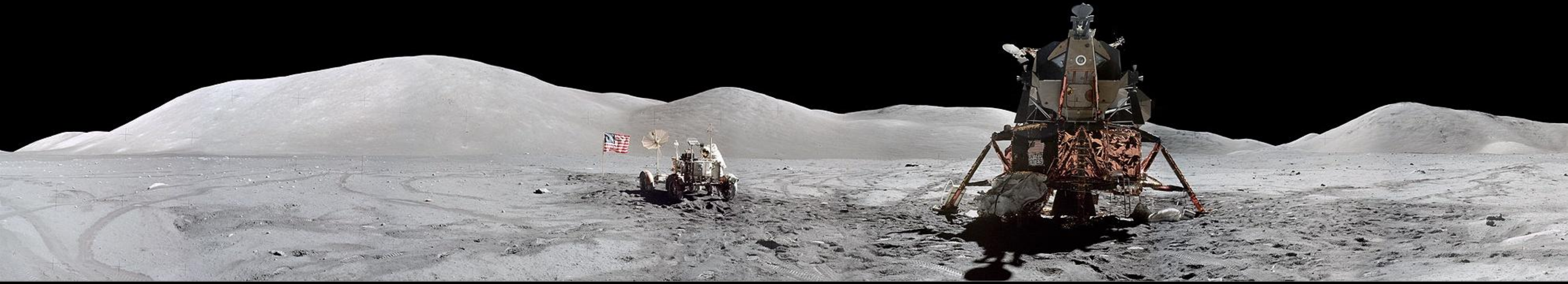
Presentation to the 2026 NASEM CoPP Meeting

# The Footprint of Landed Spacecraft in Lunar Vacuum: Sources and Transport of Molecular Contamination

**Dr. William A. Hoey**[1,2*]; Dr. J. M. Alred[1]; C. E. Soares[1,2]

*) william.a.hoey@nasa.gov

1. Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA.
2. Amentum, JETS II Contract, Houston TX - *current affiliation.*



*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*

# Approaches to Understanding 'Contamination' in Airless Environments

## [1] *How do 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.*

This work investigates key contamination source and rarefied-gas-dynamic transport vectors.

## [2] *How can engine plume flows interact with and transport microorganism-laden particles or independent microorganisms borne on a landed vehicle?*

## *How could such plumes deposit contaminants onto a lander, its instrumentation, and surfaces far from its landing site?*

Separate ROSES-funded work investigates plume-vehicle interactions; microorganism shape, size and adhesion / removal characteristics; and the potential for pluming environments to remove and transport biological contaminant particles during landings.

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# [1] Toward an Organic Inventory of Spacecraft-Generated Contaminant

To generate order-of-magnitude estimates of landed vehicle organic material, transport, loss, and deposition across the Moon while making few specific assumptions about vehicle architecture and the local lunar environment, models are needed to characterize:

1. **Source terms**: high-level inventory of organic contaminant species released by landing vehicles.
   - Common materials used on such vehicles and their available outgassing characterizations, &
   - Common propulsion systems used on such vehicles and their primary plume byproducts;
2. **Loss terms**: high-level models for loss processes relevant to species of organic contaminant.
   - Photodissociation and ionization;
   - Gravitational escape (loss to space); and
   - Adsorption / desorption onto the lunar surface and permanent deposition into cold traps.
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 frameworks for such models for e.g. water transport in lunar landings have been shown in Prem et al. 2020 and Farrell et al. 2024.

*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

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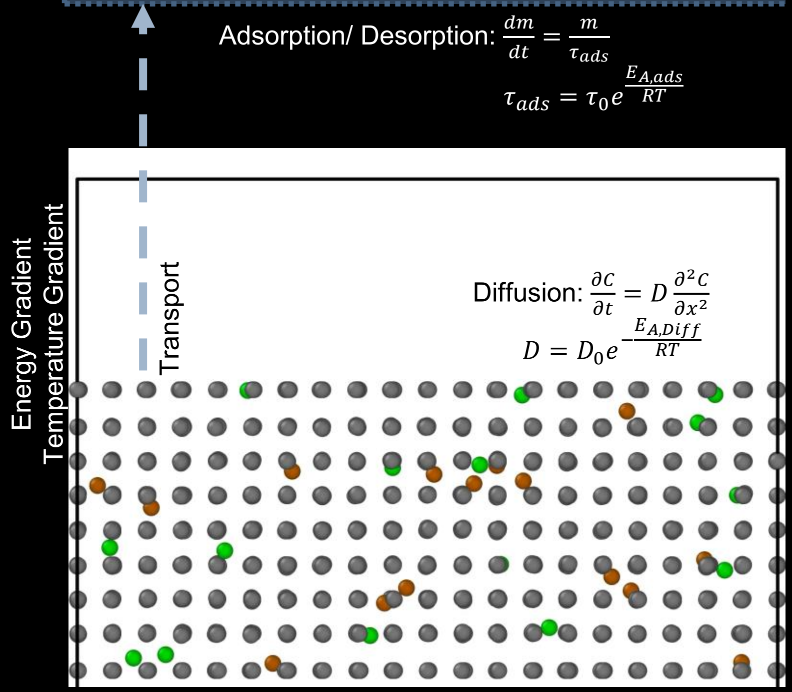
# Outgassing Sources

