SUBLIMATION LOSS FROM OPEN-GAP LUNAR WATER EXTRACTION.

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Introduction: The effectiveness of seals in ISRU water production systems is of interest as humans lay the groundwork for returning to the Moon and going on to Mars. Intuitive judgement holds that the extreme lunar-surface vacuum environment requires that every precious molecule be carefully captured. However, no extraction of any natural resource is perfectly efficient. Successful extraction systems balance the costs of product losses against the costs of higher recoveries.

Fig. 1 illustrates how increasing the recovery of a resource contained within an ore brings a greater percentage of unwanted (waste) material into the process stream, thus increasing the complexity of (and wear on) the processing technology.

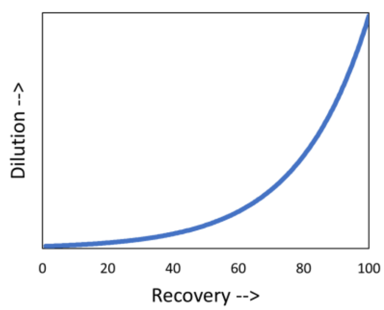

Fig. 1. Typical recovery-dilution curve shape.

This research, with previous work for the martian surface [1,2], is examining the problem from a different perspective: How much water would actually be lost through the gap between a bin or tray of icy regolith and a nearby cryotrap? Accurate prediction of this loss term will help clarify system constraints for lunar and martian water production.

Experiment: The test apparatus is configured as shown in Fig. 2 to partially simulate a lunar situation. A shallow circular tray containing a mixture of 95 wt% NU-LHT-3M lunar regolith simulant and 5 wt% water ice is heated from below, with a cryotrap suspended above, all inside a vacuum chamber. The vertical distance between the regolith surface and the cryotrap, the difference between the horizontal extents of tray and cryotrap, and the applied heat flux are adjustable.

The vacuum chamber is pumped to below 10^{-3} torr while the ice-simulant mixture is pre-chilled to approximately 250K. When these conditions have been achieved, the bottom of the regolith tray is heated while the masses of the icy regolith-filled tray and the cryotrap are monitored. After several hours the rate of mass transfer slows and the test is ended.

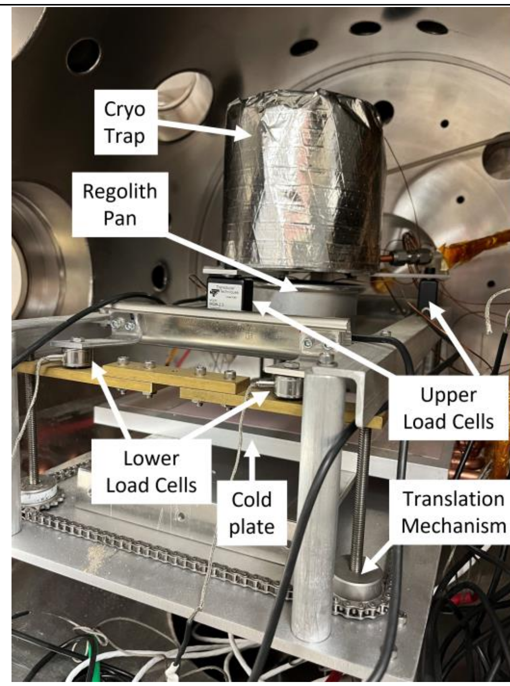

Fig. 2. The experiment configuration, installed in the 2-foot vacuum chamber at NASA GRC. The stepper motor (not shown) is positioned against the back wall of the chamber for vertical translation.

Predictive Model: Regardless of its prior travels within the regolith intergranular maze, once a sublimated water molecule has reached the surface it has a certain velocity and initial trajectory that both can be simulated mathematically. The trajectories of escaping water molecules are reasonably straight at the scale of a laboratory-test apparatus, even in Earth gravity and lunar cold-trap temperatures, if the flow can be assumed to be very sparse (molecular). These assumptions permit a gap-loss quantification that is decoupled from the water sublimation-diffusion behavior. The capture rate then becomes the fraction of water molecules leaving the regolith surface that reach the cryotrap under specific geometric conditions (gaps).

