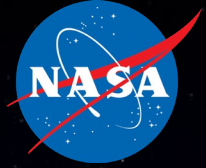


National Aeronautics and Space Administration



Lunar Regolith Simulants: *Current Simulants, Use Cases, Selection Process, and Best Practices*

Dr. Heather Oravec

The University of Akron at
NASA Glenn Research Center

April 15, 2025

International Workshop on Granular Materials & Regolith

*Granular Materials Fundamentals, Applications and Concepts for
Extraterrestrial Regolith including the Moon, Mars and Asteroids*

Université de Lorraine, Metz, France

April 14-17, 2025



www.nasa.gov



Overview

- Introduction
- Formation of Lunar Regolith
- Lunar Regolith Simulant Properties
- Past and Present Simulants
- Figures of Merit (FoM)
- Safety Considerations
- Facilities That Currently Use Lunar Simulants
- Best Practices



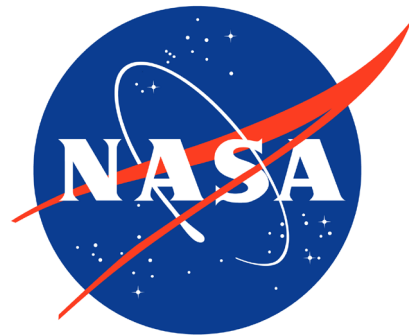


NASA's Simulant Advisory Committee

“The purpose of the Simulant Advisory Committee is to establish a NASA-wide voice of all things simulants. The committee gives advice on appropriate use and creation of simulants and assists in their production and distribution across NASA, academia, and the private sector. The committee will identify a simulant supply chain and develop guidelines and standards to facilitate consistency and efficiency for bulk-use, moderate-fidelity use, and high-fidelity use simulants.”

Simulant Advisory Committee POC's

Personnel	Role
John Gruener	JSC Simulant POC/ Committee Lead
Rostislav Kovtun	JSC Simulant POC
Hannah O'Brien	JSC Simulant POC
Jennifer Edmunson	MSFC Simulant POC
Doug Rickman	MSFC Simulant POC
Heather Oravec	GRC Simulant POC
Julie Kleinhenz	GRC Simulant POC
Laurent Sibille	KSC Simulant POC



Concept of Operations

- Small NASA Simulant Advisory Committee, led by JSC Astromaterials Research and Exploration Science (ARES)
- NASA team coordinates simulant requirements based on projects' needs across the agency
- Purchase simulants from existing vendors when possible; government development and production when warranted
- Coordinate with JHU/APL Lunar Surface Innovation Consortium

Importance of High-Quality Simulants



“Though lunar simulant is not a "technology", every technology being developed for use on the lunar surface needs to be tested with high quality lunar simulants. Currently, there is only a small, scattered supply of lunar simulant "leftovers". This project will address the current shortage of lunar simulants and supply appropriate simulants for testing new technologies. These include mineral/chemical simulants (oxygen from regolith, dust toxicity) and mechanical simulants (mobility, excavation, construction) with both lower and higher fidelities for different levels of TRL development.”

NASA/TM-20240011783



Lunar Regolith Simulant User's Guide Revision A

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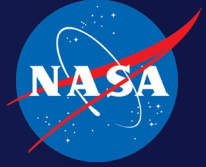
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NASA's Apollo Program



- July 1969 through December 1972
- Landed on the lunar surface at six (6) locations on the equatorial region of the near side of the Moon
 - Five (5) landed in lunar mare regions
 - One (1) landed in the lunar highlands
- Astronauts collected 362 kg (842 lb) of lunar rock and soil samples
- Three (3) Luna robotic sample acquisition missions collected 300 grams (<1 lb) for the Soviet Union (1970s)
- Most recently, Chang'e-5 and Chang'e-6 brought 3,666 grams (8 lb) to China
- 850 lbs of lunar soil and rock samples is what the current understanding of the Moon's origin and geologic history are based from

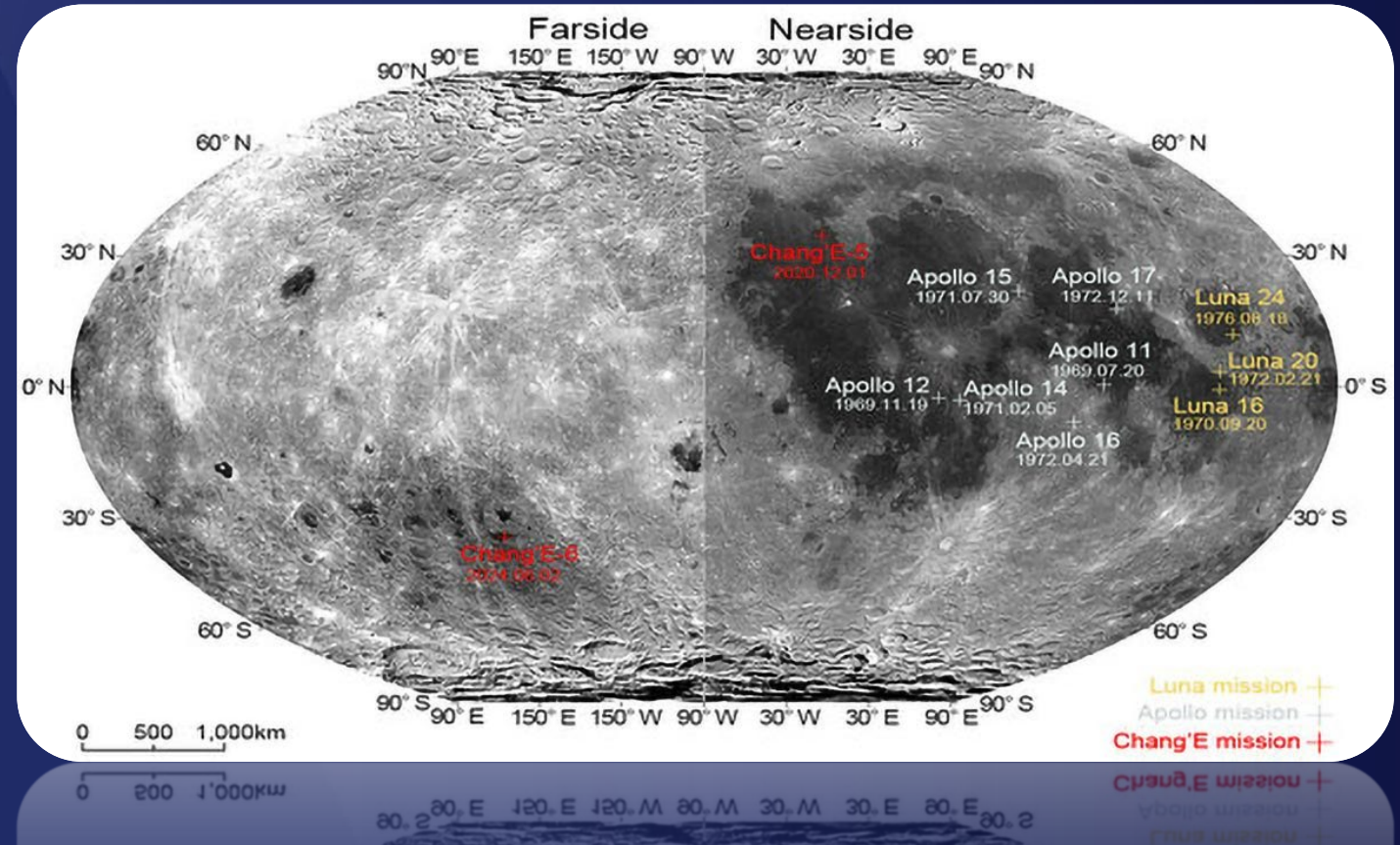
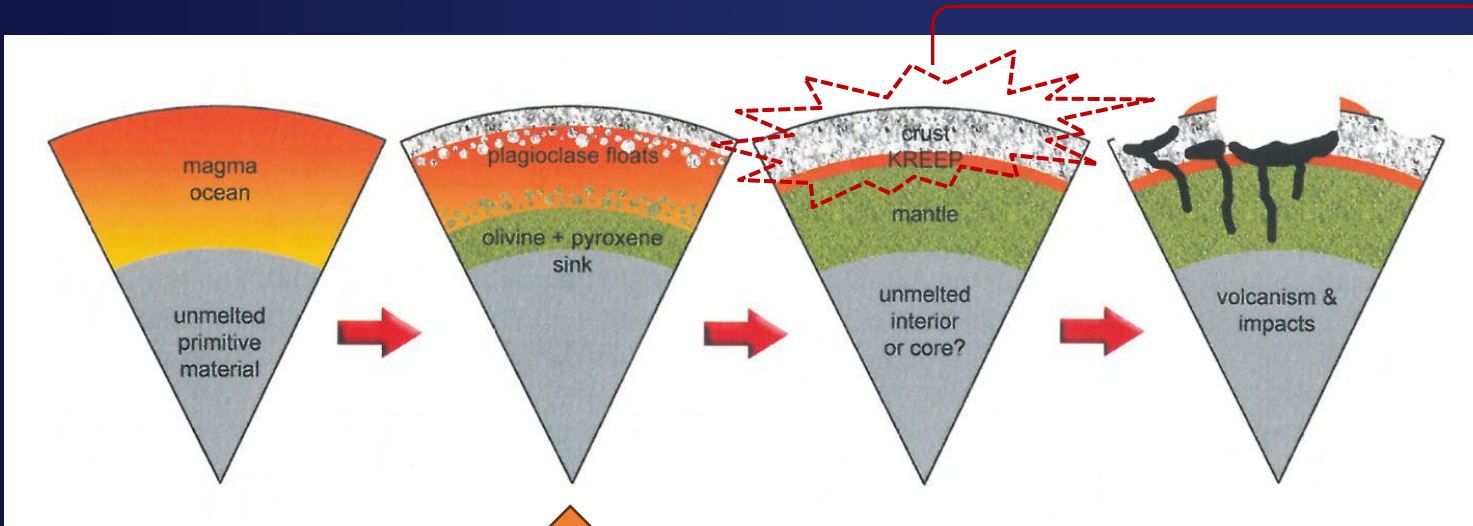


Image Credit: NAOC

The Lunar magma Ocean Hypothesis



Crystalline component:

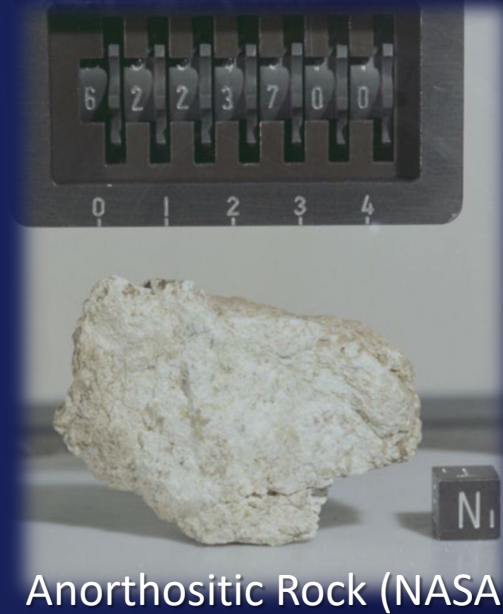
Rocks	Minerals
Anorthosite	Plagioclase Feldspar
Norite	Plagioclase, Pyroxene
Troctolite	Plagioclase, Olivine
Dunite	Olivine

