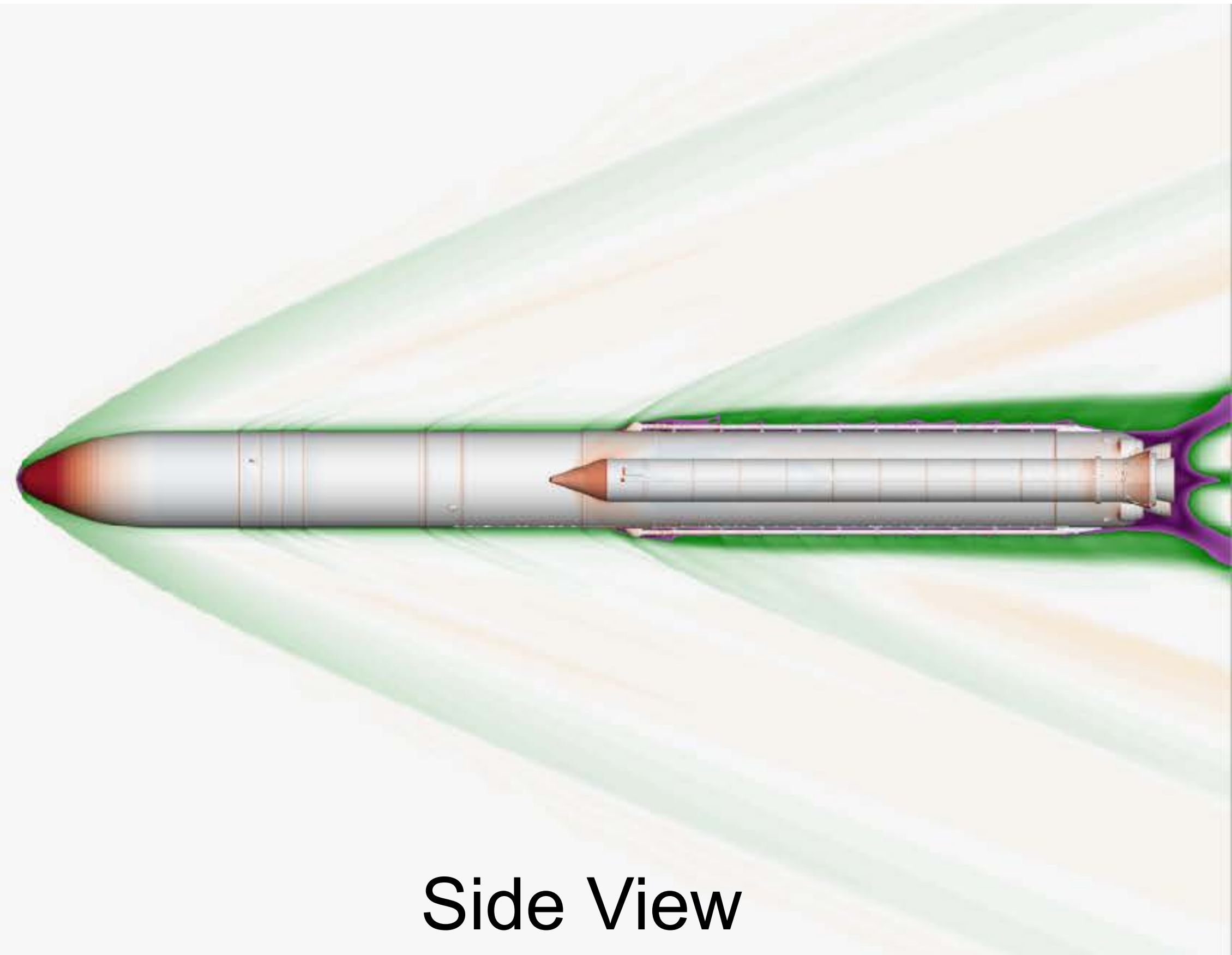
SLS Block 1B Cargo Ascent



Altitude: Low • • • • • • • • • • • • • • • • High

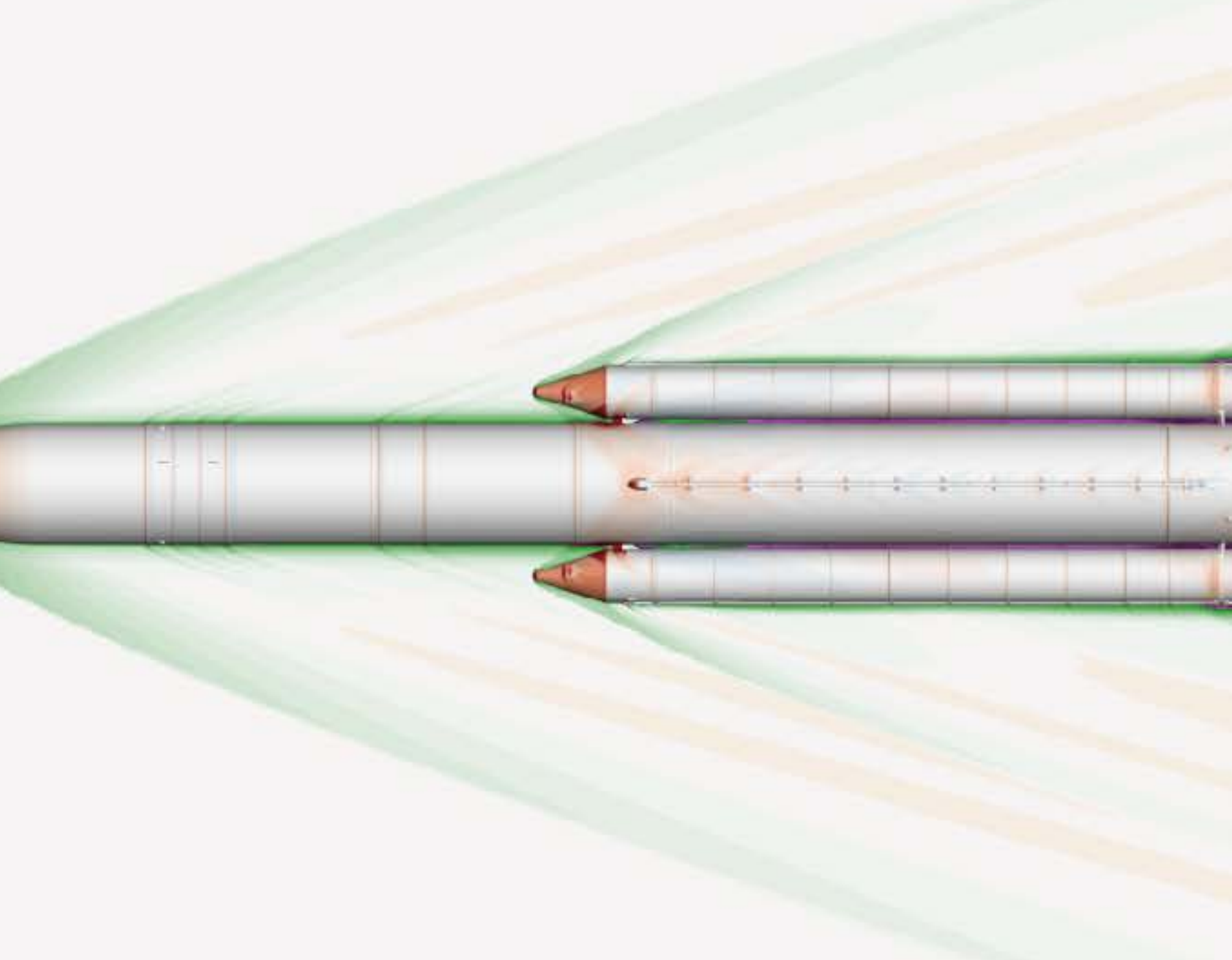


