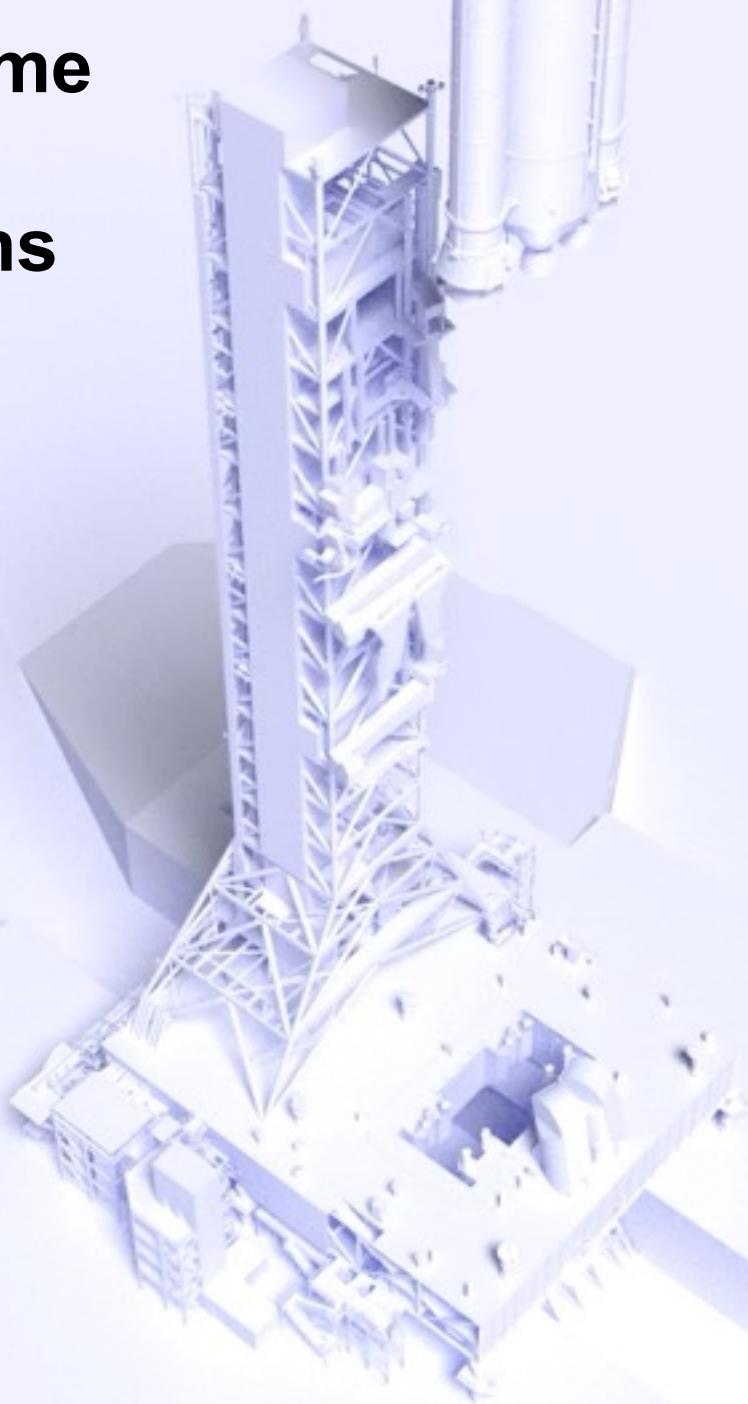


Launch Pad Rocket Plume Simulations Supporting NASA's Artemis Missions

Scott Neuhoff, Chris DeGrendele,
Michael Barad, James Jensen,
Francois Cadieux, Emre Sozer, Jared
Duensing

November 2023

SC2023, Denver, Colorado



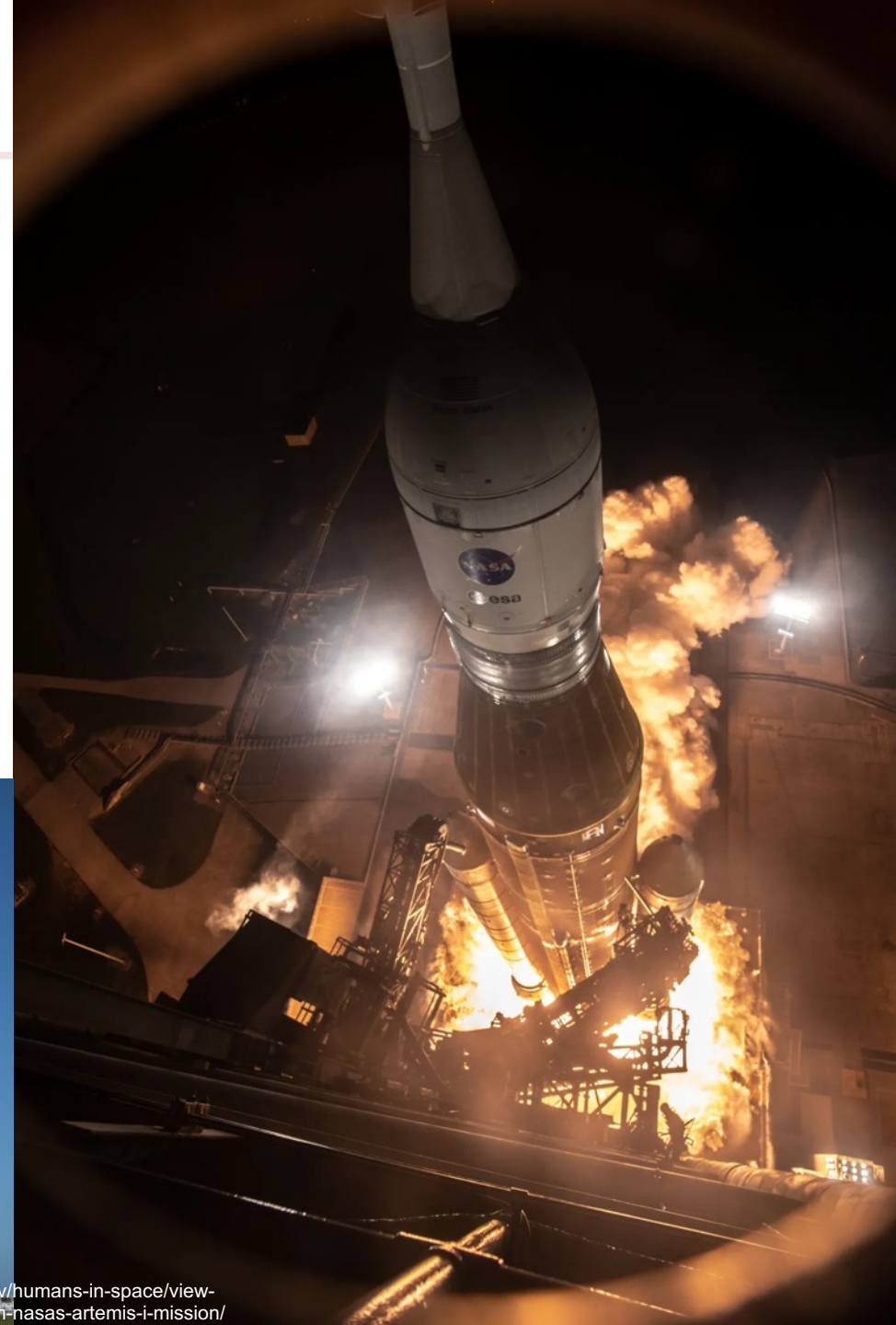
Gauge pressure on surface
Volume rendering of plume

Artemis and the Space Launch System

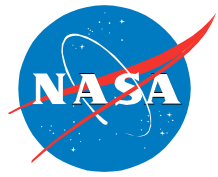
- NASA's Artemis program uses the Space Launch System to deliver the Orion crew vehicle to lunar orbit.
- SLS is the most powerful rocket NASA has ever built, which means greater loads on the launch structure like the mobile launch pad during lift-off.



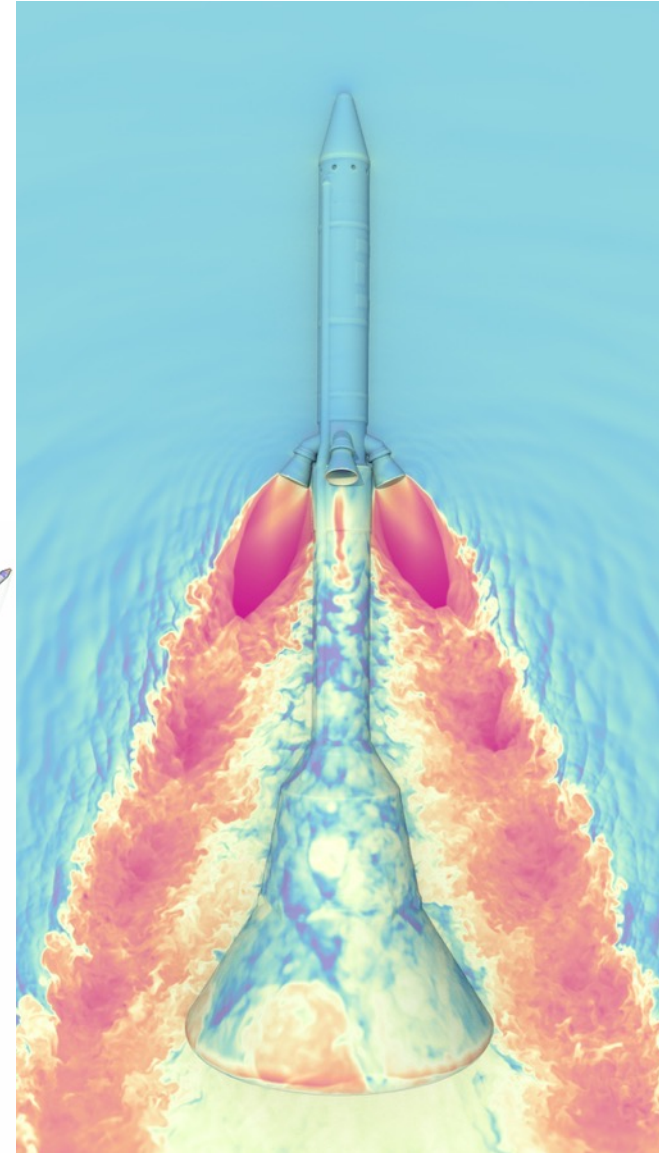
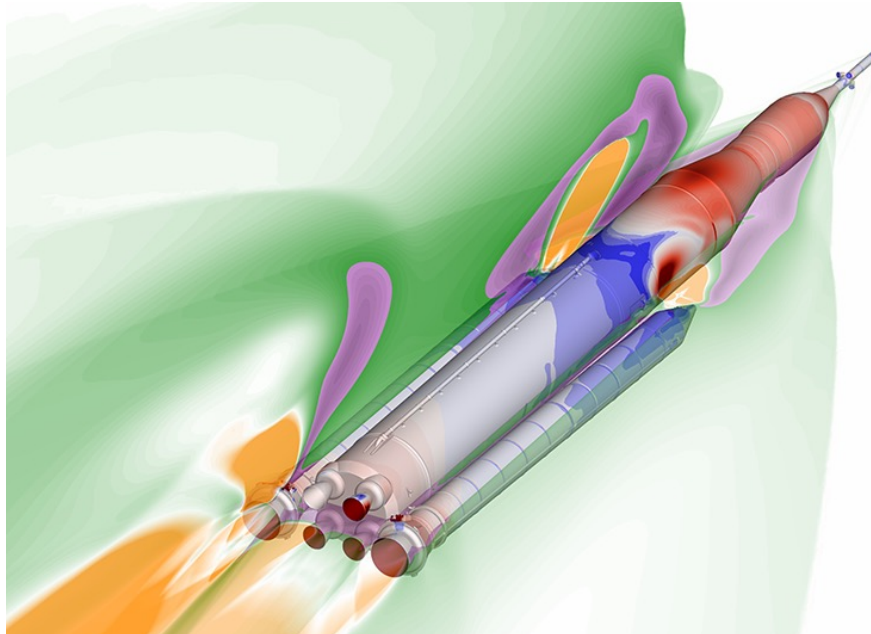
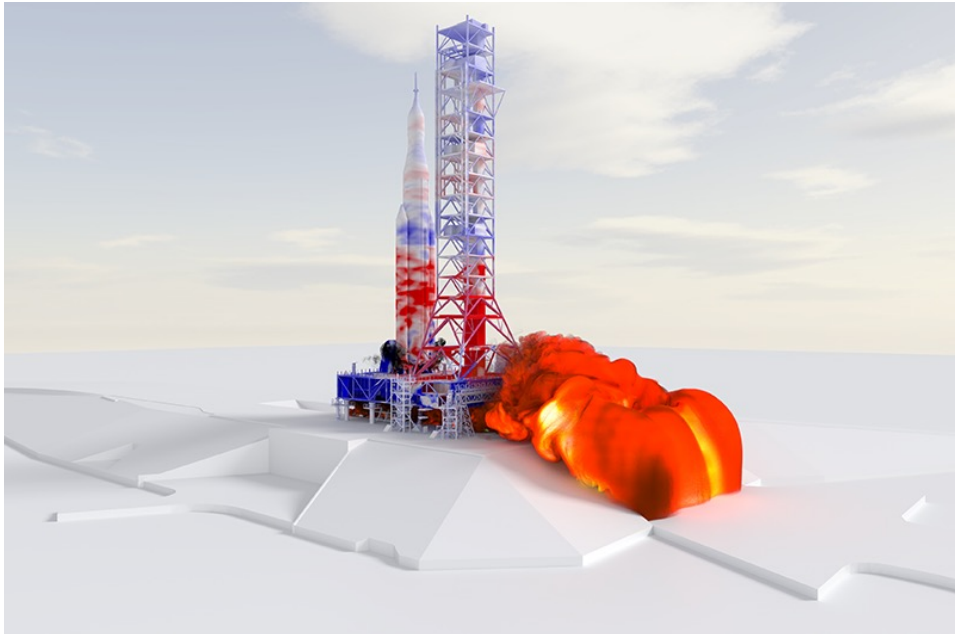
<https://www.nasa.gov/humans-in-space/view-the-best-images-from-nasas-artemis-i-mission/>



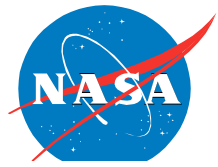
Artemis Mission and Getting Boots on the Moon



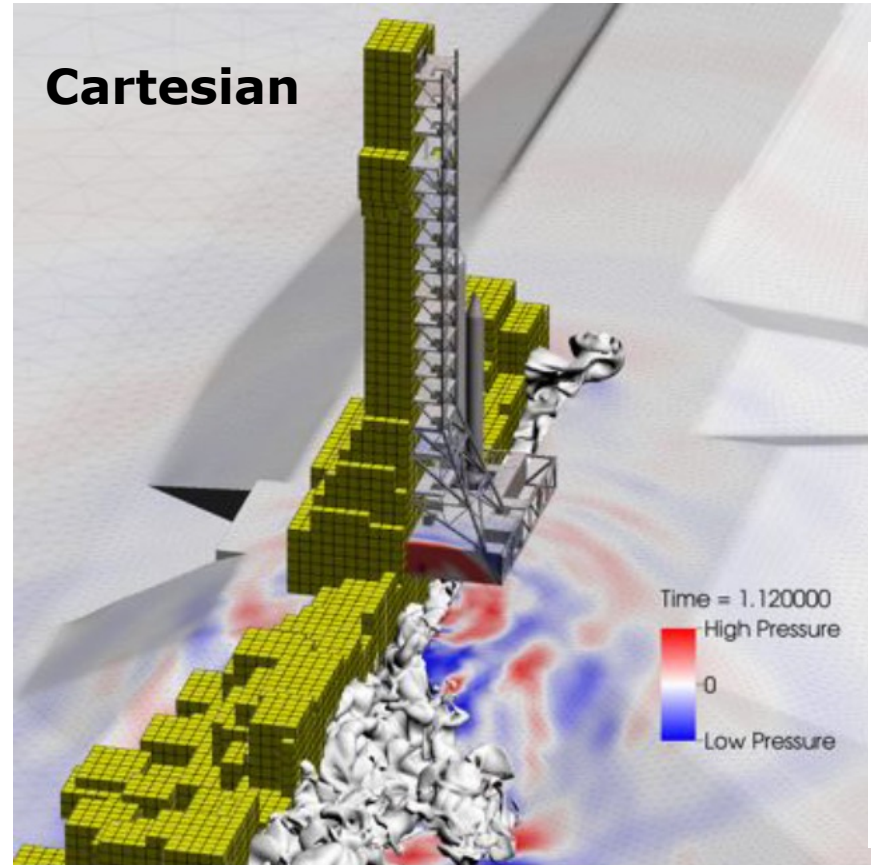
- Artemis missions will return humans to the Moon and enable future manned missions to Mars.
- NASA Advanced Supercomputing (NAS) Division at NASA Ames Research center is supporting multiple CFD efforts to enhance mission success



