A REVIEW OF LUNAR REGOLITH SIMULANTS AND THEIR APPLICATIONS.

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Introduction: Lunar regolith simulants, designed to replicate certain properties of the actual lunar regolith, are essential if robots or humans and instruments are going to emplaced on the Moon and successfully operate. Whether simulants are used in developing and advancing technologies or in verifying and certifying flight hardware here on Earth, simulants are risk reduction “tools” that will enable the success of missions to the Moon. Lunar regolith simulants have been around for well over forty years, beginning with those made during the Apollo era. The first known lunar simulants were Lunar Soil Simulant (LSS) 1 through 5, which were developed for the Apollo program by a team of geologists and soil engineers from a basalt in Napa Valley, California [1]. Simulants created post-Apollo such as JSC-1 (for Johnson Space Center, where the simulant was created), MLS-1 and MLS-2 (developed by the University of Minnesota, Minnesota Lunar Simulant), and FJS-1 (Japan Aerospace Agency) are now functionally extinct. The simulant JSC-1 was “replaced” by JSC-1A, which has become the most widely used lunar regolith simulant to date. Many other lunar simulants have been developed since the Apollo era, by many different countries, each with distinct properties and fidelities. These multiple efforts had no standard criteria of success or even of how success was defined.

After the Constellation Program was announced and NASA began the pursuit of a lunar return and establishment of an outpost, the need for lunar simulants became abundantly clear. An iniative was begun in 2004 to develop lunar simulants in a more rigorous manner. The NASA/ Marshall Space Flight Center (MSFC) was appointed to undertake this effort and develop the necessary simulants required based upon the lunar architecture. In that vein, MSFC established a Simulant Team which also includes assistance from other NASA centers, government agencies, industry and academia.

The Simulant Team itself is composed of members from MSFC, the U.S. Geological Survey (USGS), and Glenn Research Center. It is funded under the NASA Exploration Technology Development Program. The team has many interrelated tasks. They gather knowledge regarding simulants produced globally. They define standards of measurment. They assess known properties of the Moon, in turn identifying lunar properties whose values are unknown but needed, and then analyzes lunar regolith to determine the needed values, The team develops new simulant prototypes to fill the gap where existing simulants are not adequate, evaluates simulants for different engineering uses, and designs process controls for reproducing regolith characteristics and scaling up for mass production. The intent is the ability to produce simulants would be available through vendors who were awarded contracts.

Most importantly, the Simulant Team provides consultation to users in the appropriate selection and safe use of simulants, including their known limitations. A Lunar Regolith Simulant User’s Guide which includes a “Fit for Purpose” Matrix has been written which outlines the Team’s recommended simulants for specific applications as well as any known limitations. As new simulants are discovered and/or generated and new property data acquired, the Guide will be updated accordingly. Although the guide is updated frequently with new information, it is still important to discuss simulant uses and risks with the Team.

The Simulant Team is also prepared to begin other simulant developments in addition to lunar simulants as needs dictate. These future simulant developments could include Mars simulants, asteroid simulants, and other extraterrestrial body regolith simulants which NASA may choose to explore.

Purpose of Lunar Regolith Simulant: Regolith simulant is used to (1) test technology that will be exposed to the lunar regolith and increase technology readiness level, (2) test *in situ* resource utilization techniques, (3) simulate health risks to the astronauts and users of simulant and (4) evaluate dust mitigation techniques.

Lunar Regolith Challenges: While there is still debate within the lunar community as to the extent and expanse of the detrimental effects of lunar regolith, particularly the dust component, it is widely known that problems with unanticipated lunar regolith properties cropped up during the Apollo missions . The current lunar architecture calls for missions that will last much longer than any Apollo mission, so regolith challenges must be tackled. If hardware (including robots) and humans are expected to inhabit the lunar surface, it is imperative that more research and investigations occur on Earth first to understand the long-term effects of lunar regolith. Through testing and analyses of Apollo sample data and data collected from remote sensing satellites such as Clementine, Chang’e, Chandrian and others, needed characteristics of the regolith can be determined. From the Apollo missions, it was established that lunar regolith particles are sharp, jagged, and abrasive, and can damage, destroy, and interfer with functions of mechanisms such as bearings, gears, and connectors; thermal equipment such as radiators; power equipment, solar arrays; helmet visors, space suit joints and fabric; and optical instruments such as cameras and scientific equipment.

