A Review of Lunar Regolith Simulants and Their Applications

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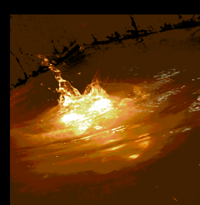
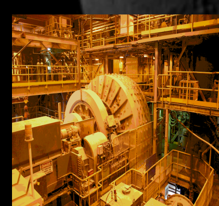
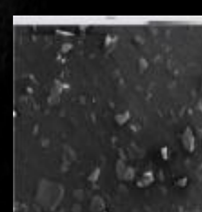


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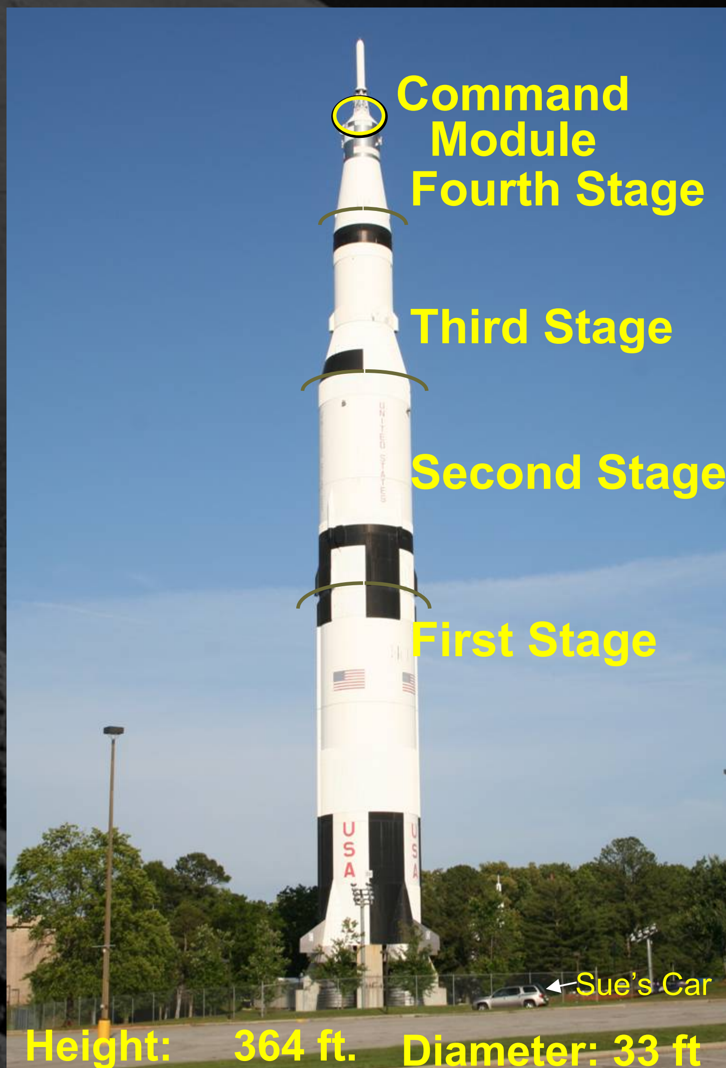


	Weight (lbs.)	Alt. (miles)	Velocity (mph)
	12,807		
Service Module	54,064		
Lunar Module	32,299		
Trans Lunar Burn	265,000	239,000	24,500
Orbital Burn		115	17,500
	1,037,000	114	15,300
	4,881,000	38	6,000
	6,600,000		

Six million, six hundred thousand pounds sat on the launch pad. Twelve thousand eight hundred came back. Dead stick! No control!

This is equivalent to taking a trip in Sue's car and coming back with <u>just</u> the left front wheel's lug nuts!

