



# Analyzing the Artemis I Launch Environment with Multiphase CFD

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

NASA Ames Research Center

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# 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.



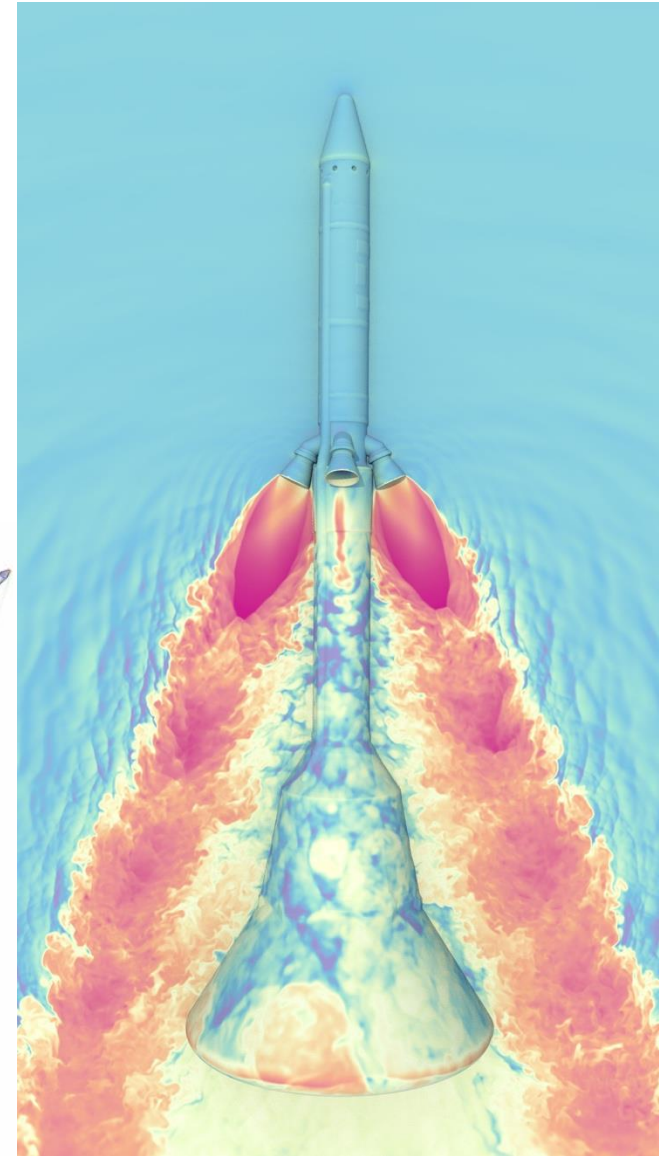
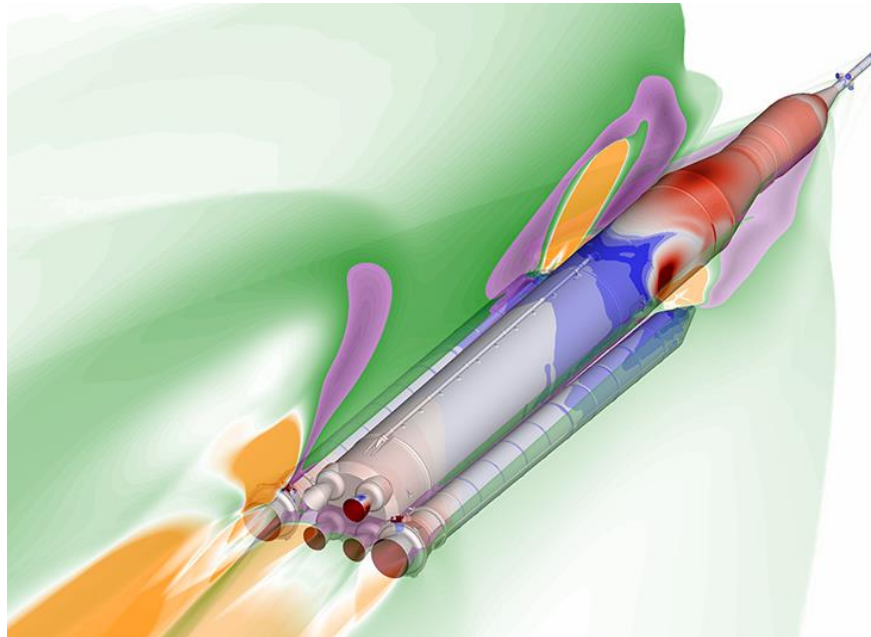
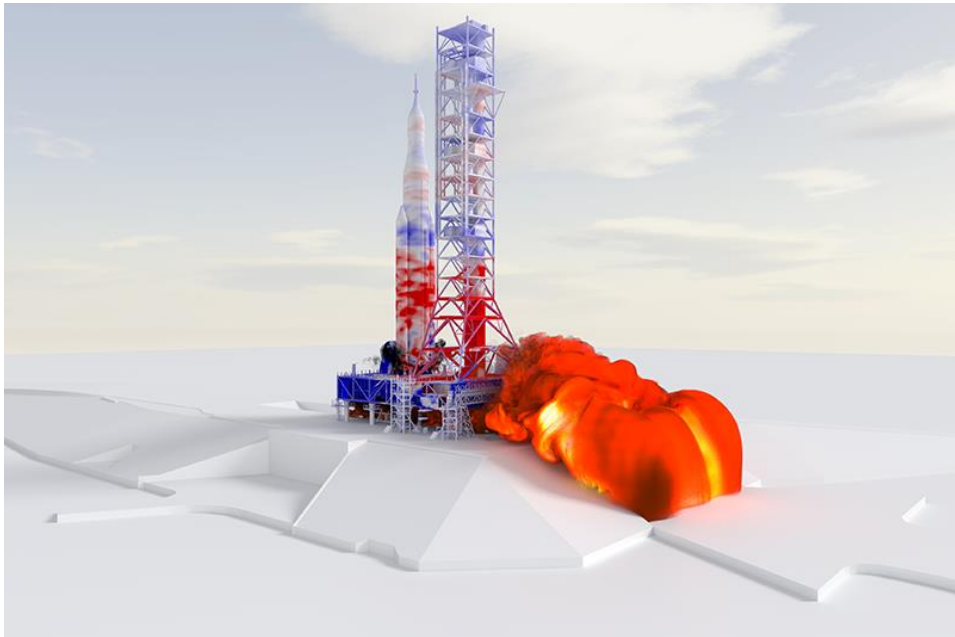
<https://www.nasa.gov/humans-in-space/space-launch-system/sls-fact-sheets/>



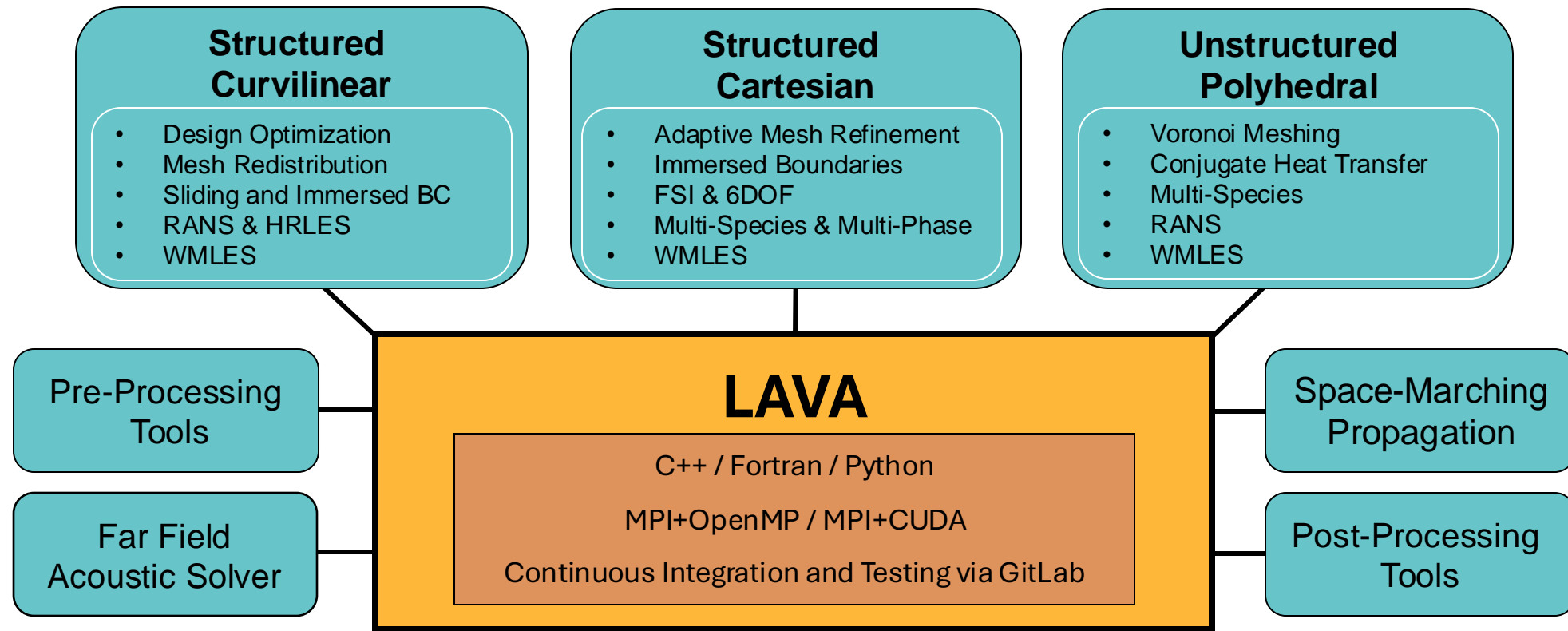
<https://www.nasa.gov/humans-in-space/view-the-best-images-from-nasas-artemis-i-mission/>

# 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



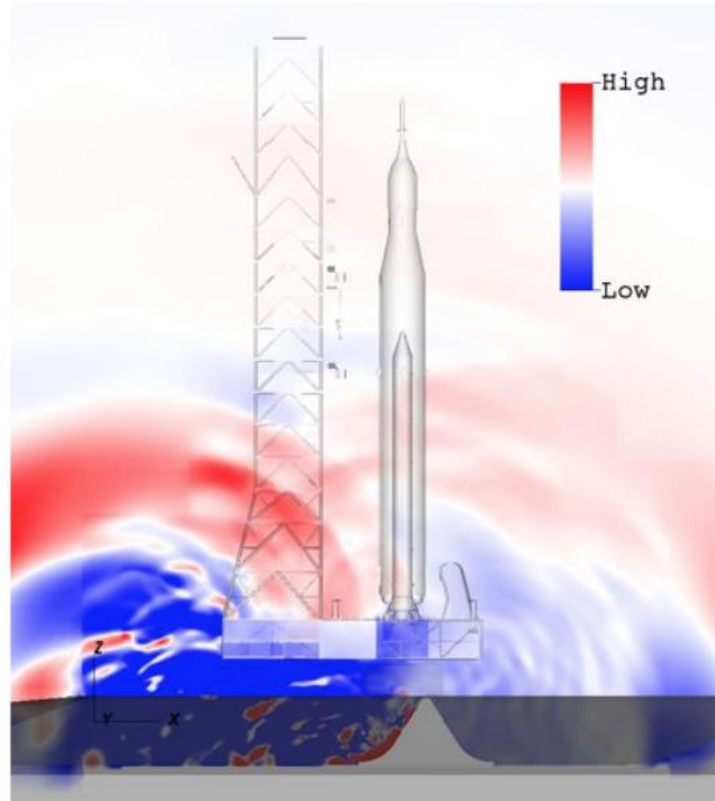
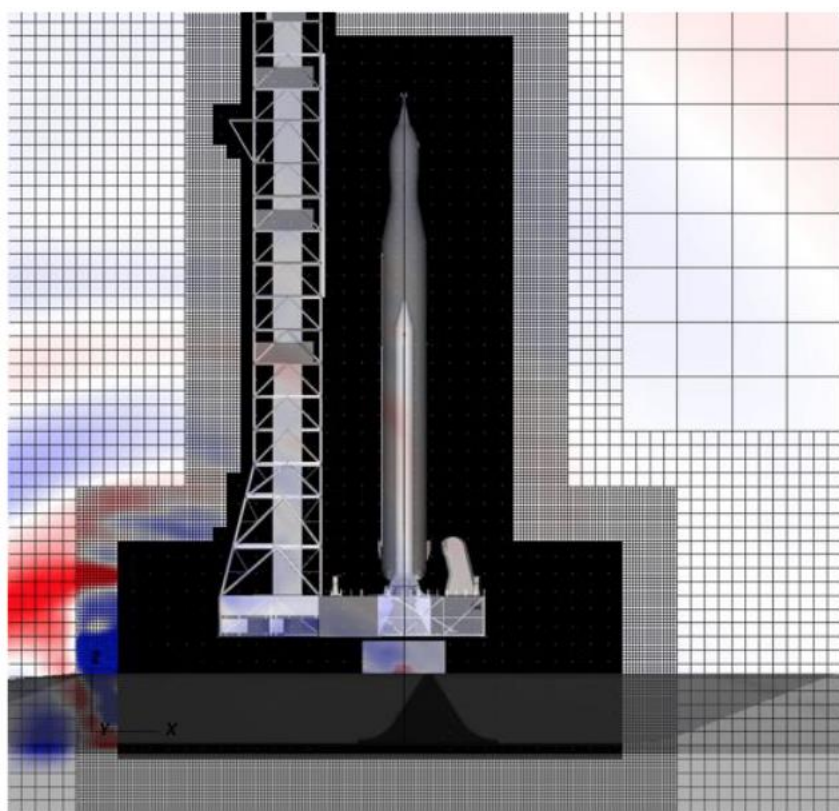
# Launch, Ascent, and Vehicle Aerodynamics (LAVA)



