THE COMPLETE SERIES OF NU-LHT LUNAR SIMULANTS. J. E. Gruener[1], D. L. Rickman[2], S. A. Wilson[3], J. E. Edmunson[2], J. E. Kleinhenz[4], L. Sibille[5], R. N. Kovtun[6], H. A. Oravec[4], K. R. Stockstill-Cahill[7], [1]NASA-Johnson Space Center (john.e.gruener@nasa.gov), [2]NASA-Marshall Space Flight Center, [3]USGS-retired, [4]NASA-Glenn Research Center [5]NASA-Kennedy Space Center, [6]Jacobs/NASA-Johnson Space Center, [7]JHU Applied Physics Laboratory.

Introduction: The National Aeronautics and Space Administration (NASA) created the Constellation Program in response to the Bush Administration's A Renewed Spirit of Discovery: The President's Vision for U. S. Space Exploration [1], and the 2005 NASA Authorization Act from the United States Congress [2]. As the Constellation program began its work, it was realized that the current supply of NASA lunar simulant (JSC-1 [3]) needed for testing of lunar surface system development, was almost exhausted. It was also realized that since global access was desired for future lunar exploration, both lunar mare and lunar highland simulants would be needed. Orbital Technologies Corporation (ORBITEC) was selected by NASA to produce a lunar mare simulant, which was referred to as JSC-1A, as it basically recreated the original JSC-1 using the same feedstock material from volcanic vents related to Merriam Crater near Flagstaff, AZ, and the same process by Dr. James Carter at the University of Texas at Dallas [4]. For the lunar highlands, NASA collaborated with the United States Geological Survey (USGS) at the Denver Federal Center in Colorado, to develop and produce a new series of simulants.

NU-LHT Series: NASA and the USGS decided to refer to their simulant as NASA-USGS Lunar Highlands Type (NU-LHT). The basis for the simulants was the Apollo 16 regolith samples, and the bulk of the feedstock for the simulants came from the Stillwater igneous complex in southern Montana [5], consisting of anorthosite, norite, and hartzburgite. Unlike the Merriam Crater feedstock, which contained about 50% volcanic glass [3], the Stillwater complex was completely crystalline. Since a large fraction of the lunar regolith contains glass (e.g., agglutinates, impact and volcanic glass, and breccias [6]), NASA and USGS decided to create glass components for their NU-LHT simulants by melting the Stillwater crystalline components.

NU-LHT-1M and -2M. NASA and USGS began their simulant development by creating a pilot simulant (NU-LHT-1M) to test out reproducible methodologies, procedures and equipment, and a prototype simulant (NU-LHT-2M) that would be produced in large amounts [5]. The primary difference between 1M and 2M is that the pilot study only specified and allowed for the major minerals (plagioclase, pyroxenes, olivine, and ilmenite); whereas, for 2M, other minor minerals were also included (i.e., synthetic whitlockite (β-tricalcium phosphate), fluorapatite, and pyrite (troilite substitute)). The glass components of these simulants, simple or "good" glass, and pseudo-agglutinate, were created from the mill waste, termed "mill sand", of the Stillwater Mining Company in Nye. MT. NU-LHT-1M had a mixing ratio 80% crystalline, 16 % agglutinate, and 4% good glass. NU-LHT-2M had a mixing ratio 65% crystalline, 30 % agglutinate, and 5% good glass. Only very small amounts of these simulants still exist for testing purposes in NASA-funded projects.

Other NU-LHT-2 simulants. NASA and USGS experimented with other prototypes, referring to them as: NU-LHT-2C was similar to -2M, but a portion of the material was partially fused to make a coarser fraction that is added back in after milling and grinding [7]. NU-LHT-2E was an attempt to simplify the development process by eliminating the milling and grinding steps, by using the mill sand (already < 600 μm) to create an 'engineering grade' simulant. NU-LHT-2EG was created by adding agglutinate material to NU-LHT-2E. Small amounts of the -2E and -2EG simulants still exist for testing purposes in NASA-funded projects.

NU-LHT-3M. This formulation was created for NASA Glenn Research Center, as another approach to making a simplified simulant primarily for mechanical testing. This simulant only consisted of Stillwater anorthosite, norite, and mill sand (Steve Wilson personal communication). Small amounts of this simulant still exists for testing purposes in NASA-funded projects.

NU-LHT-4M. As the Artemis Program began, NASA once again had dwindling stocks of lunar simulants, and commercial simulant production was just beginning to arrive on the market. To fill the gap, NASA and USGS teamed up again to produce more NU-LHT, since the focus of the Artemis Program was the lunar south pole. Existing Stillwater feedstock was used to create 1 mt of a new simulant, referred to as NU-LHT-4M. Its crystalline component predominantly consists of Stillwater anorthosite and norite, with smaller amounts of olivine, ilmenite, synthetic whitlockite, fluor-apatite, pyrite, and chromite. NU-LHT-4M has a mixing ratio 65% crystalline and 35 % agglutinate (the same as used in NU-LHT-2M). Characterization of this simulant is underway at NASA and Johns Hopkins University

Applied Physics Lab [8,9]. NU-LHT-4M is available in small amounts for testing purposes in NASA-funded projects.

Concluding remarks: The NASA-USGS-LHT simulants are some of the highest fidelity lunar simulants ever produced. Emphasis was placed on matching Apollo 16 lunar regoliths as much as possible in chemistry, modal mineralogy, glass content, particle size distribution, and particle shape. NASA is currently working with commercial simulant providers to fulfill NASA's simulant needs. A needed focus on a chemically correct glass component of lunar highland simulants is a remaining issue.

References:

[1] https://www.lpi.usra.edu/lunar_resources/pres_vision.pdf. [2] https://www.congress.gov/bill/109th-congress/senate-bill/1281. [3] McKay, D. S. et al. (1994) *Space IV*. [4] Gustafson, R. J. (2006) *AIAA 2006-7513*. [5] Stoeser, D. B. (2010) *NASA/TM-2010-216438.* [6] Simon, S. B. (1981) *JGR 91, E64-E74.* [7] Schrader, C. M. (2010) *NASA/TM-2010-216446.* [8] Kovtun, R. N. et al. (2023) *54th LPSC.* [9] Stockstill-Cahill, K. R. (2023) *54th LPSC.*