MINIMIZING VOLATILE LOSSES DURING LUNAR EXCAVATION. E. Franks[1], N. Traeden[2], P. Metzger[3], M. Schroeter[2], D.K.M. Johnson[4] and K. Bywaters[2]. [1]Cislune, Inc. (Erik@cislune.com), [2]Honeybee Robotics (NWTraeden@honeybeerobotics.com), [3]University of Central Florida (Philip.Metzger@ucf.edu), [4]McMurchie Engineering (McMurchie.Engineering@gmail.com).

Introduction: Volatiles trapped in Permanently Shadowed Regions (PSRs) and shallow polar permafrost are important for lunar science and In-Situ Resource Utilization (ISRU) [1]. Excavation-induced heating, fines generation, and vacuum exposure can drive rapid volatile loss during collection and transfer [2]. Conventional augers, plows, and bucket drums comminute material before containment, increasing exposed area and sublimation rates [3].

Recent advances in icy-regolith simulants, from granular snow-regolith mixes to vacuum-, temperature-, and pressure-sintered materials, provide more lunar-relevant mechanical behavior than legacy wet-mix analogs [4-6]. These simulants better preserve pore ice, low permeability, and brittle fracture modes needed for excavation testing.

We present an updated excavation concept downselected from earlier bucket-drum and post-hole architectures to a clamshell/dredger configuration optimized for volatile preservation. Two symmetric scoops collect large icy fragments while limiting lateral reaction loads. Integrated percussion is used to fracture consolidated material, reduce cutting forces, and reduce fines and frictional heating. The architecture is compatible with rapid transfer into a sealed hopper or processing interface.

Clamshell Mechanism Development: The team has matured a benchtop clamshell system to evaluate excavation of icy simulant material representative of the 1.5 MPa class considered for early PERDEX sizing and Break the Ice Lunar Challenge analog conditions. A lead screw drives a carriage and four-bar linkage that deploys two symmetric scoops (Figure 1). Each scoop incorporates a percussion subassembly that transmits impact energy through the back of the scoop and cutting teeth into the simulant. Recent Honeybee Robotics trade studies and internal PDR activities focused on maintaining mechanical advantage through closure, ensuring that the rear bucket surface follows the cut path, and allowing adjustable spring preload and interchangeable COTS springs to vary delivered percussion energy.

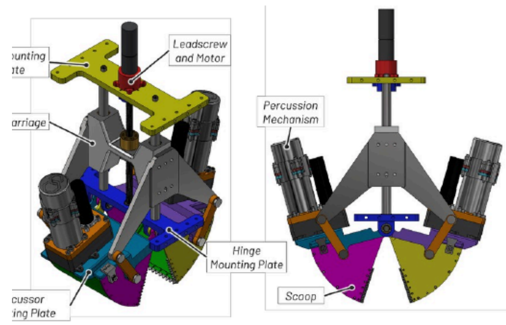

Figure 1: *Benchtop clamshell/dredger excavation prototype with integrated percussion.*

The consolidated nature of the target material drove the bucket geometry and linkage design. To minimize drag and avoid pushing intact material into the bucket interior, the bucket profile is constrained to remain within the swept path created by the cutting teeth during closure. The current benchtop buckets are sized for practical fabrication and future cryogenic/vacuum test chamber integration while remaining representative of a scalable end-effector architecture.

Simulant Preparation: The team is developing multiple icy-regolith simulant pathways spanning granular mixtures, vacuum- and temperature-sintered materials, and controlled ice-fraction cylindrical cores. Current work includes scalable production of granular ice using snowmaking and separation workflows for batch mixing with lunar simulant, as well as cylindrical LHS-1/ice cores (50 mm diameter x 71 mm) for ultrasonic screening tests.

Ultrasonic Mechanism Development:

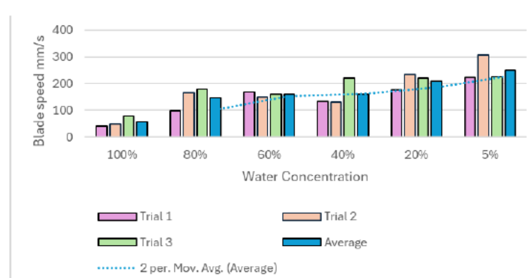

Figure 2. *Ultrasonic cutter penetration rate versus ice content in an LHS-1/ice simulant; higher ice fractions modestly reduce cut rate within the tested power band.*

Results and Discussion: Preliminary vacuum tests on sintered LHS-1/ice mixtures indicate that penetration resistance increases strongly with water content and consolidation state (Figure 3). This behavior bounds the force required for excavation and informs the degree to which percussion and alternative cutting strategies are needed to preserve volatiles. Lower penetration resistance means the excavator can penetrate with less force and lower heat generation.

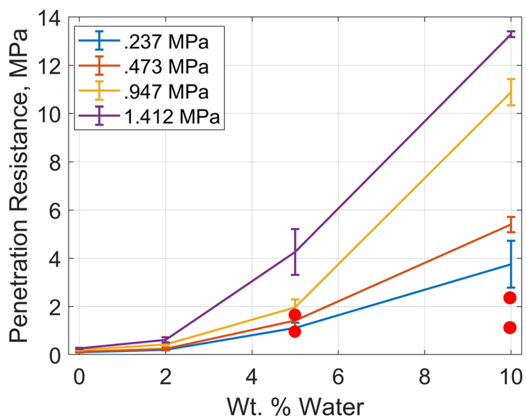

Figure 3: *Preliminary penetration resistance versus water wt% for small-batch sintered icy regolith under vacuum. Red points indicate comparative vacuum-sintered data relative to pressure-sintered samples.*

Preliminary penetration-resistance data indicate that vacuum-sintered material falls within the same general family as previously reported pressure-sintered simulants, but at the lower end of those ranges [4]. This provides a tunable pathway to create icy simulants representative of low-to-moderate strength lunar polar materials while still permitting repeated excavation tests.

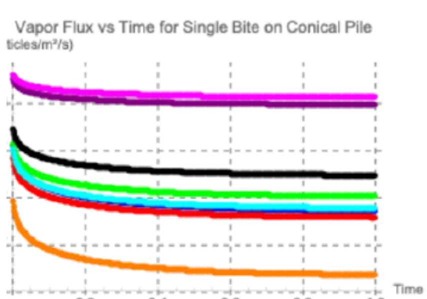

Figure 4: *Representative modeled vapor flux versus time for a freshly excavated multi-volatile regolith fragment.*

Representative model outputs for an excavated multi-volatile regolith fragment are shown in Figure 4. All species exhibit a rapid drop-off in outgassing after excavation as sublimation flux is suppressed once the material cools and the exposed skin layer is depleted.

Our heat-mass transport solver now uses updated vapor-pressure curve fits for H2O, CO2, NH3, CH4, H2S, SO2, and C2H4 over 40-260 K, and is being adapted from the original rotating-drum duty cycle to the clamshell sequence of bite, closure, transfer, and dump. Under PSR-relevant conditions, volatile loss is dominated by a shallow surface skin on the order of ~200 um, reinforcing the design strategy of maximizing fragment size, minimizing fines, and rapidly sealing collected regolith.

In conclusion, current hardware and modeling results support a lunar excavation strategy that emphasizes fracture-controlled collection of large icy fragments rather than grinding-dominated excavation. Ongoing work is focused on integrated clamshell/percussion testing, scalable simulant production, and clamshell-specific sublimation modeling to guide future cryogenic and vacuum demonstrations.

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