D Rickman
June 21, 2010 6:07 PM

Outline

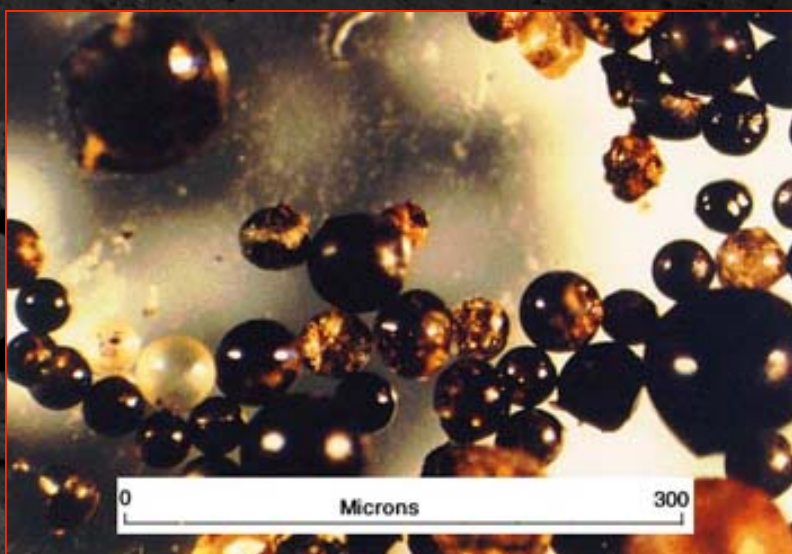
- Purpose of Lunar Regolith Simulant
- Introduction to the Simulant Team
- Documented Lunar Regolith Simulants
- Simulant User's Guide and Fit for Purpose Matrix
  - Some uses for regolith simulants
- Transition to Other Destinations (Mars/Asteroids)
- Summary

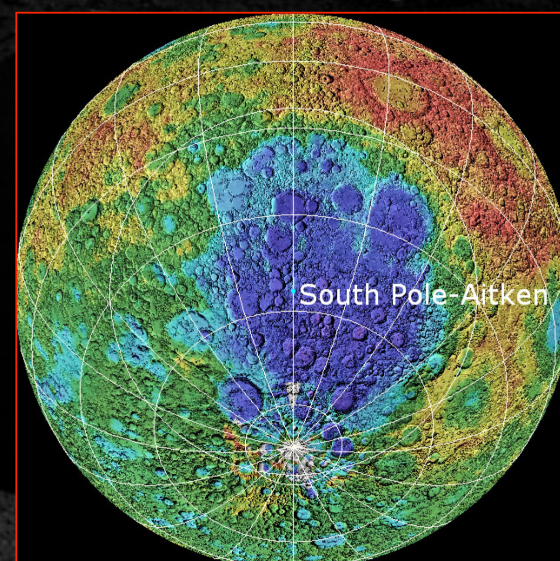
Lunar Regolith

- "Regolith" is the term for the layer or mantle of fragmental or unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface. (Lucey et al., 2006)
- It is what we measure with remote sensing satellites.
  - Radar, X-ray fluorescence, optical and infrared spectroscopy, and gamma ray techniques penetrate no more than 40m, 20μm, 1m, and 10-20cm, respectively
- All Apollo lunar materials were returned from the upper 3 meters of the surface.
- ALL of our geochemical information about the Moon was obtained from lunar regolith!

Formation of the Regolith

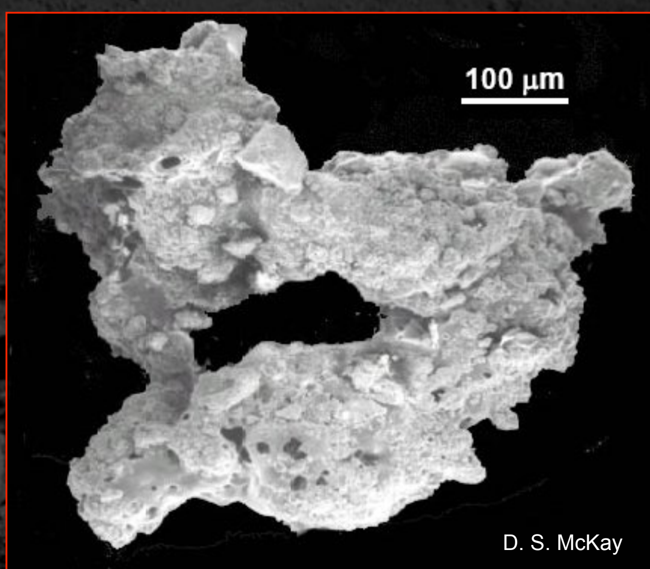
- Over 4.5 billion years, the lunar surface was bombarded with meteoroids – large and small
- Largest crater in the solar system is the South Pole-Aitken basin on the Moon
- Micrometeorites (generally less than 1mm in diameter) bombard the surface of the Moon (and Earth!) daily, adding $80 g/km^2y^{-1}$ in mass (5-10 hits per square meter per year).





