



Design and Specifications for the Highland Regolith Prototype Simulants NU-LHT-1M and -2M

D.B. Stoesser

United States Geological Survey, Denver Federal Center, Denver, Colorado

D.L. Rickman

Marshall Space Flight Center, Marshall Space Flight Center, Alabama

S. Wilson

United States Geological Survey, Denver Federal Center, Denver, Colorado

The NASA STI Program...in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

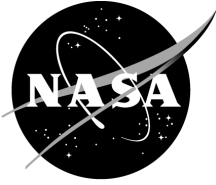
The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results...even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI program home page at <<http://www.sti.nasa.gov>>
- E-mail your question via the Internet to <help@sti.nasa.gov>
- Fax your question to the NASA STI Help Desk at 443-757-5803
- Phone the NASA STI Help Desk at 443-757-5802
- Write to:
NASA STI Help Desk
NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320



Design and Specifications for the Highland Regolith Prototype Simulants NU-LHT-1M and -2M

D.B. Stoesser

United States Geological Survey, Denver Federal Center, Denver, Colorado

D.L. Rickman

Marshall Space Flight Center, Marshall Space Flight Center, Alabama

S. Wilson

United States Geological Survey, Denver Federal Center, Denver, Colorado

National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

August 2010

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

This report is also available in electronic form at
<<https://www2.sti.nasa.gov>>

TABLE OF CONTENTS

1. INTRODUCTION	1
2. CHEMICAL COMPOSITION SPECIFICATION	2
3. SPECIFICATIONS FOR LUNAR HIGHLANDS TYPE COMPONENTS	3
3.1 Crystalline Component	3
3.2 Glass Component	5
4. MIXING SPECIFICATION	7
5. PARTICLE SIZE SPECIFICATION	8
APPENDIX	9

LIST OF FIGURES

1.	Cumulative grain size distribution for six Apollo 16 regolith samples	8
2.	Figure 2 of Carrier (1973) showing regolith grain size distribution envelope based on Carrier's compilation of grain size information for Apollo 11–15 regolith samples	8

LIST OF TABLES

1.	Average Apollo 16 “soil” composition from table 7	3
2.	Calculated normative mineral content based on the NASA (1982) average from table 1 (using IGPET 2005 and CIPW norm programs by Michael Carr, Terra Softa Inc [®])	4
3.	Crystalline source materials used for LHT-1M and -2M	5
4.	Chemical composition of Stillwater mill waste (average of two analyses, in Wt%). The only sulfur (S) value on hand is <500 ppm S, so S is not included in the analysis	5
5.	Calculated normative mineral composition of the Stillwater mill sand using data of table 3. Oxides were normalized to 100% and an estimate of FeO:Fe ₂ O ₃ calculated following the method of Irvine and Baragar	6
6.	Specified proportions of crystalline to glassy components for LHT prototype simulants	7
7.	Compilation of average composition of lunar soils for 80 elements	9

LIST OF ACRONYMS AND SYMBOLS

AN _{XX}	relative abundance of the anorthite mineral endmember in the plagioclase solid solution series
CIPW	Cross, Iddings, Pirsson, and Washington
KREEP	potassium, rare-earth elements, and phosphorus
KSC	Kennedy Space Center
LHT	lunar highlands type
LOI	lost on ignition
MSFC	Marshall Space Flight Center
S	sulfur
TM	Technical Memorandum
U.S.	United States
USGS	U.S. Geological Survey

TECHNICAL MEMORANDUM

DESIGN AND SPECIFICATIONS FOR THE HIGHLAND REGOLITH PROTOTYPE SIMULANTS NU-LHT-1M AND -2M

1. INTRODUCTION

In discussions with the Marshall Space Flight Center (MSFC), it was agreed that the first prototype regolith simulants produced by the United States (U.S.) Geological Survey (USGS) would simulate the lunar highlands regolith predicated on the NASA decision to put a base at one of the lunar poles that are highlands sites. It was also agreed that these simulants would be based on sample information for the Apollo 16 site because it is the only Apollo site that is close to being representative of the lunar highlands since it is more than 200 km away from the nearest mare. However, compositional modeling and petrographic studies indicate that Apollo 16 regolith samples contain a variable but significant amount of mare and potassium, rare-earth elements, and phosphorus (KREEP) components (up to 5% plus mare and up to 20% KREEP¹). The effect of this “contamination” is that, although the Apollo 16 regolith is not completely representative of “typical” highlands overall, it is still compositionally quite close as determined by orbital elemental and lunar highland meteorite studies.²

The goal of these prototype simulants is to develop reproducible basic methodologies and procedures to produce simulants and to match the modal mineral and glass content and grain-size distribution of the Apollo 16 regolith samples as closely as possible. The purpose of this Technical Memorandum (TM) is to detail the specifications that were used to develop the lunar highlands type (LHT)-1M pilot and LHT-2M prototype simulants.

