PLANETARY PROTECTION
ORGANIC INVENTORY WORKSHOP
FEBRUARY 27-28, 2024 - NASA HEADQUARTERS

Engineering Models:
Thruster Plume-Surface Interactions, Landing Site Alteration, Organic Footprint and Acceleration / Dispersion of Dust and Regolith

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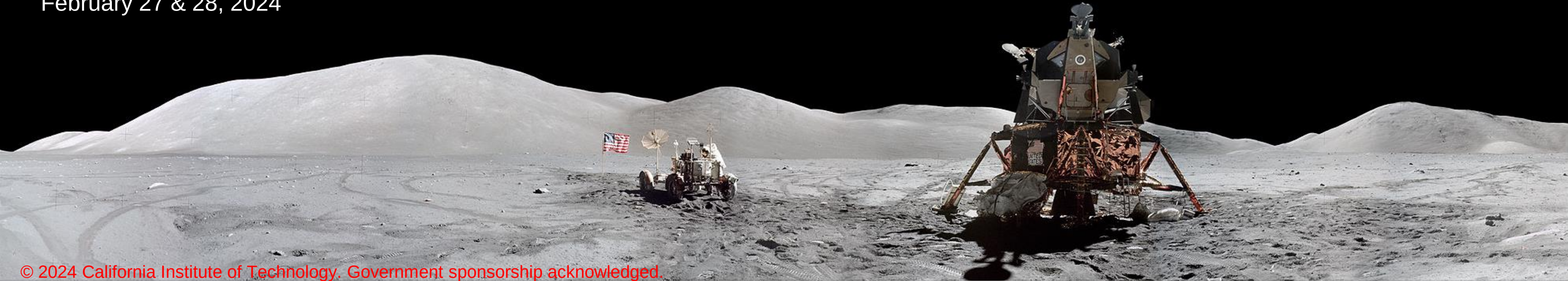

Waning gibbous Moon. Image Credit: LRO/NASA's Scientific Visualization Studio

[1] Background & Motivation

- Plume-Induced Contamination Effects
- Engineering Models for Engine Plume Effects

[2] Empirical Models for Plume Effects

- Empirical Models for Bipropellant Plumes
- Characterization of Propellant Effects

[3] Plume Effects in Icy Moon Environments

- Measuring Plume-Induced Contamination
- Plume Flowfield Modeling: Vehicle & Surface Interactions

[4] Toward Engineering Models for Lunar Landings

- Lunar Landings and Plume-Surface Interactions
- JPL Engineering Model Framework
- Simulation examples:
    - *Apollo Lunar Module Descent Engine (LMDE)*
    - *Apollo-Type Landings*

[5] Conclusions: Existing Models and Applications

[6] Discussing New Models: An 'Organic Footprint'

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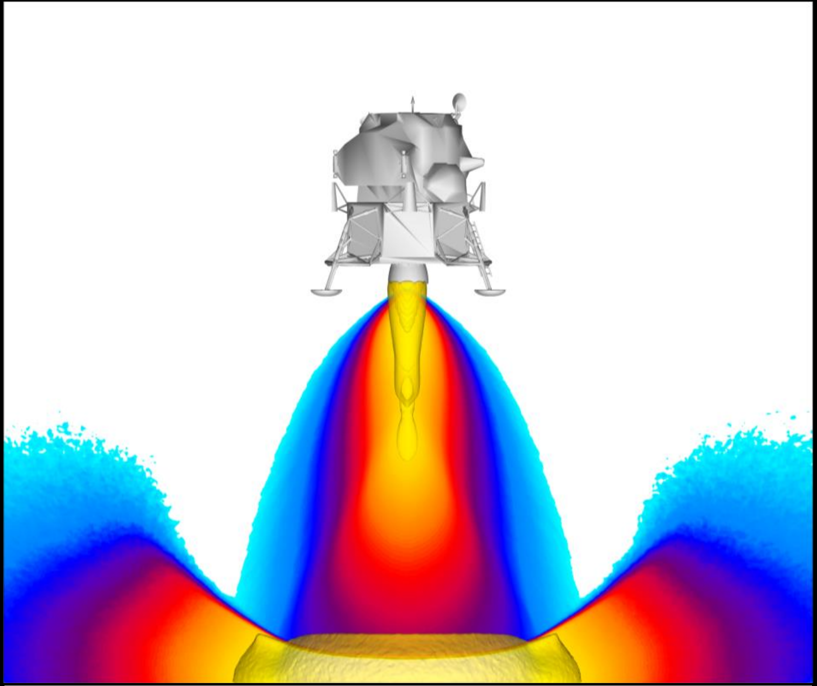
[1] Background & Motivation

JPL and other NASA teams develop and apply engineering models to characterize plume effects on vehicles and environments.

- *JPL applications include spacecraft and stations in vacuum, and in icy moon and lunar landings.*
- *Chemical propulsion systems studied include mono- and bipropellants, LOX / LH2, etc.*

<u>Physics-based models can be extended to study effects beyond the immediate landing environment and vehicle</u>, i.e. the transport of organic contaminants to scientific sites far from a lander (e.g. PSRs).

This presentation will review existing JPL models and applications and discuss utility to studies of an *'organic footprint'* of landers.



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.

Hoey, W., et al. (2022), "Spacecraft Engine Plumes in Near-Vacuum: Earth's Moon and Beyond," *RGD32*.

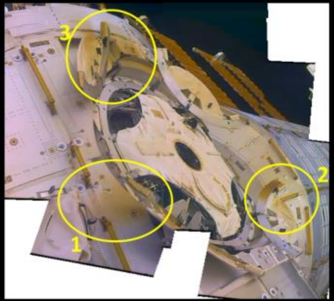
Plume-Induced Contamination Effects

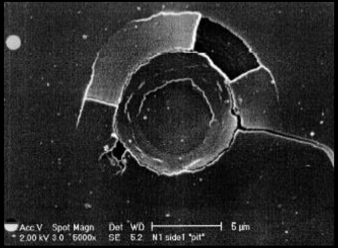
Harmful effects of molecular and particulate contamination include:

- Performance degradation –
  - *Thin film deposition may change the effective optical properties of a system; material deposited on a lens may obscure a viewed target.*
- Spurious instrument measurements –
  - *Contamination adds ‘noise’ or signal that does not originate from intended targets.*
- Material damage (e.g. chemical and mechanical erosion) –
  - *Propellant may be chemically incompatible with impinged-upon materials; dusts mobilized at high speed may erode exposed landing vehicle surfaces.*
- Landing and sampling site alteration –
  - *Plume constituents can condense onto and contaminate cold sampling sites (see e.g. Prem et al. 2020 for Earth’s moon, Hoey et al. 2020 for Europa).*
  - *Plumes heat and erode landing sites – of particular concern for stationary landers.*

Engineering models are needed to characterize these plume effects, and to inform spacecraft designs that mitigate harm.