Referred to by differences in chemistry:
"high-Low-Very low-titanium"



Lunar Basalt (NASA)

Referred to by differences in petrology:
"noritic anorthosite" vs. "anorthositic norite"

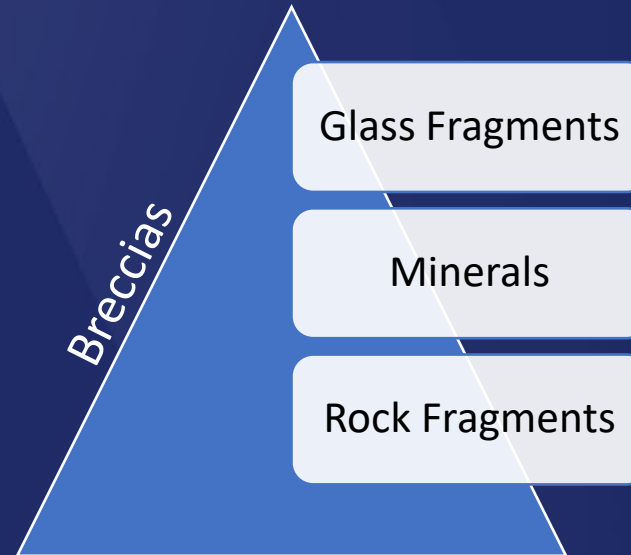


Anorthositic Rock (NASA)

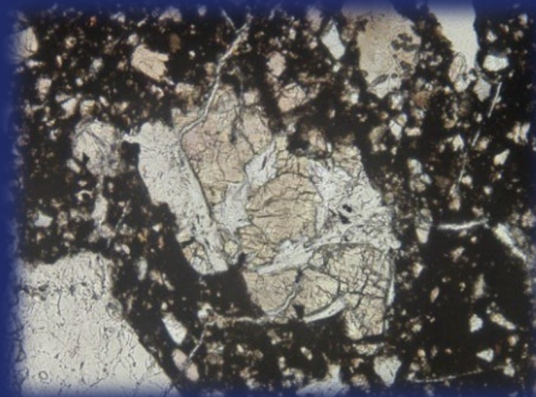
Creation of Lunar Regolith



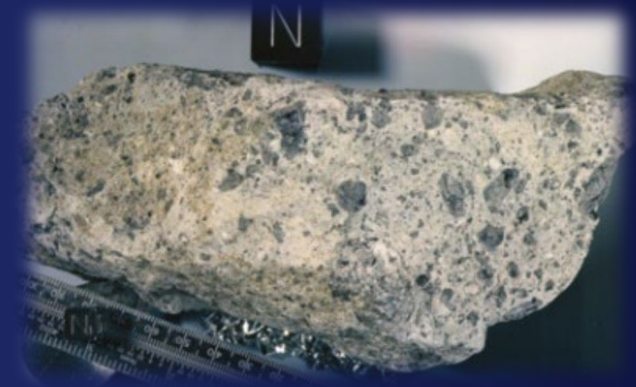
- Surface impacts cause two disparate processes to occur on the moon
 - Destruction – Bedrock surfaces broken into rubble and rubble consequently breaking down into small fragments
 - Construction – Involves the creation of complex rocks known as breccias and a variety of impact melt products (agglutinates)
- Most returned Apollo rock samples are breccias
 - Polymict – contain a variety of different rock fragments
 - Monomict – contain fragments of a single rock type
 - Microbreccia – breccias which are broken down into smaller and smaller pieces which retain their unique character



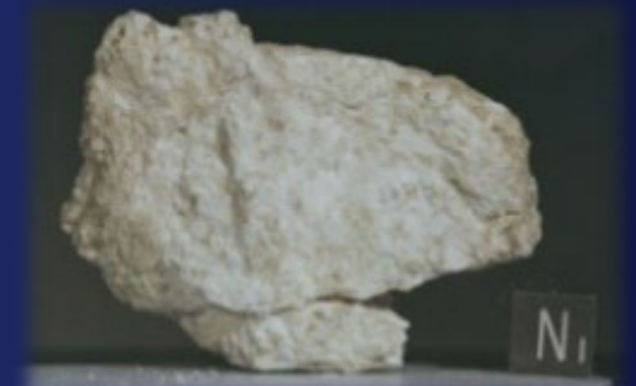
Set in fine-grained matrix bonding larger fragments together



Microbreccia (NASA)



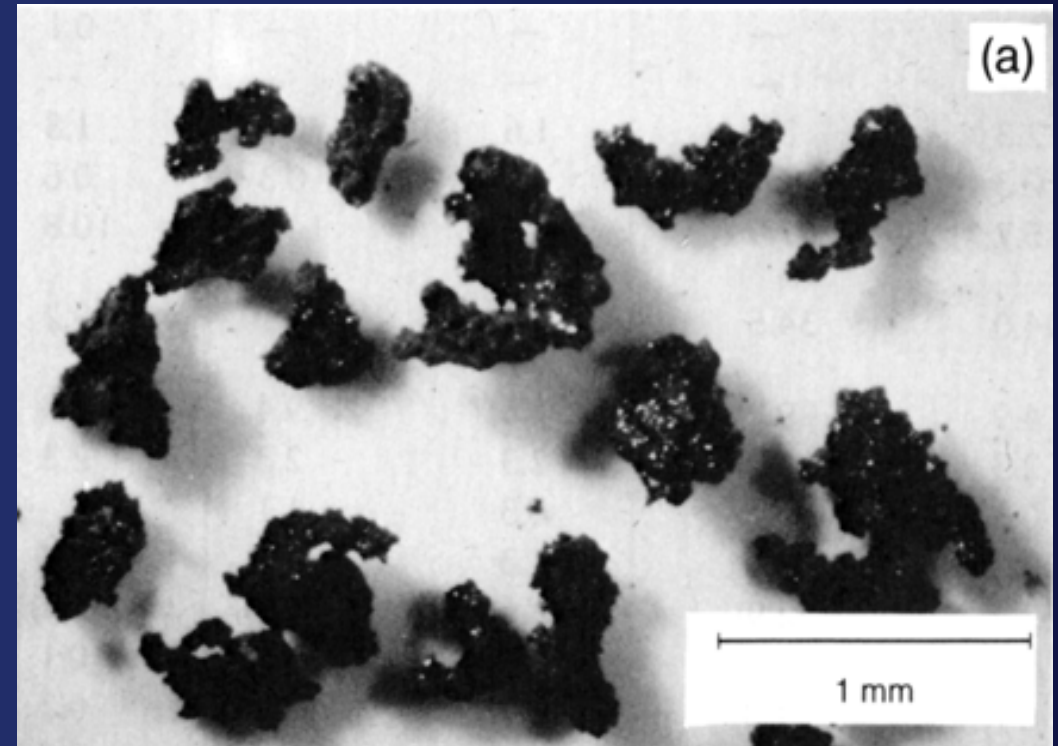
Lunar Polymict Breccia (NASA)



Lunar Monomict Breccia (NASA)

Glass Component

- Impact melt glass products are ubiquitous on the Moon
- In some basaltic mare units volcanic glass beads are also present
- Glass products are a result of high energies and high pressures created during an impact event
 - Glassy melt breccias
 - Regolith breccias
 - Agglutinates – major source of glass in lunar regolith
 - 20-40% by volume on average
 - 65% by volume in some mature regolith
 - Aggregates of smaller lunar soil, rock, and mineral fragments welded together by impact generated glasses created by micrometeoroids
 - Complex geometries
 - No terrestrial analog
 - Presence of very fine-grained single-domain nanophase iron (Fe^0) metal droplets or spheres in the glass
 - Causes an increase in ferromagnetic resonance of the lunar soil samples compared to rock samples
 - Causes a darkening of the soil
 - Clast-free impact glass

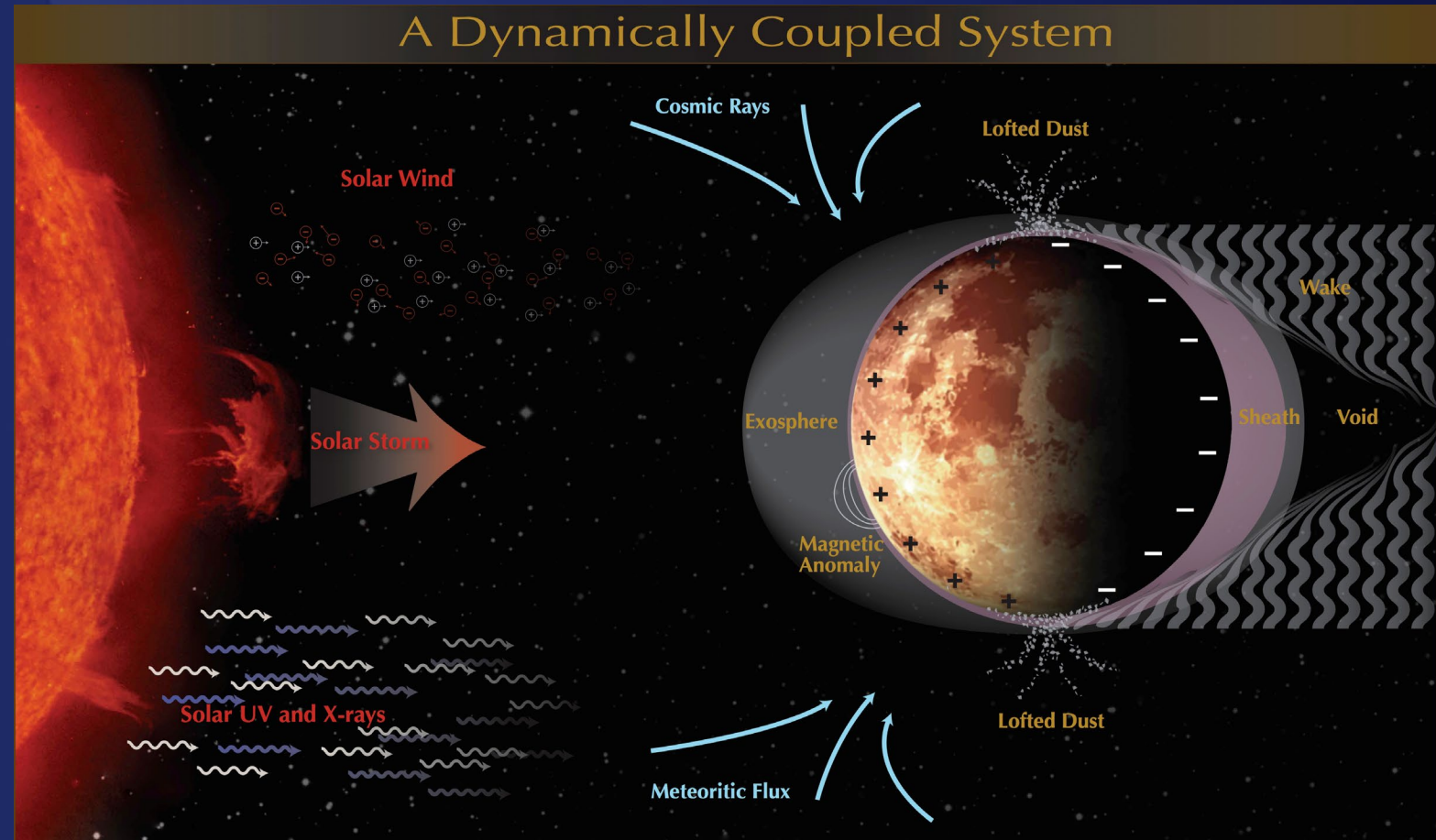


Agglutinate particles (NASA)