Choosing An Appropriate Grid Paradigm for Simulating The Launch Environment

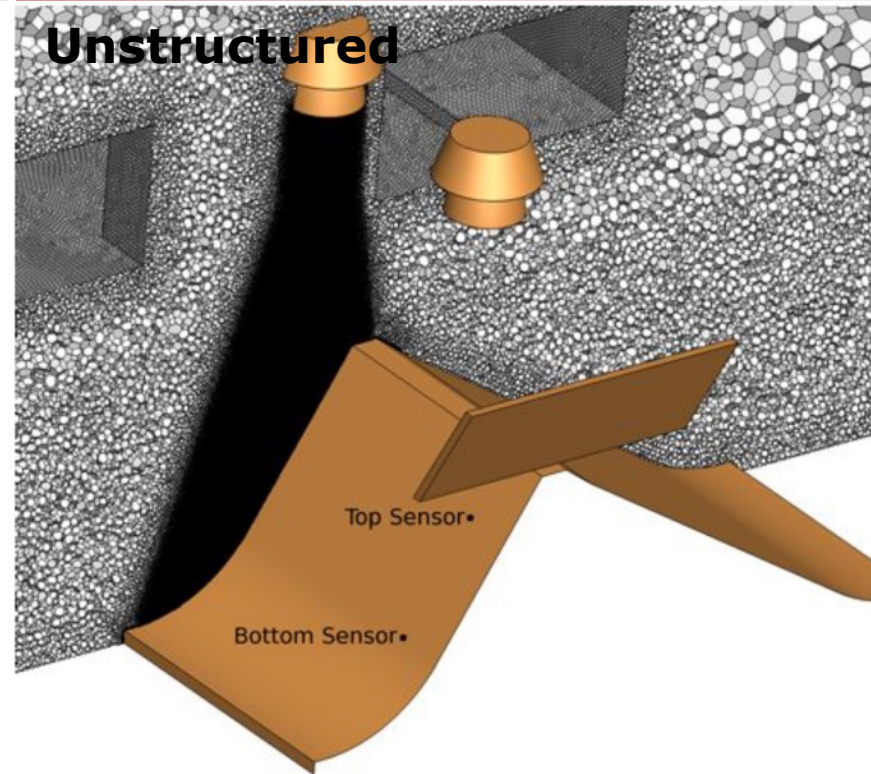


Cartesian



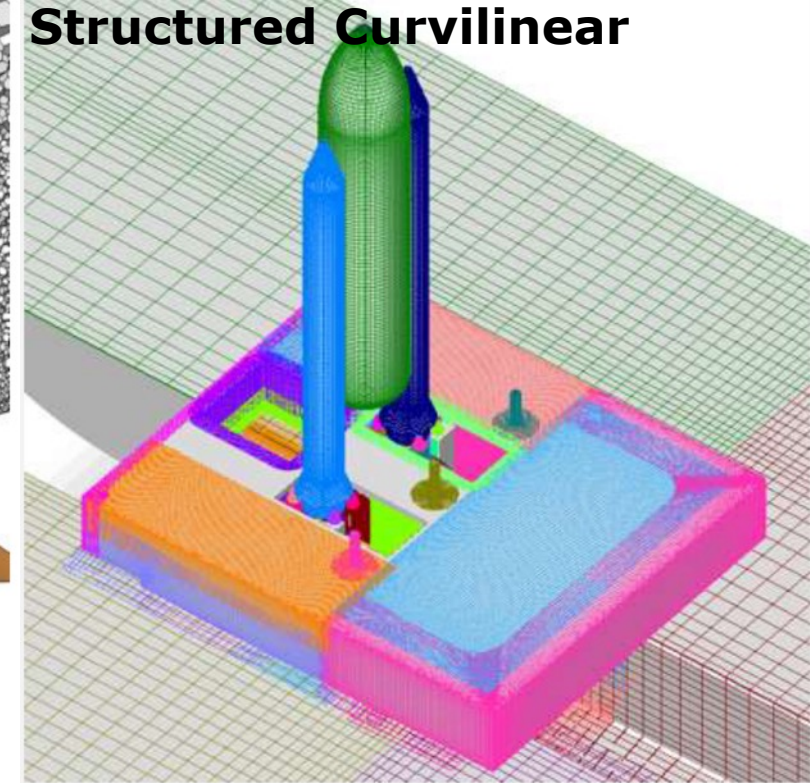
- Automatic volume grid generation
- High-order methods mature
- Isotropic grid cells nonideal for boundary layer resolution

Unstructured



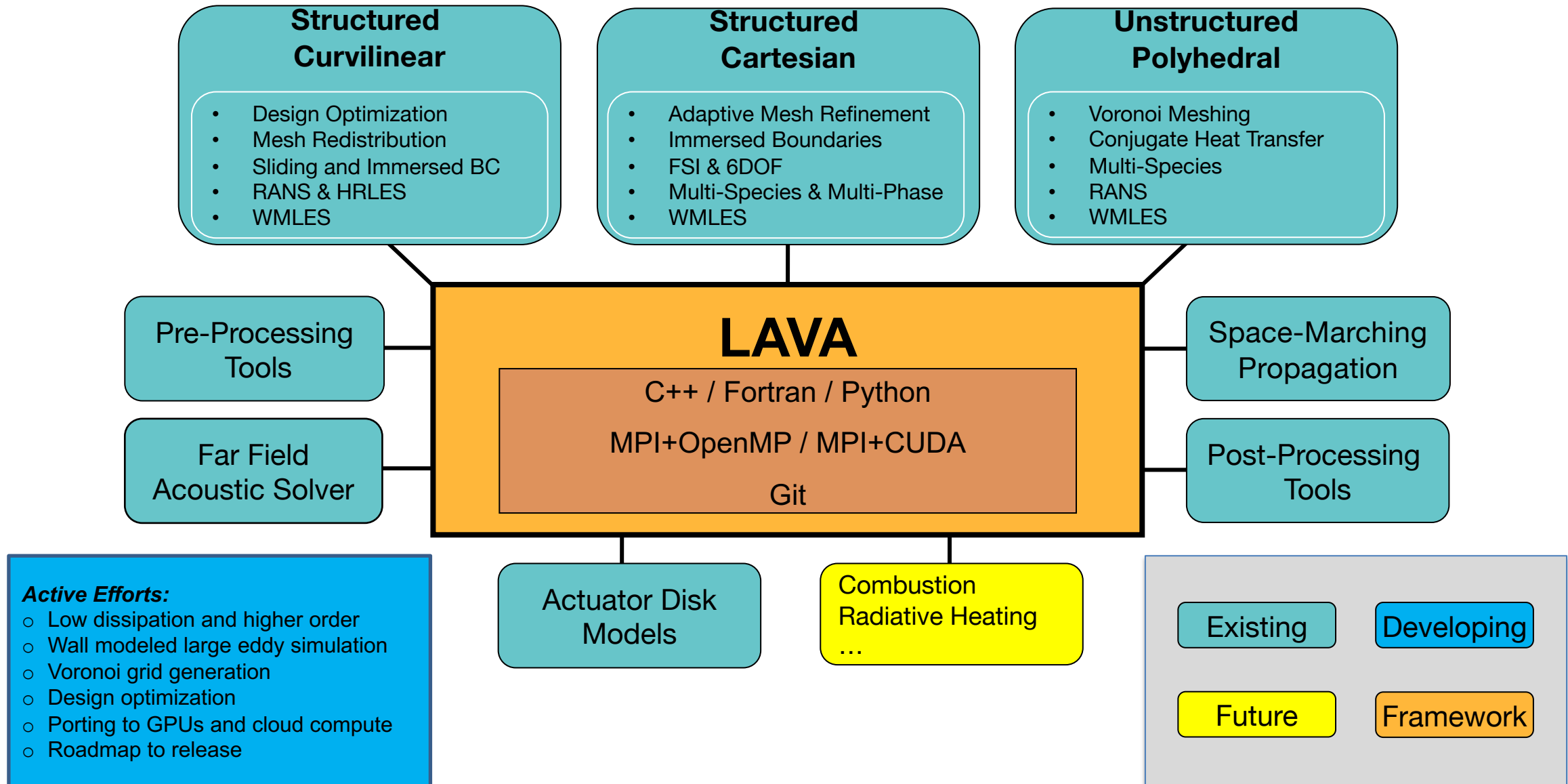
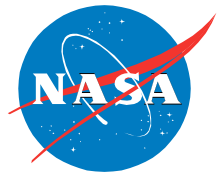
- Robust grid generation for complex geometry
- High-order methods non-trivial, computationally expensive

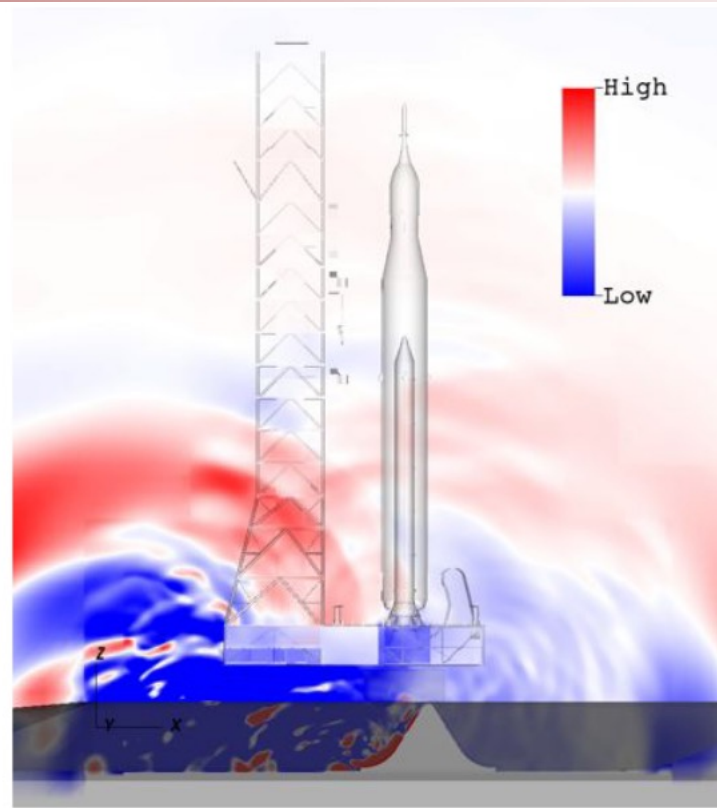
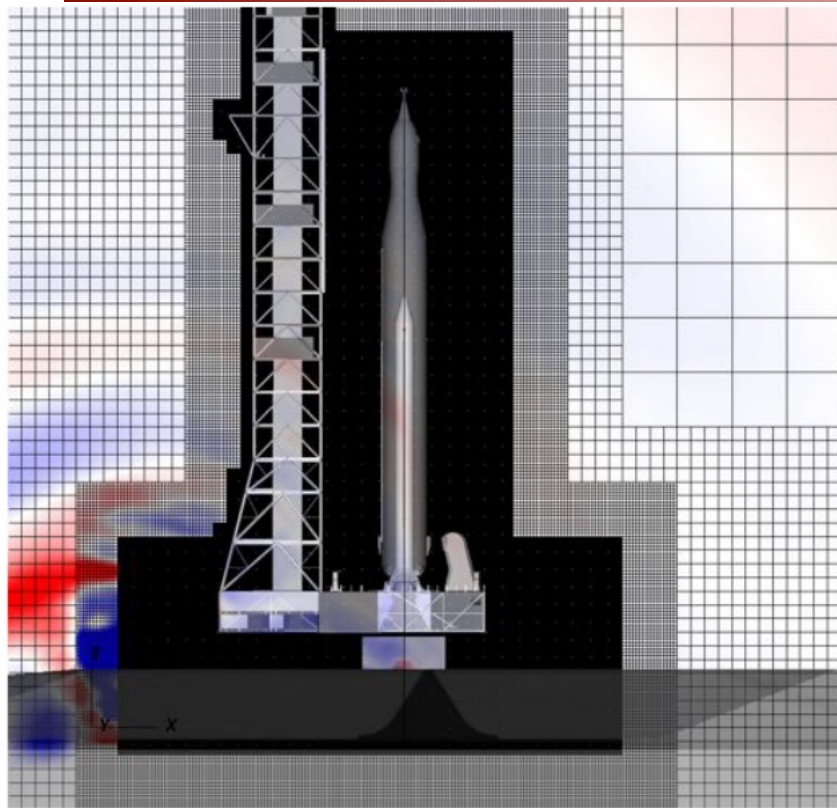
Structured Curvilinear



- Logically rectangular grids are efficient, high-order methods common
- Grid generation usually labor intensive, judging grid quality may require expertise

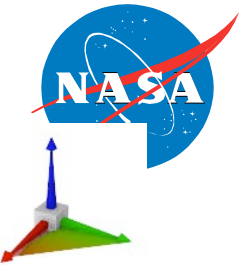
Launch, Ascent and Vehicle Aerodynamics (LAVA)



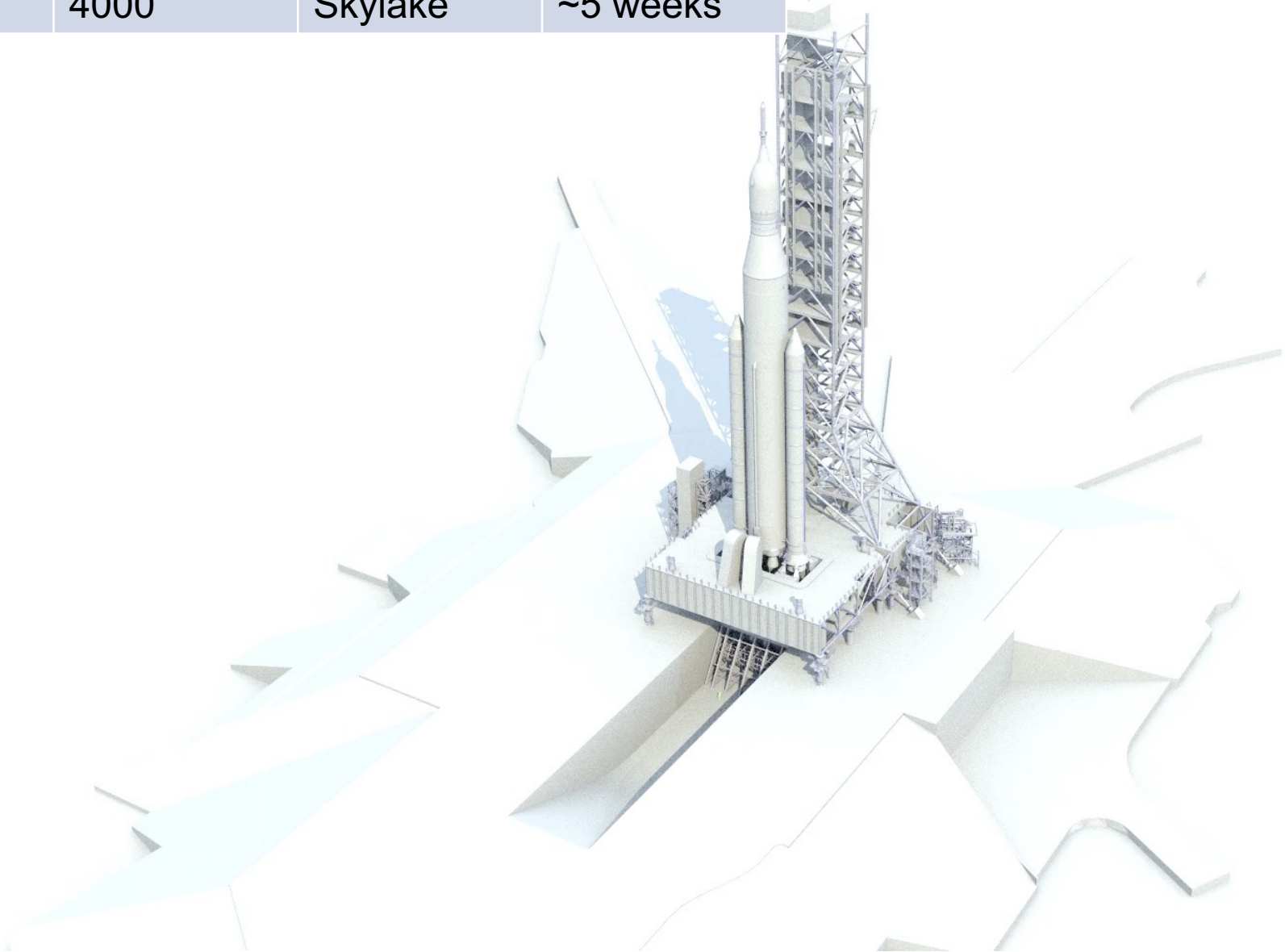


- LAVA Structured Cartesian solver ideal for inviscid flow design optimization where geometry may be changing between design iterations
- The LAVA solver was used extensively for the redesign efforts of the KSC launch pad for SLS starting in 2012.

