
Mars 2020 Launch, ULA Atlas V
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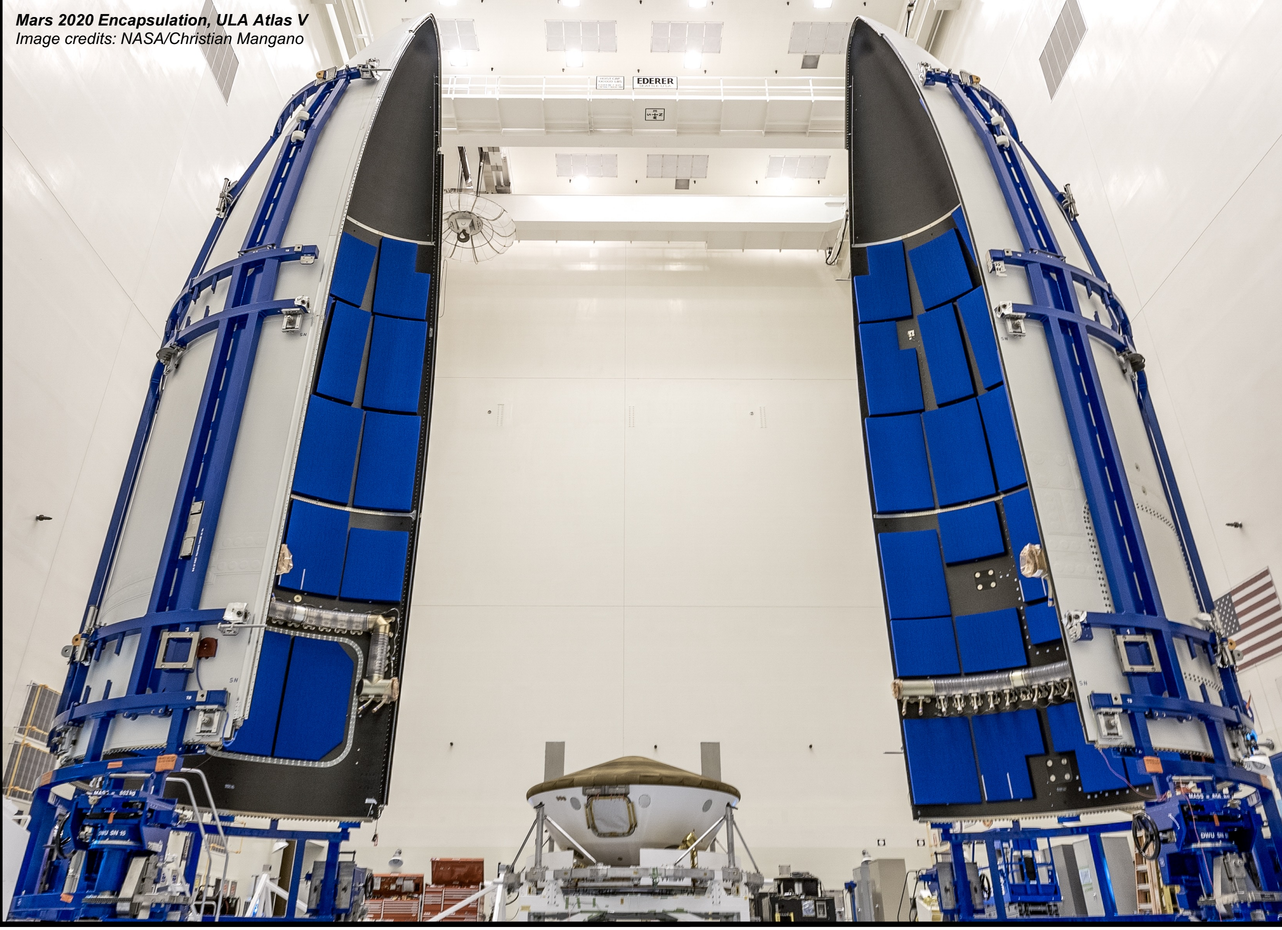
Mars 2020 Encapsulation, ULA Atlas V
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2021 NASA Contamination, Coatings, Materials, and Planetary Protection Workshop (CCMPP)

Toward Predictive Models of Launch Ascent Depressurization and Induced Particle Redistribution

Dr. William A. Hoey, Dr. John M. Alred, Dr. John R. Anderson,
Maxwell G. Martin, Carlos E. Soares, Evan Droz, Dr. Gregory S. Shallcross
Contamination Control Engineering; Propulsion, Thermal and Materials Engineering Section
NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA
Contact e-mail: < *william.a.hoey@jpl.nasa.gov* *>*

Jet Propulsion Laboratory
California Institute of Technology

Overview: Launch Depressurization and Redistribution

- During launches, rocket fairings quickly **depressurize**, generating complex and turbulent flows that mobilize particles from fairing and payload surfaces and transport them onto sensitive instruments – i.e., **redistribution**.[1,2,3,4]
- Therefore, **models of fairing launch depressurization events** have been developed at JPL for recent and upcoming NASA flight missions to enable assessment of ***contamination control risks*** posed by particle redistribution onto contamination-sensitive surfaces.
- It is important for contamination control engineers to understand and predict depressurization and particle redistribution processes, both:
  - *to inform design choices and particle cleanliness requirements*,
  - *and to quantify possible effects to instrument performance*.

