UNDERSTANDING ROCKET EXHAUST EFFECTS IN POLAR REGIONS DURING POWERED DESCENT ON THE MOON. R. N. Watkins[1], P. T. Metzger[2], D. Eppler[3], M. Munk[4], A. Dove[2], B. L. Jolliff[5], D. P. Moriarty[6]. [1]Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719, rclegg-watkins@psi.edu, [2]University of Central Florida, Orlando, FL, [3]San Antonio Mountain Consulting, Houston, TX, [4]NASA Langley Research Center, Hampton, VA, [5]Washington University in St. Louis and the McDonnell Center for the Space Sciences, St. Louis, MO, [6]University of Maryland College Park/NASA GSFC.

Introduction: During the powered landing of spacecraft on the Moon, rocket exhaust interacts with the surface, altering the physical state of the landing area and creating potential hazards to the spacecraft and nearby hardware. The effects of exhaust plume-surface interactions (PSI) differ depending on the mass and thrust of the spacecraft, the physical properties of the soil, and engine configuration.

During lunar landings, dust and small rock particles are blown away at high velocities, spreading particles across the entire surface of the Moon, potentially confounding upper surface science, and even inserting dust into lunar orbit and impacting orbital hardware [1]. While much has been learned about the physics of PSI over the last few decades, significant gaps in knowledge exist that can only be filled by taking measurements during and after spacecraft landings.

Understanding rocket exhaust interactions with planetary surfaces is crucial to safely land, protect hardware, and conduct scientific investigations. The need is especially true for Artemis, which will require multiple landings at the same site and will involve landing larger total masses than was done for Apollo. This white paper provides a concise, broad overview of the current state of knowledge of PSI and recommendations for how the Artemis III mission can contribute to addressing outstanding PSI questions.

Plume Effects on the Moon: On the Moon, PSI for small and mid-sized landers do not generally lead to the creation of a crater beneath the spacecraft, owing to the lack of an atmosphere and to the cohesive and impermeable nature of lunar regolith. Instead, the exhaust plume spreads out across the surface and blows material horizontally away from the landing zone at high velocities [2]. PSI on the Moon generally begin when the spacecraft is ~30-40 m above the surface; this altitude may increase for larger landers such as those that will deliver the Artemis III crew.

Analysis of digitized Apollo Lunar Module (LM) descent videos revealed that plume-lofted dust sheets contained 10^8-10^{13} particles/m^3 and were blown radially away from the descent engines at angles of 0-3° relative to the surface [3]. The very fine-grained (dust to sand-sized) materials that compose the regolith in the area surrounding the LM were shown to be blown at velocities up to 3 km/s, so a fraction can exceed escape velocity of the Moon and cross through the proposed orbit of the Gateway [1,2,4]. Preliminary analyses indicate that Gateway could sustain 10,000 impacts/m^2 [1]. Particle ejecta velocities increase logarithmically with lander mass, meaning an Artemis-scale lander (~40 ton) could eject material 50% faster than an Apollo-scale (~5 ton) lander [1].

***Fig. 1**: Apollo 15 descent video image showing the heaviest episode of dust flow, in which visibility is heavily obscured.*

Dust- to sand-sized grains in the upper few cm of regolith in the area beneath the LM were blown several km away, exposing a coarser, more compact and cohesive, underlying soil [4]. The dust sheet partially obscured visibility of the surface features (**Fig. 1**), and in the case of Apollo landers, caused movement of rocks as large as 10 cm or more [2].

PSI Scaling with Lander Mass: At lunar landing sites, there are visible effects of rocket exhaust-induced surface disturbances ("blast zones"), primarily caused by the winnowing of darker fine-grained regolith [5,6], that extend tens to hundreds of meters out from the lander, depending on lander size [5]. Using Lunar Reconnaissance Orbiter (LRO) images, [7] found a consistent correlation between blast zone area and lander dry mass (**Fig. 2**). While this relationship serves as an important tool in predicting the size of the disturbed areas for future landed missions, it is unknown how variables such as spacecraft design, descent engine configuration, regolith size-frequency distribution and maturity, and landing terrain will affect the scale of PSI.

Multi-engine configurations such as those on the HLS landers could redirect plume spray back up at the spacecraft [8], and hovering could extend the duration of time that PSI occurs. The larger CLPS landers' plumes will access regions of the physics that smaller landers cannot access (lower Knudsen number, possible turbulence transitions around the impingement point, higher stagnation pressure on the lunar surface), and it is unknown whether they will induce cratering phenomena.

