National Aeronautics and Space Administration

# Analysis of Launch Vehicle Liftoff Debris: Historical Perspective from Space Shuttle and Application to Artemis I


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# Launch Vehicle Debris

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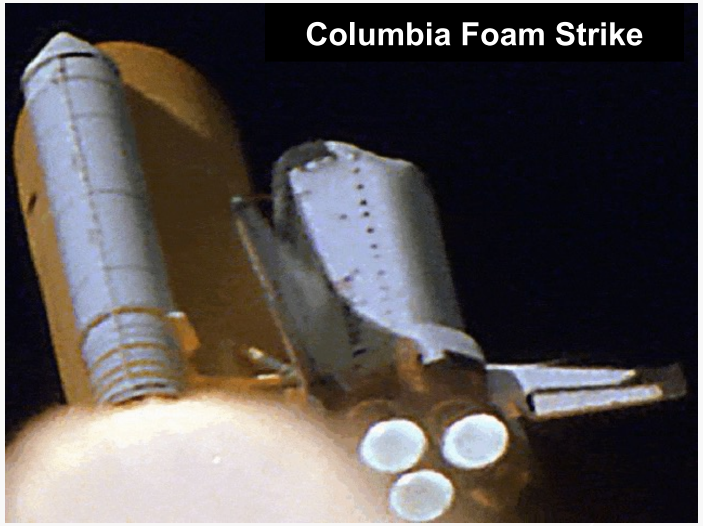
- **Exploration-class launch vehicles inherently prone to debris due to extreme environments**
  - Pre-launch Operations
  - Ignition and Liftoff
  - Ascent Aerodynamics
  - Cryogenic Propellants
- **Debris is risk to vehicle and mission success**
  - Concerns are crew safety and vehicle performance
  - Programs may accept risk if likelihood and/or consequence of debris strike fits within risk posture
- **Columbia accident changed the way NASA views and assesses debris risk**
  - Bipod Ramp foam liberation was an accepted flight risk despite previous damage
  - Shuttle Return to Flight effort initiated formal process for debris transport, damage, and risk assessments with greater weight in program and flight decisions


**Saturn V Ice Debris**

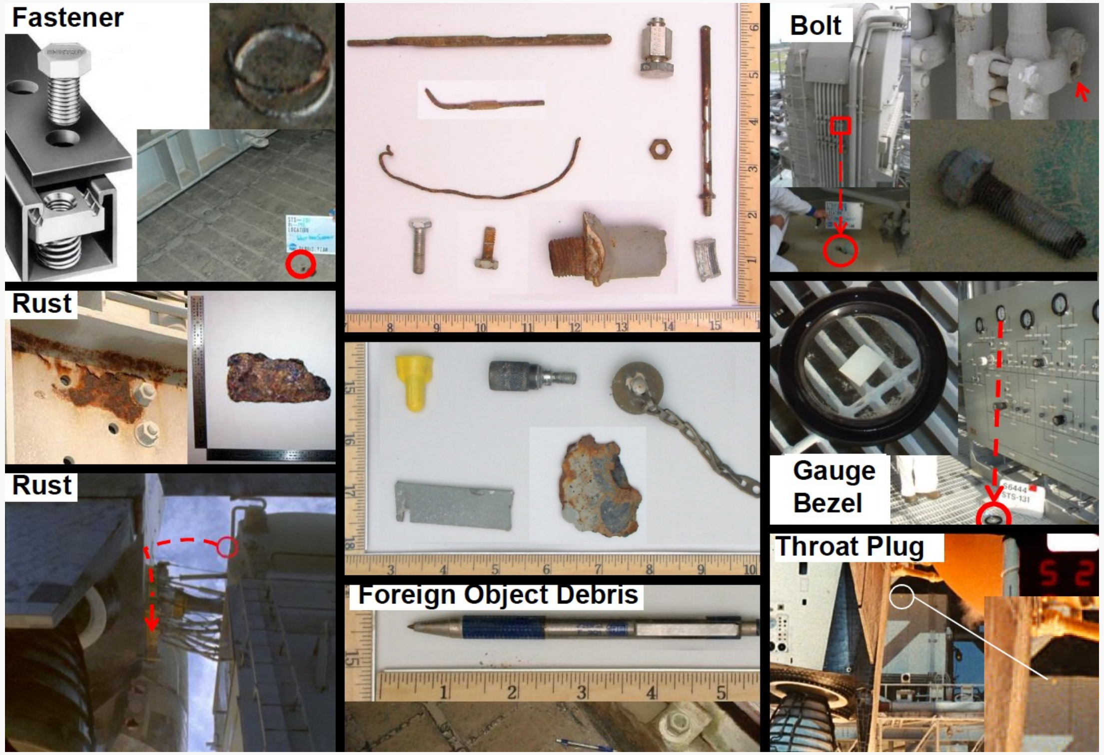


**Columbia Foam Strike**

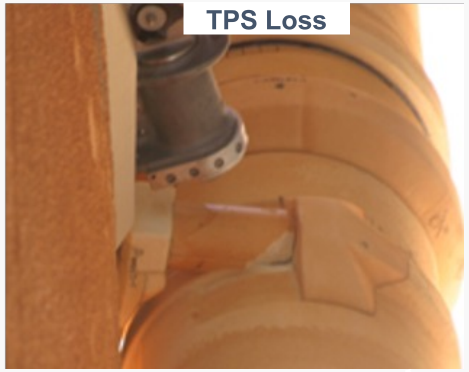
# Types of Debris



- **Ice**
  - Umbilicals, vents, uninsulated surfaces
- **Foam**
  - Cryo thermal protection system (TPS)
  - Throat plug
- **RTV/Cork**
  - Coatings, closeouts
  - Aerothermal insulation (base heat shield)
- **Rust/Metals**
  - Steel launch platform structure
  - Frangible hardware (capture failure)
- **Unexpected Debris**
  - Generated by a failure in system design/manufacture/operation
  - FOD - accidental debris left by personnel







# Debris Assessment & Mitigation

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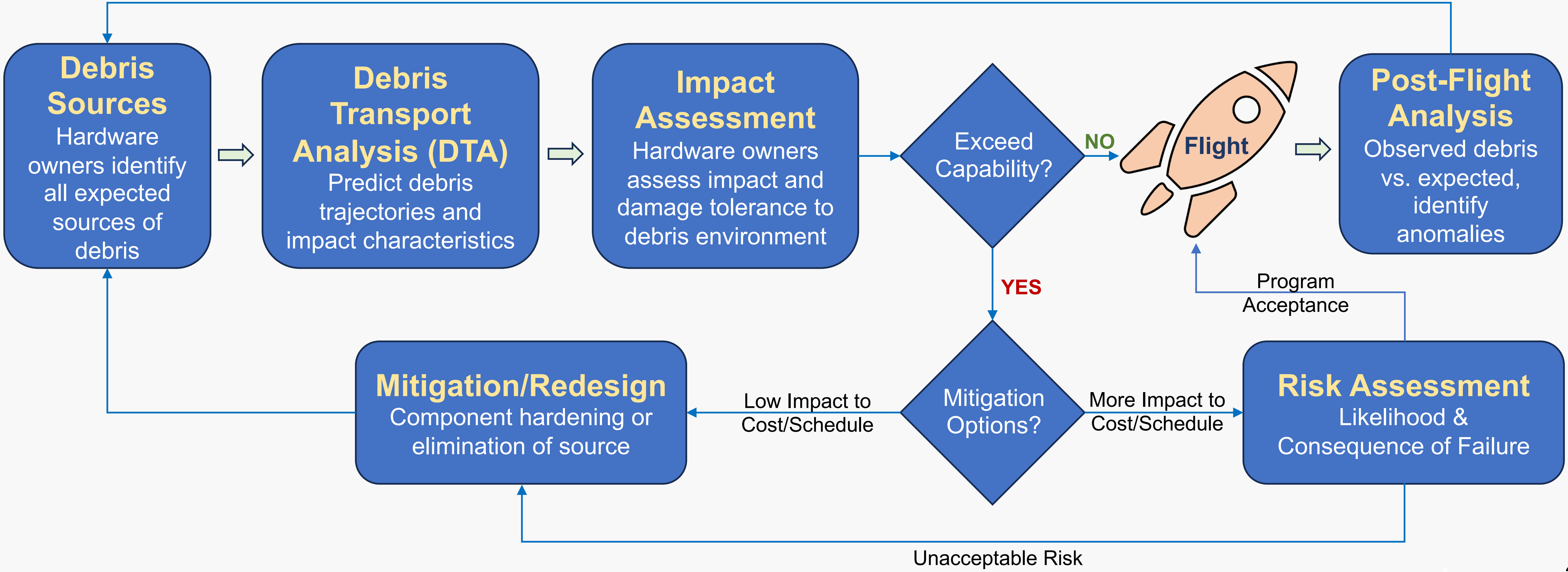
- **After Columbia accident, NASA Engineering instituted a more rigorous program for launch debris assessment and mitigation to support independent risk assessments by Safety & Mission Assurance (S&MA)**