NASA Images:
ISS Contamination Processes





Slide References:
Hoey, W., et al. (2022), “A Predictive Model of Lunar Gateway Molecular Contamination,” *ISMSE*.
Hoey, W., et al. (2022), “Spacecraft Engine Plumes in Near-Vacuum: Earth’s Moon and Beyond,” *RGD.*
Soares, C. et al. (2015), “Improvements in Modeling Thruster Plume Erosion Damage to Spacecraft Surfaces,” *ISMSE*.
Soares, C. and Mikatarian, R. (2002), “Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments,” *SPIE*.

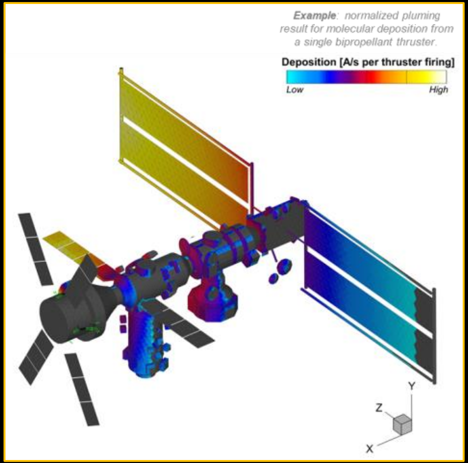
Engineering Models for Engine Plume Effects

Mission	ISS, Future Space Stations	Future Icy Moon Landers	Future Lunar Landers
Mission Type	Satellite / space station	Landed sampling platform	Landed sampling platforms, crewed vehicles, rovers
Transport Vector	Thruster plume firings from self and docking vehicles	Landing engine plume flows	Landing engine plume flows
***Ex.* Vehicle Sensitivities** *Just a few examples – there are many more engineering needs!*	Permanent depositions of molecular contaminants Droplet impingement causing chemical / mechanical damage.	Alteration of icy samples with plume byproducts Sampling system contamination	Landing site alteration Sampling site contamination Instrument / radiator / solar array interference from deposited particulate Vehicle mechanical damage by high-speed plume ejecta
***Ex.* Engineering Models**	Empirical models for line-of-sight plume transport, deposition, and erosion.	Hybrid CFD-DSMC gas dynamic solvers.	Hybrid CFD-DSMC; empirical regolith viscous erosion models; particle adhesion and transport models...

Increasing model complexity!

[2] Empirical Models for Plume Effects

Mission	**ISS, Future Space Stations**
Mission Type	Satellite / space station
Transport Vector	**Thruster plume firings from self and docking vehicles**
***Ex.* Vehicle Sensitivities** *Just a few examples – there are many more engineering needs!*	Permanent depositions of molecular contaminants Droplet impingement causing chemical / mechanical damage.
***Ex.* Engineering Models**	Empirical models for line-of-sight plume transport, deposition, and erosion.



(Left) The ***International Space Station (ISS)****. Image credit: NASA (2011)*
(Right) Example of empirical model result for ***lunar Gateway*** *bipropellant pluming.*

ISS experiences frequent pluming, as will future stations like **lunar Gateway**, as multiple docking vehicles operate a range of chemical thrusters.

- *Empirical models for permanent molecular deposition, droplet flux, and erosion have been developed (Soares et al. 2002, 2015), which JPL CC applies as above for Lunar Gateway (Hoey et al. 2022) and Europa Clipper (Anderson et al. 2024, pending).*

Empirical Models for Bipropellant Plumes

Empirical ISS **bipropellant plume contamination models** of Soares et al. (2002, 2015) report:

- Permanent molecular contaminant deposition.
- Droplet surface fluxes.
- Surface erosion.

Thruster Operations on ISS (ESA ATV)
Image from Soares, C. et al. (2015).

Used to inform engineering design, e.g.:

- Feathering angles for rotatable ISS sensitive surfaces.
- Quantifying liquid droplet distribution, velocities in plumes.

Improvements were implemented to the initial erosion and particle flux models, informed by **flight hardware experiments** (SPIFEX and PIC) and **computational analysis.**

- PIC (*Plume Impingement Contamination*) flight experiment.
- SPIFEX (*Shuttle Plume impingement Flight Experiment*) – see also Stewart & Lumpkin (2017).
- Additional work was done to generate particle induced impact damage data with the SPHINX Smooth Particle Hydrodynamics code from Los Alamos National Laboratory (LANL).

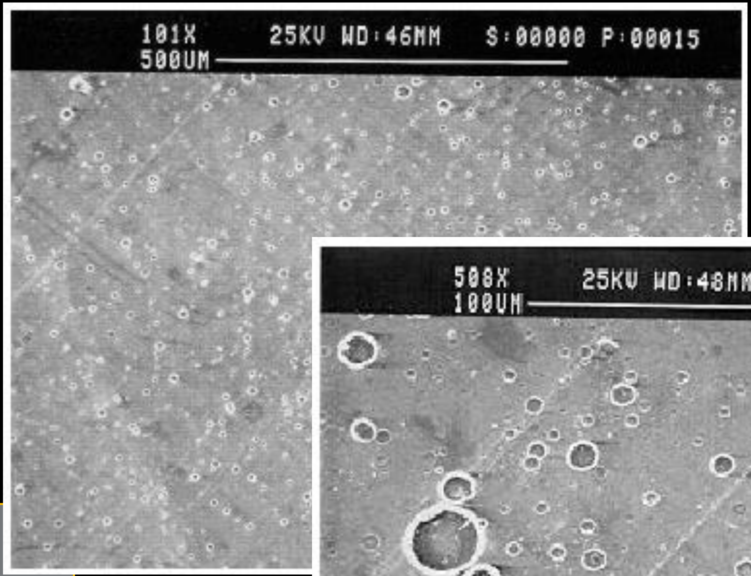
Soares, C. et al. (2015), "Improvements in Modeling Thruster Plume Erosion Damage to Spacecraft Surfaces," *ISMSE*.
Soares, C. and Mikatarian, R. (2002), "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments," *SPIE*.