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

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



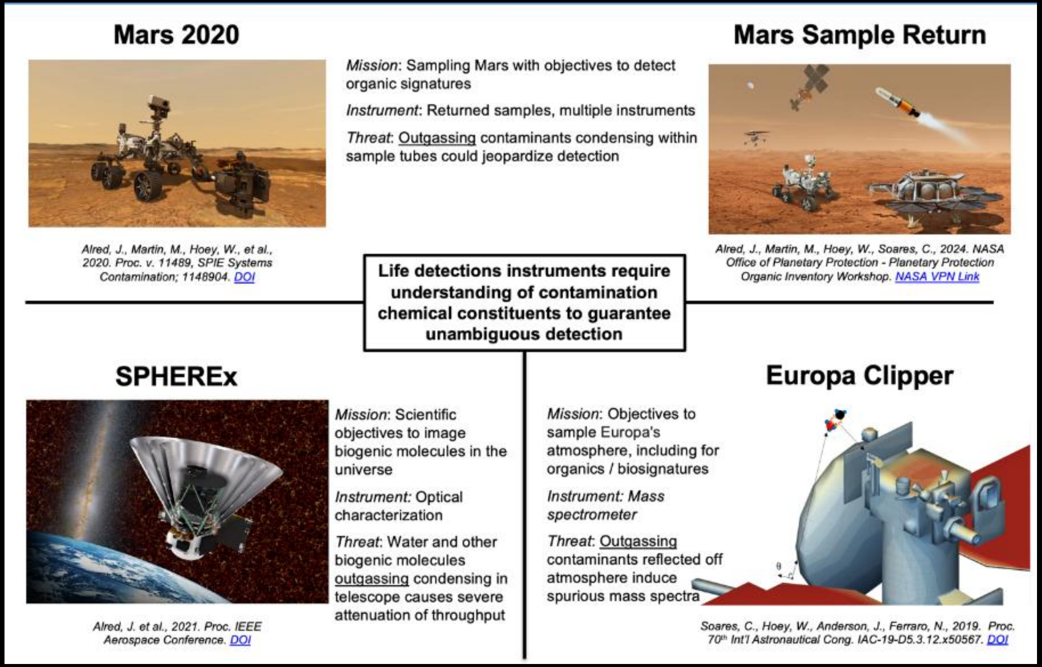
Adsorption/ Desorption: $\frac{dm}{dt} = \frac{m}{\tau_{ads}}$

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

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



**Mars 2020**

*Mission*: Sampling Mars with objectives to detect organic signatures

*Instrument*: Returned samples, multiple instruments

*Threat*: Outgassing contaminants condensing within sample tubes could jeopardize detection

*Alred, J., Martin, M., Hoey, W., et al., 2020. Proc. v. 11489, SPIE Systems Contamination; 1148904. DOI*

**Mars Sample Return**

*Alred, J., Martin, M., Hoey, W., Soares, C., 2024. NASA Office of Planetary Protection - Planetary Protection Organic Inventory Workshop. NASA VPN Link*

**Life detections instruments require understanding of contamination chemical constituents to guarantee unambiguous detection**

**SPHEREx**

*Mission*: Scientific objectives to image biogenic molecules in the universe

*Instrument*: Optical characterization

*Threat*: Water and other biogenic molecules outgassing condensing in telescope causes severe attenuation of throughput

*Alred, J. et al., 2021. Proc. IEEE Aerospace Conference. DOI*

**Europa Clipper**

*Mission*: Objectives to sample Europa's atmosphere, including for organics / biosignatures

*Instrument: Mass spectrometer*

*Threat*: Outgassing contaminants reflected off atmosphere induce spurious mass spectra

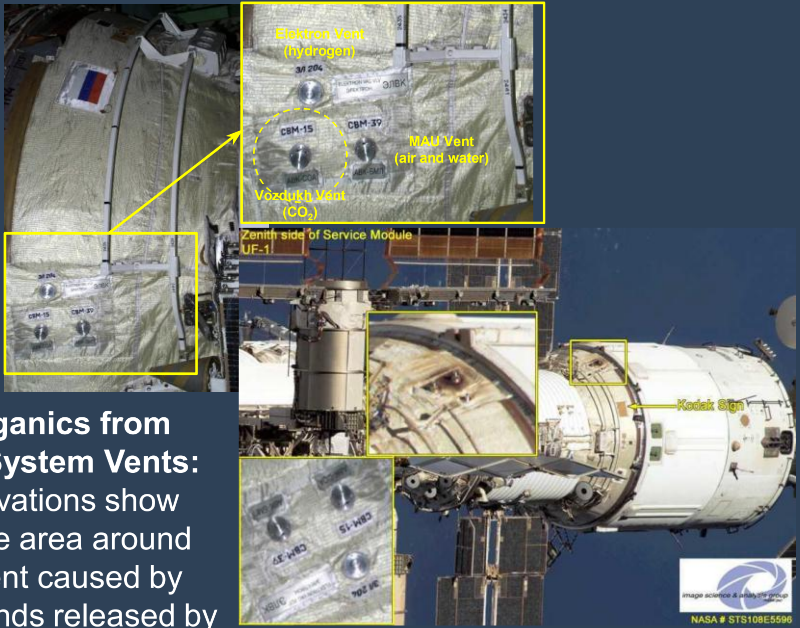
*Soares, C., Hoey, W., Anderson, J., Ferraro, N., 2019. Proc. 70th Int'l Astronautical Cong. IAC-19-D5.3.12.x50567. DOI*