## Active Efforts:

- Low dissipation and higher order
- Wall modeled large eddy simulation
- Voronoi grid generation
- Design optimization
- Porting to GPUs and cloud compute
- Roadmap to release

# LAVA Structured Cartesian CFD Solver



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

# Numerical Methods

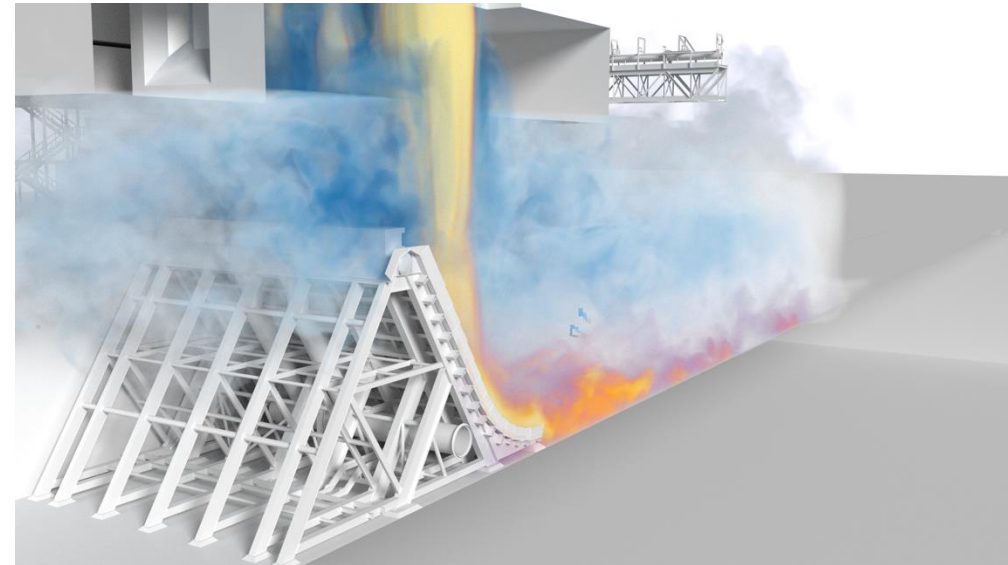
- Structured Cartesian grid
- Immersed boundary representation of geometry with slip walls (inviscid)

## Dry Simulation

- 5<sup>th</sup> order accurate weighed essentially non-oscillatory (WENO5) convective flux
- 3<sup>rd</sup> order accurate Strong Stability Preserving Runge-Kutta (SSPRK) time integration

## Wet Simulation

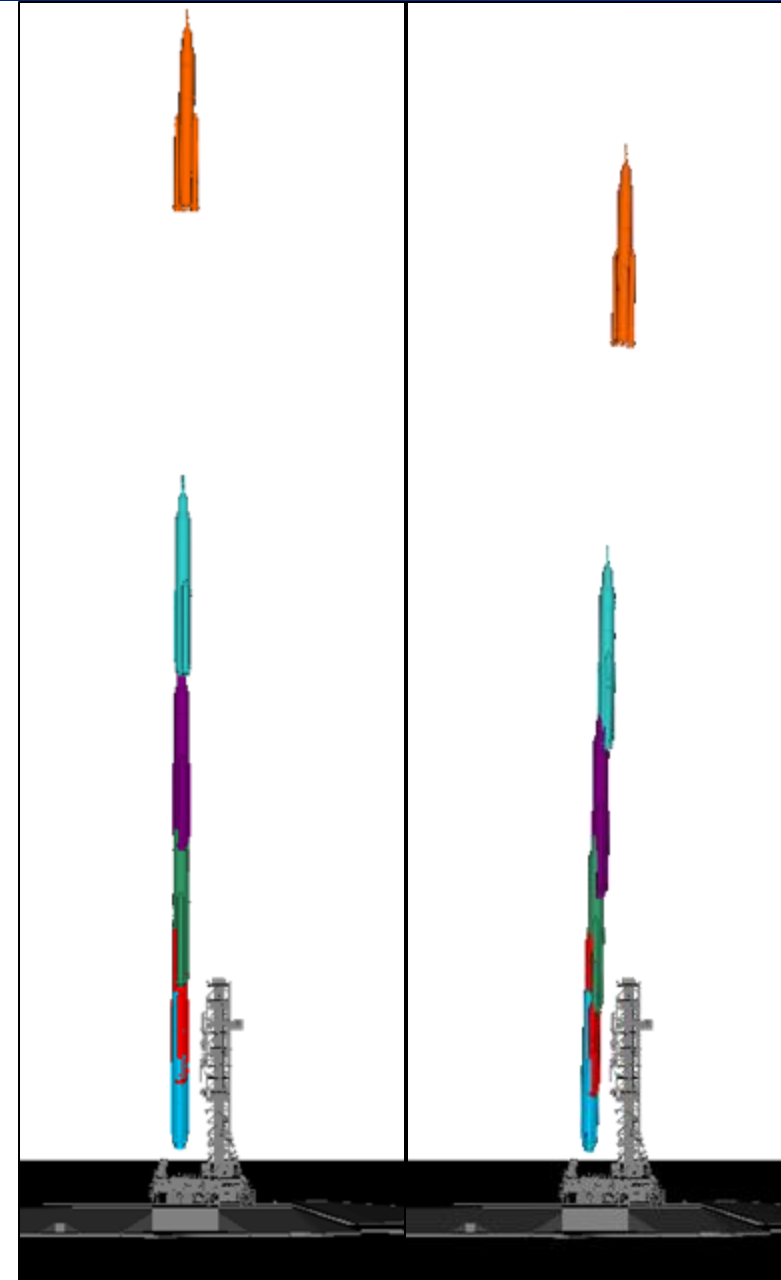
- 8<sup>th</sup> order accurate weighted compact nonlinear scheme (WCNS)
- Phase transition model to model evaporation and condensation between liquid and vapor water
- 1<sup>st</sup> order accurate forward Euler time integration



*“Predicting SLS Launch Environment using a Novel Multiphase Formulation”, AIAA SciTech Forum 2023-0645*

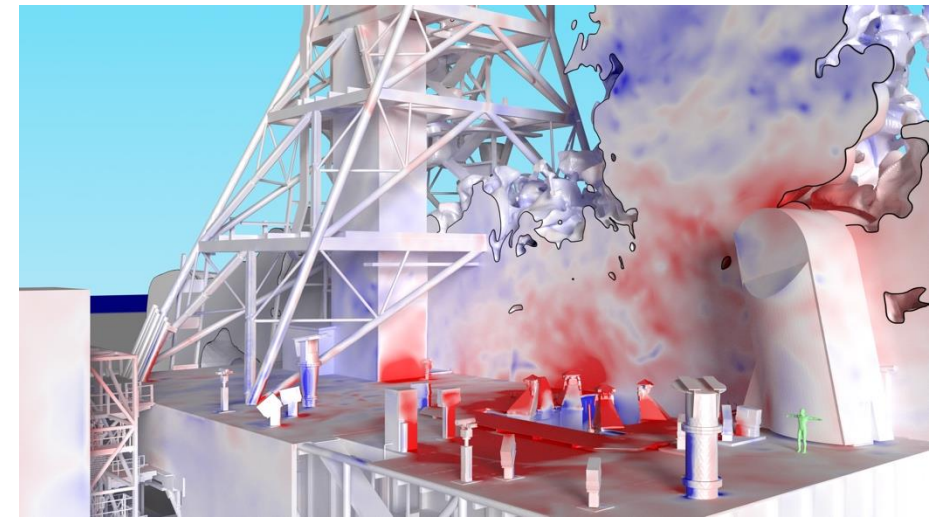
# Artemis Launchpad Simulations

- Previously we presented a suite of 13 lofted vehicle simulations at 6 different liftoff times for two different trajectories, Artemis I and Artemis II Max Drift, run within the LAVA (Launch Ascent and Vehicle Aerodynamics) Framework
  - Artemis I is the trajectory followed by the vehicle launch on November 16, 2022
  - Artemis II Max Drift is a simulated “max drift” trajectory taken from a separate set of analyses where the vehicle was closest to the tower
- All 13 simulations were run “dry” meaning there was no simulation of the water systems on the launchpad.
- **In this presentation we present a “wet” simulation where launchpad water systems are simulated for the Artemis I trajectory at 7 seconds.**
  - **We compare this simulation with its dry counterpart.**



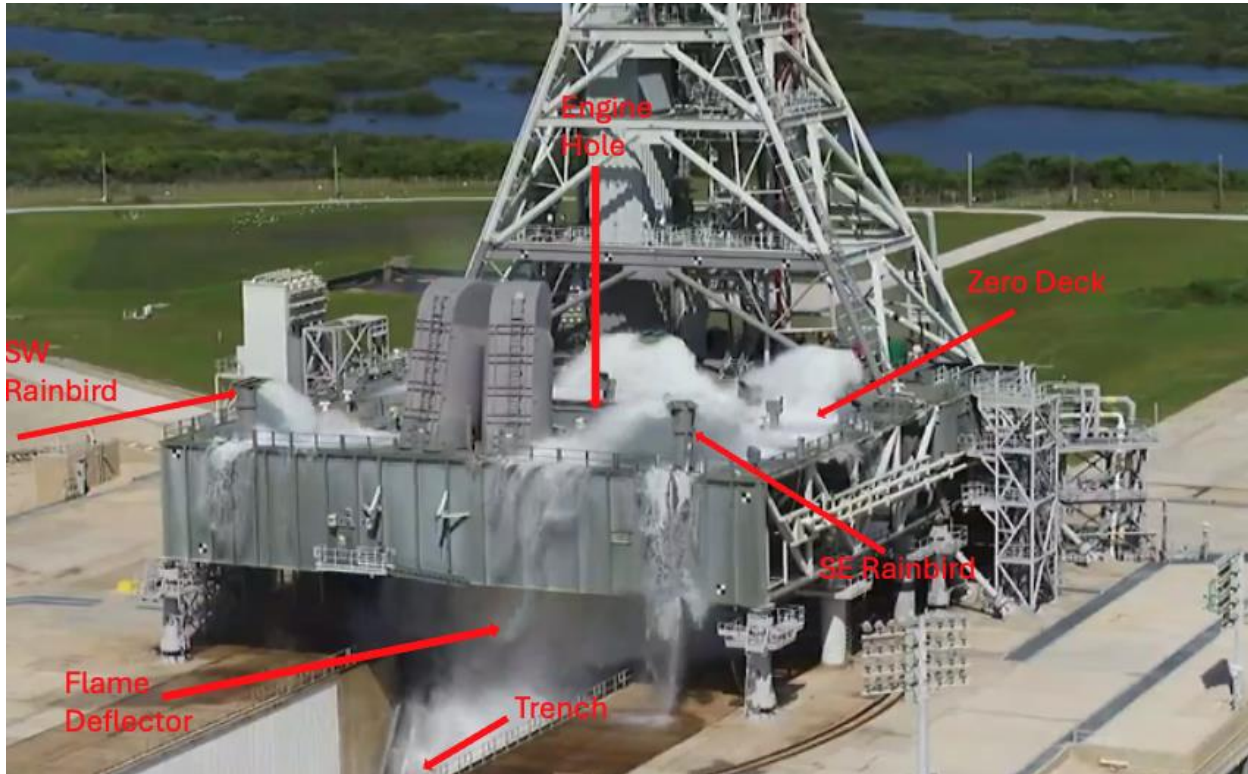
# Artemis multiphase simulation methodology