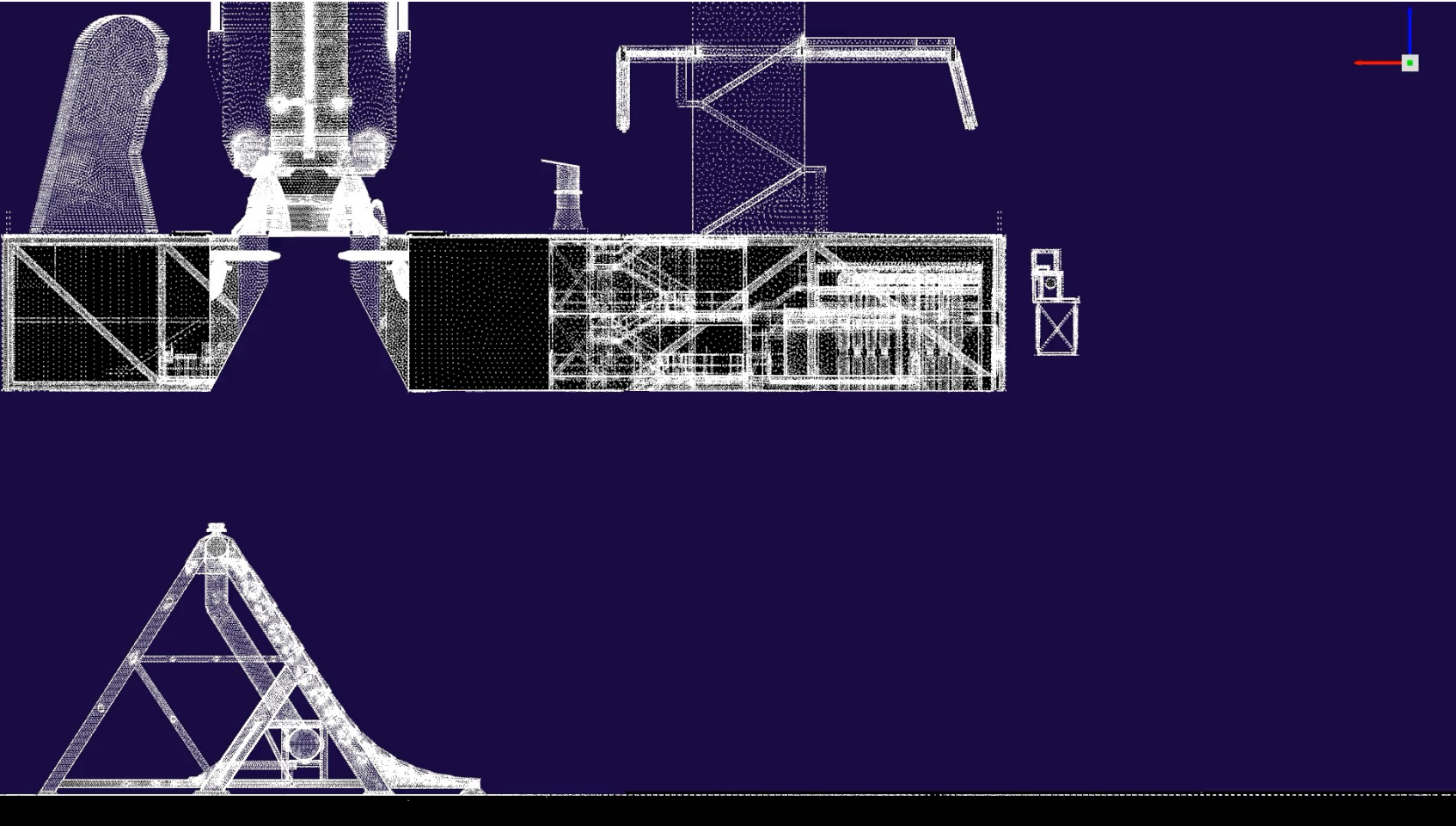
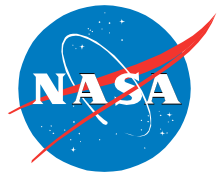
Efficient Immersed Boundary Cartesian Methods for Complex Geometry



No. Cells	No. Cores	Model	Runtime
550M	4000	Skylake	~5 weeks



LAVA Cartesian Flow Solver for the Launch Environment



- To analyze plume impingement during the first 15 seconds of flight we use:
 - 5th order accurate weighted essentially non-oscillatory (WENO5) convective flux
 - 3rd order accurate Strong Stability Preserving Runge-Kutta (SSPRK) time integration
 - Immersed boundary representation of geometry with slip walls (inviscid simulations)

Artemis Trajectory Simulations

- In Nov 2022 Artemis I launched and damaged the launch pad, specifically elevator doors were destroyed. Motivating these simulations.
- We present a suite of 12 lofted vehicle simulations at 6 different liftoff times for two different trajectories, Artemis I (actual flight) and Artemis II Max Drift (worst case)
- Here we look at the pressure environment caused by the plume impingement on the pad and surrounding structures
- Proper understanding of this interaction is crucial to mitigate potential risks and damages
- Making use of Artemis I launch data, we can also take steps in further verification and validation of LAVA



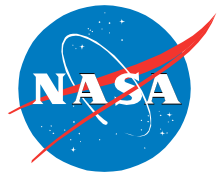
Artemis I
Trajectory



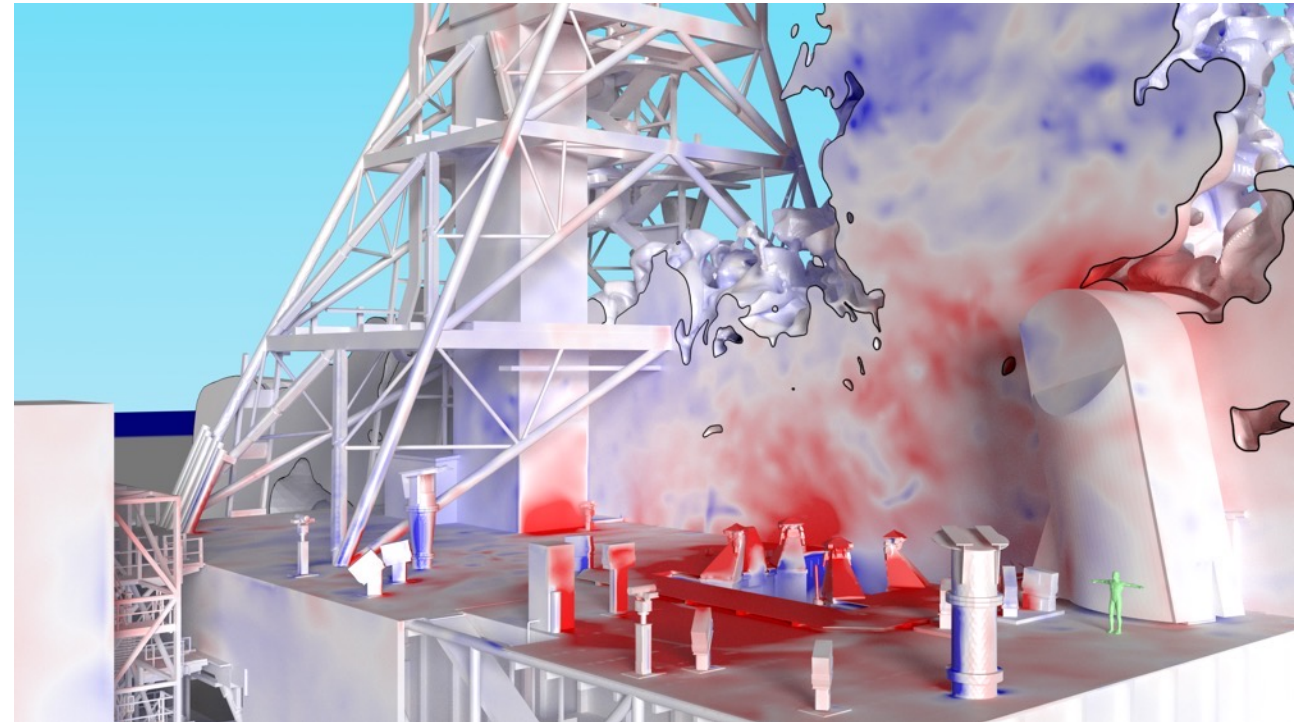
Artemis II
Max Drift
Trajectory



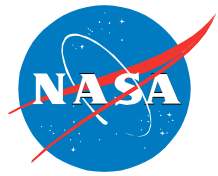
Artemis Trajectory Simulation Methodology



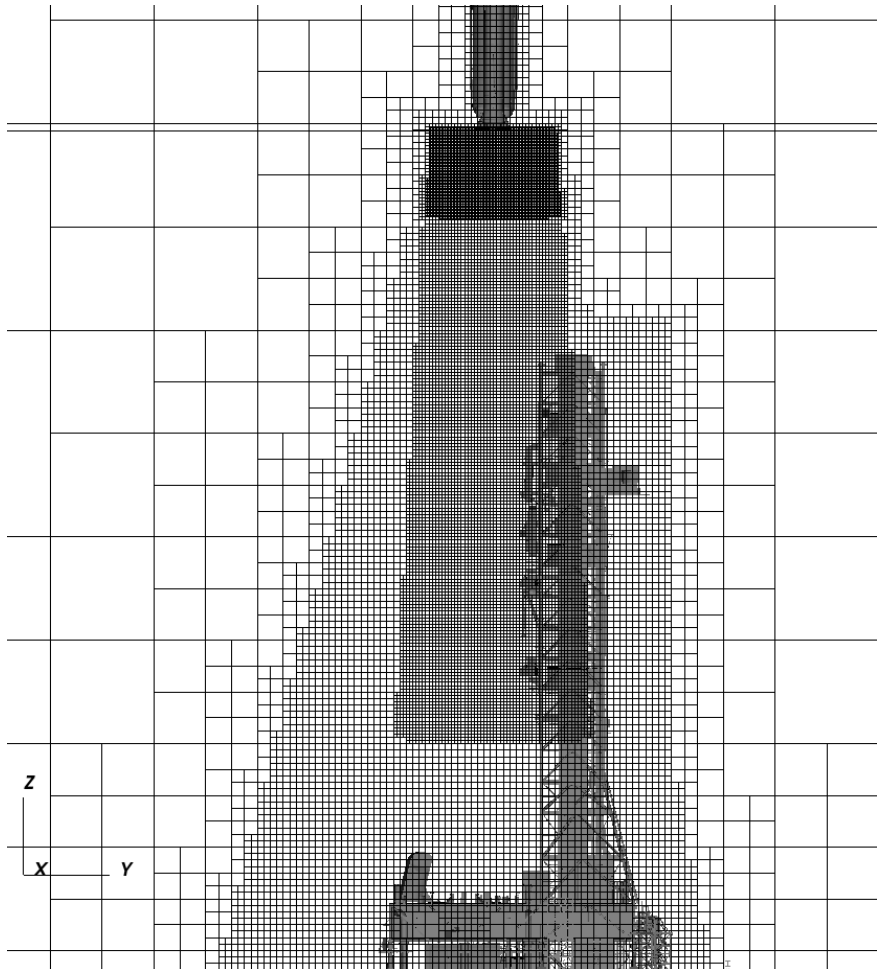
- Three species formulation with SRB plumes, SSME plumes, and air
- Four RS-25s given the same steady, radially varying boundary conditions at the exit plane
- Adiabatic wall boundary conditions for all geometry surfaces
- Simulations compute a duration of 4 physical seconds
 - Solution is stationary (in completed cases) after 2 seconds
 - Last second of completed cases are used for analysis for consistency across all cases



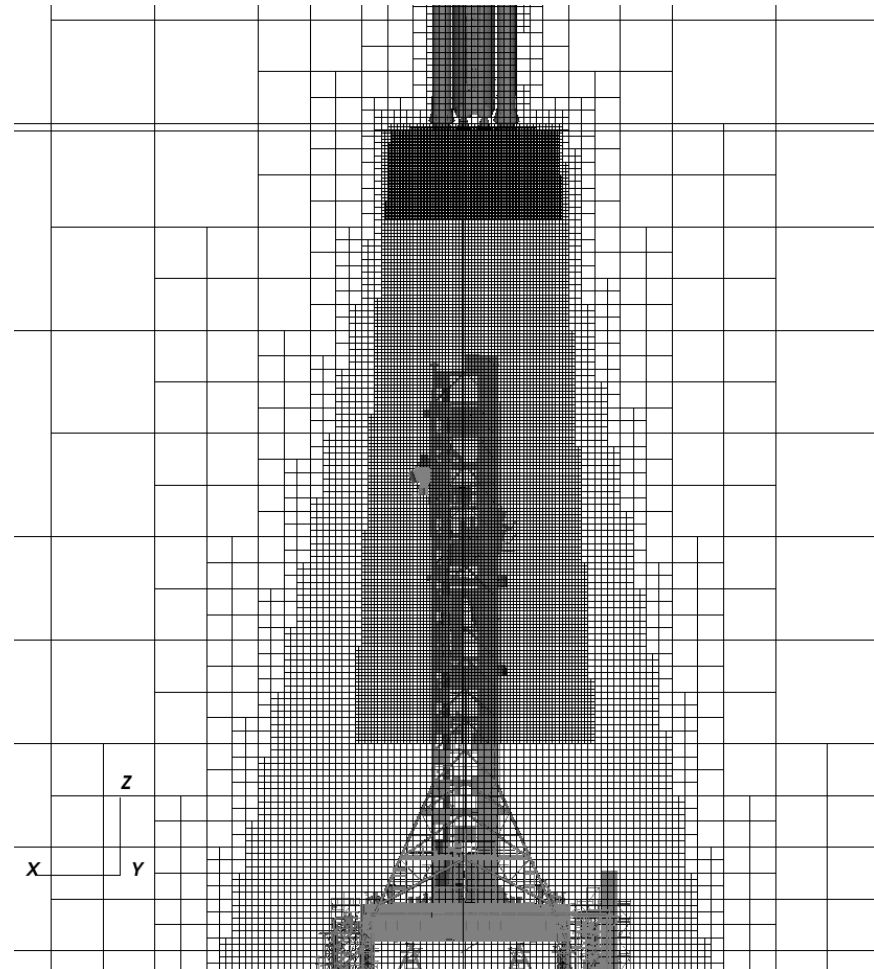
Grid Case 2 – Artemis II Max Drift: 09 Sec



