NASA LUNAR REGOLITH SIMULANT PROGRAM. J. Edmunson[1], W. Betts[2], D. Rickman[3], C. McLemore[3], J. Fikes[3], D. Stoeser[4], S. Wilson[4], and C. Schrader[5], [1]BAE Systems/NASA Marshall Space Flight Center (National Space Science and Technology Center, 320 Sparkman Drive, VP61, Huntsville AL 35805, Jennifer.E.Edmunson @NASA.gov), [2]Universities Space Research Association, [3]NASA Marshall Space Flight Center, [4]U.S. Geological Survey, [5]Oak Ridge Associated Universities/NASA Marshall Space Flight Center.

Introduction: Lunar regolith simulant production is absolutely critical to returning humans to the Moon. Regolith simulant is used to test hardware that will be exposed to the lunar surface environment, simulate health risks to astronauts, practice *in situ* resource utilization (ISRU) techniques, and evaluate dust mitigation strategies. Excepting commercial lunar regolith simulant suppliers, lunar regolith simulant design, production process development, and engineering support 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. The goals of the cooperative group are to (1) reproduce characteristics of lunar regolith using simulants, (2) develop processes to controllably reproduce regolith characteristics, (3) produce simulants as cheaply as practical, (4) produce simulants in the amount needed, and (5) 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). Futher designation of the maximum 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 American simulant currently available (in very limited quantities) is JSC-1A. This simulant was intended to replicate many properties of low-titanium lunar mare regolith, matching the composition of Apollo 14 regolith sample 14163 (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. 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 perfectly mimic the effect of nanophase iron in health and electromagnetism studies. However, the effects of having nanophase iron oxide in the simulant in addition to nanophase iron are unknown with regards to the implication to user study results. Studies are underway to find high fidelity but lower cost means to produce 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 normative mineralogy of Apollo 16 regolith. The particle size matches that of JSC-1A. 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 quanitites 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; MLS-2, a highland simulant; and FJS-1, the Japan Aerospace Agency's mare simulant, have been used in recent years, but are no longer available.

Simulant Characterization: Because of the variability in lunar geology, no single simulant can capture the range of variation expected in the lunar regolith. A further complication is that the lunar regolith has not yet been characterized to the extent necessary for extreme high fidelity simulation. This lack of detailed information is important to consider when evaluating the risk associated with the development of an instrument or process that will interact with the lunar regolith. To accommodate presently known variability in the regolith, multiple simulants have been created. With multiple simulants available, it is difficult to select the proper simulant 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 characteristics of 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 consider: bulk mineralogy, chemistry (including volatiles), particle size and 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, a numeric method for comparison has been developed at MSFC using a “Figures of Merit” (FoMs) approach. The FoMs focus on four basic concepts/properties: 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 NASA-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, and developing a lower-cost geotechnical grade highland material and a high-titanium mare basalt regolith simulant for ISRU applications.

Current challenges affecting the production of regolith simulants include identification of appropriate feedstock material with special focus on high An plagioclase (greater than An_{85}) and material with a proper clinopyroxene to orthopyroxene ratio. A second challenge is the production of high fidelity agglutinate material containing nanophase iron in sufficient quantities to meet future production needs. The necessity of producing regolith simulant in an efficient cost-effective manner is a consideration in the development and production work.

Contact: The MSFC team posted an online survey/request for simulant for users to complete, indicating the purpose of their research, the particular qualities of lunar regolith simulant 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.