

NASA LUNAR REGOLITH SIMULANT PROGRAM. J. Edmunson¹, W. Betts², D. Rickman³, C. McLemore³, J. Fikes³, D. Stoesser⁴, S. Wilson⁴, and C. Schrader⁵, ¹BAE Systems/NASA Marshall Space Flight Center (National Space Science and Technology Center, 320 Sparkman Drive, VP61, Huntsville AL 35805, Jennifer.E.Edmunson@NASA.gov), ²Universities Space Research Association, ³NASA Marshall Space Flight Center, ⁴U.S. Geological Survey, ⁵Oak Ridge Associated Universities/NASA Marshall Space Flight Center.

Introduction: Lunar regolith simulant production is absolutely critical to returning man to the Moon. Regolith simulant is used to test hardware exposed to the lunar surface environment, simulate health risks to astronauts, practice *in situ* resource utilization (ISRU) techniques, and evaluate dust mitigation strategies. Lunar regolith simulant design, production process, and management is a cooperative venture between members of the NASA Marshall Space Flight Center (MSFC) and the U.S. Geological Survey (USGS). The MSFC simulant team is a satellite of the Dust group based at Glenn Research Center. The goals of the cooperative group are to (1) reproduce characteristics of lunar regolith using simulants, (2) produce simulants as cheaply as possible, (3) produce simulants in the amount needed, and (4) produce simulants to meet users' schedules.

Simulant Nomenclature: Simulants are often named by the place they were created (e.g., JSC from Johnson Space Center), and/or by the type of geologic feature they are designed to reproduce (e.g., NU-LHT simulant was created by NASA and the USGS and is a Lunar Highlands Type regolith simulant). Further designation of the particle size may also be present (e.g., D = dust, F = fine, M = medium, and C = coarse). These designations are often accompanied by a number indicating the version of the simulant.

Currently Available Simulants: The most famous simulant currently available (in very limited quantities) is JSC-1A. This simulant was designed to replicate many properties of low-titanium lunar mare regolith, matching the composition of the Apollo 14 site (which is a mixture between highlands and mare compositions). Coarse and fine variants, JSC-1AC and JSC-1AF, are also available. These simulants are manufactured by ORBITEC inc. ORBITEC has also attempted to design simulant containing nanophase iron, but it has been determined, through analysis by transmission electron microscopy at Johnson Space Center, that some of the nanophase particles are oxidized and thus may not correctly mimic the effect of nanophase iron in health and electromagnetism studies. However, the effects of having nanophase iron oxide in the simulant as well as nanophase iron are unknown with regards to the implication to user study results. Studies are underway to find high fidelity but low cost means to pro-

duce simulants with nanophase iron and produce nanophase iron on a scale large enough to meet user needs.

The NASA-USGS partnership has produced the NU-LHT series of highland regolith simulants, including NU-LHT-1M, NU-LHT-1D, NU-LHT-2M and NU-LHT-2C. These simulants are modeled on the average composition, particle size, and particle shape of Apollo 16 samples chosen to represent the variability of the lunar surface (in particular, core sample 64001/64002). NU-LHT-1M and 1D simulants contain only major mineral and glass phases, while 2M and 2C contain additional synthetic trace minerals for higher fidelity.

Canadian highland simulants OB-1 and CHENOBI are also available. These simulants were developed by a partnership between NORCAT and Electric Vehicle Controllers Ltd., who manufactures the simulants. In recent years, the Chinese Academy of Sciences has produced a low-titanium mare simulant, CAS-1, and a highland simulant, NAO-1. The remaining reservoir quantities of these simulants is unknown.

Extinct simulants. JSC-1, a precursor to JSC-1A, MLS-1, a high-titanium mare basalt simulant produced by the University of Minnesota, and FJS-1, the Japan Aerospace Agency's mare simulant, have been used in recent years, but are no longer available.

