APPLIED LUNAR SCIENCE ON *ARTEMIS III* IN SUPPORT OF IN SITU RESOURCE UTILIZATION.

L. Keszthelyi[1], K. A. Bennett[1], L. R. Gaddis[1], L. R. Ostrach[1], L. A. Edgar[1], [1]USGS Astrogeology Science Center, Flagstaff, AZ 86001

The *Artemis* Science Goals and Strategy are focused on basic or fundamental science, neglecting the vital field of "applied" geoscience that fits between "pure" science and engineering to provide near-term practical benefits for human activities. However, the need for applied lunar science in support of *in situ* resource utilization (ISRU) is called out by the community documents that feed into the *Artemis* science plan (e.g., Goal 7b from [1] and Objective FF-A-4, FF-C-11, and Sust-B-9 from [2]). To meet the goal of a sustained human presence by 2028 (or anytime soon thereafter), it will be necessary for even the first landed *Artemis* mission to include activities that build toward ISRU.

One of the principal reasons for *Artemis III* to be a polar mission is to prepare for the utilization of polar volatiles trapped in or around the cold traps associated with the permanently shadowed regions of the Moon. However, recent studies indicate that there are sufficient engineering and life support challenges involved with working in these coldest parts of the Moon that make crew activities in those areas very high risk and dependent on the properties of the specific landing site. A lower risk approach would be to initially focus on ISRU involving lunar regolith. Given that regolith is ubiquitous on the Moon, such activities should be possible at any landing site and involve essentially no extra risk to the crew or mission.

While the *Apollo* missions and extensive global remote sensing of the Moon have provided us with much information about regolith properties [e.g., 3], there are key unanswered practical questions that an applied geoscience approach can address. For example, the geotechnical properties of the regolith as a function of depth and processing are hard to determine. The stability of slopes cut into the regolith is an important consideration in determining how one should excavate regolith. However, this property is difficult to characterize on Earth given the limitations of lunar regolith simulants and our ability to create low-gravity vacuum conditions at scale with appropriate temperature variations and mechanical disturbances. Vertical and lateral variations in grain size distributions, compaction, and composition are also not well-known at the scale of a regolith excavator. There simply is no substitute for ground truth data from the lunar surface (Fig. 1).

Simple measurements of forces and torques while sampling regolith would meet the threshold objectives of an applied geoscience investigation of lunar regolith ISRU (green elements in Table 1). Measuring torques is expected during the drilling to collect regolith cores and will provide information of the type collected by *Apollo* astronauts. The addition of strain gauges on the handles of rakes and scoops would provide important information especially relevant for future ISRU activities involving regolith excavation (Fig. 2). If the data collected by these sensors are downloaded automatically and wirelessly, there will be no extra training or EVA time required of the *Artemis III* crew. High-resolution stereo video of the sampling activities would provide essential complementary data on the geometry and rates of motion that correspond to the measured forces.

The baseline experiment (blue elements in Table 1) would involve some limited activities by the human crew directed specifically toward collecting key geotechnical information on disturbed regolith. This is the type of material that would be fed into an ISRU processor and that a robotic excavator/transporter would need to traverse. Scooping and trenching of the regolith near the lander toward the end of the surface mission could take as much as a few tens of minutes of precious EVA time but should not require significant additional training. It may be extremely valuable to have the crew test a few different techniques for excavating and transporting regolith to take full advantage of the unparalleled capabilities humans bring to the lunar surface.

An enhanced experiment (yellow elements in Table 1) would take advantage of any prototype ISRU processor or robotic excavator/transporter that the *Artemis III* mission might carry. It will be important to return samples of the products of such tests for study on Earth. Comparing the actual results to predictions based on experiments on Earth is an essential step toward reducing risk in having human missions rely on lunar ISRU.

In summary, these applied science activities fall outside the realm of traditional planetary science but are of immense importance to allow a sustained human presence on extraterrestrial bodies. The experiment described here has limited risk and impact on other crew activities. It is independent of the specific landing site and clearly demonstrates that *Artemis* is not repeating what we have done before but is reaching beyond what *Apollo* achieved.