Radiation, Plasma, and Space Weathering Effects



- The Moon does not possess a measurable magnetic field and has essentially no atmosphere
- As a result, the lunar regolith is constantly assailed by the energetic particles primarily emitted from the Sun, solar wind, and galactic cosmic radiation
 - Ion implantation (e.g., solar wind implanted hydrogen)
 - Displacement of atoms internal to the target crystalline material
 - Ion sputtering
 - Ejection of atoms or molecules
- Results in a dynamic charging environment where the sunlit side acquires a positive charge (+) and the shadow side acquires a negative charge (-)
- Space weathering – micrometeoroid impact bombardment and energetic particle interaction with the lunar regolith
 - Alter the way surface grains absorb, reflect, and emit light



The plasma environment interaction with the lunar surface (NASA)



Particle Size Distribution

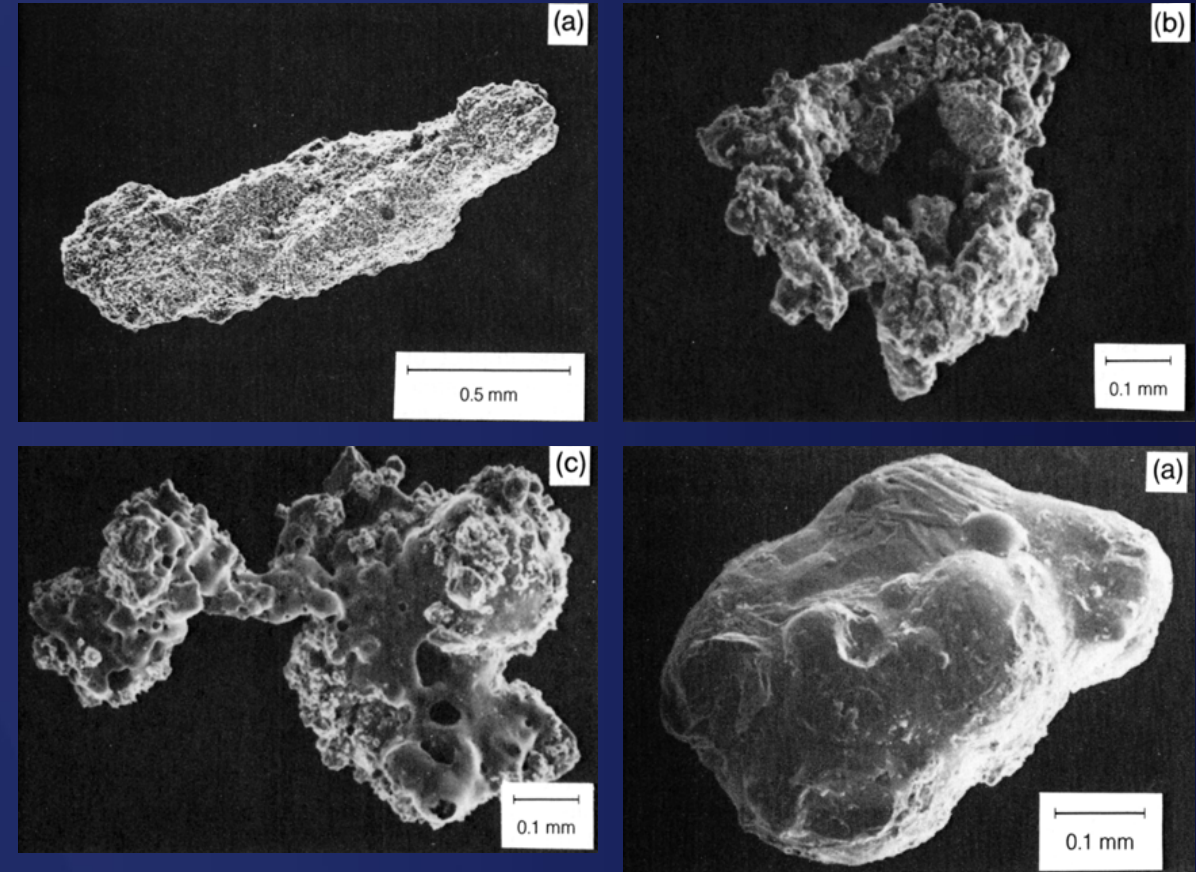
- Using conventional terrestrial descriptions most lunar regolith samples correspond to pebble- or cobble-bearing silty sands
 - Includes single-digit microns to 256 mm particles
- Most Apollo samples were on the order of >1 cm, but most detailed studies have been performed on the sub-millimeter fraction
- To understand the regolith as a whole the coarse fines (1 mm to 1 cm) and rocks need to be included (>1 cm)
- Most of the published PSD curves for Apollo only consist of the > 1 cm size fraction

Millimeters (mm)	Micrometers (μm)	Wentworth Size Class (with common sediment name)	
		Boulder	Gravel
256		Cobble	
64		Pebble	
4		Granule	
2		Very Coarse Sand	Sand
1		Coarse Sand	
1/2 (0.50)	500	Medium Sand	
1/4 (0.25)	250	Fine Sand	
1/8 (0.125)	125	Very Fine Sand	
1/16 (0.0625)	63	Silt	Mud
1/256 (0.0039)	3.9	Clay	

Wentworth grain size classification (1922)

Particle Geometry

- Wide range from perfectly spherical to highly complex and intricate agglutinates
- Early investigations described the particles as somewhat elongated and sub-angular to angular in shape.
- Recent studies using new dynamic image analysis technology suggest that the regolith particles are not as morphologically complex as we once thought (excluding agglutinates)
 - Suggests a generally more sub-round to sub-angular particle shape with the perfectly round or complex particles as the exception.



SEM images of ropy glass particle, agglutinates, and composite volcanic glass droplet (Lunar Sourcebook, 1991)



Lunar Regolith - Summary

- Regolith is made of same major rock forming chemical elements as on the Earth (oxygen, silicon, aluminum, calcium, magnesium, iron) – resulting in minerals common to Earth (plagioclase feldspar, pyroxene, and olivine)
- The surface of the Moon is unlike any surface that exists on the Earth
 - High temperature formation of the Moon
 - Billions of years of impact bombardment
 - Geologic evolution of the lunar surface in vacuum and plasma environment of space



How do we create lunar regolith simulants that come as close as practical to the true lunar regolith?

Lunar Regolith Simulant from Terrestrial Materials



How to simulate the formation of broken crystalline materials by continuous impact when the Earth is protected by its atmosphere?

- Crushing, milling, pulverizing equipment to simulate the impact of shattering rock and minerals
- Time consuming and costly, but processes have improved with time

How to simulate the glass component in the lunar regolith?

- Using volcanic glass or melted rock via traditional glass furnaces, plasma arc facilities, or lasers
- Geometry of the particles (agglutinate-like) not yet satisfactory

How to account for differences in mineralogy found in lunar-like rocks and minerals on earth?

- Water on Earth contributed to non-lunar hydrated (amphiboles, micas) and weathered minerals (clays, iron oxides)
- Quartz forms in cooling magmas (granite) or by the weathering of silicate minerals
- Carbonate minerals (calcite, dolomite) are found in the same rocks as lunar-like minerals
- Fault zones (plate tectonics) results in lunar-like minerals being metamorphosed due to high temperatures, pressures, or geothermal fluids
- Differences between terrestrial feldspars and lunar feldspars since the Moon is depleted in volatile elements Potassium (K) and Sodium (Na) compared to the Earth
 - Lunar plagioclase feldspar is more calcium rich (anorthite)
 - Terrestrial feldspars have more sodium in the crystalline structure (bytownite or labradorite)
- Non-lunar minerals account for as much as 10-20% of the rocks that simulant producers use as geologic feedstock.
- Reduction or elimination is difficult and costly
- The presence mostly affects ISRU processes that involve high temperatures to produce oxygen or metals

Apollo Era Lunar Simulants

- The first use of lunar simulant materials was during the buildup of the Apollo mission.



Original outdoor “rock pile” lunar training facility at the Manned Spacecraft Center, Houston (NASA)



Revised outdoor “rock pile” – night training (NASA)



Indoor lunar training in building 9 at MSC in Houston (NASA)



Post-Apollo Lunar Simulants

- As part of the Space Exploration Initiative (1989), a workshop “Production and Uses of Simulated Lunar Materials” was held at the Lunar and Planetary Institute in Houston, Texas.
 - Define the need for simulated lunar materials
 - Examine related issues in support of extended space exploration and development
- During this time two lunar simulants were created for the lunar exploration community:
 - MLS-1 (Minnesota Lunar Simulant #1)
 - JSC-1 (Johnson Space Center-1)

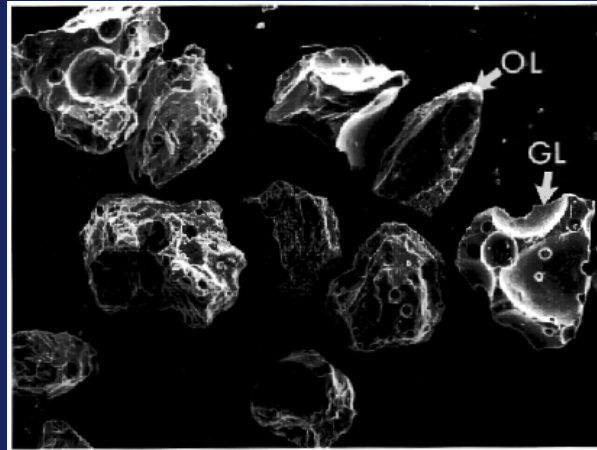
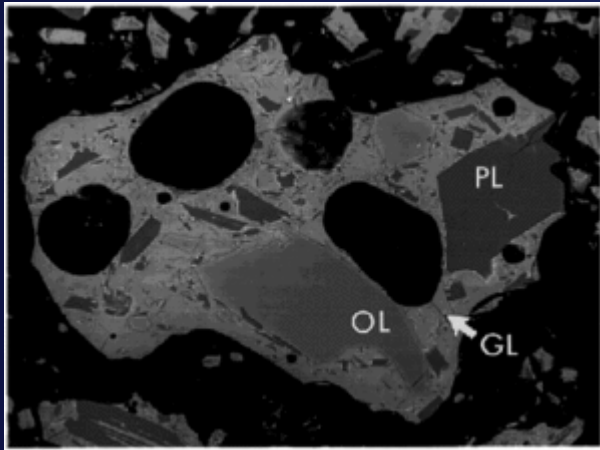


