MSFC-2222

2009 Regolith Simulant Workshop
Marshall Space Flight Center
Huntsville, Alabama

Overview of Figure of Merit analyses of Simulants and the Fit-to-Use Matrix

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Figure of merit properties

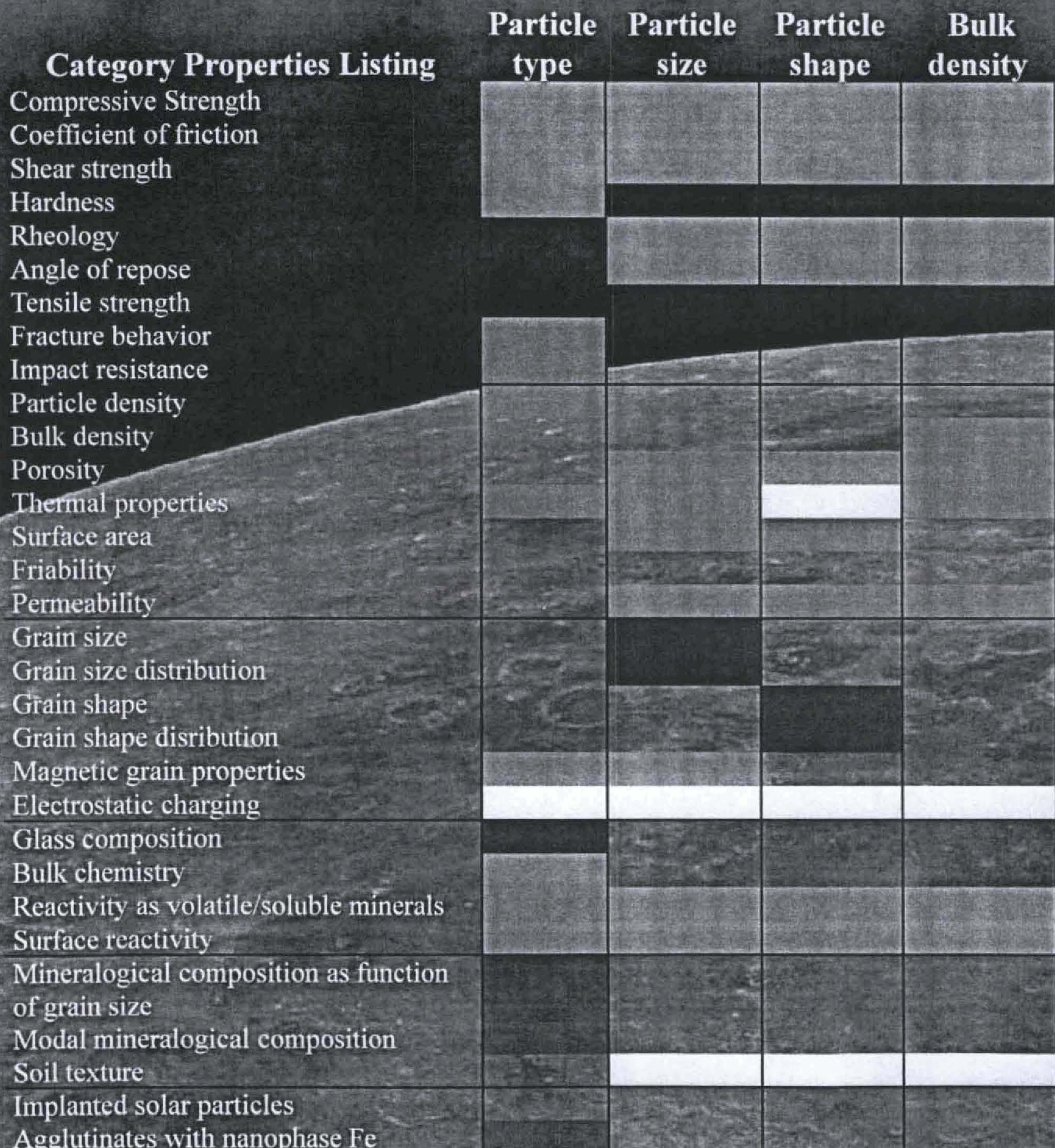
- Primary characteristics
  - Particle type
  - Particle size distribution
  - Particle shape distribution
  - Bulk density properties (e.g., maximum, minimum, average)

