MITIGATING LANDER PLUME EFFECTS WITH SPACE RESOURCES

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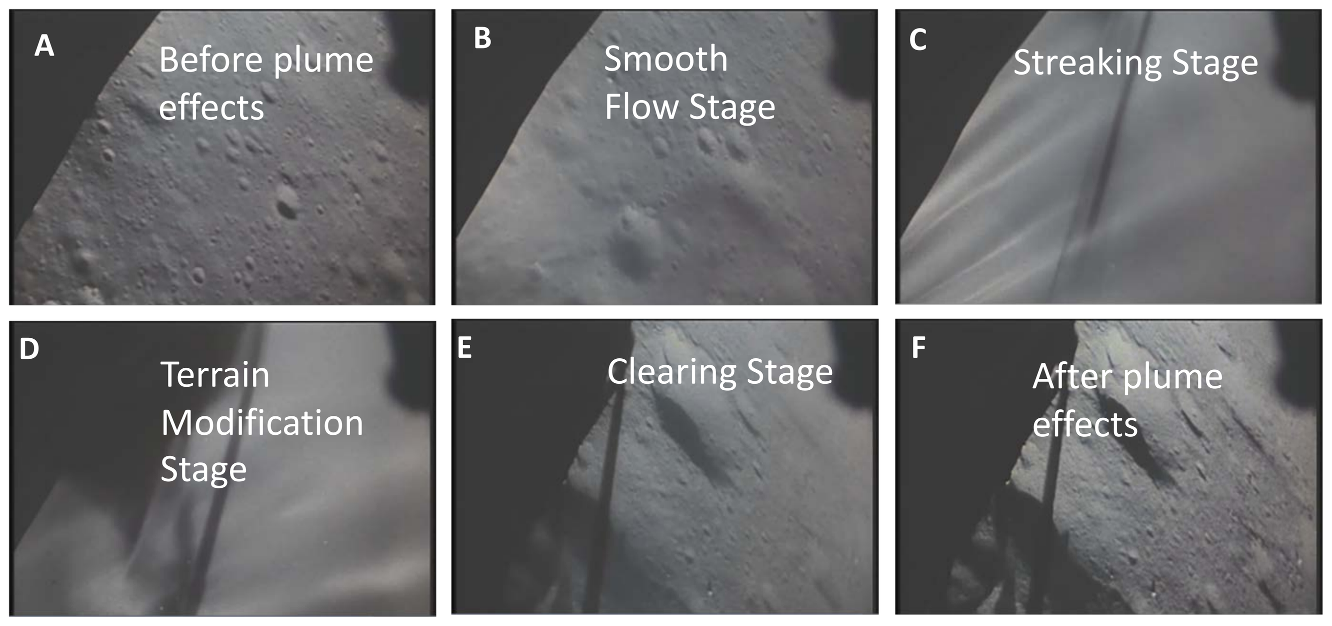
Crater formation for ~40 MT landers will be qualitatively worse than Apollo

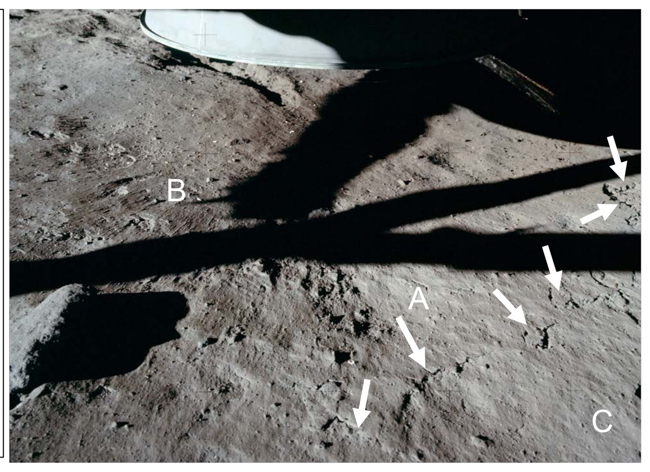
Analysis of Surveyor, Apollo, and Chang'e data plus terrestrial experiments and computer modeling determined the following:

- 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).