*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*

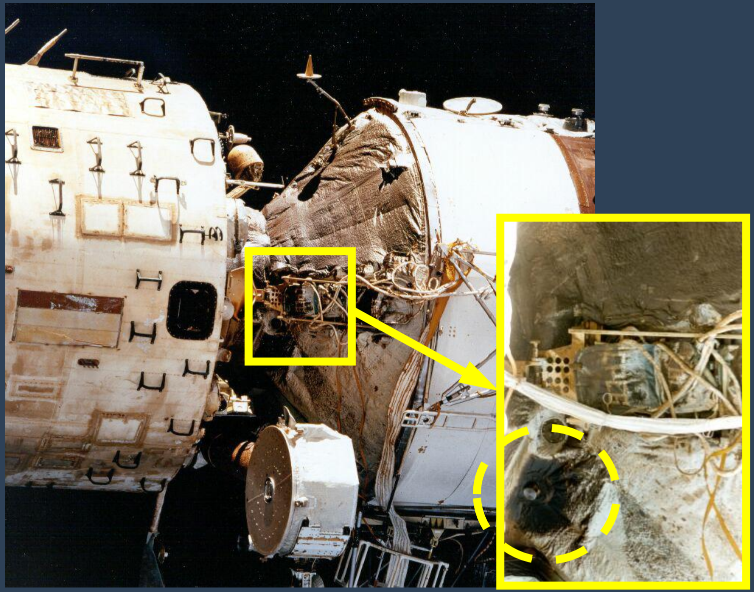
# Venting Sources

## 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.’

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# Pluming Sources

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

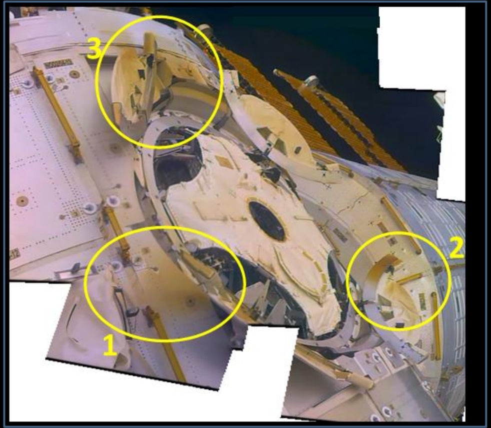
- We have applied RGD and empirical methods to simulate plume effects, including experimental materials compatibility and plume testing with DLR.

***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

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# Examples of Vehicle Self-Pluming Analyses

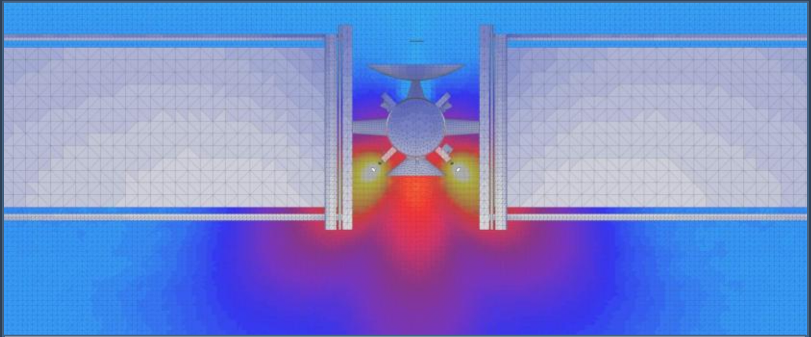
Hoey et al. have investigated **vehicle self-pluming** for in-space and landing applications with CFD/DSMC methods:

- *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.*

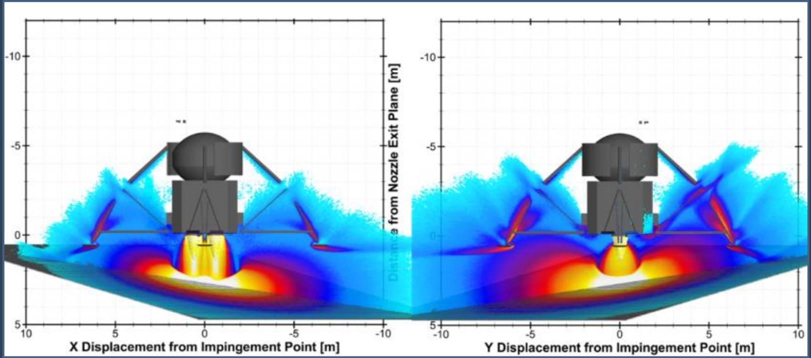
We have extended models for inert particle transport in lunar landing & launch depressurization environments to study microorganism transport.

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

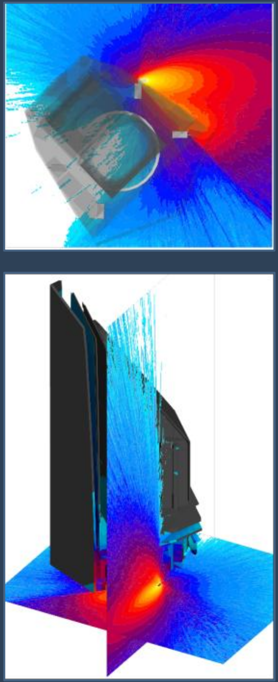
Soares, C., Hoey, W., Wong, A., Anderson, J., Grabe, M., 2024. “Experimental Characterization of Spacecraft Thruster Plume Contaminant Composition for Enceladus Orbiter and Lander Mission Concepts,” 55th Lunar and Planetary Science Conference (LPSC). Link



*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.*

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# 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!*
- **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