Ex: InSight in fairing
Image: NASA / JPL

[1] Barengoltz, J., 1989. "*Particle Adhesion to Surfaces Under Vacuum,*" J. Spacecraft, AIAA 88-2725.

[2] Scialdone, J., 1991. "*Redistribution of Particulates on a Payload During Flight Ascent,*" NASA TM 104539.

[3] Brieda, L., Barrie, A., Hughes, D., Errigo, T., 2010. "*Analysis of particulate contamination during launch of the MMS mission,*" Proc. SPIE Optical System Contamination: Effects, Measurements, and Control 2010.

[4] Anderson, J. R., Hoey, W. A., Alred, J. M., Soares, C. E., 2020. "*Space launch vehicle transient particle redistribution modeling and implications for optically sensitive payloads,*" Proc. SPIE Systems Contamination: Prediction, Control, and Performance 2020.

Overview: *Depressurization* and *Redistribution* Questions

JPL CC is developing modeling capabilities by responding to (and anticipating) flight project engineering needs. Examples of important contamination questions include:

- **How do 'open,' uncovered instrument apertures experience particulate contamination during a launch event**, i.e. from *t=0* to fairing separation**?**
  - *Under which conditions are particles removed from surfaces, entrained and transported within gas flows, and deposited into sensitive instruments?*
    - *How sensitive are instrument apertures to their angle and position within the fairing?*
    - *Are particles of particular sizes or shapes susceptible to different modes of transport?*
    - *How sensitive are particle deposition results to the cleanliness of specific regions within the fairing and payload, to distribution functions for particle shape and size (PCL or otherwise), etc.?*
    - *Can we differentiate between different modes of particulate contamination, e.g. percent area coverage (PAC) vs. absolute count limits for particles above a certain size threshold?*
- **How do covered instruments experience depressurization, and how effective are specific cover designs[4] in protecting sensitive hardware?**

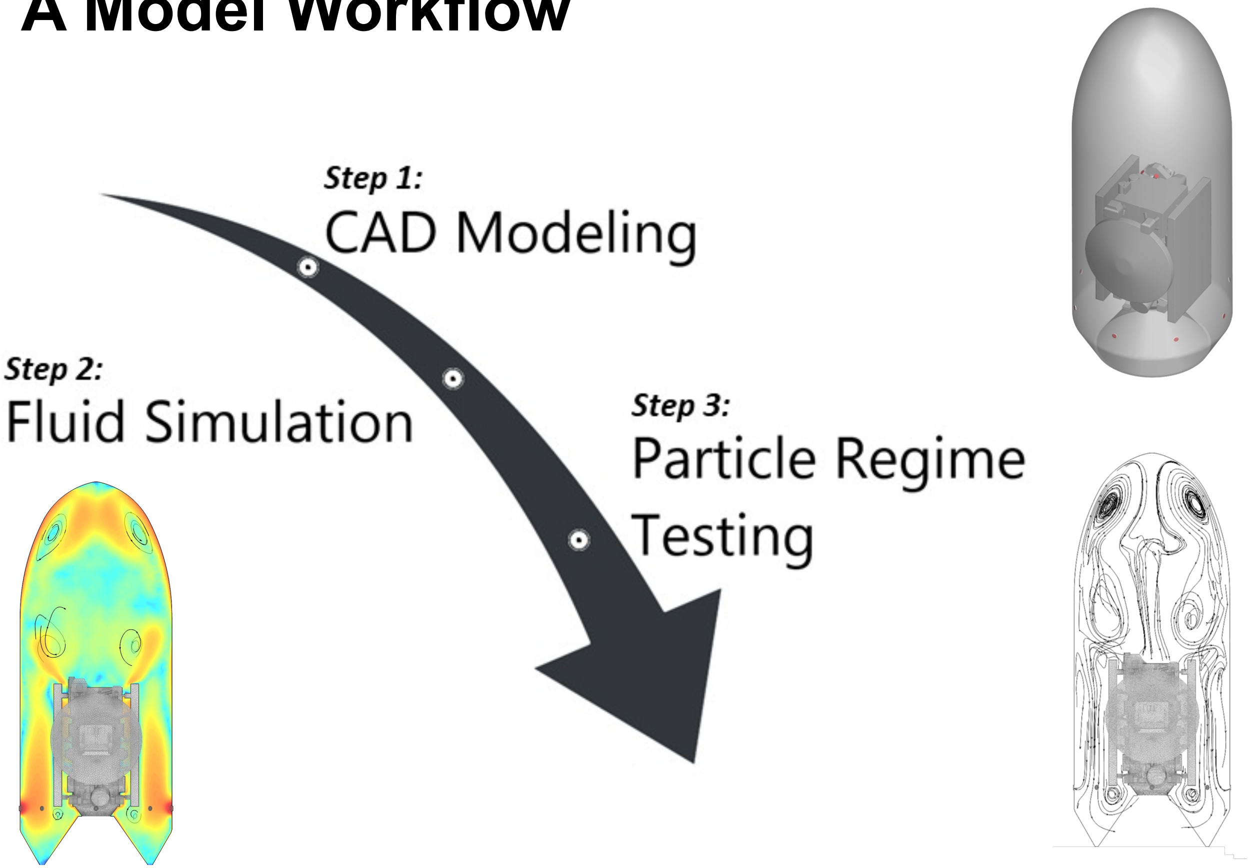
Assessing such questions requires a modeling framework[4][5] to integrate:

- *specific geometric details of fairing and payload geometries;*
- *simulations of turbulent structure in transient, depressurizing gas flows; and*
- *the removal, entrainment, transport, and deposition processes for arbitrary classes of particulate contamination in continuum-to-rarefied gas flows.*

[4] Anderson, J. R., Hoey, W. A., Alred, J. M., Soares, C. E., 2020. "*Space launch vehicle transient particle redistribution modeling and implications for optically sensitive payloads,*" Proc. SPIE Systems Contamination: Prediction, Control, and Performance 2020.

[5] Brieda, L., 2019. "*Numerical Model for Molecular and Particulate Contamination Transport,"* J. Spacecraft & Rockets, 56, 2, pp. 485-497.

Overview: A Model Workflow



Step 1:
CAD Modeling

Step 2:
Fluid Simulation

Step 3:
Particle Regime Testing

Step 1: Generate a reduced geometric model of the fairing and stowed payload.

Step 2: Mesh and simulate fluid transport through the fairing interior with a CFD tool like STAR CCM+, using boundary conditions generated by the launch provider (e.g. depressurization curves).

Step 3: Map particle trajectories through the fluid flow field, from realistically-loaded fairing surfaces and ultimately into the SRUs, using a JPL in-house one-way coupled particle tracking tool.[4][5]

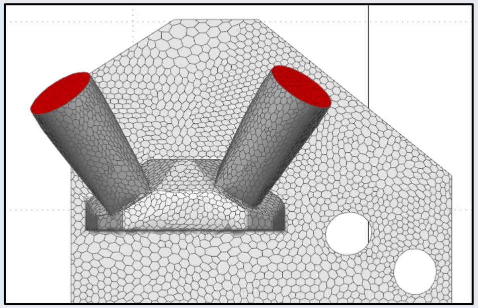
[4] Anderson, J. R., Hoey, W. A., Alred, J. M., Soares, C. E., 2020. “*Space launch vehicle transient particle redistribution modeling and implications for optically sensitive payloads,*” Proc. SPIE Systems Contamination: Prediction, Control, and Performance 2020.

[5] Brieda, L., 2019. “*Numerical Model for Molecular and Particulate Contamination Transport,”* J. Spacecraft & Rockets, 56, 2, pp. 485-497.

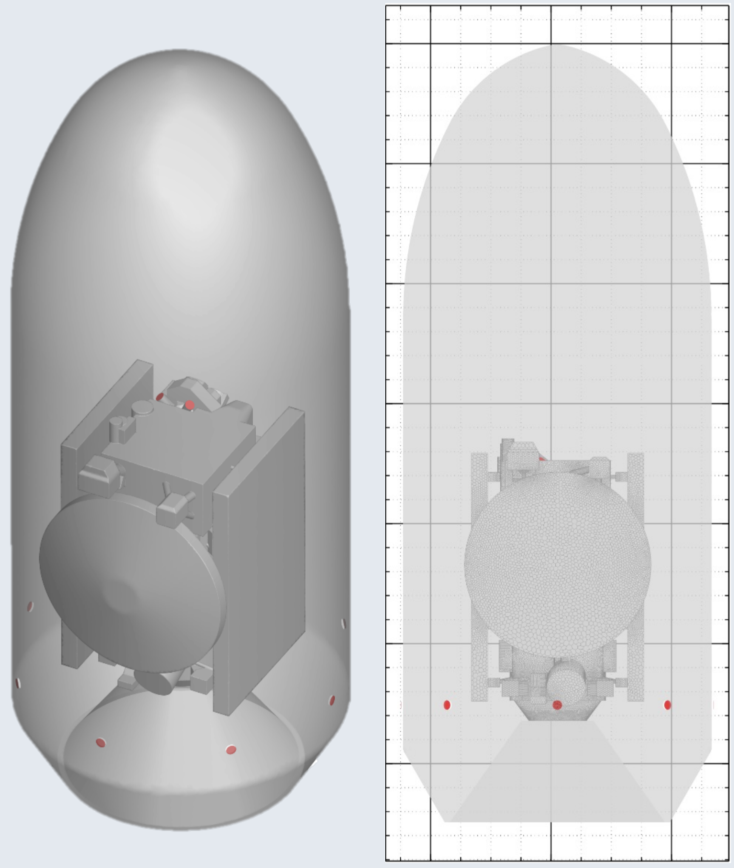
Reduced Geometric Models: Fairing and Payload

Geometric models of fairings and payloads must retain boundary elements and sensitive payload surfaces at a computationally-tractable scale.