Lunar Regolith Opportunties: Despite the concerns and challenges of the lunar regolith, there are also many opportunities that the regolith presents. Specifically, lunar regolith can be utilized *in situ* to extract oxygen as well as metals such as titanium, aluminum and silicon. The oxygen may be used for life support and propulsion. Other elements or compounds could be used as feedstocks to fabricate new parts as well as spares, tools, habitats, and surface structures thereby reducing up mass needed from Earth. The regolith can also be used to protect humans from radiation with sufficient depth. All such technologies must first be tested with simulants on Earth.

Documented Lunar Regolith Simulants: The following is a partial list of the 28 simulants currently known to the Simulant Team. The list is by no means complete, as new simulants or higher fidelity simulant components are created all over the globe. Note that each simulant in this list has distinct properties that may be ideal for some engineering purposes, but not for others. Each is mineralogically distinct, and often emulate different portions of the lunar regolith.

JSC-1A (mixture of highlands and mare compositions, commercially available through ORBITEC [2])
NU-LHT series (NASA/USGS lunar highland type)
OB-1 and CHENOBI (highlands type, available from NORCAT/Electric Vehicle Controllers Ltd. [3])
CAS-1 (Chinese Academy of Science, low-Ti mare type, may also be known as CLRS-1)
CLRS-2 (National Astronomical Observatories, Chinese Academy of Science, high-Ti mare type)
NAO-1 (National Astronomical Observatories, Chinese Academy of Science, highland type)
GSC-1 (Goddard Space Center, mare simulant)

Characterization of Simulants: There are many factors to consider when characterizing simulants (these also apply to lunar regolith): 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, etcetera. Comparing each characteristic of regolith simulant to lunar regolith (or to another simulant) is difficult. The multitude of possible comparisons stressed the need for a numeric system for evaluating the similarities and differences. In response, the Simulant Team developed the "Figures of Merit" (FoMs) algorithms. 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.

Simulant User's Guide and Fit for Purpose Matrix: 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 (or regions) they are designed to emulate and to what extent they approximate the properties which affect the engineering objective. The choice of simulant will affect test results, inmany cases very significantly. Thus, the Simulant Team wrote a User's Guide to detail the properties of different simulants. At the end of the User's Guide is a Fit for Purpose Matrix. The Matrix shows general use categories (e.g., excavation or oxygen extraction) and evaluates the simulants accordingly. It is important to recognize that the Matrix is for general use guidelines – specific engineering tasks, such as habitat building materials, may have specific properties (e.g., a chemical reaction) that require the use of a high-fidelity mineral simulant instead of an lower fidelity simulant. Repeated experience has demonstrated it can be important to contact the Simulant Team regarding the appropriate simulant to use, the limitations of use, and the consequent risks associated with simulant use. Contact information as well as the User's Guide can be found at http://isru.msfc.nasa.gov/lunarsurvey.

Application to Other Planets/Asteroids: The Simulant Team is equipped to adapt to new destinations for robotic or manned missions, including Mars and asteroids. Information regarding "space weathering" that applies to the lunar regolith is applicable to asteroid surfaces exposed to the space environment. Martian simulants may be easier to produce than lunar simulants given that weathering/alteration processes are common to both Mars and Earth, and are similar on both planets. Regardless of the ultimate destination, simulants are vital for the testing of technology.

References: [1] Sibille L. et al. (2006) NASA Technical Report 2006-214605. [2] ORBITEC website: http://www.orbitec.com/store/simulant.html. [3] NORCAT website: http://www.norcat.org/Innovation-regolith.aspx.