THE UNIQUE PHYSICAL CHARACTERISTICS OF SIMULATED LUNAR ICE.

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Introduction: Missions being sent to the lunar poles are at risk of reduced mission success due to a lack of knowledge about some of the physical characteristics of the ice/regolith mixtures in those regions. The success of current planned missions to the lunar poles is critical for our progress to a sustained and profitable lunar economy.

Mission engineers and scientists must have thorough knowledge regarding the nature of lunar ices so they can design the right hardware for these missions, thoroughly test that hardware, and appropriately plan and execute surface operations during these missions. Commercial operators planning on developing lunar resources need this information in order to build the basis for a lunar economy as well as a wider human presence in space.

These experiments are intended to replicate the possible natural formation processes of lunar polar ices in and on lunar regolith at the particle level. These ice/regolith mixtures are then tested and observed to gain an understanding of the physical nature of these materials, and how it will affect the design of future mission hardware. This information will also contribute to successful surface operations within the ice-bearing areas on the Moon.

Background: Important early experiments have been conducted by other researchers using water and/or carbon dioxide (two of the components of lunar ices) mixed into simulants. The mixtures were then frozen before testing such as in Gertsch et al [1]. Current information on the composition and likely sources of lunar ices indicate that they were formed from different processes and components. Off Planet Research (OPR) seeks to replicate these processes in their experiments.

Simulants Used: The lunar regolith simulants used in this work were OPRH1N (Off Planet Research Highland Non-Agglutinate Type 1) and OPRL1N (Off Planet Research Mare Non-Agglutinate Type 1). The simulated lunar ice created was designated as OPRFLCROSS1 which is based on the data gathered from the LCROSS impact [2] experiment shown in Figure 1; the SO_2 and OH components are not included in the simulated lunar ice for safety reasons. The specifications for these simulants can be found at Offplanetresearch.com/simulants.

Sample Preparation: The simulated lunar ice/regolith mixtures are produced using the percentage for relative ice abundance in the ejecta plume from the LCROSS impact (Figure 2).

The Importance and Effect of Fully Simulating the Ice Formation Processes: The process of cometary vapor settling into the permanently shadowed regions (PSRs) of the Moon was simulated in one of OPR's most recent experiments. By depositing lunar ice components as vapors onto super-cooled regolith particles, simulated lunar polar regolith particles with surface ice crystals were created; this changed the particle morphology and density of the regolith. Some of the ice crystals broke off of the regolith particles and effectively increased the fine portion of the regolith particle size distribution. These free ice particles had differing morphologies of their own which further altered the simulated lunar polar regolith dynamics. The interaction of these differing types of particles in simulated ice-bearing lunar polar regolith created some unexpected dynamics.

Compound	Molecules cm^{-2}	% Relative to $H_2O(g)$
H_2O	5.1(1.4)E19	100.00%
H_2S	8.5(0.9)E18	16.75%
NH_3	3.1(1.5)E18	6.03%
SO_2	1.6(0.4)E18	3.19%
C_2H_4	1.6(1.7)E18	3.12%
CO_2	1.1(1.0)E18	2.17%
CH_3OH	7.8(42)E17	1.55%
CH_4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

Figure 1: *Table 2 from Colaprete, A. et al [2]. Relative abundances of ice constituents in their gaseous state. The uncertainty in each derived abundance in shown in parenthesis.*

	Water mass (kg)			
Time (s)	Gas	Ice	Dust mass (kg)	Total water %
0–23	82.4 ± 25	58.5 ± 8.2	3148 ± 787	4.5 ± 1.4
23–30	24.5 ± 8.1	131 ± 8.3	2434 ± 609	6.4 ± 1.7
123–180	52.5 ± 2.6	15.8 ± 2.2	942.5 ± 236	7.2 ± 1.9
Average	53 ± 15	68 ± 10	2175 ± 544	5.6 ± 2.9

Figure 2: *Table 1 from Colaprete, A. et al [2]. Summary of the total water vapor and ice and ejecta dust in the NIR instrument FOV.*

Critical Lessons Learned: One of the early observations of the difference in regolith dynamics between simulated equatorial lunar regolith and lunar polar regolith/ice mixtures can be seen in Figure 3. In this test, a reproduction of the Lunokhod cone-blade penetrometer tip was pressed into icy and "dry" regolith simulant and the resulting stress/strain curves were compared. The penetrometer tip was super-cooled before being pressed it into the simulated polar regolith.

