LANDER PLUME EFFECTS AT OUTPOST ON SHACKLETON CRATER RIM.

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Introduction: NASA is implementing a five-year schedule for landing astronauts at the lunar South Pole. It is the first step in "long-term exploration and utilization" of the lunar surface as articulated in Space Policy Directive-1. If multiple surface assets are deployed at the South Pole, it is important to determine (a) the effects of rocket exhaust ejecta during descent and ascent, (b) whether topographic barriers exist near the South Pole that will protect existing surface assets from the ejecta, and (c) whether additional mitigation is needed between surface assets and landers. Here we present a preliminary assessment of the plume effects of a lander that delivers 9 metric tons (mT) to the surface from low-lunar orbit (LLO), which is the defined payload mass for the Human Landing System.

Quantity of Ejecta: Prior work by Lane and Metzger (2015) analyzed the Apollo Lunar Module (LM) landing imagery and found plume ejecta mass scales as vehicle thrust to the 2.5 power. They estimated total ejecta from an LM landing was 2.6 mT. LM landing mass was about 5 mT. The estimated 40 mT landing mass of a vehicle delivering 9 mT payload would eject (40 mT/5 mT)^2.5 = 181 times more ejecta than the LM, or 470 mT. It is likely this is an overestimate, since as the looser surface material is removed, the more compacted underlying material will be more resistant to erosion. However, we do not have data to quantify this, so we use the 470 mT figure to bound the worst case.

Shape of Crater: Analysis of terrain under the LM showed that erosion took place over a wide region several meters in diameter. For a 40 mT lander the erosion will occur within a 12 m radius as indicated by calculation of the shear stress on the surface (Fig. 1), which correlates to erosion rate. Assuming this erodes a bowl-shaped crater of radius 12 m and volume for 470 mT at 2000 km/m^3, the bowl will be 1.04 m deep in the center. (The eroded soil is not expected to be exactly a spherical cap; this is for estimating orders of magnitudes.) The exit angle from the lip of such a bowl relative to horizontal would be 9.87°.

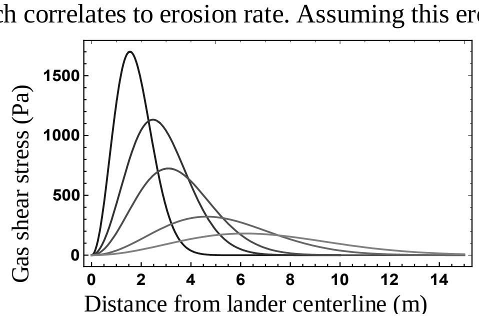

Figure 1: Shear stress from plume gas with the lander at (lightest to darkest): 20, 15, 10, 8, and 5 m altitude.

Ejecta Velocities: Prior work showed ejecta from the LM travel globally if there is no terrain blockage. Our new analysis integrates the trajectories of various sized particles in plumes from various mass landers to understand how ejecta velocities scale. The preliminary work did not include full fidelity simulations, but used analytical models of the plume and assessed cases with the lander nozzle at 5 m above the soil. Ejection velocities scale as the logarithm of lander mass (Fig. 2).

Assessing Outpost Damage: We assess the outpost location of the Constellation program on the rim of Shackleton crater. The landing zone is 2.2 km away from the habitation and energy generation zone and 290 m lower elevation. The range of particle velocities for a 40 mT lander indicate they will impact the habitation zone if they are ejected with upward angles of 10.5° for 1 µm particles, 12.4° for 10 µm, 16° for 40 µm, 21° for 100 µm, and >50° for >1 mm. The uphill slope provides some natural protection to the outpost by limiting to the smaller ejecta capable of this uphill trajectory, but considering the large quantity of ejecta and subsequent formation of a crater, the ejection angle will be modified by this crater permitting some damage to the outpost. Thus, additional mitigation may be needed.

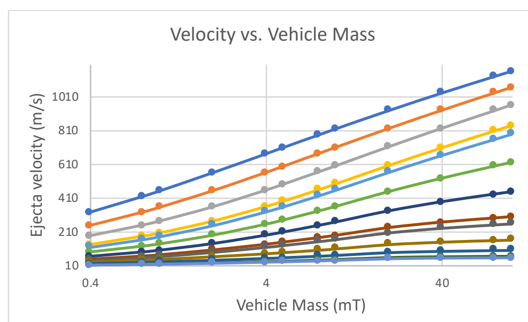

Figure 2: Approximate particle ejection velocities vs. lander mass for particle sizes (top to bottom) 1, 2, 4, 8, 10, 20, 40, 80, 100, 200, 400, 800, 1000, and 2000 microns diameter.

Reference: Lane & Metzger *Acta Geophysica* 63 (2), 568-599 (2015).