2. CHEMICAL COMPOSITION SPECIFICATION

After studying the literature on the Apollo 16 regolith and samples, it was decided to base the specification on an average chemical composition of the Apollo 16 regolith samples rather than any specific surface or core regolith sample. The basis of this decision was that an average composition would be more representative of the highlands regolith as a whole than would any specific sample. A second reason was that, after a literature survey, it was realized that the available data and information available for the Apollo 16 regolith samples was inadequate for the investigation requirements.

Specifically, no studies provided the mineralogical information required to prepare simulants. Highly detailed and excellent particle-type modal analyses exist for Apollo 16 regolith samples but no mineral modal analyses exist. That is, no mineral modal data exists that specifies the amount of minerals (or glass) present in a regolith sample. The published particle-type modes present the amount of lithic, breccia, monomineralic, agglutinate, and glass particles present in the regolith. Thus, if the question is asked of how much olivine is present in a specific sample, the only available data is for the amount of monomineralic olivine. However, olivine may also be present in the lithic, breccia, and glass clasts; therefore, the total amount of olivine present in the sample is undetermined. Also note that a particle-type mode does not provide the total amount of glass present in a sample since glass can also be present in the lithic and breccia particles, and agglutinate particles are only partially composed of glass.

The literature was reviewed for average chemical analyses and one analysis was selected to be the basis for the preparation of the LHT simulants. The one selected (see appendix A) was compiled from the database compilation of the Lunar Sample Curator, was representative when compared to other averages, and had the additional virtue of being the only compilation that included nearly complete averages for the minor and trace elements.

3. SPECIFICATIONS FOR LUNAR HIGHLANDS TYPE COMPONENTS

In order to create the LHT simulants, the two basic component materials required are crystalline and glass. The crystalline component is that portion of the simulant that is created by blending natural and synthetic crystalline source materials that contain one or more of the required minerals to simulate the lunar regolith (Stillwater norite, anorthosite, etc.). The glass component is composed of the two subcomponents pseudo-agglutinate and “good” glass. The specifications for each component are presented in sections 3.1 and 3.2, respectively. The feedstocks used were obtained with the cooperation and generous assistance of the Stillwater Mining Company of Nye, MT. The rock components were hand picked from the mine’s waste dump. The mill sand used was provided by special arrangement with the company, which provided the wet material in 55-gallon drums.

3.1 Crystalline Component

Table 1 identifies the average composition of Apollo 16 soils taken from NASA, 1982.³ The data presented is a subset of the source data that presents data for 80 elements. The subset for this TM is the elemental data required to calculate major and minor minerals.

Table 1. Average Apollo 16 “soil” composition from table 7.

SiO ₂	45.09
TiO ₂	0.56
Al ₂ O ₃	27.18
FeO	5.18
MnO	0.065
MgO	5.84
CaO	15.79
Na ₂ O	0.47
K ₂ O	0.11
P ₂ O ₅	0.12
Cr ₂ O ₃	0.107
S	0.064
Total	100.58

Table 2 presents the calculated normative mineralogy for the Apollo 16 averages of table 1. Table 2 presents two different normative mineral amounts—weight percent (Wt%) and mole percent (cationic) (Mole%). These normative mineral amounts are the target for preparing LHT-1M and -2M. That is, the goal was not matching the chemical composition shown in table 1 but matching the calculated mineral amounts of table 2 (i.e., total plagioclase, orthopyroxene, clinopyroxene, olivine, ilmenite, apatite, and pyrite).

Table 2. Calculated normative mineral content based on the NASA (1982) average from table 1 (using IGPET 2005 and CIPW norm programs by Michael Carr, Terra Softa Inc[®]).