Important Regolith Characteristics

- Lunar regolith includes everything from extremely fine (dust) particles to large surface boulders
- It was created in an impact-dominated environment, under vacuum
- It contains agglutinates, which contain nanophase iron



Need for Simulants

- All lunar technology must interact with the lunar surface environment
- The lunar environment is significantly different than the terrestrial environment
  - Earth's surface environment is dominated by weathering processes, involving water, atmosphere, and life
  - Testing with unspecialized terrestrial regolith makes test results not applicable to the lunar environment
- In order to provide a way to test lunar technology and the environmental effects on astronauts, synthetic lunar regolith must be created

The Simulant Team

- Formed under the Constellation Program in 2004, funded under the Exploration Technology Development Program
- Team members from Marshall Space Flight Center, the U.S. Geological Survey, and Glenn Research Center
- Purposes
  - Gather knowledge about existing simulants worldwide
  - Define standards of measurement
  - Assess known properties of the Moon
  - Identify unknown, but needed, properties of the regolith
  - Develop new simulant prototypes, process controls
  - Evaluate simulants for different engineering purposes
  - Point out the risks associated with simulant use

Customers: ETDP, CxP, Human Health, Outreach, etc.

MSFC:
Carole McLemore
John Fikes
Doug Rickman
Jennifer Edmunson
(Simulant Dev, Char, & Production)
- Task Management
- FoMs
- Characterization & Analysis
- Documentation)

GRC:
Mark Hyatt – *Dust PM*
Ken Street
Jim Gaier
Phil Able
Allen Wilkinson
Paul Greenberg
(Physical Properties Measurement)

GSFC:
Sharon Straka – *Dust DPM*

KSC:
Phil Metzger
(Shape Measurement)

Orbitec:
Bob Gustafson
(SBIR – Dust Simulant Component)

Zybek Advanced Products:
Mike Weinstein
(Sub to USGS and SBIR – Simulant Components)

USGS:
Doug Stoeser
Steve Wilson
Geoff Plumlee
Greg Meeker
(Contractor for Simulant Development & Characterization)

JSC:
David McKay
Dan Garrison
(Apollo Data Acquisition & Lunar Scientists Consultants)

Simulants

Pre/Post-Apollo | 1990 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009

Event Drivers: **Vision for Space Exp** — **Lunar Architecture Studies …**

- Lunar Soil Simulant

- JSC-1 (Mare Type)
  - Glass
  - Geotechnical prop
  - Not the best composition

- MLS-1 (Mare Type)
  - Good Composition (High Titanium)
  - Lacked good geotechnical prop

Depleted

- JSC-1A (Close replica of JSC-1)
  - Produced for MSFC by Orbitec (SBIR Phase III)

- NU-LHT-1M (Med) Pilot (Highland Type)
  - Developed by
  - MSFC / USGS
  - Mineralogy
  - Chemistry
  - Geotechnical

- NU-LHT-2M, -2C, & -1D (Med, Coarse, and Dust) Prototypes (Highland Type)
  - Developed by MSFC / USGS
  - Mineralogy
  - Chemistry
  - Geotechnical

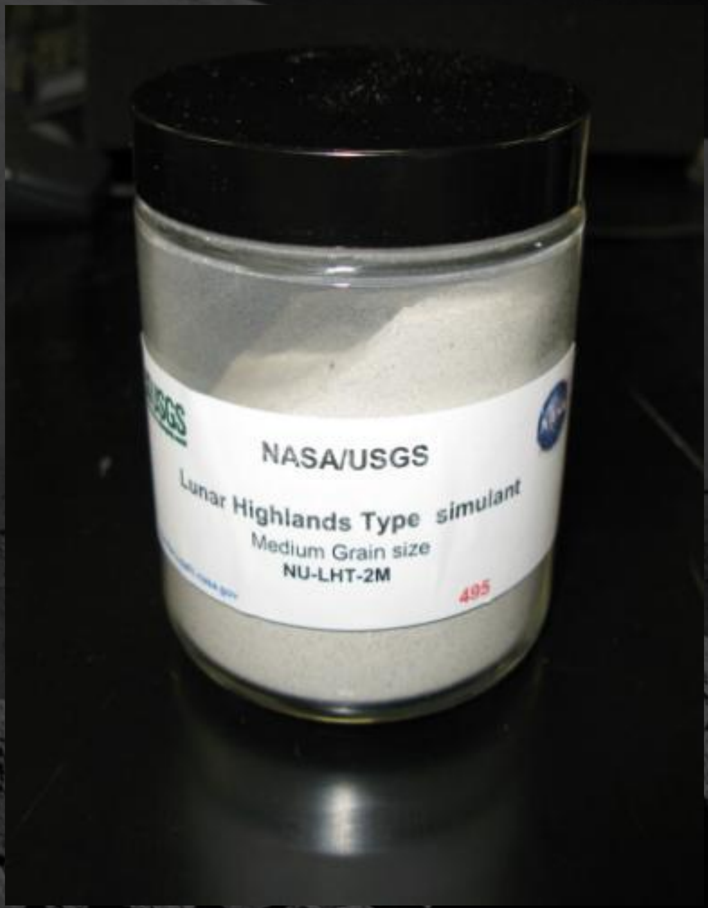
NU-LHT:
NASA/USGS
Lunar Highland Type Simulant