Developing approaches and routines to compare granular materials

- Figures of Merit algorithms were developed to quantitatively compare distributions in granular materials
  - Version 1 software released February, 2008
  - Revision 1 software was used in 2008 and will be publicly released early 2009.
  - Mathematics and algorithm documented in Rickman et al. (STAIF 2007); and MSFC-RQMT-3503 (DRAFT)

- FoM Revision 1 algorithms have been used to compare all simulants to the Apollo 16 reference material for composition and particle size distribution. This is in the *Lunar Regolith Simulant User's Guide* (http://isru.msfc.nasa.gov)

32 Characteristics from 2005 Workshop mapped to FoM properties



directly addressed by FoM

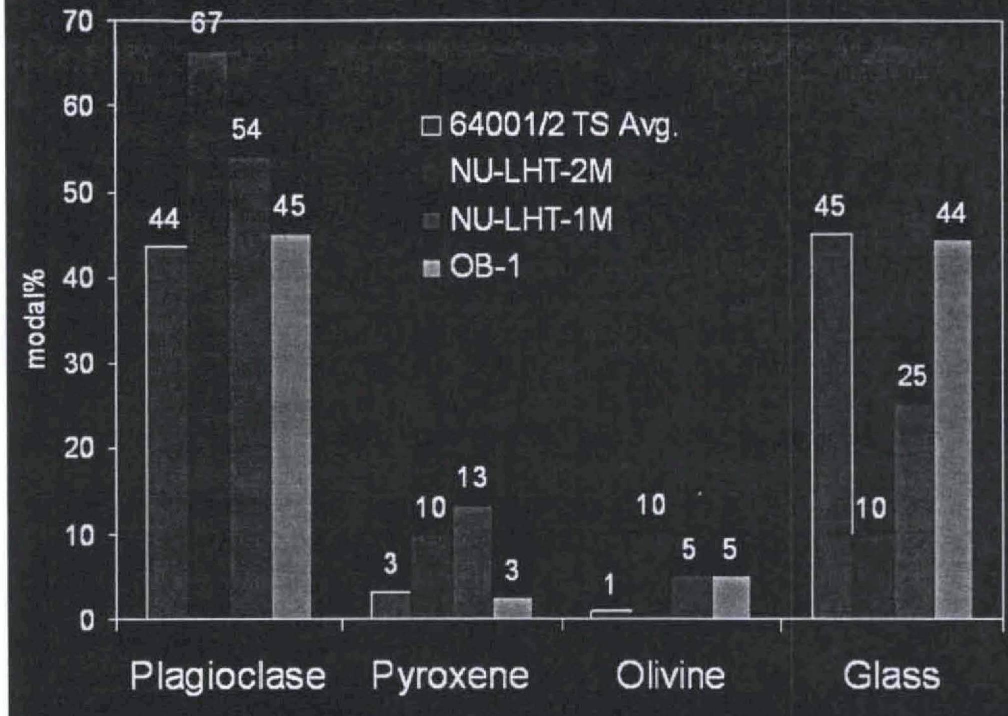
derivative of FoM property

partially dependent on environment

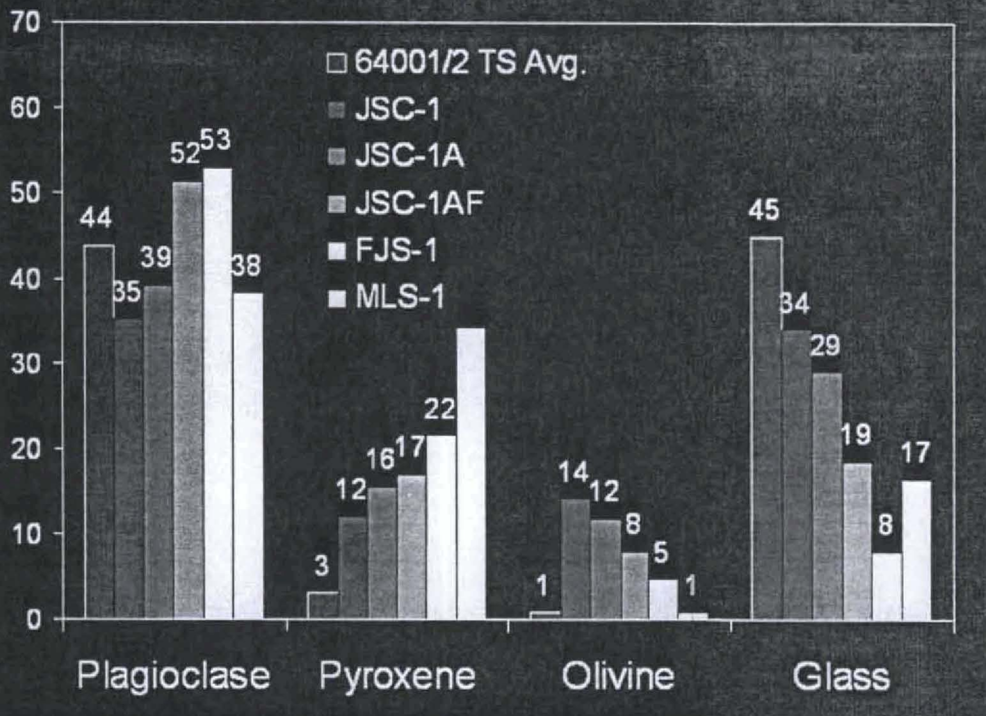
Overview of lunar simulants

Simulant(s)	Type	Primary Reported Use	Manufacturer	feedstock
NU-LHT series	Highlands	General	NASA-MSFC and USGS	Stillwater mine (MT), commercial minerals
OB-1	Highlands	Geotechnical	Norcat	Shawmere anorthosite, olivine slag glass
JSC-1 (-1A, -1AF)	Mare, low-Ti	Geotechnical and lesser chemical	Orbitec, Inc.	Basalt ash, San Francisco volcanic field (AZ)
FJS-1	Mare, low-Ti	Geotechnical	Japanese, (JAXA, LETO)	Mt. Fuji area basalt
MLS-1	Mare, high-Ti	Chemical	University of Minnesota	Basalt sill, Duluth complex