CIPW Normative Minerals		
	Wt. %	Mole %
Q (Quartz)	0.00	0.00
OR (Orthoclase)	0.65	0.64
AB (Albite)	3.96	4.19
AN (Anorthite)	71.33	71.20
Total Plagioclase	75.94	76.03
AN Content	-	94.44
DI (Diopside Clinopyroxene)	4.70	4.62
HY (Hypersthene Orthopyroxene)	10.14	10.23
Total Pyroxene	14.84	14.85
OL (Olivine)	7.60	7.92
IL (Ilmenite)	1.05	0.77
AP (Apatite)	0.28	0.25
CM (Chromite)	0.16	0.12
PR (Pyrite)	0.12	0.06

The study procedure was to use the chemical composition of available source materials (table 3) to run a reiterative process of calculating bulk chemical compositions from source material blends utilizing a mixing program (an Excel routine) and calculating Cross, Iddings, Pirsson, and Washington (CIPW) normative mineral proportions until the best possible mineralogical match was achieved. This procedure involved simply matching the amounts of the normative minerals calculated for the source materials to the target normative mineral amounts without consideration of mineral composition (i.e., the amount of target plagioclase was matched without consideration of AN_{XX} content (molecular Ca/(Ca + Na)) since composition of these minerals in the source materials is fixed). The source materials have lower Ca/(Ca + Na) and higher Mg/(Mg + Fe) ratios than lunar regolith, which will be inherent to any mix.

The calculated best match mix then determines the amount of the source materials to be mixed to create the crystalline component of LHT-1M and -2M (i.e., that will be mixed with the glass components). The primary difference between 1M and 2M is that the study only specified and allowed for the minerals (plagioclase, pyroxenes, olivine, and ilmenite); whereas, for 2M, the other minor minerals were also included (i.e., synthetic whitlockite (β -tricalcium phosphate), fluorapatite, and pyrite (troilite substitute)). The proportion of whitlockite to fluorapatite was arbitrarily set at 2:1, since data do not exist for the amount of these minerals in Apollo 16 regolith samples; however, Frondel does indicate that "...in lunar rocks, whitlockite is much more abundant than apatite..."⁵

Table 3. Crystalline source materials used for LHT-1M and -2M.

Lithology	Minerals	Used For
Stillwater Norite	Plagioclase, Orthopyroxene, Clinopyroxene	1M, 2M
Stillwater Anorthosite	Plagioclase, Clinopyroxene	1M, 2M
Stillwater Hartzburgite	Olivine, Orthopyroxene, Chromite	1M
Twin Sisters Dunite	Olivine, Chromite	2M
	Natural Ilmenite (Beach Sand)	1M, 2M
	Synthetic Whitlockite (β -tricalcium phosphate)	2M
	Natural Fluor-apatite	2M
	Natural Pyrite	2M

3.2 Glass Component

Section 3.1 specifies the mineral composition for the crystalline component of the LHT prototypes. The crystalline component is mixed with some amount of glassy materials (pseudo-agglutinate and other glass) to create the final blend. The glasses in the Apollo 16 regolith are highly variable in composition, ranging from high alumina to mafic (Mg + Fe rich). No average composition for Apollo 16 regolith glasses has been published but it is assumed that their average will be approximately the same as the bulk compositional average. On this basis, it would be reasonable to use the crystalline mix defined by the crystalline specification as the basis for making glasses; however, because of convenience, the mill waste, termed “mill sand,” from the mill processing the ore from the Stillwater Mine was used. This decision was predicated on the fact that the waste material has the composition of a feldspathic norite (table 4) and whose normative mineralogy is similar to that of the crystalline component (table 5).

Table 4. Chemical composition of Stillwater mill waste (average of two analyses, in Wt%). The only sulfur (S) value on hand is <500 ppm S, so S is not included in the analysis.

Oxide	Wt. %
SiO ₂	46.60
TiO ₂	0.115
Al ₂ O ₃	21.55
Fe ₂ O ₃ *	5.65
MnO	0.09
MgO	9.50
CaO	12.60
Na ₂ O	0.965
K ₂ O	0.12
P ₂ O ₅	0.07
LOI**	2.74
Cr ₂ O ₃	0.12
Total	100.12

Notes:

* All Fe as Fe₂O₃.

** LOI, lost on ignition volatiles.

Table 5. Calculated normative mineral composition of the Stillwater mill sand using data of table 3. Oxides were normalized to 100% and an estimate of FeO:Fe₂O₃ calculated following the method of Irvine and Baragar.