Polar regions with more volatiles and more porous surfaces could experience different surface alterations than non-polar regions. More information and modeling is needed to accurately predict the extent of surface disturbance that will occur, especially by landers much larger than those of Apollo.

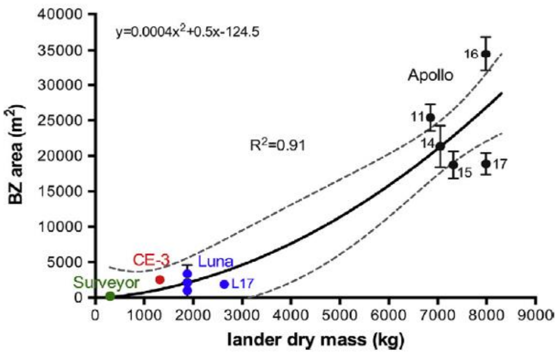

Fig. 2: *The area of the surface visibly disturbed by rocket exhaust increases quadratically with lander mass [7].*

Environmental Impacts: Observations of morphological (erosion in clods, surface smoothing) and grain size changes in the landing zone [2,5,9], and of the disturbance of surface regolith extending up to hundreds of meters away from the spacecraft, necessitate surface mobility by Artemis crews for gathering pristine upper-surface soil samples. Although the Apollo exhaust plumes only excavated regolith to a depth of a few cm [10], it is important to consider surface alterations when planning sampling strategies and surface observations in the vicinity of the lander.

While blast zones are the visible effects of rocket exhaust interacting with the lunar surface, plume effects go much further than what we observe from orbit. Even before a spacecraft reaches the altitudes at which scouring of the surface begins, it releases exhaust gases into the lunar exosphere [11] and injects volatiles into the local environment, some of which could migrate into cold traps and be measured by instruments that are directed at understanding volatile distributions in permanently shadowed regions (PSRs) near the Artemis III landing site [12]. Understanding the distribution and longevity of exhaust gases in the lunar environment is critical to planning surface operations and interpreting measurements that aim to characterize the extant lunar volatile inventory. This issue is especially important because spacecraft exhaust commonly includes species such as H_2O and NH_3 that are among those that exist at the lunar poles [13]. These effects must be quantified so that they can be accounted for in future scientific measurements both from samples and by remote sensing from orbit, and *lander providers should document the isotopic composition of their propellants before launch.*

Artemis III recommendations: Much is still not understood about the effects of rocket exhaust on the lunar surface during the powered descent and ascent of spacecraft, especially in polar regions and for landers as large as the HLS landers. To address outstanding questions regarding PSI, and to plan for protecting hardware surrounding landing sites, the Artemis III mission must have dedicated measurements of plume effects. These could include:

- Dedicated descent imagers, Doppler radar, and/or laser sensors to document the dust sheet and its dynamics, and lofted particle velocities and sizes, during landing.
- Dedicated sensors to understand if the larger, human-class landers induce cratering phenomena that were not seen during Apollo landings but that are seen in terrestrial tests.
- Surface imagery of the area directly beneath and surrounding the lander, to compare with pre-landing images, before the crew steps on the surface and further alters the area.
- Sampling techniques that capture the fine layer of dust in the disturbed zone (e.g., sticky tape) away from the direct erosive effects of the engines, for analyses of particle size distributions within the landing area.
- Dust collectors/sticky pads to collect particles blown from nearby landers during subsequent landings [e.g., 14].
- Mass spectrometers to measure the concentrations of spacecraft exhaust components, to account for potential contamination of exhaust gases in measurements of lunar volatiles.
- Surface mobility by crews, for gathering pristine upper surface soil samples.
- Core sampling to better characterize regolith bulk density with depth, to help constrain PSI models.

The Blue Moon 2023 Demo mission will serve as a prime opportunity to analyze the effects of rocket exhaust on the upper lunar surface in a polar region, with a large-scale lander, and will be able to set up instruments to analyze the exhaust plumes from subsequent landers at the same location. If we are returning to the Moon in a sustainable fashion, future landed missions should have dedicated measurements of plume effects to facilitate protecting spacecraft, crews, and surrounding hardware.

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