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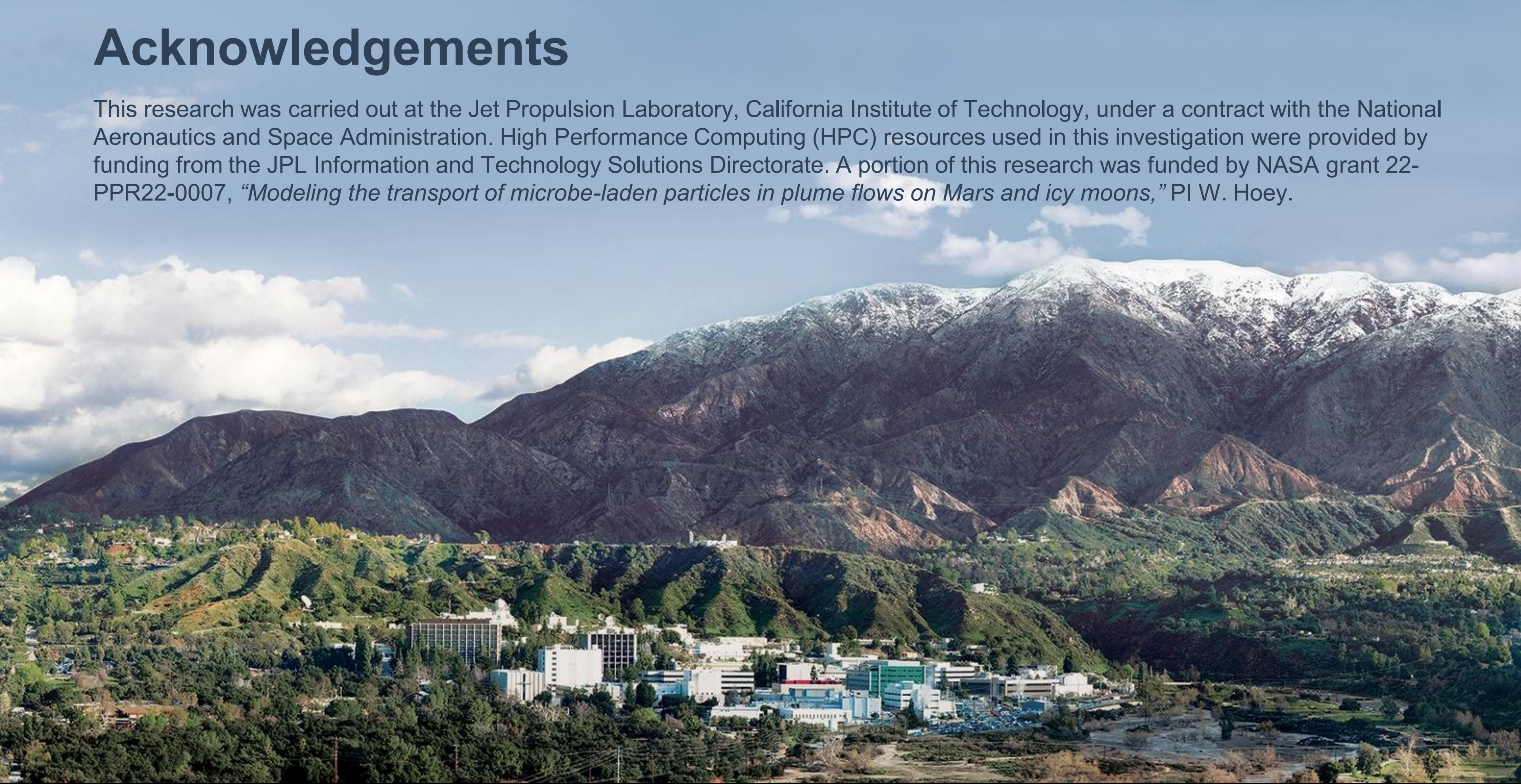

# Acknowledgements

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# Backup

# Applications to Spacecraft Vacuum Venting Operations

Spacecraft vacuum vents are concentrated sources of contamination (in many cases, organic contamination). The following table illustrates common types of vents present in crewed and robotic spacecraft systems and science payloads:

| Vent Type | Source (or system) | Effluents |
|---|---|---|
| Environmental Control and Life Support Systems | Carbon dioxide<br>Condensate water<br>Cabin air (airlocks)<br>Waste gas<br>Waste water | Cabin air, noble gases, $CO_2$, CO, **amines, waste water** |
| Thermal control systems | Active thermal control systems | **Ammonia, ethylene glycol, siloxanes** |
| Propulsion systems (propellant purging) | Monopropellants and bipropellant propulsion systems | **Hydrazine**, **MMH, MON (nitrogen tetroxide), methane**, oxygen |
| Science payloads (experiment vents) | Vacuum exhaust systems (blowdown)<br>Vacuum resource systems (maintain vacuum) | **Diverse combination of organic compounds** from science experiments |
| Leakage | Fluid (gas and liquid) systems | Varied compounds |

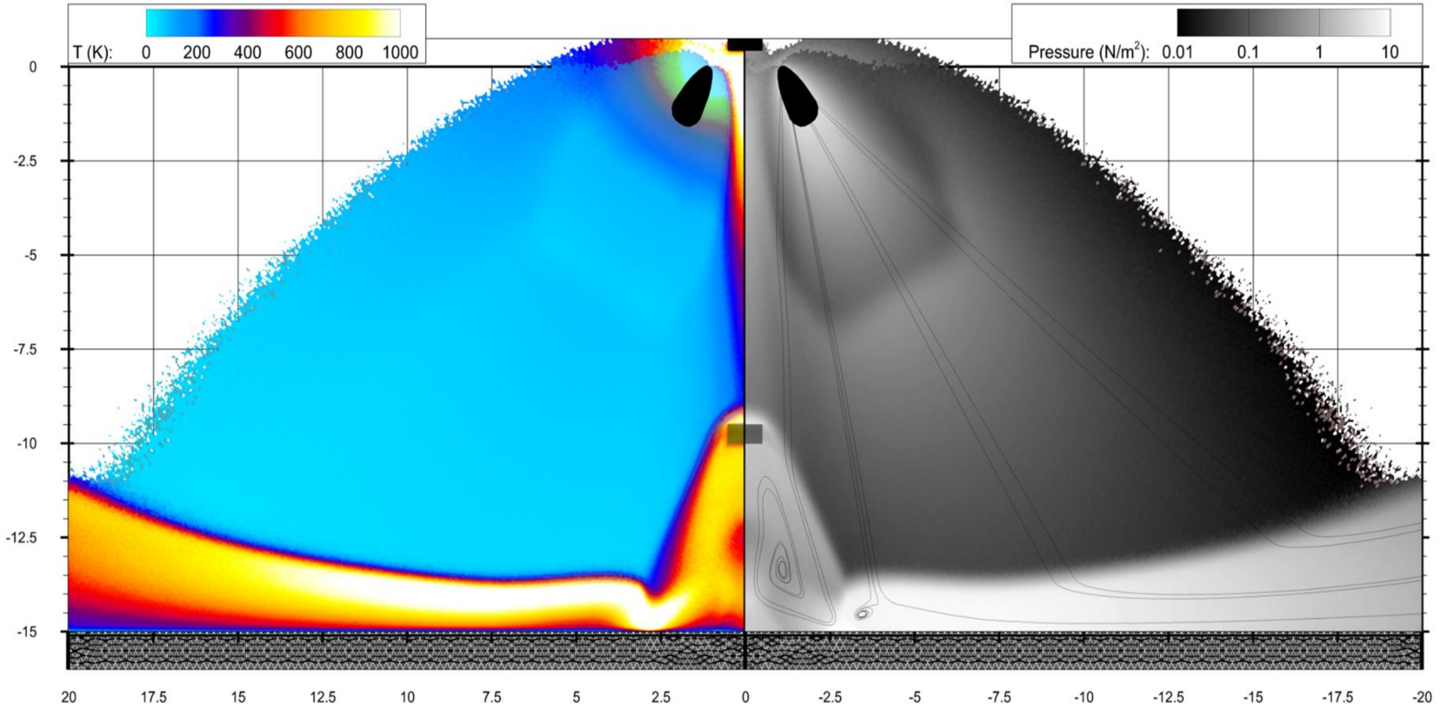
# Release of Organics from Life Support System Vents

- The Vozdukh vacuum vent on the Service Module exhausts primarily carbon dioxide ($CO_2$, 80 to 97%) in conjunction with a small amount of air and water. [Vozdukh is the name of the Russian carbon dioxide removal system.]