CIPW Normative Minerals		
	Wt %	Mole%
Q (Quartz)	0.00	0.00
OR (Orthoclase)	0.73	0.72
AB (Albite)	8.43	8.81
AN (Anorthite)	55.87	55.05
Total Plagioclase	65.03	64.58
Calculated AN Content	–	86.20
DI (Diopside)	6.51	6.46
HY (Hypersthene)	22.71	23.71
Total Pyroxene	29.22	30.17245.53
OL (Olivine)	2.93	3.22
MT (Magnetite)	2.42	1.72
IL (Ilmenite)	0.23	0.16
AP (Apatite)	0.17	0.15
CM (Chromite)	0.19	0.13

The study simulant design specified two types of glassy material, pseudo-agglutinate (or agglutinate for short) and simple or “good” glass. Both materials were prepared using a plasma melter at the laboratories of Zybeck Advanced Products[®], Boulder, CO.

The goal for producing pseudo-agglutinate was vesiculated cindery glass particles that contain a significant amount (>10%) of included crystalline material. This material was created through a custom partial melting process. The proportion of glass to crystalline material is highly variable due to the process used, and no attempt or consideration was given to trying to constrain the ratio other than it should be dominantly glass. An unplanned but useful byproduct of the agglutinate process was the generation of a small amount of glass beads (spherules) of variable composition that were also included in the simulants. In effect, these beads simulate the glass beads that occur in small amounts in most lunar soils (typically about 1–2%^{6,7}).

Complete melting of Stillwater sand without vesicles or inclusions was the method used to produce “good” glass.

4. MIXING SPECIFICATION

The amount of agglutinate in the lunar regolith is basically a function of maturity or length of time the surface material is exposed to micrometeorite impacting, which produces agglutinate.⁸ The amount of agglutinate in the regolith varies from approximately 0–65% with an average of about 25–30% for regolith surface samples.^{2,9} However, studies of Apollo 16 cores show that maturity in the cores generally decreases downwards.^{10,11} It should be noted that maturity is primarily determined by the magnetic resonance value I_S/FeO and that agglutinate content only approximately correlates.⁹ The amount of agglutinate was arbitrarily set somewhat lower than the surface average value to reflect this decrease in maturity in the Apollo 16 core for LHT-1M (table 6). On further reflection that many user applications would likely be simulations involving surface materials, the agglutinate content of LHT-2M was adjusted to reflect a more typical Apollo surface regolith value of 30% (table 6).

Table 6. Specified proportions of crystalline to glassy components for LHT prototype simulants.

	Crystalline (%)	Agglutinate (%)	Good Glass (%)
LHT-1M	80	16	4
LHT-2M	65	30	5

A survey of the literature that contain detailed modal analyses indicates glass particle contents (other than agglutinate) of approximately 1–5%, not including the glass present in the breccia and lithic particles; thus, the good-glass target was set at the high end of the range (table 6).

Note that the total glass content of the LHT simulants will be somewhat less than the total of agglutinate plus glass since the agglutinate subcomponent is vesicular and contains crystalline inclusions and, thus, is not all glass.

5. PARTICLE SIZE SPECIFICATION

It was determined by agreement that LHT-1M and -2M would not contain particles greater than 1 mm and thus would consist of grains from ≥ 1 mm to dust size. The primary guideline for particle size distribution is Butler et al.,¹² who published detailed data on 19 Apollo 16 surface soil samples for 16 size fractions (fig. 1). The grain size distribution envelope established for the lunar regolith by Carrier for the <1 -mm soil fraction (fig. 2) is also used.¹³

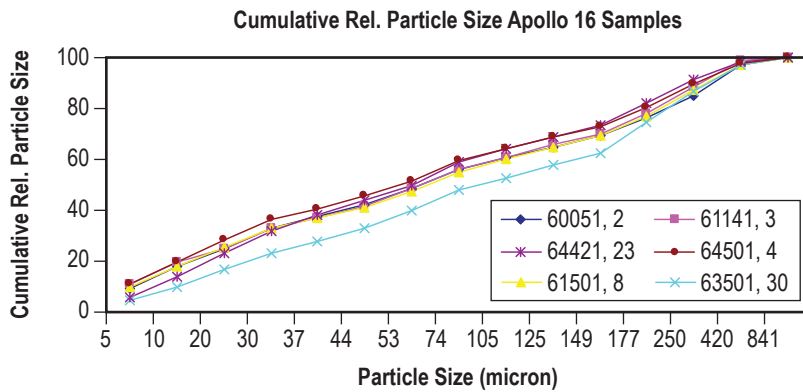


Figure 1. Cumulative grain size distribution for six Apollo 16 regolith samples.

