MINIMIZING VOLATILE LOSSES DURING LUNAR EXCAVATION

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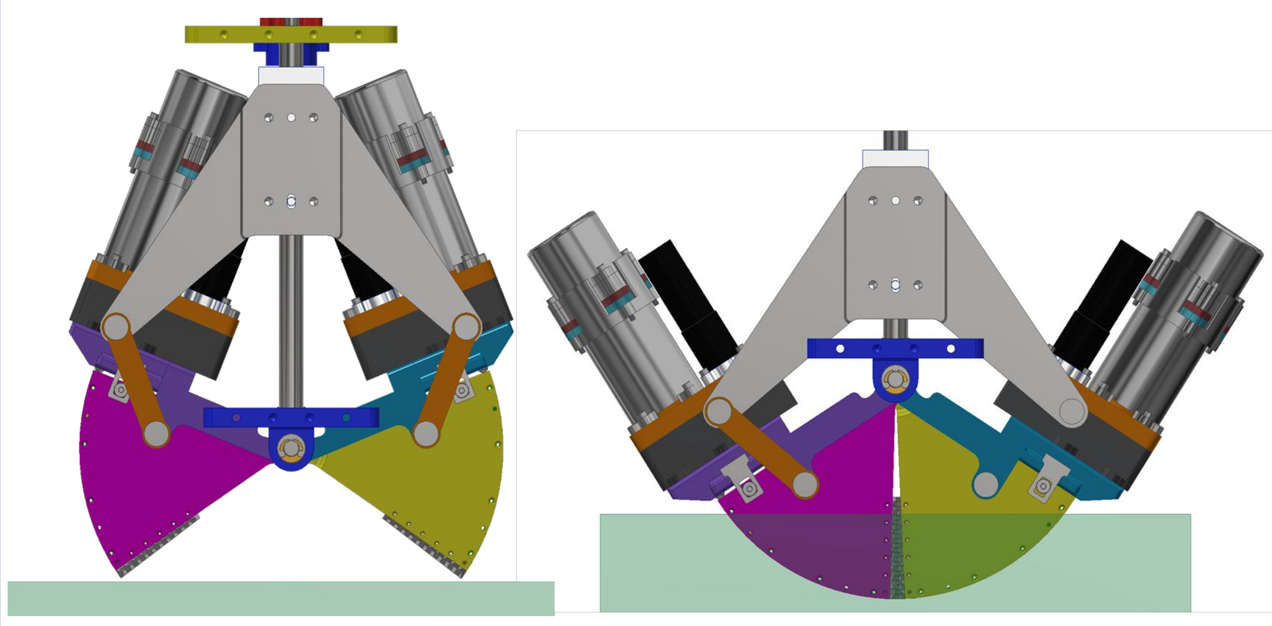
Summary

Volatile compounds buried and trapped under the lunar surface in Permanently Shadowed Regions (PSRs) are of great scientific interest for understanding the Moon's history, lunar evolution, and In-Situ Resource Utilization (ISRU) [1]. Sampling-induced heating and vacuum exposure drive volatile loss[2], and existing excavation systems like plows, augers, and bucket drums pulverize material before collection, leading to increased exposed surface area and volatile loss rates[3]. Coring drills may be difficult to scale for bulk collection on the lunar surface. Fortunately, recent work has shown that icy regolith may be more than 10 times weaker than previously thought [4,5], opening the trade space to higher-efficiency excavation methods..

