



Lunar Regolith Simulant User's Guide Revision A

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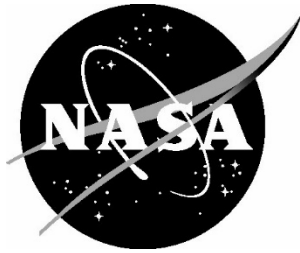
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1.0 Introduction

From July 1969 to December 1972, the National Aeronautics and Space Administration's (NASA) Apollo Program landed on the lunar surface at six different locations, all in the equatorial region of the near side of the Moon. Five of these missions landed in lunar mare regions, and one landed in the lunar highlands. During those missions, twelve Apollo astronauts collected 362 kg (842 lb.) of lunar rock and soil samples, which were brought to the Manned Spacecraft Center in Houston, Texas (now the Johnson Space Center). In addition, three Luna robotic sample acquisition missions brought 300 grams to the Soviet Union in the 1970s, and more recently the Chang'e-5 and Chang'e-6 missions brought 3,666 grams of lunar samples to China. For over 50 years, scientific analyses of these samples have yielded our current understanding of the Moon's origin and geologic history. Lunar samples are considered national treasures and have been typically awarded to researchers in very small amounts, measured in a few grams or less.

In the late 1980s and early 1990s, NASA was tasked with planning a return to the Moon with humans, sometime in the early 21st century. Because of the small allocations of lunar sample that were available, and the need for larger amounts of material for the development and testing of exploration systems and components that would interact with the Moon's surface, lunar scientists developed lunar-like granular materials from terrestrial geologic feedstock that was similar to the samples brought from the Moon. These granular materials were termed 'lunar soil simulant'. Now almost 30 years later, lunar simulants are being produced in larger amounts than ever before by several universities and private companies.

This guide is titled Lunar Regolith Simulant User's Guide, Rev A, and two points need to be made about the title. First, is the use of the term "regolith". During the Apollo Program, the term "soil" was used for taking a sample of the loose material on the surface, and then cataloging that sample in the lunar curation database as a "soil sample". By the 1980s, the term "regolith" gained favor by lunar scientists. In the Lunar Sourcebook (Heiken et al., 1991), regolith is defined as "a general term for the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers bedrock". Regolith is a terrestrial term that seems to go back to 1897, according to a recent paper by Huggett (2023). Huggett summed up his paper by writing, "soil and regolith are one in the same". "Regolith" will mostly be used throughout this guide, as it tends to separate in one's mind the unique nature of the Moon's surface when compared to the inherent bias humans have in their mind when they hear and use the word "soil". When referring to Apollo samples, "soil" is used for historical context and in some places the simple term "lunar simulant" is also used.

Secondly, Rev A is used in the title because NASA released its first Lunar Regolith Simulant User's Guide in 2010, near the end of NASA's Constellation Program (Schrader et al., 2010). This guide follows in the pattern of that first guide and will be updated on a periodic basis as new simulants are created, characterized and used, and as new information emerges about the Moon's regolith due to new lunar exploration missions, both robotic and human.

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The purpose of this Lunar Regolith Simulant User's Guide is to provide the lunar exploration community with an explanation of what lunar simulants are and how they are made, how simulants compare to real lunar samples, how to safely use lunar simulants, and what is needed in preparing lunar simulant material for engineering or operational testing. It is written from the perspective of NASA's involvement with the development and creation of lunar simulants. It is hoped that this guide will be useful for the lunar exploration community in selecting adequate simulants for their particular use cases, and in understanding the nature of the lunar regolith. The most important points to be made are (1) that there is no one best lunar simulant for everything, and (2) no lunar simulant completely replicates all aspects of the lunar regolith.

1.1 References

- Heiken, G., Vaniman, D., French, B.M., 1991. Lunar sourcebook: A user's guide to the Moon. Cambridge University Press.
- Huggett, R., 2023. Regolith or soil? An ongoing debate. *Geoderma* 432, 116387.
- Schrader, C.M., Rickman, D.L., McLemore, C.A., Fikes, J.C., 2010. Lunar regolith simulant user's guide. NASA/TM-2010-216446.

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2.0 Lunar Regolith

This section is intentionally brief and in no way should be used as a primary reference for the geologic history of the Moon. It is written using geologic terms (i.e., rock and mineral names, geologic processes that occur on the Moon) that are common on internet websites and in lunar simulant specification sheets that simulant producers have developed to describe their products. A subset of authoritative references for further reading on the scientific understanding of the Moon are listed at the end of this section.

2.1 Formation of the Moon

For centuries humankind has gazed at the Moon in our night sky, watching its phases change and noting the familiar patterns of dark and bright surface markings. Whether it is the 'man in the Moon', 'lady in the Moon', 'Moon rabbit', 'Moon toad', or 'Moon frog', the patterns have remained the same throughout recorded history (Figure 1).



Figure 1. A familiar full Moon rises over Vasquez Rocks Natural Area Park in Santa Clarita, California. NASA/Preston Dyches.

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Those patterns were set in place billions of years ago, and clearly illustrate the difference in the dark mare and the bright highlands, and the rock types that make up those geologic terrain. The origins of the surface markings can be found in three well-formulated hypotheses, based on returned lunar samples, remote sensing from lunar orbit, telescopic observations from Earth, and mathematical modeling (NRC, 2007). The *giant impact hypothesis* explains the origin of the Moon, the *lunar magma ocean hypothesis* governs the understanding of the differentiation of the Moon and the formation of lunar rocks following lunar formation, and *terminal cataclysm hypothesis* concerns the timing of the impact flux in the 600 million years (Ma) after lunar formation, particularly the largest impacts that created the great lunar basins. The lunar magma ocean hypothesis provides the scientific framework on how the dominant lunar minerals and rocks were formed, which became the feedstock for the creation of the lunar regolith (Figure 2).