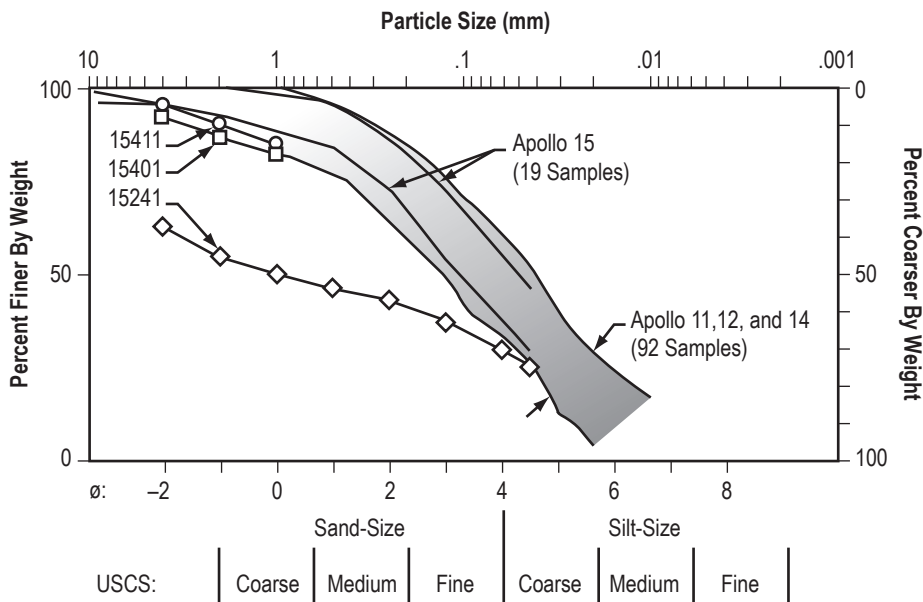


Figure 2. Figure 2 of Carrier (1973) showing regolith grain size distribution envelope based on Carrier's compilation of grain size information for Apollo 11–15 regolith samples.

APPENDIX

Data from (NASA, 1982) is presented in table 7. Major elements (>0.1%) are reported first as both the usual oxide notation and elements. Data is compiled from the Data Base Compilation of the Lunar Sample Curator, NASA Johnson Space Center, Houston, TX.

Table 7. Compilation of average composition of lunar soils for 80 elements.

	Mare					Highland		Basin Ejecta		
	High Ti		Low Ti							
	A-11	A-17	A-12	A-15	L-16	A-16	L-20	A-14	A-15	A-17
Al ₂ O ₃ , Wt. %	13.78	10.97	13.71	10.32	15.51	27.18	23.07	17.41	17.54	20.6
CaO, Wt. %	12.12	10.62	10.55	9.74	12.07	15.79	14.07	10.79	11.57	12.86
Cr ₂ O ₃ , Wt. %	0.3	0.46	0.35	0.53	0.29	0.107	0.15	0.22	0.28	0.26
FeO, Wt. %	15.76	17.53	15.41	19.75	16.41	5.18	7.35	10.36	11.58	8.59
K ₂ O, Wt. %	0.15	0.076	0.27	0.1	0.1	0.11	0.08	0.58	0.17	0.16
MgO, Wt. %	8.17	9.62	9.91	11.29	8.79	5.84	9.26	9.47	10.41	10.29
MnO, Wt. %	0.21	0.24	0.22	0.25	0.21	0.065	0.11	0.14	0.16	0.11
Na ₂ O, Wt. %	0.44	0.35	0.48	0.31	0.36	0.47	0.35	0.7	0.42	0.41
P ₂ O ₅ , Wt. %	0.12	0.07	0.31	0.11	0.14	0.12	0.11	0.5	0.16	0.14
SiO ₂ , Wt. %	42.17	39.87	46.17	46.2	43.96	45.09	44.95	48.08	46.59	45.08