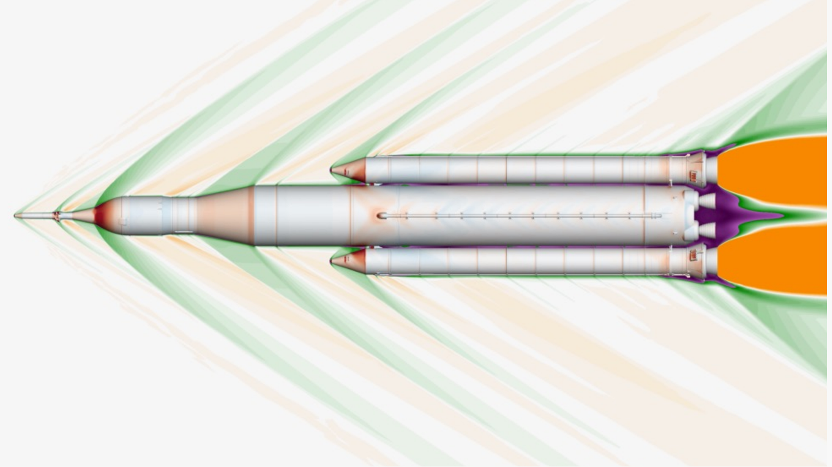
# Debris Regimes



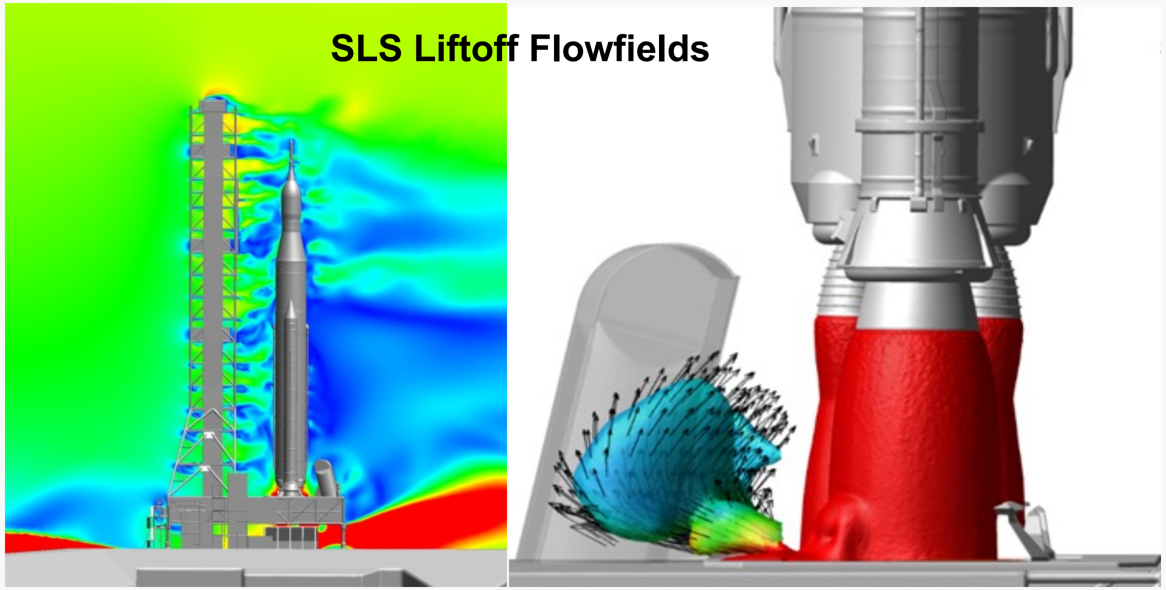
- **Ascent Debris**
  - Time: Tower Clear through Separation
  - Typically ice and TPS foam sources
  - Debris accelerated by vehicle aerodynamics
  - Fore-to-aft debris trajectories
  - Very high impact speeds possible, >1000 ft/s
- **Liftoff Debris**
  - Time: Pre-Launch through Tower Clear
  - Ice, foam, metal/rust, and other materials
  - Gravity, wind, entrainment, and plume impingement all generate debris transport
  - Debris trajectories may be in downward, lateral, or forward directions
  - Lower impact speeds, generally <500 fps

**Contrasts in transport mechanisms and impact characteristics require different approach for Liftoff DTA**

**SLS Ascent Aerodynamics†**



**SLS Liftoff Flowfields**



†Dalle, D. "Launch Vehicle Aerodynamics Database Development for SLS", Advanced Modeling & Simulation Seminar, Feb. 2018.

# Liftoff Debris Transport Analysis Process

10..9..8..7..6..5..4..3..2..1..

**Debris Source Definition** → DTA Model Choices → Debris Trajectory Calculation → Extract Debris Impacts → Report Impact Characteristics

**Hardware owner supplies all information needed to model debris:**

- Location
- Release time
- Release velocity
- Material
- Shape
- Dimensions
- Mass
- Density

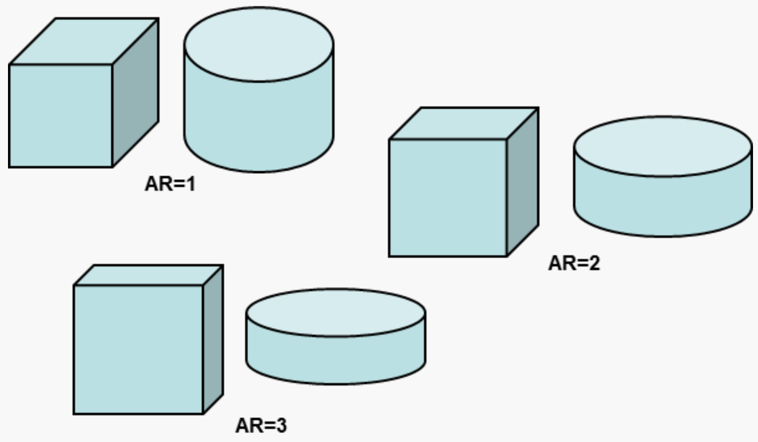
# Liftoff Debris Transport Analysis Process



Debris Source Definition → DTA Model Choices → Debris Trajectory Calculation → Extract Debris Impacts → Report Impact Characteristics

**Analyst makes decisions on appropriate modeling choices based on knowledge of system and historical observations of liftoff debris**

- Possible transport mechanisms
- Required model fidelity (engineering model vs. 3D CFD)
- Parametrics for size/shape variation
  - DTA tools use idealized shapes
  - High/low drag shapes capture cross-range behavior



# Liftoff Debris Transport Analysis Process

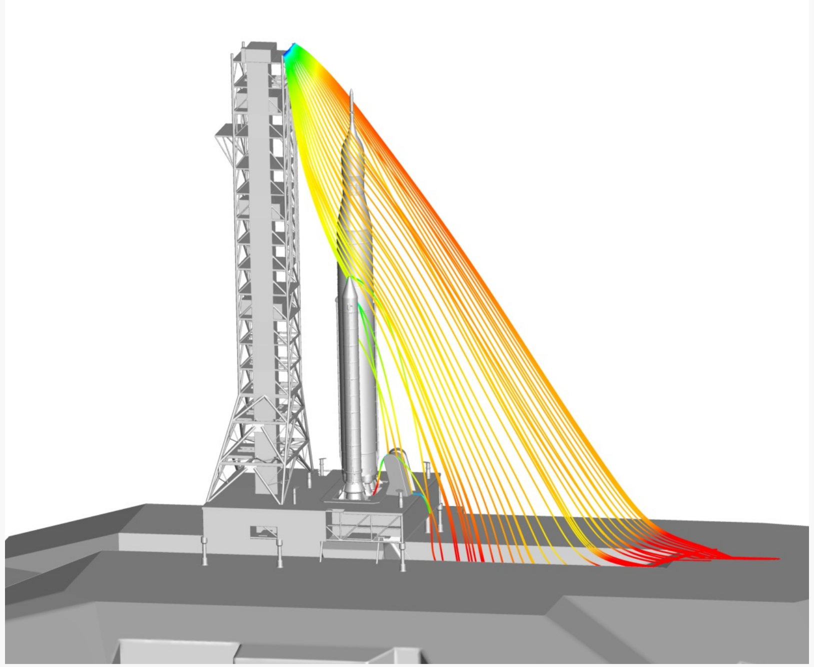
10..9..8..7..6..5..4..3..2..1..

