QUANTIFYING ENGINE EXHAUST EJECTA FROM LANDING LARGE SPACECRAFT ON THE MOON.

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Introduction: 20+ years of research into the interactions of lunar lander engine exhaust with regolith has produced a compelling overall understanding of the phenomena [1-5], but important gaps exist including the lack of theory to predicts how much regolith will be ejected as a function of lander mass. The ejecta travels globally and intersects the orbit of the proposed Lunar Orbital Gateway [6] as shown in Fig. 1. At relative hypervelocity it will cause vaporization of spacecraft surface materials on impact. It currently impossible to determine environmental specifications for hardware operating around or on the Moon. Here, I report progress to predict soil ejection from larger landers and how ejecta will affect lunar operations.

Figure 1. Cross sectional view of lunar lander ejecta (blue dots) leaving the Moon (small circle) from the landing site (top of the circle). Ejecta cross the Lunar Gateway orbit (dashed ellipse).

Background: Ambient-pressure experiments of jets eroding granular materials showed erosion scales as the square of the densimetric Froude number with an added cohesion term in the denominator [7],

$$\dot{m} \propto \frac{\rho U_0^2}{\rho_m g d + f(c)}$$

where $\dot{m}$ is local erosion rate in kg/s/m2, ρ is density of the gas acting on the soil, U_0 is friction velocity of the gas in the boundary layer, $\tau = \rho U_0^2$ is shear stress acting on the soil in fully rough, turbulent conditions, ρ_m is mineral density in the soil, g is gravity, d is sand grain diameter, assumed to be an average diameter for polydisperse mixtures like lunar soil, and $f(c)$ is an undetermined function of cohesion inferred from reduced gravity tests [8]. However, tests in vacuum chambers with constant τ while lowering ρ show erosion increasing when Knudsen number Kn>0.01 (relative to sand grain radius = $d/2$) [9]. Furthermore, analysis of Apollo landings show $\dot{m} \propto \tau^{2.5}$ in Kn>0.1 conditions [10], contradicting the earlier results. The analysis measured that Apollo landings with 5 t (landing mass) Lunar Modules (LM) ejected 2.6 t of soil. τ scales as vehicle mass, so applying $\dot{m} \propto \tau^{2.5}$ predicts a 40 t Artemis lander will blow 470 t of regolith, while a 100 to 300 t lander (which has been discussed) would blow 4.6 to 72 kt of soil creating very deep holes. However, additional flow features such as bulk soil failure would likely “turn on” in those conditions, and other factors contribute to the large uncertainty of the predictions. Progress is needed.

New Results: New mathematical insight has now reconciled the terrestrial and Apollo data sets making predictions for the full range of Kn as shown in Fig. 2.

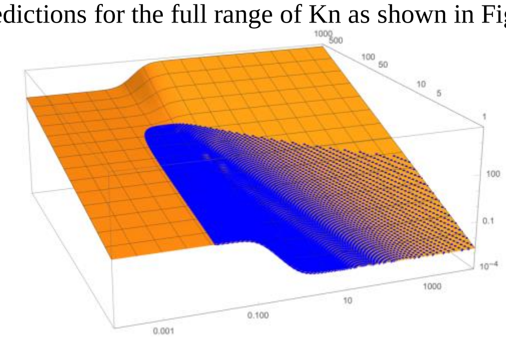

Figure 2. Horizontal: Kn. Vertical: $\dot{m}$. Back into page: τ. Blue: conditions imposed on lunar soil by a 40 t lander, which crosses into Kn<0.01.

The new theory predicts ejecta masses for the range of lander masses in Fig. 3. This can be applied to estimating the effects upon global lunar operations.

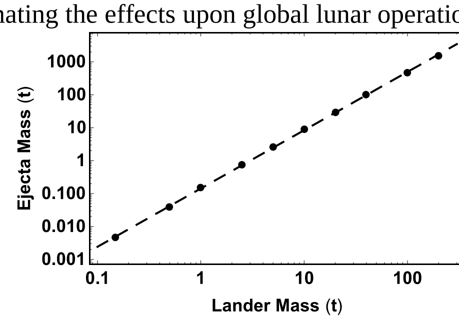

Figure 3. Predicted ejecta masa vs. lander mass.

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