

DESIGN OF NU-LHT-5M AND -6M, LUNAR HIGHLAND SIMULANTS. Douglas Rickman¹, Holly Shulman², Matthew Creedon³, Mike Effinger⁴. ¹Jacobs (Jacobs Space Exploration Group/NASA Marshall Space Flight Center, Huntsville, AL, 35812, douglas.l.rickman@nasa.gov), ²Unaffiliated, (DrHollyShulman, LLC, Belmont, NY 14813, drhollyshulman@gmail.com), ³Washington Mills (Washington Mills, 1801 Buffalo Ave., Niagara Falls, NY 14302-0423, mcreedon@washingtonmills.com), ⁴NASA (NASA Marshall Space Flight Center, Huntsville, AL 35812, michael.r.effinger@nasa.gov).

Introduction: With NASA's plans to return to the Moon, and specifically to a landing site at the lunar South Pole, additional high-fidelity simulant is sorely needed. Here we describe the design and efforts for the production of new highlands simulants using natural analog materials (NU-LHT-5M) and fully synthetic materials (NU-LHT-6M).

Background: It is difficult to make a general-purpose lunar highland simulant. Stoesser and Rickman [1] concluded that, in contrast to the Merriam Crater volcanic ash, which is the feedstock for the JSC-1 series of lunar mare simulants, no single terrestrial rock could be milled to produce a high quality, general use simulant of the lunar highland regolith. Using the average chemical composition of the Apollo 16 samples as a target [2], it was concluded that multiple rock-types would have to be acquired, milled and blended. Further, as no natural glass source of appropriate composition exists, glass would have to be made.

Of all the many potential rock sources examined, the Stillwater Complex of Montana had multiple, major advantages for this work. Multiple desired rock-types were available in close proximity to each other. There was an active mine in the Complex, making access to the rock-types practical. In principle, enormous tonnages of the desired rocks could be available. The rocks were in the United States, significant for strategic access and greatly simplifying shipping. The metamorphic grade and intensity of metamorphism are both relatively low for such terrestrial rocks. Surficial weathering products are very minimal. And importantly, the mine operator was very cooperative. Hand selected Stillwater rocks were milled, an accurate glass and synthetic agglutinate fabricated, minor/trace minerals added, and collectively blended together to make what became the NU-LHT-2M (NASA-USGS Lunar Highland Type-design 2, medium, i.e. <1 mm particle size) simulant [3]. Arguably, this simulant is the most complex and sophisticated lunar simulant made to date. Other simulants in this series include -1M, -2C, -3M, and -4M. Each was designed for specific purposes.

As opposed to mass production, the primary purposes of the simulants design and creation was to "develop reproducible basic methodologies and procedures to produce simulants and to match the

modal mineralogy and glass content and grain-size distribution of the Apollo 16 regolith samples as closely as possible" [2]. Partially in consequence of these goals, the supply of these simulants was limited.

The glass fabrication capability of Zybek Advanced Products, Boulder, CO, which was used in making the original series, no longer exists. Dr. Steve Wilson of the USGS, who made the existing simulant, has retired without the critical transfer of know-how. Together these make producing more of the existing simulants impractical.

NASA projects and partners have substantial needs for large volumes of high-fidelity simulants. For example, the MSCC (Microwave Sintering Construction Capabilities) project at MSFC needs multiple tons of simulant in the NU-LHT-series to test microwave sintering technology. Therefore, new options for simulant production had to be created, and it was decided to develop new simulants in the NU-LHT-series, based on NU-LHT-2M. Progress toward this end are well advanced. Doing so took advantage of the extensive work previously done on the series, with consequent shortening of schedules and lowered developmental cost. It would also be possible to utilize existing stockpiles of Stillwater rocks while proving out manufacturing. Development of both simulants are now well advanced.

Considerations: Simulant development would be done in two major stages, resulting in NU-LHT-5M and NU-LHT-6M. The former had 4 primary objectives in its development: speed, cost, large scale commercial production, and fidelity. NU-LHT-6M, had the additional objective of being made from synthetic minerals as much as practical.

NU-LHT-5M uses Stillwater rocks, and synthetic glass. The challenges would be to make the glass, and to do the milling and mixing of the disparate materials to match the target particle size distribution. NU-LHT-6M will be made with purely synthetic minerals: anorthite, enstatite, diopside, and forsterite, as well as synthetic glass. Note, neither simulant was designed with an agglutinate-like material, thus both qualify as medium fidelity in the terminology of NASA Lunar Simulant Advisory Team.

Making the simulant at larger scales via an industrial plant was desired to reduce per ton costs, which is quite different from costs per kg. Inherently,

this also means there could be no product customization and quantities will be made in multi-ton lots once development ends.