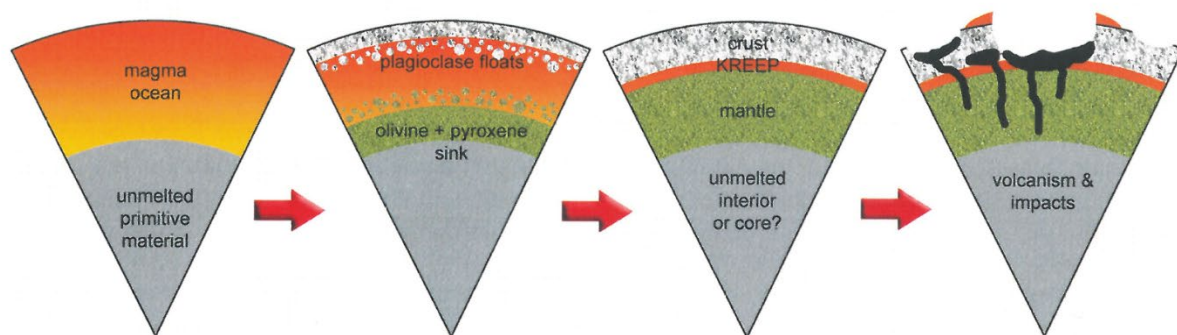


Figure 2. The lunar magma ocean hypothesis. National Research Council (NRC), *The Scientific Context for Exploration of the Moon* (2007).

2.2 Major Rocks and Minerals of the Moon

Though the cooling of the lunar magma ocean and the creation of rocks and minerals is a very complex geologic story, for the purpose of creating lunar regolith simulants the story can be generally simplified to a few rock types and minerals that dominate the Moon's surface. For a more detailed discussion of the lunar regolith, a list of selected sources is provided at the end of this section.

Plagioclase feldspar, pyroxene, and olivine are the most abundant minerals in the rocks that make up the lunar crust and mantle. These high-temperature silicate minerals are thought to have formed as the lunar magma ocean cooled, with the dense pyroxenes and olivines settling toward the bottom of the magma ocean, and the less dense and buoyant plagioclase feldspar floating to the surface. The plagioclase feldspar at the surface primarily accumulated in a rock known as anorthosite. As the mantle grew upwards and the crust thickened downwards, the rocks norite (primarily plagioclase and pyroxene), troctolite (primarily plagioclase and olivine) and dunite (mostly olivine) also formed in lesser amounts. This newly created crust was instantly bombarded by impactors of all sizes, which continues to this day. The largest impacts that created the great circular lunar basins are thought to have

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been concentrated early on, fracturing the surface to depths of many tens of kilometers, mixing all the crustal rock types into the newly formed regolith.

As the lunar crust was getting pummeled for 100s of millions of years, the interior of the Moon and the growing mantle was heated by the radioactive decay of heat producing elements (i.e., Th, U, K). Partial melting of mantle rocks and cumulates resulted in an interior magma that buoyantly rose through the dense mantle and fractured crust and erupted out on the lunar surface as basaltic lava. Basalt is the most common rock in the inner solar system, covering much of the surfaces of Mercury, Venus, Earth, the Moon, and Mars. Many people have seen flowing basaltic lavas in places like Hawaii and Iceland, making the thought of flowing mare basalts on the Moon easier to imagine than the formation of the anorthositic crust. As with the crust, the minerals plagioclase feldspar, pyroxene, and olivine are dominant in basaltic lavas, though an iron-titanium oxide mineral known as ilmenite is also an important secondary mineral in the lavas.

While the mare basaltic rocks and regolith are typically referred to by differences in chemistry, such as high-, low-, or very low-titanium basalts related to their ilmenite content, highland rocks and regolith are typically referred to by their rock components (petrology), such as noritic anorthosite, or anorthositic norite. Figure 3 shows examples of basaltic and anorthositic rocks collected during the Apollo missions.



Figure 3. Lunar basalt (sample 15529; left) and anorthositic (sample 62237; right) rocks. NASA/JSC lunar curator.

2.3 Creation of the Lunar Regolith

The discussion so far has focused on the major geologic rock types and minerals that were created during the formation of the Moon and differentiation of the Moon into a crust, mantle, and core. Almost immediately after any solid surfaces were formed on the Moon, impacts from objects of all sizes (from large asteroids and comets to the tiniest individual grains) bombarded these surfaces, beginning the creation of the regolith. This impact process had both destructive and constructive consequences. The

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easy-to-understand destruction involved bedrock surfaces being broken up into rubble, with the rubble further broken down into smaller and smaller pieces.

The constructive process of impact bombardment of the lunar surface is less intuitive and involves the creation of complex rocks known as breccias, and a variety of impact melt products, particularly particles called agglutinates. Most rock samples returned by Apollo are breccias, which is a clear demonstration that impact cratering is the dominant geologic process in the creation of the lunar regolith. Breccias are described as complex rocks composed of discrete rock, mineral, or glass fragments set in a fine-grained matrix that bonds the larger fragments together (Heiken et al., 1991). Lunar breccias can be broadly classified as polymict and monomict breccias. Polymict breccias are the most common in the Apollo collection and contain a variety of different fragments, whereas the rarer monomict breccias only contain fragments of a single rock type (see Figure 4). Even as breccias are broken down into smaller and smaller pieces by impact, they often retain their unique character in the form of microbreccias.

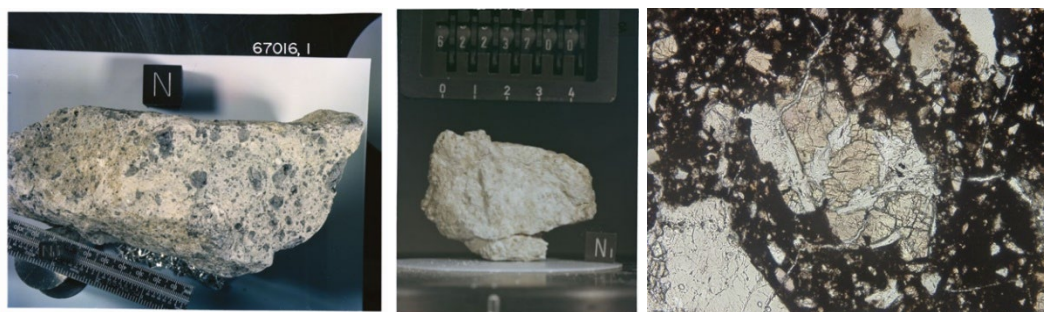


Figure 4. Lunar polymict breccia (sample 67016,1; left), monomict breccia (sample 62237; middle), and microbreccia (sample 10056,45, plane polarized light, field of view = 1.15 mm, magnification 10x; right). NASA/JSC lunar curator.