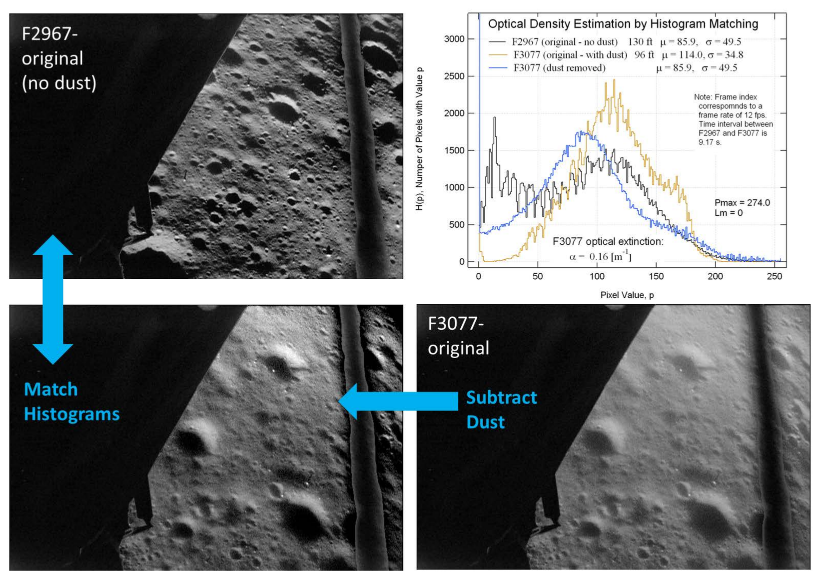


A crater is not directly observable but is detectable by presence of

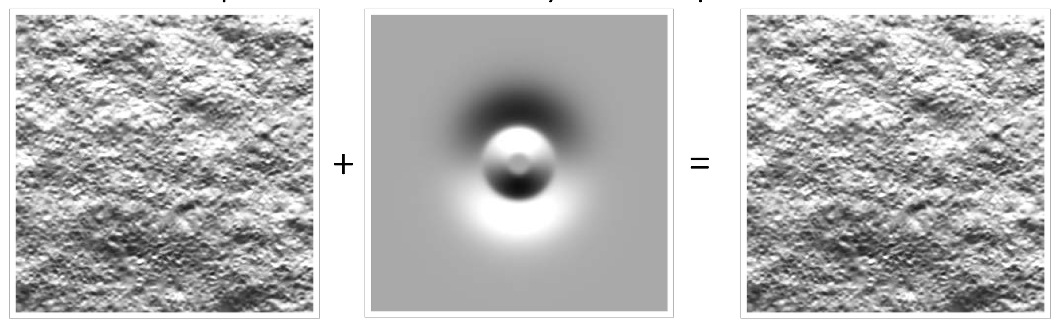
- erosive crestline failure between lunar sedimentary strata (micro-scarps) (A);
- headed (B) & unheaded (C) erosion remnants



- 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 erosive depression predicted 0.25 cm deep, too tiny for microscarps. Probably impossible to measure anything in imagery.
- CLPS crater impossible to identify in computer simulations:



6 degree sun angle. Left: simulated lunar terrain; center: Chang'e 4 erosion on smooth surface. Right: both added together

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.

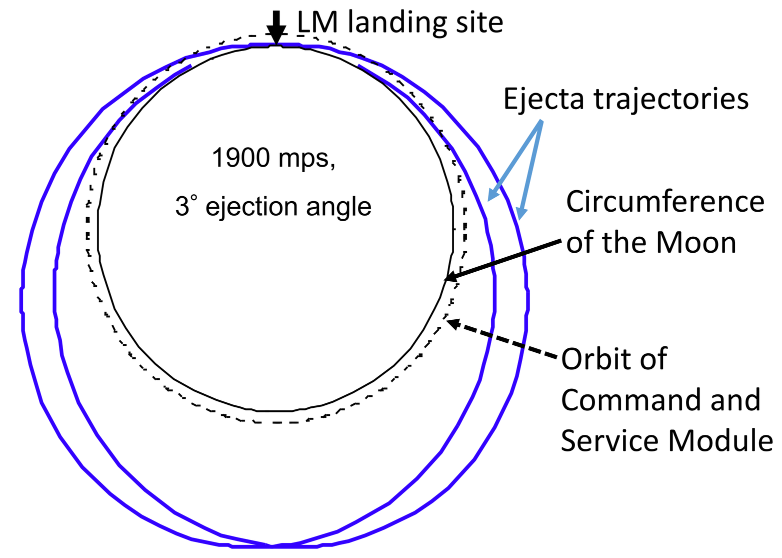
It is likely that additional regimes will "turn on" at these high thrust levels. Bearing capacity failure? Diffusion-driven shearing? Bulk failure?