Top View

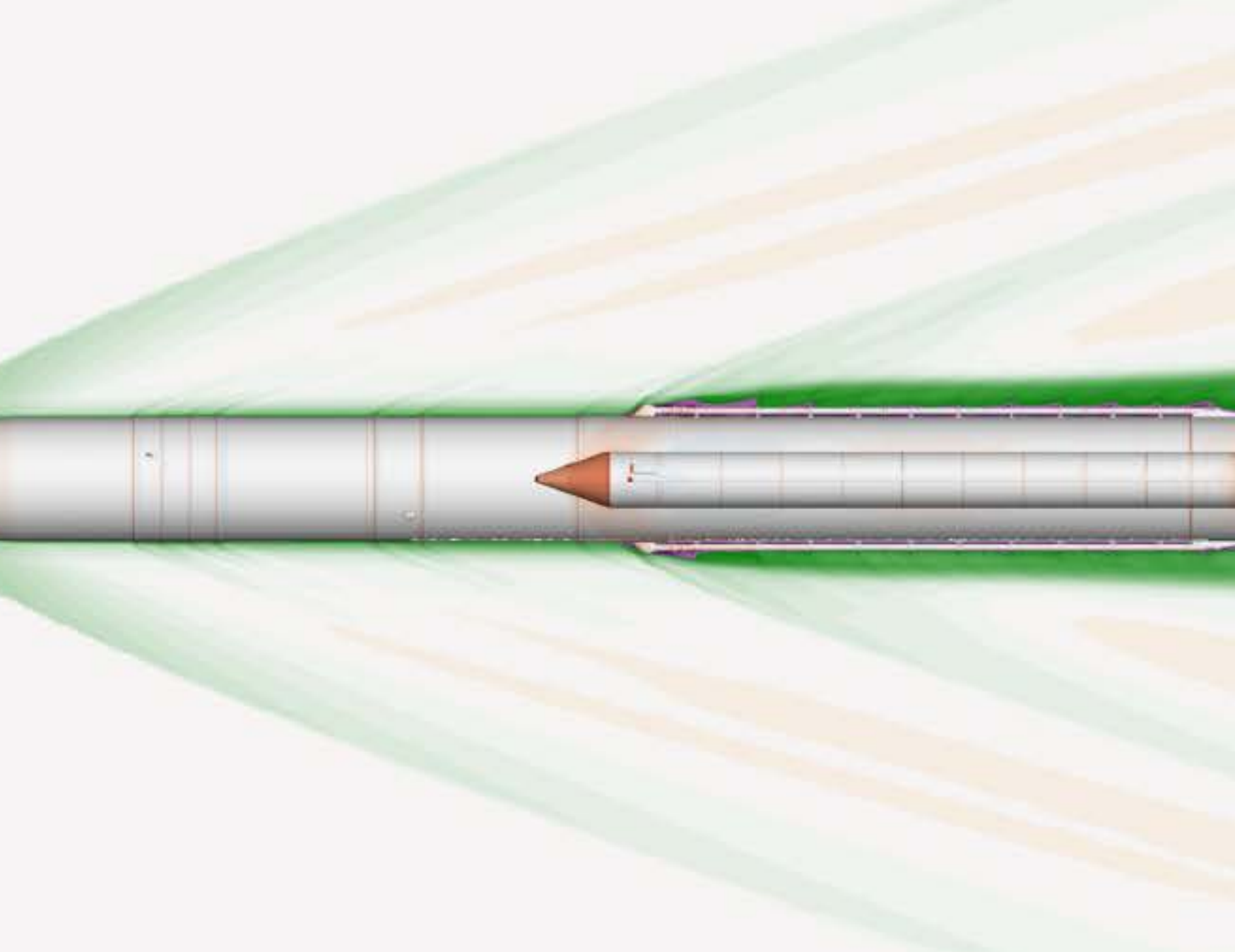


Side View

Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures



Top View

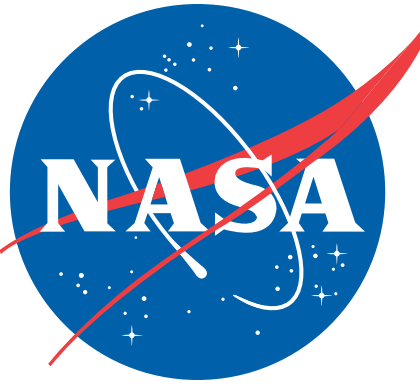
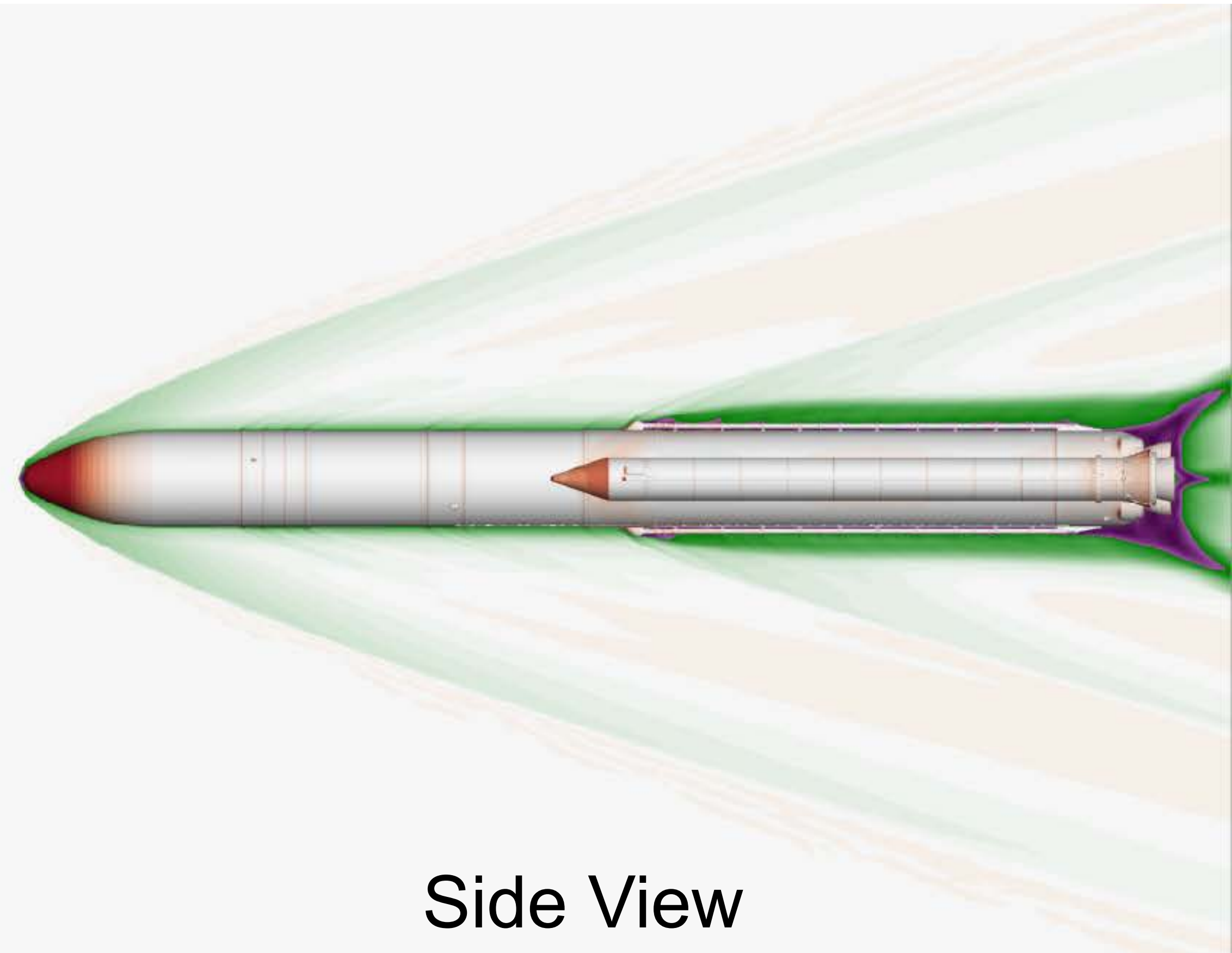
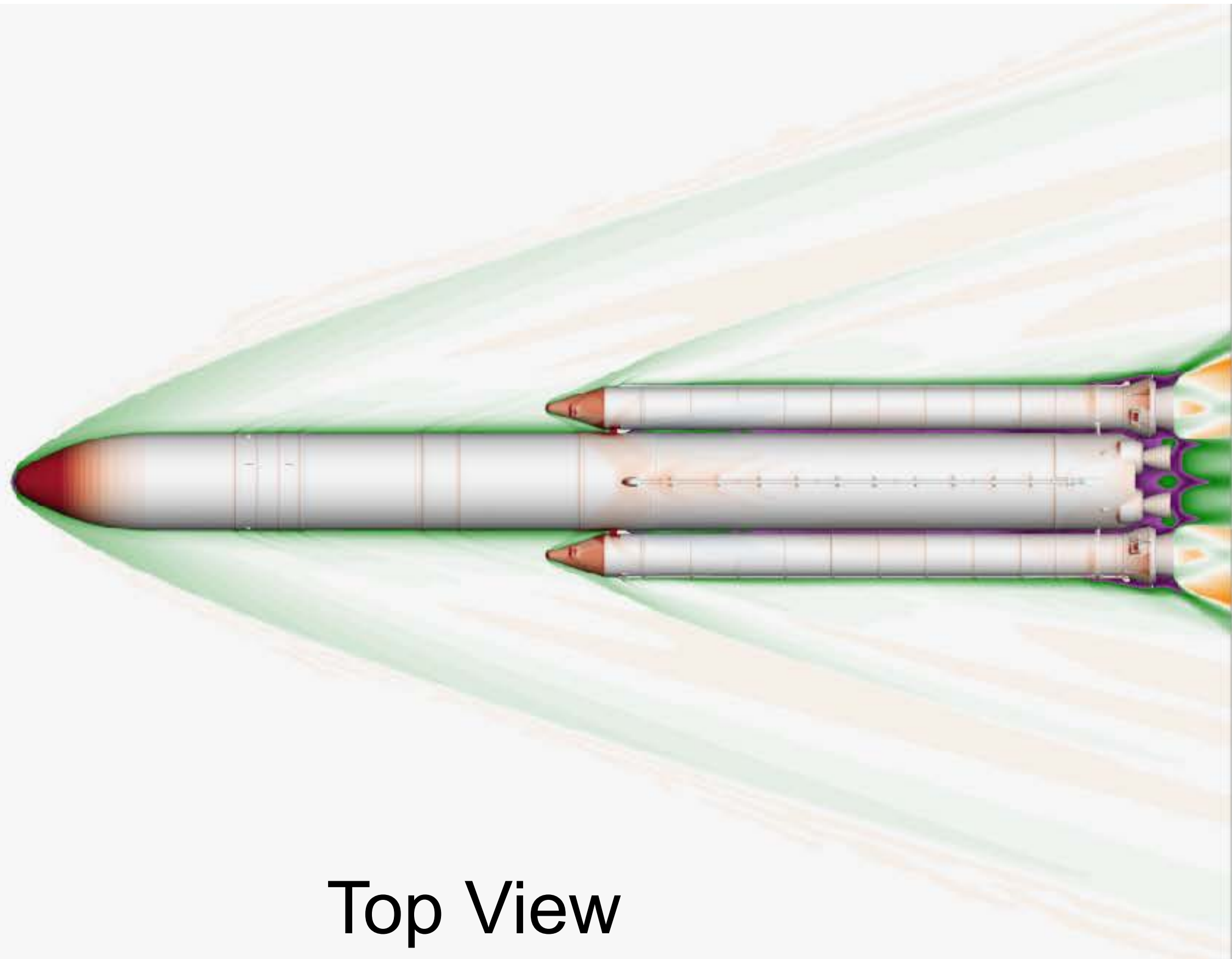