The discussion so far has focused on the crystalline component (i.e., minerals and rocks) of the lunar regolith. However, there is another component that is important to the understanding how the regolith was formed and the physical properties of the Moon's surface, and that is the glass component (see Figure 5). Impact melt glass products are ubiquitous on the Moon, and in some basaltic mare units volcanic glass beads are also present, particularly in regional pyroclastic deposits where volcanic “fire fountaining” (like an eruption from Mount Etna in Italy) created the glass beads. The impact melt glass products are a result of the high energies and high pressures created during an impact. These products include glassy melt breccias, regolith breccias, agglutinates, and clast-free impact glass. Agglutinates are the major source of glass in the lunar regolith (Taylor et al., 2019) and make up a large proportion of the lunar regolith, roughly 20-40% vol% on average, with some mature regolith about 65 vol% (Cannon, 2023; Jolliff et al., 2006). Agglutinates have generally been described as aggregates of smaller lunar soil rock and mineral fragments welded together by impact generated glasses created by micrometeoroids. They were an unanticipated component of the lunar regolith, have very complex geometries, and have no terrestrial analog (Jolliff et al., 2006).

Another surprising discovery associated with impact-generated glass components, particularly with the agglutinates, was the presence of very-fine-grained, single-domain Fe^0 metal droplets or spheres in the glass (Heiken et al., 1991). These tiny blebs are typically 4-33 nm in size (hence the common term "nanophase Fe") and cause an increase in the ferromagnetic resonance (FMR) of the lunar soil samples as compared to rock samples, and a darkening of the soil (Jolliff et al., 2006). Micrometeorite impacts have also been found to create patinas, or thin glassy rims, on individual grains that include nanophase iron, even on plagioclase grains (Keller et al., 2000). The magnetic property of nanophase Fe could be potentially useful for dust mitigation approaches during future lunar missions.

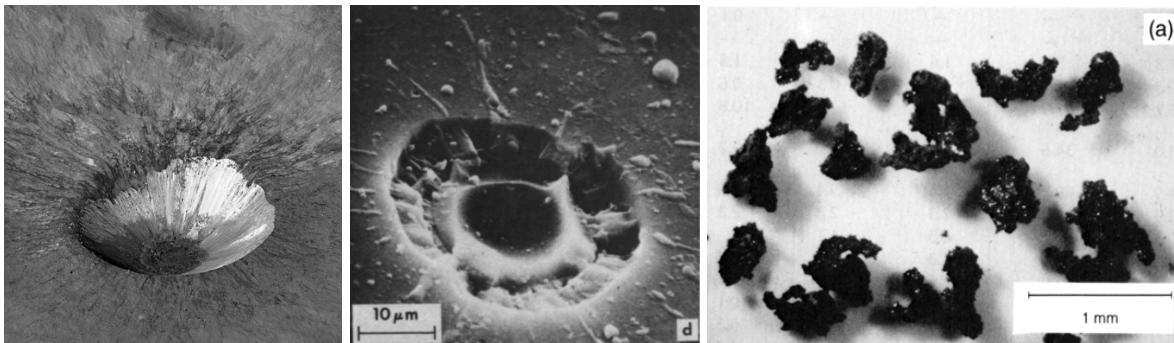


Figure 5. Hell Q impact crater (3.4 km diameter) with dark streamers interpreted to be impact glass (NASA/GSFC/ASU; left), micrometeoroid impact crater with glass streamers and droplets (NASA SP-370), agglutinate particles (NASA Photo S69-54827; right).

2.4 Radiation, Plasma, and Space Weathering Effects on the Lunar Regolith

Because the Moon does not currently possess a measurable magnetic field and has essentially no atmosphere, the lunar regolith is constantly assailed by the energetic particles primarily emitted from the Sun, the solar wind, and to a lesser extent galactic cosmic radiation. Hydrogen and helium are the dominant energetic particles reaching the lunar surface. Energetic particle interactions with the lunar regolith have been generally described as ion implantation (i.e., solar wind implanted hydrogen), displacement of atoms internal to the target crystalline material, and ion sputtering, or the ejection of atoms or molecules (Neal et al., 2023). This plasma interaction with the lunar regolith also results in a dynamic charging environment where the sunlit side of the Moon acquires a positive charge while the side of the Moon in shadow acquires a negative charge (Farrell et al., 2007).

