PLUME-SURFACE INTERACTIONS AND CONTAMINATION EFFECTS FOR MISSIONS TO EARTH'S MOON, MARS, AND THE ICY MOONS

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Introduction: The nominal operation of spacecraft chemical propulsive systems, i.e. engines and thrusters, generate gaseous plumes that interact with their local environment, and may induce effects that interfere with or harm collection and interpretation of science data. Space exploration missions and concepts with chemical propulsive systems are susceptible to *plume-induced contamination*, for instance as plume effluents deposit onto instrument surfaces or are collected within sampling instruments and hardware [1]. Missions and concepts with *landed elements* are growing common – targets for landings include Mars, the icy moons (e.g. Europa, Enceladus), and Titan. Landed missions to Earth's Moon are also planned via NASA's Commercial Lunar Payload Services (CLPS) and Human Landing Systems (HLS) programs. Proposed science objectives for such missions include characterizations of habitability; *in situ* searches for signs of life and for resources; and the return of samples to Earth. A major challenge for landed missions is the landing event itself, which presents distinct operational, engineering and scientific hazards to spacecraft and payloads [2−6].

Plume-Surface Interactions: Propulsive landers experience *plume-surface interactions* (PSI) during the *entry, descent and landing* (EDL) procedure. When landings occur onto granular material – as for the Moon and Mars – PSI phenomena lead to large scale fluidization and transport of granular matter that can [3−6]:

- obscure visibility during landing,
- damage mission-critical hardware,
- alter and deform the landing site itself, and
- impact sensor and scientific instrument operation during and after the landing event.

These effects have been observed repeatedly by lunar and Martian missions. Novel landings onto icy moons pose a related but distinct set of PSI problems including the possible melting or evaporation of surface material and the local condensation of plume contaminant [2]. In any case, PSI will be highly dependent on landing profiles, engines, and environmental conditions.

Advance characterization of PSI and the development of mitigation strategies is critical to achieving landed mission science objectives. Therefore, JPL has pursued a multi-disciplinary effort to experimentally characterize and computationally simulate the contamination effects of chemical propulsion systems, including during powered landings [1,2].

Physics of PSI: While a lander descends its engine plumes interact with the surface, leading to compressible gas phenomena and recirculation. For landings onto granular material, there are five mechanisms responsible for crater formation and dust transport, which differ in rarefied and continuum gas dynamic regimes [3−5]:

1) *Diffusion-driven flow*: Aerodynamic forces through granular material that leads to shear and subsequent material motion.
2) *Diffused gas eruption*: Fluidization and excitation of granular material via penetration of gas into soil.
3) *Bearing capacity failure*: Forces overcome the bearing capacity of the granular material, resulting in a crater that can crumble under gravity.
4) *Viscous erosion*: Shear forces exceed inter-particle cohesion forces; particles subsequently move across the impinging surface and collide with one another.
5) *Diffusive gas explosive erosion*: Generation of localized pressure gradients in granular material due to use of pulsated jets.

Rarefied Environments: Powered landings onto planetary bodies without continuum atmospheres, like the Moon or Europa, result in near-nozzle continuum regimes that transition to rarefied and free-molecular flows as plumes expand into near-vacuum. For such landings onto granular material, viscous erosion is the primary mechanism for granular transport [4,6] as has been repeatedly observed by lunar surface missions.

Continuum Environments: Landings into atmospheric environments, such as Mars or Titan, lead to continuum effects such as diffusion-driven flow, diffused gas eruption, and bearing capacity failure in addition to viscous effects as mechanisms for granular transport. Particle transport in these cases is further complicated by particle-turbulence interactions resulting in entrainment and granular transport. The JPL Sky Crane maneuver was designed to minimize such effects; however significant erosion and particle transport has still been observed during Mars EDL procedures. [Figure 1.]

