

## STANDARD LUNAR REGOLITH SIMULANTS FOR SPACE RESOURCE UTILIZATION TECHNOLOGIES DEVELOPMENT: EFFECTS OF MATERIALS CHOICES.

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**Introduction:** As NASA turns its exploration ambitions towards the Moon once again, the research and development of new technologies for lunar operations face the challenge of meeting the milestones of a fast-paced schedule, reminiscent of the 1960's Apollo program. While the lunar samples returned by the Apollo and Luna missions have revealed much about the Moon, these priceless materials exist in too scarce quantities to be used for technology development and testing. The need for mineral materials chosen to simulate the characteristics of lunar regoliths is a pressing issue that is being addressed today through the collaboration of scientists, engineers and NASA program managers. The issue of reproducing the properties of lunar regolith for research and technology development purposes was addressed by the recently held 2005 Workshop on Lunar Regolith Simulant Materials at Marshall Space Flight Center. The recommendation of the workshop of establishing standard simulant materials to be used in lunar technology development and testing will be discussed here with an emphasis on space resource utilization. The variety of techniques and the complexity of functional interfaces make these simulant choices critical in space resource utilization.

**Standard Lunar Regolith Simulants (SLRS):** A lunar simulant is manufactured from terrestrial components for the purpose of simulating one or more physical and chemical properties of the lunar regolith. A *root* simulant represents an end-member in terms of simulant properties, and a *derivative* simulant is formed from a root by modification or addition of material [1]. The degree of duplication of soil characteristics in the simulant is the simulant *fidelity*. The 2005 Workshop recommended production of two root simulants corresponding to a low-Ti mare basalt and a high-Ca highland anorthosite. These roots represent compositional end-members of mare and highland materials, and can in principle be physically mixed to target the range of soil compositions in the Apollo inventory. Specific lunar regolith properties can be addressed by addition of ilmenite, glassy agglutinates, nanophase iron, and other materials [2]. The fidelity of root simulants is thus increased by addition to form derivative simulants. While the larger size fraction of the lunar regolith has been reproduced in several simulants in the past, little attention has been paid to the 'fines' fraction, commonly referred to as lunar dust. As reported by McKay and Carrier, this fraction of the

lunar regolith below 20 microns can represent up to 30% by mass of the total regolith [3]. Lunar dust simulants are critical for studies on human toxicology and mechanical abrasion and fouling of systems including space resource utilization technologies.

**Importance of using SLRS in space resource utilization:** Lunar regolith simulants have a grain size distribution and distinct modal mineralogy at each size fraction that must be retained in order to match the target lunar regolith. As the sample size is reduced, at some point it is no longer representative. The deviation in properties is typically monitored by chemical analysis using major, minor, and trace element analytical data of progressively smaller sample sizes, and comparing these data with replicate analyses performed on bulk material. This problem is illustrated in the case of lunar simulant MLS-1 [4], where a ~10% variation in SiO<sub>2</sub> is observed, compared to a 160% variation for Cr. This is a chemical contrast effect, illustrating small differences in the major element Si for silicates, but large differences for the trace element Cr. Such variations play an important role in the behavior of the simulant when chemically processed for elemental extraction or transformation. The standardization of the modal composition of these simulants is also critical to obtain accurate simulation of phase diagrams and related properties such as viscosity at given temperatures and pressures.

Similarly, geotechnical properties may be dominated by a large difference in mineral hardness, and rogue grains would stand out in tests using too small a quantity of material. The variability of simulant material thus is an inherent property but must be taken into account for both quality control and for simulant use by the scientific community.

**References:** [1] Sibille L. et al. (2005) *Lunar Regolith Simulant Materials: Recommendations for Standardization, Production and Usage*, NASA Technical Publication. [2] Taylor L. et al. (2004) Space Resources Roundtable VI, 46. [3] D.S. McKay et al. (1991) Ch. 7 in *Lunar Sourcebook*, Eds. G. Heiken, D. Vaniman, B.M. French; and W.D. Carrier et al. (1991) Ch. 9 in *Lunar Sourcebook*, Eds. G. Heiken, D. Vaniman, B.M. French; [4] Weiblen P.W., Murawa M.J., and Reid K.J. (1990) *Engineering, Construction and Operations in Space II*, ASCE, 428-435.