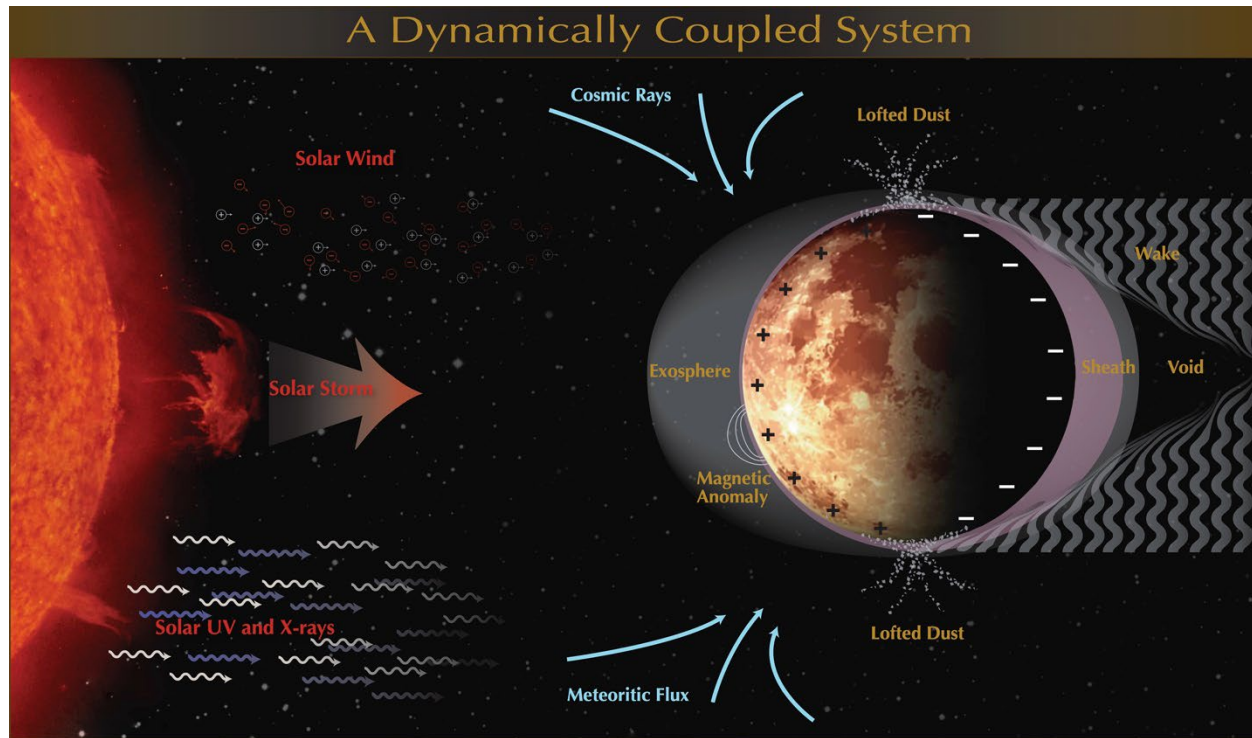


Figure 6. The plasma environment interaction with the lunar surface (NASA / SSERVI / DREAM2)

Together, micrometeoroid impact bombardment and energetic particle interaction with the lunar regolith is commonly referred to as space weathering, and the physical and chemical changes to the regolith due to these weathering processes is termed maturation, or the accumulated effects of space weathering (Jolliff et al., 2006). At these small scales, each grain of regolith is likely to show damage tracks from high-energy cosmic rays, have a surface transformed by exposure to the solar wind, and be coated with vapor deposits from micrometeoroid impacts (Neal et al., 2023). The effects of space weathering alter the way surface grains absorb, reflect, and emit light.

2.5 Particle Size Distribution in the Lunar Regolith

Using Conventional terrestrial descriptions, most lunar regolith samples would correspond to pebble- or cobble-bearing silty sands (Jolliff et al., 2006). This would include particles from single-digit microns to 256 mm according to the Wentworth grain size classification, as illustrated Figure 7 (Wentworth, 1922). While the bulk of the Apollo soil samples consisted of particles < 1 cm in size, and most of the detailed regolith studies have been performed on the < 1 mm fraction (Heiken et al., 1991) (i.e., the silty sand portion and sometimes referred to as the "fine fines"), to understand the regolith as a whole one needs to include the 1 mm to 1 cm portion (i.e., "coarse fines") and the > 1 cm rocks that were removed from the soil samples (i.e., pebbles and cobbles) and given separate sample numbers. For example, during the Apollo 17 surface mission, 113 rake samples (see Figure 8) were collected from the regolith surface and just below the surface at 4 different stations, with the longest dimension of the small rocks ranging from 1.2 cm to 11.0 cm (Keil et al., 1974). A similar report on 109 Apollo

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16 rake samples from 2 different stations listed longest rock dimensions ranging from 0.75 cm to 7 cm (Smith and Steele, 1972). Also, a recent analysis of 25 Apollo 16 surface soil samples showed that granules (2-4 mm), pebbles (4-64 mm) and cobbles (64-256 mm) on average made up about 20% of the entire content of soil samples (Kovtun et al., 2024). It should be noted that most of the published particle size distribution (PSD) curves for the Apollo lunar soil samples only consist of the < 1 cm size fraction (Carrier III, 2003).

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

Figure 7. Wentworth grain size classification, 1922.



Figure 8. Apollo 17 astronaut Harrison H. Schmitt collects a rake sample at Station 1 (NASA Photo AS17-134-20425).

2.6 Particle Geometry in the Lunar Regolith

The investigation of the lunar regolith brought back by the Apollo astronauts included measuring the geometry of individual particles. This was typically done by scientists looking through a variety of microscopes, manually making individual measurements of various parameters one at a time. The detail and time involved in making these manual measurements resulted in analyses that looked at only a few tens of particles to several thousand particles. It was quickly seen that individual lunar regolith particles have a wide range of geometries, from the almost perfectly spherical glass beads to the very complex and intricate agglutinates. Carrier et al., provide an excellent overview of these early measurements in the Lunar Sourcebook (Heiken et al., 1991), and their importance in understanding the bulk physical properties of the lunar regolith. Generally, these early studies described individual particles as being somewhat elongated and sub-angular to angular in shape. More recent studies using a new technology known as dynamic image analysis (DIA) systems, have automatically measured many particle geometry parameters on hundreds of thousands to millions of individual particles in

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relatively brief periods of time (Wilkerson et al., 2024). Initial interpretations of these new statistically robust data sets on morphological and particle size data suggests that lunar regolith particles are not as morphologically complex as once thought (with the agglutinates being the exception). Wilkerson et al. (2024) commented that though the nearly perfect spheres of glass and extremely complex shapes of relatively larger agglutinate particles were easily seen in petrographic thin sections, their data demonstrates that such particles are clearly the exception rather than the rule. Thus, it is the more numerous yet comparatively mundane crystalline particles (i.e., rock and mineral fragments) that give this new view of lunar regolith particle geometry suggesting a generally more sub-round to sub-angular particle shape.

2.7 Summary

Though the lunar regolith is made up of the same major rock forming chemical elements as the Earth (i.e., oxygen, silicon, aluminum, calcium, magnesium, and iron), resulting in minerals common to Earth (i.e., plagioclase feldspar, pyroxene and olivine), and found in terrestrial-like rocks such as anorthosite and basalt, the Moon's surface is unlike any surface or substrate that exists on the Earth. This is due to the high temperature formation of the Moon, the billions of years of impact bombardment from objects of all sizes, and the geologic evolution of the lunar surface in the vacuum and plasma environment of space. The next section describes the efforts underway to create lunar regolith simulants that come as close as practical to the true lunar regolith.