A side-view illustration of a rocket traveling from left to right. The rocket is white with a red nose cone and a black base. A large, green, teardrop-shaped shockwave surrounds the rocket's nose. Behind the shockwave, several orange streamlines flow parallel to the rocket's body. The background is a light blue gradient.

Side View

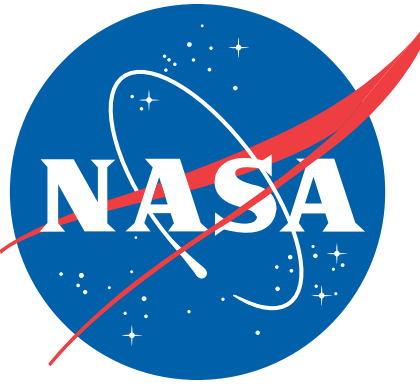
Background slice purple-green-white-orange color contours represent low to high velocities
Vehicle surface blue-white-red color contours represent low to high pressures

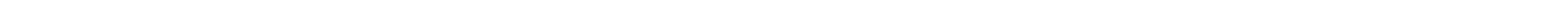
SLS Block 1B Cargo Ascent

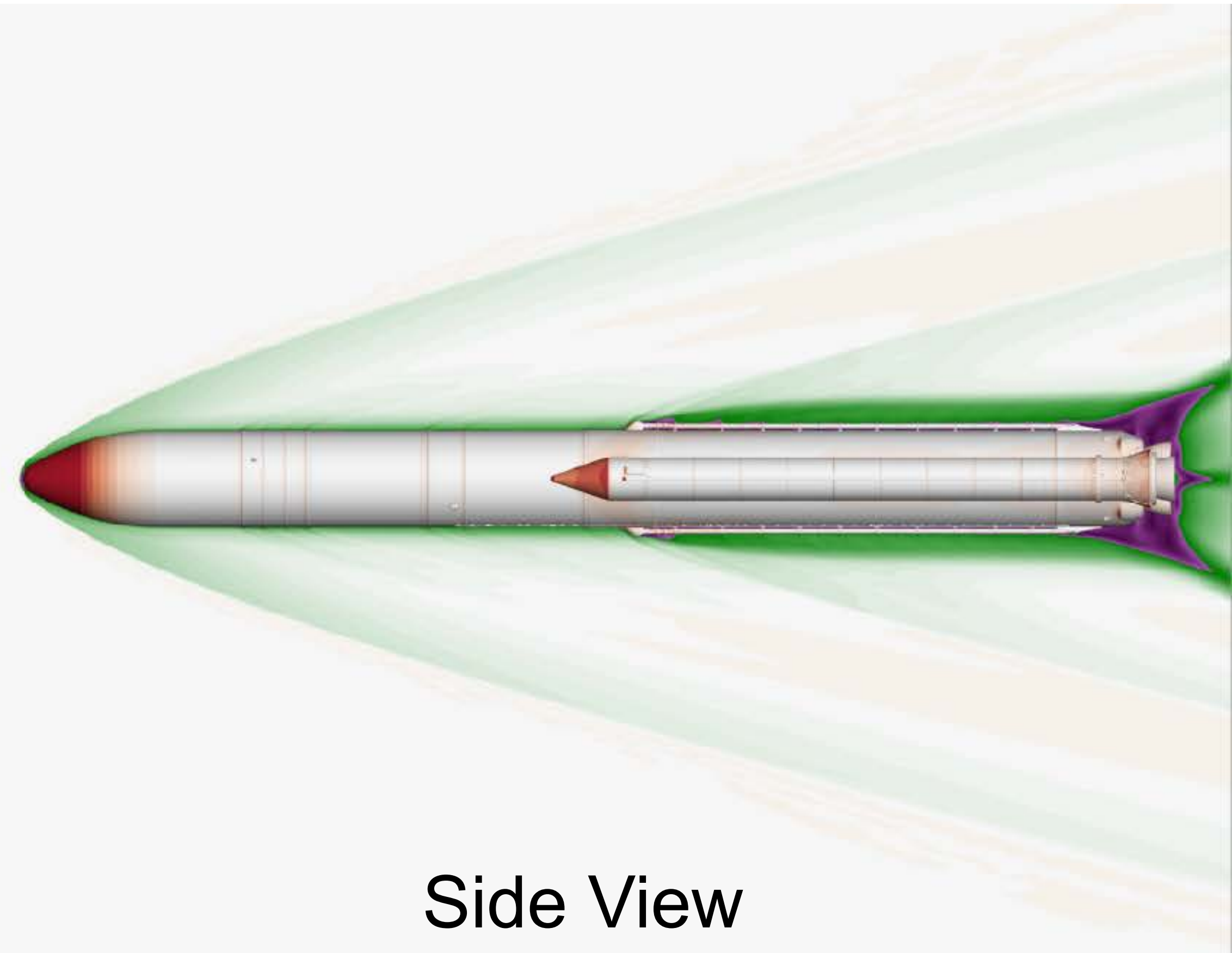
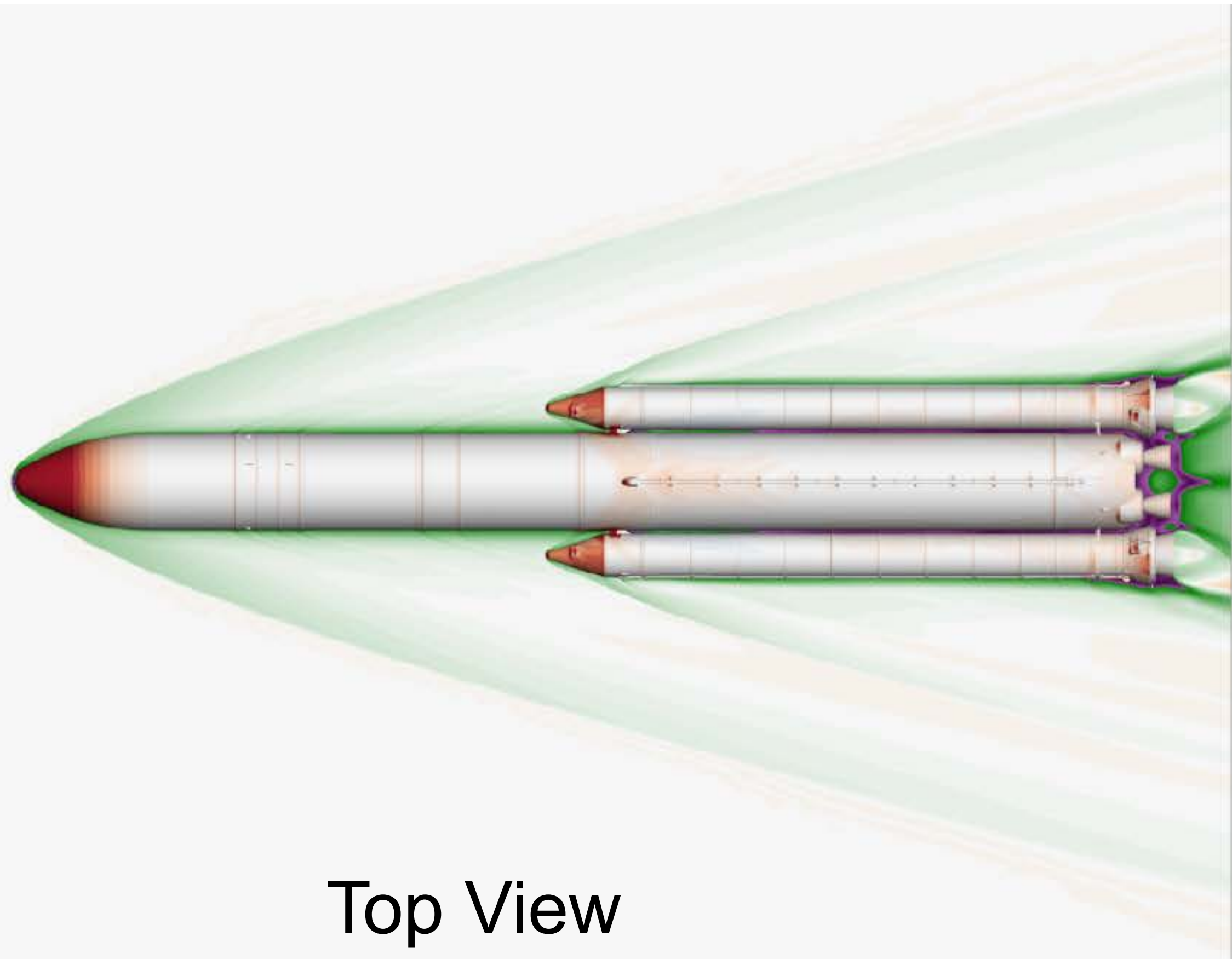
[illegible]