Debris Source Definition → DTA Model Choices → **Debris Trajectory Calculation** → Extract Debris Impacts → Report Impact Characteristics

**Simple engineering models may be used for rapid/early assessments**

**Most DTA is performed with 3-DoF trajectory simulation coupled to high fidelity CFD**

- Thousands of trajectories in single simulation
- Pre-computed CFD database for liftoff DTA covers variation of wind speed/direction, and transient effects of ignition and liftoff
- One-way coupling of debris motion to CFD includes aerodynamic drag and gravity (or other frame of reference)



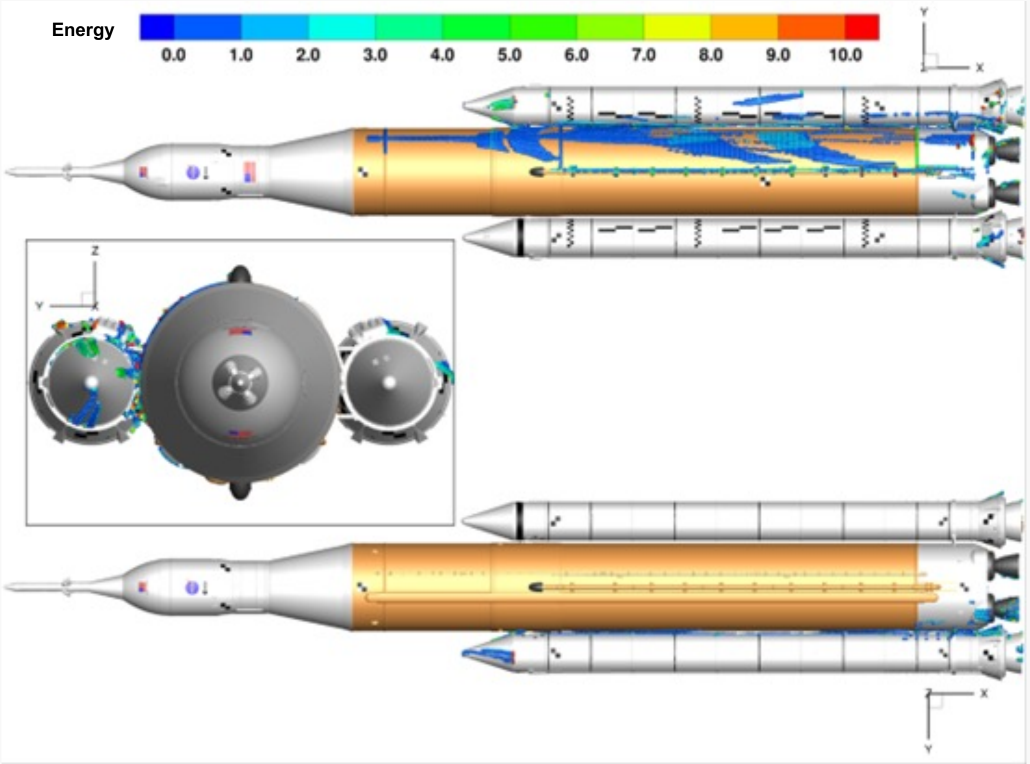
# Liftoff Debris Transport Analysis Process



**Debris Source Definition** → **DTA Model Choices** → **Debris Trajectory Calculation** → **Extract Debris Impacts** → **Report Impact Characteristics**

**Impact detection tool traces debris trajectories and records impact characteristics at every possible surface collision**

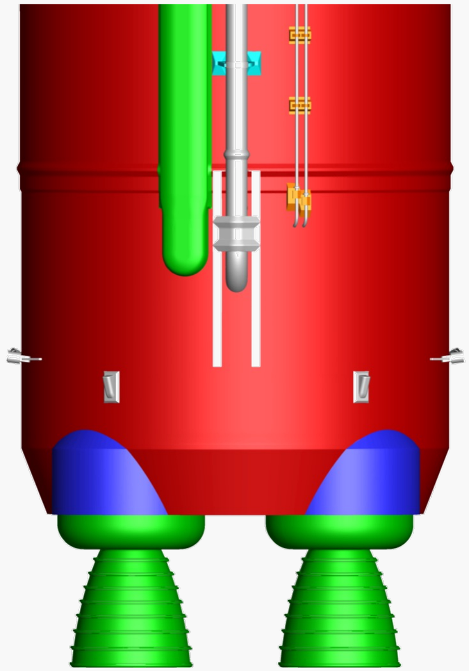
- Not restricted to rebounds in trajectory - uses size of debris + specified buffer to capture physical envelope and avoid "near misses"
- Debris velocity and angle-to-surface used to calculate impact energy, normal momentum, and other metrics

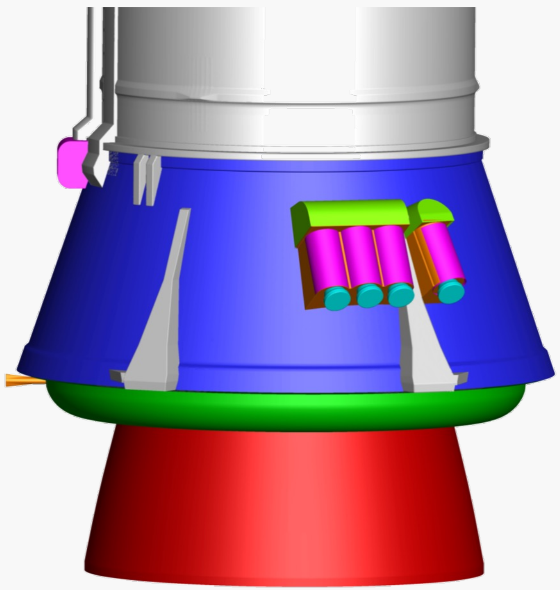


# Liftoff Debris Transport Analysis Process



**Debris Source Definition** → **DTA Model Choices** → **Debris Trajectory Calculation** → **Extract Debris Impacts** → **Report Impact Characteristics**





**Post-process impact data to provide to hardware owners for impact/damage tolerance assessments**

- Decompose model surface into components of interest
- Filter and report maximum impact per component