2.8 Selected Sources for more Detailed Information on the Lunar Regolith

This section describing the lunar regolith was intentionally brief and focused on regolith characteristics that are important in the creation of lunar simulants. For a more detailed discussion on the lunar regolith, there are over 50 years' worth of scientific papers and books on the geologic history of the Moon. A few selected sources are listed below:

- Handbook of Lunar Soils, <https://www.lpi.usra.edu/lunar/samples/LunarSoils.pdf>
- Lunar Sample Compendium, <https://www-curator.jsc.nasa.gov/lunar/lsc/index.cfm>
- Apollo Sample and Photo Database, <https://curator.jsc.nasa.gov/lunar/samplecatalog/index.cfm>
- Lunar Sourcebook, https://www.lpi.usra.edu/publications/books/lunar_sourcebook/
- New Views of the Moon, <http://www.minsocam.org/MSA/RIM/Rim60.html>
- New Views of the Moon 2, <https://pubs.geoscienceworld.org/rimg/issue/89/1>
- NASA Cross-Program Design Specification for Natural Environments (DSNE), <https://ntrs.nasa.gov/citations/20210024522>

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3.0 Lunar Regolith Simulant

Section 2.0 shows that the lunar regolith is dusty, gritty, rocky, and glassy. It is unique from any surface material on Earth, created by billions of years of impacts in the vacuum of space and constant interaction with a dynamic plasma environment. Trying to truly simulate the lunar regolith is quite a challenging, if not impossible, endeavor. Differences between terrestrial and lunar mineralogy and chemistry force unavoidable compromises when using terrestrial natural materials as simulant sources, and the glass component is impossible to completely recreate at a large scale. However, lunar regolith simulant producers have made progress in creating practical and useful, yet affordable simulants.

3.1 Lunar Regolith Simulant Limitations

People have been intrigued and entertained by shooting stars and meteor showers for centuries. The Earth's surface is protected from the constant rain of cosmic dust and small rocks by its atmosphere, where the high speeds, pressures and temperatures involved vaporize the incoming debris. Thus, broken crystalline materials like those that are created by impact on the Moon must be created by crushing, milling, and pulverizing equipment that best simulate the impact shattering of rock and minerals, which simulant producers have steadily improved their ability to reproduce. The glass component in simulants has been created by using volcanic glass or melted rock using traditional glass furnaces, plasma arc facilities or lasers. However, the geometry of the glass particles, particularly agglutinate-like particles has not routinely reached satisfactory results.

The Earth has often been referred to as 'water world' because of the great oceans covering most of the planet. Water in magmas and underground aquifers, as well as the oceans, rivers, lakes, and even in the atmosphere, all contribute to non-lunar hydrated minerals (i.e., amphiboles and micas) and weathered minerals (i.e., clays and iron oxides). These hydrated and weathered minerals are often found in the same rocks and associated with the lunar-like minerals of plagioclase feldspar, pyroxene, and olivine. Quartz is another non-lunar mineral that can form in either cooling magmas (i.e., granite) or by the weathering of silicate minerals.

Carbonate minerals (i.e., calcite and dolomite) can also be found in the same rocks as lunar-like minerals. These minerals are associated with the carbon cycle on Earth, that includes carbon from both organic and inorganic origins. The lunar regolith has very little carbon content, typically ≤ 100 mg/g implanted by the solar-wind or deposited by impacts of comets or carbonaceous asteroids.

Also, fault zones associated with plate tectonics often result in lunar-like minerals being metamorphosed due to high temperatures, high pressures, or geothermal fluids. As discussed above, these altered minerals are mixed in with the lunar-like minerals in the resulting metamorphic rocks.

Finally, even with the lunar-like mineral plagioclase feldspar there can be significant differences between terrestrial feldspars and lunar feldspars. The Moon is rather depleted in the volatile elements Potassium (K) and Sodium (Na) when compared to the Earth, and this depletion is generally attributed to how the Moon formed (see previous section). Hence, lunar plagioclase feldspar is typically more

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calcium rich (i.e., anorthite) and the terrestrial feldspars tend to have more sodium in the crystalline structure (i.e., bytownite or even labradorite).

Non-lunar minerals can reach amounts as high as 10-20% of the rocks that simulant producers use as geologic feedstock. Reduction or elimination of non-lunar minerals is difficult and costly, and thus they typically remain in the lunar regolith simulants. The presence of these minerals will mostly affect systems that are being developed for in situ resource utilization (ISRU) processes that involve high temperatures to produce oxygen or metals. For instance, in the plagioclase feldspar example, higher amounts of calcium in the crystalline structure of lunar feldspars will increase the melting temperature and melt viscosity greater than terrestrial feldspars with more sodium.

3.2 The Apollo Era

During the buildup to the Apollo missions, geologic field trips to various locations on the Earth that were similar to lunar terrains were used to train the astronauts how to conduct scientific field work on the Moon. However, for the testing of spacesuits, geologic tools, and other hardware that would be used on the lunar surface, facilities with lunar-like surfaces were created at NASA centers. These facilities probably represent the first use of what people today would refer to as lunar simulant materials. William Phinney (2015) documented these various facilities, which are briefly summarized here. The outdoor "Rock Pile" at the Manned Spacecraft Center (MSC) in Houston was initially installed in 1964-1965 and consisted of a rather rough surface of volcanic rocks and cinders and included a concrete ridge (Figure 9). This initial design was based on telescope-based photos of the lunar surface. As images from the Ranger, Surveyor and Lunar Orbiter missions became available, the rock pile was revised by geologist Mike McEwen to make it more lunar-like. McEwen chose to use blast furnace slag for the surface material and added rocks and craters. A "Sand Pile" was likewise created for astronaut training at the Kennedy Space Center in Florida, where volcanic cinders from Arizona, anorthosite from California, and granites and other rocks from Texas were added into the local Florida sands.



Figure 9. Outdoor lunar training facility at the Manned Spacecraft Center (MSC). Left: Original "Rock Pile" (NASA photo S65-22083). Right: Night training in the revised "Rock Pile" (NASA photo S67-35312).

For an indoor facility, Building 9 at MSC had at least two rooms where a lunar-like surfaces were created. For these facilities pumice, ground-up Knippa basalt from Knippa, Texas near San Antonio, and tin slag from the Galveston area were used (Figure 10).



Figure 10. Indoor lunar training in Building 9 at the Manned Spacecraft Center (MSC) in Houston, Texas (NASA photo S69-18998).