Major phase modal comparison between simulants and regolith



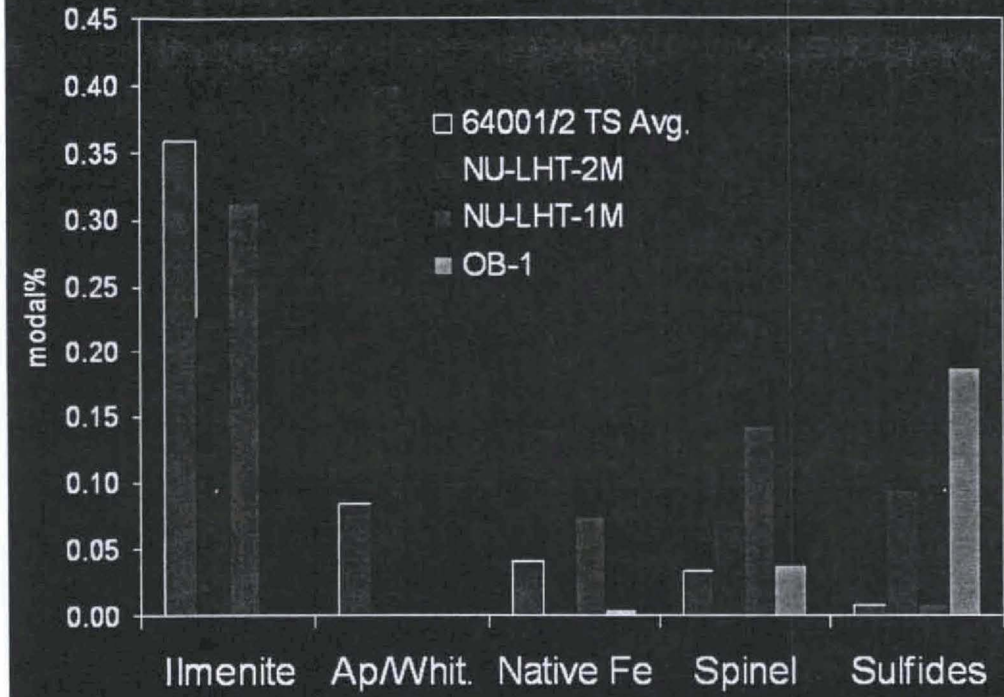
Highland simulants



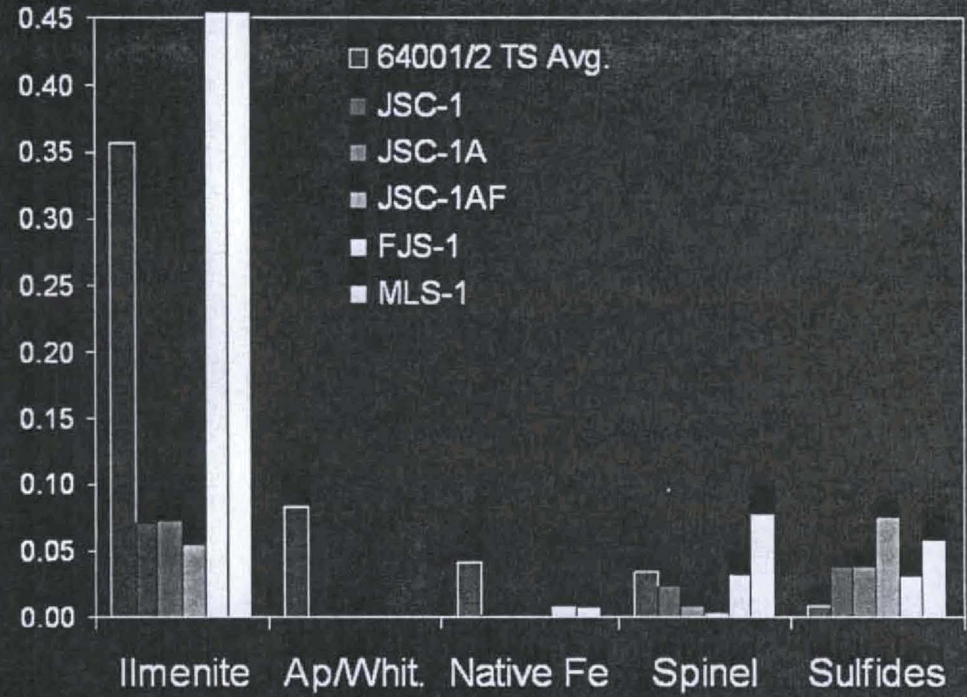
Mare simulants

These data report volume% of phases (minerals and glass) without regard to their occurrence as free particles, in lithic fragments, in agglutinates, in breccias, etc.