MLS-1 source rock in abandoned quarry in Duluth, Minnesota. Brownish basalt sits on top of a gray anorthosite layer. (Photo credit: Jimmy Lovrien – Duluth News Tribune)

Post-Apollo Lunar Simulants

MLS-1

- Developed at the Mineral Resources Research Center at the University of Minnesota
- Created to match the Apollo 11 soil sample 10084 – lunar mare simulant
- Material from 1-2 m thick high-Ti basalt sill from abandoned quarry in Duluth
- 1000 kg created – 1st bulk simulant



(Left) JSC-1 grains in polished section including glass, plagioclase, and olivine. (Right) Glass and olivine grains from SEM image. (Credit: NASA)

JSC-1

- Most widely used simulant in the 1990s-2000s – lunar mare simulant
- Feedstock from volcanic basaltic ash deposit erupted from vents related to Merriam Crater
 - Plagioclase feldspar, pyroxene, olivine
 - ½ volume of the deposit is glass (basaltic composition)
 - Material broken down using impact mill to simulate lunar surface bombardment
- >12 tons produced to support large-scale human activity studies
 - Material handling
 - Construction
 - Excavation
 - Transportation
 - Dust control
 - Spacesuit durability
 - Agriculture
 - Oxygen production
 - Sintering
- Major limitation is the restricted PSD (<1 mm)

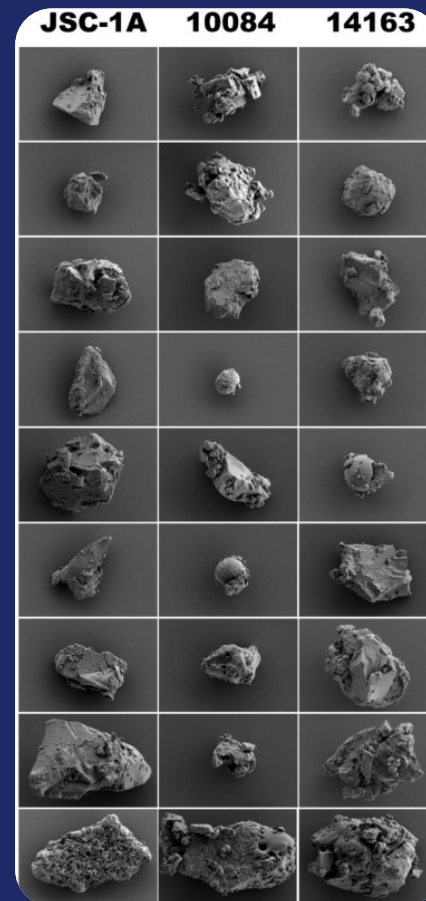
Constellation Program Simulants

As a result of the desire for global lunar access, there was a need for both lunar mare and highland simulants.

JSC-1A (mare)

- Produced by Orbital Technologies Corporation (ORBITEC)
- 14 metric tons produced using the same feedstock and processing as JSC-1
- JSC-1AF (27 μm) and JSC-1C (up to 5 mm) also produced in smaller quantities
- One of the best characterized and documented lunar simulants

SEM images of JSC-1A, Apollo 11, and Apollo 14 regolith (Credit: Goguen et al. 2024)



NU-LHT Series (highlands)

- Collaboration between NASA and USGS
- First lunar highlands simulant mass produced in the US
- Several rock types and minerals used to create a noritic anorthosite similar to Apollo 16 samples
 - Anorthosite and Norite – Stillwater Mine (Nye, Montana)
- Synthetic glass component with highlands-like chemical composition (all glass, no mineral inclusions) and pseudo-agglutinates
 - Created from Stillwater mill sand with plasma arch facility (Zybek Advanced Products of Boulder, CO)
- NU-LHT-1M: pilot simulant
 - 80% crystalline, 16% agglutinate, 4% glass
- NU-LHT-2M: prototype produced in large amounts
 - 65% crystalline, 30% agglutinate, 5% glass
- NU-LHT-2C: Like 2M, but with coarser fraction added after milling
- NU-LHT-2E: Engineering grade
- NU-LHT-2EG: Engineering grade with agglutinate material
- NU-LHT-3M: Mechanical testing grade

Constellation Program Simulants, cont.

OB-1 (Highlands)

- Feedstock Shawmere anorthosite (Canada)
- Olivine glass slag added (42% glass to 58% anorthosite)
- Chenobi – variant of OB-1 incorporating glass and pseudo agglutinates created from anorthosite using the NU-LHT Zybek facility



BP-1 lunar simulant (Credit: ASCE)

BP-1

- Not created, but discovered as a waste pile at an aggregate quarry at the Black Point lava flow in the San Francisco Volcanic Field (Gray Mountain, AZ)
- Alkaline basalt – high in sodium and potassium (not lunar-like)
- Completely crystalline – no glass or agglutinates
- Includes pebble- and cobble-sized rocks mixed with finer particles
- Good physical simulant
 - Construction
 - Excavation
 - Surface mobility technology

Artemis Program Simulants

NU-LHT-4M (Highlands)

- Similar to NU-LHT-2M
- 1 metric ton produced with remaining Stillwater feedstock (anorthosite and norite)
- Smaller amounts of olivine, ilmenite, synthetic whitlockite, fluor-apatite, purite, and chromite
- No 'good' glass remained in the USGS stock (35% glass component consisted of pseudo-agglutinates)

OB-1A (Highlands)

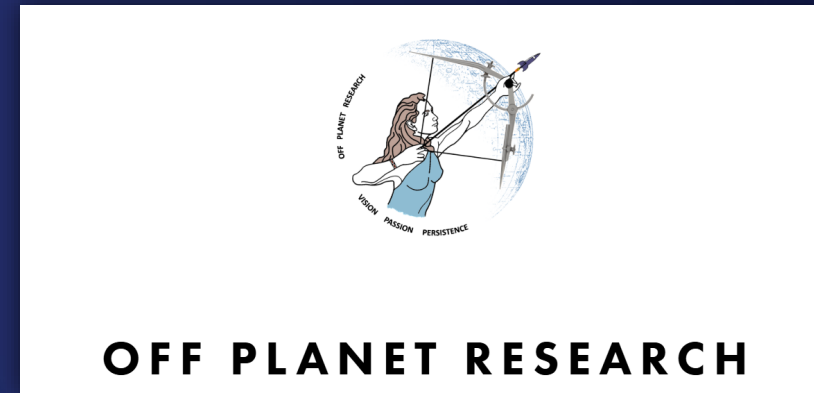
- Commercial purchase of 500 kg made by NASA
- Deltion (Canada)
- Advertised as 60% Shawmere anorthosite, 40% glass slag

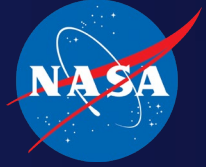


NU-LHT-2M Lunar Highlands Simulant (Credit: NASA)

Commercial Enterprises

- Exolith Lab (University of Central Florida) – Now Space Resource Technologies
 - Off Planet Research (Everett, Washington)
 - Colorado School of Mines
-
- Greatest benefit is to private industry who can commercially acquire these simulants to develop their products/services
 - Simulants can be tailored for specific project needs to be purchased in bulk so multiple NASA projects can test different technologies in the same simulant
 - Offer general purpose simulants
 - Most vendors use the same basaltic cinders from the Merriam Crater that NASA used to make JSC-1 and -1A
 - Can be 100% basaltic cinders or contain other components (anorthosite in small amounts)
 - Using anorthositic rocks from Shawmere (Canada), Greenland (White Mountain), and Stillwater (US) for highlands simulants
 - Typically, 70-80% anorthosite, 20-30% basalt cinders and can include other rock types or minerals





Lunar Regolith Simulant Classification

Basic Simulants

- Made from one rock type and don't include glass
- Major minerals are present, but not necessarily in the correct relative abundances
- No major effort has been made to match PSD
- E.g., BP-1, Greenspar, bunker sands (golf)

General Purpose Simulants

- Contain a mixture of rock types, resulting in the major minerals with relative proportions more like the lunar regolith than basic simulants
- Glass is present, though not in the same percentage as impact-generated glass in the lunar regolith (or the same shape, or chemistry)
- Some effort has been made to process the materials for correct particle shape and PSD
- Broadest category of simulants (most commercial simulants fall in this category)

Enhanced Simulants

- Considerable effort to closely match several lunar regolith attributes beyond that of general-purpose simulants
 - Proportions of major minerals to match a particular region
 - Addition of agglutinate-like particles or chemically correct glass
 - An overall glass component that makes up about 40% of the simulant
 - The presence of minor minerals such as ilmenite
- E.g., NU-LHT series

Specialty Simulants

- Designed for a very specific technical focus area and produced in small amounts
- E.g., Lunar simulants containing frozen volatiles to mimic ice-bearing lunar regolith at the lunar poles
- E.g., Simulant containing agglutinate-like particles that contain nanophase iron



Regolith simulants (from: Space Resource Technologies)

Example Uses of Lunar Regolith Simulants

High Temperature Processes

- Mineralogy and chemistry are critical
- E.g., Microwave or laser sintering for additive manufacturing
- E.g., Oxygen or metal production via molten regolith electrolysis

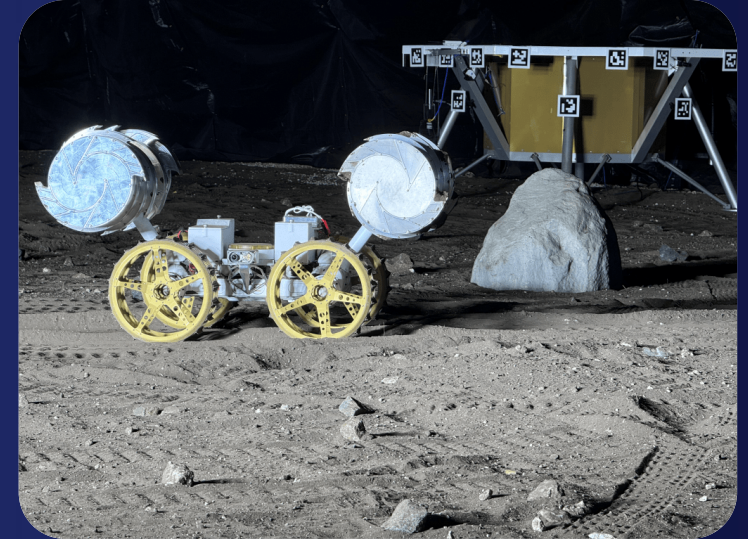
Dust Mitigation

- Particle shape, size, and glass content are critical
- E.g., Testing mechanisms, surfaces, filters, and fabrics
- Typically, simulants focus on $\leq 100 \mu\text{m}$ for dust testing

Excavation

- Simulant should contain the full PSD of the bulk lunar regolith
- A large glass component should be present as the softer glasses will likely break down and inevitably get into excavation mechanisms

No single lunar regolith simulant will satisfy all the technology needs of a broad-based lunar exploration program!



A photo taken from the ISRU Pilot Excavator (IPEX) as it is tested in a blacked-out facility with minimal lighting that mimics the harsh, feature-less terrain of the Moon (Credit: NASA).