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3.3 Post-Apollo Lunar Regolith Simulants

On the 20th anniversary of the Apollo 11 landing, President George H.W. Bush proposed a long-term space exploration program for the United States that included a space station in Earth orbit, a lunar base on the Moon, and human missions to Mars (Bush, 1989). This program would be known as the Space Exploration Initiative (SEI), and NASA formed the Exploration Program Office to lead this effort. In September of 1989, a workshop titled “Production and Uses of Simulated Lunar Materials” was convened at the Lunar and Planetary institute in Houston, Texas, to define the need for simulated lunar materials and examine related issues in support of extended space exploration and development (McKay and Blacic, 1991). In roughly this same time period two lunar simulants were created for the lunar exploration community.

At the Second Conference on Lunar Bases and Space Activities of the 21st Century held in Houston, Texas in April 1988, a presentation was given on new lunar simulant called Minnesota Lunar Simulant #1, or MLS-1 (Weiblen and Gordon, 1988). This lunar mare simulant was created at the Mineral Resources Research Center at the University of Minnesota to match the Apollo 11 soil sample 10084 and used a material from a 1-2 m thick high-Ti basalt sill from an abandoned quarry in Duluth, Minnesota. Approximately 1,000 kg of this simulant was created, making this the first lunar simulant produced in bulk quantities. Though this simulant only had a crystalline component, Weiblen et al. (1990) experimented with making a glass component from the crushed basalt by using an in-flight sustained shockwave plasma reactor. Experimental runs of the reactor produced unreacted mineral fragments, massive, globular glass, and vesicular glass in a variety of textures. Also, even though the basalt sill in the abandoned quarry intrudes a thick layer of anorthositic gabbro of the Duluth Complex, no efforts were made to create a lunar highland simulant. Today this abandoned quarry is a city park in Duluth (see Figure 11).



Figure 11. MLS-1 source rock in an abandoned quarry in Duluth, Minnesota. The brownish basaltic sill sits on top of the gray anorthosite layer. Photo courtesy of Jimmy Lovrien, Duluth News Tribune. Used with permission.

Probably the most widely used lunar simulant in the 1990s and early 2000s is a simulant known as JSC-1 (Johnson Space Center-1). Over 12 t of this simulant was produced to support large- and medium-scale engineering studies in support of future human activities on the Moon, including material handling, construction, excavation, and transportation, as well as dust control, spacesuit durability, agriculture, oxygen production and sintering (McKay et al., 1994). The geologic feedstock for JSC-1 comes from a volcanic basaltic ash deposit erupted from vents related to Merriam Crater located in the San Francisco volcano field near Flagstaff, AZ. The major crystalline phases are plagioclase feldspar, pyroxene, and olivine. Approximately half of the volume of the deposit is glass of basaltic composition. Trying to mimic the micrometeoroid bombardment on the lunar surface to create the desired particle shape, Dr. James Carter at the University of Texas at Dallas used an impact mill that broke down the material by means of multiple impacts with other ash particles. The primary limitation of JSC-1 is its restricted PSD, with all particles < 1 mm.

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3.4 Lunar Regolith Simulants for NASA's Constellation Program

The National Aeronautics and Space Administration (NASA) created the Constellation Program in response to the Bush Administration's A Renewed Spirit of Discovery: The President's Vision for U. S. Space Exploration (Bush, 2005), and the 2005 NASA Authorization Act from the United States Congress (US Congress, 2005). As the Constellation program began its work, it was realized that the current supply of NASA's JSC-1 lunar simulant needed for testing of new lunar surface system development, was almost exhausted. It was also realized that since global access was desired for future lunar exploration, both lunar mare and lunar highland simulants would be needed. Orbital Technologies Corporation (ORBITEC) in Madison, Wisconsin, was selected by NASA via the Small Business Innovative Research (SBIR) program to produce 14 mt of a lunar mare simulant, which was referred to as JSC-1A, as it basically recreated NASA's original JSC-1 using the same Merriam Crater feedstock and production process at The University of Texas at Dallas. ORBITEC also produced smaller amounts of two variants of JSC-1A: JSC-1AF with a very fine PSD (average 27 μm), and JSC-1C with a coarser PSD up to 5 mm. Because of its broad use, JSC-1A is one of the best characterized and documented lunar simulants.

For the lunar highlands, NASA collaborated with the United States Geological Survey (USGS) at the Denver Federal Center in Colorado, to develop and produce a new series of simulants. It was this new series of lunar highlands simulants that was ground-breaking in several ways. First, it was the first lunar highlands simulant mass produced in the United States. Second, NASA and the USGS used several rock types and minerals to make their NU-LHT (NASA USGS-Lunar Highland Type) series of simulants, versus earlier simulants that just used one type of rock. The two dominant rocks in the NU-LHT simulants were Anorthosite and Norite from the Stillwater Mine in Nye, Montana, with the primary purpose of creating a noritic anorthosite simulant like the Apollo 16 regolith samples (see Figure 12). Third, NASA and the USGS included a synthetic glass component with a highlands-like chemical composition, consisting of 'good' glass (essentially all glass with no mineral inclusions) and pseudo-agglutinates that were created from Stillwater mill sand with a plasma arc facility built and owned by Zybek Advanced Products of Boulder, Colorado.