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SLS Block 1B Cargo Ascent

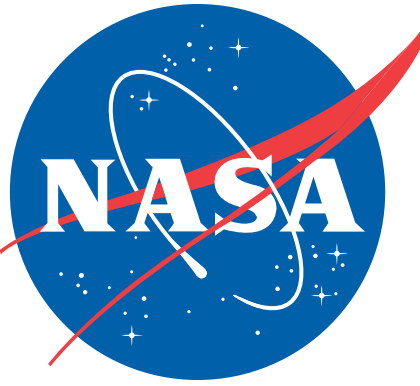


Altitude: Low  High

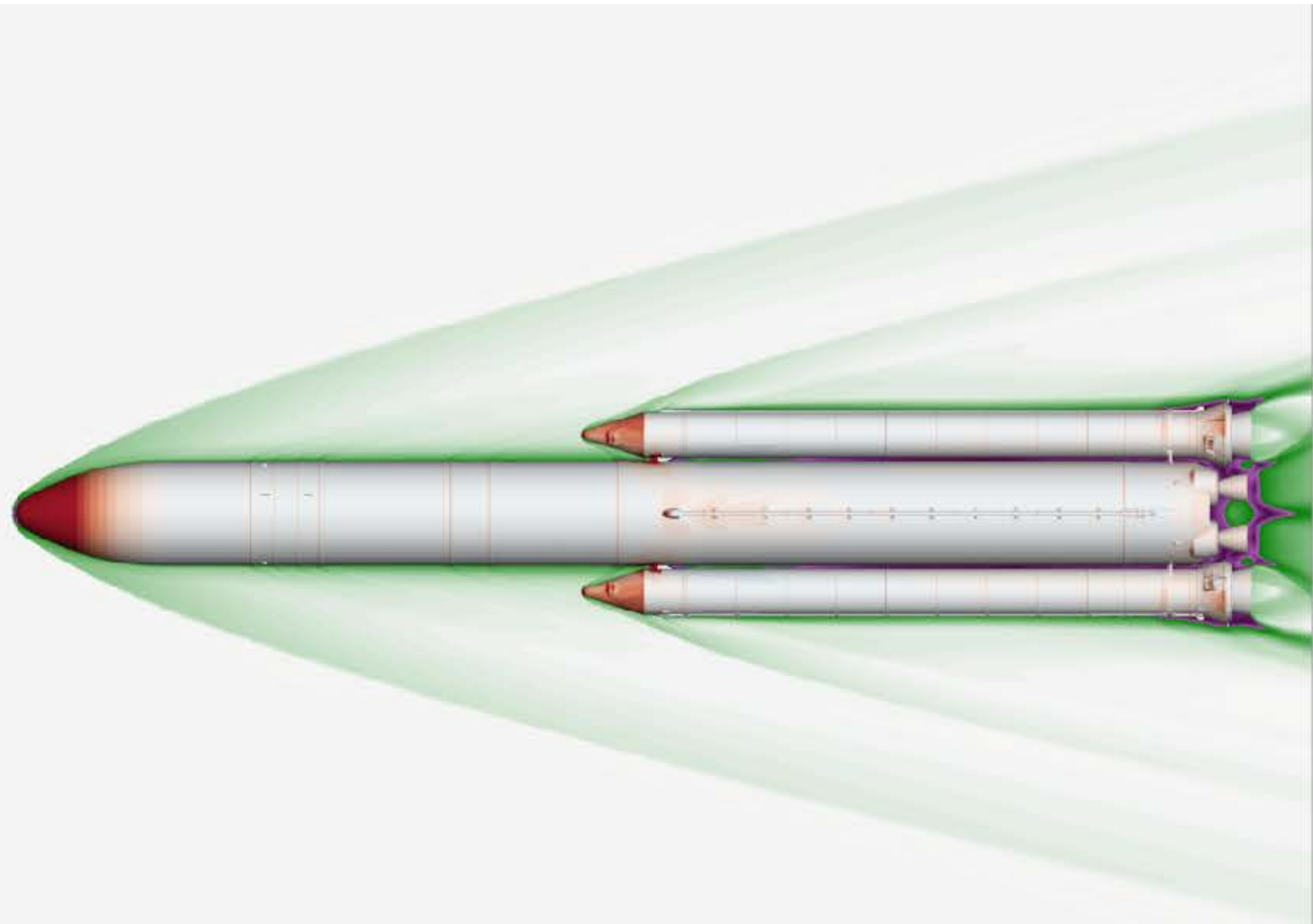


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SLS Block 1B Cargo Ascent



Altitude: Low • • • • • • • • • • • • • • • • • High



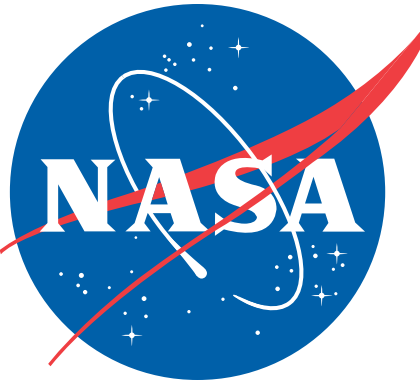
Top View



Side View

Background slice purple-green-white-orange color contours represent low to high velocities
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Conclusions



- NAS Pleiades Supercomputer enabled the creation of a CFD-based database for SLS booster separation
 - Created 4 aerodynamic databases for 3 vehicles
 - Over 71 Million core-hours over the last year
 - Over 8000 FUN3D cases
 - Over 1100 Overflow cases
 - Over 2.0 Million core-hours for moving body simulation to validate static-database method
- Successfully developed very complex aerodynamic databases
 - Most complex databases using CFD data in SLS program
 - Used extensively throughout the design process of the SLS rocket family