- *Ex:* Fairing depressurization vents can be modeled as a pressure outlet boundary, while instrument aperture planes can be modeled as sensitive surfaces into or onto which particles accumulate.



***Figures**: Consider this reduced representation of the NASA Europa Clipper payload in a generic fairing environment. Instrument aperture planes are shown in red in inset at **left**, and along with representative fairing vent planes at **right**.*

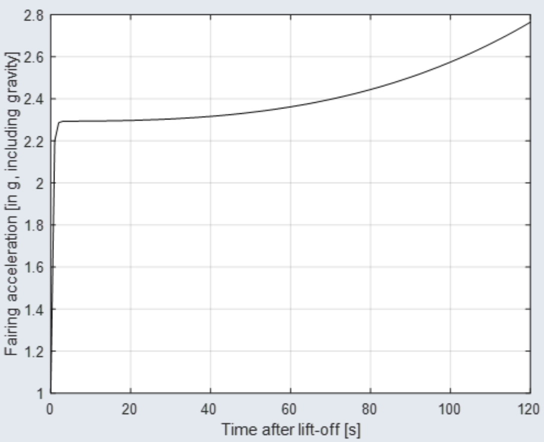


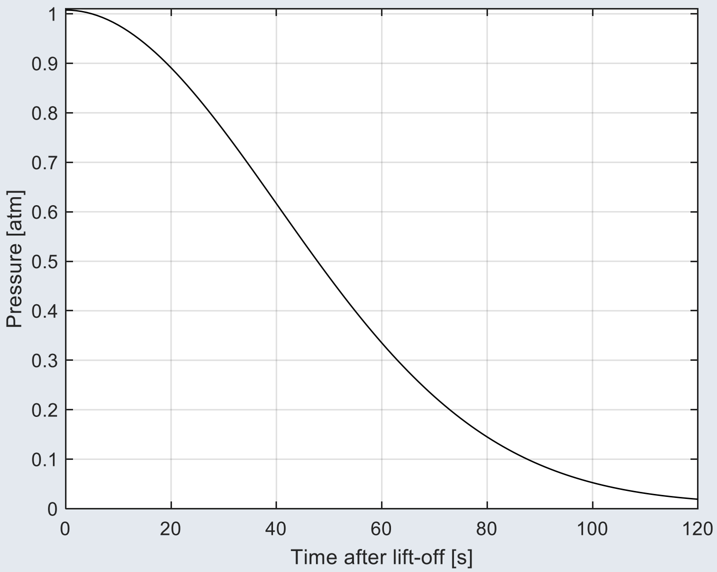
- In some cases, an aperture plane is enough to model *total* transport into an instrument; e.g. if it is simple to map deposition from an aperture plane to deposition onto an interior sensitive surface with an area scaling.
- *Payload* reduced geometric models suitable for other types of assessment (e.g. for free-molecular outgassing transport modeling) may not be suitable for CFD simulations requiring volume meshing.
- *Fairing* reduced geometric models may need to be developed from incomplete information, like launch provider manuals, where full mechanical CAD models are unavailable to the CCE.
  - *The details most significant to depressurization phenomena are the position, shape, and number of vents.*

Fluid Boundary Conditions

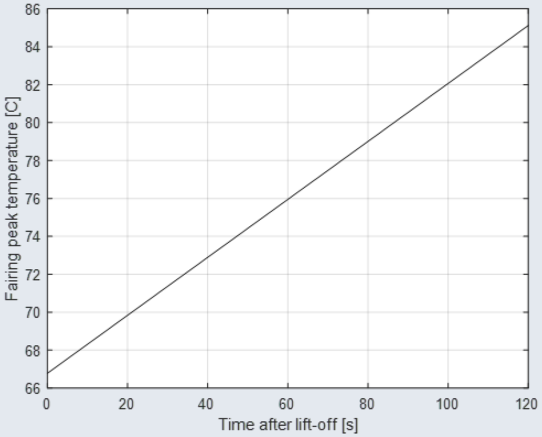
Thermodynamic and acceleration conditions in the fairing can be derived from launch provider manuals and, whenever possible, measured data.

- In this model, fairing outlet *P* is ~ 0.02 atm at 120 s after lift-off.
- Fairing and payload temperatures could be taken as a bounding maximum fairing temperature throughout this interval.





***Figures**: Examples of fairing depressurization at **left**, and bounding acceleration and wall temperature curves at **right**. Whenever possible, provider-measured data and payload-specific thermal predicts should be used.*



A pressure curve *P(t)* can be integrated from a measured *-dP/dt* which would represent operational effects like vent cover deployment, transition through max *q*, etc.

- Care should be taken to consider where pressure sensors would be located relative to modeled boundary surfaces.