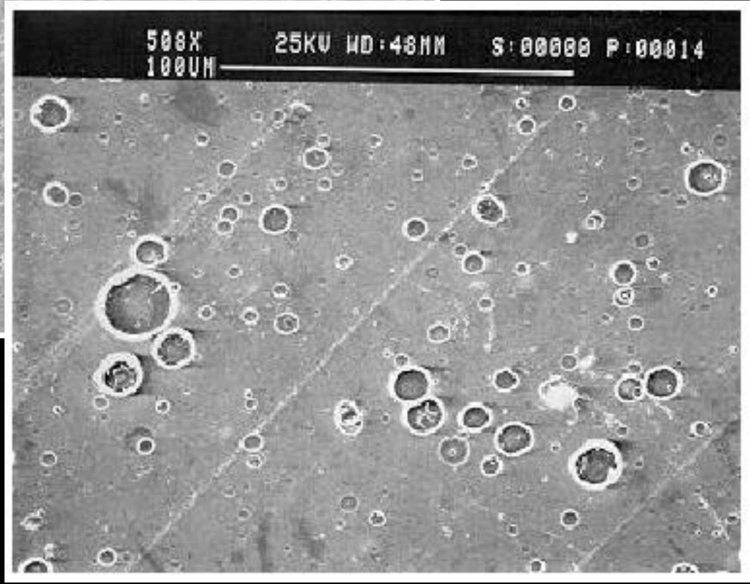
Characterization of Propellant Effects

Craters on Kapton tape are the result of impingement of **chemically-reactive liquid drops**.

- *Crater sizes: 1 – 40 mm in diameter (not visible to the unaided eye)*
- *From analysis of SEM photos 2,200 impacts/mm^2 observed on samples.*
- *Pitted area represents ~ 10% of the surface area of coupon.*

<u>Models informed by</u>: ISS on-orbit observations and vacuum chamber testing including recent material compatibility tests at White Sands, pending bipropellant plume tests at DLR.

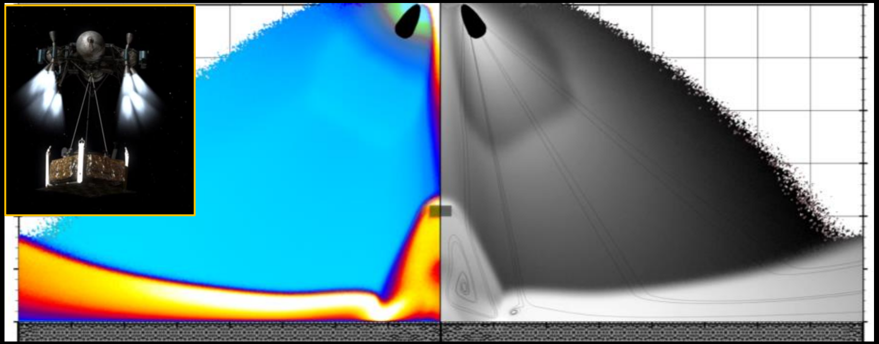




See Soares, C. and Mikatarian, R. (2002), "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments," *Proc. SPIE*.

[3] Plume Effects in Icy Moon Environments

Mission	Future Icy Moon Landers
Mission Type	Landed sampling platform
Transport Vector	**Landing engine plume flows**
***Ex.* Vehicle Sensitivities** *Just a few examples – there are many more engineering needs!*	Alteration of icy samples with plume byproducts Sampling system contamination
***Ex.* Engineering Models**	Hybrid CFD-DSMC gas dynamic solvers.



Europa Lander Sky Crane Descent Plume Simulation *(Hoey et al. 2020, IEEE)*

In study of **icy moon mission concepts** including the proposed Europa Lander, JPL CC developed modeling capabilities for plume flows in airless environments.

Joint JPL-DLR monopropellant plume-induced contamination testing:

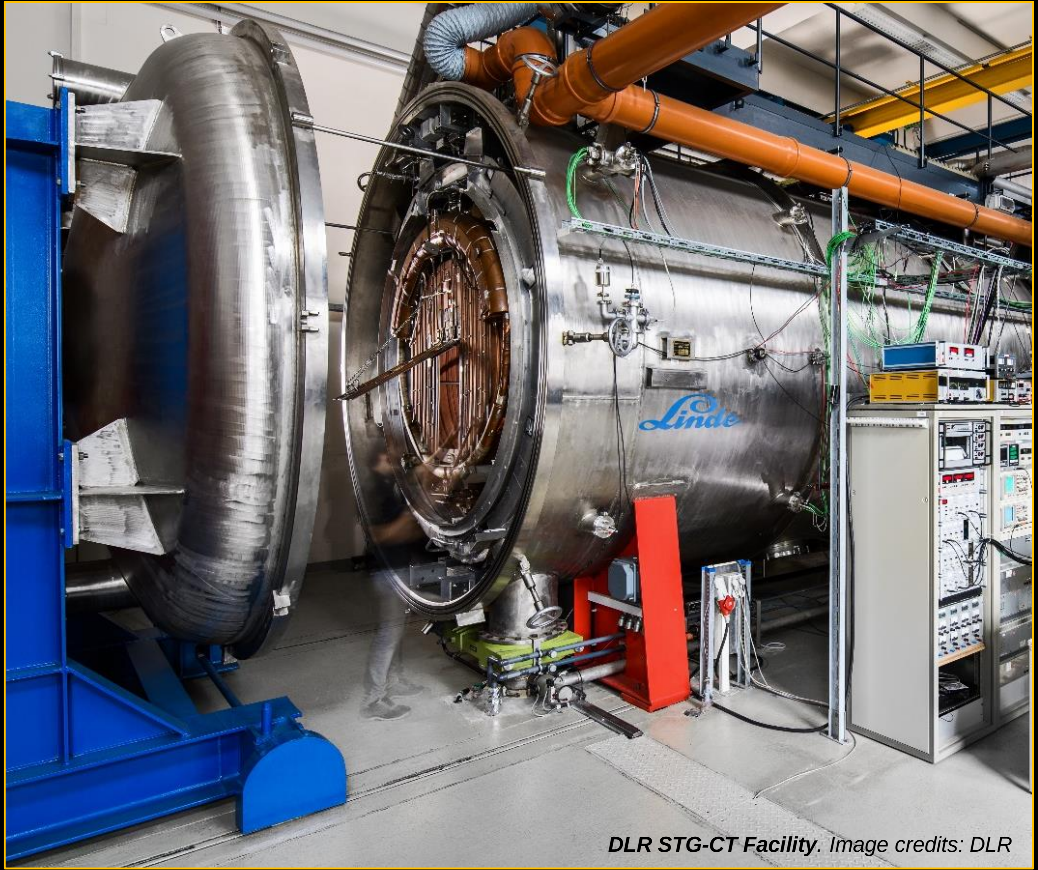
- *The Europa Lander Plume-Induced Contamination (EPIC) test program provided novel data about effects of the landing plume environment on materials and simulants (Grabe et al. 2022, ISMSE).*

Full-scale engine plume simulations with CFD/DSMC:

- *JPL investigations included Lam et al. 2019 (individual plumes), Hoey et al. 2020 (multiple plumes in Sky Crane configurations).*

Hoey, W., et al. (2022), "Spacecraft Engine Plumes in Near-Vacuum: Earth's Moon and Beyond," *RGD32*.
Hoey, W., et al. (2020), "Europa Lander Engine Plume Interactions with the Surface and Vehicle," *IEEE*.