Selecting a Simulant

- Figures of Merit (FoM) – an algorithm for quantifying a single characteristic of a simulant, provides a clear measure of how well a simulant and reference material compare. ***The goal of FoM is to provide an objective metric for available lunar regolith simulants that can be iterated on to encompass future granular analog material development.***
- Serves as a method for rating the fidelity of analogous materials for scientific and engineering purposes
- Outputs a value between 0 and 100, where 0 is nothing like the lunar regolith and 100% is an exact match
- Original FoMs calculated as inner products between unit vectors (one for a particular simulant and one for the lunar reference point). These ranged from 0 to 1, with 1 being a perfect match
- Initially four quantities were used to characterize simulant
 - Material composition (lithic fragments, mineral grains, glasses, agglutinates, chemistry)
 - Particle size distribution
 - Particle shape (mean width, shape factor, aspect ratio, convexity)
 - Material density

$$FoM = 1 - \frac{\left\| W_{adjusted} \left(C_{adjusted\ reference} - C_{adjusted\ simulant} \right) \right\|_1}{\left\| W_{adjusted} C_{adjusted\ reference} \right\|_1 + \left\| W_{adjusted} C_{adjusted\ simulant} \right\|_1}$$
$$= 1 - \frac{\sum_i W_{adjusted_i} \left| C_{adjusted\ reference_i} - C_{adjusted\ simulant_i} \right|}{\sum_i W_{adjusted_i} C_{adjusted\ reference_i} + \sum_i W_{adjusted_i} C_{adjusted\ simulant_i}}$$

where $\|w\|_1$ denotes the **L1** norm of vector **w**.

i.e., the sum of the absolute value of the entries in the vector -or-

$$\|w\|_1 = \sum |w_i|$$



JSC ARES – Updated FoM Project

- Based on the variation of the FoM system developed by Metzger et al. 2019
- Existing equations for each simulant property were rewritten
- Additional properties for FoM assessment were included
 - Mineralogy
 - Chemistry (oxide)
 - Particle size distribution
 - Particle geometry (aspect ratio and form factor)
 - Material Density
 - Magnetic Susceptibility
 - Shear Strength (cohesion and angle of internal friction)
- Mathematical models redefined to best suit FoM calculations for specific properties

Regolith Property	Data Source
Mineralogy	Taylor et al., 2019
Chemistry	Taylor, 1973; Wanke, 1973; Rhodes, 1974; Christian, 1976; Warren et al., 1978, Korotev, 1982; Papike and Simon, 1982
Particle Size Distribution	Lunar Soils Grain Size Catalog Graf, 1993
Particle Geometry	Novel measurements via Laser Diffraction (LD) and Dynamic Image Analysis (DIA) accomplished by Walker (nee Deitrick) and Cannon, 2022 (unpublished) using MicroTrac SYNC on 4 Apollo samples (10084, 15601, 64501, 67461)
Material Density	Costes and Mitchell, 1970; Carrier et al., 1971; Houston and Mitchell, 1971; Scott et al., 1971; Vinogradov, 1971; Carrier et al., 1972a; Mitchell et al., 1972a; Mitchell et al., 1972b; Vinogradov, 1972; Mitchell et al., 1973a; Carrier, 1974; Florensky et al., 1977; Barsukov, 1977
Magnetic Susceptibility	Rochette et al., 2010
Shear Strength	Carrier et al., 1999

The Johns Hopkins University Applied Physics Laboratory was responsible for several simulant assessments under the NASA Lunar Surface Innovation Initiative (LSII):

- *2020 Lunar Simulant Assessment*
 - Overview of simulant manufacturers
 - Available simulant offering
 - Physical (PSD) and compositional descriptions
- *2021 Lunar Simulant Assessment*
 - Deep dive into existing simulants
- *2022 Lunar Simulant Assessment*
 - Geotech focused study of commercially available simulant (PSD, density, specific gravity, shear strength)
 - NASA/USGS materials also characterized



Current FoM Scores

FoM scores calculated for 14 commercially available and government simulants stores at the NASA-JSC-ARES Simulants Development Lab.

Simulant	Region	Source
BP-1	Low-Ti Mare	NASA KSC
CSM-LHT-1	Highlands	Colorado School of Mines
CSM-LMT-1	High-Ti Mare	Colorado School of Mines
GreenSpar	Highlands	Lumina
JSC-1A	Low-Ti Mare	Orbitec**
LHS-1	Highlands	Exolith Labs/Space Resource Technologies
LMS-1	Low-Ti Mare	Exolith Labs/Space Resource Technologies
MLS-1	High-Ti Mare	Univ. of Minnesota**
NU-LHT-2M	Highlands	USGS/NASA**
NU-LHT-4M	Highlands	USGS/NASA**
OB-1(A*)	Highlands	Deltion Innovations**
OPRH3N	Highlands	Off Planet Research
OPRH4W30	Highlands	Off Planet Research
OPRL2N	High-Ti Mare	Off Planet Research

* Some measurements performed on OB-1 were extrapolated to OB-1A due to the similarity in their feedstock composition.

** These entities no longer manufacturer the associated simulant.



FoM Limitations

1. Data gathering and aggregation from various sources and laboratories is an imperfect method when comparing material properties directly.
2. Inherent constraints on the extent to which a measured sample is representative of a bulk material.
 - Is the sample representative of the bulk material?
 - How good are the manufacturer's processing and quality control measures?
3. A fundamental decision has to be made on which simulant properties must be compared to which lunar regolith properties.
4. The content included is based on available data at the time of publication.



FoM – Mineralogy (Φ_M)

Importance:

- Knowing the composition of the bulk granular material
- Chemical processing (ISRU, oxide/metal production)
- Human health (radiation shielding, respiration)
- Particle-surface interactions (plume surface interaction, dust mitigation)
- Particle bonding (polymer binding, sintering)

Apollo Modal Mineralogy (wt.%)			
Mineral	Highlands	High-Ti Mare	Low-Ti Mare
Pyroxene	7.92	26.79	24.97
Plagioclase Feldspar	59.05	19.42	28.46
Olivine	5.11	5.80	6.89
Ilmenite	0.15	10.27	3.86
Glass	27.77	35.38	32.98

Averaged regional lunar modal mineralogy based on Apollo returned sample XRD analysis by Taylor et al. 2019. Five general mineral groups selected for comparison due to their ubiquity in both Apollo sample and simulant analyses, as well as their role as major modal constituents within both highlands and mare lunar regions.

$$\Phi_M(\vec{S}_M, \vec{R}_M) = \|\vec{S}_M \cap \vec{R}_M\|_1 = \sum_{i=1}^{N_M} \min(s_i, r_i)$$

Mineralogy Figures of Merit	
<i>Simulant</i>	<i>Score</i>
BP-1	62
CSM-LHT-1	n/a
CSM-LMT-1	n/a
GreenSpar	n/a
JSC-1A	84
LHS-1	84
LMS-1	89
MLS-1	67
NU-LHT-2M	89
NU-LHT-4M	78
OB-1(A*)	82
OPRH3N	n/a
OPRH4W30	n/a
OPRL2N	n/a

Mineralogy FoM scores. n/a indicated simulants with insufficient data to perform FoM.



FoM – Chemistry (Φ_E)

Importance:

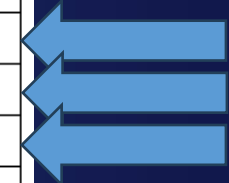
- Knowing the composition of the bulk granular material
- Chemical processing (ISRU, oxide/metal production)
- Human health (radiation shielding, respiration)
- Particle-surface interactions (plume surface interaction, dust mitigation)
- Particle bonding (polymer binding, sintering)

Apollo Bulk Chemistry (wt. %)								
Region	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O
Highlands	45.62	0.84	24.47	6.6	6.98	14.65	0.48	0.2
High-Ti Mare	41.27	7.48	12.5	16.47	9.75	11.26	0.39	0.11
Low-Ti Mare	45.62	2.09	13.2	16.45	10.19	10.65	0.42	0.19

Oxide chemistry results were organized by lunar regions (i.e., highlands, low-Ti mare, and high-Ti mare) and averaged across region to produce bulk regional surface oxide chemistry. Eight (8) oxides were selected for comparison between lunar reference materials and simulants: These oxides were chosen due to their ubiquity in both Apollo sample and simulant analyses, as well as their role as majority constituents within both surficial highlands and mare lunar regions.

$$\Phi_E(\vec{R}_E, \vec{S}_E) = \|\vec{S}_E \cap \vec{R}_E\|_1 = \sum_{i=1}^{N_E} \min(v_i, w_i)$$

Chemistry Figures of Merit	
<i>Simulant</i>	<i>Score</i>
BP-1	85
CSM-LHT-1	92
CSM-LMT-1	89
GreenSpar	86
JSC-1A	88
LHS-1	91
LMS-1	88
MLS-1	96
NU-LHT-2M	96
NU-LHT-4M	95
OB-1(A*)	87
OPRH3N	93
OPRH4W30	88
OPRL2N	87



Chemistry FoM scores.



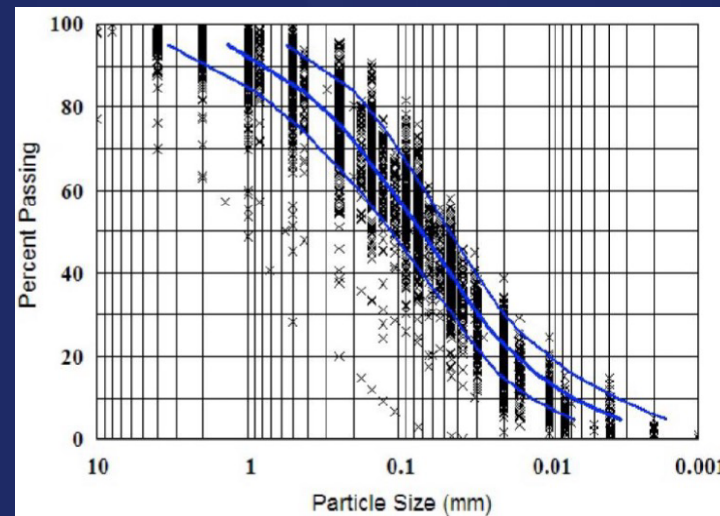
FoM – Particle Size Distribution (Φ_{PSD})

Importance:

- Deciphering the physical nature of bulk granular material
- Geotechnical engineering (excavation, drilling)
- Human health (radiation shielding, respiration)
- Particle-surface interactions (plume surface interaction, dust mitigation)
- Particle bonding (polymer binding, sintering)
- Provides information on soil compressibility and strength
- Insight into thermal conductivity, permeability, porosity, optical properties, seismic properties, depositional history of material

Apollo Particle Size Distribution (avg. Q_N in μm)			
% Passing	Highlands	High-Ti Mare	Low-Ti Mare
Q_{25}	24.1	25.1	24.4
Q_{50}	118.8	67.2	65.1
Q_{75}	386.2	194.6	182.1

Lunar PSD data was aggregated from the Lunar Soils Grain Size Catalog (Graf, 1993), separated by lunar region, and broken into the four quartiles.