International Simulants: FJS-1 OB-1 CAS-1 Chenobi

JSC-1A

JSC-1A Lunar Regolith Simulant (Mare/Hybrid Type)

Highland Type NU-LHT-2M



NU-LHT-2M Lunar Regolith Simulant
NASA/United States Geological Survey Lunar Highland Type Simulant -2 Medium (M)

Highland Type NU-LHT-2D

Documented Simulants

Simulant	Produced by	Contact Info
NU-LHT - 1M, 2M, 1D, 2C	NASA / USGS Simulant	Carole McLemore 256-544-2314 / Carole.A.McLemore@nasa.gov http://isru.msfc.nasa.gov
JSC-1		no longer available
JSC-1A , 1AF	Orbitec created under a NASA contract .	http://orbitec.com/store/simulant.html
GSC-1	Goddard Simulant ; "Other, special purposes simulant materials"	-
GRC (Series 1-3)		-
BP-1	KSC / Arizona Black Point quarry waste (Basalt)	-
MLS-1	Minnesota Lunar Simulant	no longer available (created in the late 1980s)
International:		
OB-1	Canada	Jim Richard PH: 705-521-8324 x205 / jrichard@norcat.org http://www.norcat.org/innovation-regolith.aspx
Chenobi	Canada	http://www.evcltd.com/index_005.htm
FJS-1	Japan	http://www.shimz.co.jp/english/index.html
CUG-1	Chinese basalt geotechnical simulant	presentation at LPSC 2010 conference
CAS-1 and CLRS-1, CLRS-2, and NAO-1	China; high-Ti, low-Ti, and highlands respectively	Li Y., Liu J., and Yue Z. (2009), NAO-1: Lunar highland soil simulant developed in China (and others)
TJ-1 , TJ-2	China (Tongji University) ; a basaltic ash feedstock with olivine and glass	presentation at Earth & Space 2010: Jiang M.J., Liqing Li, Chuang Wang, He Zhang, A New Lunar Soil Simulant in China
KOHLS-1	Korea ; ground basalt and also a geotech sim	presentation at Earth & Space 2010: Experimental Study of Waterless Concrete for Lunar Construction by Sung Won Koh, Jaemin Yoo, Leonhard Bernold, and Tai Sik Lee, Hanyang University, Korea.

User’s Guide/Fit for Purpose Matrix

	excavation/flow*	drilling*	abrasion/wear
NU-LHT-1M	**recommended:** it has been demonstrated that pseudo-agglutinates affect geomechanical behavior that may be important to excavation	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith
NU-LHT-2M	**recommended:** it has been demonstrated that pseudo-agglutinates affect geomechanical behavior that may be important to excavation	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith	**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	**not recommended**: unrealistically fine PSD	**recommended with reservations**: unrealistically fine PSD for many uses
NU-LHT-2C	**most recommended:** it has been demonstrated that pseudo-agglutinates affect geomechanical behavior that may be important to excavation	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith, good PSD	**recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; presence of pseudo-agglutinates may aid fidelity to regolith
OB-1	**recommended:** good PSD at coarse end; lack of lithic fragments or pseudo-agglutinates may affect flowability or angle of repose -- this should be examined	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions
Chenobi	**recommended:** good PSD at coarse end; lack of lithic fragments or pseudo-agglutinates may affect flowability or angle of repose -- this should be examined	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions	**most recommended**: fidelity to mineral and glass% should yield appropriate abrasiveness; best PSD for coarse fractions

* We lack quantitative data on shape, and shape is important to geomechanical behavior