**Approach uses deterministic analysis to assess "worst case" impact**

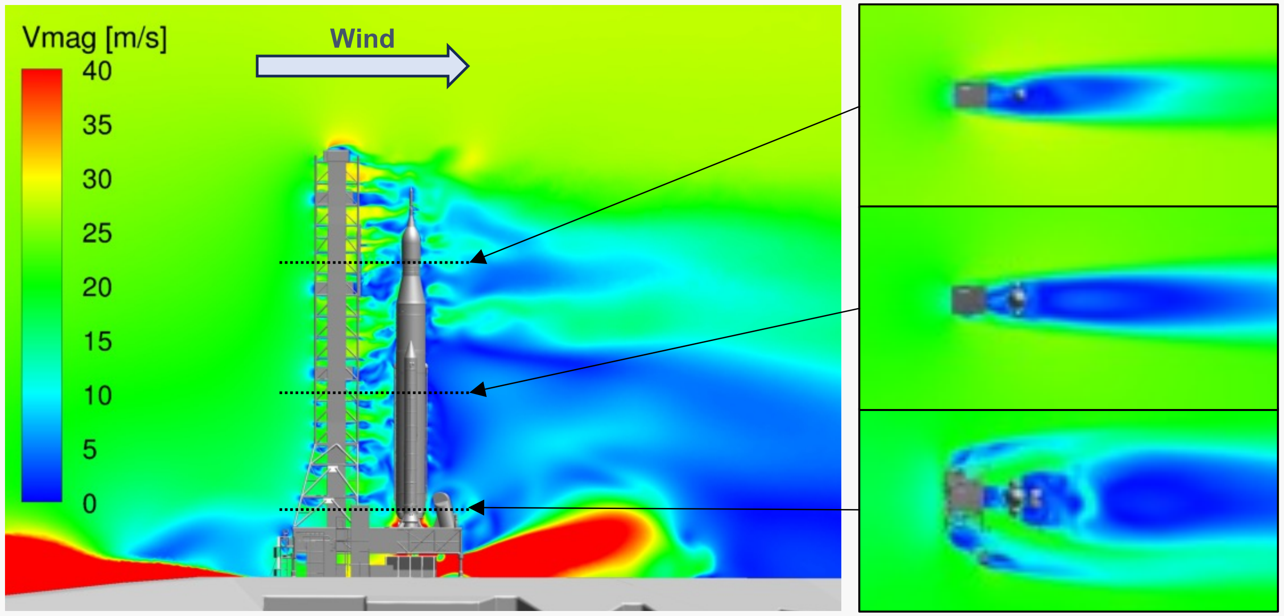
- Likelihood requires probabilistic analysis, much larger effort and not straightforward

# Liftoff Debris Transport Mechanisms

10..9..8..7..6..5..4..3..2..1..

- **Gravity, Wind, Plume Entrainment (GWPE) Transport**
  - Gravity provides primary fore-to-aft acceleration
  - Wind expands debris trajectory cloud through lateral motion
  - Air entrainment from plumes accelerates debris near aft end of vehicle
  - Generally low speeds, <100 ft/s
- **SLS CFD Database for GWPE DTA**
  - Vehicle at hold-down position
  - No plumes or all engine/motor plumes at full power
  - Winds: 0-24 kt profiles, every 45° on compass
  - Captures variation of flowfield with wind direction, speed, and elevation

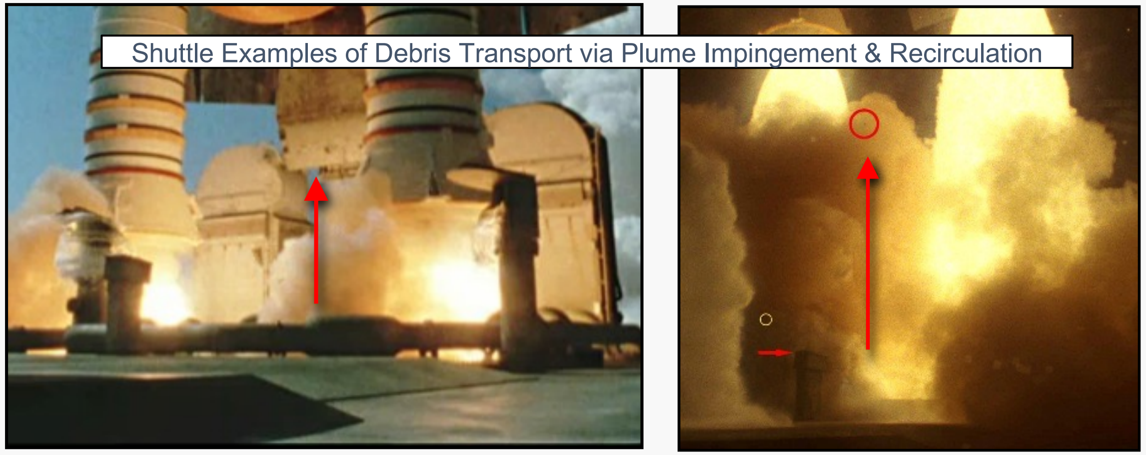
Shuttle Example of GWPE Transport of Ice Debris Impacting Orbiter



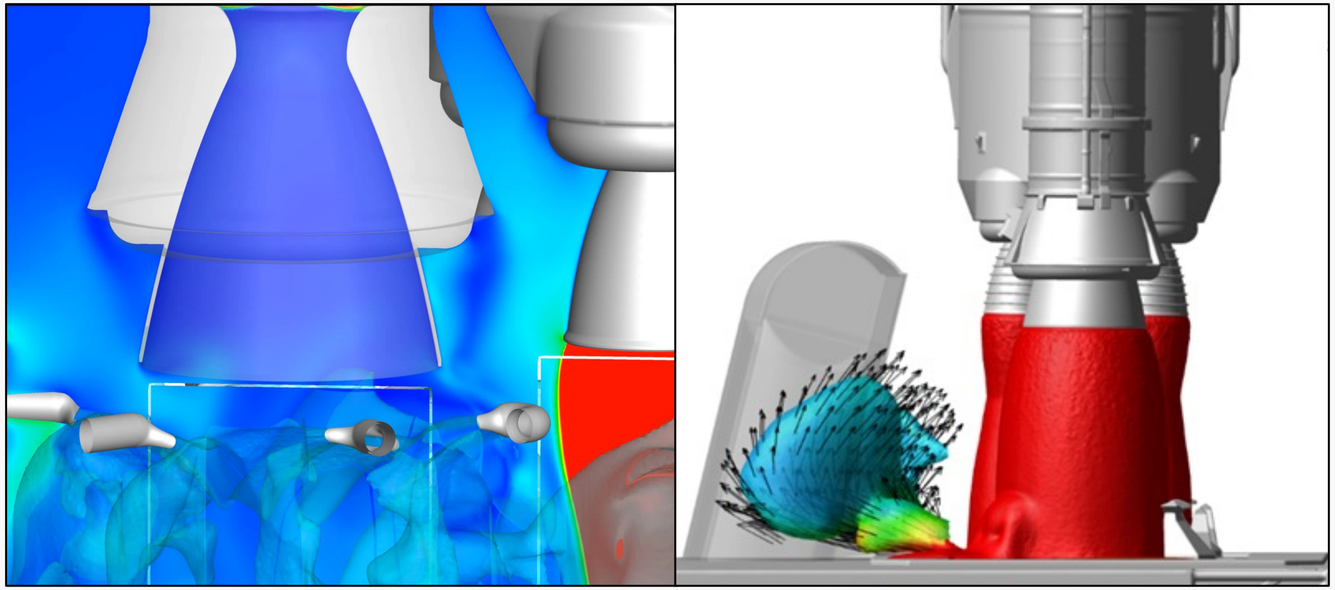
# Liftoff Debris Transport Mechanisms



- **Plume-Driven (PD) Transport**
  - Debris directly accelerated by plume, very high speeds possible
  - Booster ignition creates strong transient flow near aft end of vehicle
  - Plume impingement on deck may recirculate toward vehicle during liftoff
  - Upward trajectories able to impact hardware that is shielded from GWPE
- **SLS CFD Database for PD DTA**
  - **Ignition Transient**
    - Time accurate simulations capture ignition overpressure, plume-water interaction
  - **Liftoff**
    - Quasi-steady simulations at multiple altitudes where plume impingement and recirculation expected