Later versions of the model are planned to incorporate more precise estimation of the behavior of water (and perhaps other volatiles) within the regolith tray.

This will permit evaluation of apparatus configurations other than those tested in this program. The flow regime to which the model is applicable will also be expanded from molecular to Knudsen flow to represent a wider range of process pressures.

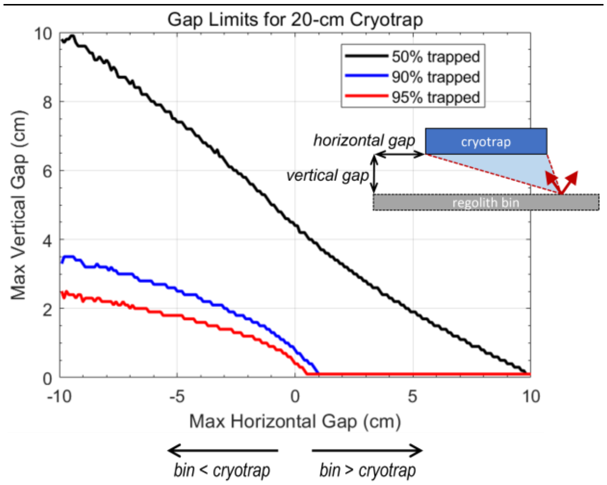

Fig. 3. In this one-dimensional simulation, a 20-cm-wide cryotrap is predicted to capture 97% of the offgasses from a 12.7-cm-wide regolith tray (bin) if the vertical distance between tray and trap is 1.0 cm.

Preliminary Results: At the time of this abstract's submission, the experiment apparatus and procedures are being checked out and finalized, and the predictive model has been validated in one dimension. The first phase of experiments will have been completed, and the model expanded to two dimensions, before the Roundtable meets.

Predictive Model. Fig. 3 plots the maximum gaps that allow capture of 50%, 90%, and 95% of the water that escapes from the surface of a container of icy regolith. The caption illustrates an example of the chart's use. In practice, the larger the regolith surface area, the less effect that practical gap dimensions will have on the loss.

Experiment. Fig. 4 compares the relative mass loss and capture of a representative test. The rate of mass release from the regolith bin begins rapidly and gradually slows as the test progresses. The rate of mass capture in the cold trap follows a similar trend of rapid growth followed by a plateau in the later stages of the test.

The percentage of mass captured plateaus to about 25%. This value is much lower than the predictive model, which may speak to the differences between the test conditions and the model assumptions, namely the influence of the flow regime. The model assumes the flow regime to be molecular flow, whereas the flow regime of the tests was closer to Knudsen flow.

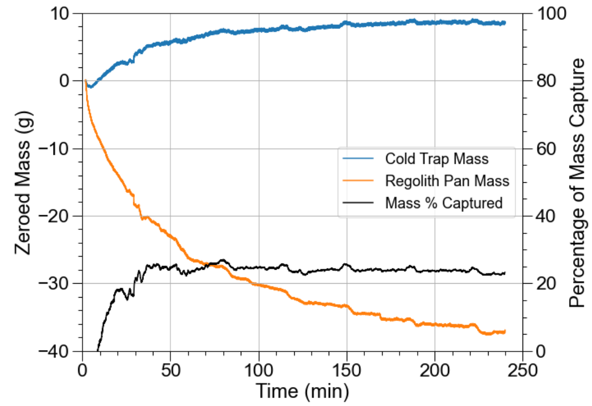

Fig. 4. Change in mass in the regolith bin and the cold trap for a representative case (vertical gap of 1.0 cm, regolith tray of 12.7 cm)

Future Work: A separate task of this research program is evaluating time constraints caused by the depth of the icy regolith in its container; in other words, finding the best ratio of depth (through which sublimated volatiles must travel through constantly changing, tortuous paths) and horizontal extent of the bin/tray.

References: [1] Linne, D. L. et al. (2016) *9th Symposium on Space Resource Utilization*, 0226. [2] Trunek, A. J. et al. (2018) *Earth and Space: Engineering for Extreme Environments*, 490-500.