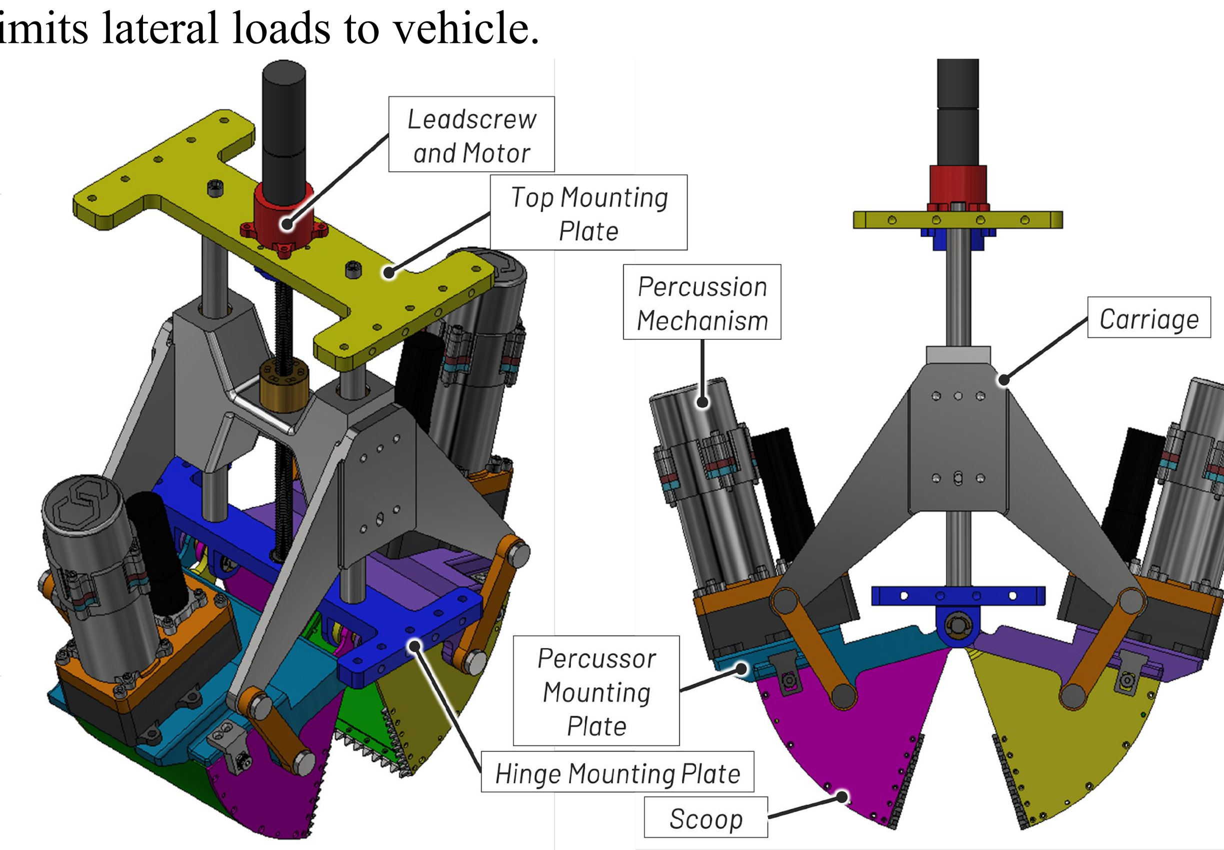
We present a novel mechanism for collecting large intact icy regolith material, trapping stored volatiles until they can be deposited in a collection and processing system. This system uses two bucket scoops operating in a dredger/clamshell configuration to capture and collect icy fragments. This configuration is highly scalable and limits lateral loads from being imparted into the excavation vehicle. A percussor system attached to the buckets allows the scoops to push through consolidated, cementitious material, characteristic of high-volume percentages of cryogenic water ice mixed into lunar regolith.

Clamshell Mechanism and Development

- Two dredger-style buckets fracture, then enclose icy chunks within scoops, Independent percussors transmit impacts through scoops and teeth to break cementitious icy regolith.
- Benchtop rig sized to UCS ≈ 1.5 MPa (Break-the-Ice guideline). Lead-screw, four-bar carriage; bucket profile follows cutter sweep to reduce drag/wear.
- Kinematic optimization cut peak scoop loads >30%; percussor mount isolates carriage.
- Modular chisel plates enable rapid wear/geometry iteration; limits lateral loads to vehicle.