Shuttle Examples of Debris Transport via Plume Impingement & Recirculation

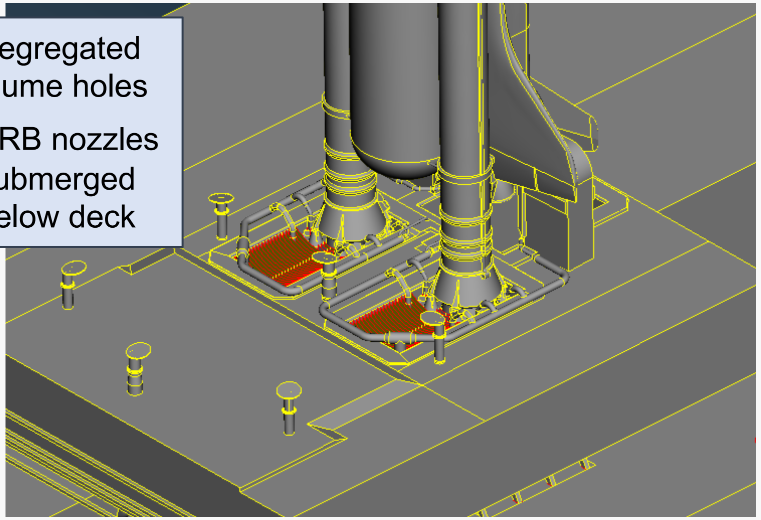


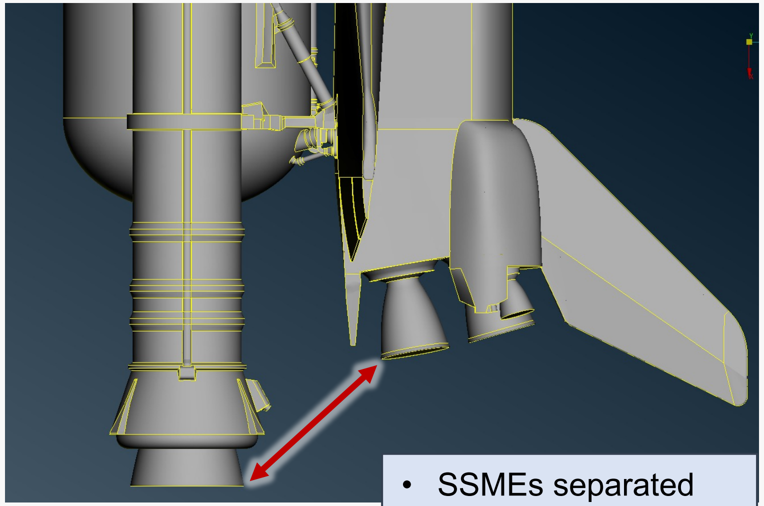
# SLS Differences from Shuttle



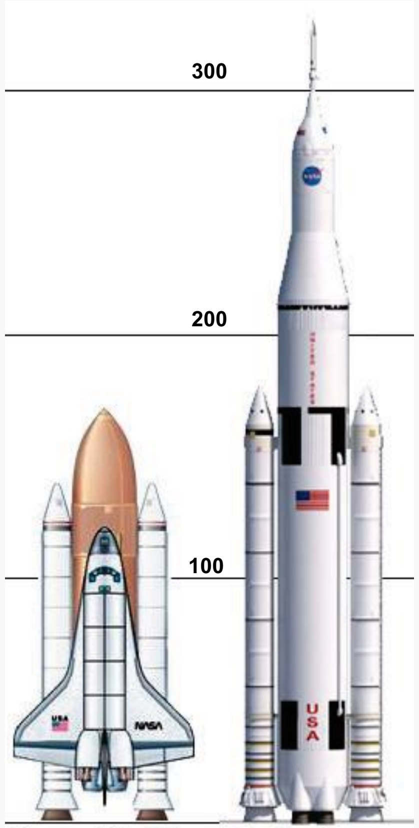
## Shuttle

- Segregated plume holes
- SRB nozzles submerged below deck



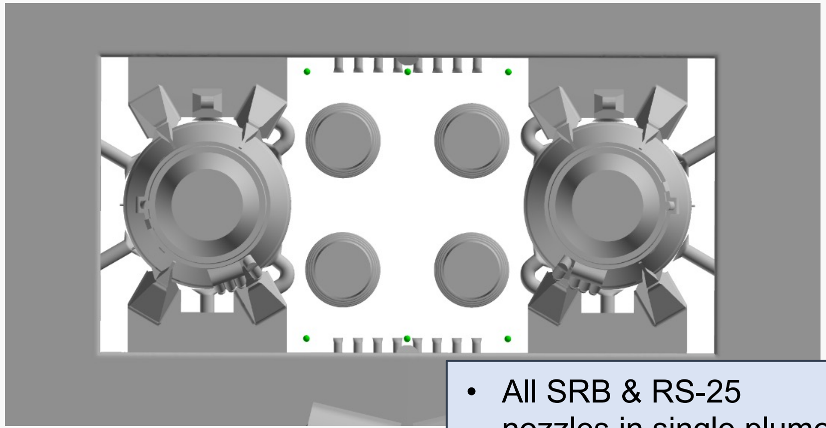


- SSMEs separated from SRBs by ~25ft

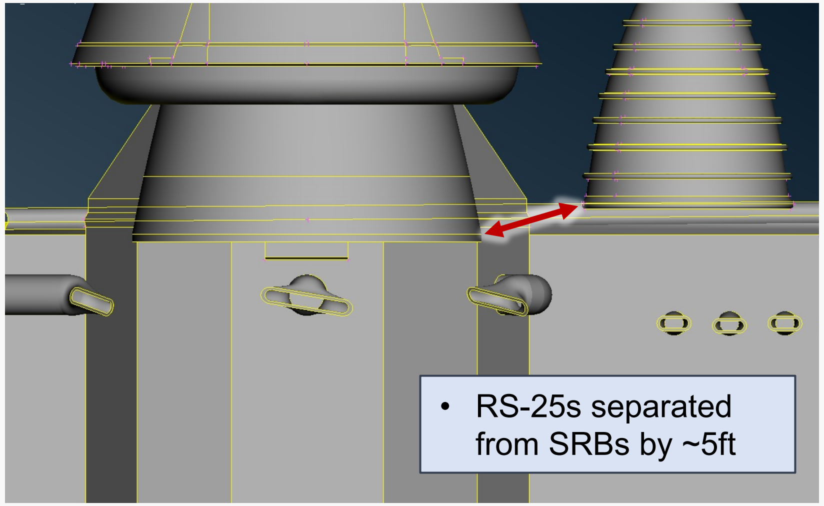



- Taller SLS vehicle gives debris more time to accelerate
- Crew capsule located at top of vehicle, above most debris sources