PSD for all Apollo returned samples (Carrier, 2003).

$$\Phi_{PSD} = \int_0^{\infty} \min(f_S, f_R) dD$$

$$\hat{\Phi}_{PSD} = \sum_{i=1}^N \min(f_i^S, f_i^R)$$

Particle Size Figures of Merit	
<i>Simulant</i>	<i>Score</i>
BP-1	95
CSM-LHT-1	96
CSM-LMT-1	97
GreenSpar	79
JSC-1A	92
LHS-1	84
LMS-1	92
MLS-1	99
NU-LHT-2M	84
NU-LHT-4M	83
OB-1A	94
OPRH3N	89
OPRH4W30	97
OPRL2N	94

PSD FoM scores.



FoM – Particle Geometry (Φ_G)

Importance:

- Deciphering the physical nature of bulk granular material
- Geotechnical engineering (excavation, drilling)
- Human health (radiation shielding, respiration)
- Particle-surface interactions (plume surface interaction, dust mitigation)
- Particle bonding (polymer binding, sintering)
- Provides information on soil compressibility and shear strength
- Insight into thermal conductivity, permeability, porosity, optical properties, seismic properties, depositional history of material

Apollo Particle Geometry Bulk Values	
Aspect Ratio (AR)	0.70
Root Form Factor ($\sqrt{FF}$)	0.94

Lunar particle geometry data was measured by a MicroTrac SYNC Particle Size and Shape Analyzer at CSM. The shape parameter was characterized by laser diffraction and dynamic image analysis. Each sample run produced shape data from 50,000-200,000 individual particles. The form factor and aspect ratio values were averaged for each measured Apollo sample to create a bulk reference point.

$$\phi_G = \frac{\sqrt{FF} + AR}{2}$$

$$\sqrt{FF} = \max \left\{ 0, 1 - \frac{1}{w} \frac{|S_{\sqrt{FF}} - R_{\sqrt{FF}}|}{R_{\sqrt{FF}}} \right\}$$

$$AR = \max \left\{ 0, 1 - \frac{1}{w} \frac{|S_{AR} - R_{AR}|}{R_{AR}} \right\}$$

$$FF = \frac{4\pi A}{P^2}$$

$$\sqrt{FF} = \frac{2\sqrt{\pi A}}{P}$$

$$AR = \frac{B}{L}$$

Particle Geometry Figures of Merit	
<i>Simulant</i>	<i>Score</i>
BP-1	94
CSM-LHT-1	92
CSM-LMT-1	72
GreenSpar	84
JSC-1A	93
LHS-1	84
LMS-1	69
MLS-1	88
NU-LHT-2M	88
NU-LHT-4M	85
OB-1A	78
OPRH3N	86
OPRH4W30	84
OPRL2N	86

Particle geometry FoM scores.



FoM – Density (Φ_D)

Importance:

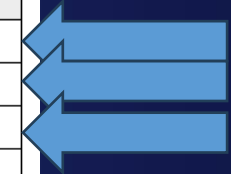
- Deciphering the physical nature of bulk granular material
- Geotechnical engineering (excavation, drilling)
- Human health (radiation shielding, respiration)
- Particle-surface interactions (plume surface interaction, dust mitigation)
- Particle bonding (polymer binding, sintering)
- Provides information on bearing capacity, slope stability, seismic wave velocity, electrical resistivity, thermal conductivity, depth of penetration of ionizing radiation of the material

Lunar Regolith Density values (g/cm ³)			
Mission	$\rho(\text{min})$	$\rho(\text{max})$	Reference
Apollo 11	1.54	1.75	Costes and Mitchell, 1970
	0.75	1.75	Scott et al., 1971
Apollo 12	1.60	2.00	Scott et al., 1971
	1.55	1.90	Houston and Mitchell, 1971
	1.70	1.90	Carrier et al., 1971
Luna 16	1.20	1.20	Vinogradov, 1971
Apollo 14	1.45	1.60	Carrier et al., 1972a
Apollo 15	1.36	1.85	Carrier et al., 1972a; Mitchell et al., 1972a
	1.62	1.93	Mitchell et al., 1972a; Carrier, 1974
Luna 20	1.10	1.80	Vinogradov, 1972
Apollo 16	1.40	1.80	Mitchell et al., 1972b; Carrier, 1974
	1.47	1.75	Carrier, 1974
Apollo 17	1.57	2.29	Mitchell et al., 1973a
	1.74	1.99	Carrier, 1974
Luna 24	1.60	2.10	Barsukov, 1977; Florensky et al., 1977

Averaged max and min density values for lunar regolith samples from various locations and sources.

$$\phi_D = \max \left\{ 0, 1 - \frac{1}{w} \frac{|\rho_S - \rho_R|}{\rho_R} \right\}$$

Material Density Figures of Merit	
<i>Simulant</i>	<i>Score</i>
BP-1	99
CSM-LHT-1	99
CSM-LMT-1	98
GreenSpar	n/a
JSC-1A	81
LHS-1	73
LMS-1	92
MLS-1	76
NU-LHT-2M	91
NU-LHT-4M	75
OB-1A	75
OPRH3N	69
OPRH4W30	n/a
OPRL2N	71



Density FoM scores. Simulants with insufficient data to perform FoM calculations are marked n/a.



FoM – Shear Strength (Φ_{SS})

Importance:

- Deciphering the physical and mechanical nature of bulk granular material
- Geotechnical engineering (excavation, drilling, terramechanics, surface construction)
- Provides information on compressibility, bearing capacity, slope stability, and trafficability of the material

Lunar Regolith Cohesion and AoIF Values				
Depth Range (cm)	ϕ (degrees)		C (kPa)	
	Avg	Range	Avg	Range
0-15	42	41-43	0.52	0.44-0.62
0-30	46	44-47	0.90	0.74-1.10
30-60	54	52-55	3.0	2.40-3.80
0-60	49	48-51	1.6	1.30-1.90

Lunar regolith cohesion and angle of internal friction values modified from Carrier et al, 1999.

$$\phi_{SS} = \frac{C + \phi^{\circ}}{2}$$

$$C = \max \left\{ 0, 1 - \frac{1}{w} \frac{|S_C - R_C|}{R_C} \right\}$$

$$\phi^{\circ} = \max \left\{ 0, 1 - \frac{1}{w} \frac{|S_{\phi^{\circ}} - R_{\phi^{\circ}}|}{R_{\phi^{\circ}}} \right\}$$

$$\tau = \sigma \tan(\phi) + C$$

$C = y - \text{intercept on the } \sigma - \tau \text{ plane}$

$$\phi^{\circ} = \tan^{-1} \left(\frac{\tau_{\max} - c}{\sigma_N} \right)$$

Shear Strength Figures of Merit	
Simulant	Score
BP-1	84
CSM-LHT-1	43
CSM-LMT-1	45
GreenSpar	n/a
JSC-1A	91
LHS-1	44
LMS-1	45
MLS-1	91
NU-LHT-2M	n/a
NU-LHT-4M	46
OB-1A	44
OPRH3N	45
OPRH4W30	n/a
OPRL2N	46

Shear strength FoM scores. Simulants with insufficient data to perform FoM calculations are marked n/a.



FoM – Magnetic Susceptibility (Φ_{MS})

Importance:

- Deciphering the physical nature of bulk granular material
- Particle-surface interactions (dust mitigation and plume surface interactions)

Apollo Magnetic Susceptibility Values (avg. of χ in $10^{-9}\text{m}^3/\text{kg}$)		
Highlands	High-Ti Mare	Low-Ti Mare
4.34	4.09	4.40

Averaged Apollo magnetic susceptibility values modified from Rochette et al., 2010.

$$\Phi_{MS} = \max \left\{ 0, 1 - \frac{|\log_{10} \chi^S - \log_{10} \chi^R|}{\log_{10} w} \right\}$$

Magnetic Susceptibility Figures of Merit	
<i>Simulant</i>	<i>Score</i>
BP-1	90
CSM-LHT-1	77
CSM-LMT-1	90
GreenSpar	06
JSC-1A	83
LHS-1	79
LMS-1	84
MLS-1	99
NU-LHT-2M	78
NU-LHT-4M	74
OB-1A	81
OPRH3N	n/a
OPRH4W30	n/a
OPRL2N	93

Magnetic susceptibility FoM scores.
Simulants with insufficient data to perform
FoM calculations are marked n/a.

FoM Summary



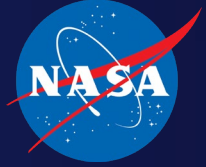
Simulant	Region	Simulant Figures of Merit Summary						
		Compositional		Physical and Textural				Mechanical
		Chemistry	Mineralogy	Particle Size Distribution	Particle Shape	Bulk Density	Magnetic Susceptibility	Shear Strength
BP-1	Low-Ti Mare	85	62	95	94	99	90	84
CSM-LHT-1	Highlands	92	n/a	96	92	99	77	43
CSM-LMT-1	High-Ti Mare	89	n/a	97	72	98	90	45
GreenSpar	Highlands	86	n/a	79	84	n/a	06	n/a
JSC-1A	Low-Ti Mare	88	84	92	93	81	83	91
LHS-1	Highlands	91	84	84	84	73	79	44
LMS-1	Low-Ti Mare	88	89	92	69	92	84	45
MLS-1	High-Ti Mare	96	67	99	88	76	99	91
NU-LHT-2M	Highlands	96	89	84	88	91	78	n/a
NU-LHT-4M	Highlands	95	78	83	85	75	74	46
OB-1A	Highlands	n/a	82	94	78	75	81	44
OPRH3N	Highlands	93	n/a	89	86	69	n/a	45
OPRH4W30	Highlands	88	n/a	97	84	n/a	n/a	n/a
OPRL2N	High-Ti Mare	87	n/a	94	86	71	93	46

*Note: Simulants with insufficient data to perform FoM calculations are marked as "n/a".

