The Contaminant Footprint of Landed Spacecraft: Toward an Inventory and Modeling Framework

William A. Hoey & Carlos E. Soares — Amentum Space Missions Division, JETS II | NASA JSC ES4 Space Environments
william.a.hoey@nasa.gov | carlos.e.soares@nasa.gov

John M. Alred — Jet Propulsion Laboratory, California Institute of Technology

Nick Benardini — NASA Headquarters

Erin Lalime — NASA Goddard Space Flight Center

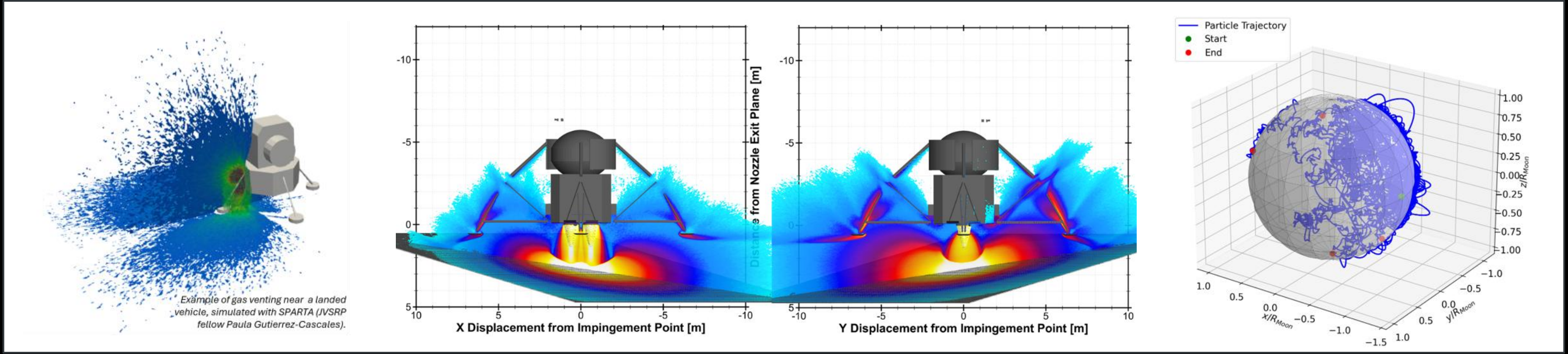
With contributions from 2024 JPL JVSRP fellows **P. Gutierrez Cascales** and **R. Alves Hailer**

The Lunar Surface Molecular Contamination Environment

Lunar landing vehicles and surface assets generate molecular contamination that alters the lunar environment.

- Landed spacecraft contribute ***pluming*** sources in descent and ascent.
- Landed spacecraft and surface assets also contribute ***materials outgassing*** and ***venting*** (propellant, ECLSS, crew waste, etc.)

These sources of contamination are also relevant to Planetary Protection and planetary science, particularly for organic molecules!



Landed vehicle local- and lunar-scale models of molecular contamination from venting and plume effects.

Left: Hoey et al. (2025), LPSC. | Center: Hoey et al. (2023), ICES. | Right: Alves Hailer et al. (2024).

Understanding 'Contamination' in Airless Environments

How can we quantify the "organic contaminant footprint" of a landing vehicle?

A Planetary Protection (PP) Organic Inventory and Archiving Workshop was held at NASA HQ in Feb. 2024 in which **molecular contamination topics** were explored to (per the Workshop site):

- *Evaluate the current organic inventory and archiving requirements in NASA PP policy.*
- *Provide a modernized, updated scientific and engineering-balanced rationale and approach to capturing molecular contamination to enable current and future science investigations.*
- *Identify knowledge gaps or additional policy inconsistencies that need to be addressed.*

Source terms and processes relevant to organic molecular contamination on the lunar surface were described based on NASA flight project engineering experience (Mars 2020, Europa Clipper…)

- *Examples include materials outgassing, venting from uncrewed and crewed systems, propulsion…*

Q: If a combination of source terms can be described for an asset on the lunar surface – for instance, a landed spacecraft – **how can we understand the "organic contamination footprint" of that asset**?

- *E.g., Where does molecular contamination transport and deposit – is this local or at lunar scale?*

This talk investigates key organic source and transport vectors and how they can be modeled.

