Entry title: Lunar Simulants

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Synonyms: Lunar Regolith Simulants, Lunar Soil Simulants

Definition: Material comprised of terrestrial components that mimic aspects of lunar regolith

Main Text:

Application: Lunar simulants are terrestrial materials that mimic aspects of lunar regolith for testing of technology that would interact with lunar surface material. The goal of simulants is mission risk reduction by providing confidence, through testing with simulants, that a technology will perform as designed on the lunar surface. Lunar simulants are often used in education and outreach activities to increase public knowledge about lunar surface materials and to inspire the next generation of space explorers.

Need for Simulants: Sufficiently large quantities of lunar materials do not exist to test large-scale equipment such as excavators, drills, and many in-situ resource utilization technologies. In order to increase the Technology Readiness Level [Banke and Werries, 2010] of a device for flight, it must be tested in a relevant simulated operation environment; lunar simulants provide the simulated lunar regolith for this testing. The material allows technology developers to characterize the interaction of hardware components with the regolith and the consequences of such interaction, as well as the processing efficiency of the technology to produce a desired resource.

Types of Simulants: Different types of simulants exist for the testing of different types of lunar surface technology. For example, excavation equipment can be tested effectively with minimally-weathered terrestrial crushed basalt, whereas an oxygen production technology would need a simulant with a more specific geochemical and mineralogical match to lunar regolith as an indicator of processing efficiency on the lunar surface. Thus, different grades of simulants are produced. Excavation-grade simulants are relatively inexpensive and mimic the bulk geotechnical properties of lunar regolith. Geochemical and mineralogical simulants are more expensive; some components must be produced in a laboratory environment because the temperatures, pressures, and environments of formation of lunar rocks do not exist naturally on Earth. Components such as agglutinates, including some with nanophase iron, have been produced in terrestrial laboratories and are included in a small number of lunar simulants.

Producing a Simulant: Guidelines, recommendations, and considerations for the production of a simulant can be found in Schrader et al. [2009, 2010]. This work includes established Figures of Merit, which are used to determine how well a simulant replicates properties of real lunar material. Currently, four Figures of Merit exist to compare simulants with the lunar samples they are designed to mimic. They are composition (including the bulk mineralogy and geochemistry of the simulant), particle size distribution, particle shape, and density [Schrader et al., 2009 and 2010].

The cost of producing a simulant is a consideration as well. The cost includes the amount of feedstock to be processed, mining the feedstock (which may include choosing individual rocks by hand), shipping the feedstock, beneficiating the feedstock if necessary, producing the feedstock in the laboratory if components cannot be found on Earth, purchasing trace minerals (sometimes gemstones), purchasing or maintaining equipment for processing feedstock, processing the feedstock into simulant, waste

material from processing, documenting the production of a simulant, as well as overhead, advertising, characterization, storage, and shipping the simulant. The cost of manufacturing does not include the work required to choose a lunar sample or set of samples to emulate, design the simulant, and locate suitable feedstock materials.

Limitations of Simulants: No simulants to date replicate the lunar surface material perfectly. Understanding the properties of the simulants, how they differ from lunar regolith, and how that difference impacts test results is extremely important. As important is the selection of a proper simulant for the task at hand. An excavation-grade simulant will not be geochemically analogous to lunar materials, as it is not cost-effective to include the often expensive trace phases that are applicable to some resource extraction technologies.

Examples of Simulants: Simulants highlighted here provide examples of the types of lunar simulants; this should not be considered a comprehensive list of lunar simulants. Simulants are being created all over the world and used up routinely.

Black Point 1 (BP-1): The Black Point lava flow, an alkaline basalt from northern Arizona in the United States, is mined commercially for aggregate. The BP-1 simulant is produced from waste material from the crushing process [Rahmatian and Metzger, 2010]. This simulant was not designed to resemble a specific lunar sample, but it does mimic much of the geotechnical properties of lunar regolith.

Chinese Academy of Sciences 1 (CAS-1): Low-titanium mare basalt simulant produced from a basaltic cinder cone in Jilin Province, China, and similar to Apollo sample 14163 [Zheng et al., 2008].