Ejecta Characteristics

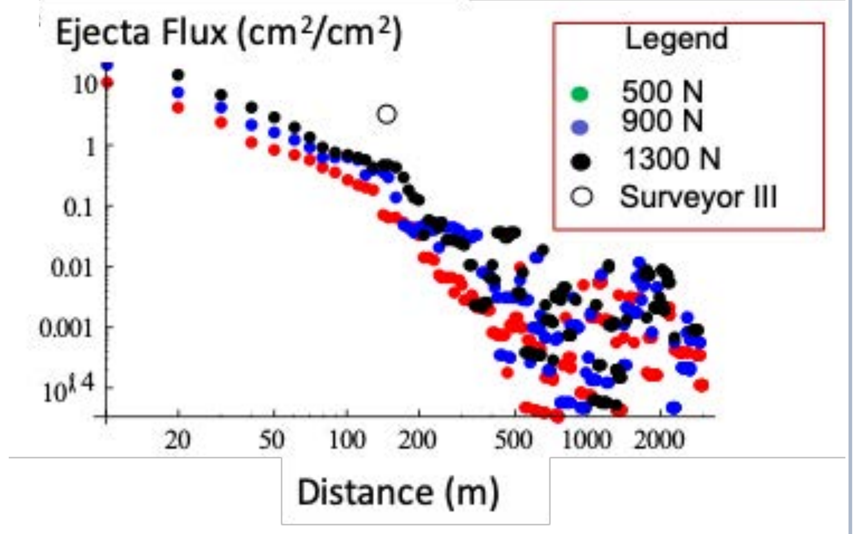
For the LM, some ejecta exceeded lunar escape velocity (2.43 km/s)

Particle Size	Ejecta Speed for LM
Dust	1000 – 3000 m/s
Sand	100 – 1000 m/s
Gravel	~30 m/s
Cobbles	~10 m/s

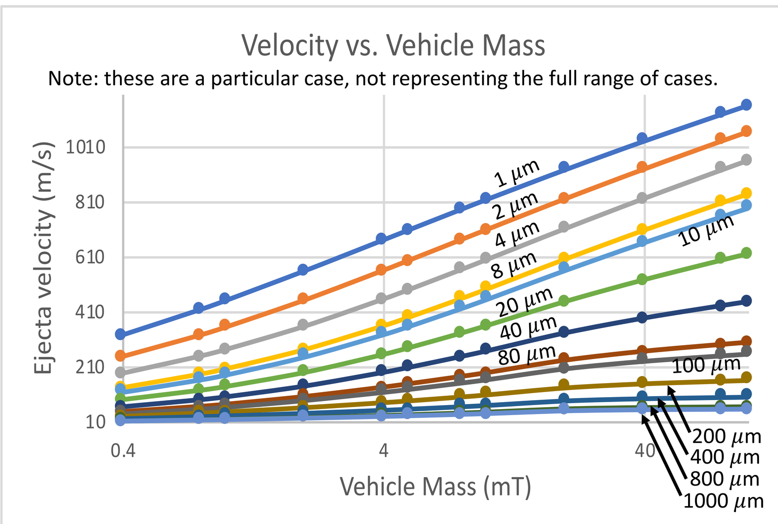
Ejecta were dispersed globally though flux was small a great distances. Can destroy orbiting spacecraft.