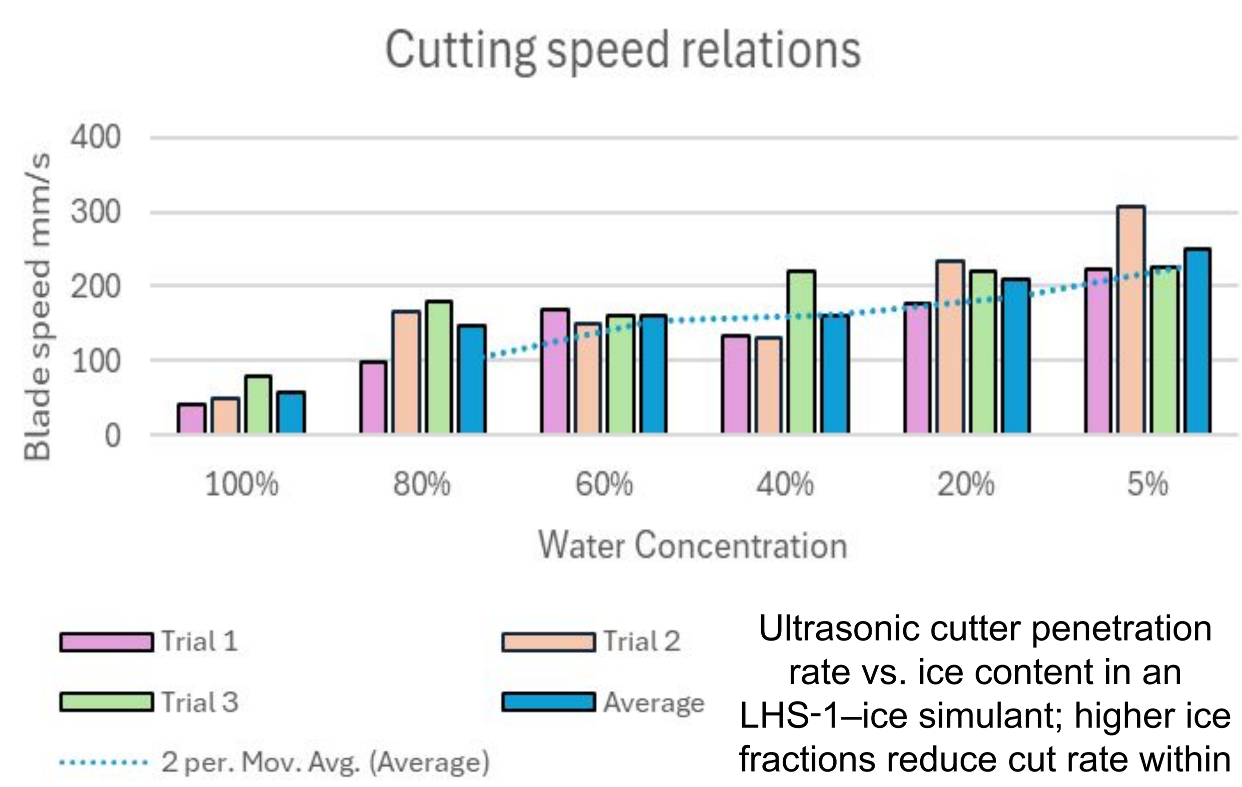
Benchtop ConOps showing the path swept by the buckets through simulant.