TiO ₂ , Wt. %	7.67	9.42	3.07	2.16	3.53	0.56	0.49	1.7	1.32	1.62
Al, Wt. %	7.29	5.8	7.25	5.46	8.31	14.38	12.2	9.21	9.28	10.9
Ca, Wt. %	8.66	7.59	7.54	6.96	8.63	11.29	10.06	7.71	6.27	9.19
Cr, Wt. %	0.21	0.31	0.24	0.36	0.2	0.07	0.1	0.15	0.19	0.18
Fe, Wt. %	12.25	13.63	11.98	15.35	12.76	4.03	5.71	10.36	9	6.68
K, Wt. %	0.12	0.063	0.22	0.08	0.08	0.09	0.066	0.46	0.14	0.13
Mg, Wt. %	4.93	5.8	5.98	6.81	5.3	3.52	5.59	5.71	6.28	6.21
Mn, Wt. %	0.16	0.19	0.17	0.19	0.16	0.05	0.085	0.11	0.12	0.085
Na, Wt. %	0.33	0.26	0.36	0.23	0.27	0.35	0.26	0.52	0.31	0.3
O, Wt. %	41.6	39.7	42.3	41.3	41.6	44.6	44.6	43.8	43.8	42.2
P, Wt. %	0.05	0.03	0.14	0.05	0.06	0.05	0.05	0.22	0.07	0.06
S, Wt. %	0.12	0.13	0.1	0.063	0.21	0.064	0.08	0.088	0.08	0.06
Si, Wt. %	19.84	18.63	21.57	21.28	20.54	21.07	21	22.46	21.77	21.06
Ti, Wt. %	4.6	5.65	1.84	1.29	2.11	0.34	0.29	1.02	0.79	0.97
Ag, ppb	9	9.8	62	50	95	9.6	16.2	17.5	56	6.5
Ar, ppm	1	1.2	0.3	0.7	-	1.2	-	1	-	-
As, ppm	0.32	-	0.082	0.01	0.41	0.14	0.28	0.066	-	-
Au, ppb	3.7	2.5	2.2	2.11	2.5	8.47	4.93	6.7	3.3	4.9
B, ppm	3.5	2	9.3	-	4.3	5.9	39	19	-	-
Ba, ppm	140	85.7	413	122	215	127.3	89.6	767.5	279	190
Be, ppm	2	-	5	1.31	2.2	1.2	-	5.5	2.8	-
Bi, ppb	1.5	7.7	1.5	0.36	4.9	1.8	2.7	1.7	0.17	-
Br, ppm	0.239	0.093	0.165	-	0.21	0.217	0.13	0.41	0.06	-
C, ppm	135	82	104	95	-	106.5	-	130	125	155
Cd, ppm	0.045	0.032	0.046	0.062	0.8	0.097	0.048	0.181	0.042	0.04