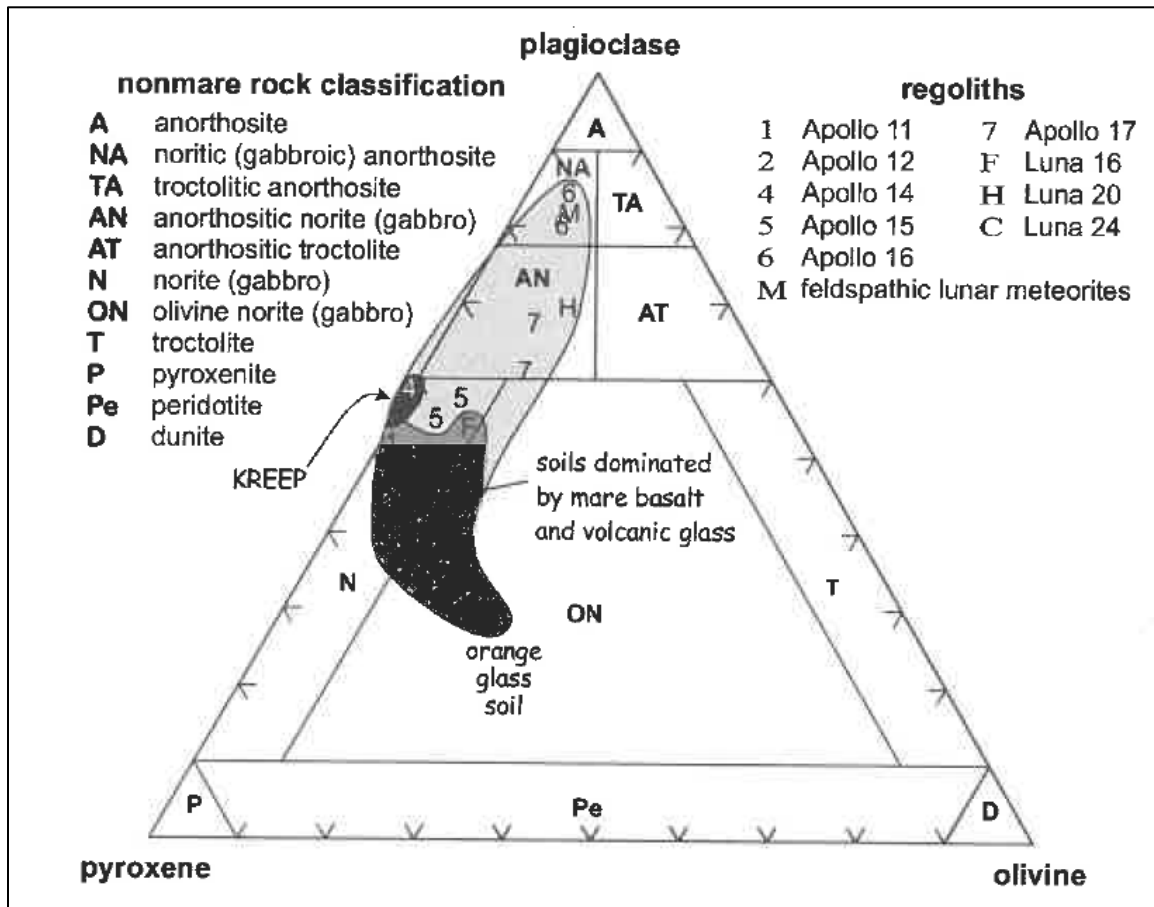


Figure 12. A nonmare lunar rock classification Ternary diagram based on the three dominant minerals in the lunar regolith. (Jolliff, et al., 2006.) Copyright Mineralogical Society of America. Used with permission.

NASA and USGS began their simulant development by creating a pilot simulant (NU-LHT-1M) to test out reproducible methodologies, procedures and equipment, and a prototype simulant (NU-LHT-2M) that would be produced in large amounts (Stoesser et al., 2010a; Rickman and Lowers, 2012). The primary difference between -1M and -2M is that the pilot study only specified and allowed for the major minerals (plagioclase, pyroxenes, olivine, and ilmenite); whereas, for -2M, other minor minerals were also included (i.e., synthetic whitlockite (β -tricalcium phosphate), fluorapatite, and pyrite (troilite substitute). NU-LHT-1M had a mixing ratio 80% crystalline, 16 % agglutinate, and 4% good glass. NU-LHT-2M had a mixing ratio 65% crystalline, 30 % agglutinate, and 5% good glass. Only very small amounts of these simulants still exist for NASA testing purposes.

NASA and USGS experimented with other prototypes, referring to them as the following (Gruener, 2023). NU-LHT-2C was similar to -2M, but a portion of the material was partially fused to make a coarser fraction that is added back in after milling and grinding (Schrader et al., 2010). NU-LHT-2E was an attempt to simplify the development process by eliminating the milling and grinding steps, by using the mill sand (already < 600 μ m) to create an 'engineering grade' simulant. NU-LHT-2EG was

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created by adding agglutinate material to NU-LHT-2E. Small amounts of the -2E and -2EG simulants still exist for NASA testing purposes.

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

Other notable lunar simulants created in this timeframe were OB-1 and BP-1. OB-1 was a small-scale demonstration production of a lunar highlands physical simulant based on the Shawmere anorthosite in Canada (Battler and Spray, 2009). Olivine glass slag was added as a glass component at a ratio of 42% glass, 58% anorthosite. A variant of OB-1 called Chenobi, was also developed using Shawmere anorthosite that incorporated glass and pseudo agglutinates created from the anorthosite using the same Zybek facility as the NU-LHT series of simulants.

BP-1 (Black Point -1) lunar simulant wasn't really created as it was more found as a waste pile at an aggregate (road metal) quarry at the Black Point lava flow in the San Francisco Volcanic Field near Gray Mountain, Arizona (Stoeser et al., 2010b). The Black Point basalt is an alkaline basalt (i.e., high in sodium and potassium), and thus not lunar-like in composition. It also is completely crystalline. However, the attraction of BP-1 as a lunar simulant comes from the fact that it has pebble- and cobble-sized rocks mixed in with finer particles, making it a good physical simulant, particularly for excavation, construction, and surface mobility technology projects.

3.5 NASA's Artemis Program and Commercial Lunar Regolith Simulants

As NASA began working on what would become known as the Artemis Program, lunar simulants came into focus once again. While there were still scattered supplies of JSC-1A and BP-1 lunar mare simulants, the NU-LHT supply of lunar highlands simulants was about spent. At the same time, an emerging commercial simulant production capability was just arriving on the market.

Since the Artemis Program was targeting the lunar south pole, NASA quickly addressed the shortfall of lunar highland simulant by working with the USGS to determine what could be made with the remaining Stillwater geologic feedstocks at the USGS Denver location. The new simulant, designated as NU-LHT-4M, was designed and 1 mt was produced and distributed to NASA centers. The NU-LHT-4M was very similar to the earlier version of NU-LHT-2M in that its crystalline component predominantly consisted of Stillwater anorthosite and norite, with smaller amounts of olivine, ilmenite, synthetic whitlockite, fluor-apatite, pyrite, and chromite. However, concerning the glass component, no 'good' glass remained in the USGS stock, so the 35% glass component consisted solely of pseudo-agglutinates (Gruener et al., 2023).