From these experiments, the results showed the icy regolith simulant appears much more "slippery" on the surface than its dry counterpart. One issue that may arise is rovers struggling to climb the slopes that current plans anticipate, especially smaller rovers. Additional challenges could come from drilling into icy regolith, dealing with volatizing components and "wet" regolith, and the increased cohesion and density of icy regolith affecting the material's flow through machinery. Mission equipment sent to the lunar PSRs may also need to be designed and operated differently including wheels, scoops, landing foot pads, and probes.

Another important aspect of these experiments is the knowledge gained while handling and working with these ice/regolith mixtures. Dry regolith is known for its ability to cling to everything and cause problems; ice-bearing regolith retains this challenging characteristic and adds several new challenges when it is exposed to working equipment, or interacts with focused sources of heat temporarily. This raises concerns about how a lander may interact with the surface material in a lunar PSR during and after decent, or how a relatively hot rover might encounter difficulties working in proximity to lunar ice/regolith mixtures.

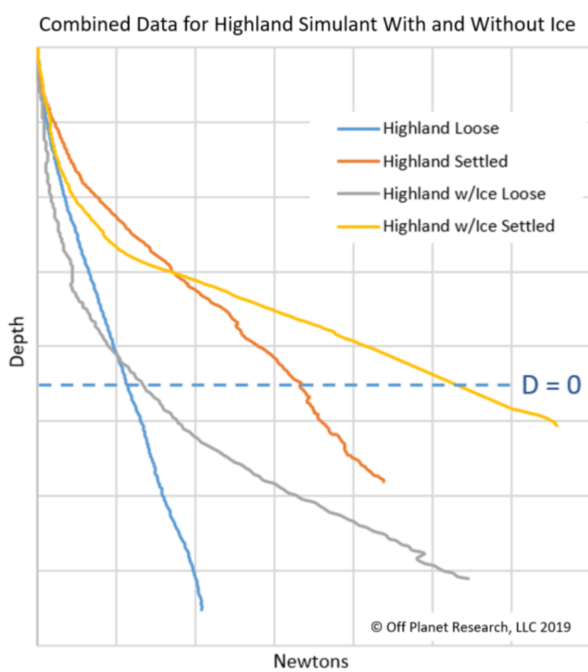

Figure 3: *Comparison of the stress/strain curves produced by pushing a replica Lunokhod penetrometer tip into "dry" and ice-bearing lunar regolith simulants during experiments at OPR.*

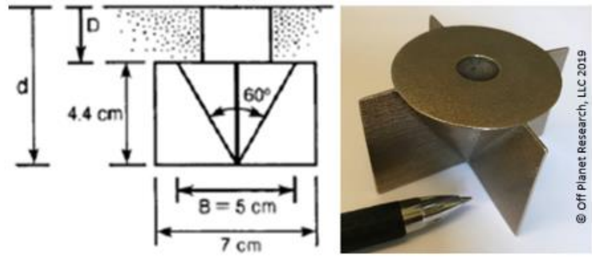

Figure 4: *Lunokhod cone-blade penetrometer tip specifications from pg. 511 of the Lunar Sourcebook [3] (left). 3D printed steel replica of the Lunokhod penetrometer tip (right) produced by OPR.*

Results and Next Steps: These experiments are providing valuable insights into the physical nature and behavior of lunar polar ice/regolith mixtures in a variety of conditions. Understanding the dynamics and characteristics of this valuable and unique material is crucial to the success of missions to lunar PSRs, and the development of lunar resources in support of a larger space economy and an enduring human presence in space. There is a great deal more work that must be done to ensure that all of these important goals are realized.

Figure 1: *Simulated lunar ice formed by freezing gaseous ice components onto super-cooled lunar Highland regolith simulant before it is mixed in during the ice manufacturing process.*

References:

[1] Gertsch, L. & Gustafson, R. & Gertsch, L. (2006). *Effect of Water Ice Content on Excavatability of Lunar Regolith.* 813. 10.1063/1.2169290.

[2] Colaprete, A. et al. (2010) *Detection of Water in the LCROSS Ejecta Plume. Science* 330, 463, DOI:10.1126/science.1186986.

[3] Heiken, G. et al. (1991) *Lunar Sourcebook a user's guide to the Moon*. Cambridge University Press ISBN 0-521-33444-6