Trace mineral modal comparison between simulants and regolith



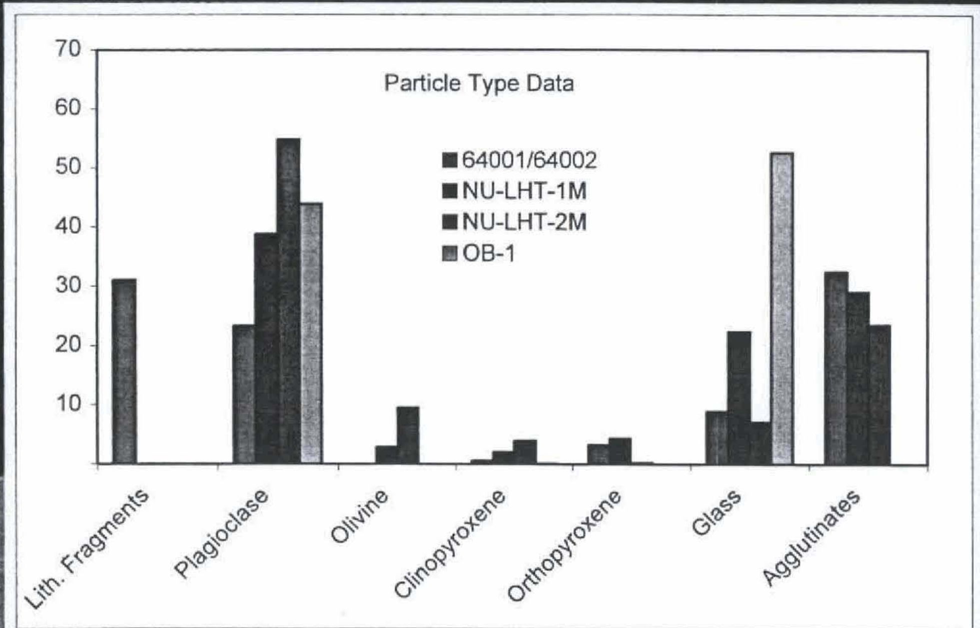
Highland simulants

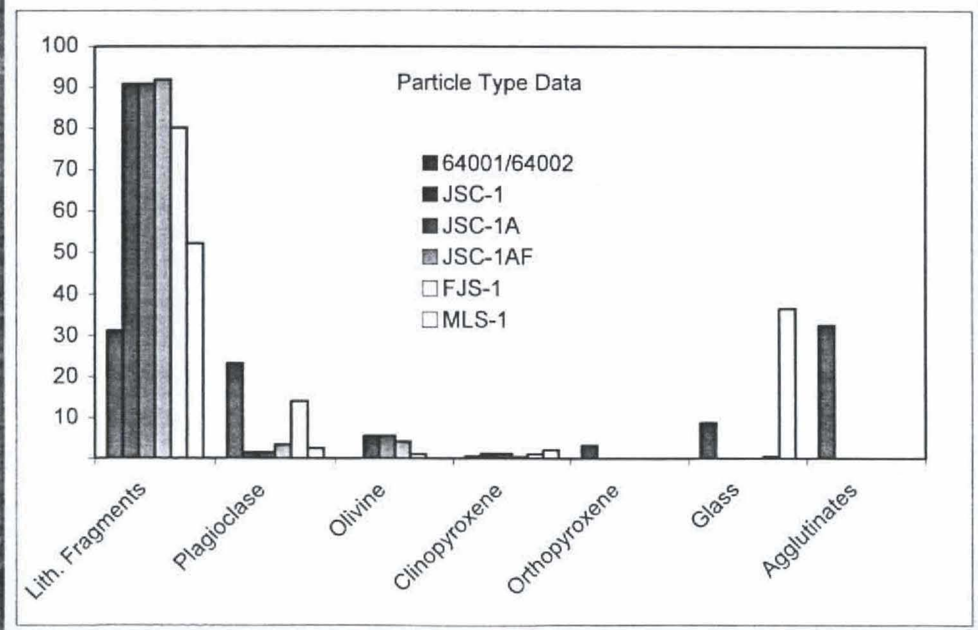


Mare simulants

These data report volume% of phases (minerals and glass) without regard to their occurrence as free particles, in lithic fragments, in agglutinates, in breccias, etc.

Particle type modal data: regolith and simulants





We use these data for the composition FoM.

It is a useful but incomplete picture of the material composition.

It does not incorporate total mineralogy/glass%, glass composition, or other characteristics.

Particle type composition FoM scores: simulants compared to 64001/2 highlands regolith

simulant	64001/64002 reference
NU-LHT-1M	0.65
NU-LHT-2M	0.55
OB-1	0.28
JSC-1	0.33
JSC-1A	0.35
JSC-1AF	0.43
MLS-1	0.35
FJS-1	0.36

	64001/2 bulk	64001/2 <1 mm	64001/2 <90 µm
Data from image analysis of thin sections			
OB-1	0.23	0.54	
NU-LHT-1M	0.23	0.58	
NU-LHT-2M	0.17	0.48	
JSC-1	0.22	0.53	
JSC-1A	0.25	0.56	
JSC-1AF	0.06	0.23	0.60
MLS-1	0.20	0.29	
FJS-1	0.26	0.45	
Dry sieve data			
OB-1	0.59		
NU-LHT-1M	0.26	0.75	
JSC-1A	0.35	0.74	
Laser diffractometry data			
NU-LHT-2M	0.29	0.82	
NU-LHT-1D			0.54
NU-LHT-1M	0.26	0.64	
JSC-1A	0.28	0.74	

Particle Size Distribution FoM

FoM score is dependent on the portion of the distribution you examine.

Extraction and pourability

NU-LHT-1M	**recommended:** it has been demonstrated that pseudo-agglutinates affect geomechanical behavior that may be important to excavation
NU-LHT-2M	**recommended:** it has been demonstrated that pseudo-agglutinates affect geomechanical behavior that may be important to excavation
NU-LHT-1D	**not recommended**: unrealistically fine PSD
OB-1	**recommended:** best PSD at coarse end; lack of lithic fragments or pseudo-agglutinates may affect flowability or angle of repose -- this should be examined
JSC-1, -1A	**recommended:** relatively angular particles, reasonable PSD
JSC-1AF	**not recommended**: unrealistically fine PSD
FJS-1	**recommended:** low-g tests show it has a high angle of repose; relatively angular particles, reasonable PSD
MLS-1 (with glass)	**not recommended:** relatively poor PSD; shape distribution is skewed towards well-rounded particles