- The carbon dioxide scrub system is based on solid-phase amine $CO_2$ sorbents. The amines react with the airborne $CO_2$ and water vapor, scrubbing the cabin air. The system can be thermally regenerated as the chemisorption reactions are reversed under heat and/or vacuum. The vacuum vent is used to eliminate the trapped $CO_2$ and water vapor during the regeneration phase.

- On-orbit observations; however, have shown darkening in the area around the Vozdukh vent. The cause of this darkening is amine compounds released by the $CO_2$ scrub system.

# JPL Model Application to an Europa Lander Mission Concept



***Thruster plume flow-field generated at 15 m above the surface by four 30°-canted engines at full-throttle.***

Peak Europan surface pressure: 29 Pa

Peak Europan surface net convective heating: 17 kW/m$^2$

Peak Lander shock $T_{Total}$: 1250 K

Peak Lander surface net convective heating: 5.5 kW/m$^2$

**"Europa Lander Engine Plume Interactions with the Surface and Vehicle."**
Hoey, W., Lam, R., Wong, A., Soares, C., 2020. *Proceedings of the 2020 IEEE Aerospace Conference.*

# Lunar Landings and Dust Problems

## JPL Engineering Model Framework

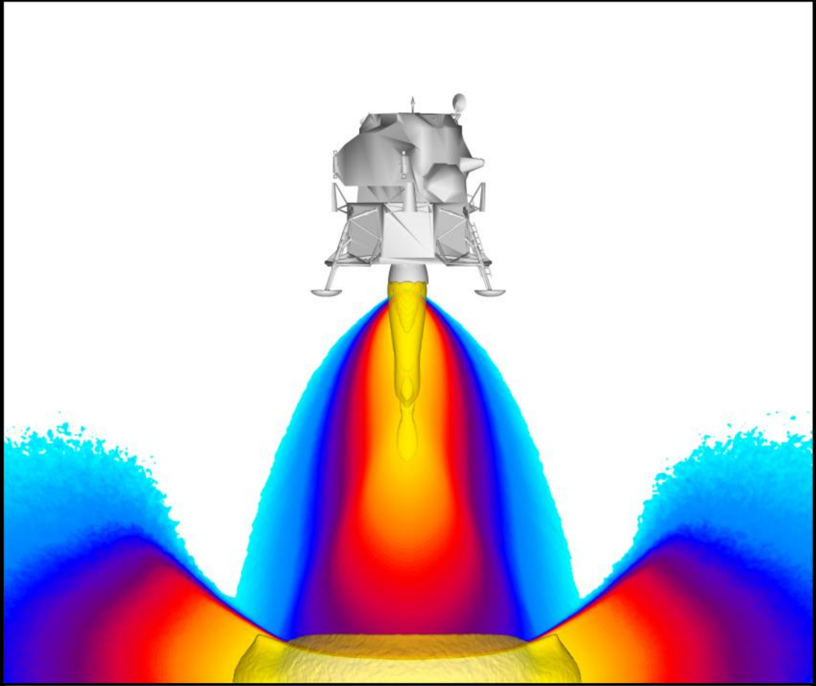
JPL applies a physics-based engineering model framework for landing plume flows:

- *A hybrid CFD / DSMC approach for modeling high-speed gas plume flows into vacuum,*
- *Particle entrainment and tracing models, and*
- *Particle adhesion and removal physics models.*

Relevant lunar landing applications include:

- *Removal and transport of dust and regolith from the lunar surface by impinging plumes*
- *Dust / regolith flux to lander sensitive surfaces to enable degradation assessments, e.g. of :*
  - obscuration of cameras and optical sensors required for landing / docking
  - degradation of active radiator surfaces

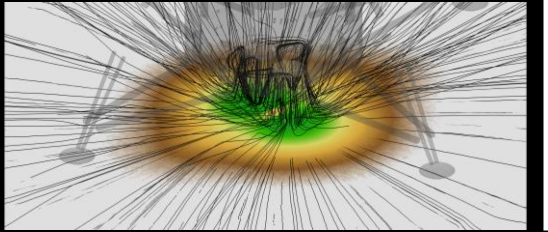
**"Spacecraft Engine Plumes in Near-Vacuum: Earth's Moon and Beyond"**
Hoey, W., Soares, C., Alred, J., Anderson, J., Martin, M., Shallcross, G., Wong, A., 2022.
*Invited presentation; 32nd International Symposium on Rarefied Gas Dynamics (RGD32).*