Simulant Characterization: No single simulant can capture the range of variation observed in the lunar regolith, and as of yet simulants do not have all the characteristics of the regolith which they are designed to duplicate. In addition, the lunar regolith has not yet been characterized to the extent necessary for extreme high fidelity simulation, which will always add to the risk associated with the development of an instrument or process that uses regolith material. To accommodate presently known variability in the regolith, multiple simulants have been created. With multiple simulants available to choose from, it is difficult to choose the proper simulant for an engineering need if one does not know the background information on the simulants, such as which lunar samples they are designed to emulate and to what extent they approximate the properties which affect the engineering objective. Choice of simulant can affect the test results, and comparing the results of studies performed with different simulants is an added complication.

Choosing the Appropriate Simulant: It is the responsibility of the lunar regolith simulant team at MSFC to communicate with simulant users (and vice versa) to make sure that everyone understands (1) what type of analyses will be completed (from health studies to excavation), (2) what scale of fidelity is necessary for the tests, (3) what properties (physical or chemical or both) of the simulants are necessary for the user, (4) what risks are associated with using particular simulants in terms of precision and accuracy of the results, and (5) what constraints (budgetary or simulant fidelity or amount needed) may affect the results of user studies. It is the responsibility of the MSFC team to (1) know the feedstocks, processes, and fidelity of lunar simulants, (2) know how well the simulants reproduce the lunar regolith, (3) encourage new simulant development techniques (e.g., the manufacture of nanophase iron and mineral separation techniques to increase simulant fidelity), and (4) understand user test results and the effects of certain regolith simulant properties on each user test (and if it is a characteristic of the lunar regolith or a failure of the simulant to accurately represent the lunar regolith that influenced the results).

Figures of Merit: Comparing regolith simulant to lunar regolith (or to another simulant) is incredibly difficult. There are many factors to include: bulk mineralogy, bulk chemistry (including volatiles), particle size, particle size distribution, lithic fragments, agglutinates, nanophase iron, vapor-deposited rims, volcanic glass beads, albedo, angularity, packing density, electrostatic charge, thermal properties, etc. Given the multitude of possible comparisons, the numerous possible measurement techniques for each comparison, and the complexity of determining which simulant would be “good” for a specific task (i.e., engineering need), the simulant group reduced the number of “Figures of Merit” (FoMs) to four: material composition, particle size distribution, particle shape, and material density. Material composition considers items like mineral composition, as well as bulk material composition (i.e., the modal composition of lithic fragments, minerals, glasses, and agglutinates). These four characteristics directly or indirectly control most of the other properties of the simulant. For each of these FoMs, numerical criteria can be utilized to compare the fidelity of the simulant to a reference sample. By comparing the FoMs, the most appropriate simulants can be identified for an engineering use. The MSFC simulant team maintains a simulant users guide and Fit-to-Use Matrix to facilitate simulant selection based on the FoMs.

Simulant Development: The MSFC-USGS partnership is developing new simulants to meet the needs of the lunar engineering community. Priorities for future simulant development include producing a high-

fidelity dust simulant with nanophase iron, developing a lower-cost geotechnical grade highland simulant, and developing a high-titanium mare basalt regolith simulant for ISRU applications.

Current challenges affecting the production of regolith simulants include production of high fidelity nanophase iron, production of nanophase iron in quantities sufficient to meet demand, production of simulant in quantities large enough to meet user needs, creating or identifying terrestrial feedstock sources for plagioclase with sufficiently high An content, obtaining the proper feedstock for a more lunar-like clinopyroxene to orthopyroxene ratio, and funding the proper development and characterization efforts.

Contact: The MSFC simulant team posted an online survey/request for simulant for users to complete, indicating the purpose of their research, the particular qualities of lunar regolith they are interested in, and the quantity they require for their needs. This survey is located at <http://isru.msfc.nasa.gov/lunarsurvey/>. Once the survey is completed, members of the MSFC simulant team will contact the user in order to better understand user hardware and test objectives, and provide advice regarding simulant selection and use. Once the users complete their studies, it is the responsibility of the user to contact the MSFC simulant group to report test results relevant to the simulant, and allow the simulant group to ascertain the needs of simulant users for future simulant development. Without this vital feedback, the simulant group cannot produce better simulants in the future.