+x view



+y view



Grid Stats

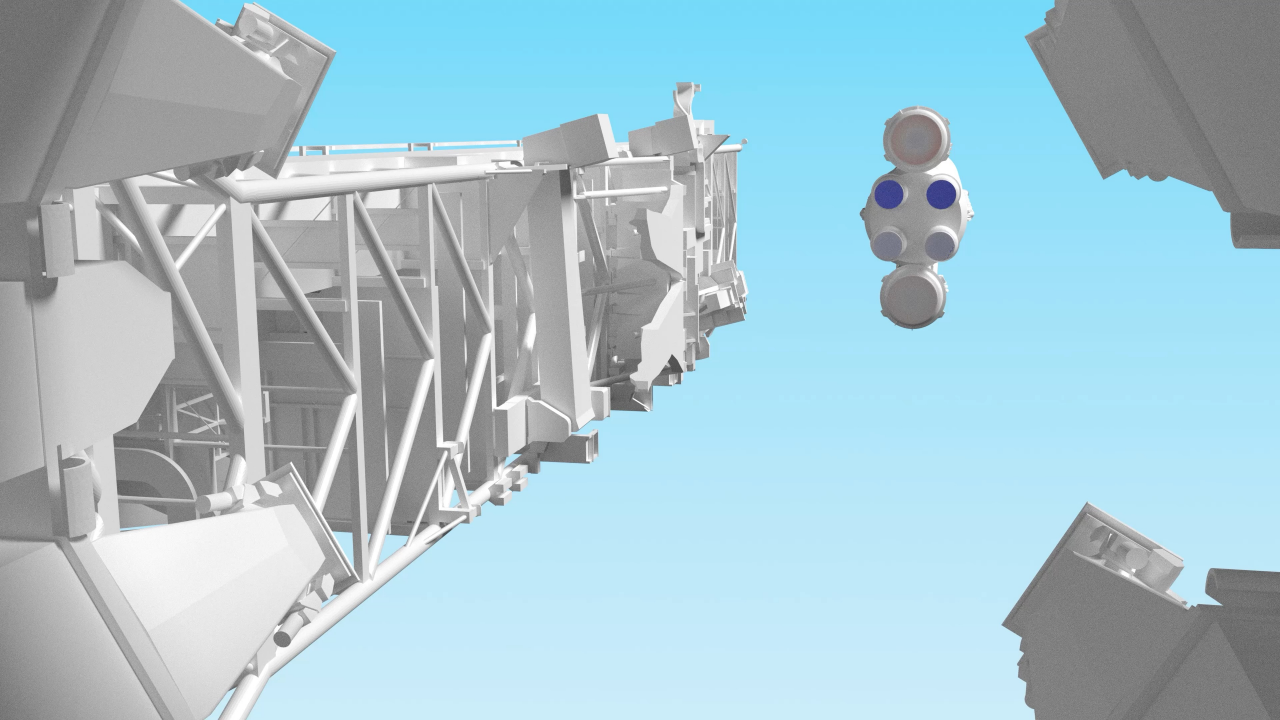
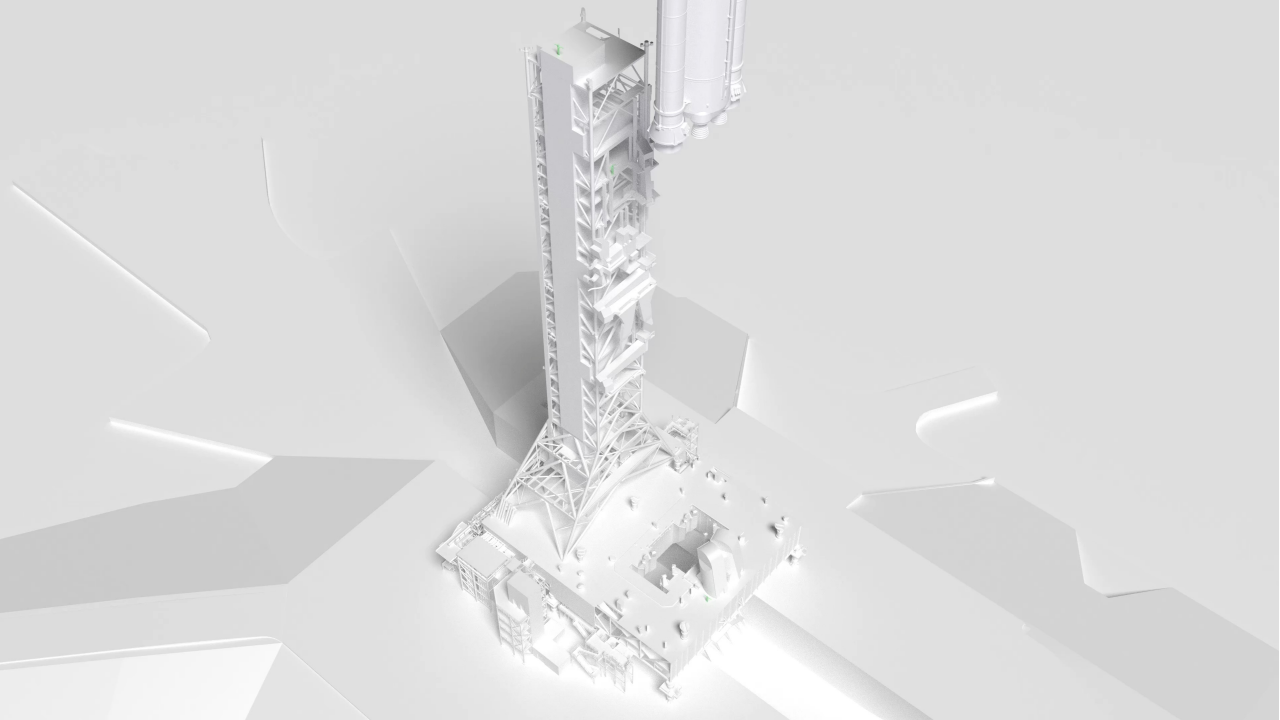
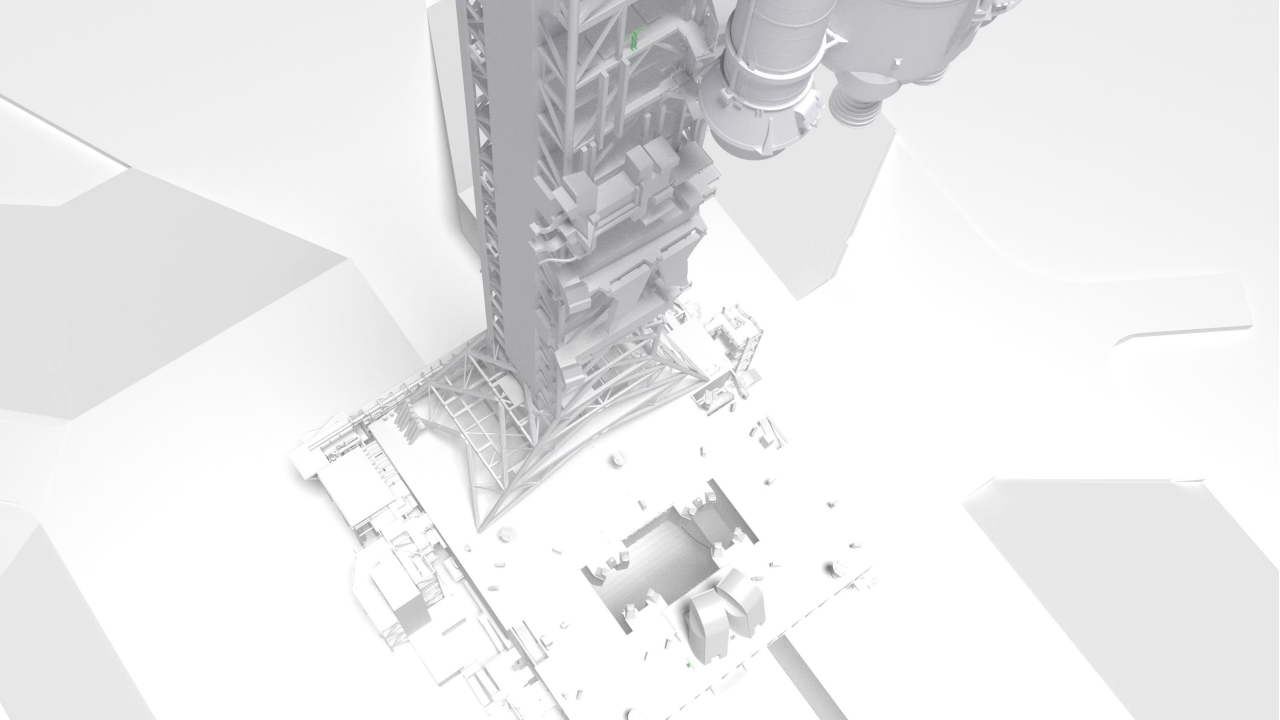
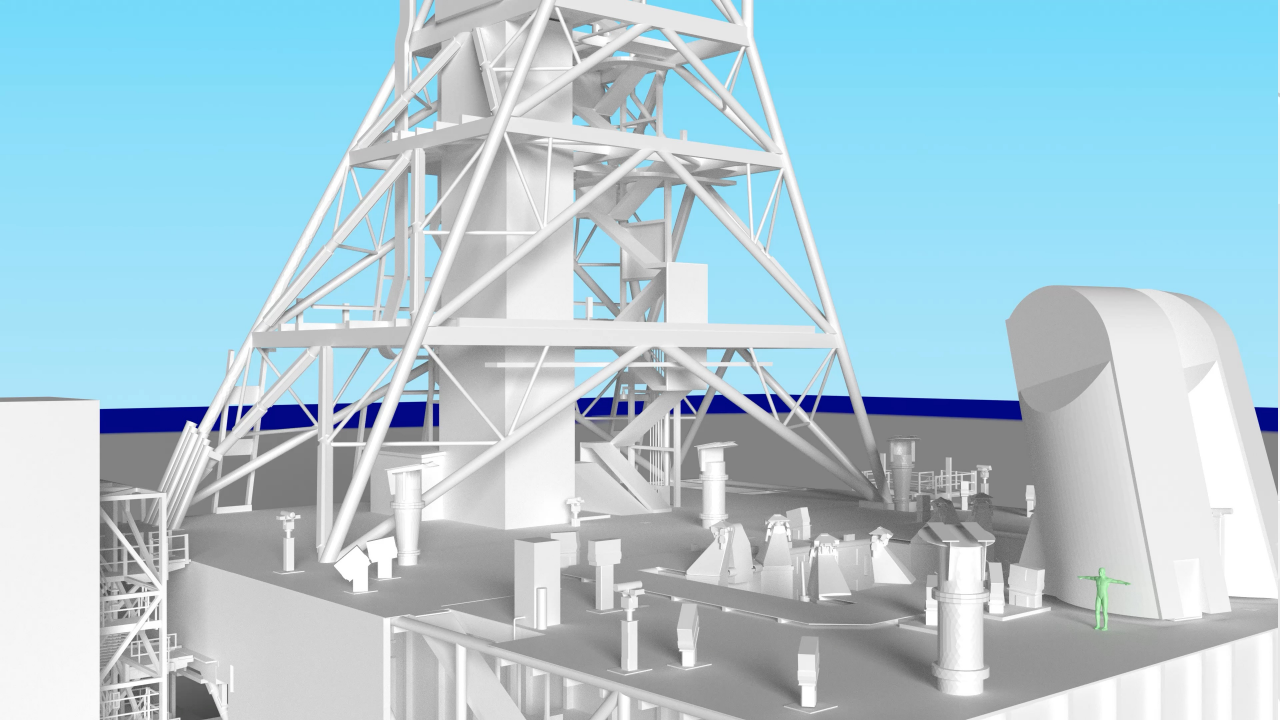
12 Levels

Level 12 – 2 cm

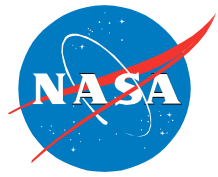
Boxes – 1.18M

Cells – 603M

Boxes shown on left
each contain 8^3
cells.

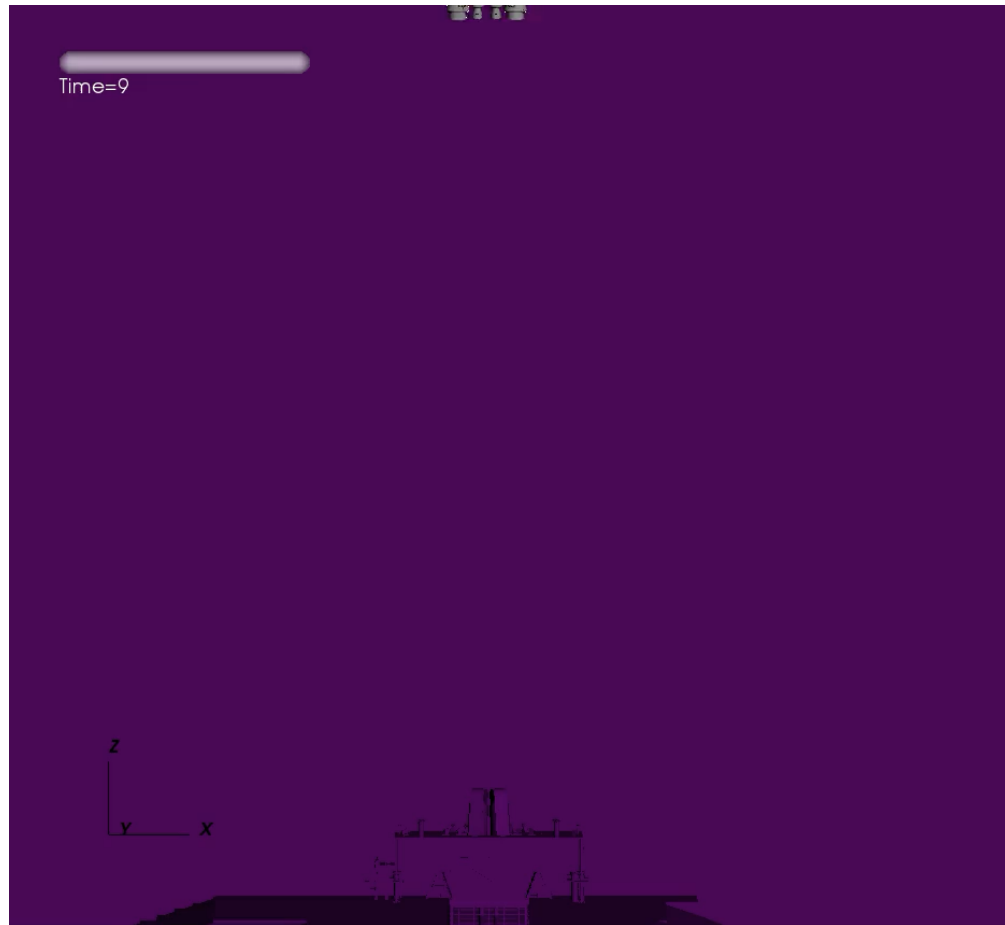


Artemis I: 09 sec visualization

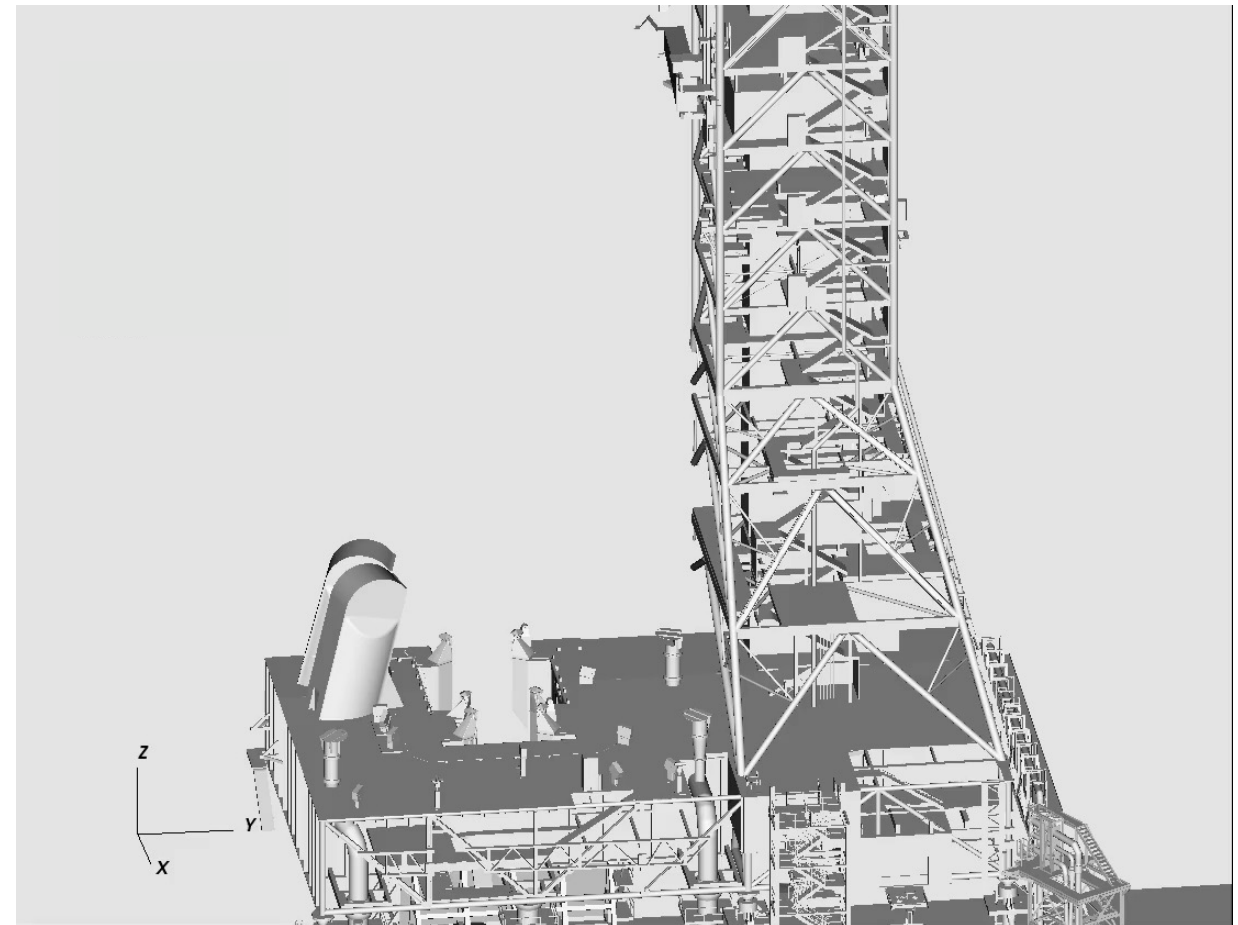


Colored by mass fraction of total plume species
[0, 0.25], purple is pure air (0)