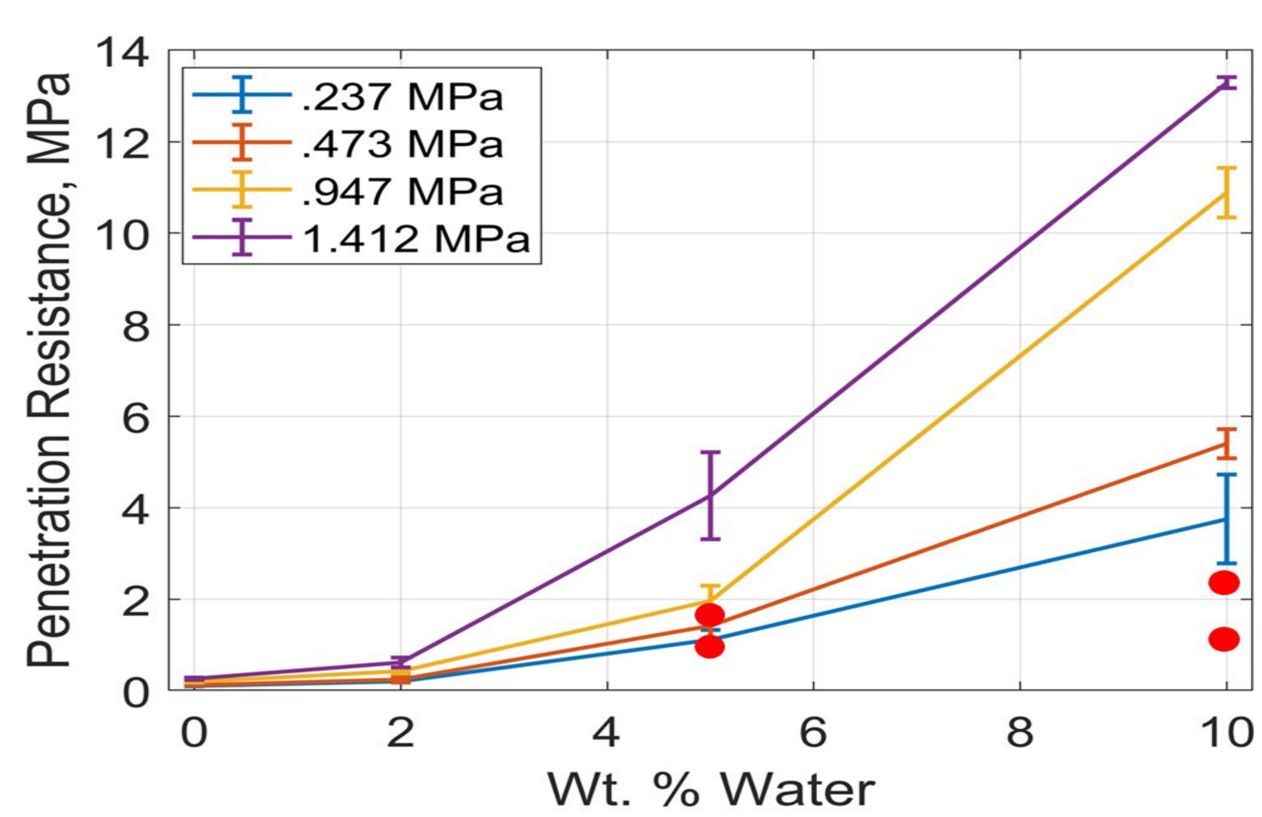
Integrated percussive clamshell excavator hardware for final benchtop, cold-soak, and environmental test campaigns.

Ultrasonic Mechanism and Simulant Testing

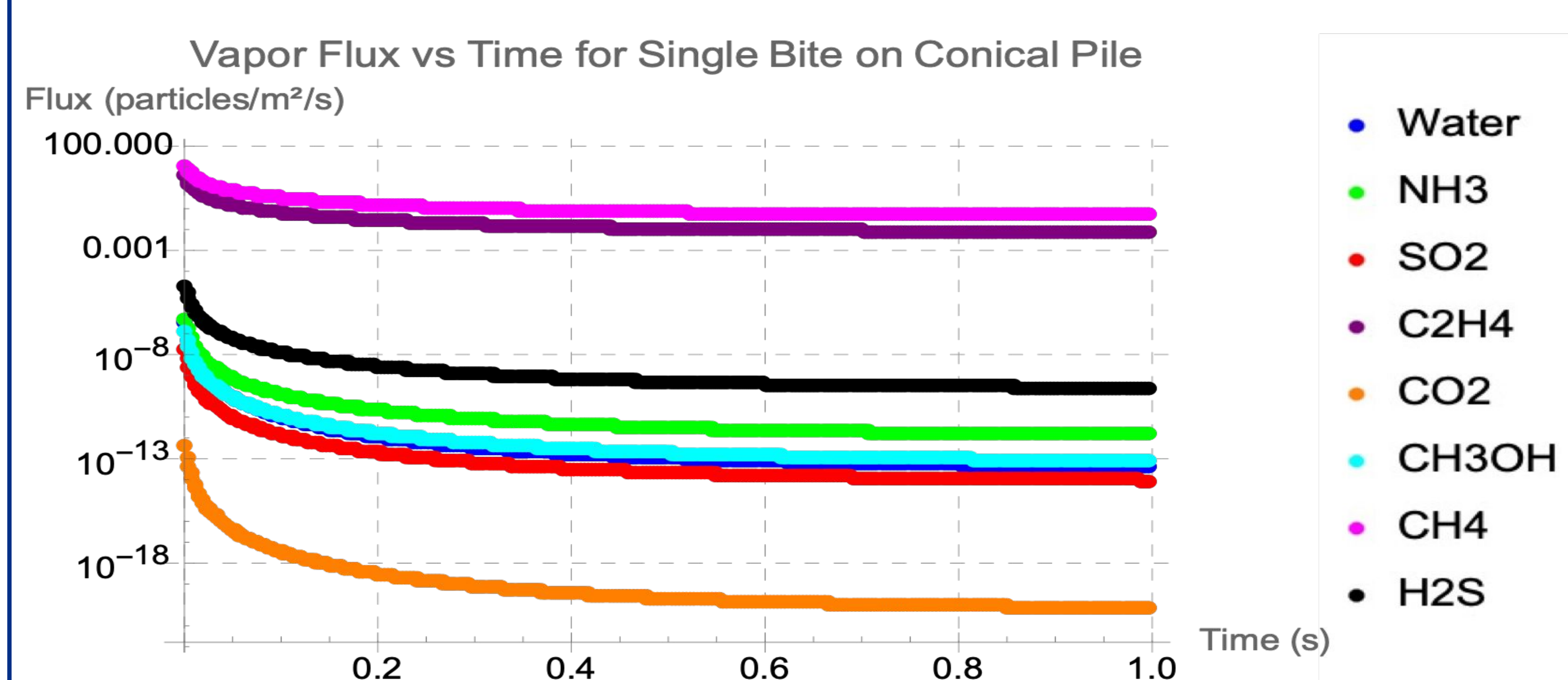
- LHS-1–ice cores Ø50×71 mm, 5–100 wt% H_2O; −20 °C pre-condition, 35 psi clamp.
- Sectioned with 40 kHz Ti blade; force/position/power + 240 fps video logged.
- Outputs: specific energy and penetration rate for each ice fraction.
- Higher ice modestly reduces rate within tested power band.
- Energy partition (early result): ≈ 50% fracture / 50% heat → control agitation, not only tool temp.
- Penetration resistance vs weight % water in batch sintered icy regolith under vacuum after performing excavation. Red points indicate vacuum sintered comparative to pressure sintered.