Drilling

NU-LHT-1M	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith
NU-LHT-2M	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith
NU-LHT-1D	**not recommended**: unrealistically fine PSD
OB-1	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions
JSC-1, -1A	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness
JSC-1AF	**not recommended**: unrealistically fine PSD
FJS-1	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness, low glass
MLS-1 (with glass)	**not recommended:** high pyroxene/plagioclase may adversely affect particle cleavage behavior; rounded grains

Abrasion and wear

NU-LHT-1M	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith
NU-LHT-2M	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith
NU-LHT-1D	**recommended with reservations**: unrealistically fine PSD for many uses
OB-1	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions
JSC-1, -1A	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness
JSC-1AF	**recommended with reservations**: unrealistically fine PSD for many uses
FJS-1	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness, low glass
MLS-1 (with glass)	**not recommended:** high pyroxene/plagioclase may adversely affect particle cleavage behavior; rounded grains

Oxygen production

NU-LHT-1M	**recommended for highlands**: chemistry: slightly low FeO relative to lunar reference (~4 vs. 5 wt.%), but significantly closer than other simulants; mineralogy: contains ilmenite; high Fe in silicates relative to reference, which will slow reduction
NU-LHT-2M	**most recommended for highlands**: chemistry: slightly low FeO relative to lunar reference (~4 vs. 5 wt.%), but significantly closer than other simulants; mineralogy: contains ilmenite, phosphates and sulfides, the presence of which are realistic but possibly hazardous to ISRU processes; high Fe in silicates relative to reference, which will slow reduction
NU-LHT-1D	**recommended for highlands**: should be similar to NU-LHT-1M, but possibly with lower FeO
OB-1	**not recommended:** it is expected that the abundance of Fe-rich glass will result in unrealistically high oxygen yields per energy input; no glass analyses are available
JSC-1, -1A	**recommended with reservations**: chemistry: FeO is significantly high relative to lunar reference (~11 vs. 5 wt.%); mineralogy: contains natural phosphates, Ti-magnetite instead of ilmenite; use will likely result in unrealistically high oxygen yields; may be a good mare simulant (e.g., Apollo 14) for this use
JSC-1AF	**recommended with reservations**: should be similar to JSC-1A
FJS-1	**recommended with reservations**: chemistry: FeO is significantly high relative to lunar reference (~11 vs. 5 wt.%); mineralogy: contains natural phosphates, Ti-magnetite instead of ilmenite; use will likely result in unrealistically high oxygen yields; may be a good mare simulant (e.g., Apollo 14) for this use
MLS-1 (with glass)	**not recommended for highlands**: chemistry: FeO is very high relative to lunar reference (>14 vs. 5 wt.%); mineralogy: contains abundant ilmenite but also hydrous minerals; may result in extremely unrealistically high oxygen yields; may be an acceptable high-Ti (Apollo 11) simulant, but hydrous minerals are still problematic