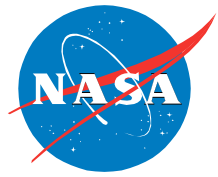
+x view



Colored by gauge pressure



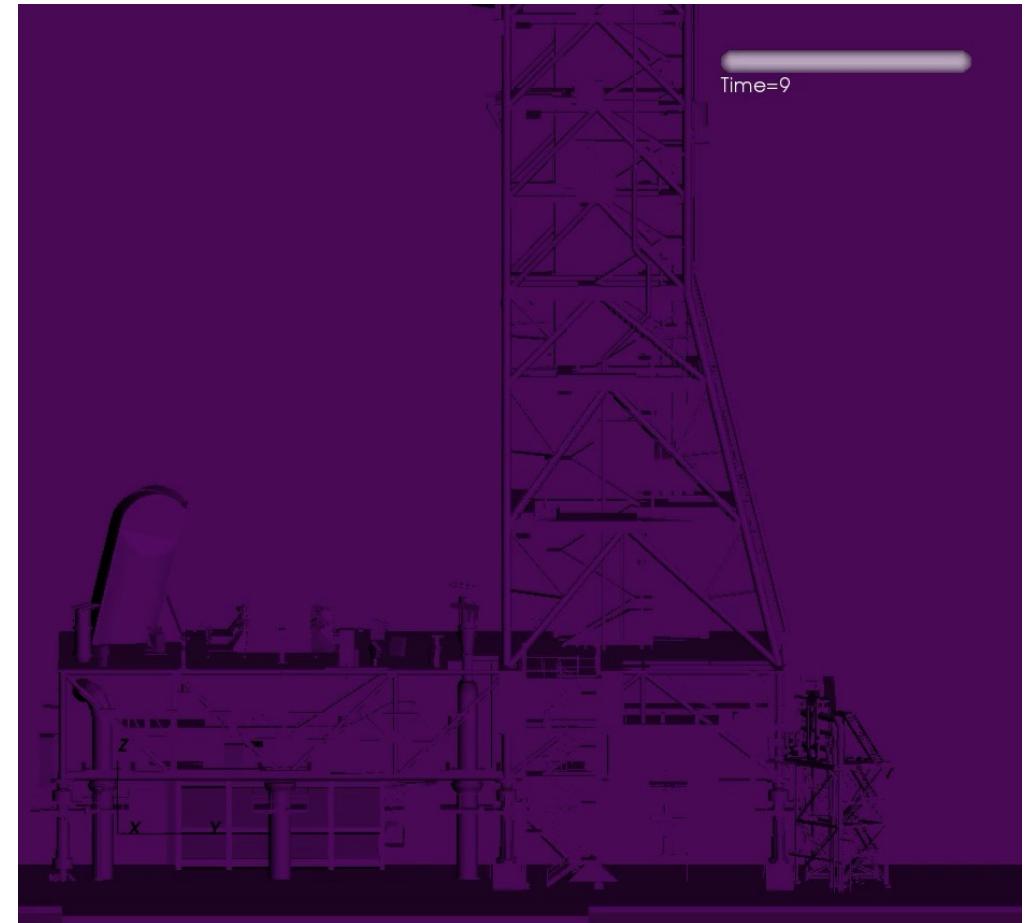
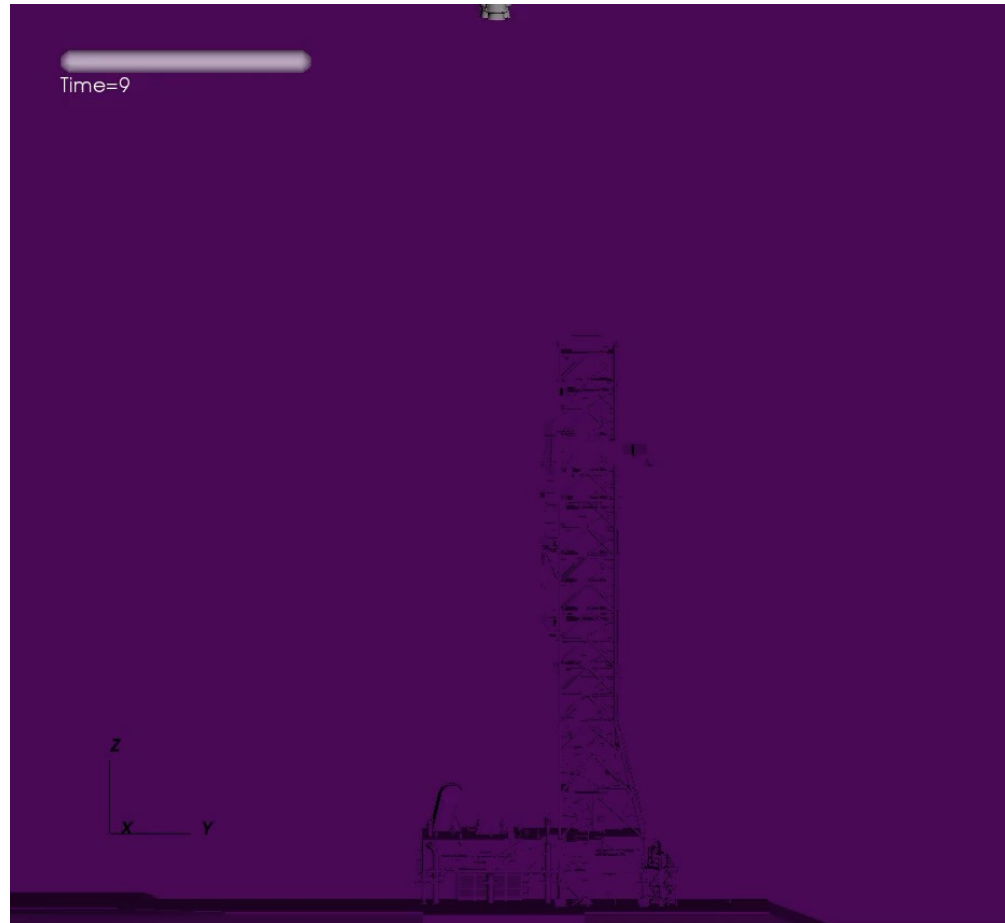
Artemis I: 09 Sec Mass Fraction Viz



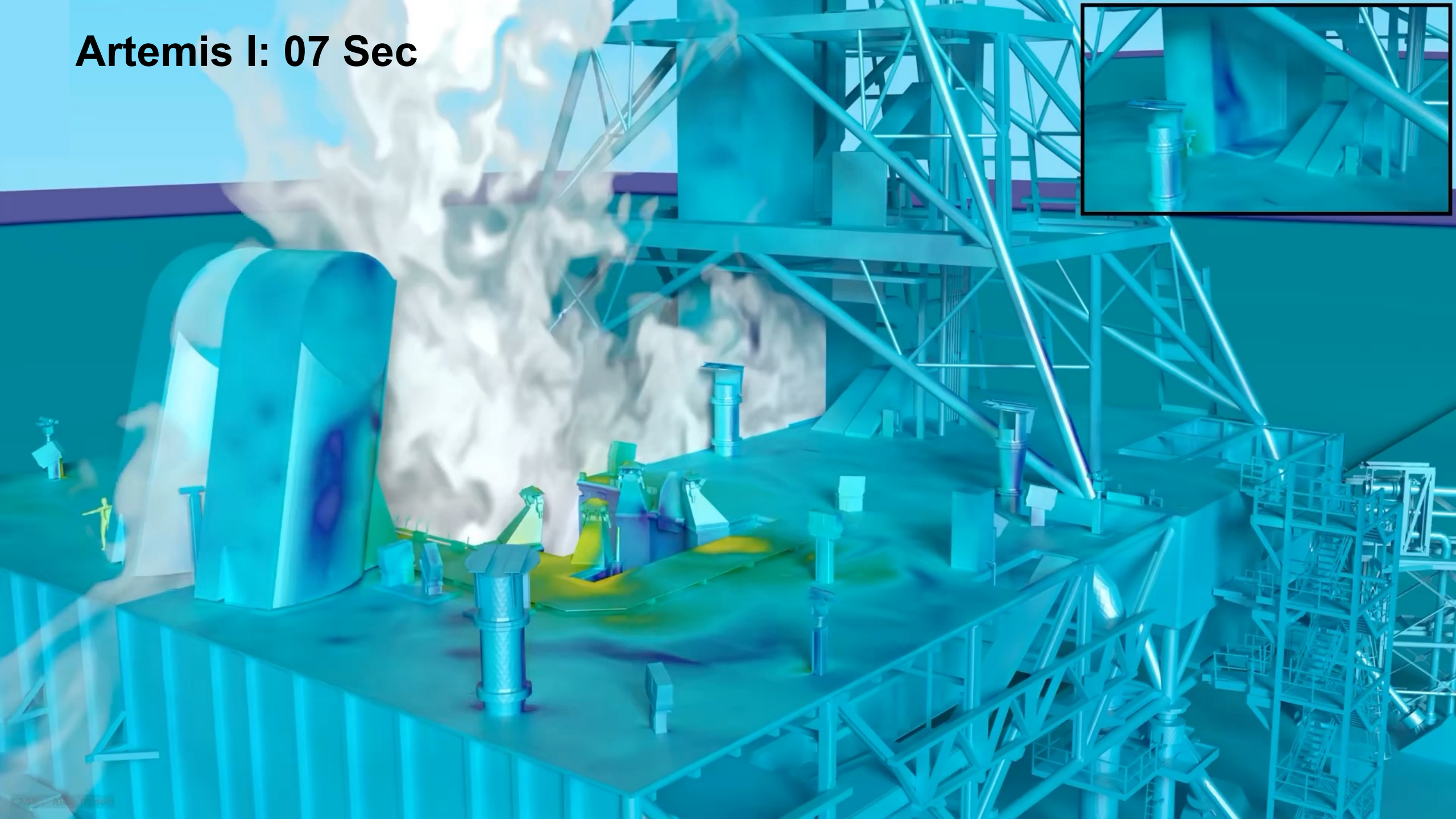
Colored by mass fraction of total plume species [0, 0.25], purple is pure air (0)

+y view

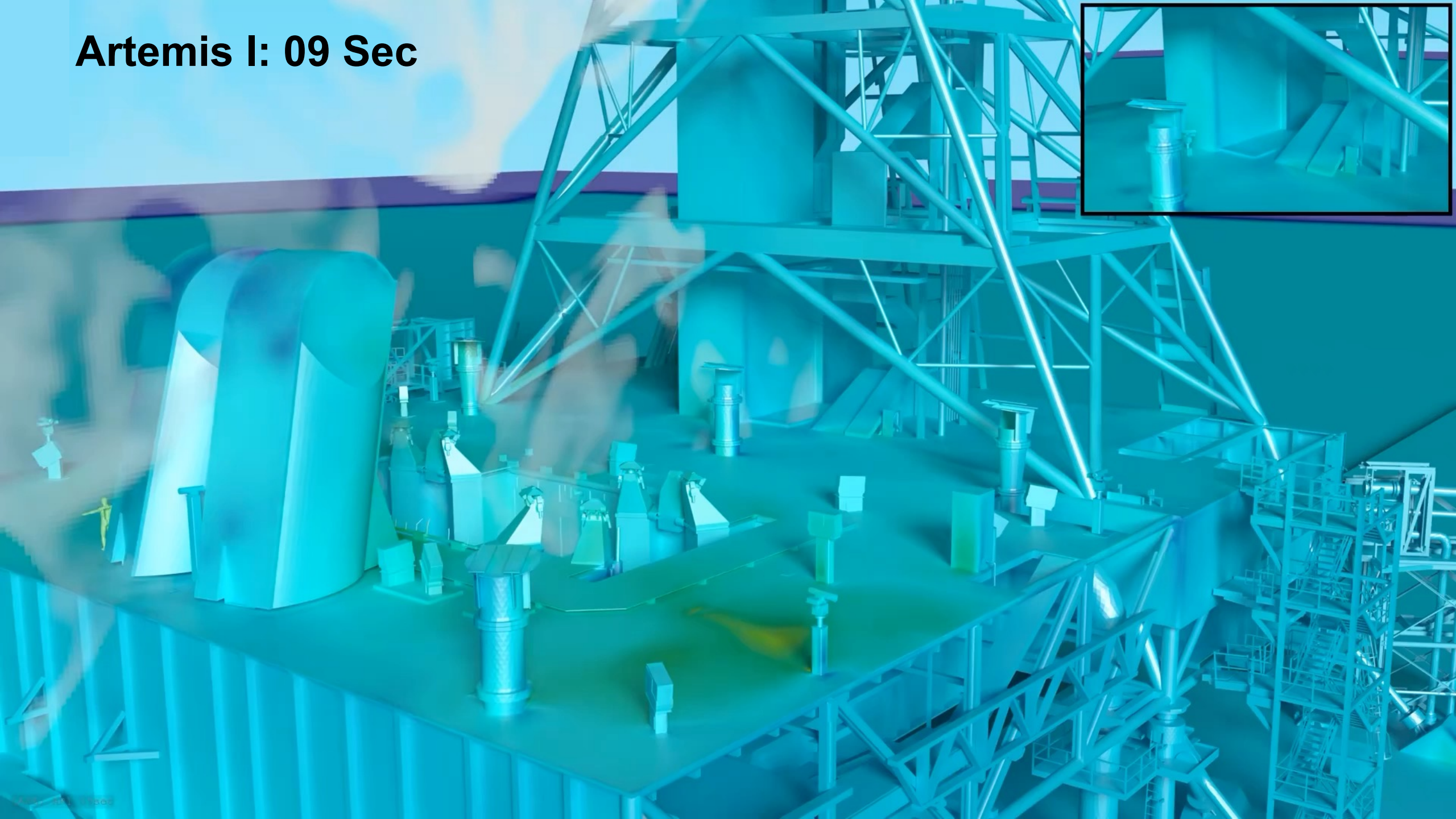
+y view (zoomed)