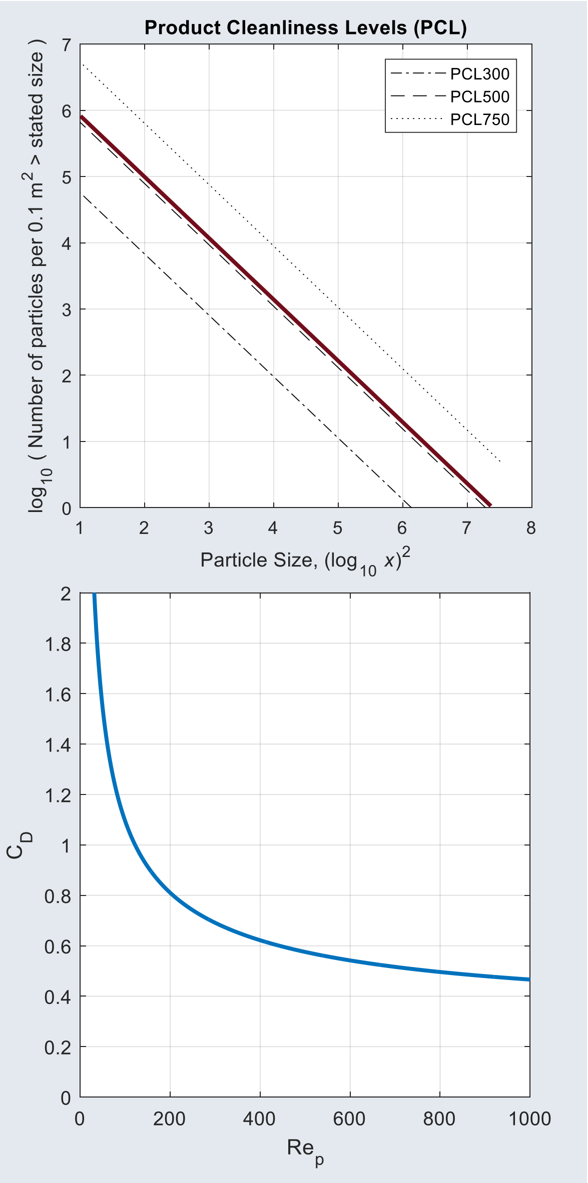
Particulate Boundary Conditions

- Representative particles are loaded onto fairing and payload surfaces, released at defined intervals, and mobilized within the depressurizing fairing flow.
- Particle sizes may be defined in this case by the IEST-STD-1246E standard distribution[6], i.e. per a required PCL. A representative fairing surface might be assumed clean to level **500** with distribution slope $C = 0.926$ as $\log_{10}(N_{cum}) = C(\log_{10}^2(L) - \log_{10}^2(x))$.
  - PCL boundary conditions are useful to assess the suitability of requirements levied on a fairing or onto payload surfaces, particularly in early mission phases, and can be supplemented by assessments against measured particulate shape / size distributions later on.
- Particles experience drag within the fairing flow; we can model this as a one-way coupling to first order using the drag model of Clift and Gauvin[7]:

$$\mathrm{C}_D = \frac{24}{\mathrm{Re}_p}\left(1 + 0.15\,\mathrm{Re}_p^{0.687}\right) + \frac{0.42}{1 + 4.25\times10^4\,\mathrm{Re}_p^{-1.16}}$$

$$\mathrm{Re}_p < 800,\ Re_p = \frac{\rho_p u_{fp} d_p}{\mu_f}.$$

  - … if redistribution under depressurization is a subsonic process.



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[6] IEST-STD-CC1246E: Product Cleanliness Levels – Applications, Requirements, and Determination, 2013.

[7] Clift R. and Gauvin W. H., 1971. "*The Motion of Entrained Particles in Gas Streams,*" Canadian Journal of Chemical Engineering, Vol. 49, No. 4, pp. 439–448.