Chenobi: A highlands simulant made from the same Shawmere Anorthosite material as its predecessor simulant OB-1 (olivine bytownite 1) [Richard et al., 2006] and containing laboratory made glass from the same anorthosite material.

Fuji, Japan Simulant 1 (FJS-1): A ground basalt from Mount Fuji, Japan, used to mimic the geotechnical properties of lunar regolith [Kanamori et al., 1998]. Other types (-2 and -3) of the FJS simulant contain additional olivine, and olivine and ilmenite, respectively [Kanamori et al., 1998].

Johnson Space Center 1 (JSC-1) series: Low-titanium mare basalt simulant produced from a basaltic cinder cone (Merriam Crater) near Flagstaff, Arizona with a general mare basalt composition but most similar to Apollo sample 14163 [Allen, 1993].

Minnesota Lunar Simulant 1 (MLS-1): High-titanium mare basalt simulant produced from a gabbro sill emplaced in the Duluth Complex (Minnesota, United States) and designed to mimic Apollo sample 10084 [Weiblen and Gordon, 1988]. A synthetic glass was later added to the simulant to further mimic the properties of lunar soil [Weiblen et al., 1990].

National Aeronautics and Space Administration / United States Geological Survey - Lunar Highlands Type (NU-LHT) series: Highlands simulant based on an average composition of Apollo 16 regolith samples and produced from rocks of the Stillwater Complex (Montana, United States) with laboratory-developed glasses [Stoeser et al., 2011]. The second generation of NU-LHT simulant contains trace apatite, pyrite, and synthetic whitlockite [Stoeser et al., 2011].

References

Allen CC (1993) New lunar simulant available. Space Resources News 2(4): 1-2.

Banke J and Werries M (2010) Technology Readiness Levels Demystified. In: Aeronautics Topics. National Aeronautics and Space Administration.
https://www.nasa.gov/topics/aeronautics/features/trl_demystified.html Accessed 20 August 2017

Kanamori H, Udagawa S, YoshidaT, Matsumoto S, and Takagi K (1998) Properties of lunar soil simulant manufactured in Japan. Paper presented at the American Society of Civil Engineers 6th Engineering, Construction, and Operations in Space conference, Albuquerque, 26-30 April 1998

Rahmatian LA and Metzger PT (2010) Soil test apparatus for lunar surfaces. Paper presented at the American Society of Civil Engineers Earth and Space 2010 conference, Honolulu, 14-17 March 2010

Richard J, Boucher DS, and Battler MM (2006) Lunar physical simulant evolution, production, and use. Paper presented at the 8th Space Resources Roundtable, Golden, 31 October to 2 November 2006

Schrader CM, Rickman DL, McLemore CA, Fikes JC, Stoeser DB, Wentworth SJ, McKay DS (2009) Lunar Regolith Characterization for Simulant Design and Evaluation Using Figure of Merit Algorithms. Paper presented at the 47th American Institute of Aeronautics and Astronautics aerospace sciences meeting, Orlando, 5-8 January 2009

Schrader CM, Rickman DL, McLemore CA, Fikes JC (2010) Lunar regolith simulant user's guide. National Aeronautics and Space Administration Technical Memorandum NASA/TM-2010-216446

Stoeser D, Rickman D, and Wilson S (2011) Design and specifications for the highland regolith prototype simulants NU-LHT-1M and -2M. National Aeronautics and Space Administration Technical Memorandum NASA/TM-2010-216438

Weiblen PW, Gordon K (1988) Characteristics of a simulant for lunar surface materials. Paper presented at the 2nd conference on lunar bases and space activities of the 21st century, Houston, 5-7 April 1988

Weiblen PW, Murawa MJ, and Reid KJ (1990) Preparation of simulants for lunar surface materials. Paper presented at the American Society of Civil Engineers 2nd Engineering, Construction, and Operations in Space conference, Albuquerque, 22-26 April 1990

Zheng Y, Wang S, Ouyang Z, Zou Y, Liu J, Li C, Li X, and Feng J (2008) CAS-1 lunar soil simulant. Advances in Space Research 43(3): 448-454