Modeling the Contaminant Footprint of Spacecraft Operating in Near-Vacuum

William A. Hoey, J. R. Anderson, J. M. Alred, and C. E. Soares [1]; P. Gutierrez Cascales [1,2]; R. Alves Hailer [1,3]

[1] Jet Propulsion Laboratory, California Institute of Technology, USA; [2] Imperial College London, UK; [3] State University of Campinas, Brazil

Link to poster: **https://lpsc2025.ipostersessions.com/Default.aspx?s=DE-06-DE-CD-40-F3-3D-AD-8B-1E-E8-2D-96-9F-62-82**

Abstract

All spacecraft generate and carry *contaminant*, i.e. unwanted material that may impact mission engineering and science objectives.

At NASA, the spacecraft engineering disciplines of Planetary Protection and Contamination Control are each concerned with the identification, mitigation, and effective control of contaminant.

- Planetary Protection (PP) interests include preventing ‘forward’ transport of terrestrial biological contaminant – e.g. microbes, spores, and inert particles loaded with these – to solar system bodies; preventing ‘backward’ transport of extraterrestrial contaminant to Earth; and controlling contamination that could make biosignature detection ambiguous in measurements or samples.
- The Contamination Control (CC) discipline is concerned with preventing degradation of spacecraft hardware, instrumentation, and scientific targets by any type of contaminant – molecular or particulate; self-induced or environmental; biologically active or inert.

An area of shared interest between PP and CC disciplines is the ***preservation of special regions and sampling sites of high scientific value from inadvertent contamination by spacecraft***.

As an example, vehicles that would operate above or land onto bodies with near-vacuum surface conditions, like Earth’s Moon:

1. Generate plume effluents during deorbit, descent and landing operations;
2. Release molecular contaminants as their materials outgas under vacuum exposure;
3. Release molecular and droplet contaminant as they vent their propulsion and / or life support systems; and
4. May also disperse particles of terrestrial origin, including biological contaminant, under vibrational or plume-induced loads.

Recent multidisciplinary work at NASA's Jet Propulsion Laboratory (JPL) includes the development of models for these processes and affirms that long-distance (i.e. global) transport vectors for both molecular and particulate contaminant exist in nominal spacecraft operation above, and landings onto, ‘airless’ bodies including Earth’s Moon and icy moons like Europa and Enceladus.

Gas Dynamic Transport

Modeling capabilities that span gas dynamic regimes have been developed to describe pluming, outgassing, venting, and particle removal and transport vectors. Computational fluid dynamics (CFD) and rarefied gas dynamic models like direct simulation Monte Carlo (DSMC) are used to model engine plume and vent flows at vehicle length scales, where inter-molecular collisions are significant.

How is molecular contaminant released from a landed spacecraft as it vents, and how can this contaminant alter the vehicle-local environment?

Figure 1 shows a vehicle-local model of gaseous water venting for an Apollo lander, simulated with the SPARTA DSMC code for a generic set of water vapor venting inputs derived from International Space Station experience.

- Models for several varieties of vent have been examined under this study varying source species, flow rates, vent locations and shapes (e.g. straight vs. T-vent).
- Properties investigated include fluxes of condensable gas species to the lunar surface.
- A framework has also been developed to pass the results of vehicle-local simulations into long-distance, free-molecular transport models using an in-house Python code.

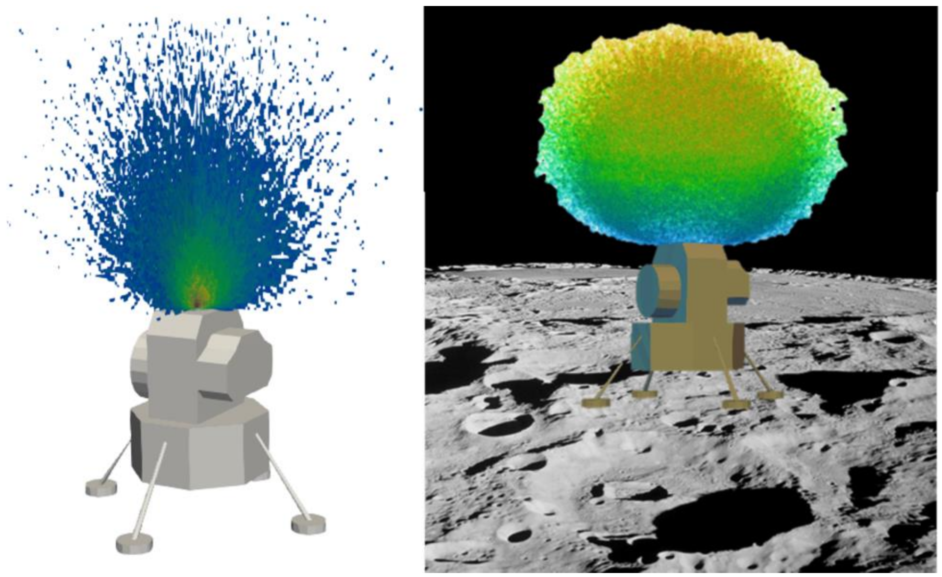

Figure 1. *Representative example of a vent releasing gaseous water from an Apollo lunar module, modeled with DSMC.*

How does contaminant reach from a specific lunar lander and its landing site to distance sites of science interest, including permanently shadowed regions (PSRs)?