Future Work:

- Ongoing effort to include currently available simulants and guide new development efforts
- Expand to include additional parameters for direct comparison to the lunar regolith
 - Electrical conductivity
 - Thermal conductivity
 - Emissivity
 - Absorptivity
 - Solar reflectance

Safety Considerations – Silicates



- Silicates (SiO_4) - minerals composed predominantly of silicon and oxygen
 - Most abundant mineral constituent in lunar and terrestrial rocks
 - 92% of the Earth's crust is composed of silicate minerals
- Silicon-oxygen tetrahedron consists of a single silicon atom at the center and four oxygen atoms located at the four corners of the tetrahedron
 - Each oxygen ion has a -2 charge, and the silicon ion has a +4 charge
- Lunar mineralogy is dominated by:
 - plagioclase feldspar $(\text{Ca,Na})(\text{Al,Si})_4\text{O}_8$
 - pyroxene $(\text{Ca,Fe,Mg})_2\text{Si}_2\text{O}_6$
 - olivine $(\text{Mg,Fe})_2\text{SiO}_4$
- Earth is abundant in:
 - potassium feldspar $(\text{KAlSi}_3\text{O}_8)$ and
 - silica minerals (SiO_2 ; silicon dioxide),
- Silicon dioxide - silicate mineral common on the Earth, but rare on the Moon
 - Simulants derived from terrestrial feedstock likely contain some crystalline silica.
 - Occurs naturally as:
 - Quartz (α -quartz is the only thermodynamically stable form of crystalline silica, resistant to chemical and mechanical weathering, composes 12% of the Earth's crust)
 - Tridymite
 - Cristobalite
 - Coesite
 - Stishovite
- Non-crystalline forms of silica exist naturally as well (e.g., opal, diatomaceous earth)
 - Under elevated heating conditions these amorphous phases can be converted to crystalline silica phases

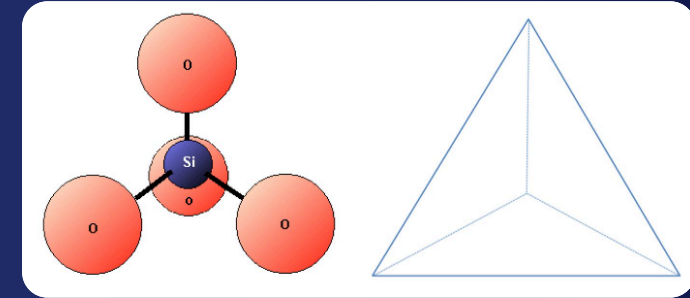
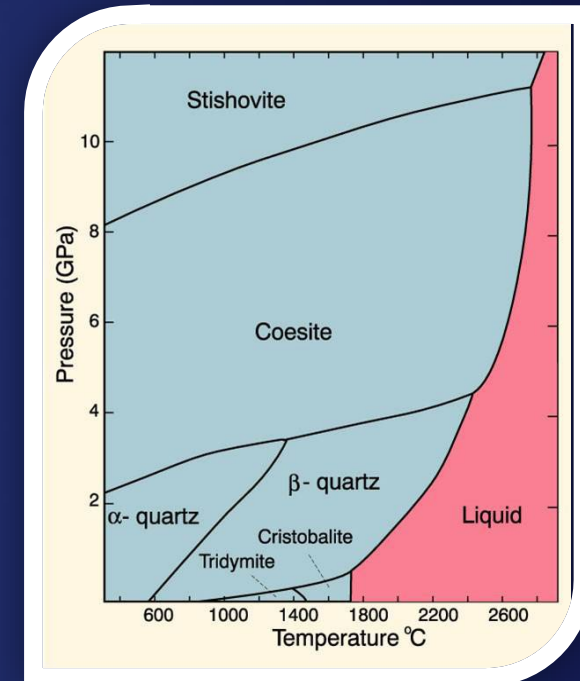


Illustration of silicon-oxygen tetrahedrons – the building blocks of silicate minerals.



Equilibrium P-T phase diagram for SiO_2 .



Crystalline Silica Content in Lunar Simulants

- Simulants are derived from natural or synthetic feedstocks of glass, minerals, and rocks.
 - Feedstock materials may contain silica-bearing materials (e.g., quartz)
 - When processed for grain size or shape requirements, simulants may contain respirable crystalline silica particles (< 10 µm in size)
 - Potential hazard to employees who work directly with or near a testbed containing simulants

*	Total Percent Crystalline Silica (wt%) = Quartz (wt%) + Cristobalite (wt%) + Tridymite (wt%).
§	DCM Science Laboratories. The respirable fraction (<10µm) was removed by wet sieving through a 10µm sieve to determine percent passing.
†	Herndon Solutions Group
□	Innovative Health Applications - Industrial Hygiene Office; RJ Lee Group
‡	Percent passing values are associated with only DCM analyses. Percent passing of the respirable fraction (<10 µm) was determined by wet sieving samples through a 10 µm sieve.
<	Indicates below the limit of detection for the analytical method used.
P	Indicates samples that were washed in phosphoric acid to remove interferences.

Lunar Highlands Simulant	*Total Percent Crystalline Silica (wt%)	†Percent Passing (<10 µm) Respirable Fraction	Total Respirable Crystalline Silica (wt%)	Analysis Source (Analysis Year)
CSM-LHT-1	2.56	13.0	0.33	§ (2023)
CSM-LHT-1G	3.21	11.4	0.37	§ (2022)
GreenSpar (Greenland Anorthosite)	6.37	3.33	0.16	§ (2022)
GRC-1	96.32	0.4	0.39	§ (2023)
GRC-3	29.8	2.2	0.66	§ (2023)
LHS-1	3.05	7.0	0.21	§ (2023)
LHS-1D	2.77	15.2	0.42	§ (2023)
LHS-2	3.68	5.1	0.19	§ (2023)
NU-LHT-2M	0.67	10.1	0.07	§ (2023)
NU-LHT-2M	0.82	No data	No data	† (2021)
NU-LHT-4M	0.92	8.1	0.07	§ (2023)
NU-LHT-4M	1.94	No data	No data	† (2021)
NU-LHT-4M	1.23	No data	No data	§ (2022)
NUW-LHT-5M	0.84	13.9	0.13	§ (2023)
OB-1A	0.84	3.0	0.03	§ (2023)
OB-1A	0.61	No data	No data	§ (2022)
OPRH4W30	1.60	16.3	0.26	§ (2023)
OPRH4W30	1.73	No data	No data	† (2021)
OPRH2N-J1	0.90	9.8	0.09	§ (2023)
OPRH3N	0.87	11.5	0.10	§ (2023)
OPRH3N-J1	1.18	11.9	0.14	§ (2023)
Lunar Mare Simulant	*Total Percent Crystalline Silica (wt%)	†Percent Passing (<10 µm) Respirable Fraction	Total Respirable Crystalline Silica (wt%)	Analysis Source
BP-1	1.89	No data	No data	□ (2010)
BP-1	0.36	No data	No data	† (2022)
BP-1	0.52	11.5	0.06	§ (2023)
CSM-LMT-1	0.29	12.1	0.04	§ (2023)
JSC-1A	0.13	3.4	<0.01	§ (2023)
JSC-1A	0.21	No data	No data	§ (2022)
LMS-1	0.18	10.2	0.02	§ (2023)
LMS-2	2.31	2.2	0.05	§ (2023)
MLS-1	0.14	4.2	0.01	§ (2023)
OPRL2N	0.29	16.8	0.05	§ (2023)
Lunar Simulant Feedstocks	*Total Percent Crystalline Silica (wt%)	†Percent Passing (<10 µm) Respirable Fraction	Total Respirable Crystalline Silica (wt%)	Analysis Source
Stillwater Anorthosite	0.65	No data	No data	§ (2022)
Stillwater Norite	0.86	No data	No data	§ (2022)
Stillwater Mill Sand	0.67	6.4	0.04	§ (2023)
Stillwater Waste Rock	0.77	25.6	0.19	§ (2023)

Total percent crystalline and respirable silica contents in simulants and feedstock materials.



Potential Hazards from Simulants

Review the SDS of the material you are going to be working with as well as the laboratory's Hazard Analysis!!!

Acute Injury

- Slips trips and falls
 - Loose material on surfaces
- Irritant (skin and eye)
- Pulmonary
 - Coughing
 - Breathing difficulty
 - Wheezing
- Acute silicosis (exposure of high concentrations for up to 2 years)
 - Severe disabling shortness of breath
 - Weakness
 - Weight loss

Chronic Illness

- Pneumoconiosis – lung disease
 - Chronic silicosis (high exposure for 15-20 years)
 - Extreme shortness of breath
 - Poor oxygen/carbon dioxide exchange
 - Fatigue
 - Chest Pain
 - Respiratory failure
- Asbestosis
- Black Lung (coal)



GMRO Lab at NASA Kennedy Space Center (Credit: NASA).



Permissible Exposure Limits – Crystalline Silica

- OSHA PEL of no greater than 0.05 mg/m^3 ($50 \text{ } \mu\text{g/m}^3$) of respirable crystalline silica
 - 8-hour time-weighted average (TWA)
- NASA PEL no greater than 0.025 mg/m^3 ($25 \text{ } \mu\text{g/m}^3$) TWA
 - OSHA's Action Level (AL)
 - $\text{AL} < \text{Exposure} < \text{PEL}$: Monitoring to be completed every 6 months
 - $\text{AL} < \text{PEL} < \text{Exposure}$: Monitoring to be completed every 3 months
 - $\text{AL} \leq \text{Exposure}$ for >30 days: Medical surveillance required
- OSHA PEL 15 mg/m^3 (Total) and 5 mg/m^3 (Respirable) TWA for Particulates Not Otherwise Regulated

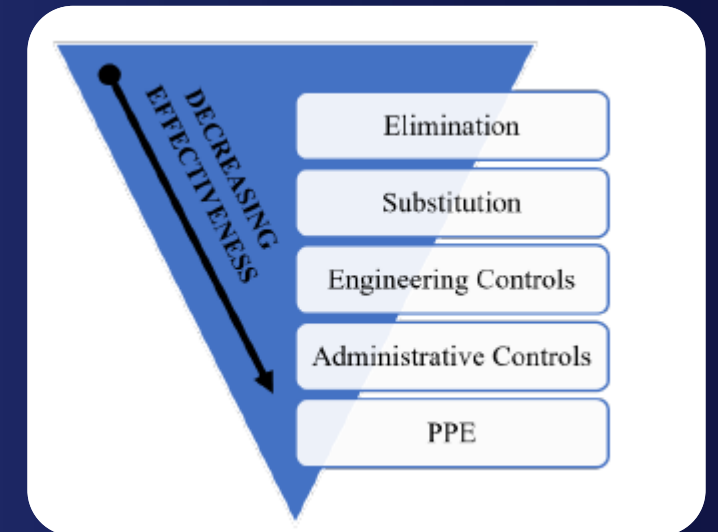


Controls



The National Institute for Occupational Safety and Health established a Hierarchy of Controls - Safeguards to protect workers from hazards.

- Elimination – Remove the silica at the point where it is made
- Substitution – substitute silica with a less hazardous material
- Engineering Controls
 - Wet methods – simulant clean up
 - Vacuum dust collection system – remove dust at the point it is made
 - Isolation – separate the employee from the silica dust
 - Local exhaust ventilation
 - Restricting access to activity generating dust
 - Portable HEPA vacuums
 - Covering of ancillary equipment
- Safe Work Practices
 - Completing tasks using methods to reduce dust exposure (e.g., verify engineering controls, prohibit dry brushing or use of compressed air, prohibit eating/drinking in laboratory, hand washing, etc.)
- Administrative Controls – documentation, signage, limiting work exposure time, personnel training
 - Exposure Control Plan
- PPE – based on task, previous exposure monitoring, environment
 - Respiratory protection
 - Protective clothing
 - Gloves
 - Safety glasses/goggles





NASA Facilities Using Simulants - JSC

- Simulants Development Laboratory
 - Supports the analysis, curation, development, distribution, testing of planetary simulants/granular materials.
 - Houses >30 metric tons of planetary simulants/feedstock materials
 - Simulant processing tools
 - Analytical instruments

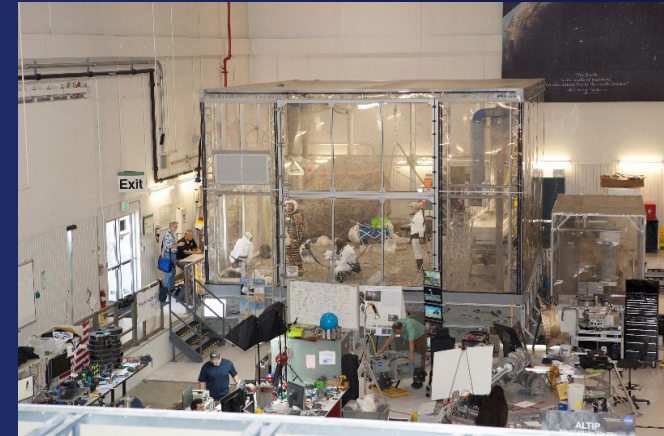


SDL active testing lab, particle size analyzer, and digital microscope.