*Repurposed from "**The Footprint of Landed Spacecraft in Near-Vacuum: Contamination Sources and Transport Terms**," by Hoey et al., presented at the 33rd International Symposium on Rarefied Gas Dynamics, July 2024. JPL CL#24-3655. https://doi.org/10.48577/jpl.QCQ9TL*

The Contaminant Footprint of Landed Spacecraft

The "footprint" of a lunar surface asset – its contributions of organic molecular contaminant to the lunar environment inclusive of release, transport, loss, and deposition processes – encompasses:

1. **Source terms**: high-level inventory of organic contaminants released by lunar surface assets.
   - *Common materials used on such vehicles and their available outgassing characterizations, &*
   - *Common propulsion systems used on such vehicles and their primary plume byproducts, &*
   - *Common modes and quantities of vented material, e.g., through passivation, ECLSS, etc.*
2. **Loss terms**: high-level models for loss processes relevant to species of organic contaminant.
   - *Photodissociation and ionization; related surface chemistry;*
   - *Gravitational or thermal escape (loss of molecules to space); &*
   - *Adsorption / desorption onto the lunar surface and permanent deposition into 'cold traps' like PSRs.*
3. **Transport terms: a probabilistic free molecular transport model** for organic molecules from release and their first contact with the lunar surface until their loss, that can compare and report on each generation and loss process (i.e., which are driving, and for which class of vehicle?)
   - Examples of RGD/FM frameworks for, e.g., water transport in lunar landings have been published by Prem et al. 2020 and Farrell et al. 2024, and recently also for methane by Paiva and Sinibaldi (2025).

See also: Hoey, W., Soares, C., 2024. "Engineering Models: Thruster Plume-Surface Interactions, Landing Site Alteration, Organic Footprint and Acceleration / Dispersion of Dust and Regolith," Invited presentation, NASA Office of Planetary Protection Organic Inventory Workshop. Link

*Repurposed from "**The Footprint of Landed Spacecraft in Near-Vacuum: Contamination Sources and Transport Terms**," by Hoey et al., presented at the 33rd International Symposium on Rarefied Gas Dynamics, July 2024. JPL CL#24-3655. https://doi.org/10.48577/jpl.QCQ9TL*

Source Terms: Outgassing

Material outgassing is a predominant source of molecular contamination in vacuum.

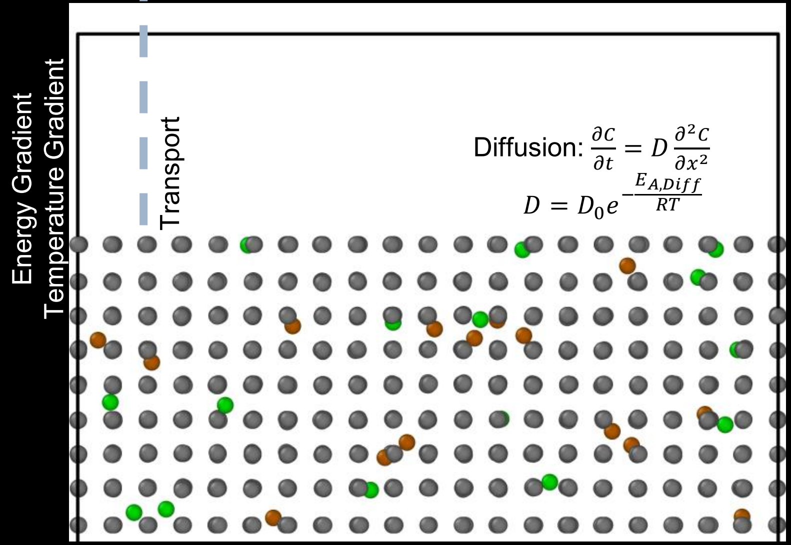
*Example **receiver** surface onto which adsorption occurs*