- Five species formulation with Liquid Water, Water Vapor, SRB plumes, SSME plumes, and air
  - Phase transition effects between liquid water and water vapor
- Four RS-25s given the same steady, radially varying boundary conditions at the exit plane
- Two RSRMs 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



AR1 07 sec 10% plume mass fraction

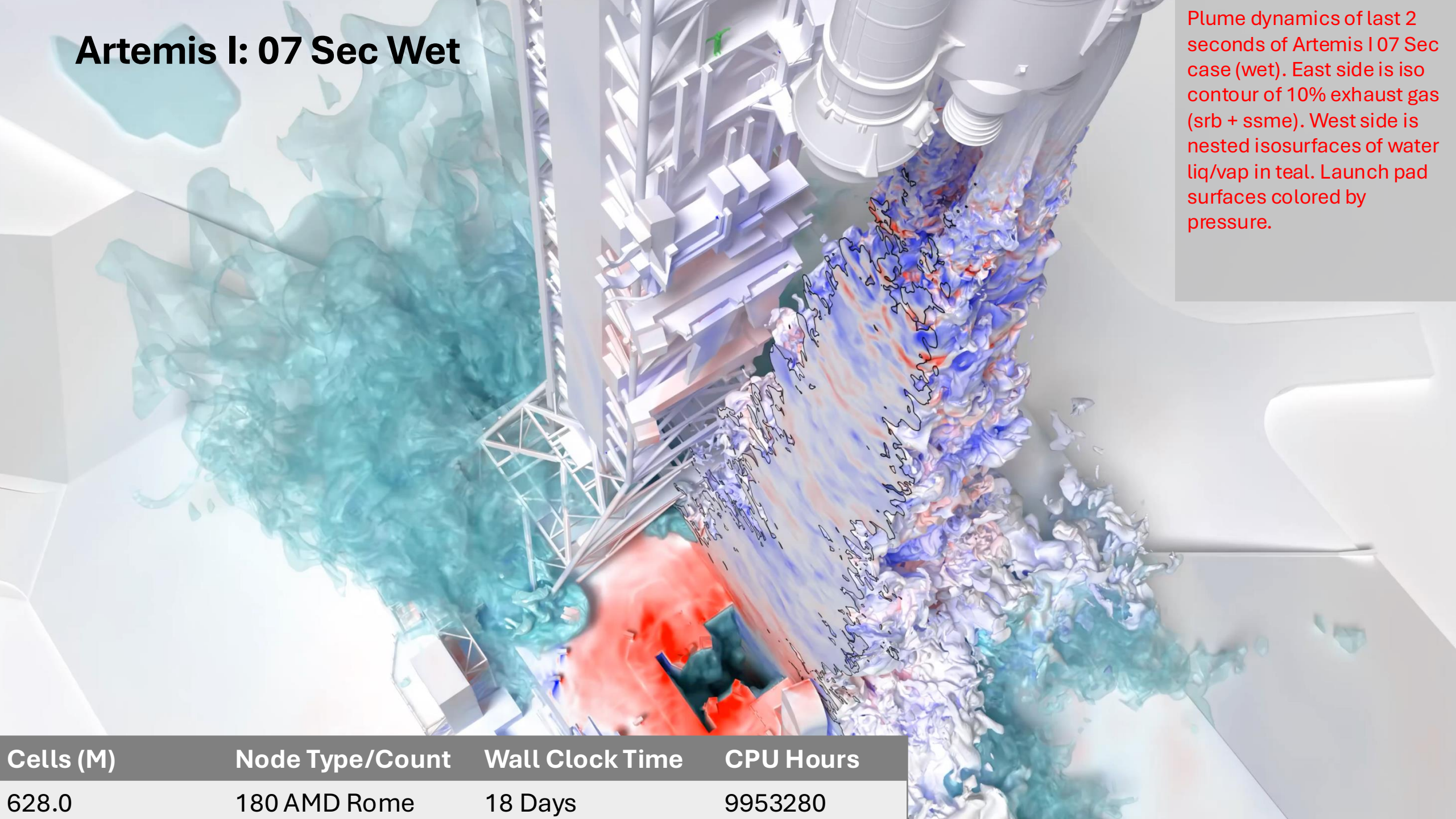
# Mobile Launcher Water Systems



[https://images-assets.nasa.gov/video/KSC-20231024-MH-CSH01-0001-Artemis\\_II\\_Water\\_Deluge\\_Test\\_39\\_B-M1718/KSC-20231024-MH-CSH01-0001-Artemis\\_II\\_Water\\_Deluge\\_Test\\_39\\_B-M1718~orig.mp4](https://images-assets.nasa.gov/video/KSC-20231024-MH-CSH01-0001-Artemis_II_Water_Deluge_Test_39_B-M1718/KSC-20231024-MH-CSH01-0001-Artemis_II_Water_Deluge_Test_39_B-M1718~orig.mp4)

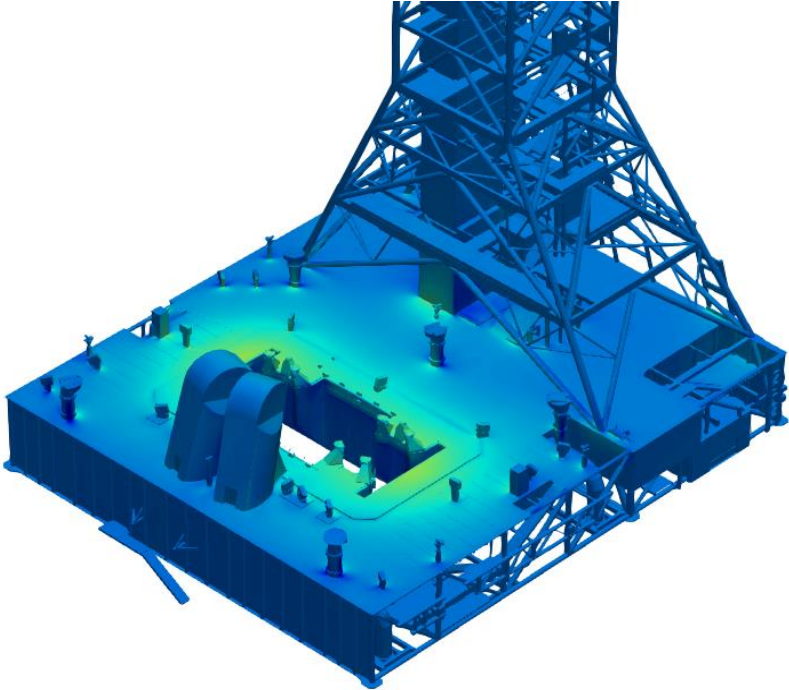
# Artemis I: 07 Sec Wet

Plume dynamics of last 2 seconds of Artemis I 07 Sec case (wet). East side is iso contour of 10% exhaust gas (srb + ssme). West side is nested isosurfaces of water liq/vap in teal. Launch pad surfaces colored by pressure.

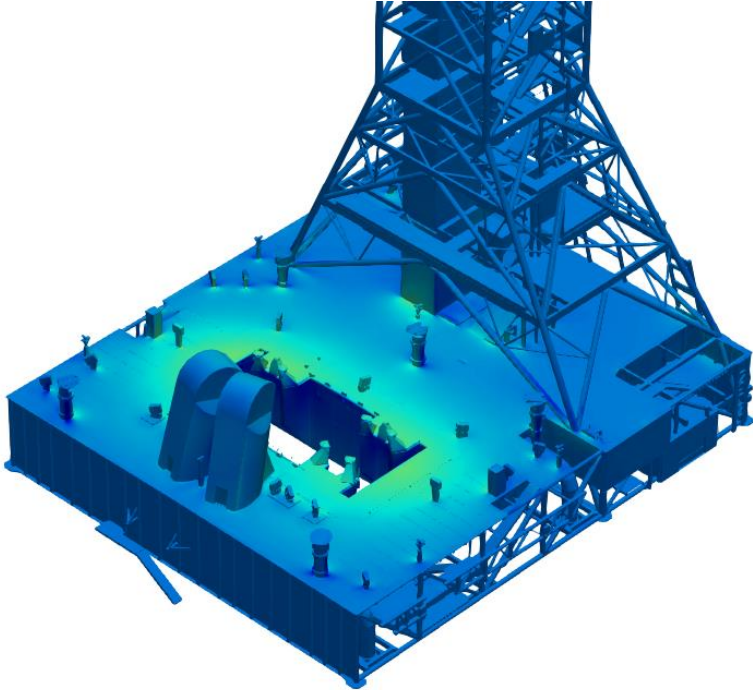


| Cells (M) | Node Type/Count | Wall Clock Time | CPU Hours |
|-----------|-----------------|-----------------|-----------|
| 628.0     | 180 AMD Rome    | 18 Days         | 9953280   |