References: [1] LEAG (2017) Advancing Science of the Moon, https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf. Lunar Exploration Roadmap Steering Committee (2016) The Lunar Exploration Roadmap, Version 1.3, https://www.lpi.usra.edu/leag/LER-2016.pdf. [3] McKay, D.S. et al. (1991) Chapter 7, Lunar Sourcebook. [4] Schuler, M.J. et al. (2019) Lunar ISRU 2019 Conf., Abstract #5061 https://www.hou.usra.edu/meetings/lunarisru2019/pdf/5061.pdf.

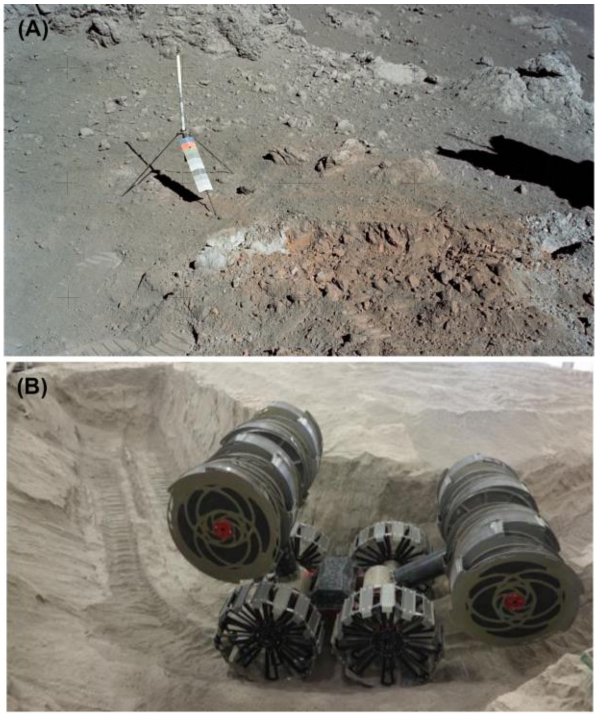

Figure 1. (A) Apollo 17 image AS17-127-20990 showing that vertical walls ~10 cm tall can be made in lunar regolith. (B) NASA JSC RASSOR vehicle trenching ~1 m into BP-1 lunar regolith simulant [4]. Will such a deep trench with vertical walls really be possible on the Moon?

Figure 2. Jack Schmitt sampling regolith on *Apollo 17*. Important geotechnical parameters can be obtained from similar crew activities on *Artemis III* if the forces applied to the tools can be measured, for example by adding strain gauges to the rake handle. Much effort was taken during *Apollo* to obtain samples of pristine regolith. For ISRU, the nature of disturbed regolith is also important to characterize.

Table 1. Science Traceability Matrix for an applied geoscience experiment on the *Artemis III mission* to support regolith ISRU. Green denotes the threshold experiment, blue + green is the baseline, and the yellow elements are enhancement options if prototype ISRU processors are part of the mission.

Goals	Objectives	Measurements	Observables
Understand how lunar regolith can be used for ISRU	Determine the depth of accessible regolith	Mechanical and physical properties of regolith as a function of depth	Forces on drills/scoops while trenching and coring; stability of slopes cut to various depths into regolith
	Determine the geotechnical properties of disturbed regolith	Mechanical and physical properties of regolith that has been disturbed by crew activities	Forces on scoops, wheels and/or rakes in disturbed areas; stability of features pressed into regolith
	Determine the rate at which regolith can be delivered to the processor	Rate regolith is delivered to the processor as a function of distance and depth	Fraction of regolith lost in transport; time and energy to transport as a function of distance and depth
	Determine the difference between processing regolith simulant on Earth and actual lunar regolith on the Moon	Mechanical properties of processed regolith	Abrasion resistance, tensile and compressional strength etc., of lunar “bricks” compared to simulants on Earth.
		Efficiency of oxygen extraction from regolith	Oxygen content of regolith before and after processing; mass of oxygen collected; impurities in collected gas