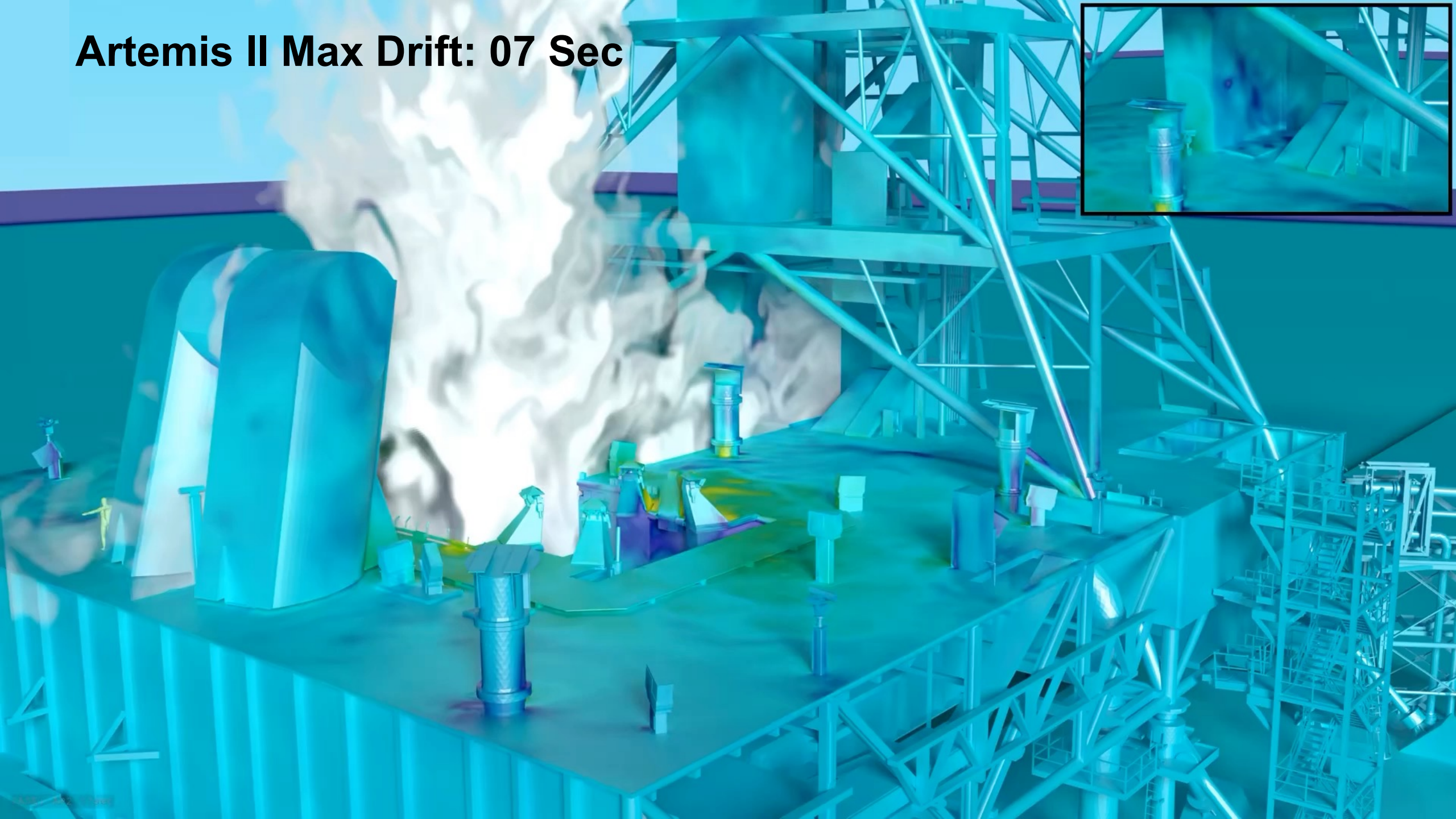
Artemis I: 07 Sec



Artemis I: 09 Sec



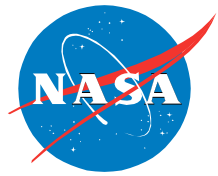
Artemis II Max Drift: 07 Sec



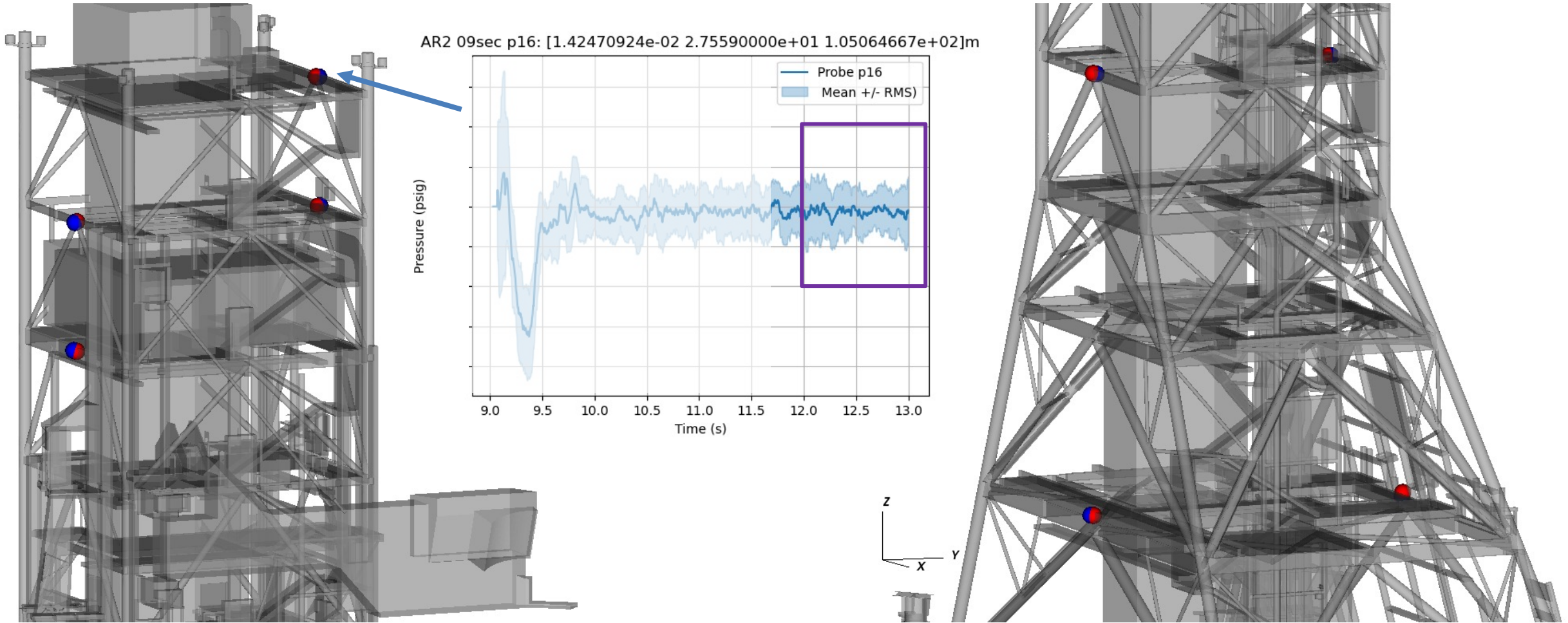
Artemis II Max Drift: 09 Sec



Artemis II Max Drift @ 9 sec: CFD pressure time series

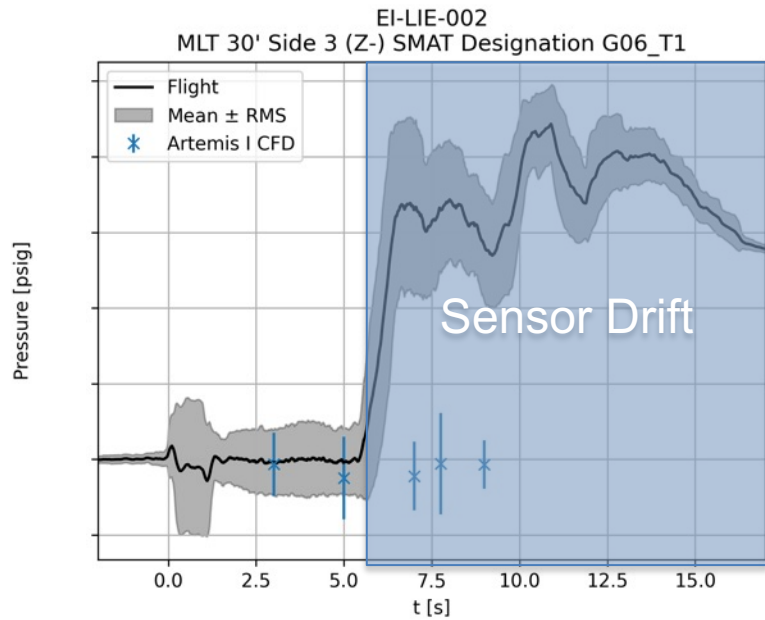
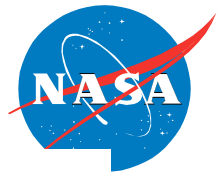


Node locations for all probes are at most 20cm away from their requested locations (due to surface mesh resolution)

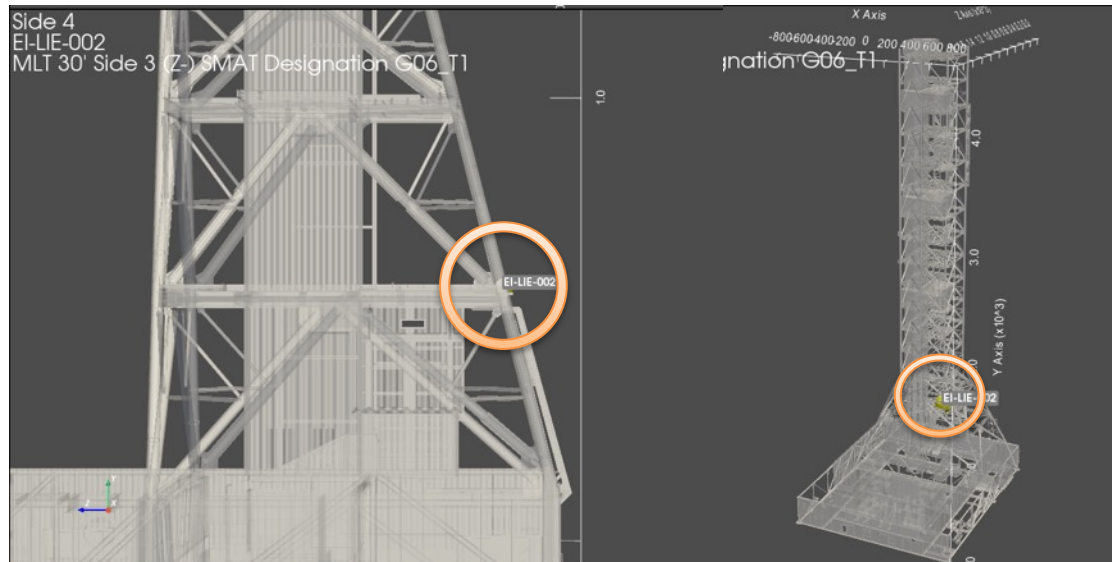
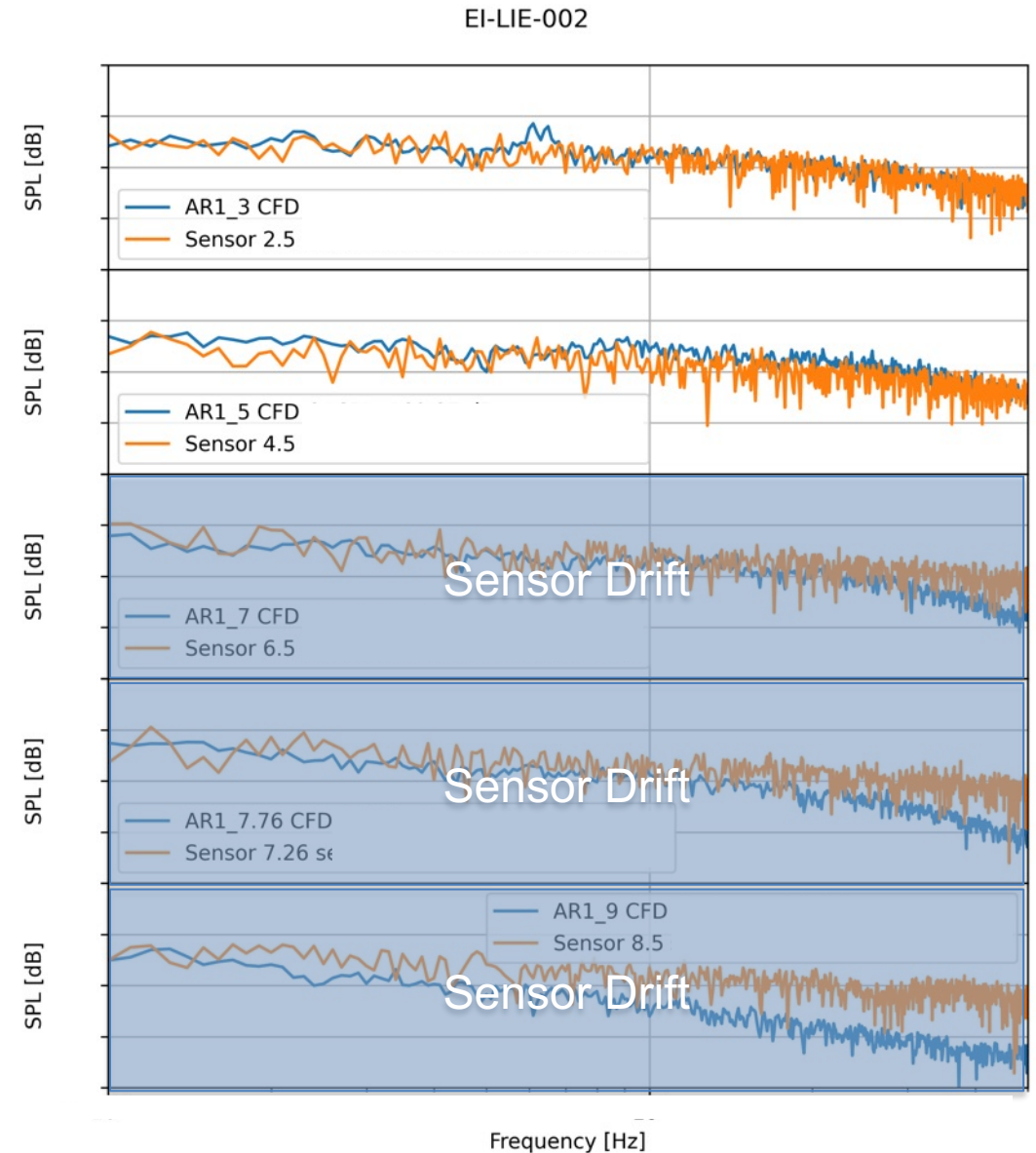


Node locations with as requested in red and as actually located in blue; center plot of gauge pressure at the top probe location, excluding numerical startup portion

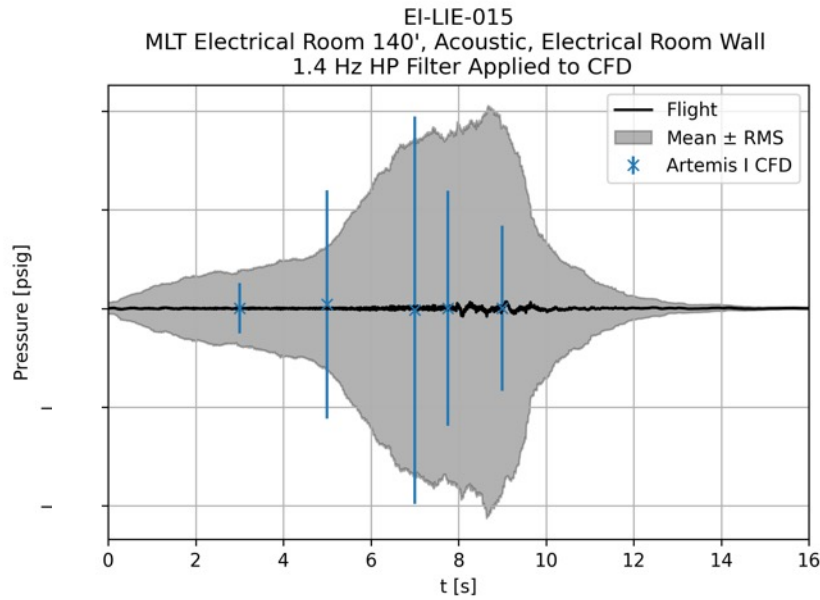
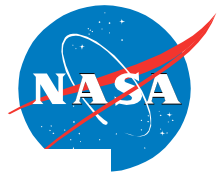
Comparison to measurement: North face (not plume facing)



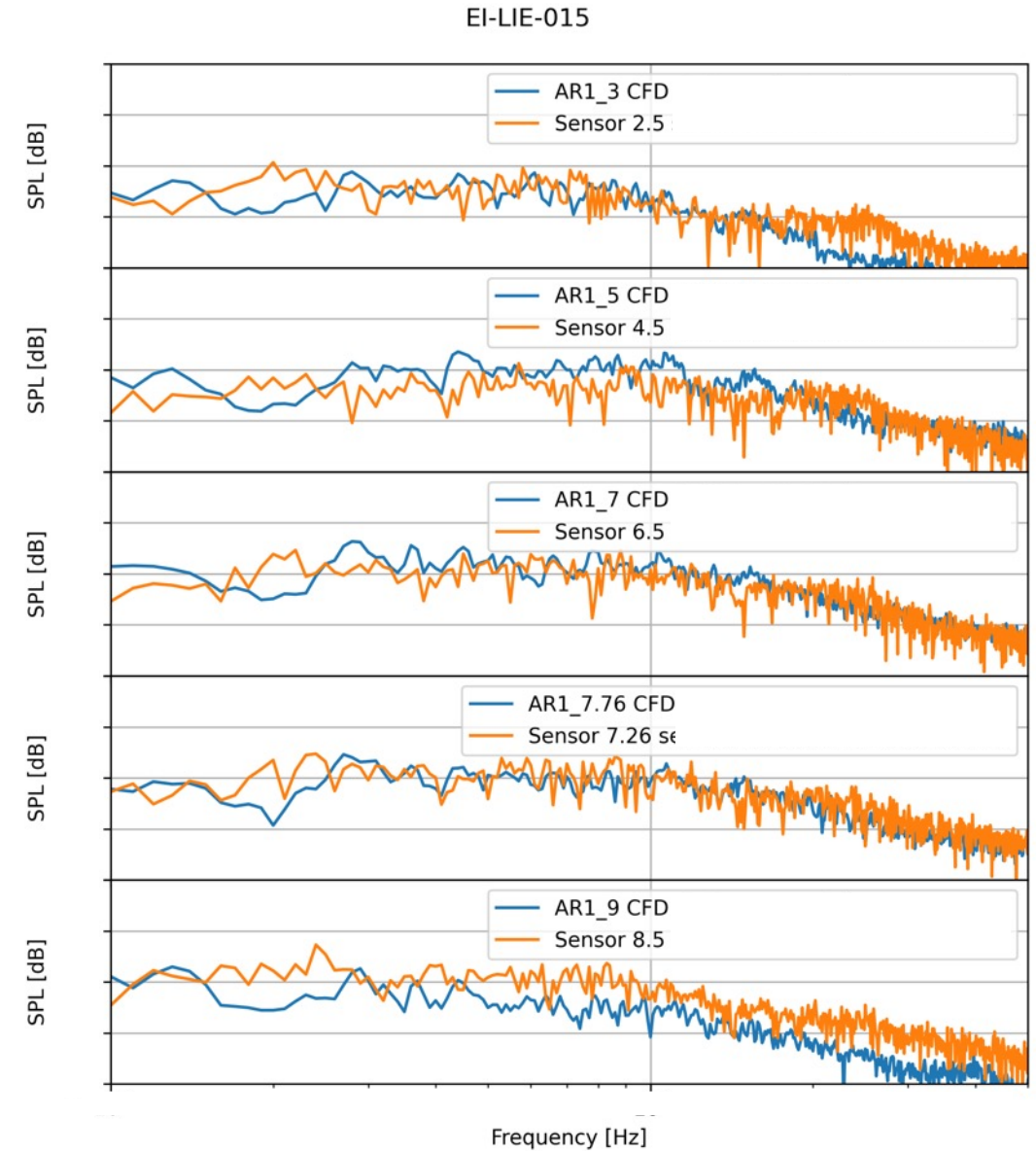
Last-second gauge pressure averages for each simulation compared to ML tower measurements. Error bars indicate +/-std. (Z-) indicating north face. Some drift is evident at later times in the measurements.