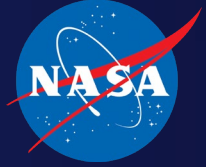
NASA Facilities Using Simulants - KSC

- Swamp Works (2012) – facility devoted to innovation and leveraging skills and capabilities across KSC. Focus on:
 - Granular mechanics and regolith operations (GMRO Lab)
 - Applied chemistry
 - Electrostatics and surface physics
 - Advances materials and systems
 - Applied physics
 - Corrosion technology
- Hazard Field – landscape of simulated craters and boulders in sandy regolith.

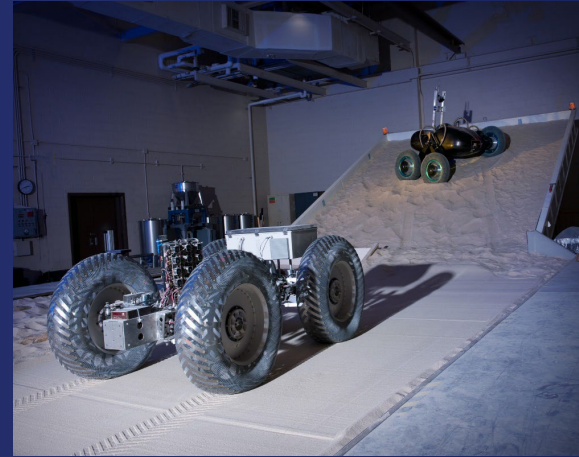


KSC's Swamp Works (above) and co-founder Rob Mueller with Buzz Aldrin discussing the RASSOR robot developed by Swamp Works for space mining applications.

NASA Facilities Using Simulants - GRC



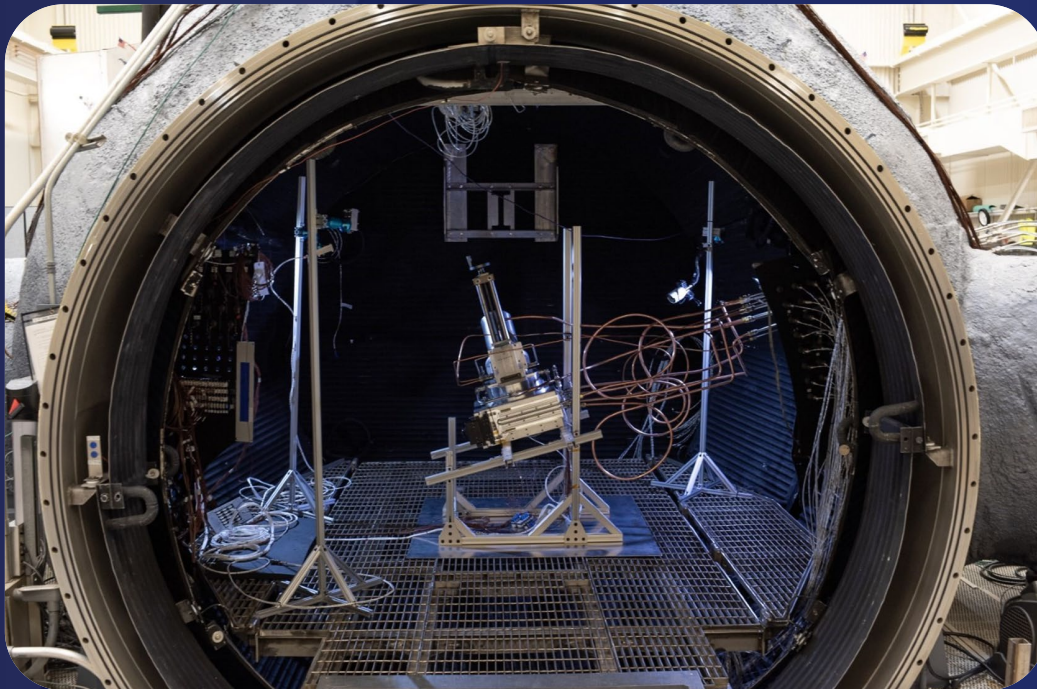
- Home of the SLOPE and Excavation Labs as well as a growing number of extraterrestrial tire test rigs.
 - Provides controlled test condition to evaluate tractive performance and power consumption of roving vehicles on lunar terrain.
 - Indoor facility with stable temperature and humidity.
 - Currently houses simulants GRC-1, GRC-3 and Fillite (Mars).
- Excavation lab houses the Advanced Planetary Excavator (APEX).
 - Heavy-duty 4-DOF robotic arm capable of excavating from multiple adjacent soil bins.
- XTERRa-II test rig
 - Environmentally controlled single-wheel life test rig.
 - Carousel can be interchanged with various rock or soil profiles, currently houses JSC-1A



Some of GRC's planetary exploration facilities: SLOPE (top left), APEX (top right), XTERRa-II (bottom left), Excavation Lab (bottom right).

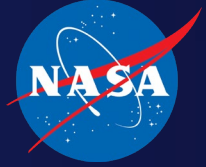
NASA Facilities Using Simulants - Others

- Additional NASA Centers:
 - Marshall Space Flight Center - Dirty thermal vacuum chamber
 - Johnson Space Center – 15-foot dirty thermal vacuum chamber
- Federally Funded Research and Development Centers
 - Jet Propulsion Lab - Outdoor terrain field



(Left) ISRU experiment at MSFC's Dirty T-Vac Chamber. (Right) JPL's outdoor Mars Yard test facility.

Test Preparation Methods – Applicable References



- Constellation Era Documents:
 - Sibille et al., 2006 – Lunar Regolith Simulant Materials: Recommendations for Standardization, Production, and Usage
 - Schrader et al., 2010 – Lunar Regolith Simulant User's Guide
- Recent Documents:
 - NASA-STD-1008 (2021)– Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments
 - Slabic et al., 2024 - The Lunar Regolith Simulant Users' Guide – Rev A



Simulant preparation for VIPER testing at NASA GRC
(Credit: NASA).

Common Practice – Hardware Development/Maturation



Developmental hardware tested in low fidelity, readily available simulants in ambient terrestrial conditions (cost, budget, schedule effective)

Evaluate preliminary data, evaluate the impact of the simulant selection on the resulting data, scale-up or mature hardware

Hardware tested in higher fidelity simulants to challenge the technology adequately for the achievement of the targeted TRL



Best Practices

- Water content of the simulant should be measured and reported prior to test.
 - Simulants should be stored dry in a location with active humidity control.
 - Simulant should be desiccated – NASA follows NASA-STD-1008
 - For 10s of kilograms of material it is recommended to desiccate simulants to 200°C in dry circulating air for 2-3 hours to remove the surficial water
- Hardware that interacts with regolith mechanically should be tested in simulants that include representative particle size fractions from 10 to 80 mm.
 - The Apollo PSD curves are limited to the arbitrary 1 mm limit which accounts for 90% of the volume of samples. Actual lunar soil contains pebbles and rocks up to 80 mm in size (Kovtun, 2024).
 - PSD should be reported for test data interpretation.
 - Note that the PSD does not remain the same throughout the material during transportation or storage since the larger more buoyant particles migrate upward during vibrations.
 - Stored simulant should be homogenized by rolling, overturning or mixing
 - The PSD may evolve over time through repeated friction against hardware, mixing with contaminants, and loss of fine particles.

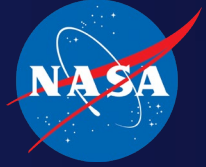
Clast Name	Diameter Range (mm)	% Average Content
Gravel	4.75 – 80.0	15 %
Sand – Coarse	2.0 – 4.75	5 %
Sand – Medium	0.425 – 2.0	14 %
Sand – Fine	0.074 – 0.425	30 %
Silt	< 0.074	36 %

Particle size average % content and associated clast nomenclature for Apollo 16 surface samples (Kovtun, 2024).



Best Practices, cont.

- It is important to perform bulk/relative density measurements or estimates at the relevant depths of regolith test beds where changes in density occur during the creation of the bed to account for this defining parameter accurately during test data analysis.
- The preparation of test beds should strive to achieve shear strength values similar to those of lunar surface material as well as their dependence on depth.
- For extractive processing (ISRU) projects, it is important to obtain the mineralogy and chemical composition data, including minor and trace constituents that are specific to the production lot of the purchased simulant.
 - Low- and high-temperature processing of regolith
 - Components in simulants, not found in lunar materials, are likely to affect measured yields and some may react with hardware and detectors and cause damage
 - E.g., the presence of chlorine and fluorine form acidic effluents in reduction reactions of regolith simulants by hydrogen
 - Select regolith simulants with weight fractions of non-lunar components and impurities as low as possible
 - Perform impurity removal steps to prepare the simulant for processing tests if selected simulants still contain undesired components.
 - Removal of organic impurities is achieved by calcination at moderate temperatures (300-600°C) in an oxygen-rich environment



Best Practices, cont.

- Vacuum Conditions
 - Particulate matter poses a risk to the vacuum chamber and associated hardware (pumps, instrumentation)
 - Regolith simulant tends to off-gas violently during rapid pump-down
 - At room temperature, the physi-adsorbed water evolves at pressures below 20 torr potentially resulting in soil movement, including spouts of airborne particles
 - Can disturb the soil compaction or preparation of the soil bed
 - Recommended to regulate the pump rates to keep pressure decay very slow
 - Chamber evacuation will result in the removal of moisture from the regolith simulant albeit the ambient temperature desiccation is limited
 - Pre-test desiccation is recommended (for samples not using ice-regolith mixtures)
 - Ice- regolith simulant materials created for tests should be characterized to report relevant physical properties for results interpretation
 - Ice-regolith simulants should be prepared in vacuum when possible and their degradation measured or estimated when they are prepared in ambient condition prior to test

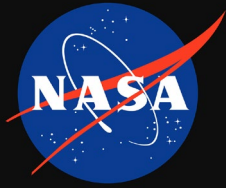


Summary

- More than 50 years after Apollo, lunar simulants are being produced in larger amounts than ever before!
- It is important to select the best material for the technology or hardware technology level (TRL) that you are trying to achieve.
- No single simulant is capable of replicating all aspects of the various types of lunar regolith.
- Safety is a big consideration when selecting and using simulants for testing.
- Follow current best practices when using lunar regolith simulant materials for testing.



Lunar mare (LMS-1) High-Fidelity Regolith Simulant
(From: Space Resource Technologies).



THANK YOU

For more information please visit

<https://ares.jsc.nasa.gov/projects/simulants/advisory-committee.html>

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