CFD Depressurization Modeling

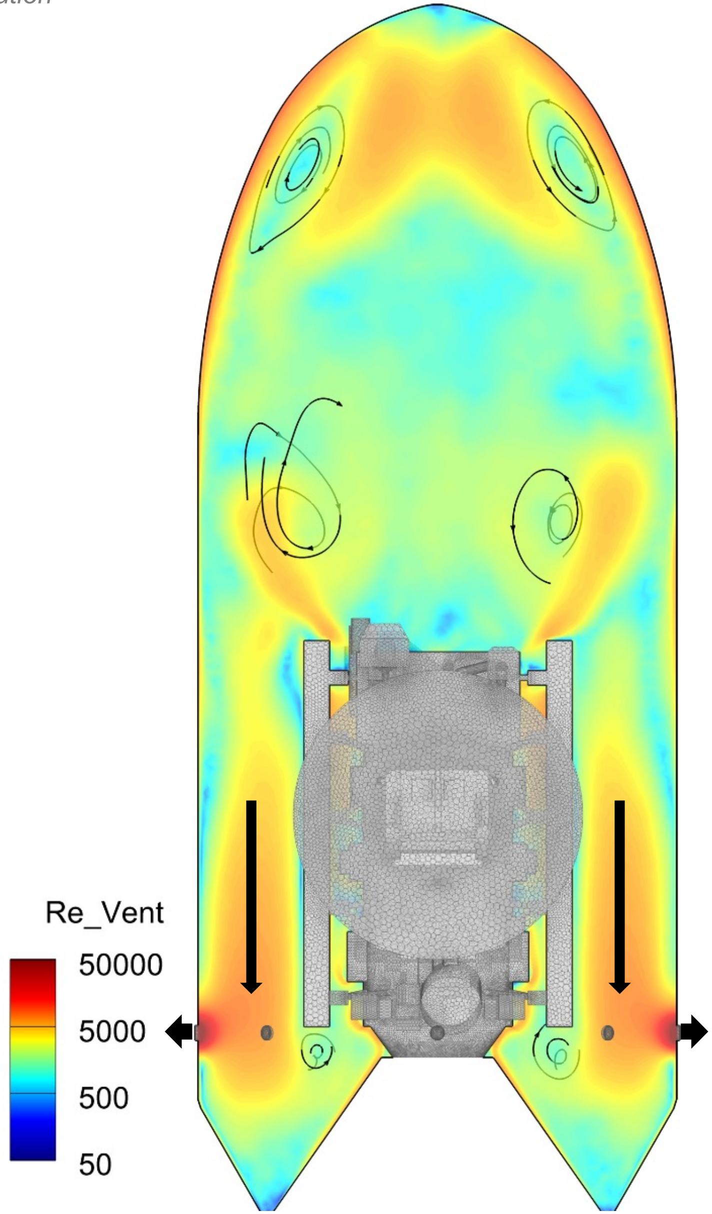
JPL uses the commercial CFD tool STAR-CCM+ to generate **transient computational fluid dynamic (CFD) simulations** of launch event depressurization from *t=0* until fairing separation.

Several primary modes of flow are apparent in our initial results, across several fairings and payloads:

- The predominant pattern is the *flow of atmosphere out of the depressurization vents* located around the base of the fairing, driven by the pressure gradient between the fairing and the increasingly rarefied external atmosphere in ascent.
- This pressure gradient drives a *stable current of air down toward the vents through the open annulus* between the payload and fairing wall.
- Above the payload, *complex and turbulent recirculatory structures form*. These create conditions by which contaminant particulates can detach and be swept above, and subsequently deposited into, sensitive instrumentation.

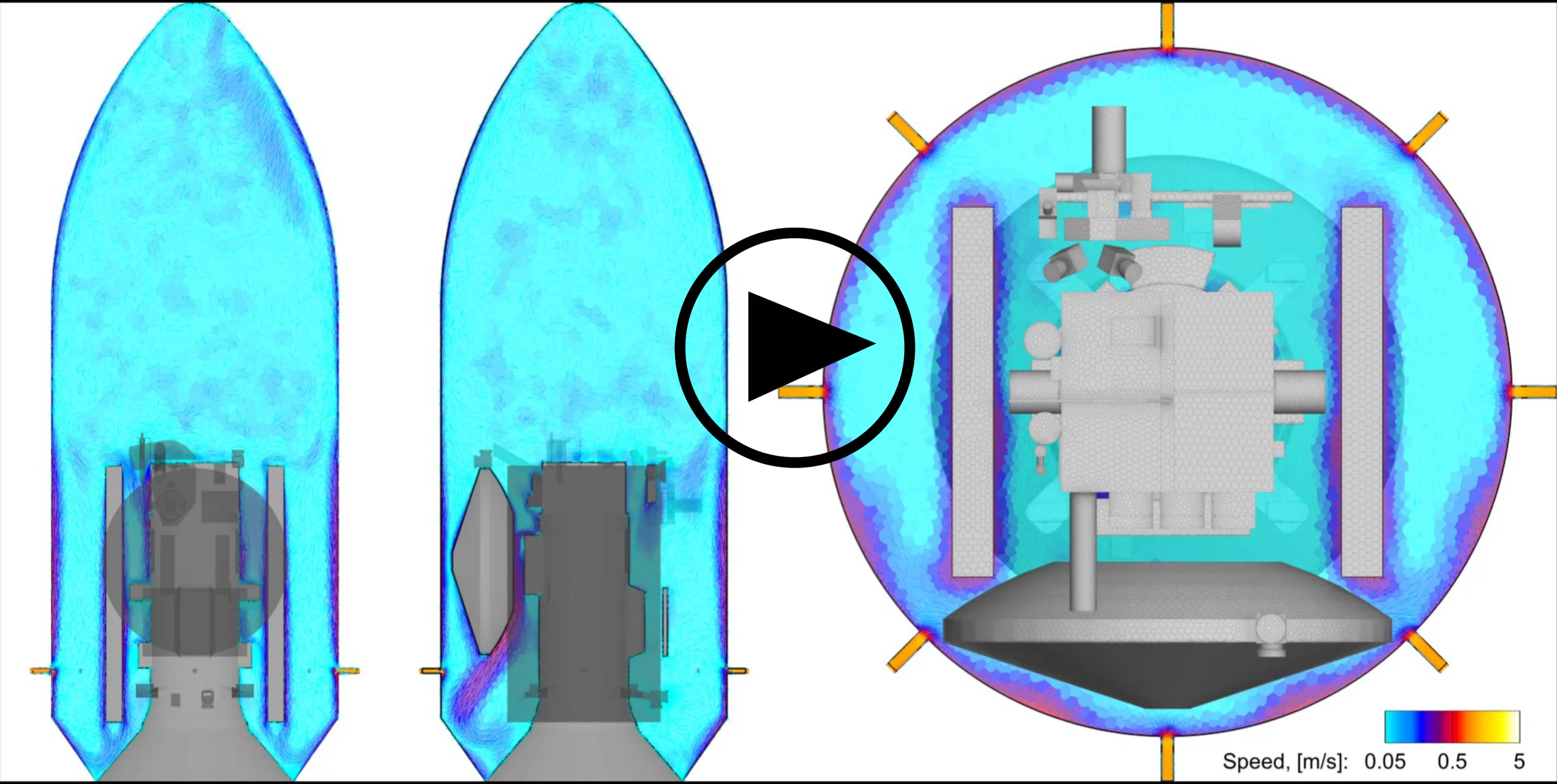
These structures are comparable to those observed in past, published steady-state[3] and transient[4] launch event models.