Measuring Plume-Induced Contamination: Ongoing and Future Work



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

Plume free expansion computed with a CFD-DSMC methodology.
Image source: JPL JVSRP fellow Antonietta Conte.

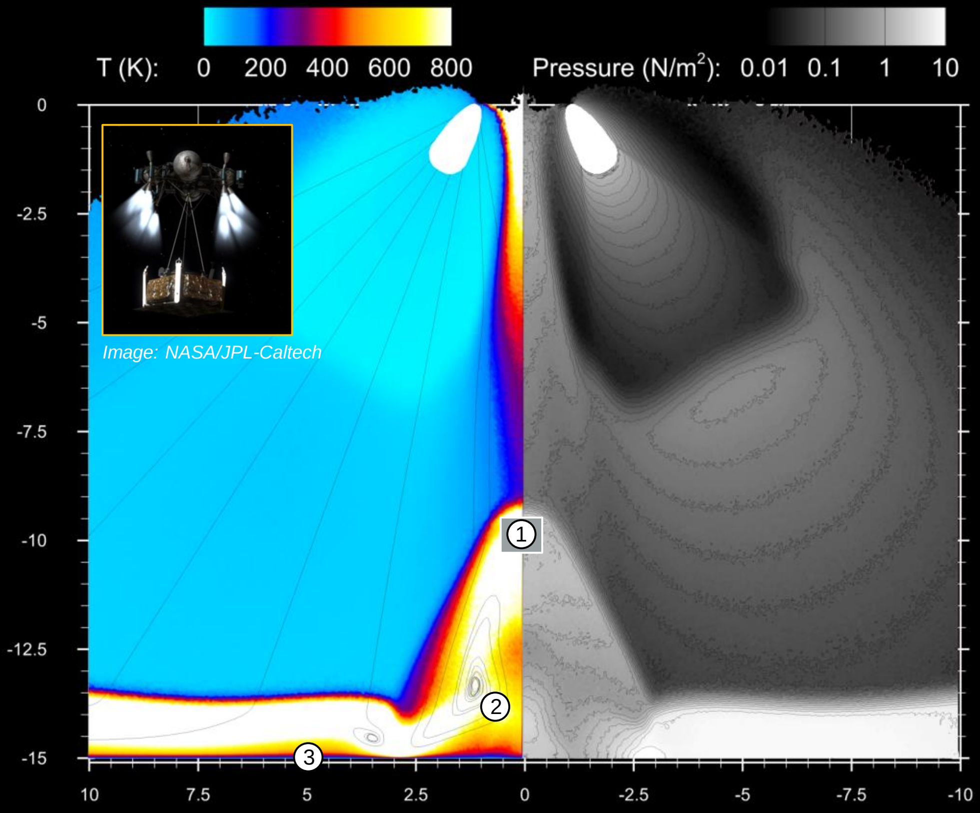
DLR STG chamber copper-lined test section; thruster pack at center.
Image source: DLR

 jpl.nasa.gov

Plume Flowfield Modeling: Vehicle & Surface Interactions

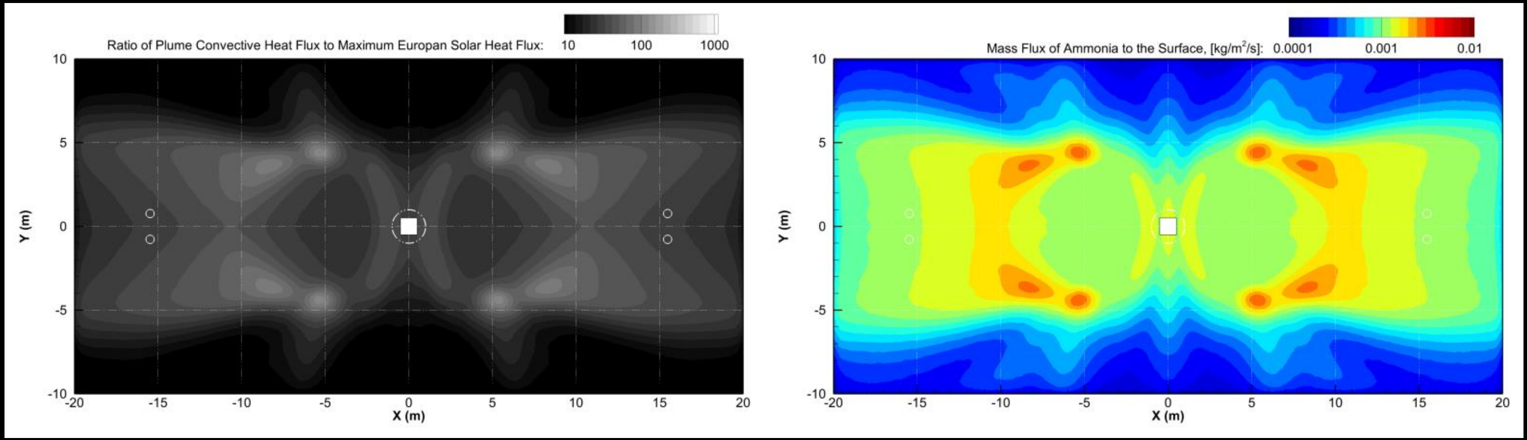
In this study of a proposed Europan landing with **monopropellant** thrusters, preliminary results showed that:

1. Engine plumes will interact, and can form **shocks over a lander and landing site**.
2. Streamlines show the formation of multiple **recirculation zones**.
3. Surface ammonia fluxes are above detection thresholds, and surface heat fluxes are higher than peak solar flux.
4. Engine plumes can support a rarefied **‘atmosphere’ of exhaust byproducts** over a lander and landing site during descent.