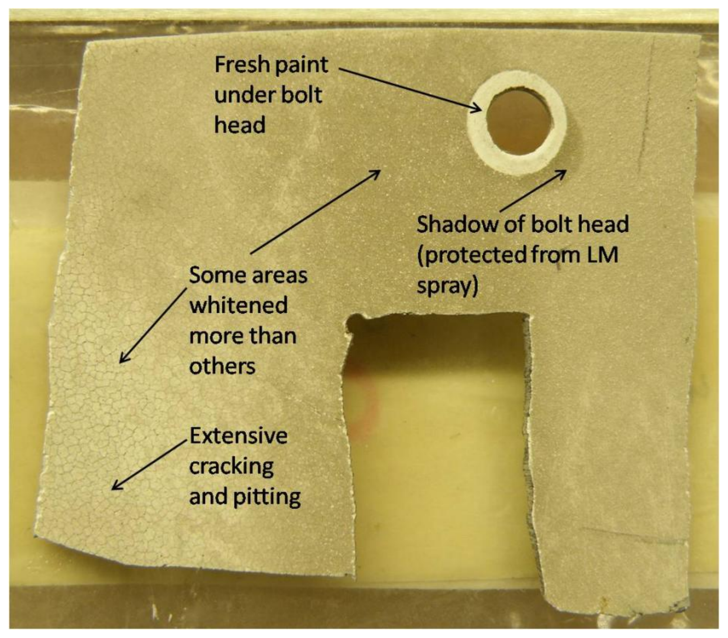
For CLPS landers, ejecta travel multiple kilometers (up to 10s or 100s).

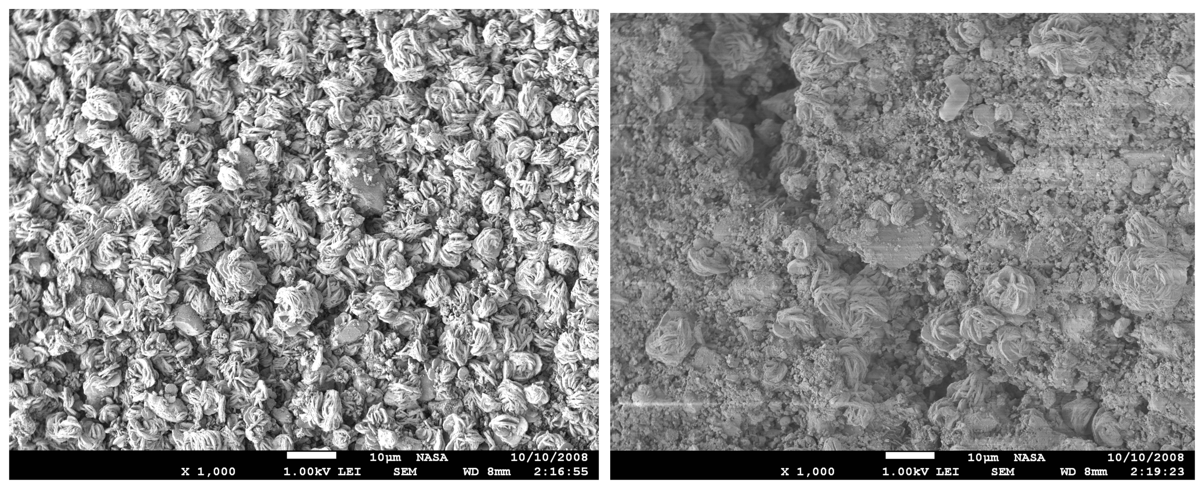


For 40 t landers, ejecta particle velocities are nearly double the LM's, so will travel much farther and disperse globally with vastly larger impact flux



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





SEM images of Surveyor 3 surface. Left: original condition. Right: after sandblasting by Apollo 12 LM.

For 40 t landers, the higher ejecta quantity and higher ejecta velocities indicate great damage can occur to an outpost or an ISRU mining operation.

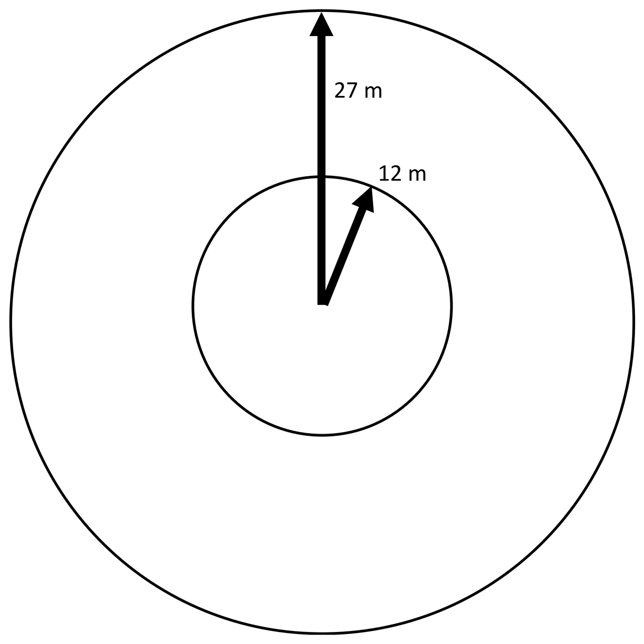
Mitigation is necessary.