Introduction

Lunar regolith simulant is a vital for proving technology that will be exposed to and used on the lunar surface. This includes systems to ensure astronaut health, equipment to utilize resources found on the Moon, tools or techniques to mitigate the effects of dust on machinery and humans, lunar rover mobility, and human habitat design. Excepting commercial lunar regolith simulant suppliers, the design, production process development, and engineering support for lunar regolith simulant use is a cooperative venture between members of the NASA Marshall Space Flight Center (MSFC), the U.S. Geological Survey (USGS), and Glenn Research Center. The lunar regolith simulant project is funded by the NASA Exploration Technology Development Program.

Goals

- Reproduce characteristics of lunar regolith using simulants
- Develop processes to controllably reproduce regolith characteristics
- Produce simulants as cheaply as practical
- Produce simulants in the amount needed
- Produce simulants to meet users' schedules

Challenges

- **Nanophase iron**
Various techniques to produce nanophase iron in simulants have not met with success. Research into the production of nanophase iron, as well as scaling up the production to be sufficient for users' needs is ongoing. Promising results by patented techniques have been recorded, and the addition of nanophase iron into simulant is forthcoming.
- **Fidelity grades**
Inclusion of nanophase iron as well as (fairly expensive) trace mineral phases is necessary for a high fidelity simulant. However, not all tests require such high fidelity simulant. Massive amounts of simulant required for excavation technology would be prohibitively expensive if small amounts of trace phases were added. Thus, an excavation grade simulant, a relatively low fidelity simulant, is being developed.
- **Characterization of the lunar regolith**
Sufficient analyses of the Apollo lunar regolith samples have not been obtained to reproduce the characteristics of the regolith by milling techniques. Characterization of Apollo regolith samples is also included in this project.
- **Choosing the appropriate simulant**
Significant variation in the lunar regolith has led to the creation of multiple simulants. Each simulant has unique characteristics that are well suited to different testing purposes. It is important to understand what types of analyses will be completed (from health studies to excavation), what scale of fidelity is necessary for the tests, what properties (physical or chemical or both) of the simulants are necessary for the user, what risks are associated with using particular simulants in terms of precision and accuracy of the results, and what constraints (budgetary or simulant fidelity or amount needed) may affect the results of the user studies.

Future Work

The group will soon develop an excavation grade simulant, as well as a high-titanium mare regolith simulant for in situ resource utilization technology applications. The team also encourages new technology to increase the fidelity of simulants, including the development of nanophase iron, increased agglutinate fidelity, and mineral separation techniques for ease of feedstock use. The group also continues to speak with simulant users to understand their needs and modify development processes if necessary.

Some Available Simulants



JSC-1A

- Developed at Johnson Space Center
- Second version (JSC-1 was the predecessor)
- Designed to match Apollo 14 regolith sample 14163 (mixture between a highlands and mare composition)
- Coarse (JSC-1AC) and fine (JSC-1AF) fractions are available
- Manufactured by ORBITEC



NU-LHT-2M

- Developed by NASA and the USGS
- Lunar Highlands Type simulant
- Second version (2)
- Medium grain size ($\leq 1\text{mm}$) as opposed to coarse (greater range in grain size) or dust ($\leq 20\mu\text{m}$)
- Manufactured by the USGS; 1M, 1D, 2M, and 2C available

CHENOBI

- Developed by NORCAT with Electric Vehicle Controllers Ltd. (EVC) and manufactured by EVC
- Highlands simulant
- Increase in geochemical fidelity from predecessor simulant OB-1



Contact Information

An online survey/request for simulant can be found at:

<http://isru.msfc.nasa.gov/lunarsurvey/>

Once the survey is completed, members of the MSFC simulant team will contact the user in order to better understand the user hardware and test objectives, and provide advice regarding simulant selection and use.

It is requested that the simulant users share the results of their studies, particularly relevant to the simulant, with the simulant team. This will allow the simulant team to compare the behavior of the simulant to that of the lunar regolith and design future generations of simulant with higher fidelity.