# Time-averaged Pressure on Mobile Launcher Surfaces

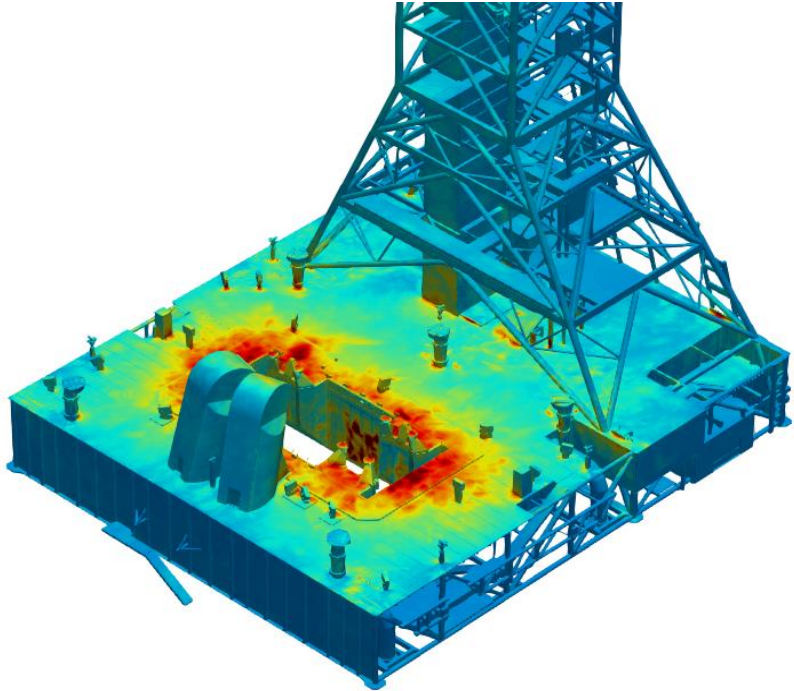


Artemis I 07 Wet

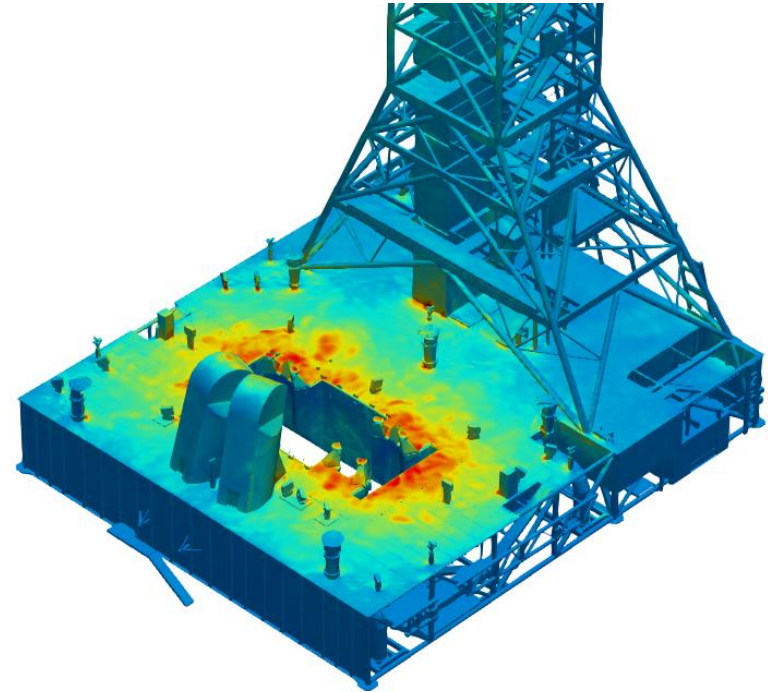


Artemis I 07 Dry

# Maximum Pressure Over Time on Mobile Launcher Surfaces

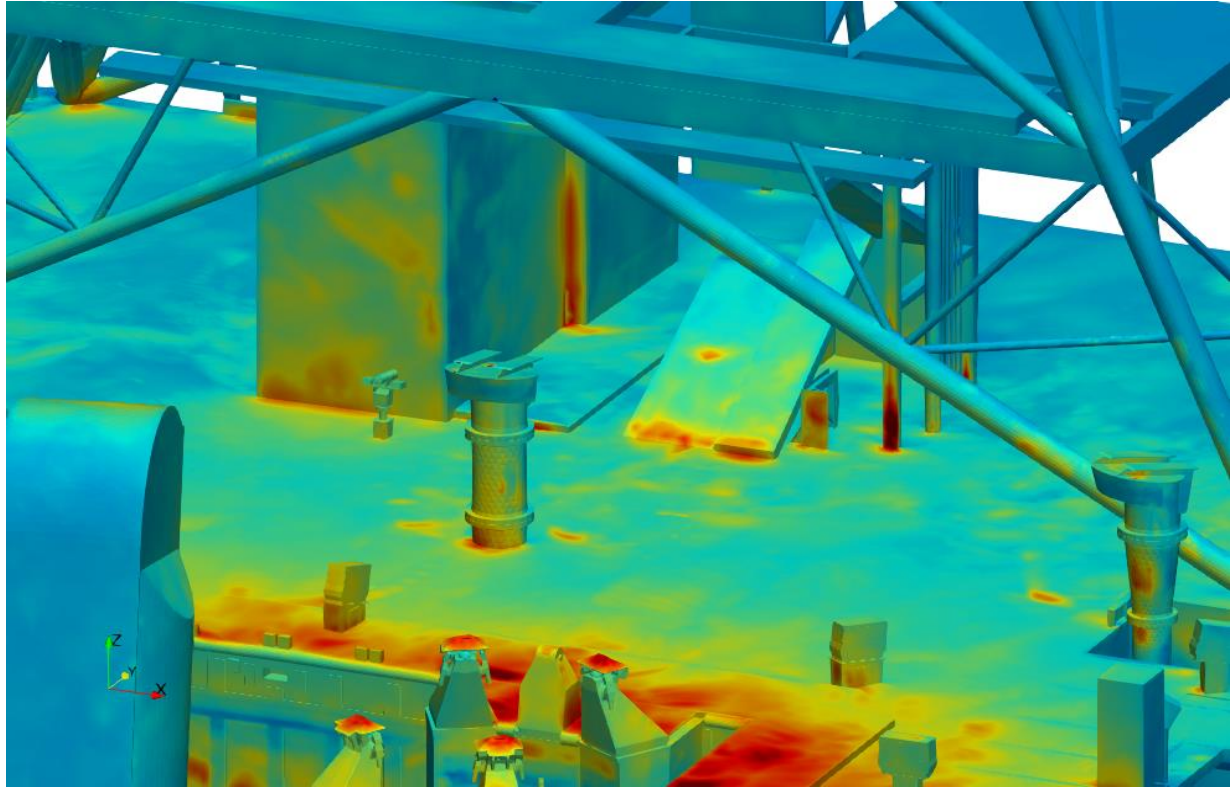


Artemis I 07 Wet

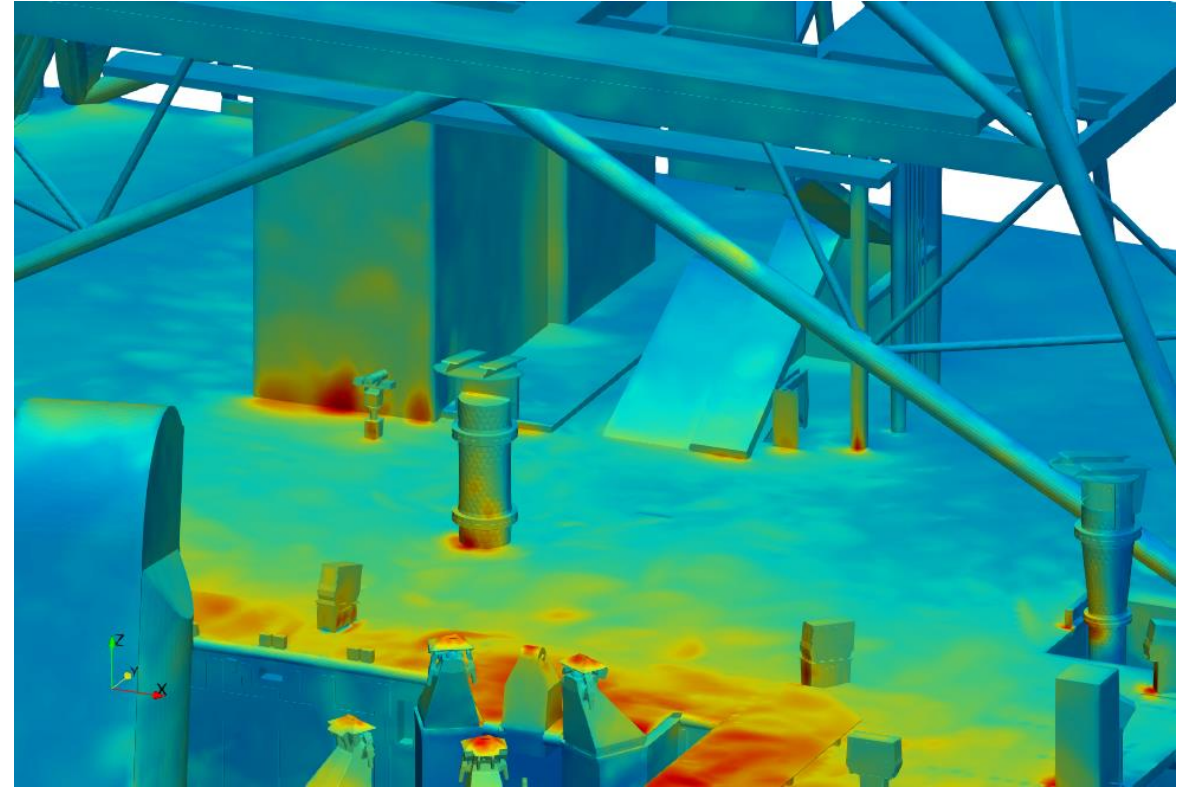


Artemis I 07 Dry

# Maximum Pressure Over Time on Mobile Launcher Surfaces

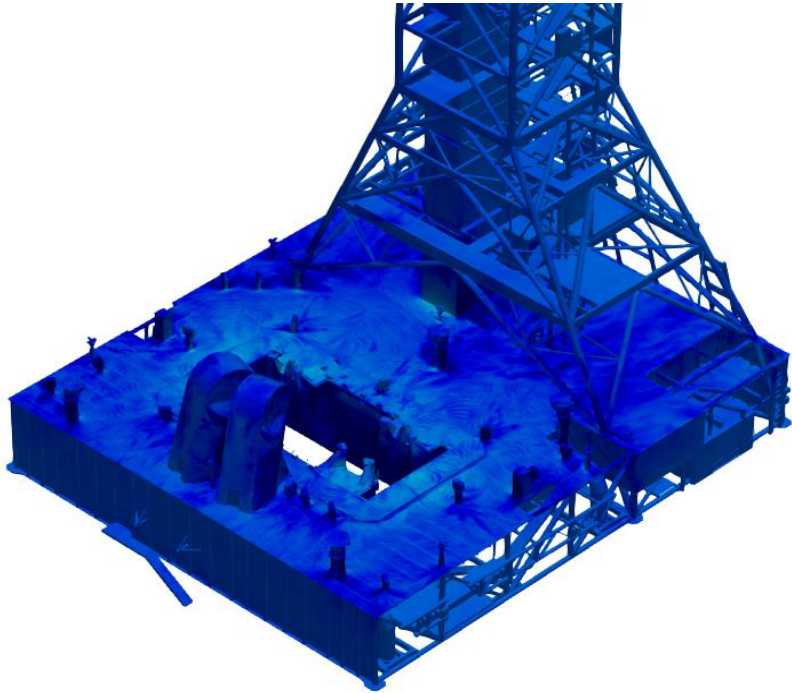


Artemis I 07 Wet

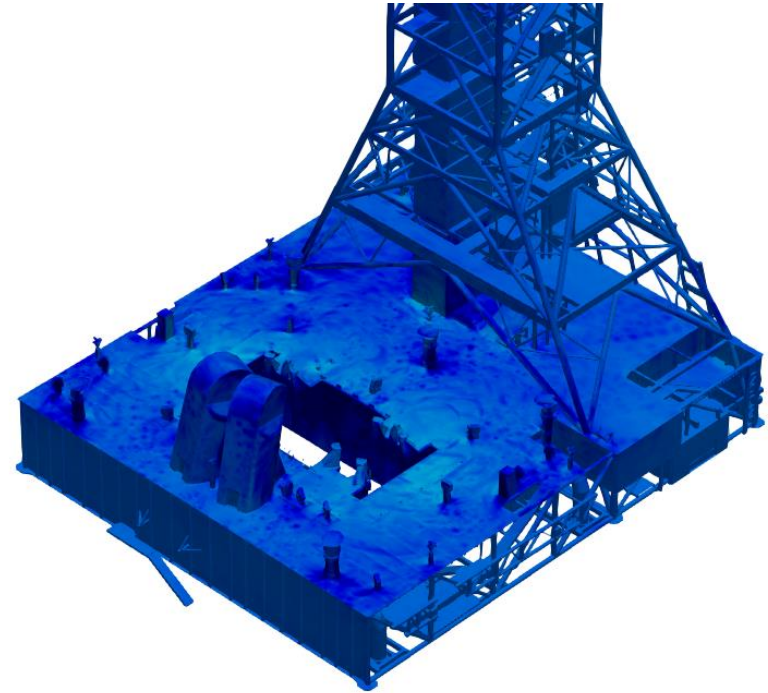


Artemis I 07 Dry

# Minimum Pressure Over Time on Mobile Launcher Surfaces

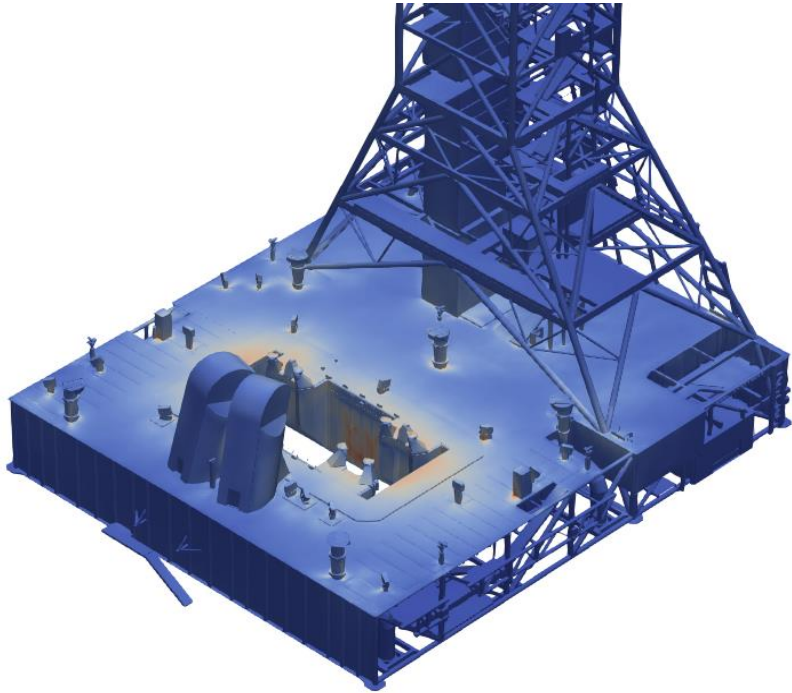


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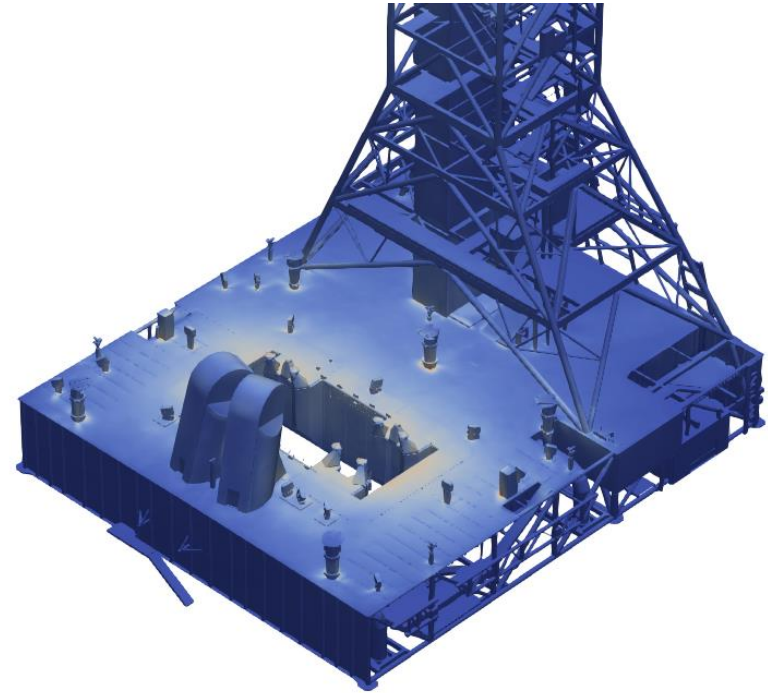