## SLS



- All SRB & RS-25 nozzles in single plume hole, near deck level

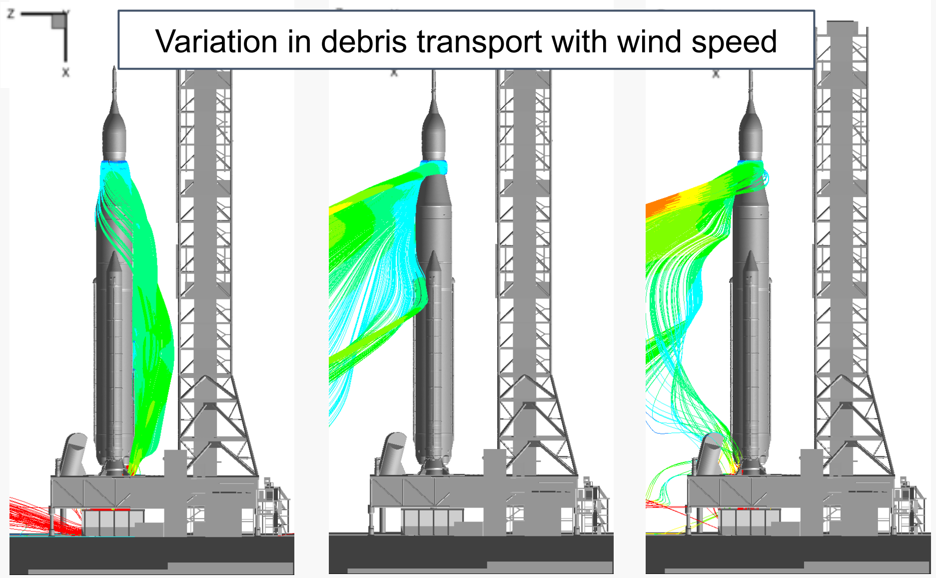


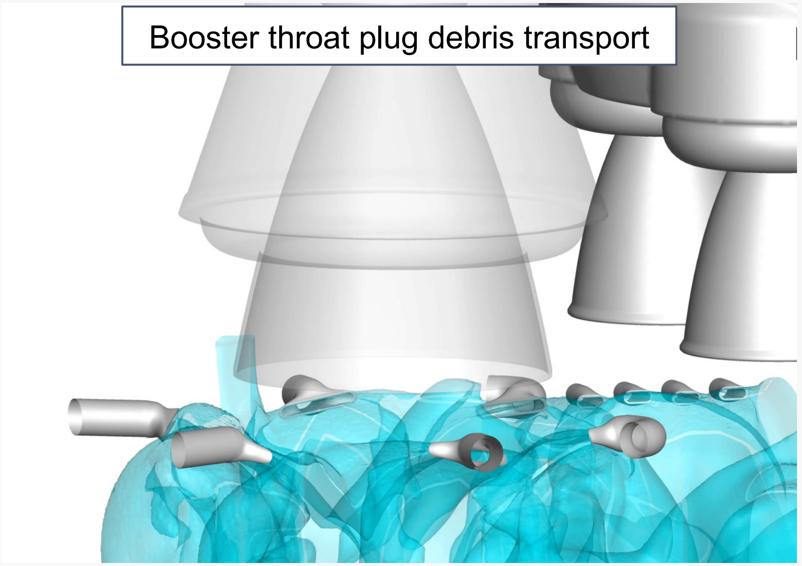
- RS-25s separated from SRBs by ~5ft

# Pre-Artemis I Analysis



- **Prior to Artemis I, liftoff DTA team analyzed >50 debris sources (GWPE and PD)**
  – Variations in debris location & size, wind speed & direction result in **thousands** of DTA cases
- **All GWPE impacts to vehicle and ground systems were cleared deterministically**
- **Impacts on RS-25 engine nozzles from Booster throat plug debris could not be cleared**
  – Established cross-program Issue Resolution Team (IRT)
  – Substantial effort examining transport characteristics, potential mitigation solutions, nozzle impact testing
  – S&MA constructed probabilistic risk assessment (PRA) to quantify likelihood of critical impact
- **SLS Program accepted Booster throat plug debris risk for Artemis I, pursuant to gathering launch imagery to better inform future assessments**

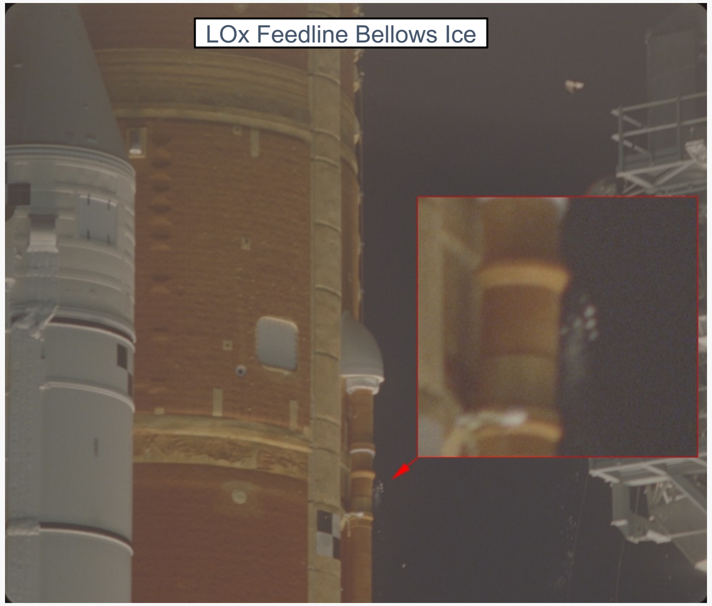

Variation in debris transport with wind speed

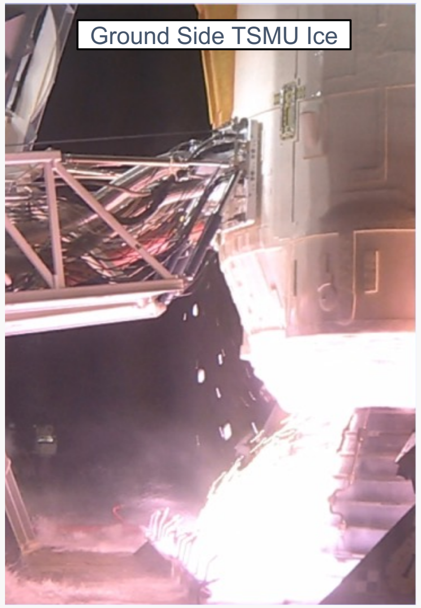

Booster throat plug debris transport

# Artemis I Liftoff Debris Observations



- **Thorough review of launch imagery identified many pieces of ice and other debris**
  - Imagery quality presented challenges due to night launch, camera exposure, obscuration
  - No launch imagery observations resulted in confirmed liftoff debris exceedances
- **Most significant items selected for further analysis and validation of DTA models**
  - Includes Core Stage GOx vent ice and Booster nozzle throat plug on following slides
- **Unexpected debris resulted in in-flight anomalies (IFA) to be addressed prior to Artemis II**
  - Ice release from ground side umbilicals, debris recovered in post-flight walkdowns

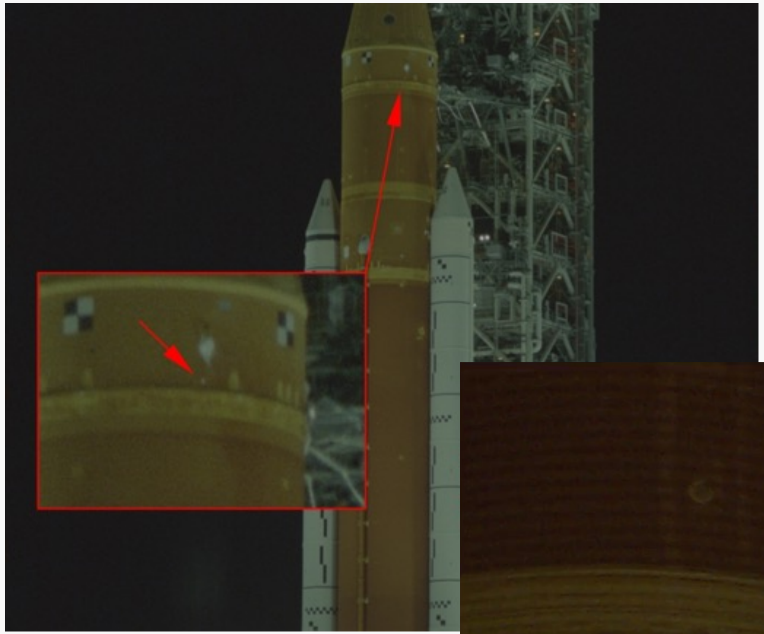


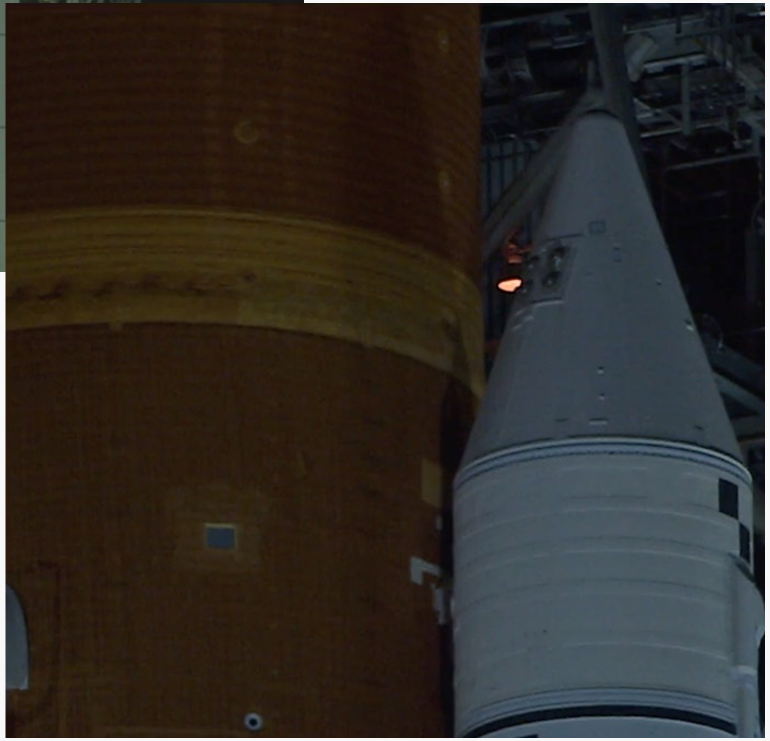



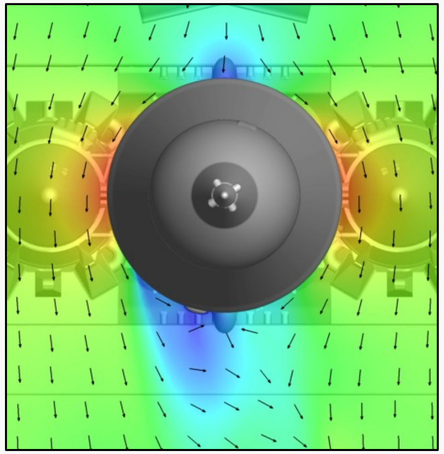

# Artemis I: Core Stage GOx Vent Ice



- **Ice/frost forms where cold gaseous oxygen (GOx) is vented from cryo tank**
- **Artemis I imagery shows:**
  - Debris releases after engine ignition
  - Southerly wind pushes debris toward RH Booster as it falls
  - Ice impacts the Booster nose cone prior to T0
- **Pre-launch imagery shows effect of wind on GOx vapor, CFD captures flow patterns**