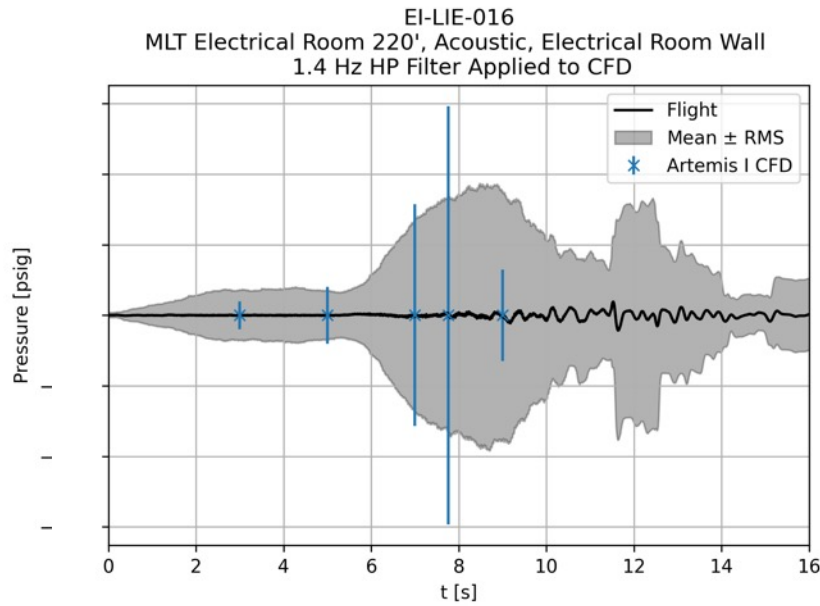
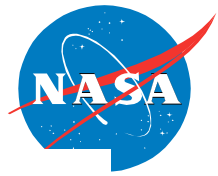
Comparison to measurement: Microphone



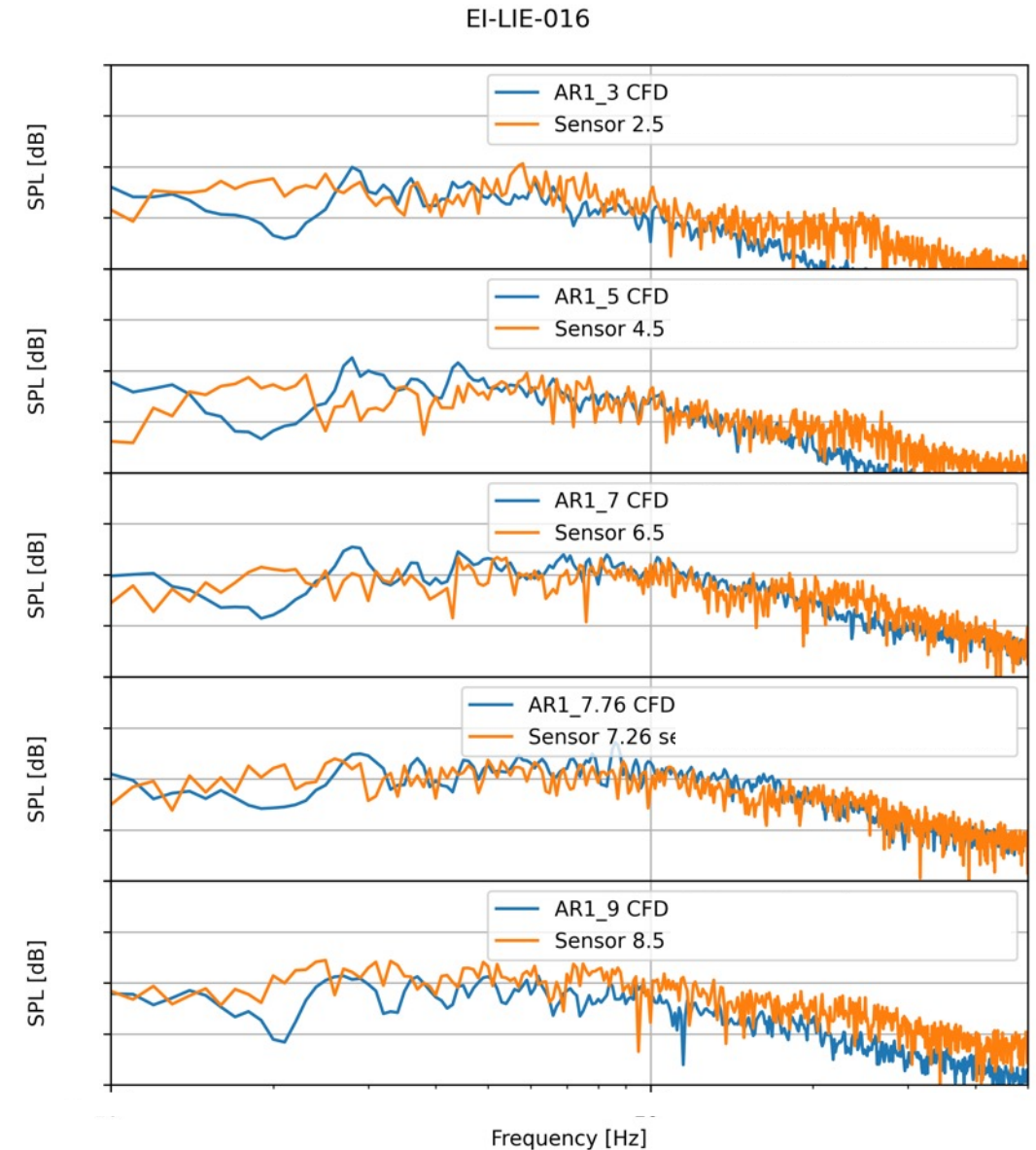
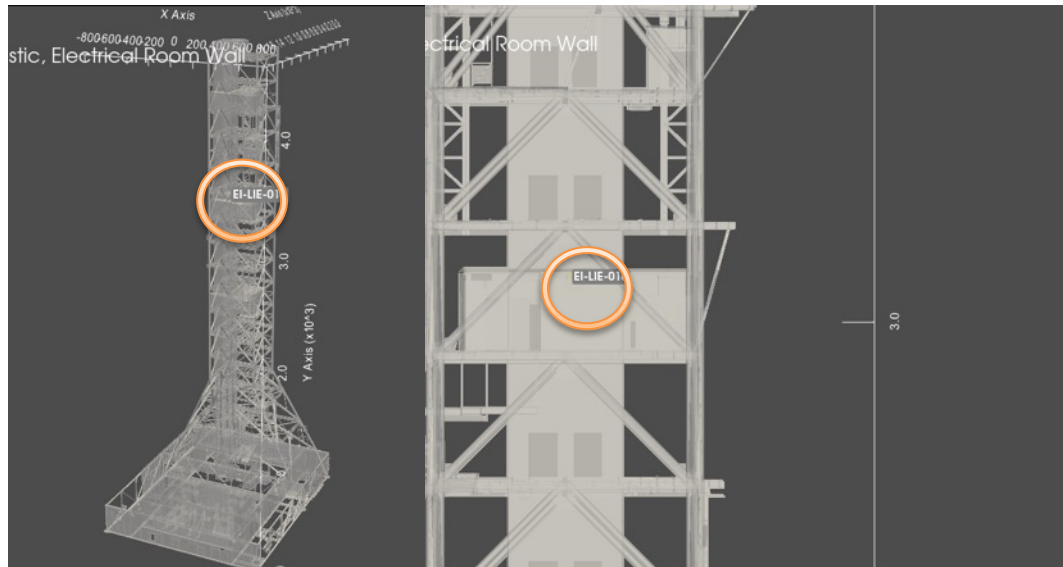
Last-second gauge pressure averages for each simulation compared to ML tower measurements. Error bars indicate +/-std. (Z-) indicating north face. Some drift is evident at later times in the measurements.



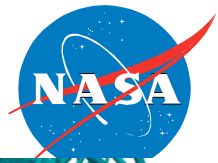
Comparison to measurement: Microphone



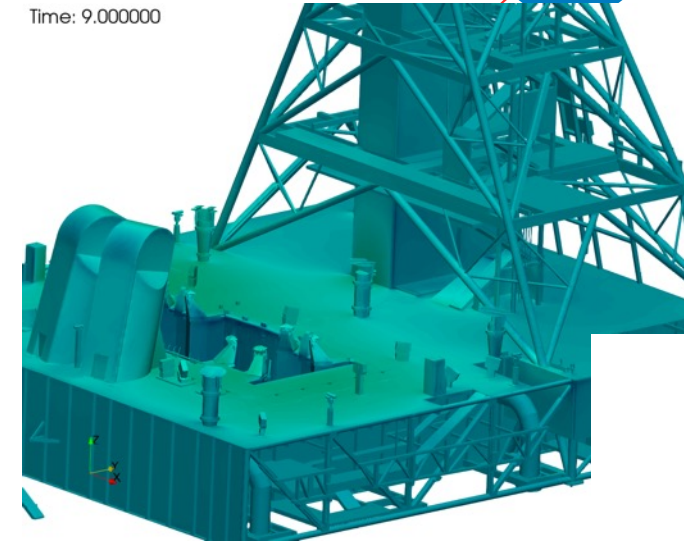
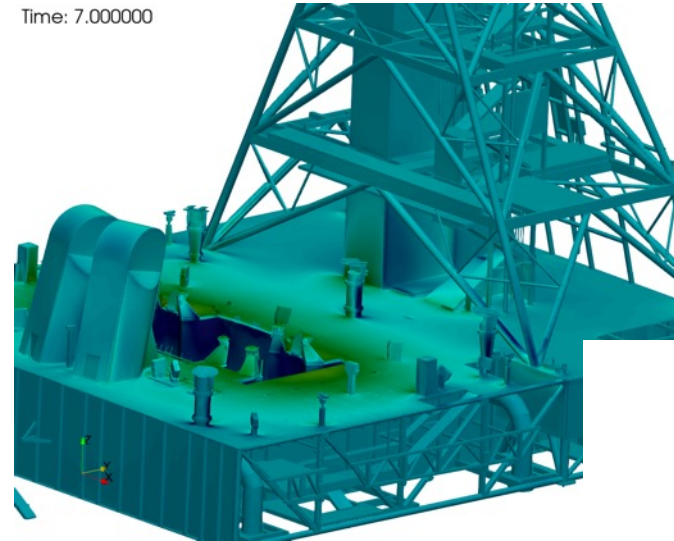
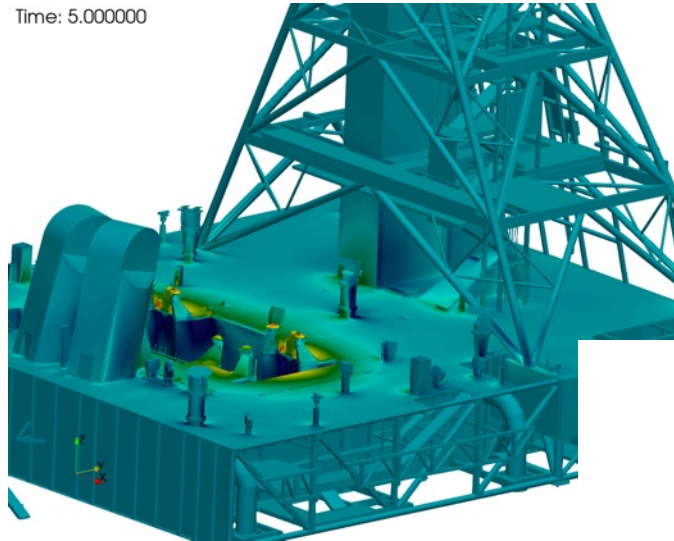
Last-second gauge pressure averages for each simulation compared to ML tower measurements. Error bars indicate +/-std. (Z-) indicating north face. Some drift is evident at later times in the measurements.



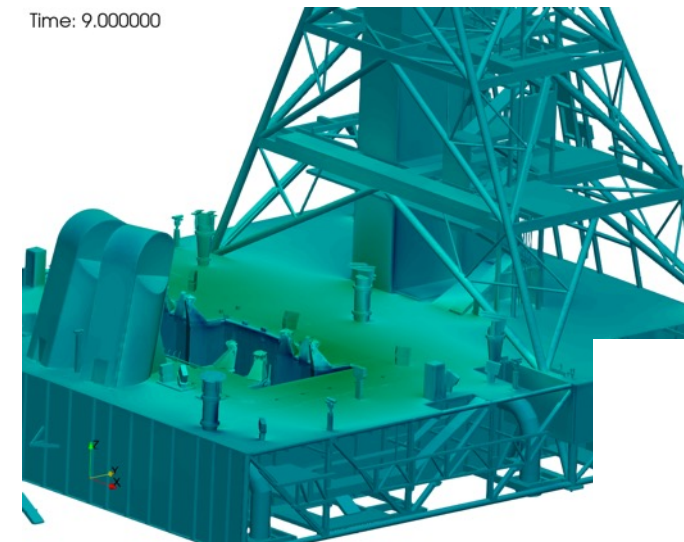
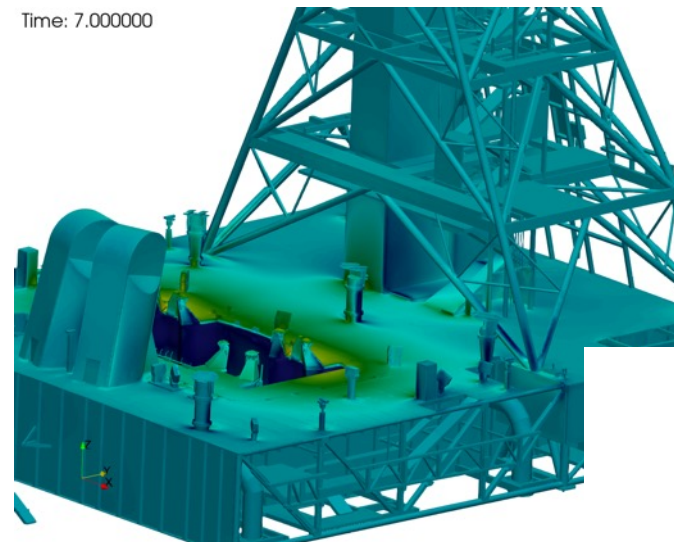
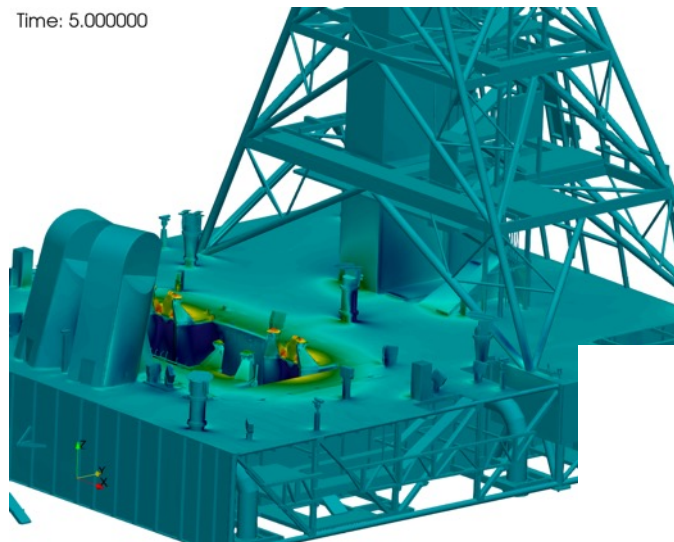
Artemis I/II: avg psig over time