While industrial scales might result in a major cost advantage, it certainly introduces problems not previously addressed in simulant manufacturing. To work on the necessary development, Washington Mills of Niagara Falls, NY, a major producer of electro fused minerals, has agreed to collaborate with NASA in the development of these simulants.

Design: According to [4] and then internationally adopted as an ISO standard [5], four properties are used to robustly characterize a lunar simulant: composition (mineralogy and glass), particle size distribution, particle shape distribution, and density. In this design, composition and particle size distribution are specified, while particle shape and density are not strictly specified. To date, within our knowledge, the latter two are not controlled by any manufacture of lunar simulants.

Specifications for NU-LHT-5M are given in the following sections:

Crystalline mineralogy. Stillwater anorthosite, Stillwater norite, and a commercial olivine will be mixed in the ratios 17.6/37.7/4.7, totaling 60% of the mass in the simulant. These proportions are identical to those of NU-LHT-2M. The minor and trace minerals: ilmenite, pyrite, whitlockite, fluorapatite, which were used in NU-LHT-2M, are not included. Together, these 4 minerals total only 0.8wt% in NU-LHT-2M. Not including them at this stage was done to save time and costs, with very minimal sacrifice of simulant fidelity to the Apollo 16 target.

High Quality (HQ) Glass. This term was used in the development of the NU-LHT-series to denote glass that is functionally lacking in any crystalline material, and also lacking in vesicles. It was the original intention to make the NU-LHT-2M glass by melting some of the milled and mixed crystalline material. However, during development it was decided to use the waste product from the Stillwater Mine mill, termed “Mill Sand”, see Table 1. This simplified the work and conserved the limited amount of crystalline material. In contrast, for NU-LHT-5M the HQ glass is being made from commercially available oxides. In addition, there is a return to the precise baseline Apollo 16 average (less the trace elements). The biggest difference this will introduce is an increase in the fidelity of the glass by raising the amount of calcium in NU-LHT-5M versus -2M. This will raise the melting temperature of this glass compared to the -2M glass, making it a more realistic analog material. At a glass content of 40 wt%, the NU-LHT-5M and -6M designs call for substantially more HQ glass than was called for in the NU-LHT-2M design. -2M was specifically aimed at an immature regolith.

Particle Size Distribution. The target particle size distribution for NU-LHT-5M and -6M is from Table 1 of Carrier [6], and formally accepted by NASA [7]. It is noted that staying within the ± 1 standard deviation limits in the final product is difficult, with feedstocks having significantly different milling properties.

Conclusion: NASA needs substantial tonnage of cost effective, highland simulant of high quality. NU-LHT-5M and -6M designs are aimed specifically at that target. As a result, many refinements in -2M are not included, with little loss of utility. Finally, by proving out these simulants, NASA is preparing for the next missions and new *in situ* analyses to provide new targets for simulant design and manufacture. These designs and their corresponding manufacturing technology are easily amended.

Table 1 High Quality Glass for NU-LHT-5M & -6M

Oxides	Apollo 16 Average [2]	Stillwater Mill Sand	NU-LHT- 5M
SiO ₂	45.09	46.6	45.1
TiO ₂	0.56	0.115	0.6
Al ₂ O ₃	27.18	21.55	27.2
Fe ₂ O ₃	5.18	5.65	5.2
MnO	0.065	0.09	-
MgO	5.84	9.5	5.8
CaO	15.79	12.6	15.8
Na ₂ O	0.47	0.965	0.5
K ₂ O	0.11	0.12	-
P ₂ O ₅	0.12	0.07	-
Cr ₂ O ₃	0.107	0.12	-
S	0.064	-	-
LOI	-	2.74	-
Sum Oxides	100.576	97.38	100.2

References: [1] Stoesser and Rickman, pers. comm, 2006. [2] Stoesser et al. (2010) “Design and Specifications for the Highland Regolith Prototype Simulants NU-LHT-1M and -2M.” NASA TM 2010–216438. [3] Stoesser, et al. (2008) “The LHT (Lunar Highlands Type) Regolith Simulant Series.” GSA Annual Meeting, Vol 40, No. 6, 40:554. [4] Rickman and Schrader. (2010) “Figure of Merit Characteristics Compared to Engineering Parameters.” NASA TM 2010-216443. [5] Slane and Rickman. (2014) “Space Systems–Lunar Simulants: ISO 10788.” [6] Carrier. (2005) “The Four Things You Need to Know about the Geotechnical Properties of Lunar Soil.” LPI. [7] Cross-Program Design Specification for Natural Environments (DSNE, SLS-SPEC-159)