Crater formation for ~40 MT landers will be qualitatively worse than Apollo

Analysis of Surveyor, Apollo, and Chang’e data plus terrestrial experiments and computer modeling determined the following:

- Different regimes of gas/granular behavior exist (like different behaviors of frozen water vs. liquid water vs. vapor).
- (Non)Occurrence of each regime depends on size of the lander + environmental conditions (atmosphere, soil permeability, etc.).
- Martian and the Lunar plume effects are not comparable.
- Apollo LM effects were dominated by Viscous Erosion regime (smooth & streaking stages) with rare occurrences of Bearing Capacity Failure (in terrain modification stage).

A crater is not directly observable but is detectable by presence of:

- erosive crestline failure between lunar sedimentary strata (micro-scars) (A);
- headed (B) & unheaded (C) erosion remnants

- New image analysis technique (Lane & Metzger, 2014) determined erosion scales as plume shear stress to the 2.5 power.
- Therefore, it scales as vehicle mass to the 2.5 power.
- All data agree that about 2.5 tons of soil were ejected by each LM landing.

- Effects for ~1 ton CLPS landers will be tiny: ~20 kg ejecta predicted
- Chang’e 4 (~0.8 t) ejecta measured at 19 kg, confirming the 2.5 power index.
- For CLPS landers, there will be blowing dust and some rolling gravel but no other significant effects
- CLPS erosion depression predicted 0.25 cm deep, too tiny for microscars. Probably impossible to measure anything in imagery.
- CLPS crater impossible to identify in computer simulations.

Applying the 2.5 power index to a 40 t lander predicts ~470 t ejected soil, forming a crater many meters deep

However, we cannot extrapolate this far.

It is likely that additional regimes will “turn on” at these high thrust levels. Bearing capacity failure? Diffusion-driven shearing? Bulk failure?

Ejecta Characteristics

For the LM, some ejecta exceeded lunar escape velocity (2.43 km/s)

Ejecta were dispersed globally through flux was small a very great distances. Can destroy orbiting spacecraft.

For CLPS landers, ejecta travel multiple kilometers (up to 10s or 100s).

For 40 t landers, ejecta particle velocities are nearly double the LM’s, so will travel much farther and disperse globally with vastly larger impact flux

Analysis of impact damage on returned Surveyor 3 hardware shows extensive surface cracking, pitting, and dust impregnation.

Mitigation Techniques

Berms may help but are not a complete solution

- Evidence indicates ejecta “bounce” off terrain (dust bounces off sand, sand bounces off rocks)
- 40 t landers will cause too much cratering under the lander

Landing pad requirements differ for inner and outer zones

Many groups have done tests of various technologies.

These & future tests provide input for trade studies.

Conclusions & Future Work

- Human-class landers (~40 t) will cause severe plume effects.
- CLPS pluming will be very minimal but this may be deceptive because scaling is a 2.5 power law of vehicle mass.
- Pluming can damage surrounding hardware including ISRU operations, habitats, and scientific equipment.
- Pluming can damage or destroy spacecraft in lunar orbit if the timing is unfortunate.
- Need to continue developing individual mitigation technologies.
- Need to complete the mitigation trade study.
- Need to develop robotics to implement the mitigation techniques.
- This work is feed-forward to Mars.
- The CLASS Planetary Landing Team is set up to advance this effort.