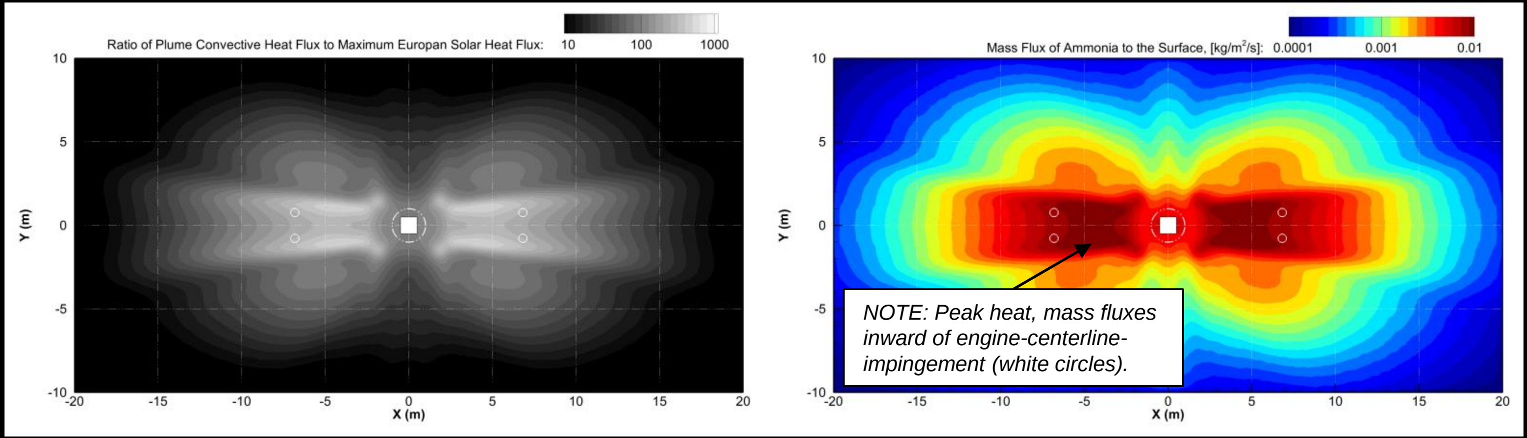
Lam, R., et al. (2019), “Numerical Study of Lander Engine Plume Impingement on the Surface of Europa,” *JANNAF*.
Hoey, W., et al. (2020), “Europa Lander Engine Plume Interactions with the Surface and Vehicle,” *IEEE*.
Hoey, W., et al. (2020), “Europa Lander Mission Concept Plume-Induced Contamination: Experimental Testing and Computational Analysis,” *SPIE*.

[25 m] ***Europa Lander Example****: Surface heating, NH3 fluxes during bridle deployment.*



Hoey, W., et al. (2020), "Europa Lander Engine Plume Interactions with the Surface and Vehicle," *IEEE*.

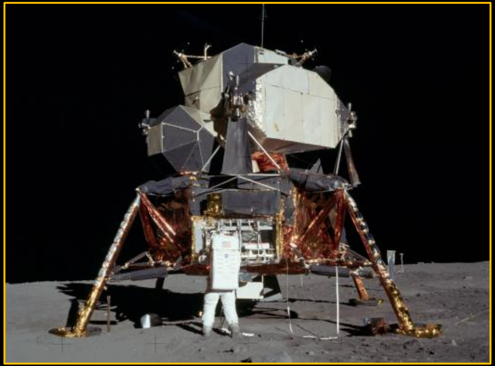
[10 m] ***Europa Lander Example****: Surface heating, NH3 fluxes at lander touchdown.*



Pre-Decisional Information: For Planning and Discussion Purposes Only

[4] Toward Engineering Models for Lunar Landings

Mission	**Future Lunar Landers**
Mission Type	Landed sampling platforms, crewed vehicles, rovers
Transport Vector	**Landing engine plume flows**
***Ex.* Vehicle Sensitivities** *Just a few examples – there are many more engineering needs!*	Landing site alteration Sampling site contamination Instrument / radiator / solar array interference from deposited particulate Vehicle mechanical damage by high-speed plume ejecta
***Ex.* Engineering Models**	Hybrid CFD-DSMC; empirical regolith viscous erosion models; particle adhesion and transport models...



*Buzz Aldrin, the **Apollo 11** lunar module. Image credit: NASA/Neil Armstrong.*

Future lunar landers and payloads will experience plume-induced effects during landing including lunar regolith erosion and transport, as did the **NASA Apollo landers**.

- JPL CC has developed engineering models incorporating CFD/DSMC, empirical treatments for viscous erosion, and particle transport in collaborations with commercial lunar landing service providers through the NASA HLS and CLPS programs.

Hoey, W., et al. (2022), “Spacecraft Engine Plumes in Near-Vacuum: Earth’s Moon and Beyond,” *RGD32*.

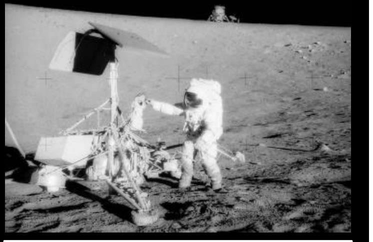
Hoey, W., et al. (2023), “Analyses of Blue Origin Blue Moon Lunar Landing Descent Engine Plume Effects,” *ICES*.

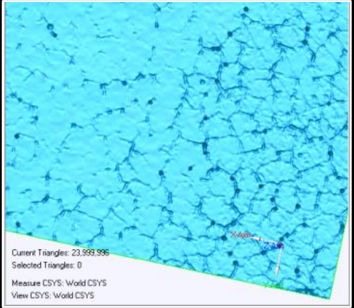
Lunar Landings and Plume-Surface Interactions

- Apollo observations confirmed that **lunar regolith can cause severe operational impacts** to landing systems and cargo, especially when mobilized within high-speed engine plume flows (> 1 km/s).
  - *E.g. Apollo 12 landing induced a ‘sand-blasting’ of exposed surfaces on the Surveyor 3 probe (at left).*

- Per NASA astronaut Gene Cernan in the Apollo 17 Technical Debriefing:

  “I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.”





Plume-motivated dust impingement: Pitting and cracking of a Lunar Surveyor III coupon visible on laser scan. **Figures from Immer et al. 2011a,b.**

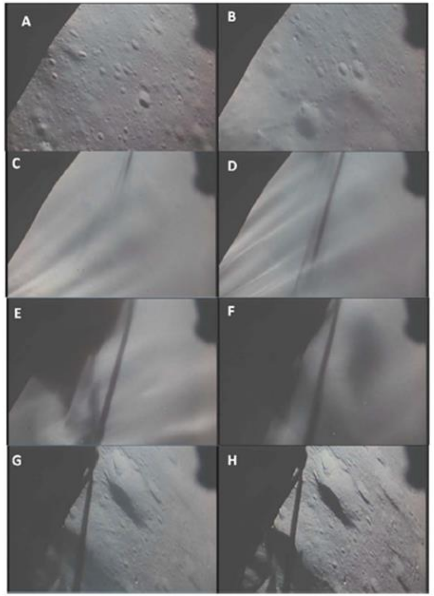


Figure 2. Data Acquisition Camera views for Apollo 15, showing the stages of plume/soil interaction: (a) before incipient erosion, (b) smooth flow stage, (c and d) streaking stage, showing increasing structure in the streaks, (e and f) terrain modification stage, showing opaque masses of blowing soil, (g) clearing stage, and (h) after clearing has completed, showing increased contrast and resolution of shadow edges.