Artemis I 07 Dry

# Standard Deviation of Pressure Over Time on Mobile Launcher Surfaces

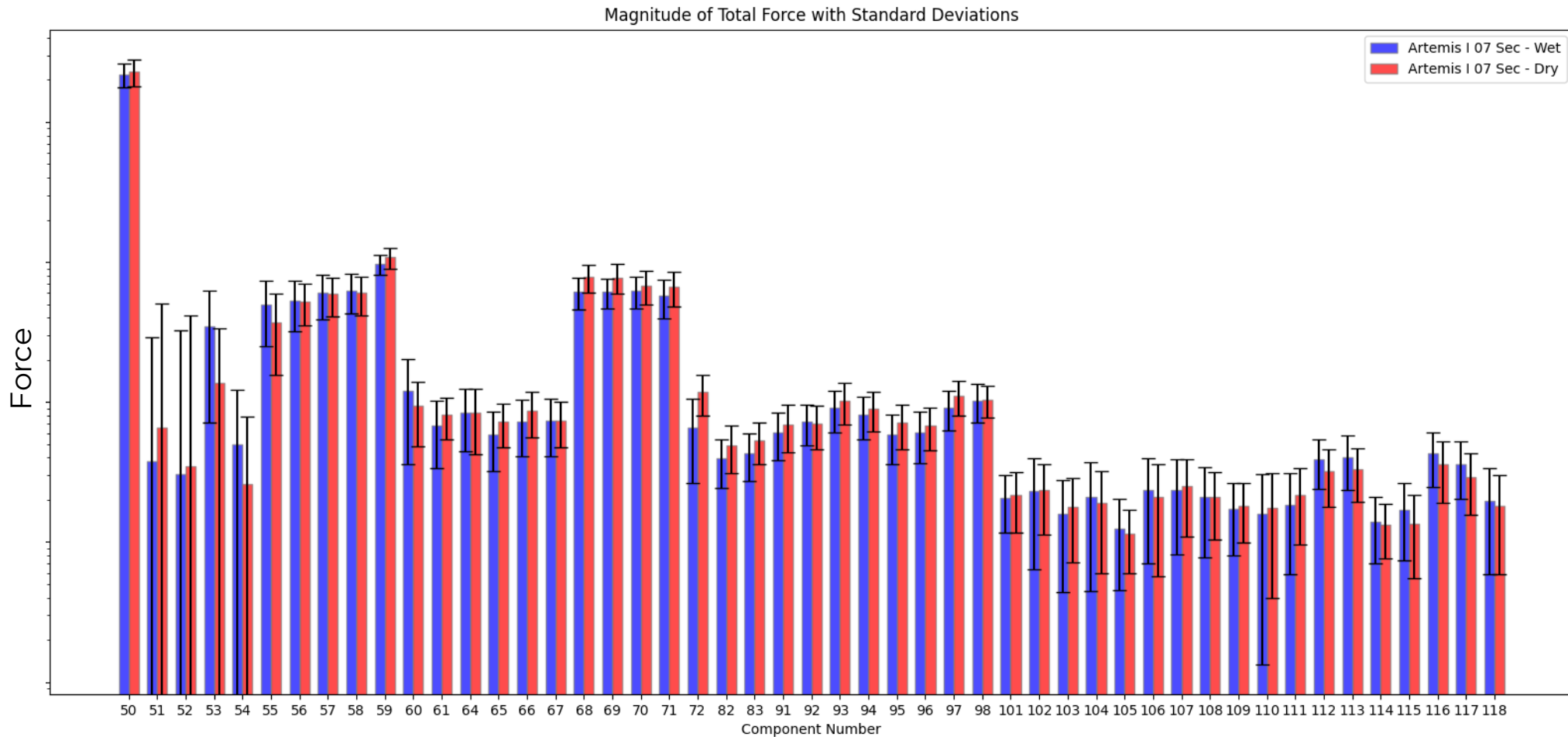


Artemis I 07 Wet

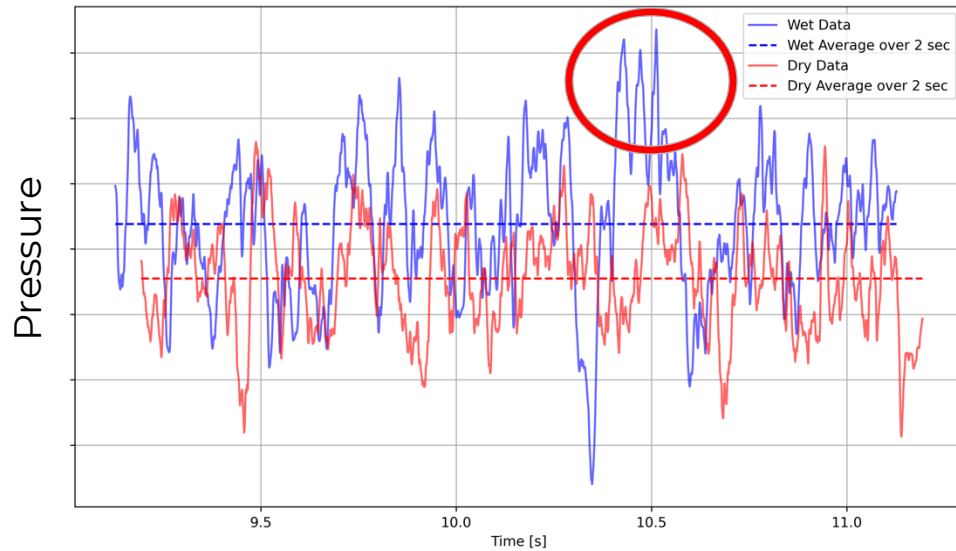


Artemis I 07 Dry

# Magnitude of Total Force with Error Bars using +/- 1 Standard Deviation on Mobile Launcher Components

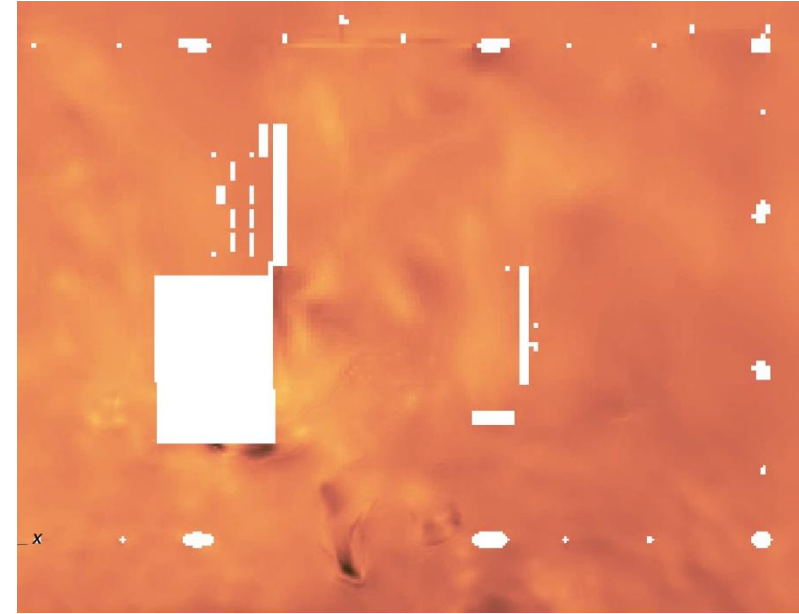


# Analysis of Unsteady Increased Pressure Forces



- Spikes in pressure can come from temporary blockage of the plume with rainbird water or water being slammed into the side walls.
- This could be one of the mechanisms that increased the pressure force significantly on this component.

Vertical slice in first level of Mobile Launcher colored by pressure

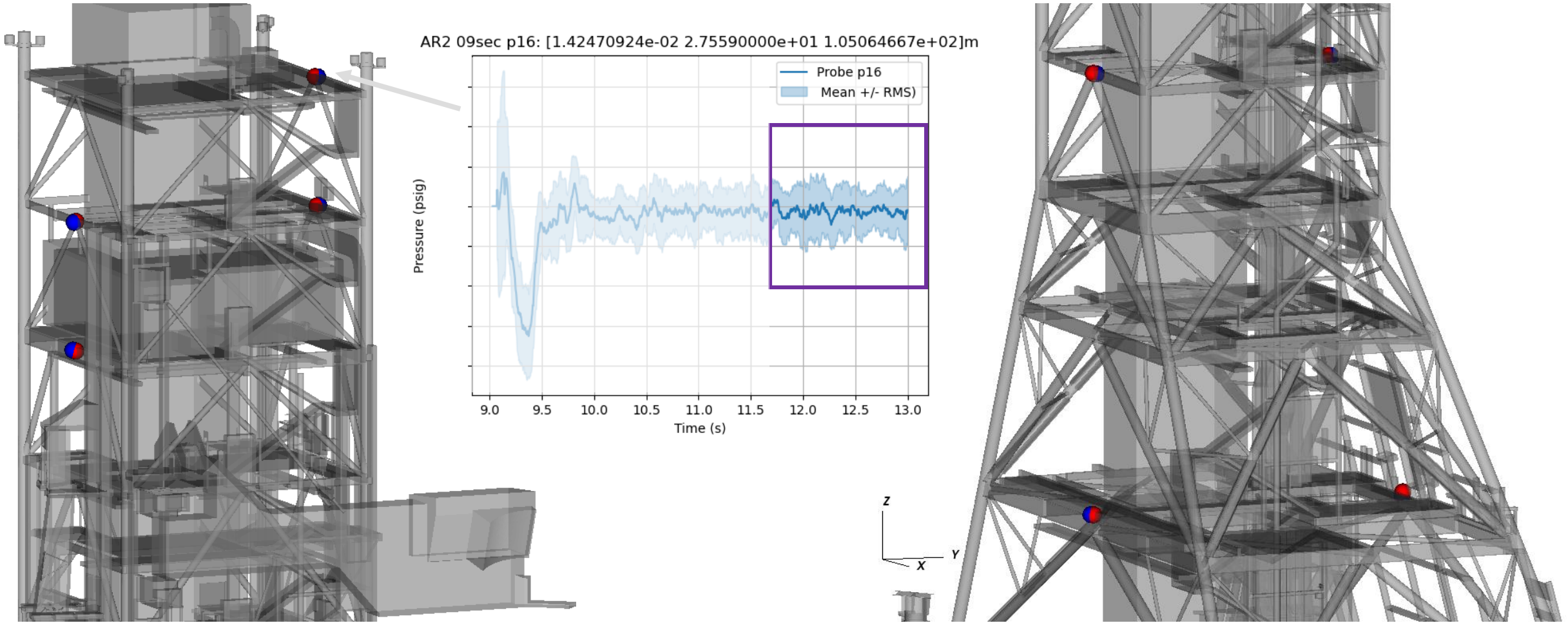


Vertical slice in first level of Mobile Launcher colored by mass fraction of water



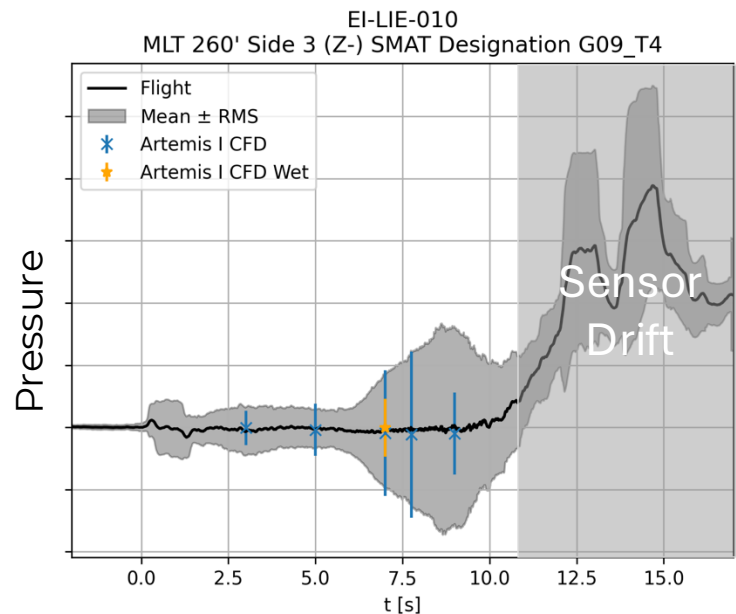
# Artemis II Max Drift @ 9 sec: CFD pressure time series