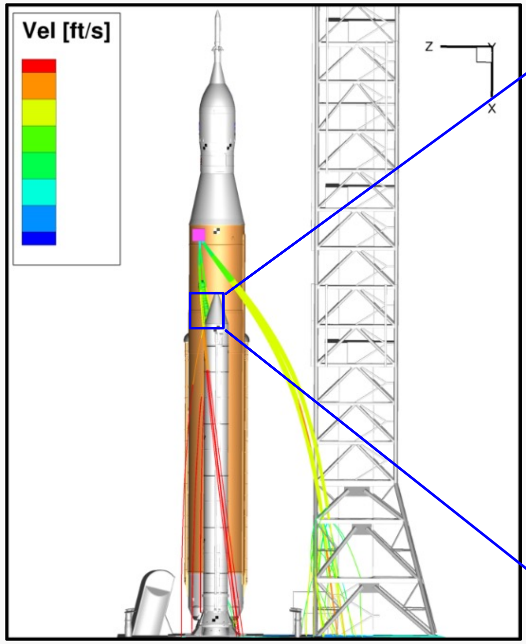


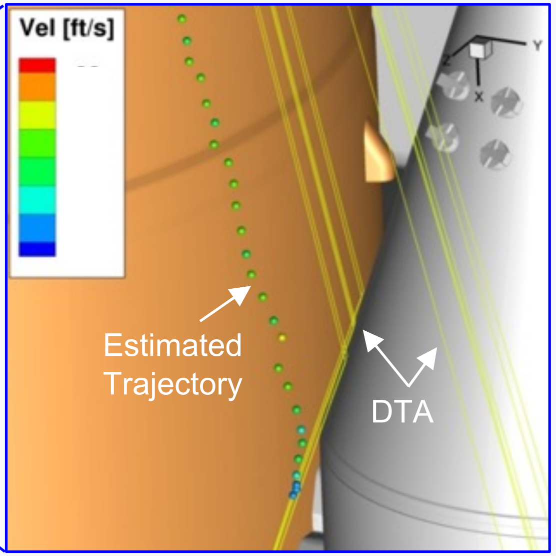


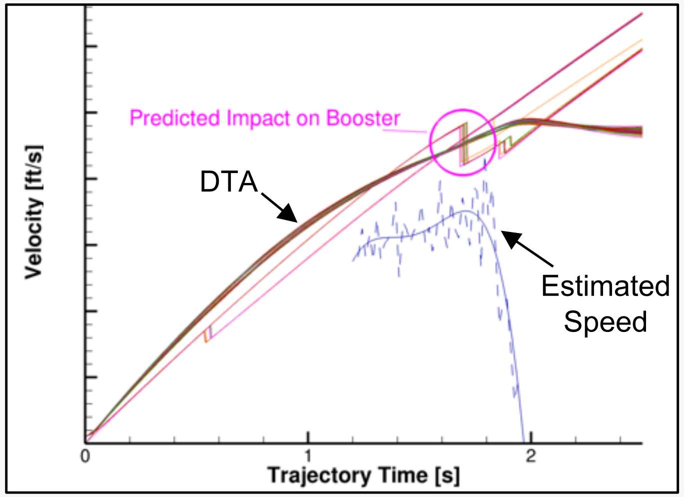
# Artemis I: Core Stage GOx Vent Ice

10..9..8..7..6..5..4..3..2..1..

- **Debris characteristics approximated from development testing, bounding launch imagery measurements, and more detailed pre-launch measurements**
  - Analyzed range of sizes due to uncertainty
- **Pre-launch size estimate trajectories closest to observed trajectory, impact Booster nose cone in same location**
- **Predicted debris speeds bound the Artemis I estimates from imagery**
- **Results are consistent with Shuttle validation of similar debris**



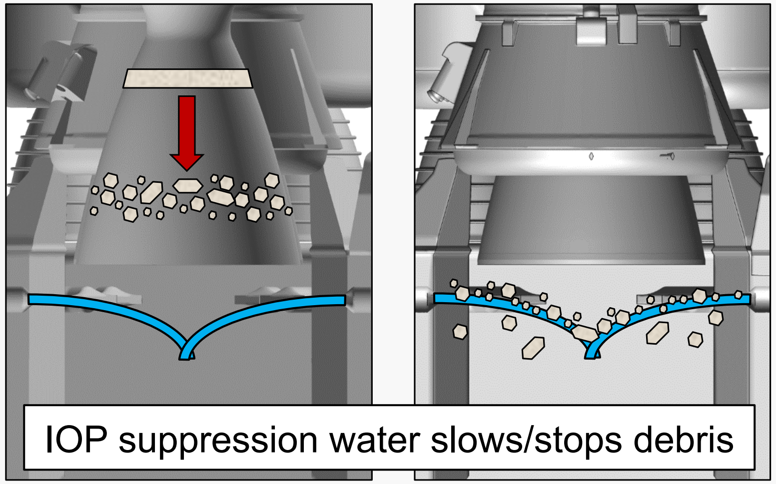

**GWPE DTA model is validated through comparison of DTA results and Artemis I photogrammetry speed/trajectory estimates**

# Artemis I: Throat Plug Debris

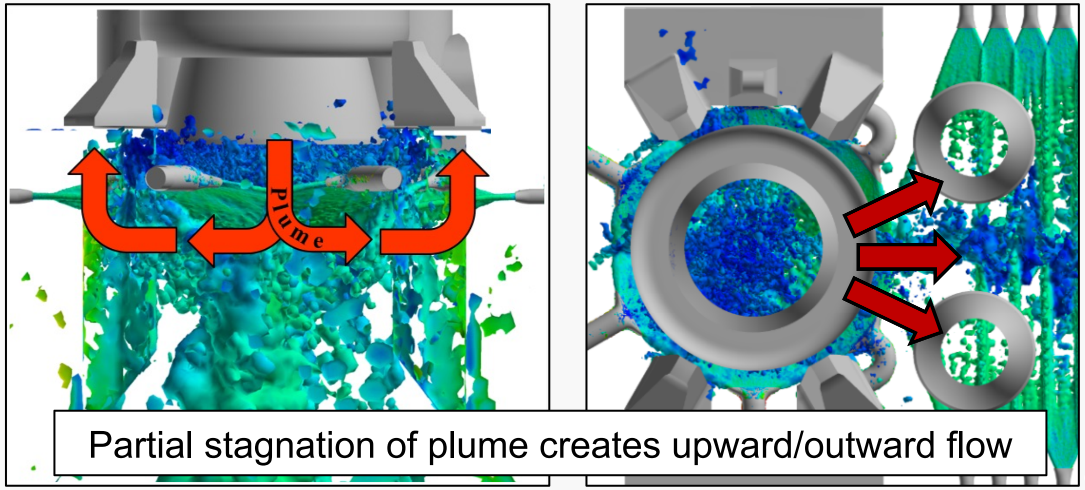


- **Booster nozzle throat plug**
  - Protective barrier for solid rocket propellant
  - Breaks up at ignition and expelled from nozzle ahead of plume, but quickly overtaken
- **Throat plug debris was observed on <u>every</u> Shuttle launch**
  - No direct observation of transport mechanism possible
- **Analysis and empirical evidence leads to conclusion that plume/water/debris interactions and IOP are driving forces**