Chart from Metzger *et al.* 2011.

JPL Engineering Model Framework

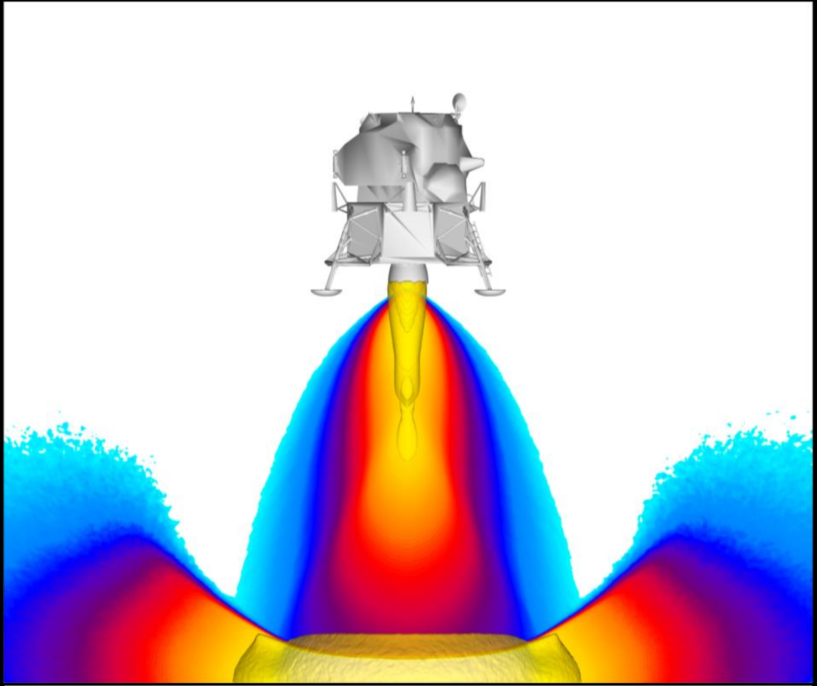
In support of NASA HLS and CLPS programs, JPL has developed and applied **physics-based engineering models for engine plume flow analysis**, linking:

- *A hybrid CFD / DSMC approach for modeling high-speed gas plume flows into vacuum, and*
- *surface erosion and particle tracing 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

Hoey, W., et al. (2022), "Spacecraft Engine Plumes in Near-Vacuum: Earth's Moon and Beyond," *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.

Ex: JPL Engineering Model Framework

Inputs

Nozzle flow condition (throat or exit plane)

Inputs provided by vehicle team

Mechanical CAD Model

Landing Trajectory

Inputs provided by vehicle team

Empirical Viscous Erosion Model

Regolith Properties

Inputs derived from literature review

Analysis Workflow

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

one-way coupling

Perform **3-D DSMC simulations of engine plumes** expanding into vacuum & interacting with the landing surface and descent element

one-way coupling

Use JPL SPLAT to **generate and transport regolith particles through the gas flow field,** and **calculate particle deposition** onto each sensitive vehicle surface

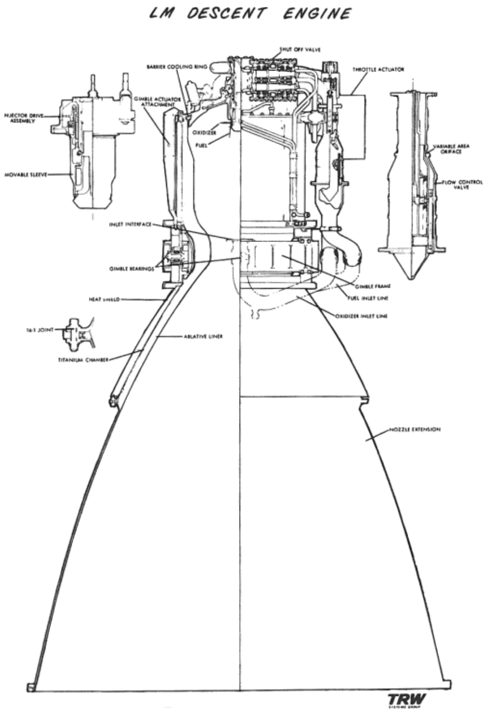
Convert regolith areal coverage to optical property degradation

Deliverable Results

Plume exhaust flow field surrounding the descent element and interacting with the landing surface

Lunar regolith erosion and transport during landing, including **impingement and deposition** onto sensitive descent element surfaces

Optical property degradation of thermal / sensor surfaces



Simulation example:
Apollo Lunar Module Descent Engine (LMDE)

Figure from
Morris et al. (2012)
NASA DPLR CFD

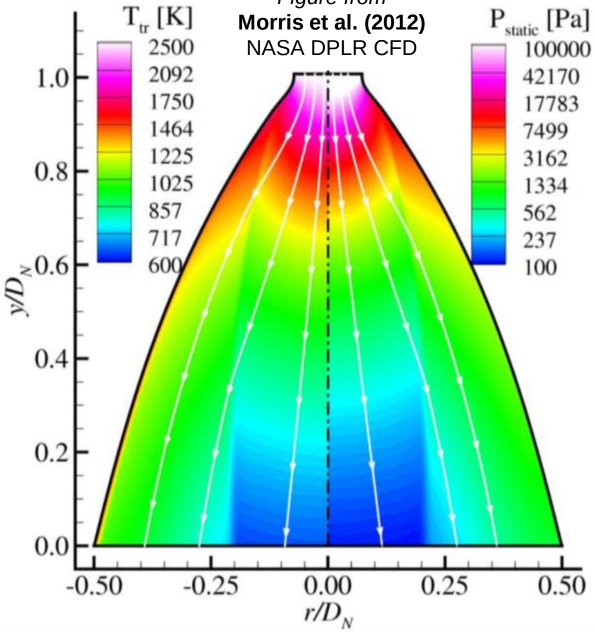
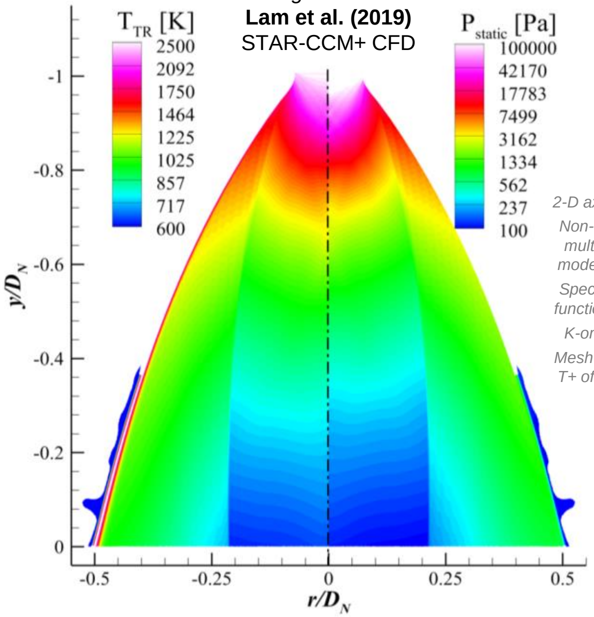


Figure from
Lam et al. (2019)
STAR-CCM+ CFD



2-D axisymmetric model

Non-reacting Eulerian. multi-component gas model, real gas model.