Long-distance (global) free-molecular simulations may then study transport away from landing sites, e.g. to lunar permanently shadowed regions: **Figure 2** shows an example of global results generated with a tool that can take input from vehicle-local simulations and simulate a ‘hopping’ process of molecular transport across an arbitrary solar system body with near-vacuum surface conditions.

- Currently this model incorporates a time-variant lunar surface temperature map, a library of PSR locations as cold-traps, a surface adsorption / desorption model for water species, and permits molecular loss by gravitational escape.
- Future work may investigate non-water contaminant species and other significant physics including photo-dissociative loss processes.

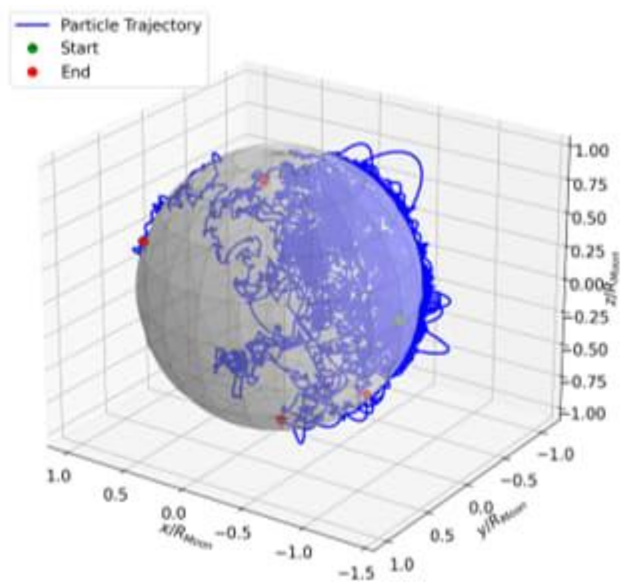

Figure 2. *Example of free-molecular transport simulations for water across a single lunar day; four molecules ‘hopping’ with their shared initial position shown in green and final positions in red.*

<u>Plume-Induced Particle Transport</u>

How might spacecraft thruster or engine plumes disperse particles of terrestrial origin?

In the nominal operation and powered landing of spacecraft with chemical propulsion systems, plume flows that wash over a spacecraft and its landing site can entrain and disperse particles of terrestrial origin including biological contaminant.

- Spacecraft thruster and engine plume flows can exceed 2,000 m/s in core flow. Descent and landing engine flows, in particular, may directly or indirectly impinge on vehicle surfaces, e.g., as for the Sky Crane.
- Plume impingement on vehicles may provide a unique vector for long-distance particle dispersal in near-vacuum as no appreciable atmospheric drag would limit transport.

- **Figure 3** provides examples of relevant plume flow simulations in near-vacuum conditions performed by the JPL authors. These simulations span thrusts from ~1 N for attitude control systems to landing engines of approximately Apollo scale at ~47 kN, and also include common propellant mixtures. (Hoey et al., 2025, publication pending).