SLS Booster QM-2 Static Test



IOP suppression water slows/stops debris

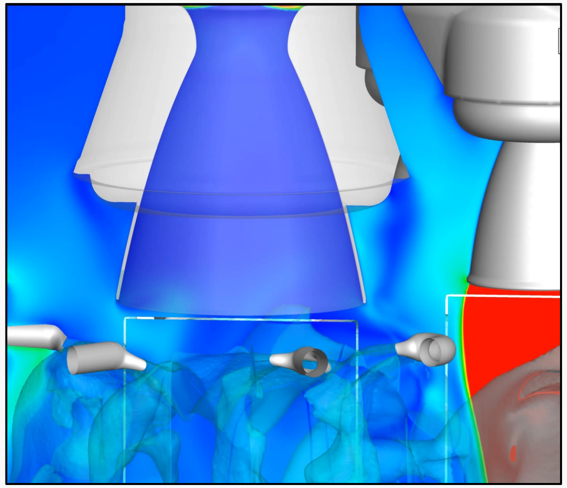



Partial stagnation of plume creates upward/outward flow

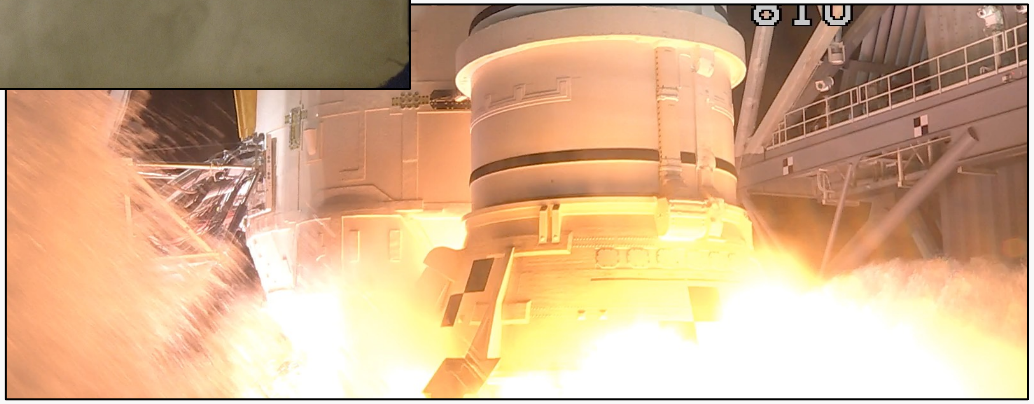
# Artemis I: Throat Plug Debris

10..9..8..7..6..5..4..3..2..1..

- **Multiple observations of potential throat plug debris near RH Booster**
  - Difficult to estimate sizes, speeds, trajectories with smoke/water obscuration
- **Debris driven at high speeds from region between nozzle and suppression water during Booster ignition transient**
  - Primarily upward/outward trajectories, some are pulled back into plume hole by entrainment
- **CFD predicts plume-water interaction and water spray transport consistent with Artemis I**



Artemis I Throat Plug Observations

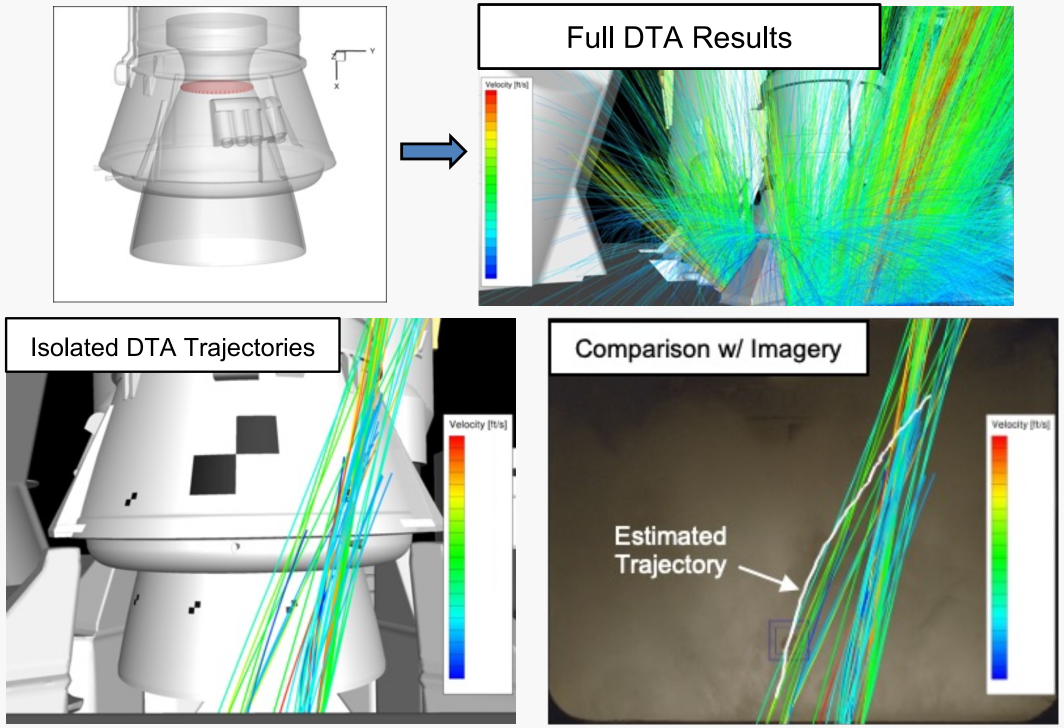


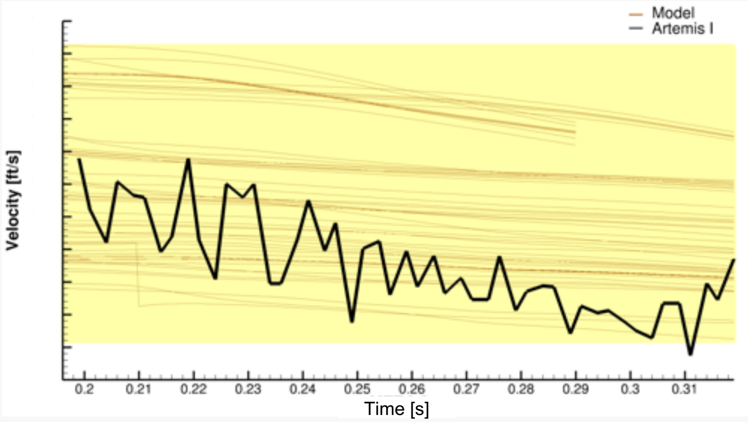
**Artemis I imagery confirms throat plug debris transport via plume-water interaction predicted by CFD & DTA**

# Artemis I: Throat Plug Debris



- **Selected pieces with higher quality imagery data near the nozzle for analysis**
  - Representative range of size/mass
  - Example at right observed on outboard side of RH Booster
- **Due to range of potential release conditions and locations in nozzle, DTA predicts trajectories in all directions**
  - Isolated DTA trajectories near estimated debris path and at time of observation for comparison with imagery
- **Model predictions envelope Artemis I trajectory and speed estimates**
  - Photogrammetry limited to 2D estimates




**Partial validation of throat plug DTA model is achieved through comparison of DTA results and Artemis I photogrammetry speed/trajectory estimates**

# Preparation for Artemis II & Beyond



- **Debris assessment process and liftoff DTA methodology developed during the Shuttle Program have been adapted for the Artemis Program**
  - Integrated pre-launch debris assessments resolved all issues and contributed to successful Artemis I launch
  - Artemis I post-flight analysis confirmed liftoff DTA methodology and results are accurate and bounding
- **Results of Artemis I IFA assessments and review of launch data are being used to update the expected debris sources for Artemis II**
  - DTA of new/updated sources has been completed, expect only minor additional changes
- **Probabilistic risk assessment of Booster throat plug debris to be updated to reflect Artemis I observations**
- **Improving imagery capabilities to gather better data on system performance and inform future missions**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