Adsorption/ Desorption: $\frac{dm}{dt} = \frac{m}{\tau_{ads}}$

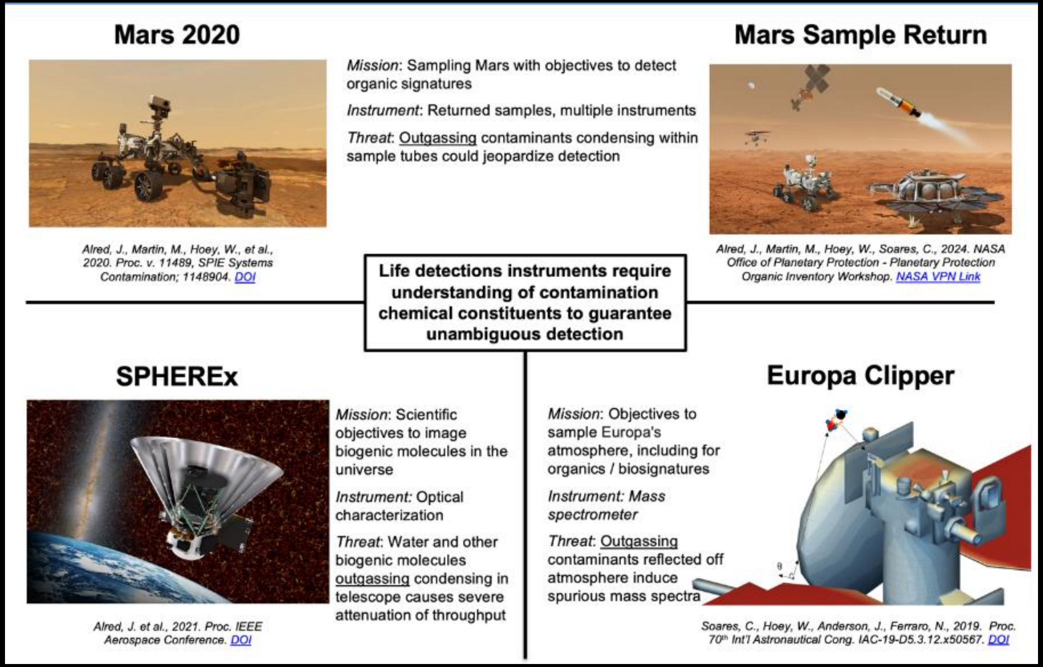
$$\tau_{ads} = \tau_0 e^{\frac{E_{A,ads}}{RT}}$$

Diffusion: $\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}$

$$D = D_0 e^{-\frac{E_{A,Diff}}{RT}}$$



Figures by co-author J. Alred, derived from: Alred, J., et al. 2024. “Outgassing Contaminant Species Extraction, Characterization and Modeling,” Invited presentation to the NASA Office of Planetary Protection - Planetary Protection Organic Inventory Workshop. *See also:* DOI



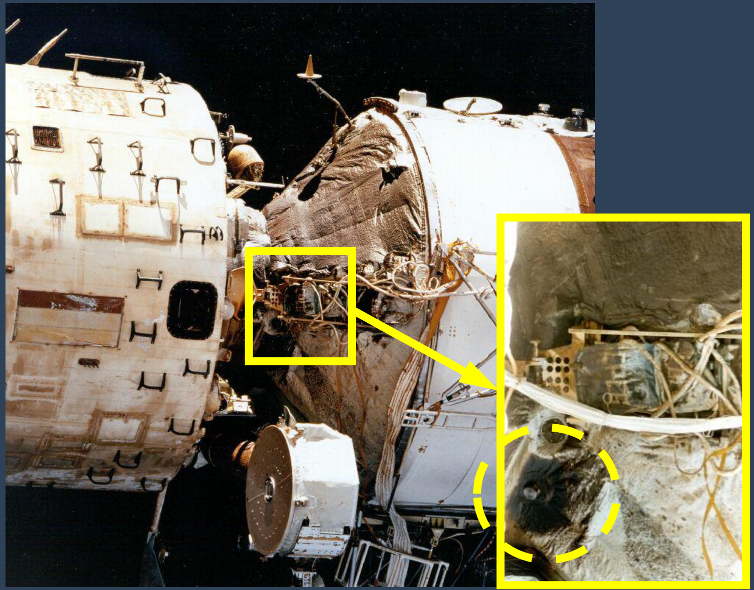
*Repurposed from “**The Footprint of Landed Spacecraft in Near-Vacuum: Contamination Sources and Transport Terms**,” by Hoey et al., presented at the 33rd International Symposium on Rarefied Gas Dynamics, July 2024. JPL CL#24-3655. https://doi.org/10.48577/jpl.QCQ9TL*

Source Terms: Venting

Crewed vehicles release high amounts of organic contaminant from venting systems.

Figures by co-author C. Soares, derived from: Soares, C. 2024. "Organic Contamination From Venting and Leakage (Environmental Control, Life Support Systems, IVA Science and Spacecraft Systems) - The ISS Experience," Invited presentation to the NASA Office of Planetary Protection – PP Organic Inventory Workshop. ***See also: our RGD 33 talk!***

Release of Organics from Life Support System Vents: 'On-orbit observations show darkening in the area around the Vozdukh vent caused by amine compounds released by the CO_2 scrub system.'



'The Mir Space station had the highest recorded levels of **organic contamination** from vacuum venting causing >10,000 Angstrom depositions and impacts to thermo-optical properties.'