[3] Brieda, L., Barrie, A., Hughes, D., Errigo, T., 2010. "*Analysis of particulate contamination during launch of the MMS mission,*" Proc. SPIE Optical System Contamination: Effects, Measurements, and Control 2010.
[4] Anderson, J. R., Hoey, W. A., Alred, J. M., Soares, C. E., 2020. "*Space launch vehicle transient particle redistribution modeling and implications for optically sensitive payloads,*" Proc. SPIE Systems Contamination: Prediction, Control, and Performance 2020.



Transient Flow Speed Visualization

Logarithmic scale, initial 120 s span of launch depressurization, units [m/s].



Key Q: **How do external flows create paths to mobilize and deposit particulate into uncovered instruments?**

O[10,000] CPU-hour expense on the JPL Gattaca supercomputing cluster.
STAR-CCM+ CFD calculation with approximately 6M volume and prism cells.
Conditions reflect worst-case-hot thermal predicts for t=0 air and surfaces.

Particle Transport Modeling

JPL is developing a Lagrangian particle transport model, SPLAT, in collaboration with Particle-In-Cell Consulting, LLC,[4][5] for use in particulate transport simulations including launch redistribution.

Example simulation parameters:

For each particulate source, an array of simulations on the JPL Gattaca cluster build up Monte Carlo statistics on redistribution, transport, and deposition, e.g.:

512 cores × 25,000 particles per core =

12.8 million representative particles.

Each CPU at ~2 hours, for 1k CPU-hr. cost.

Example simulation boundary conditions:

- For each set of initial conditions, a unique release surface is set with: PCL or tapelift size distribution, time-scale of release, release initial velocity, etc.
- In this example: the fairing starts with a condition of PCL 500, and releases that entire load at a uniform rate over the *t=0* to *t+120* time span, with a very low initial velocity (~0.01 m/s). Particles fall out from surfaces and move under the acceleration vector and drag in the depressurizing flow field.
- In this slide illustration: instrument aperture planes collect all incident particles redistributed from the fairing. Other distinct source groups can include the payload bus and solar arrays.

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[4] Anderson, J. R., Hoey, W. A., Alred, J. M., Soares, C. E., 2020. "*Space launch vehicle transient particle redistribution modeling and implications for optically sensitive payloads,*" Proc. SPIE Systems Contamination 2020.

[5] Brieda, L., 2019. "*Numerical Model for Molecular and Particulate Contamination Transport,*" JSR, 56, 2, pp. 485-497.

Transient Flow Speed Visualization: *Internal Volumes*

Logarithmic scale, initial 120 s span of launch depressurization, units [m/s].

NEOS Fairing Depressurization: [0-120s]

William Hoey, JPL 353D
06/09/2021

Key Q: **How do enclosed volumes vent, and how can we quantify cover efficacy in mitigating particle ingestion?**

O[20,000] CPU-hour expense on the JPL Gattaca supercomputing cluster.
STAR-CCM+ CFD calculation with approximately 10M volume and prism cells.
Estimated bounding temperature values for t=0 air and surfaces.

Particle Transport Modeling: *Internal Volumes*

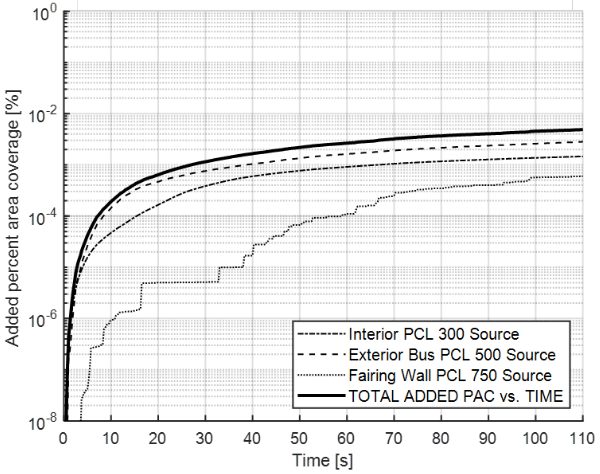
Contamination threats from multiple particulate source groups, both external and internal to an instrument volume, may need to be distinguished and compared in setting requirement values.