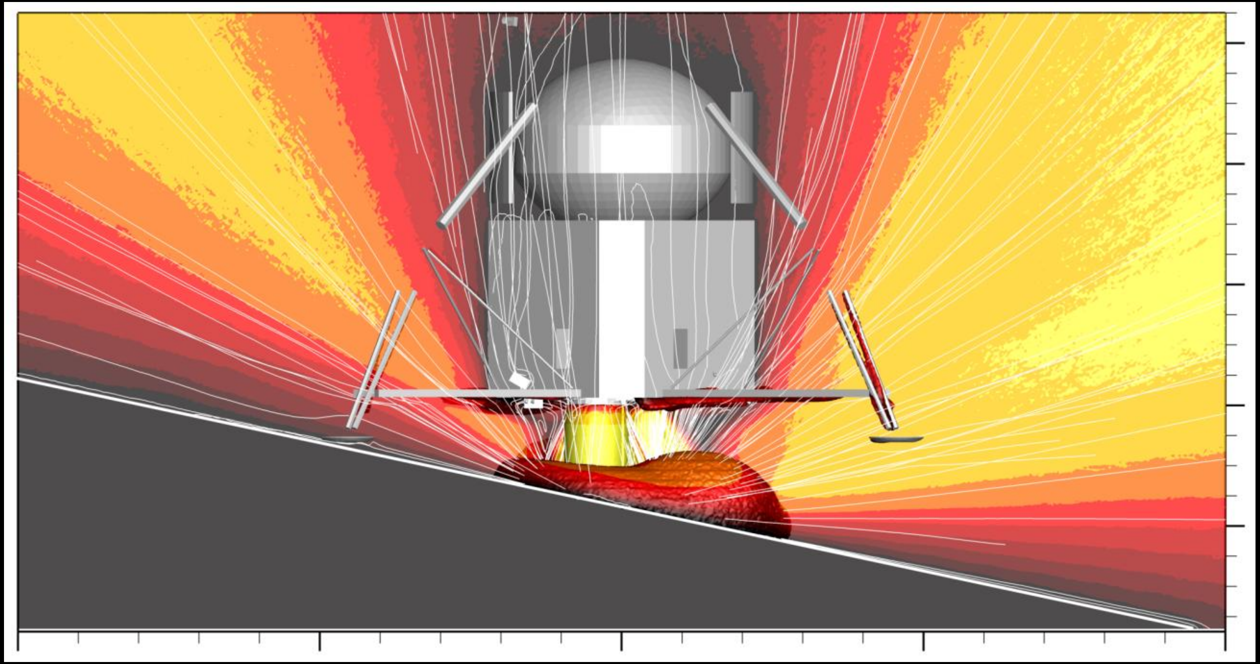


***JPL 353D results for rarefied gas dynamic dual engine plume flows in lunar landing, representative contours of pressure on an Apollo DE***. Note shock formation between engines and surface, free expansion elsewhere. CFD-DSMC 1-way coupling.

# *Simulation Example: Generic Multi-Engine Lander Configuration*

- Traces represent the trajectories of Lunar dust/regolith particles entrained in the interacting multi-engine plume flowfields.
- Landing on a surface with slope.



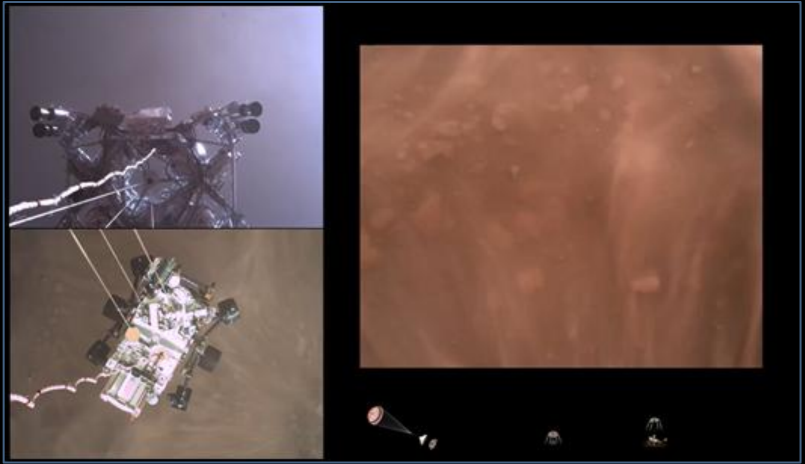


*Example 3-D results for a lunar lander in a theoretical multi-engine configuration.*

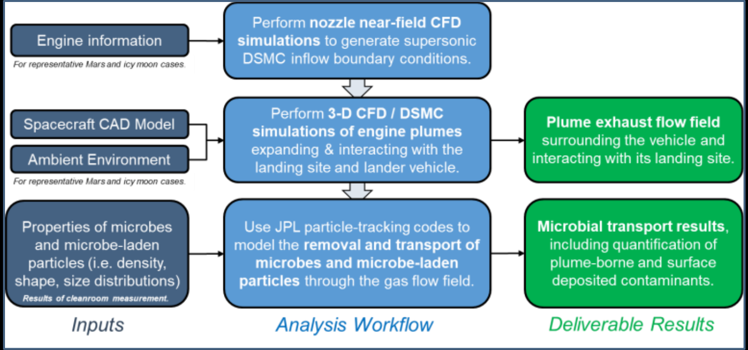
# [2] Toward a Dispersion Model for Microorganisms Borne on Spacecraft

In any powered landing, engine plume flows of O[1000 m/s] in core flow wash over parts of a landing vehicle and landing site, and can disperse particles of terrestrial origin borne on the landing vehicle. High-velocity landing plume flows provide an important vector that may transport biological contaminant far from a lander – especially in vacuum! A JPL CC / PP team is currently studying:

- Microorganism shape and size distributions, as compared to inert particles;
- The ability of microorganisms to attach to and ‘hitchhike’ on larger inert particles, and
- The landing plume flow environments that could disperse microorganisms.



**Notional model workflow.**



Inputs

Engine information

*For representative Mars and icy moon cases.*

Spacecraft CAD Model

Ambient Environment

*For representative Mars and icy moon cases.*

Properties of microbes and microbe-laden particles (i.e. density, shape, size distributions)

***Results of cleanroom measurement.***

*Analysis Workflow*

Perform **nozzle near-field CFD simulations** to generate supersonic DSMC inflow boundary conditions.

Perform **3-D CFD / DSMC simulations of engine plumes** expanding & interacting with the landing site and lander vehicle.

Use JPL particle-tracking codes to model the **removal and transport of microbes and microbe-laden particles** through the gas flow field.