*Repurposed from "**The Footprint of Landed Spacecraft in Near-Vacuum: Contamination Sources and Transport Terms**," by Hoey et al., presented at the 33rd International Symposium on Rarefied Gas Dynamics, July 2024. JPL CL#24-3655.* https://doi.org/10.48577/jpl.QCQ9TL

Source Terms: Engine Plumes

Spacecraft descent engine and attitude control thruster plumes generate gas- and liquid-phase contaminants that can alter landing and science-sampling environments.

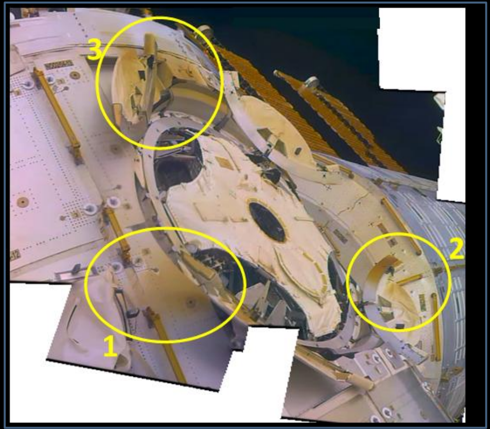
- We have applied RGD and empirical methods to simulate plume effects, including experimental materials compatibility and plume testing with DLR.

***DLR STG-CT Facility**. Image credits: DLR*

Plume free expansion computed with CFD/DSMC.
Image credit: JPL JVSRP fellow Antonietta Conte.

DLR STG-CT test section; thruster pack at center.
Image credit: DLR

NASA Images: ISS Contamination Processes



See also: Hoey, W., Soares, C., 2024. "Engineering Models: Thruster Plume-Surface Interactions, Landing Site Alteration, Organic Footprint and Acceleration / Dispersion of Dust and Regolith," Invited presentation, NASA Office of Planetary Protection Organic Inventory Workshop. Link

*Repurposed from "**The Footprint of Landed Spacecraft in Near-Vacuum: Contamination Sources and Transport Terms**," by Hoey et al., presented at the 33rd International Symposium on Rarefied Gas Dynamics, July 2024. JPL CL#24-3655. https://doi.org/10.48577/jpl.QCQ9TL*

Examples of Vehicle Self-Pluming Analyses

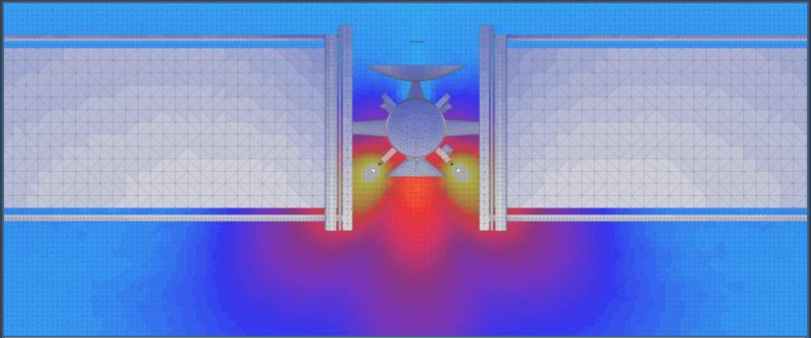
Hoey et al. have investigated **vehicle self-pluming** for in-space and landing applications with CFD/DSMC methods:

- *Moon:* Blue Origin Blue Moon concept (Hoey et al. 2023) and a CLPS lander.
- *Europa:* a Europa Lander concept (Lam et al. 2019, Hoey et al. 2020).
- *Enceladus:* Enceladus concepts (ex. figure at right from Soares et al. 2024).
- *In-space: Near-Earth Object Surveyor.*

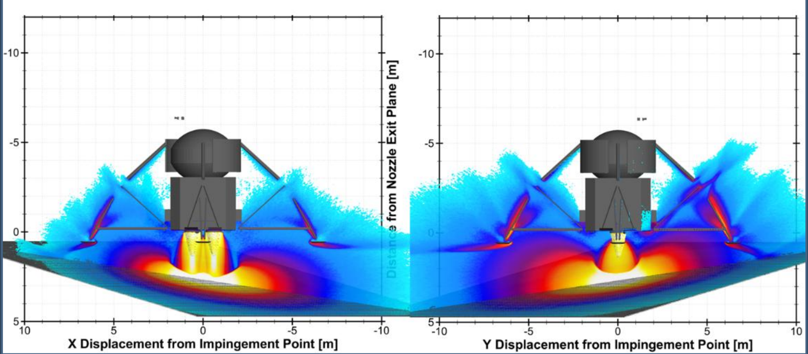
We have extended models for inert particle transport in lunar landing & launch depressurization environments to study microorganism transport.