Example simulation parameters:

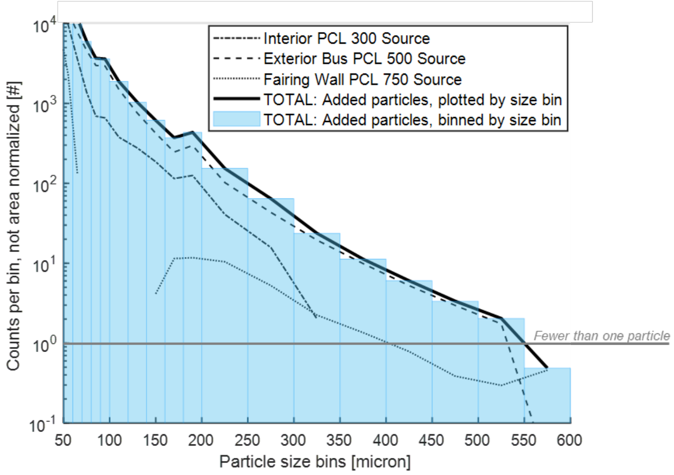
- *Fairing, bus, and sample instrument surfaces start from different PCL conditions, and release all of their particulate load over the 110 s launch depressurization event (from t=0 to t=+110).*
- *Particles are released at a constant rate and at a small initial normal velocity (< 0.01 m/s) distributed uniformly across their release surface.*
- *Particles travel under the rocket acceleration vector and entrainment & drag in the fairing gas flow, and experience inelastic collisions with fairing and spacecraft surfaces (coefficient of restitution = 0.5) while accumulating on sensitive instrument surfaces (c_r = 0). They otherwise exit the flow volume through the exhaust vents or by settling below a threshold velocity.*

Transport of sample particles generated from *within* the interior volume

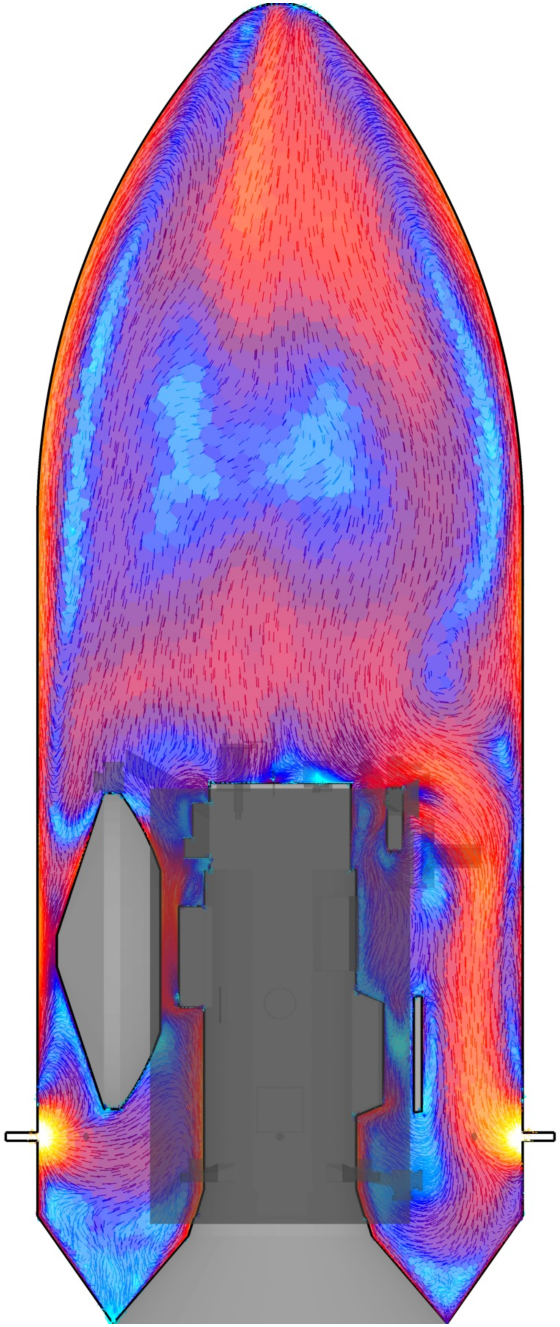
Percent area coverage onto a representative interior surface



Particle size distribution onto a representative interior surface



Conclusion: Toward Depressurization and Redistribution Models



JPL CC is developing modeling capabilities by responding to and anticipating flight project engineering needs – including questions related to the contamination of exposed and covered instruments by particles redistributed during launch.

- In this presentation, we reviewed the fluid and particulate boundary conditions and the technical capabilities necessary to generate ***transient CFD simulations of fairing depressurization flows coupled to Lagrangian simulations of particle transport and deposition***.
- We showed several examples of such simulations, their applications and results in cases of exposed and covered or enclosed sensitive instruments.
- There are many ways these capabilities can be improved, several of which are under active development by JPL CC.

Thanks for your interest!

Any questions?

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