Specific heat (C_p) as a function of temperature.

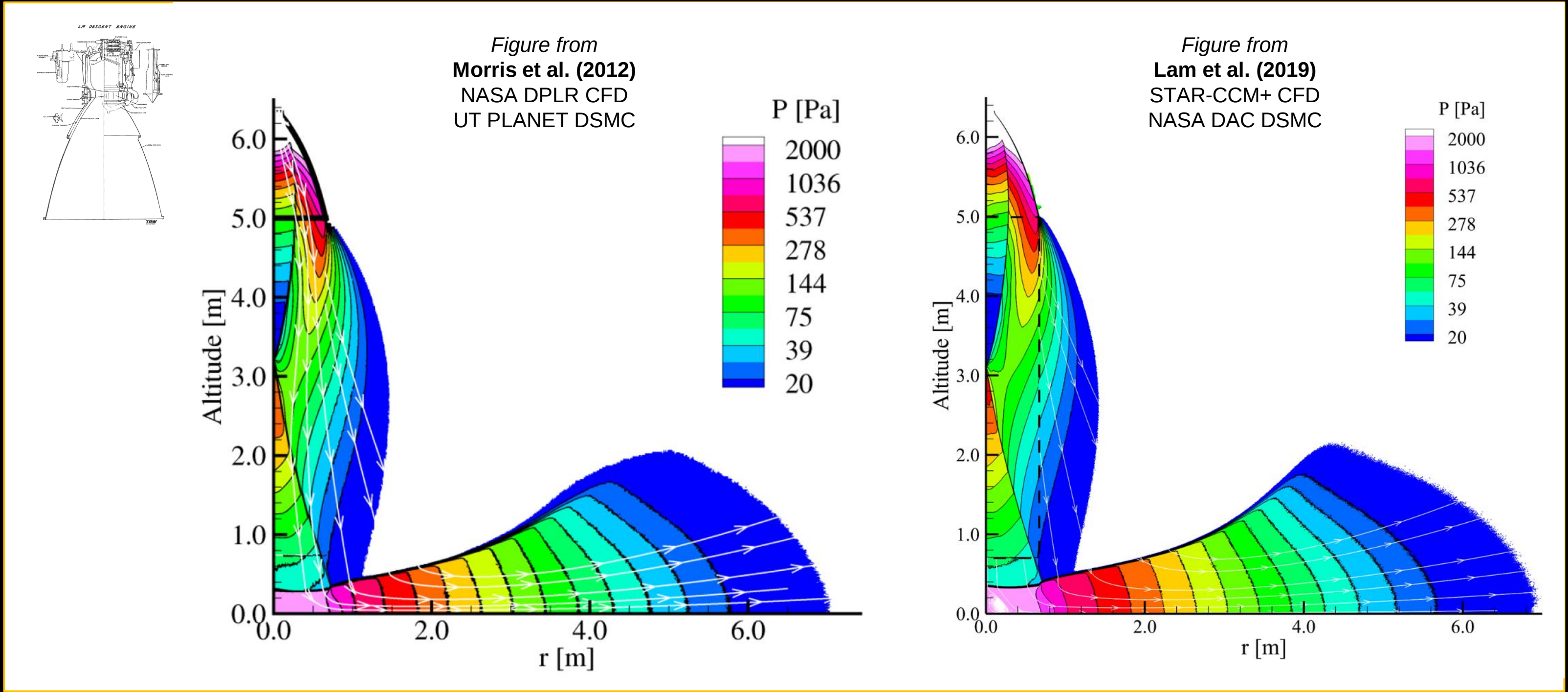
K-omega turbulence.

Mesh refined to achieve T+ of 1 at nozzle walls.

Apollo Lunar Module Decent Engine (LMDE) nozzle-internal flow CFD, from sonic throat.

- Alternately, exit-plane conditions may be used as input, eliminating the need for nozzle contours.
- *See a JPL approach in Lam et al. (2019), compared to A. Morris et al. (2012, 2015a,b).*

Simulation example:
Apollo Lunar Module Descent Engine (LMDE)



Example 2-D result – one-way coupled CFD-DSMC approaches for Apollo LMDE at 5m.

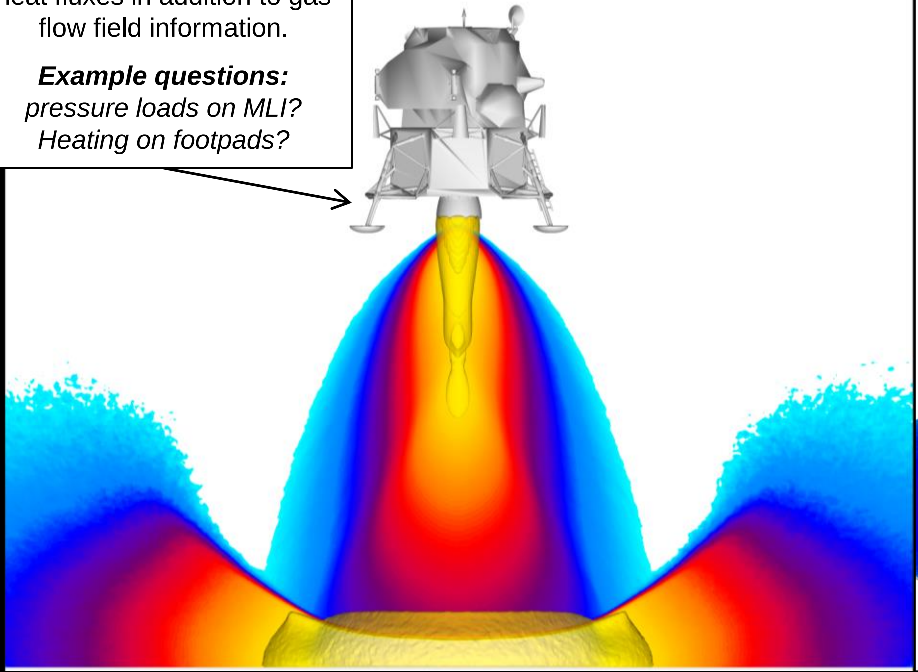
- *See a JPL approach in Lam et al. (2019), compared to A. Morris et al. (2012, 2015a,b).*