Hoey, W., Martin, M., Alred, J., Soares, C., Ababneh, M., 2023. “Analyses of Blue Origin Blue Moon Lunar Landing Descent Engine Plume Effects,” Proc. 52nd International Conference on Environmental Systems (ICES); no. 42. HDL

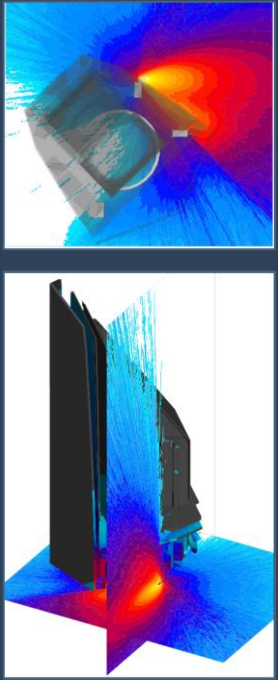
Soares, C., Hoey, W., Wong, A., Anderson, J., Grabe, M., 2024. “Experimental Characterization of Spacecraft Thruster Plume Contaminant Composition for Enceladus Orbiter and Lander Mission Concepts,” 55th Lunar and Planetary Science Conference (LPSC). Link



Notional Enceladus Concept Thruster Pluming (Soares et al. 2024).



Blue Origin Blue Moon 2019-2020 Concept Pluming (Hoey et al. 2023).



Near-Earth Object Surveyor Single-Engine Pluming Example

All example charts show normalized contours of pressure and are examples of one-way-coupled CFD/DSMC approaches.

Comparing and Contrasting Source Terms

Hoey, W., et al. "The Contaminant Footprint of Landed Spacecraft: Toward A Modeling Framework." Manuscript in draft.

	Materials Outgassing	**Chemical Propulsion System Pluming**	**Venting** Uncrewed Systems, e.g., Passivation	**Venting** Crewed Systems: e.g., ECLSS, Airlock Cycling
Contaminant Phase	Molecular	Primarily molecular May contaminate regolith particulate, may release droplet or soot products	Molecular Droplet or particulate waste	Molecular Droplet or particulate waste
Driver of Total Source	Vehicle dry mass of nonmetallic and vacuum-exposed materials	Vehicle propellant mass (fuel and oxidizer), as used in descent, landing, and ascent operations	Unspent vehicle propellant mass ejected at end-of-life; ejected waste from instrument or vehicle processes	Total crew count and duration of operations on the solar system body
Nature of Release	Spontaneously and gradually while exposed to vacuum; could span years	Continuous periods of engine firing in descent, landing, and ascent; could span minutes-to-hours	Discrete events to deplete reservoirs, each could span seconds-to-minutes.	May include continuous gas-phase venting from ECLSS, discrete airlock cycling events, or ejections of waste
Rate of Contaminant Release	Driven by local temperatures; time of vacuum exposure; material selection and pre-conditioning.	Driven by total thrust, therefore by vehicle total mass during descent, landing, and ascent operations	Open-ended; driven by the design, requirements, and operation of venting systems	Driven by crew count and mission duration (ECLSS) and operations (EVAs, waste ejections, etc.)
Organic Contaminants?	Typical spacecraft materials will contain some organic molecules that outgas in near-vacuum	Generated as combustion products, dependent on propellant choice and engine operation	May be present in vented propellant and instrument or vehicle waste	Present in ECLSS venting, cabin atmospheres and crew waste
Potential Mitigations of Organic Component	Standard approaches exist for sensitive missions – material screening and selection of low-organic-outgassing materials; pre-conditioning of materials and spacecraft with bake-outs	Unlikely – could relate to choice of propellant, engine firing modes, landing site selection	Mission-dependent – vehicles could plan to retain or scrub certain waste	Mission-dependent – vehicles could plan to retain or scrub certain waste