*Deliverable Results*

**Plume exhaust flow field** surrounding the vehicle and interacting with its landing site.

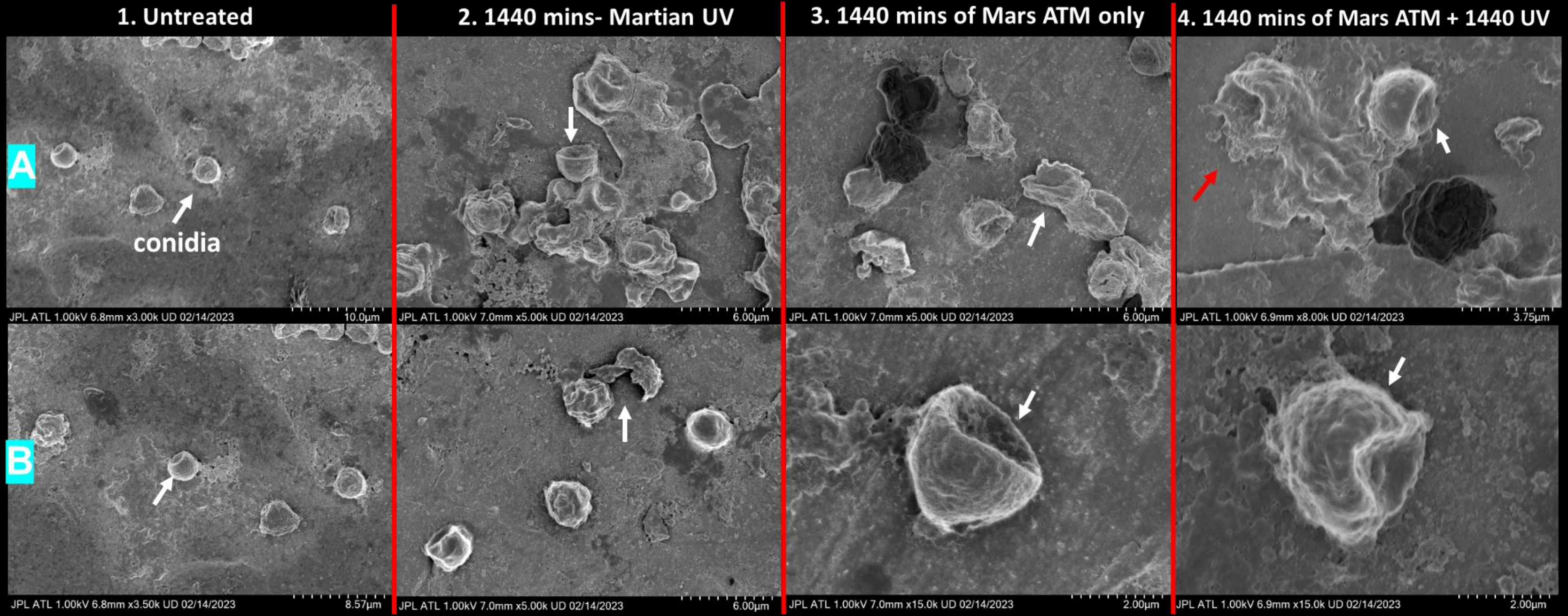
**Microbial transport results**, including quantification of plume-borne and surface deposited contaminants.

**Sky Crane Mars landings.** Images from Mars 2020 Perseverance rover landing including *[1]* views up from the rover’s top deck; *[2]* down from the Sky Crane; and *[3]* down from the rover’s bottom deck. Surface obscuration is due to erosion of Mars dusts under plume flows. *Image credits NASA/JPL-Caltech.*

# Microorganisms: Particle Shapes and Sizes ( 1 / 2 )

Examples of << 10 µm fungal conidia: exposure to simulated Mars UV and atmospheric environments induces morphological changes and ruptures. When mixed with other particulate material, e.g. Mars regolith, adhesion can occur.

*From:* Chander, A. M., et al., 2022. “Survival of fungi isolated from Mars 2020 mission assembly facilities exposed under simulated Mars conditions”, American Society for Gravitational and Space Research (ASGSR-2022), Houston, Texas, USA. *Further publication pending.*



# Microorganisms: Particle Shapes and Sizes ( 2 / 2 )

Biological particles (individually small, O[<<10μm]) can attach themselves to the larger inert particles present in spacecraft cleanroom facilities or in landing environments, e.g. regolith!

- This adds complexity to spacecraft particle dispersal analyses: particle removal is strongly influenced by shape and size. Large inert particles may be relatively easier to remove from surfaces under spacecraft gas dynamic and vibrational loads than individual biological particles.
- *Right:* ‘Visualization of biological and inert particle and spore revival by time’ from Fig. 6 of a JPL PP study by Malli Mohan et al., 2019.
  - *Inset fig. arrow: a likely biological particle associated with an inert particle!*

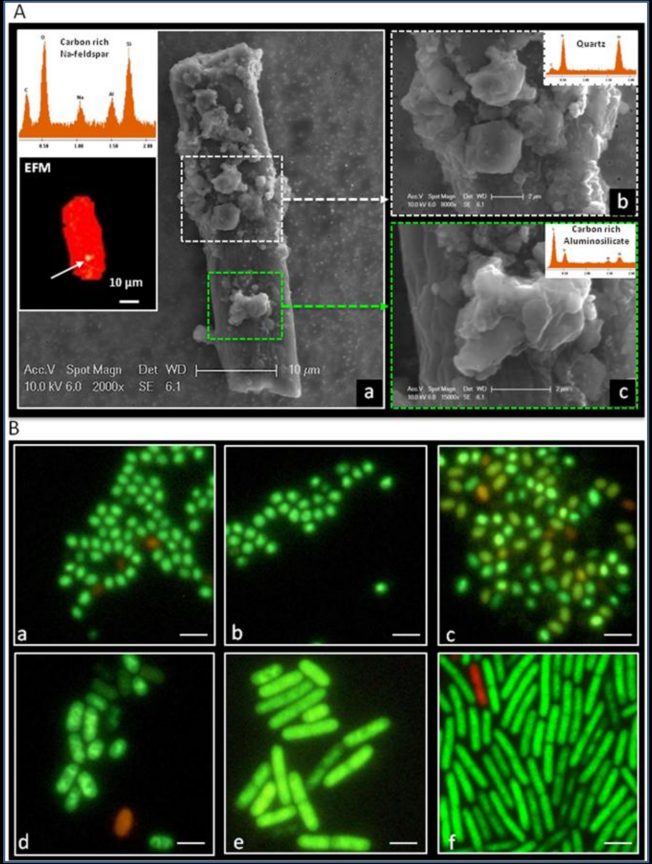
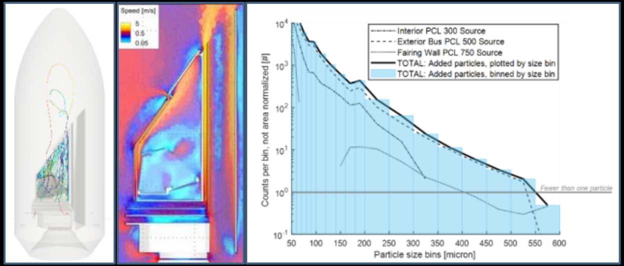