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

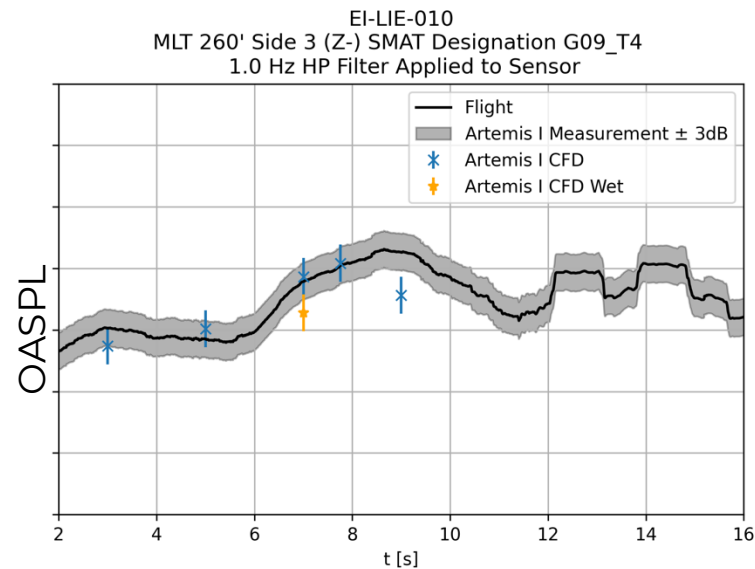
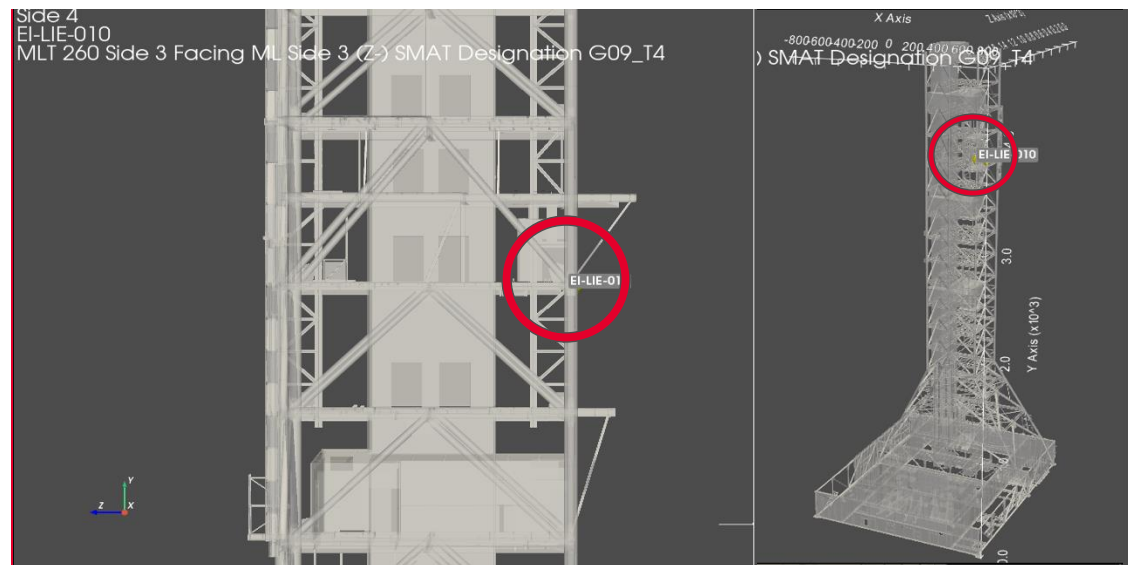
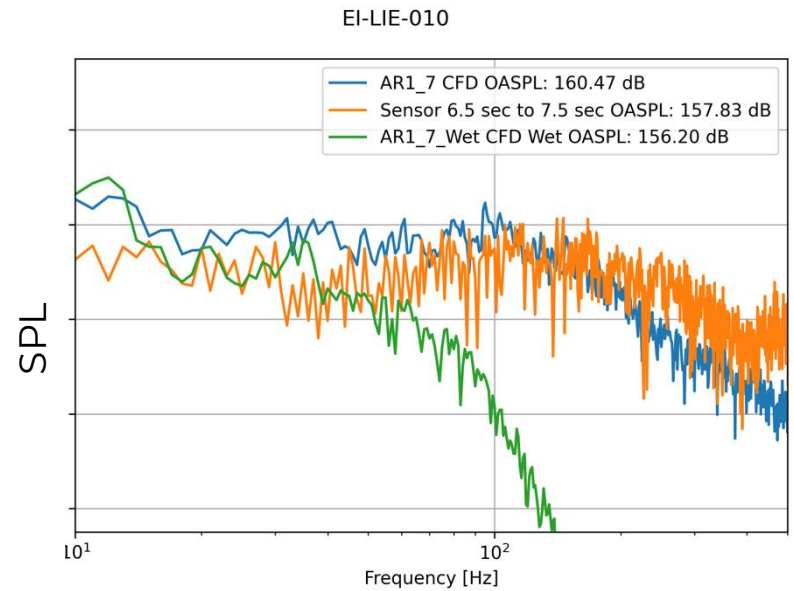


Node locations with as requested in red and as actually located in blue; center plot of gauge pressure at the top probe location, excluding numerical startup portion

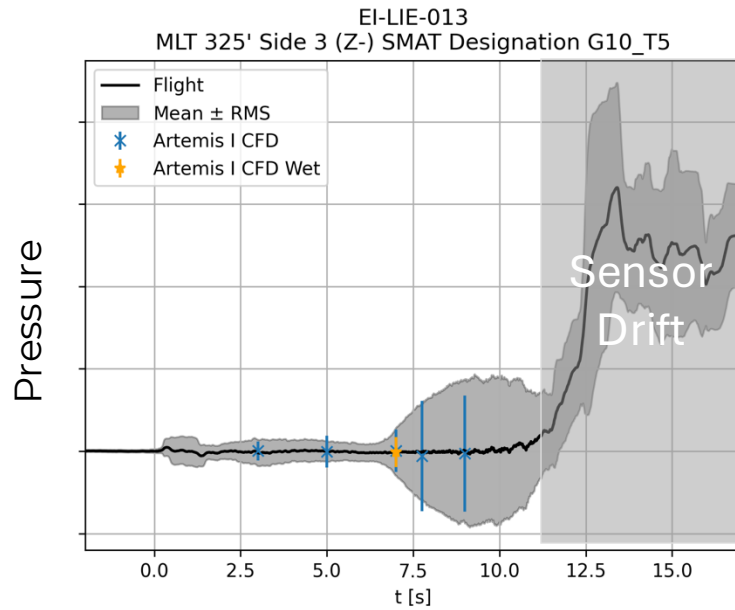
Comparison to measurement:  
North face (not plume facing)



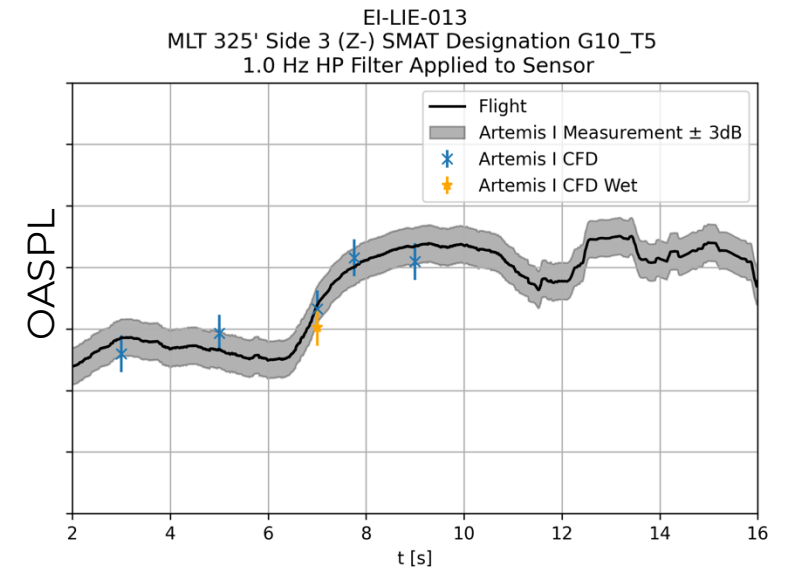
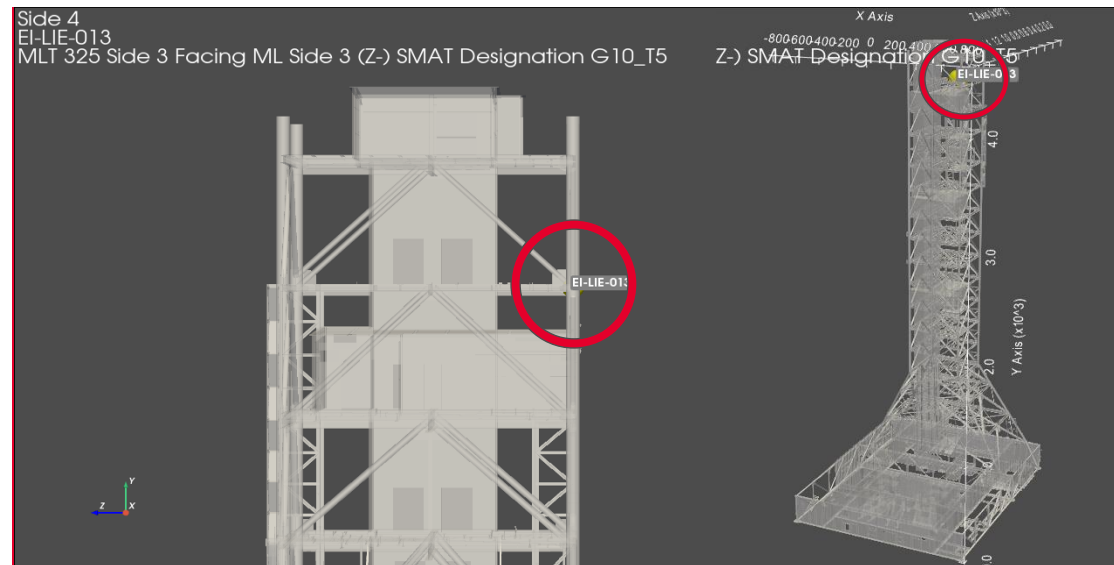
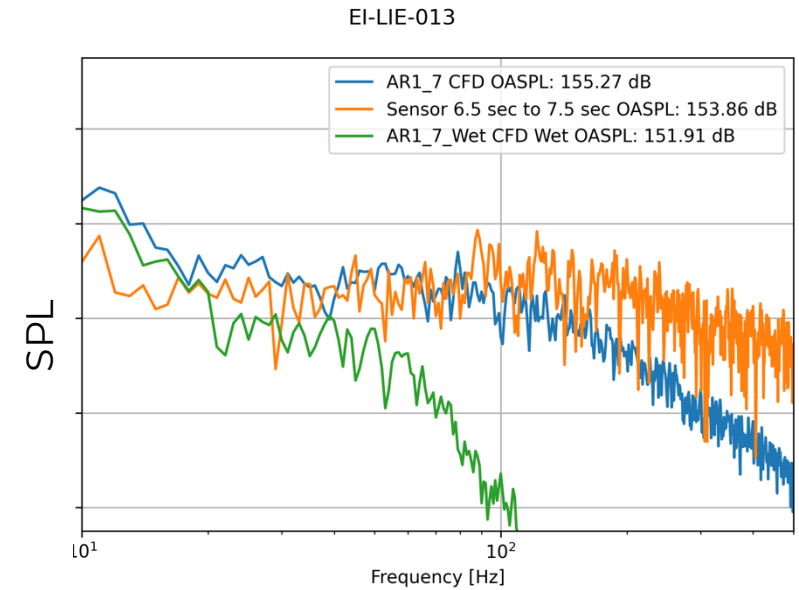
*Last-second gauge pressure averages for each simulation compared to ML tower measurements. Error bars indicate +/-std. (Z-) indicating north face. Some drift is evident at later times in the measurements.*