Table 7. Compilation of average composition of lunar soils for 80 elements (Continued).

	Mare					Highland		Basin Ejecta		
	High Ti		Low Ti			A-16	L-20	A-14	A-15	A-17
	A-11	A-17	A-12	A-15	L-16					
Ce, ppm	50	25.3	104	31.4	33.4	30.3	20.5	185	54	46
Cl, ppm	30.2	5.7	31	7.6	53.5	20.9	13	44	5.9	–
Co, ppm	32	35	43	54.4	37	25.3	40.5	35.8	42	33
Cs, ppm	0.18	0.3	0.3	0.23	0.95	0.11	0.11	0.63	0.19	0.18
Cu, ppm	11.5	11	10.3	8.2	31	8.26	19	11.1	7.9	6.4
Dy, ppm	20.2	12.2	24.6	8.6	10.9	6.8	5	39	13.6	11
Er, ppm	11.5	7.9	15.35	5.13	6.3	4.39	2.5	23.5	7.86	6.5
Eu, ppm	2	1.66	1.9	1.01	2.3	1.23	0.98	2.64	1.3	1.35
F, ppm	278	–	132	45	242	72	37	219	60	–
Ga, ppm	4.3	7.5	4.3	4.43	4.4	4.5	3.7	6.8	3.6	4.7
Gd, ppm	16.3	11.4	25.7	8.1	9.8	6.7	3.06	34.8	11.74	10.07
Ge, ppm	1	0.198	0.32	0.17	1.44	0.76	0.46	0.7	0.42	–
H, ppm	51	59.6	45	63.6	–	56	–	79.6	52	98
He, ppm	60	36	10	8	–	6	–	8	–	–
Hf, ppm	8.9	7.3	12.7	5.2	4.75	3.9	2.9	22.2	7.6	5.5
Hg, ppm	0.015	–	0.023	–	–	0.004	–	–	–	–
Ho, ppm	5.4	–	5.3	1.7	2.5	1.5	0.88	7.8	3.3	–
I, ppb	–	2	–	–	–	5.6	12	–	35	–
In, ppb	–	2.4	90	3.4	35.6	31	19	89	7.6	3.4
Ir, ppb	7.8	5.4	5.6	3.1	9.7	12.4	9.5	12.4	8.3	8.8
La, ppm	17.3	7.32	38.8	11.3	11.5	11.7	7.6	69.4	24	16.9
Li, ppm	16.5	9.77	19.5	9.09	9.7	7.4	5.7	29.8	10.8	11.7
Lu, ppm	1.6	1.03	1.93	0.72	0.84	0.59	0.4	3.1	0.98	0.88
Mo, ppm	0.7	–	0.34	–	–	0.34	–	–	–	–
N, ppm	119	60	84	80	134	89	107	92	190	81
Nb, ppm	15.8	19.1	34	13	15.9	12.8	12	56	16	18
Nd, ppm	42.6	23	75.6	23	26.9	19.3	10.8	105	35	27.6
Ne, ppm	5	2	2	2	–	1	–	2	–	–
Ni, ppm	206	131	189	146	174	345	208	321	282	286
Os, ppb	14	–	6	1.79	30	22	–	–	–	–
Pb, ppm	2.9	0.8	4.8	1.033	6	2.58	1.15	10.02	2.5	1.922
Pd, ppb	21	–	9.7	6.2	–	24	–	50	–	–
Pr, ppm	7.7	–	10.1	3.8	–	4.97	4	23	–	–
Rb, ppm	3	1.2	7.28	2.7	1.85	2.48	1.65	15.25	5	4.21
Re, ppb	5.26	0.47	0.34	0.39	0.36	0.82	3.19	1.15	–	–
Rh, ppm	0.1	–	0.4	–	0.077	–	–	–	–	–
Ru, ppm	0.6	–	0.047	–	0.046	0.01	–	–	–	–
Sb, ppb	4.1	25.4	47	30	3.8	9.7	5.7	3.4	–	26
Sc, ppm	62.8	65	39.2	37.1	39.9	8.9	17	21.9	22	18
Se, ppm	0.39	0.27	0.3	0.18	0.39	0.24	0.3	0.031	–	0.23
Sm, ppm	11.7	8	20.3	5.85	8.8	5.38	3.39	30.9	9.6	8.1
Sn, ppm	0.7	–	0.3	–	1.7	0.22	0.8	–	–	–
Sr, ppm	193	166	138.9	104.2	234	168	140.8	183.8	152	150
Ta, ppm	1.5	–	1.58	0.55	1.4	0.5	0.5	4.1	1.05	0.87
Tb, ppm	3.3	2.63	4.07	1.4	1.5	1.07	0.8	6.4	4.2	1.72
Te, ppm	0.07	0.01	0.05	–	0.088	0.023	0.051	0.031	–	–
Th, ppm	2.24	0.82	6.63	1.76	1.07	1.87	1.44	13.5	4.15	3.01
Tl, ppb	2.1	1.4	2	0.94	1.6	7.7	6.2	22	–	2.4

Table 7. Compilation of average composition of lunar soils for 80 elements (Continued).

	Mare					Highland		Basin Ejecta		
	High Ti		Low Ti			A-16	L-20	A-14	A-15	A-17
	A-11	A-17	A-12	A-15	L-16					
Tm, ppm	1.5	–	2.02	–	0.73	0.67	0.41	3.9	–	–
U, ppm	1.37	0.26	1.61	0.483	0.3	0.52	0.45	3.48	0.99	0.9
V, ppm	66	128	110	191	73.5	25.5	38	49	84	52
W, ppm	0.24	0.14	0.74	0.31	–	0.31	–	1.9	–	0.52
Y, ppm	107	74	145	47	48	39.3	49	242	73	64
Yb, ppm	10.6	7.48	13.7	4.53	5.59	3.86	2.4	22.7	7.3	6.15
Zn, ppm	23	49	6.3	12.8	25	24	34.1	28	14.5	20
Zr, ppm	331	236	503	175	308	163.8	192	842	278	262