Comparing and Contrasting Source Terms

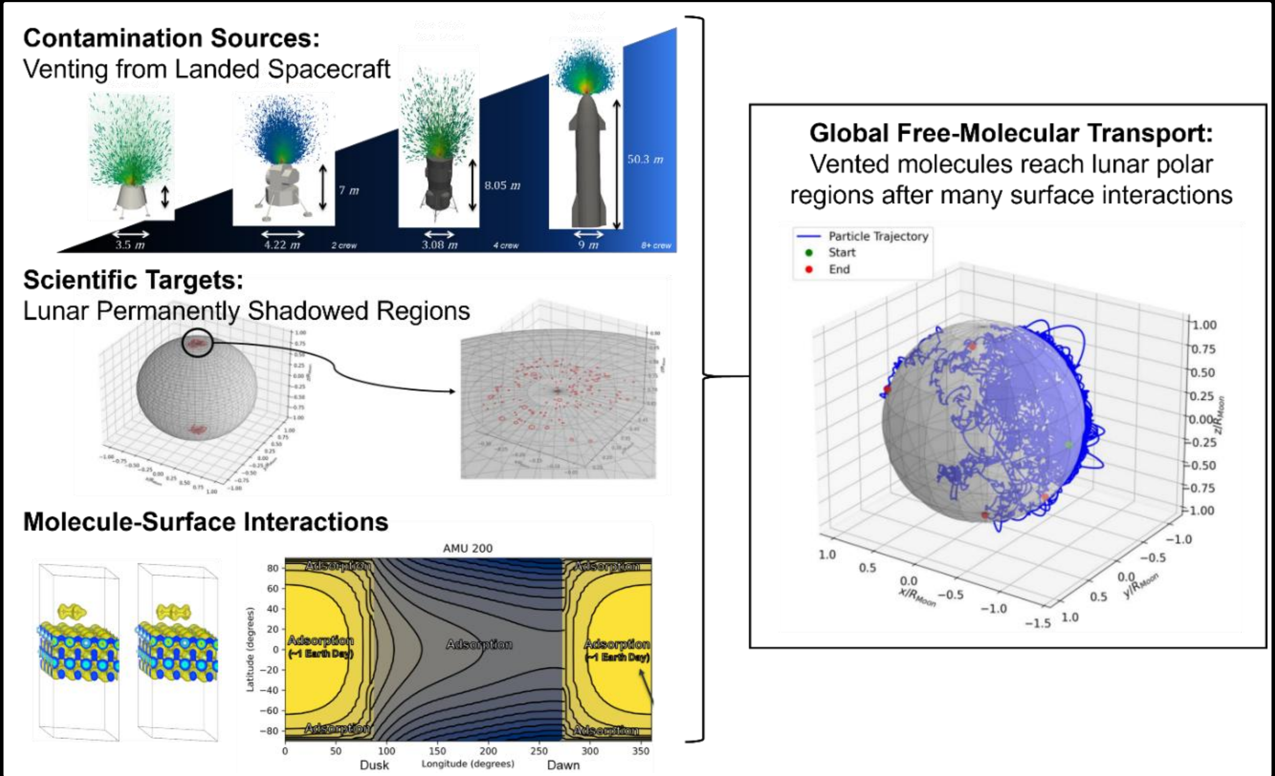
Hoey, W., et al. "The Contaminant Footprint of Landed Spacecraft: Toward A Modeling Framework." Manuscript in draft.

	Blue Ghost M1 Firefly Aerospace; NASA CLPS (2025)	Chang'e 5 CNSA Lunar Exploration (2020)	Apollo Landing Module NASA; Apollo 17 (1972)	Blue Moon Blue Origin (TBD)	Starship HLS SpaceX (TBD)
Propellant	Bipropellant: MMH fuel, MON-3 oxidizer	Bipropellant: MMH fuel, NTO oxidizer	Aerozine 50 fuel, NTO oxidizer	Liquid hydrogen fuel, liquid oxygen oxidizer	Liquid methane fuel, liquid oxygen oxidizer
Main Engines	×1 Descent (Nammo LEROS-4)	×1 Descent ×1 Ascent	×1 Descent (LMDE) ×1 Ascent (LMAE)	BE-7; May use multiple engines in descent and ascent.	Raptor Vacuum (RVAC); May use multiple engines in descent and ascent.
Max Thrust (Descent)	≥ 1.0 kN	~ 7.5 kN	~ 47 kN (throttlable)	TBD	TBD
Max Thrust (Ascent)	--	3 kN	16 kN	TBD	TBD
Lander Total Mass	1,500 kg	3,200 kg (lander) 700 kg (ascent element)	16,000 kg	TBD	TBD
Propellant Mass	1,000 kg (launch)	1,900 kg (used in descent) 390 kg (used in ascent)	8,200 kg (total for descent) 2,400 kg (total for ascent)		
Dry Mass	469 kg	1,200 kg	4,920 kg	TBD	TBD
Nominal Crew Capacity	0	0	2	2	2 – 4+

+ Added complexity of crewed vehicles: need to account for airlock cycling, ECLSS, crew waste, etc.!