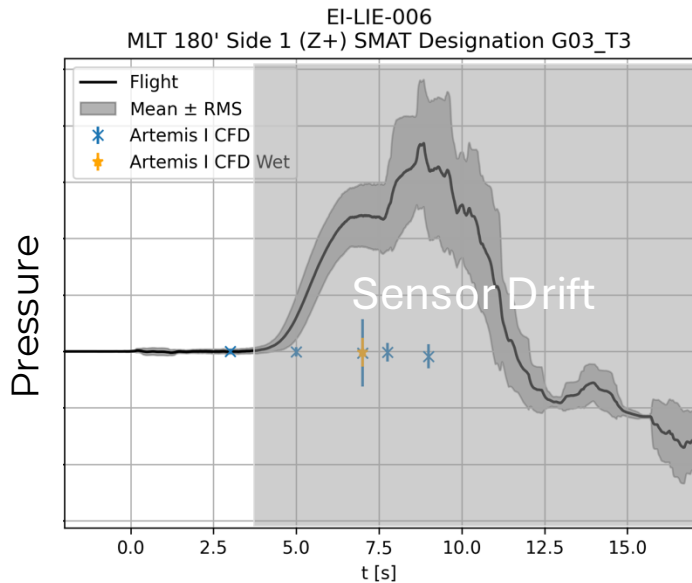
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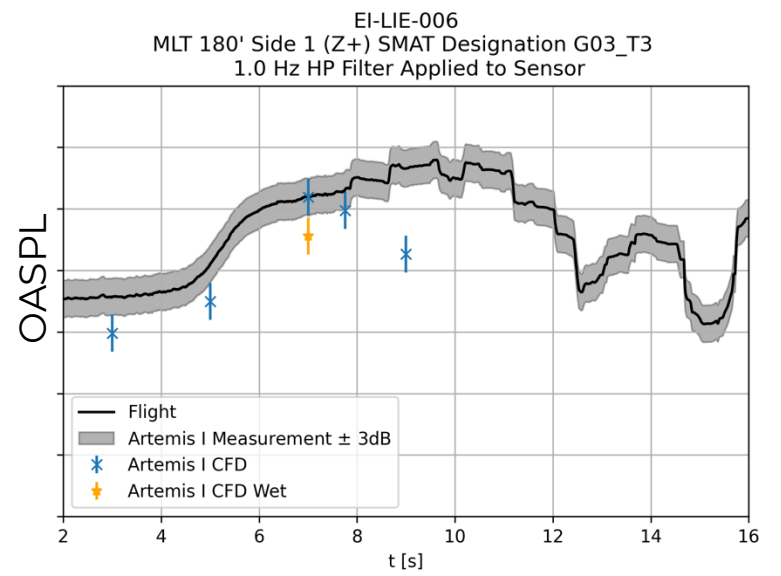
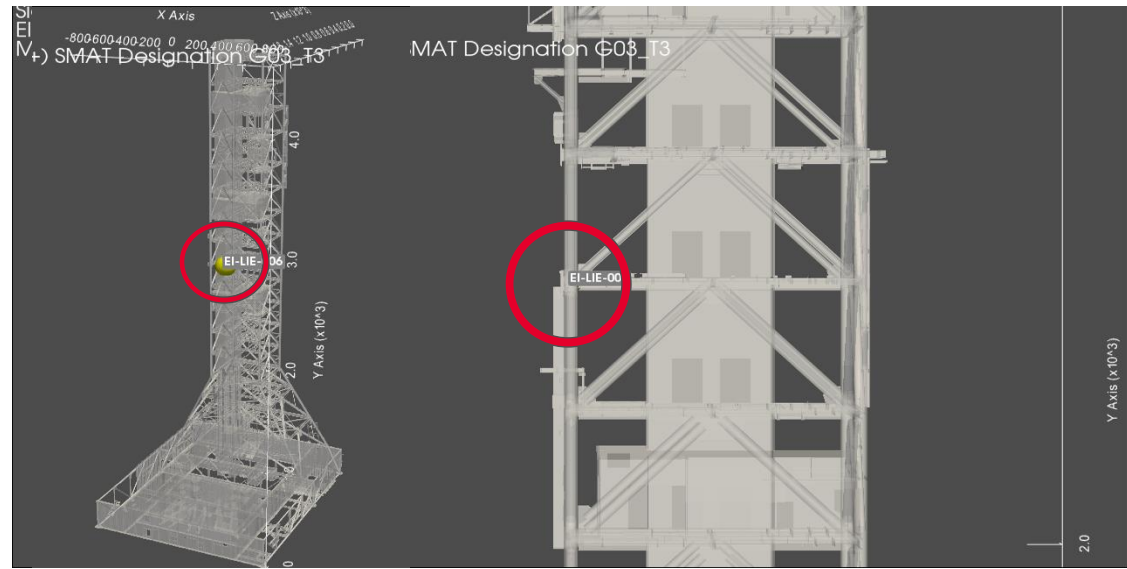
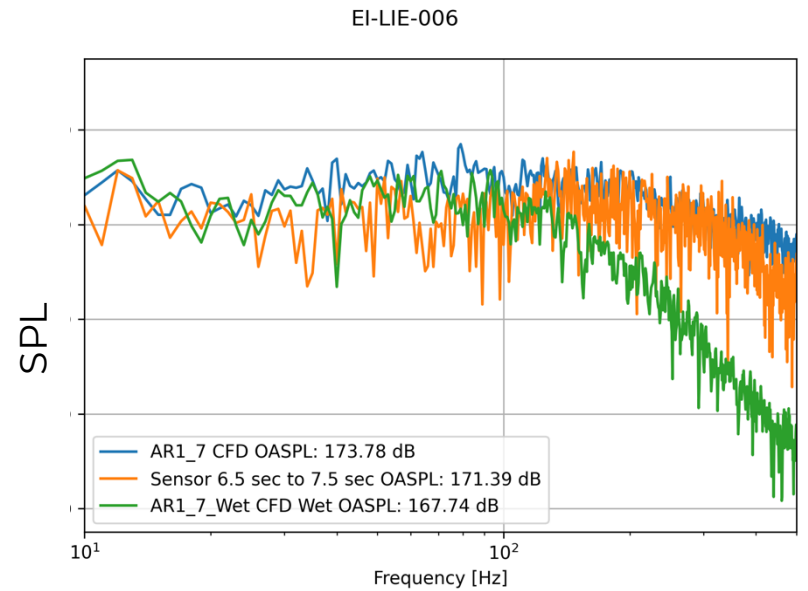
*Last-second gauge pressure averages for each simulation compared to ML tower measurements. Error bars indicate +/-std. (Z-) indicating north face. Some drift is evident at later times in the measurements.*



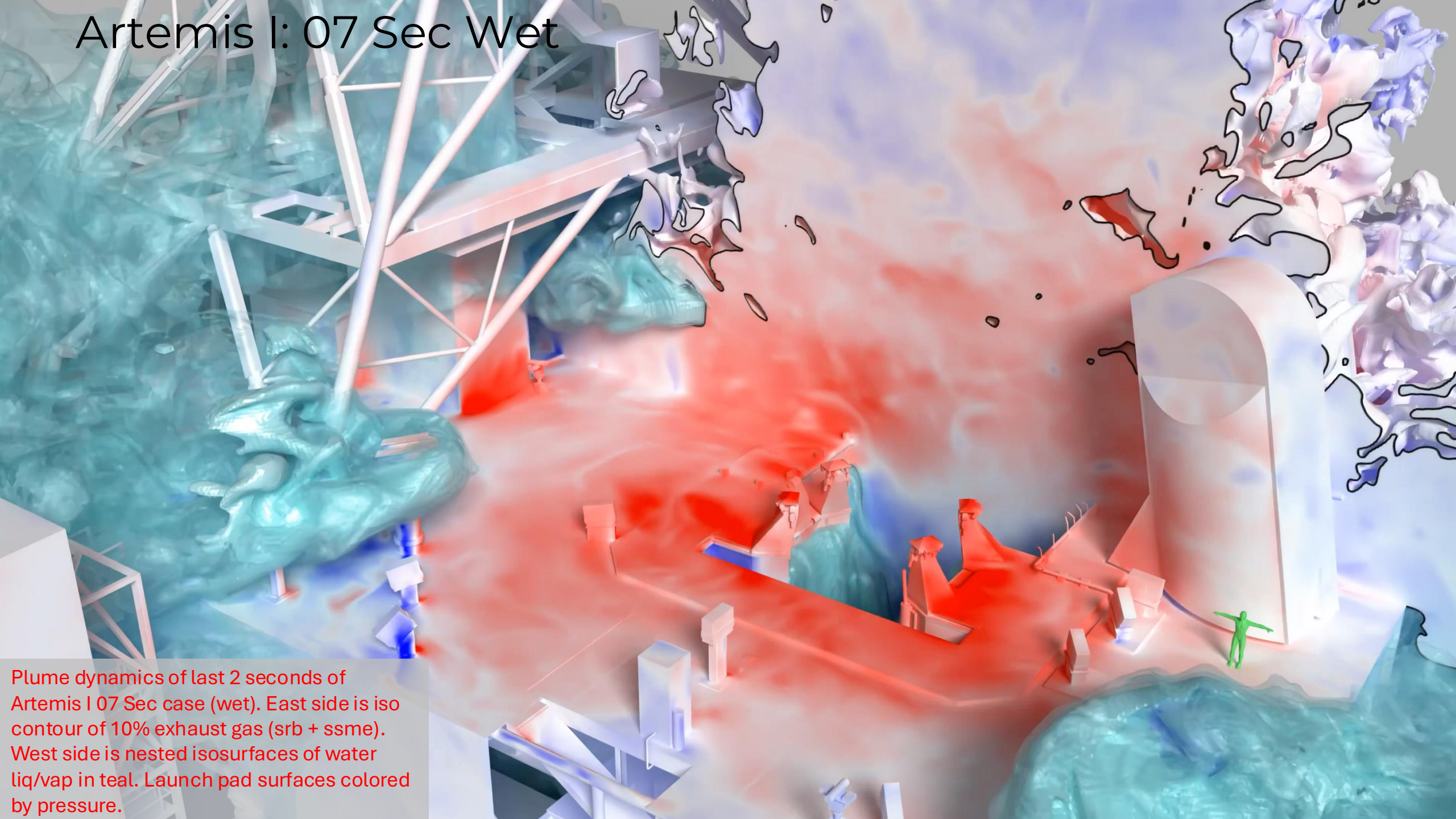
# Comparison to measurement: South face (plume facing)