Ultrasonic cutter penetration rate vs. ice content in an LHS-1–ice simulant; higher ice fractions reduce cut rate within the tested power band.



Modeling and Simulation



Modeled vapor flux versus time for an excavated regolith material containing multiple volatile species.

- Heat–mass solver with 40–260 K vapor-pressure fits for H_2O, CO_2, NH_3, CH_4, H_2S, SO_2, C_2H_4.
- Initial transient degassing → multi-order decay as latent cooling develops.
- Diffusion-limited loss from ~200 µm skin under PSR conditions.
- Sealed clamshell suppresses total flux >50× by ~30 s post-capture.
- Solver returns <1 µs equilibrium steps → rapid scenario scans for ops windows

CLSM and Icy Regolith Simulants

- Cislune's aerocrete-based CLSM provides a high-porosity, high-UCS excavation simulant targeting a 1.5 MPa load case for the NASA Break the Ice Lunar Challenge.
- CLSM for ambient-condition mechanism development for repeatability, cost, throughput.
- Icy regolith in permanently shadowed lunar craters is likely to exhibit higher porosity and lower effective strength than dense concrete analogs, so porosity retention is important for realistic penetration and fracture behavior.
- Cislune and McMurchie Eng. developed vacuum/temperature-sintered icy simulants that reach comparable UCS and porosity, while better representing cold icy-regolith structure.
- The resulting test ladder: ambient aerocrete CLSM, −20 °C icy simulant, then TVac. This separates mechanism tuning from environmental effects and supports consistent comparison of force, wear, and excavation behavior.

References/Acknowledgements

[1] Colaprete, A., Schultz, P. H., Heldmann, J. L., et al. (2010). Science, 330(6003), 463–468. [2] Zacny, K., Paulsen, G., Szczesiak, M., Craft, J., Chu, P., McKay, C., Glass, B., Davila, A., Marinova, M., Pollard, W., & Jackson, W. (2013). Journal of Aerospace Engineering, 26(1), 74–86. [3] Just, G. H., Smith, K., Joy, K. H., & Roy, M. J. (2019). Planetary and Space Science, 180, 104746. [4] Johnson, D. K.M et al. (2024). *Icarus*, *410*, 115885. Johnson, Daniel KM, et al. JPC C 129.4 (2025): 2152-2164.

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