Artemis I

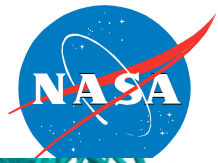


Artemis II
Max Drift

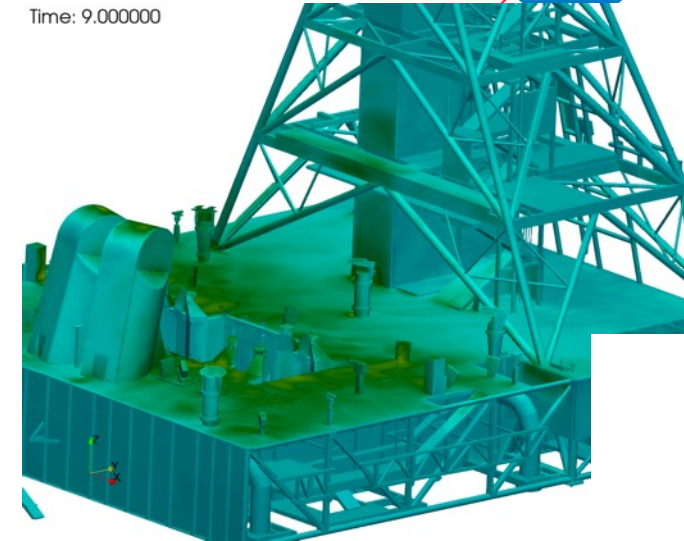
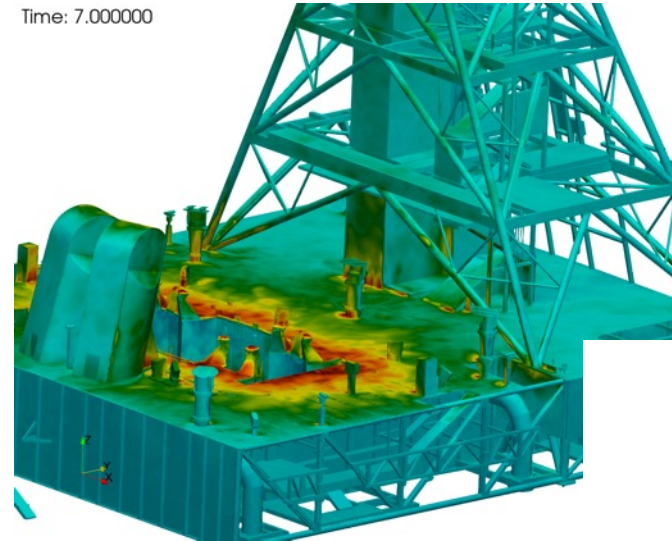
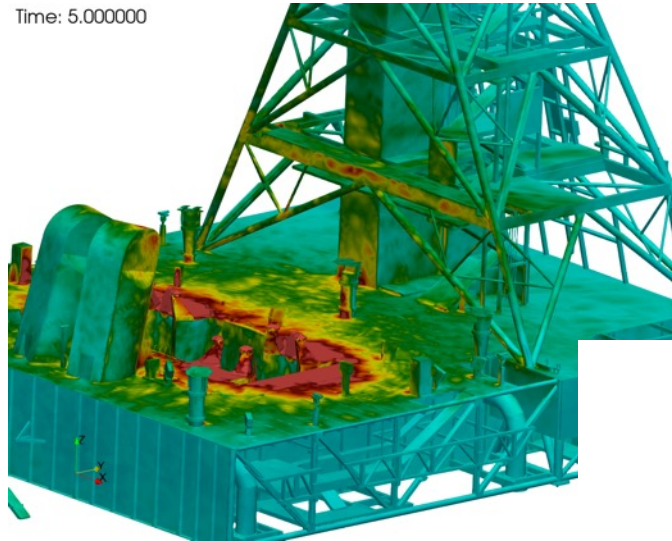


Avg PSIG experienced in the last second of each completed Artemis I/II Max Drift simulation

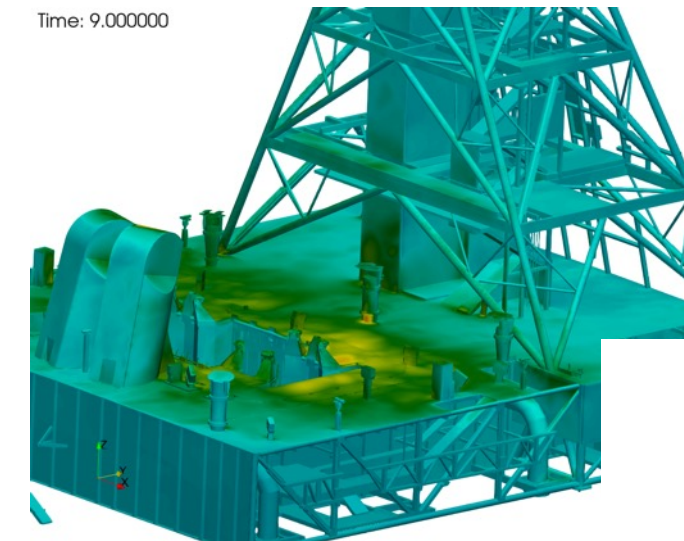
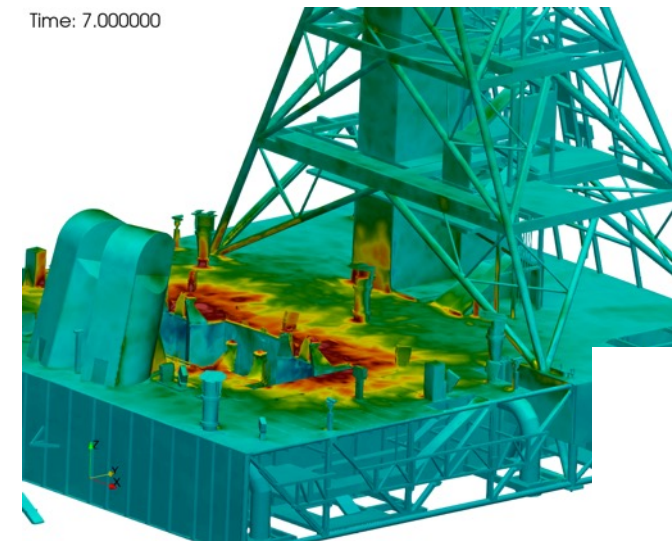
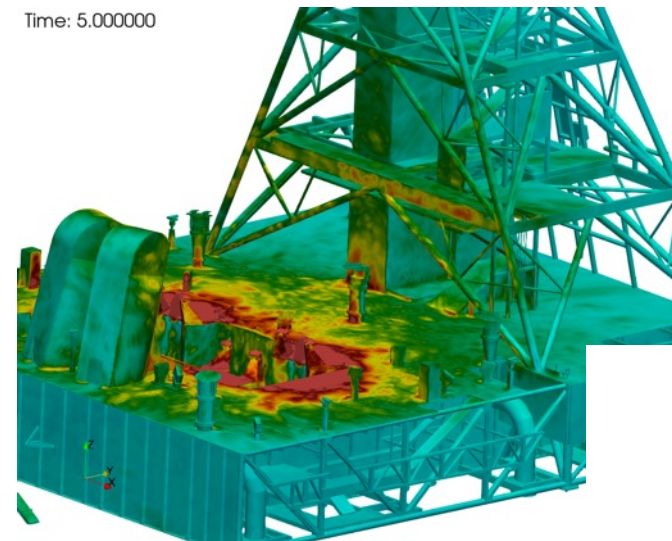
Artemis I/II: max psig over time



Artemis I

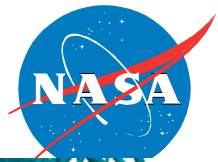


Artemis II
Max Drift

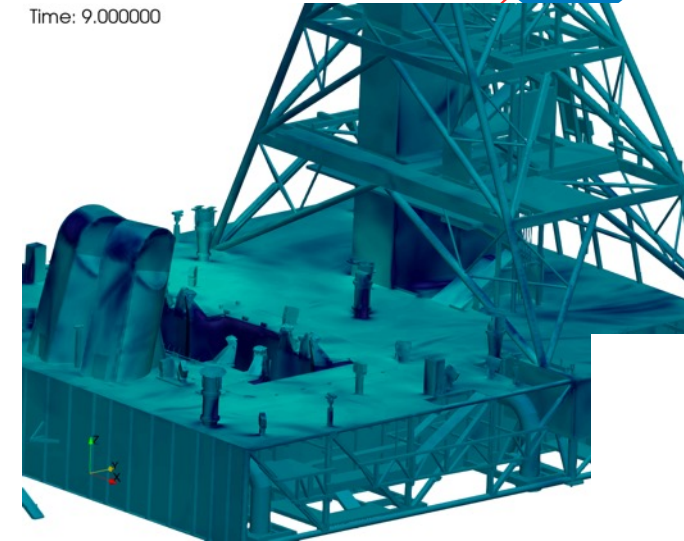
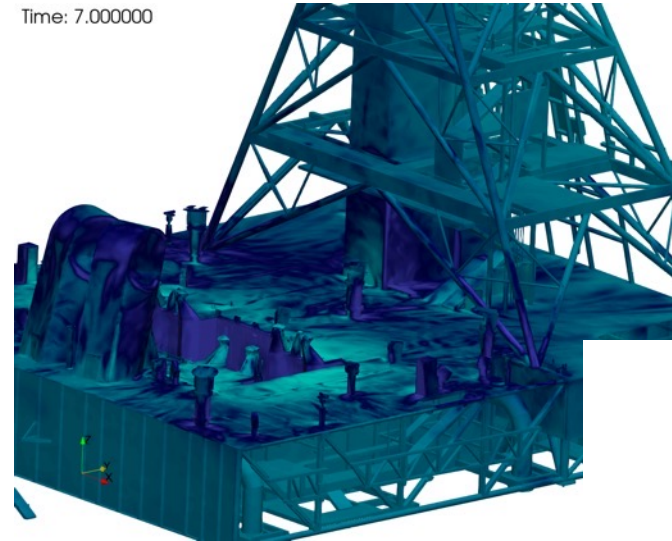
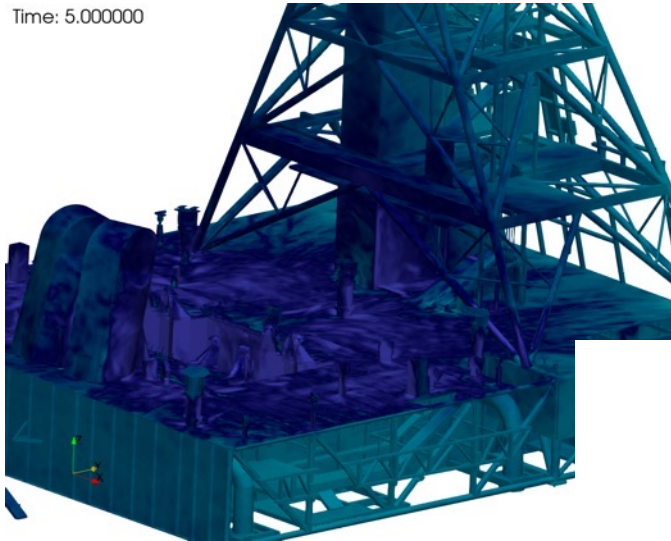


Max PSIG experienced in the last second of each completed Artemis I/II Max Drift simulation

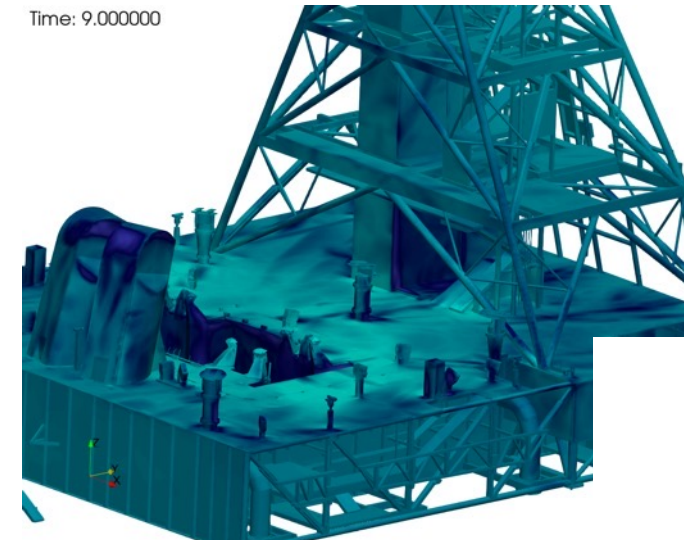
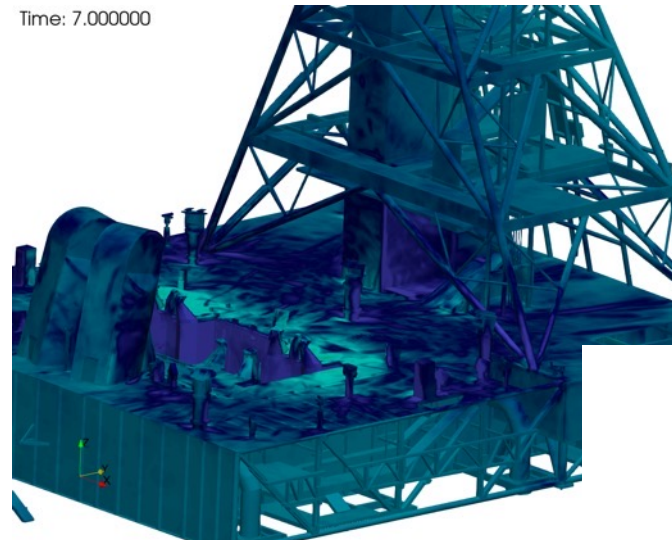
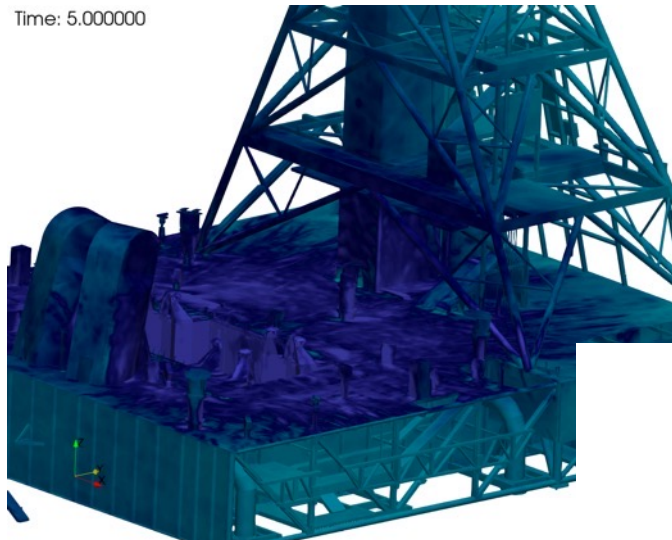
Artemis I/II: min psig over time



Artemis I

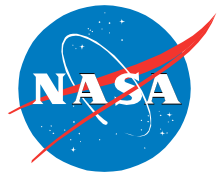


Artemis II
Max Drift



Min PSIG experienced in the last second of each completed Artemis I/II Max Drift simulation

Acknowledgements / References



Acknowledgements:

- KSC EGS Team
- NAS for computational resources and support
- Tim Sandstrom for visualizations
- Exploration Ground Systems (EGS) project under the Exploration Systems Development Mission Directorate (ESDMD)

Relevant References:

- “Computational framework for launch, ascent, and vehicle aerodynamics (LAVA)”, Aerospace Science and Technology, 55, 189-219
- “Predicting SLS Launch Environment using a Novel Multiphase Formulation”, AIAA SciTech Forum 2023-0645
- “Computational Prediction of Pressure and Thermal Environments in the Flame Trench with Launch Vehicles”, AIAA 2013-2538
- “Predicting Orion Launch Abort Acoustics”, ICCFD11-1204.

Space Launch System (SLS) at LC-39B: Multiphase Simulations with LAVA

Volume rendering of exhaust and liquid water mass fractions.

For the liquid water, dark blue is high and light blue is low.

The exhaust plume mass fraction is colored so that high is yellow and low is purple.