All inputs are estimated from publicly available data.

Modeling Long-Distance Free Molecular Transport



Modeling Global Free-Molecular Transport for Organic Molecules

(*Top Left*): Molecular contaminants vented from lunar landed spacecraft are simulated with DSMC.

(*Center Left*): Lunar permanently shadowed regions (PSRs) of high science and ISRU value are modeled as sinks for contaminant.

(*Bottom Left*): Simulations of molecular-surface interactions, combined with a time-variant lunar surface map, provide insight into the residence time of certain *n*-alkane species on the lunar surface.

(*Right*): In combination, these elements are incorporated into a simulation for the transport of organic molecular contaminant from a landing site to distant regions of the Moon.

Venting analyses and figures by JPL JVSRP P. Gutierrez Cascales, 2024.

Lunar-scale free molecular transport analyses and figures by JPL JVSRP R. Alves Hailer, 2024.

See also: Hoey, W., Anderson, J., Alred, J., Soares, C., Gutierrez Cascales, P., Alves Hailer, R. "*Modeling the Contaminant Footprint of Spacecraft Operating in Near-Vacuum.*" 56th Lunar and Planetary Science Conference, The Woodlands, TX; Mar. 2025. Link

Conclusions and Discussion

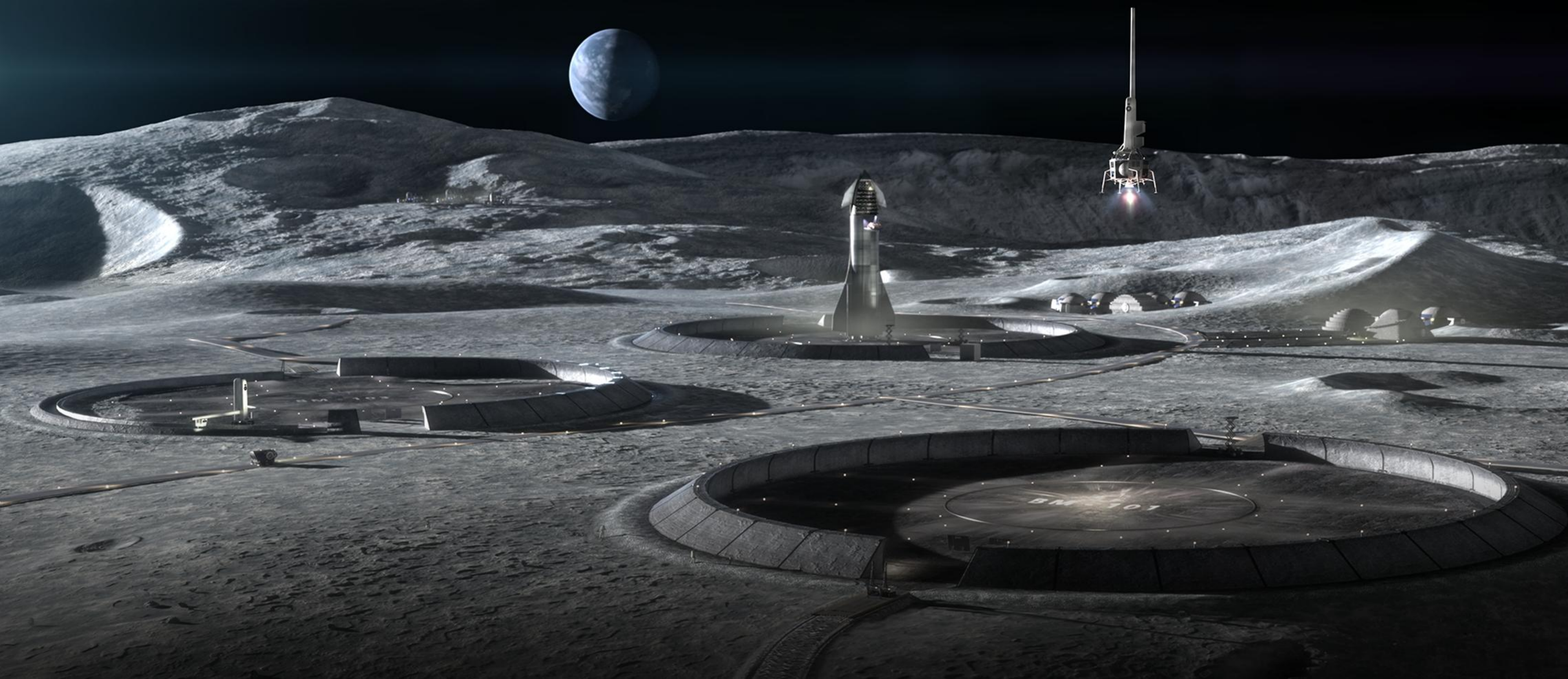
- **Spacecraft alter their environments** and may compromise their engineering or science objectives as they generate and disperse contaminant (inert or biological).
  - *This is never more true than during landings and surface operations!*
- **Engineering models** for spacecraft outgassing, venting, and engine pluming processes can be helpful in characterizing contaminant environments.
  - *Spacecraft designs are already directly informed by such models in order to mitigate threats of contamination, heating, chemical or mechanical erosion, etc.*
- **Established tools exist** for some gas-dynamic problems in engineering:
  - *These tools are being extended to study effects beyond the immediate landing environment and vehicle, i.e., the transport of organic outgassing, venting and plume effluent products as well as regolith and biological contaminants to scientific sampling sites far away from a lander.*
- Work is underway to **link engineering knowledge and capabilities** (including in rarefied gas dynamics) to best protect and inform future science missions.