REFERENCES

1. Korotev, R.L.: “Lunar Terranes and the Composition of the Regolith,” *Lunar and Planetary Science Conference XXX*, Abstract 1302, 1999.
2. Lucey, P.; Randy, L.; Korotev, R.L.; et al.: “Understanding the Lunar Surface and Space-Moon Interactions,” *Rev. in Mineral. and Geochem.*, Vol. 60, pp. 83–219, 2006.
3. NASA: “Table 4.1—Compilation of Average Composition of Lunar Soils for 80 Elements,” *Proceedings of the 1980 NASA/ASEE Summer Study, NASA Conference Publication 2255*, (table available online at <<http://www.answers.com/topic/advanced-automation-for-space-missions-chapter-4-2>>), 1982.
4. Frondel, J.W.: *Lunar Mineralogy*, John Wiley & Sons, New York, NY, 1976.
5. Irvine, T.N.; and Baragar, W.R.A.: “A Guide to the Chemical Classification of the Common Volcanic Rocks,” *Can. J. Earth Sci.*, Vol. 8, pp. 523–548, 1971.
6. Rao, K.J.; and Cooper, A.R.: “Optical Properties of Lunar Glass Spherules From Apollo 14 Fines,” *Proceedings of the Third Lunar Science Conference, Supplement 3, Geochim. et Cosmochim. Acta*, Vol. 3, pp. 3143–3155, 1972.
7. Scarlett, B.; Buxton, R.E.; and Faulkner, R.G.: “Formation of Glass Spheres on the Lunar Surface,” *Geological Society of London*, Abstract 285, pp. 279–284, 1977.
8. McKay, D.S.; and Basu, A.: “The Production Curve for Agglutinates in Planetary Regoliths,” *Proceedings of the Fourteenth Lunar and Planetary Science Conference, Part 1, J. Geophys. Res.*, Vol. 88, pp. B193–B199, 1983.
9. Simon, S.B.; Papike, J.J.; Hörz, F.; and See, T.H.: “An Experimental Investigation of Agglutinate Melting Mechanisms: Shocked Mixtures of Apollo 11 and 16 Soils,” *Proceedings of the Seventeenth Lunar and Planetary Science Conference, Part 1, J. Geophys. Res.*, Vol. 91, pp. E64–E74, 1986.
10. Morris, R.V.: “The Surface Exposure (Maturity) of Lunar Soils; Some Concepts and I_S/FeO Compilation,” *Proceeding of the Lunar and Planetary Science Conference 9*, pp. 2287–2297, 1978.
11. Korotev, R.L.; and Morris, R.V.: “On the Maturity of the Lunar Regolith,” *Workshop on New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets*, Houston, TX, Abstract 6019, 2 pages, 1998.

12. Butler, J.C.; Greene, G.M.; and King, Jr., E.A.: "Grain Size Frequency Distributions and Modal Analyses of Apollo 16 Fines,: Proceedings of the Fourth Lunar Science Conference, Supplement 4, *Geochim. et Cosmochim. Acta*, Vol. 1, pp. 267–278,1973.
13. Carrier, III, W.D.: "Lunar Grain Size Distribution," *The Moon*, Vol. 6, pp. 250–263, 1973.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operation and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 01-08-2010		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Design and Specifications for the Highland Regolith Prototype Simulants NU-LHT-1M and -2M			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) D.B. Stoesser,* D.L. Rickman, and S. Wilson,*			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) George C. Marshall Space Flight Center Marshall Space Flight Center, AL 35812			8. PERFORMING ORGANIZATION REPORT NUMBER M-1287		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITOR'S ACRONYM(S) NASA		
			11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2010-216438		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category 91 Availability: NASA CASI (443-757-5802)					
13. SUPPLEMENTARY NOTES Prepared by the Earth Sciences Office Trade names and trademarks are used in this report for identification only. * United States Geological Survey, Denver Federal Center, Denver, Colorado 80225					
14. ABSTRACT The first two prototype lunar regolith simulants were to replicate characteristics of the lunar highlands. A major change from initial plans was to use an estimate of typical Apollo 16 highland material rather than a specific core. This change was compatible with project objectives and necessitated by the lack of adequate data from a single core. To make the initial simulant, a crystalline component and a glass component were deemed necessary. Lithic feedstocks were obtained with the assistance of the Stillwater Mining Company. The mixing of the rock constituents was done based on normative mineralogy rather than modal mineralogy. This was done to simplify development. A major design decision was not to attempt simulation of the range of glass chemistries observed in Apollo samples. A single glass was assumed to be adequate for engineering purposes for which the simulant would be used. Glass was made in a process developed at Zybek Advanced Products of Boulder, Colorado. Mill sand was used as the feedstock for this process. A second generation of the simulant was made that incorporated the additional minerals apatite, synthetic whitlockite, and pyrite. The olivine source was changed to the commercially produced Twin Sisters Dunitite, and a pseudo-agglutinate product was invented and added to the -2M product. The pseudo-agglutinate captures all of the lunar agglutinate features but does not attempt to incorporate nanophase Fe.					
15. SUBJECT TERMS Lunar simulant, NU-LHT-1M, NU-LHT-2M, design, specification					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk at email: help@sti.nasa.gov
U	U	U	UU	20	19b. TELEPHONE NUMBER (Include area code) STI Help Desk at: 443-757-5802

National Aeronautics and
Space Administration
IS20

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812