User’s Guide/Fit for Purpose Matrix

	excavation/flow*	drilling*	abrasion/wear
JSC-1, -1A	**recommended:** relatively angular particles, reasonable PSD	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness
JSC-1AF	**not recommended**: unrealistically fine PSD	**not recommended**: unrealistically fine PSD	**recommended with reservations**: unrealistically fine PSD for many uses
FJS-1	**recommended:** low-g tests show it has a high angle of repose; relatively angular particles, reasonable PSD	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness, low glass	**recommended with reservations**: uncertain but probably reasonable fidelity to highland abrasiveness, low glass
MLS-1 (processed for glass component)	**not recommended:** relatively poor PSD; shape distribution is skewed towards well-rounded particles	**not recommended:** high pyroxene/ plagioclase may adversely affect particle cleavage behavior; rounded grains	**not recommended:** high pyroxene/ plagioclase may adversely affect particle cleavage behavior; rounded grains

* We lack quantitative data on shape, and shape is important to geomechanical behavior

User's Guide/Fit for Purpose Matrix

	oxygen production**	human health studies
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	**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 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	**most suitable composition**; **reasonable PSD** but too coarse in fine fraction
NU-LHT-1D	**recommended for highlands**: should be similar to NU-LHT-1M, but possibly with lower FeO	**suitable composition** though it lacks the added phosphates and sulfides of NU-LHT-2M; **good PSD** in fine fraction
NU-LHT-2C	**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	**most suitable composition**; **good PSD**
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	**unsuitable composition** due to high Fe-glass; may be acceptable for testing where abrasiveness is of primary importance
Chenobi	**recommended for highlands with reservations**: will serve, in a way, as a worst-case example of the highlands regolith with the highest anorthositic fraction and that with the least mare contamination (i.e., very low FeO)	**partially suitable composition** though it lacks added phosphates and sulfides, and it represents one end-member of regolith composition; **good PSD** in fine fraction

** See associated text for details on different oxygen production methods

User’s Guide/Fit for Purpose Matrix

	oxygen production**	human health studies
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	**possibly suitable composition**; **reasonable PSD** but too coarse in fine fraction
JSC-1AF	**recommended with reservations**: should be similar to JSC-1A	**possibly suitable composition**; **good PSD** in fine fraction
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	**possibly suitable composition**; **poor PSD** in fine fraction
MLS-1 (processed for glass component)	**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	**unsuitable composition**; **unsuitable PSD** in fine fraction

** See associated text for details on different oxygen production methods

User's Guide/Fit for Purpose Matrix

- The Fit for Purpose Matrix only covers general purpose use
- Specialized use requires a greater understanding of the simulants and the characteristics of the lunar regolith they emulate best
  - Creating building habitat materials with a chemical process requires a simulant that matches the chemistry of the lunar regolith best; an excavation-grade (low-fidelity) simulant would not be acceptable
  - Thermal equipment testing requires a mineralogical match, not just a bulk chemistry match
- The Fit for Purpose Matrix only serves as a general guideline – it is not meant to be a substitute for the advice of the Simulant Team on the appropriate simulant to use for a specific task

Simulant Customers and Needs

- Regolith and/or simulants needed for Technology Development, Hardware Testing/Verification and Certification, Human Health Research, and Education/Public Outreach
  - Roadmaps and Infusion Points drive schedule dates
- Received 35 Simulant Survey responses from Constellation, ETDP Projects, Human Health, SBIRs, and Internationals
  - ETDP Projects: Dust, ISRU, EVA, AEMC, ELS, FDPS, AEMC, TCS, Robotic Mobility, Regolith Operations, …
  - CxP Projects: Lunar Surface Systems (LSS), EVA, Altair, Habitation …
- Expect more requests from simulant users

Transition to Other Destinations

- Mars and asteroids have been named possible destinations for the NASA manned spaceflight program
- Asteroid surface environments are similar to the lunar surface environment
  - Change the mineralogy and geochemical properties of lunar simulant for asteroids
- Martian geology is radically different from lunar geology
- Martian surface environment is very different from both the lunar and terrestrial surface environments
  - Presents a new set of challenges

Summary

- There is no “one size fits all” simulant
  - Different simulants must be created to be cost-effective
    - Low-fidelity excavation grade simulant (large quantities)
    - High-fidelity oxygen extraction simulant (smaller quantities)
  - Different simulants must be created to reflect different possible landing sites on the Moon
    - Highlands and mare locations, each with unique properties
- No terrestrial-made simulant will completely emulate the lunar regolith (very different environments of formation)
- We still do not know everything there is to know about the lunar regolith
- Each point above adds risk to the mission design

Contacts

- Official NASA website to request lunar simulant
  - http://isru.msfc.nasa.gov/lunarsurvey/

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- Dr. Jennifer Edmunson

  256-961-7546

  jennifer.e.edmunson@nasa.gov