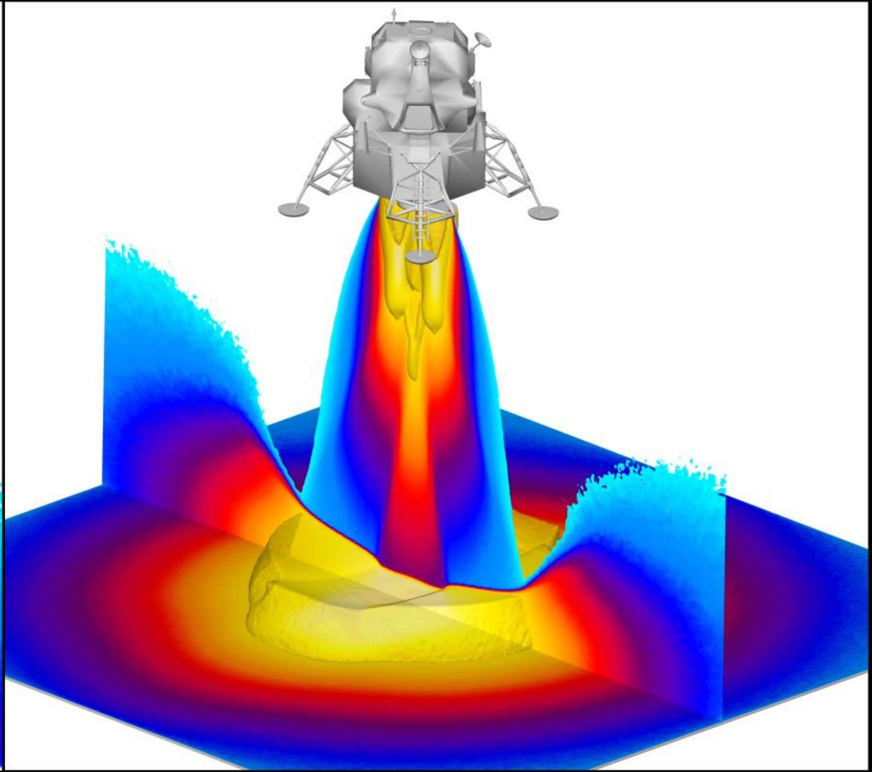
Lam, R., et al. (2019), “Numerical Study of Lander Engine Plume Impingement on the Surface of Europa,” *JANNAF*.

Simulation example: ***Apollo Landing***

Engineering gas plume models must contain 3-D vehicle and surface geometries and must deliver e.g. surface pressures, species number fluxes, and heat fluxes in addition to gas flow field information.

Example questions:
pressure loads on MLI?
Heating on footpads?





Example 3-D results including Apollo DE geometric models. *Theoretical multi-engine configuration.*

Hoey, W., et al. (2022), "Spacecraft Engine Plumes in Near-Vacuum: Earth's Moon and Beyond," *RGD32*.

[5] Conclusions: Existing Models and Applications

- **Spacecraft alter their environments**, and may compromise their engineering or science objectives through the nominal action of their propulsion systems.
  - *This is never more true than during landings!*
- Engineering models for engine plumes – in free-expansion and in plume-plume, plume-vehicle, plume-surface interactions – are **needed** for future missions.
  - *Spacecraft designs can be directly informed by such models in order to mitigate threats of contamination, heating, chemical or mechanical erosion, etc.*
  - *High-level models can be informed by available on-orbit data, terrestrial vacuum chamber testing campaigns and detailed physics-based simulations.*
- **Established tools exist** for some gas-dynamic problems in engineering:
  - *Empirical tools exist with well-defined uses and limits (i.e. ISS bipropellant models).*
  - *<u>These tools can be extended to study effects beyond the immediate landing environment and vehicle</u>, i.e. the transport of organic plume effluents, regolith and other contaminants to scientific sampling sites far away from a lander!*

[6] Discussing New Models: An 'Organic Footprint'

A High-Level Model for the Organic Footprint of Lunar Landing Vehicles:

"How far does the footprint of a lunar landing vehicle extend?"

- As discussed throughout this section of the workshop, landed spacecraft generate complex contamination environments and release organic material through processes including:
    1. *the operation of descent propulsion systems;*
    2. *venting processes, which are of particular importance for crewed missions; and*
    3. *materials outgassing.*
- In the low-gravity, near-vacuum lunar environment, **released contaminant material can travel great distances, and can permanently deposit in sufficiently cold sites including permanently shadowed regions (PSRs) of scientific interest**.
- This contamination environment generated by lunar landing vehicles can be characterized by further developing suites of physics-based modeling tools, including those in use at JPL.
    - *We already study the immediate vicinity of the vehicle, but we can extend this study over the horizon to understand vehicle effects on distant sites of scientific interest (e.g. PSRs).*

[6] Discussing New Models: An ‘Organic Footprint’

What would it take to develop a high-level model for order-of-magnitude estimation of landed vehicle organic material generation, transport, loss, and deposition across the Moon that makes few specific assumptions about vehicle architecture and the local lunar environment?

1. **Source terms:** Study and develop a high-level inventory of **specific species** of organic contaminant likely to be released by landing vehicles, including:
   - a survey of common materials used on such vehicles and their available outgassing characterizations, &
   - a survey of common propulsion systems used on such vehicles and their primary plume byproducts;
2. **Loss terms:** Study and develop high-level models for loss processes relevant to relevant species of organic contaminant, including:
   - photodissociation and ionization;
   - gravitational escape (loss to space); and
   - adsorption / desorption onto the lunar surface and permanent deposition into cold traps.
3. **Transport:** Develop a **probabilistic free molecular transport model** for organic molecules from release and their first contact with the lunar surface until their loss, and compare and report on each generation and loss process (i.e. which are driving, and for which class of vehicle?)
   - The key question this model would answer: *Over what distances could certain specific organic molecules travel, and what proportion of these might be expected to reach permanently shadowed regions (PSRs) at defined distances away from a landing site?*

Acknowledgements

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See also the JPL presentations from which this OPP talk has been derived:

- Lam, R., et al. (2019), “Numerical Study of Lander Engine Plume Impingement on the Surface of Europa,” *JANNAF*.
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