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



May use different construction methods in inner and outer zones

Inner methods (high temp, gas impermeable)

- Sintering
- Pavers with grouting
- High temperature polymer infusion in soil
- Rock welded pavers
- Bring sheet material from Earth

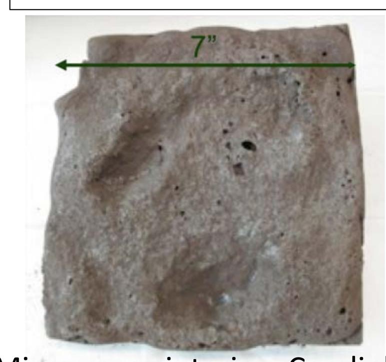
Outer methods (low temp, resist scouring erosion)

- Sintering
- Pavers (grouting not required)
- Low temperature polymer
- Rock filtration system

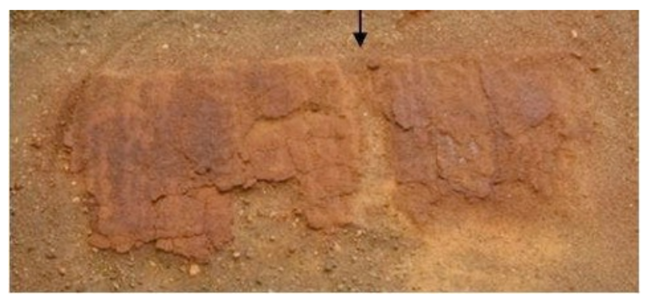
Many groups have done tests of various technologies.

These & future tests provide input for trade studies.

Solar sintering. PSI. Mauna Kea Field Test, 2010.



Microwave sintering. Ceralink, Hintze, et al.



IR Sintering, Hintze, 2010

Polymer application, Adherent Tech; Ablation tests, Swamp Works and the Space Portal.

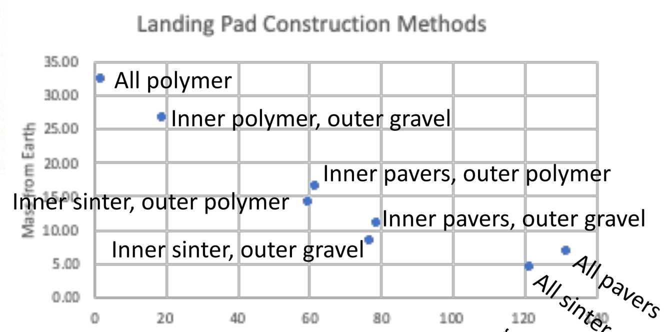
Left: Pavers; PISCES, Swamp Works, et al. 2016. Right: Paver plume tests; van Susante & Metzger

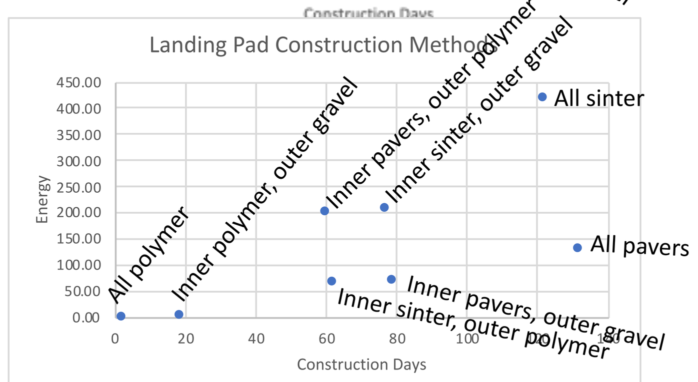
Left: Gravel Bed plume tests; van Susante & Metzger, 2010

Preliminary trade study is in work

Considerations:

- Mass brought from Earth;
- Energy required (high energy systems cannot be landed until after the landing pads are built);
- Construction time;
- Reliability.





Conclusions & Future Work

- Human-class landers (~40 t) will cause severe pluming 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.