Modeling: Capturing the effects of PSI requires a combination of continuum, rarefied, and particle transport methods depending on the proposed environment of operation. Across recent lunar, Mars, and Europan missions and concepts, JPL has applied a combination of Computational Fluid Dynamics (CFD) and Direct-Simulation Monte Carlo (DSMC) to generate physics-based plume flowfields, with granular erosion and particle transport modeled using Lagrangian particle tracking methods. Figure 2 illustrates the results of a conceptual analysis for a lander mission concept [2]. These methodologies can capture several critical features of the plume exhaust flow field. For this multi-engine problem, simulations capture the dense core formed along the descent axis, forming a steady shock structures over and along the vehicle. Streamlines reveal recirculation zones under the lander and below the vehicle of interest.

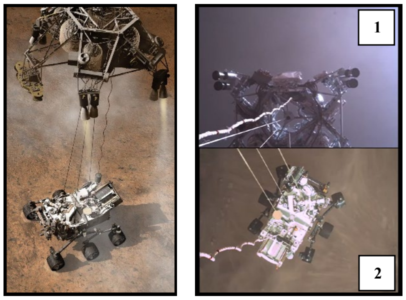
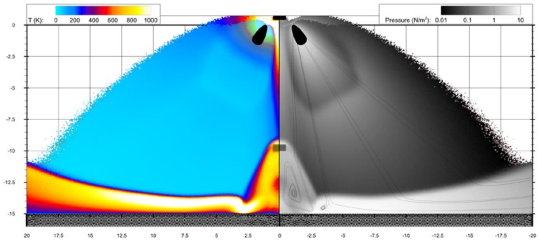
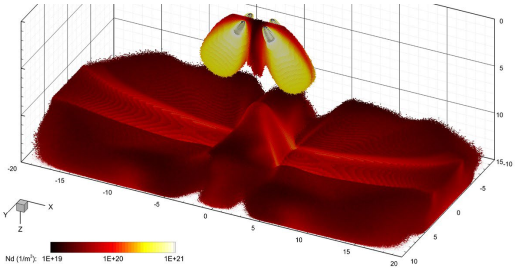


Figure 1: Sky Crane Mars landings. *L:* Artist's concept of the MSL Curiosity rover's landing. *R:* images from the Mars 2020 Perseverance rover's landing including (1) views upward from the rover top deck; (2) downward from the Sky Crane. *Images: NASA/JPL-Caltech.*



Gas flow-field generated at 15 m above the landing surface by four 30°-canted engines at full-throttle



Iso-surfaces of pressure show the shape of shock layers formed over the surface and lander.

Figure 2: Europan landing simulation, monopropellant hydrazine thrusters, from Hoey et al. (2020) [2]

Contamination Considerations: Results from physics-based modeling are used by JPL to characterize effects of plume molecular contaminant and dust deposition onto sensitive surfaces; damage induced by dust impact or abrasion; and the performance degradation of solar arrays and scientific payload instruments. From an environmental standpoint, covers and enclosures should be removed/deployed at appropriate times to account for the kick-up of granular material. Specific landing conditions affect the timeline for cover removal after regolith excitation. In addition to granular transport, one must consider the impacts of gas- and liquid-phase byproducts of chemical propulsion that constitute descent engine plumes. Mission science objectives may be undesirably affected by powered landing events, particularly if landing sites to be sampled are disturbed during crater formation, or are seeded with droplets of unreacted propellant [2]. Likewise, spacecraft instruments or other sensitive surfaces (i.e. radiators or solar panels) may be impacted by particles removed from the landing surface by engine plumes.

Conclusions: Plume-induced contamination poses a threat to all spacecraft which operate chemical propulsion systems, and plume-surface interactions are inevitable with the need to land for future space exploration missions. The characterization of plume phenomena including PSI effects and the proactive development of mitigation strategies are critical to mission science objectives and should be initiated during the Phase A of a Flight Project. Neglecting such effects can lead to unintended damage to mission-critical hardware and to the degradation of mission operations and data collection.

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