See also: Hoey, W., Anderson, J., Alred, J., Soares, C., Gutierrez Cascales, P., Alves Hailer, R. "*Modeling the Contaminant Footprint of Spacecraft Operating in Near-Vacuum.*" 56th Lunar and Planetary Science Conference, The Woodlands, TX; Mar. 2025. Link

*Repurposed from "**The Footprint of Landed Spacecraft in Near-Vacuum: Contamination Sources and Transport Terms**," by Hoey et al., presented at the 33rd International Symposium on Rarefied Gas Dynamics, July 2024. JPL CL#24-3655. https://doi.org/10.48577/jpl.QCQ9TL*

Acknowledgements

This research was carried out under the direction of the NASA HQ Office of Planetary Protection.



The Contaminant Footprint of Landed Spacecraft: Toward an Inventory and Modelling Framework

William A. Hoey[1], Carlos E. Soares[1], John M. Alred[2], Nick Benardini[3], Erin Lalime[4], Raphael Alves Hailer[1*], Paula Gutierrez Cascales[1*]

[1)] Amentum Space Missions Division, JETS II | NASA JSC ES4 Space Environments; william.a.hoey@nasa.gov | carlos.e.soares@nasa.gov
[2)] Jet Propulsion Laboratory, California Institute of Technology
[3)] NASA Headquarters
[4)] NASA Goddard Space Flight Center
[*)] JPL Visiting Student Research Program (JVSRP)

Abstract: All spacecraft generate and carry *contaminants*, i.e., unwanted and potentially harmful material. When a spacecraft lands and operates in near-vacuum, as onto Earth's Moon, it introduces contaminants into its environment that may compromise mission science objectives and engineering performance. Contamination of solar system bodies may irrevocably degrade targets of unique value to planetary scientists, for instance, as lunar landed spacecraft introduce propellant effluents into the otherwise pristine ice of the Moon's permanently shadowed regions.

NASA's planetary protection discipline seeks to ensure that solar system bodies are not contaminated, for scientific purposes, by terrestrial material (i.e., *forward* contamination). This interest aligns with planetary science interest in mitigating the transport of terrestrial contaminants onto solar system bodies and in controlling types of contamination that could compromise the scientific value of samples or measurements. NASA, and other entities that practice planetary science, have compelling and multidisciplinary interests in the preservation of special regions and sampling sites of high scientific value – including lunar permanently shadowed regions (PSRs) – from inadvertent contamination by *any* spacecraft, and in understanding the contamination of such regions by *all* spacecraft.

Organic molecular contamination here represents a primary threat. Organic molecules will be introduced to solar system bodies by nominal landed spacecraft and crew processes – including by the action of descent and ascent engines; natural materials outgassing; and crew environmental and life support system sources. Molecular contaminants can also travel in the free-molecular sense at global scale across near-vacuum bodies, including into regions where they may be permanently trapped.

This presentation will address a high-level study to identify *sources* of contaminants – in particular, organic material – generated by landed spacecraft along with the *transport* vectors by which these contaminants can reach sites of scientific interest on bodies like the Moon. A vision for an integrated modeling framework for the organic contamination footprint of spacecraft missions, individually and collectively, will also be described and presented along with initial conclusions related to organic molecular transport.