*Figure 6 from:* Malli Mohan, G. B., Cooper, M., Venkateswaran, K., 2019. “Microscopic Characterization of Biological and Inert Particles Associated with Spacecraft Assembly Cleanroom”, Nature Scientific Reports, 14251. DOI



*Left:* Example analysis of inert particle redistribution in a launch fairing environment for the NEO-S spacecraft, using IEST-STD-1246E Product Cleanliness Level (PCL) initial inert particle size distributions.

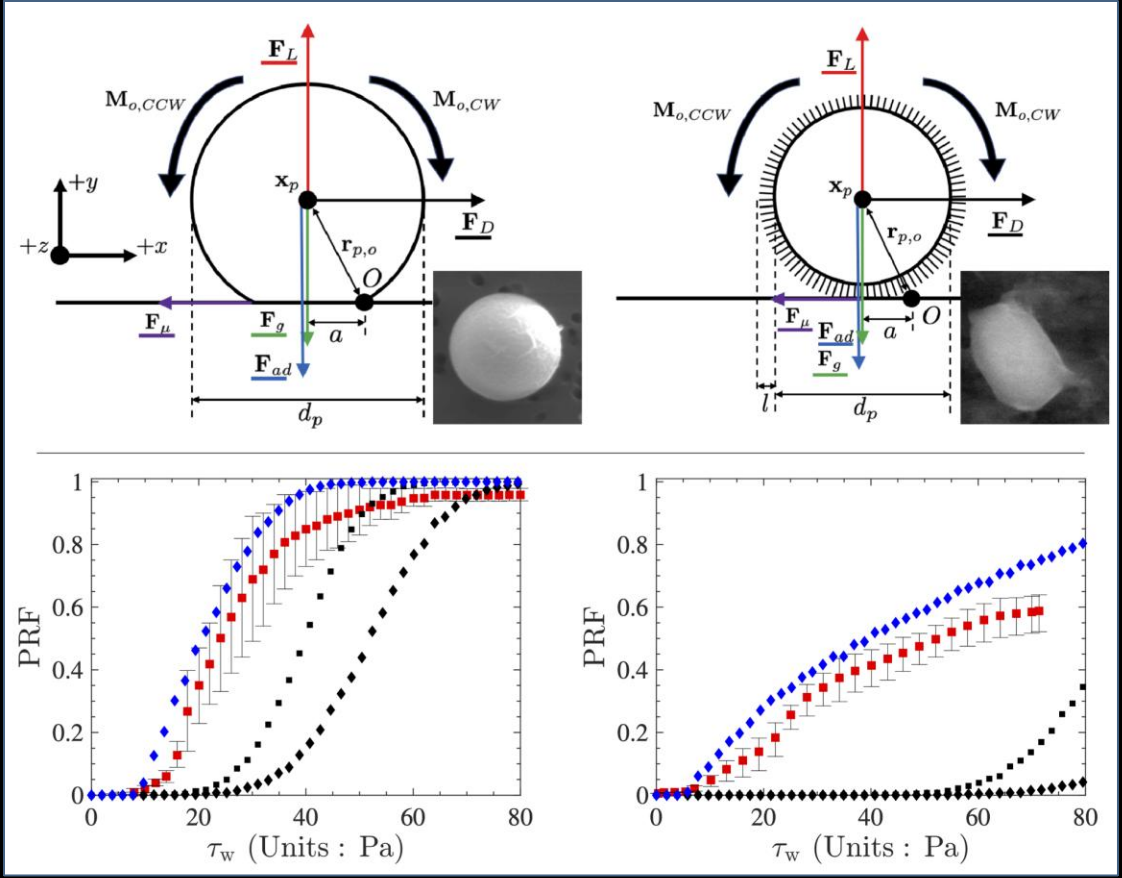
*From:* Hoey, W. et al., 2021. “Toward Predictive Models of Launch Ascent Depressurization and Induced Particle Redistribution,” NASA Contamination, Coatings, Materials, and Planetary Protection Workshop (CCMPP). Link

# Adhesion / Removal Analyses for Microorganisms

Collaborative JPL CC / PP research into **microorganism adhesion and removal under aerodynamic loads** has been performed while studying rocket fairing launch depressurization (Shallcross et al. 2024).

- *Microorganisms have complex adhesion behaviors that vary by strain, with environmental conditions, etc.!*
- *More work is needed including studies under vibration and in cryo-vacuum.*

*Right* – Modeling Adhesion and Aerodynamic Removal of Particles and Spores: illustrations of inert particle and spore force and moment balances and model evaluation examples.



*J. Aerosol Science Feb. 2024 cover image from:* Shallcross, G., Hoey, W., Anderson, J., Soares, C., Cooper, M., 2023. "Modeling Adhesion and Aerodynamic Removal of Particles and Spores from Substrates," J. Aerosol Science, 176, 106294. DOI

SEM images by Dr. Ganesh Babu Malli Mohan (L) and Ron Ruiz (R).