Human health studies

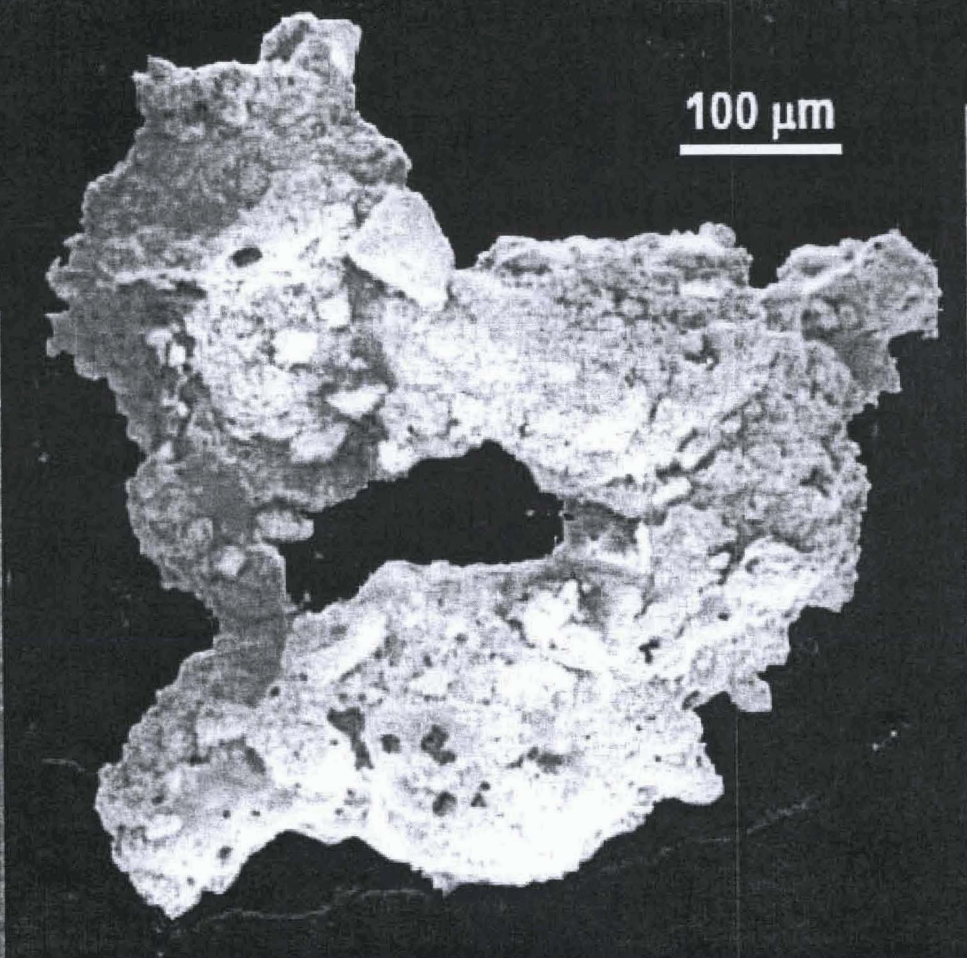
NU-LHT-1M	**suitable composition** though it lacks the added phosphates and sulfides of NU-LHT-2M; **reasonable PSD** but too coarse in fine fraction
NU-LHT-2M	**most suitable composition; reasonable PSD but too coarse in fine fraction**
NU-LHT-1D	**suitable composition** though it lacks the added phosphates and sulfides of NU-LHT-2M; **good PSD** in fine fraction
OB-1	**unsuitable composition** due to high Fe-glass; may be acceptable for testing where abrasiveness is of primary importance
JSC-1, -1A	**possibly suitable composition**; **reasonable PSD** but too coarse in fine fraction
JSC-1AF	**possibly suitable composition**; **good PSD** in fine fraction
FJS-1	**possibly suitable composition**; **poor PSD** in fine fraction
MLS-1 (with glass)	**unsuitable composition**; **unsuitable PSD** in fine fraction

Particle type modal data: regolith and simulants

	64001/ 64002	NU-LHT-1M	NU-LHT-2M	OB-1	JSC-1	JSC-1A	JSC-1AF	FJS-1	MLS-1
Lithic Fragments	31.11	0.00	0.00	0.00	90.92	90.92	91.93	80.18	52.28
Glass	8.88	22.37	7.17	52.63	0.00	0.00	0.00	0.53	36.57
Agglutinates	32.51	29.02	23.49	0.00	0.00	0.00	0.00	0.00	0.00
Plagioclase	23.32	38.78	54.89	43.95	1.54	1.54	3.39	14.11	2.60
(Plag. An%)	*95*	*80*	*80*	*75*	*68*	*70*	*70*	*50?*	*47*
Olivine	0.00	2.88	9.51	0.04	5.63	5.63	4.13	1.13	0.01
Clinopyroxene	0.64	2.04	3.98	0.07	1.33	1.33	0.42	1.20	2.21
Orthopyroxene	3.24	4.37	0.20	0.00	0.01	0.01	0.01	0.04	0.03
Spinel minerals	0.03	0.05	0.01	0.19	0.00	0.04	0.02	0.05	0.03
Fe-sulfide	0.01	0.00	0.04	0.00		0.00	0.00	0.00	0.00
Ca-phospates	0.12	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00
Ilmenite	0.13	0.33	0.19	0.00	0.00	0.08	0.00	0.15	1.07
Native Iron	0.01	0.00	0.00	0.00		0.00	0.00	0.00	0.00
Other (sim. only)		0.16	0.07	3.12		0.46	0.09	2.62	5.21
Total	100	100	100	100	100	100	100	100	100

These data report volume% of particles.
Plagioclase compositional data is also included
This data is used in the Figure of Merit for composition.

Particle type modal data



- Particle type data records free minerals, free glass particles, lithic fragments, agglutinates, breccia, etc.
- Our identification routines group breccias with lithic fragments.
- E.g., particle type data record this as an agglutinate. Phase modal data record it as glass and minerals.