*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.*

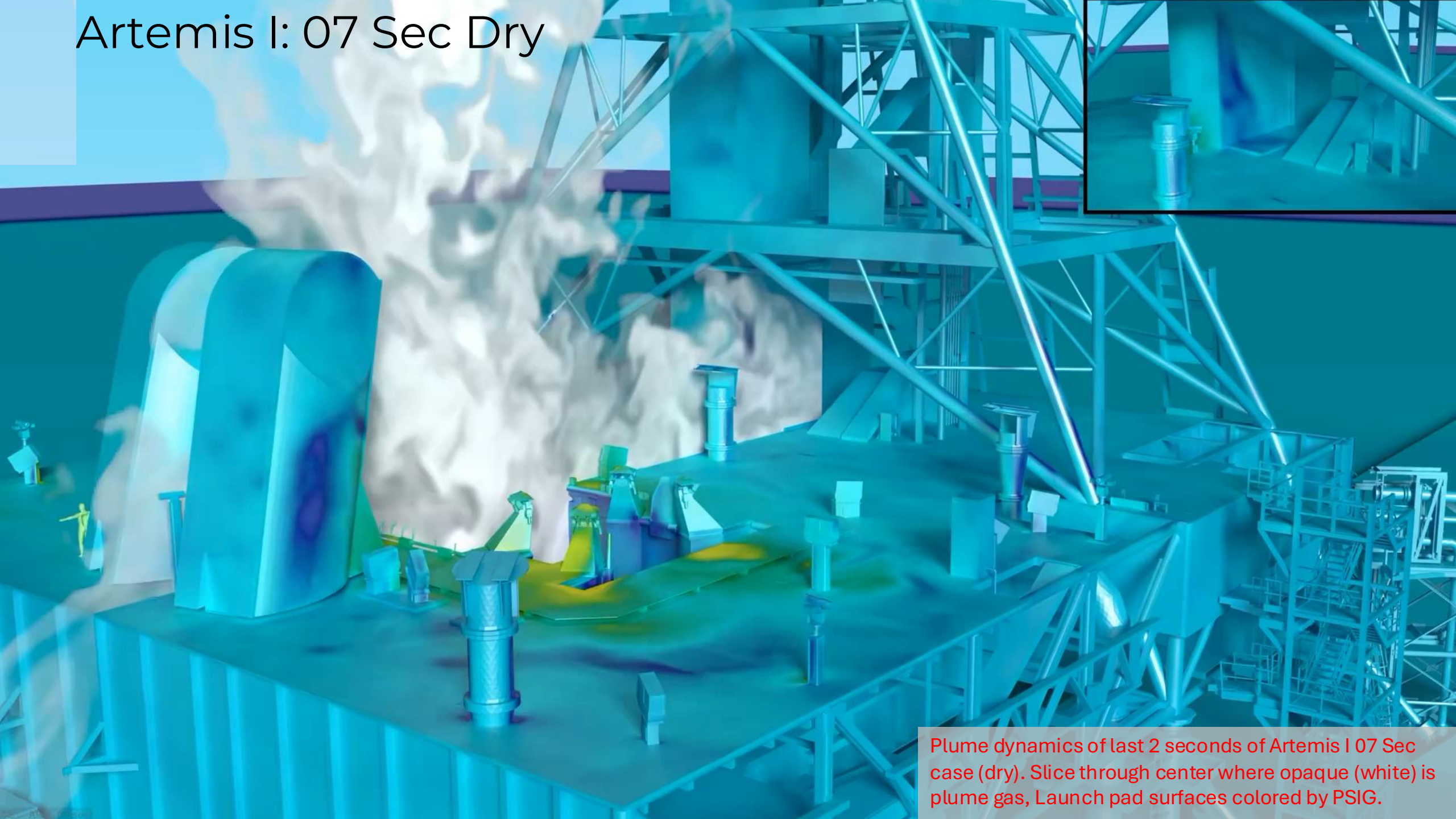


# Artemis I: 07 Sec Wet



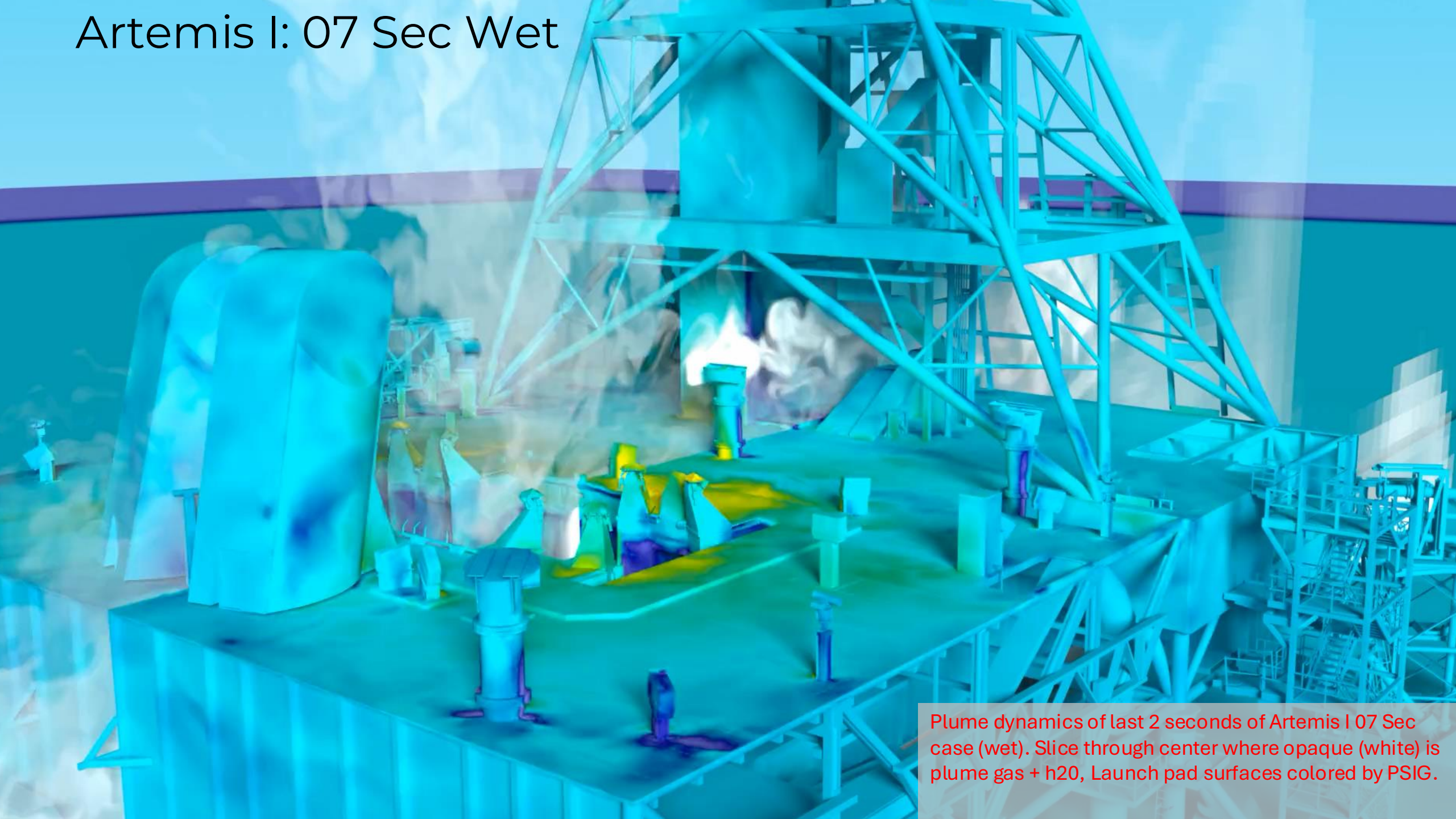
Plume dynamics of last 2 seconds of Artemis I 07 Sec case (wet). East side is iso contour of 10% exhaust gas (srb + ssme). West side is nested isosurfaces of water liq/vap in teal. Launch pad surfaces colored by pressure.

# Artemis I: 07 Sec Dry



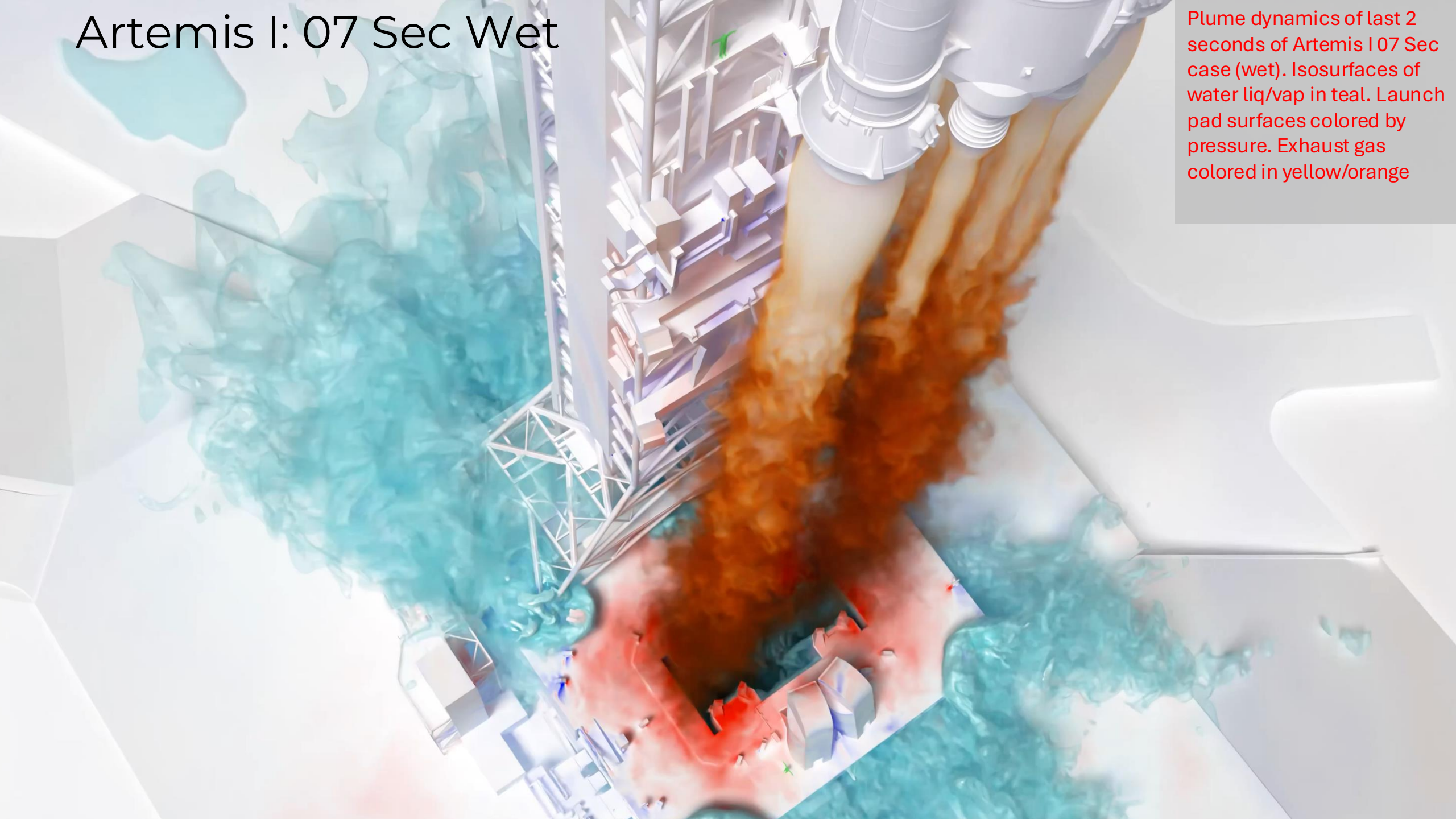
Plume dynamics of last 2 seconds of Artemis I 07 Sec case (dry). Slice through center where opaque (white) is plume gas, Launch pad surfaces colored by PSIG.

# Artemis I: 07 Sec Wet



Plume dynamics of last 2 seconds of Artemis I 07 Sec case (wet). Slice through center where opaque (white) is plume gas + h2o, Launch pad surfaces colored by PSIG.

# Artemis I: 07 Sec Wet



Plume dynamics of last 2 seconds of Artemis I 07 Sec case (wet). Isosurfaces of water liq/vap in teal. Launch pad surfaces colored by pressure. Exhaust gas colored in yellow/orange

# Overview of Computational Resources Used

| Traj time (s) | Flight               | Cells (M)    | Node Type/Count     | Wall Clock Time | CPU Hours      |
|---------------|----------------------|--------------|---------------------|-----------------|----------------|
| 3             | Artemis I            | 567.2        | 150 AMD Rome        | 4 Days          | 1843200        |
| 3             | Artemis II MD        | 541.2        | 150 AMD Rome        | 4 Days          | 1843200        |
| 5             | Artemis I            | 601.3        | 150 AMD Rome        | 4 Days          | 1843200        |
| 5             | Artemis II MD        | 560.7        | 150 AMD Rome        | 4 Days          | 1843200        |
| 7             | Artemis I            | 593.1        | 150 AMD Rome        | 4 Days          | 1843200        |
| 7             | Artemis II MD        | 568.3        | 150 AMD Rome        | 4 Days          | 1843200        |
| <b>7</b>      | <b>Artemis I Wet</b> | <b>628.0</b> | <b>180 AMD Rome</b> | <b>18 Days</b>  | <b>9953280</b> |
| 7.76          | Artemis I            | 605.3        | 150 AMD Rome        | 4 Days          | 1843200        |
| 9             | Artemis I            | 614.0        | 150 AMD Rome        | 4 Days          | 1843200        |
| 9             | Artemis II MD        | 603.3        | 150 AMD Rome        | 4 Days          | 1843200        |
| 11            | Artemis I            | 683.7        | 150 AMD Rome        | 4 Days          | 1843200        |
| 11            | Artemis II MD        | 647.4        | 150 AMD Rome        | 4 Days          | 1843200        |
| 15            | Artemis I            | 907.4        | 150 AMD Rome        | 4 Days          | 1843200        |
| 15            | Artemis II MD        | 839.9        | 150 AMD Rome        | 4 Days          | 1843200        |

# Acknowledgments / 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)
- All current and former LAVA Team members

## 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.



# Questions?

[christopher.j.degrendele@nasa.gov](mailto:christopher.j.degrendele@nasa.gov)

[jared.c.duensing@nasa.gov](mailto:jared.c.duensing@nasa.gov)