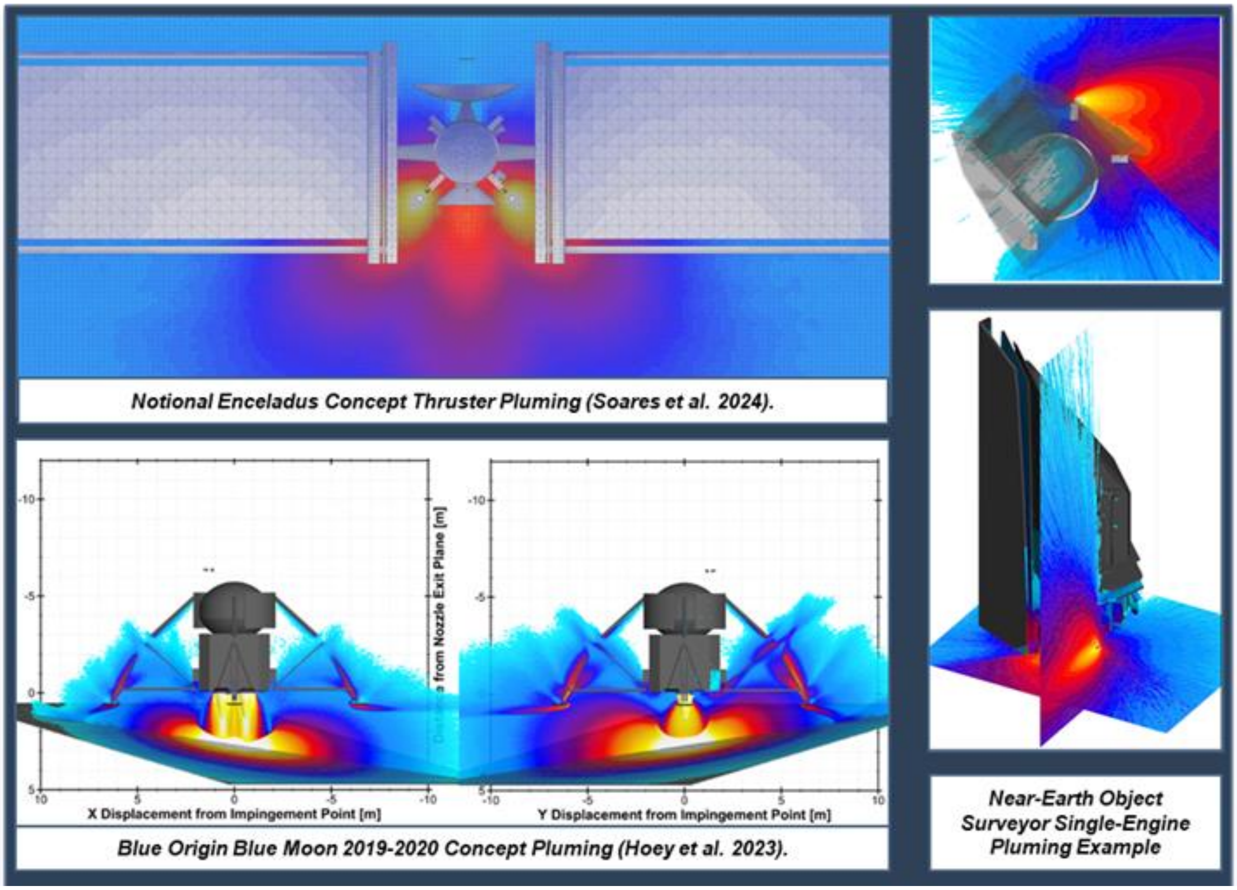

Figure 3. *JPL investigations of self-pluming for space and landing applications with CFD-DSMC methods; models for inert particle transport in such environments are being extended to study microorganism transport in near-vacuum. Representative contours show pressure on log-scales.*

The authors are developing a particle dispersal model to generate, e.g., densities and body-surface depositional results for particles dispersed by such plume firings as a function of plume-induced flow field and vehicle-surface properties.

This section is derived from a 2024 conference presentation and pending proceedings paper by Hoey et al. to the 33rd Int'l Symposium on Rarefied Gas Dynamics, "Toward a Model for Biological Contaminant Dispersal by Spacecraft Operating and Landing in Near-Vacuum."

Conclusion

Spacecraft generate molecular and particulate contamination that can impact their own science collection and local environments. They may also impact future science collection in distant environments, particularly on bodies with near-vacuum surface conditions.

- JPL Contamination Control Engineering has developed knowledge and modeling tools to characterize contamination-generative and transport processes across spacecraft engineering applications.
- The authors are developing and applying these models to topics of interest to NASA's Planetary Protection discipline.

In examples relevant to lunar landing environments, initial model results have found viable vectors exist for the long-distance transport of molecular and particulate contaminant.

Ongoing and future work will improve models both for *organic molecular contamination* generated by materials outgassing, venting and pluming processes, and also for *biological particle mobilization and transport* in plume flows.

- For more detail on organic contamination processes and concerns, refer to the agenda and presentations to the [2024 NASA Office of Planetary Protection Organic Inventory Workshop].

Disclosures

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). P. Gutierrez Cascales and R. Alves Hailer participated in gas dynamic modeling related to vehicle venting and lunar-scale free-molecular transport, respectively, through the JPL Visiting Student Research Program (JVSRP). Research into long-distance particle transport under plume loads was partially funded by ROSES grant 22-PPR22-0007, PI Dr. W.A. Hoey. High performance computing resources were provided by funding from the JPL Information and Technology Solutions Directorate.

Background Image Credit: NASA Johnson.

Author Information

William A. Hoey[1], J. R. Anderson[1], J. M. Alred[1], C. E. Soares[1], P. Gutierrez Cascales[1,2], R. Alves Hailer[1,3]

[1] Jet Propulsion Laboratory, California Institute of Technology

[2] Department of Aeronautics, Imperial College London

[3] School of Mechanical Engineering, State University of Campinas