To further bolster its lunar highland simulant supply, NASA made its first commercial purchase of lunar simulant by acquiring 500 kg of a simulant called OB-1A from Deltion, a Canadian company. Deltion scaled up the process that had earlier been used to produce OB-1 and was offering several tons

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of OB-1A to the lunar exploration community. Like its predecessor, OB-1A was advertised as a lunar highland physical simulant, and consisted of 60% Shawmere anorthosite, and 40% glass slag.

This new era of NASA purchasing commercially produced simulants follows the pattern of NASA buying commercial services and products to help stimulate the growing space economy that started in 2006 with the Commercial Orbital Transportation Services (COTS) program, resulting in the current Commercial Resupply Services (CRS) Program for delivery cargo to the International Space Station (ISS). Other programs that followed include the Commercial Crew Program for delivering astronauts to the ISS, Commercial Lunar Payload Services (CLPS) initiative to delivery science and technology payloads to the Moon, and the Exploration Extravehicular Activity Services (xEVAS) contract solicitation to acquire spacesuits for use on the ISS and the Moon.

Exolith Lab at the University of Central Florida (now Space Resource Technologies), Off Planet Research in Everett, Washington, and the Colorado School of Mines were the first commercial enterprises in the United States to offer lunar simulants for sale to the government, academia, and industry. Private industry stands to benefit the most from the ability to commercially acquire lunar simulants to develop their products and services that will be available on the Moon in the future. Individual NASA projects can also now work with these vendors to get lunar simulants tailored for their specific needs, and NASA in general can acquire lunar simulants in bulk amounts so multiple projects can test their technologies with the same simulant.

While these lunar simulant vendors have the flexibility to 'produce on demand' tailored simulants, they also offer general purpose simulants that will satisfy the needs of many projects. For mare simulants, most of the vendors use the same basaltic cinders from Merriam Crater that NASA used to create JSC-1 and JSC-1A. While the mineralogy, chemistry and glass components are similar to the original NASA mare simulants, the particle shape varies as the vendors use their own crushing and grinding processes that differ from UT Dallas' impact mill. Commercial mare simulants can be 100% basaltic cinders or contain other components such as anorthosite in small amounts.

For highland simulants, commercial vendors are using anorthositic rocks from Canada (Shawmere), Greenland (White Mountain), and the United States (Stillwater). This provides the opportunity for a diversity of anorthosite compositions that will better prepare lunar exploration systems for the subtle but complex differences that will be found in the Moon's highland terrains, including the south pole. Typical general purpose lunar highlands simulants contain 70-80% anorthosite, 20-30% basalt cinders, and can include other rock types or minerals. Creating lunar highland simulants is much more challenging than mare simulants. For example, one of the primary reasons for the inclusion of basaltic cinders is to get a glass component into the highland simulants. Anorthosite on the Earth forms underground as magma cools, without any glass being produced. The one shortfall of using 20-30% basaltic cinders results in the overall glass component in the highland simulants only being in the range of 10-15%.

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NASA worked with Washington Mills, a company in Niagara Falls, New York that specializes in manufacturing industrial fused minerals, to create a lunar highlands simulant that is a variant of the NU-LHT series of simulants. Designated NUW-LHT-5M, this simulant contains Stillwater anorthosite and norite, a commercial olivine, and synthetic glass based on the average chemistry of the Apollo 16 soil samples (Rickman et al., 2024). The crystalline to glass ratio for NUW-LHT-5M is 60:40.

As the commercial lunar simulant industry grows, NASA will continue to work in partnership with vendors to produce practical and affordable general-purpose simulants as well as simulants that more closely match the various attributes of the lunar regolith.

3.6 Lunar Regolith Simulant Classification

Lunar regolith simulants can be differentiated into four broad classifications: Basic, General Purpose, Enhanced, and Specialty simulants. The progression from basic to enhanced and specialty involves matching an increasing number of lunar regolith attributes discussed in the previous section. The cost of creating lunar regolith simulants also increases as more and more lunar regolith attributes are incorporated into a lunar regolith simulant. Hence, to keep project costs down, simulant testing with low technology readiness level (TRL) projects can be adequately conducted with basic and general-purpose simulants, and as a project advances up the TRL scale, enhanced or specialty simulants can be employed. For example, a TRL 5 designation requires system/subsystem/component validation in a relevant, representative environment. If the environment requires interaction with lunar regolith, testing with regolith, or a lunar regolith simulant, is required. Also, as mentioned previously, the type of technology testing will determine the type of lunar simulant. For example, an enhanced simulant for dust mitigation would not be the same as an enhanced simulant for excavation.

3.6.1 Basic Simulants: Basic simulants are typically made from one rock type and don't include a glass component. The major minerals are present (i.e., plagioclase feldspar, pyroxene, olivine), but not particularly in the relative abundances as in the lunar regolith. For these simulants, no real effort has been made to match the particle size distribution (PSD) of the lunar regolith. Examples of this type of simulant include BP-1 (Black Point lava flow), Greenspar (Greenland anorthosite), or bunker sands used in the golf course industry.

3.6.2 General Purpose Simulants: General purpose simulants are more lunar-like in nature, usually containing a mixture of rock types that results in the major minerals being in relative proportions closer to the lunar regolith than basic simulants. Glass is present in this class of simulants, though generally not in the same percentage as impact-generated glass in the lunar regolith, or the same particle shape such as agglutinate-like particles or having the correct chemistry. Also, some effort has been made to crush rocks and blend rock particles so that particle shape and PSD matches the lunar surface. This is by far the broadest category of lunar simulants, and where most of the commercially available lunar simulants occur. Examples of this class of simulant is a typical lunar highlands simulant that is commercially available, consisting of 70% anorthosite and 30% basaltic cinders, with the cinders providing an overall simulant glass content of about 15% (basaltic cinders used in simulant production are typically 50% glass by nature), or the mare simulants made primarily from the same basaltic

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cinders, but now with an overall simulant glass content of approximately 50%. An emerging example is the production of a bulk lunar regolith simulants that more closely matches the lunar regolith PSD up to particles sizes measured in centimeters.

3.6.3 Enhanced Simulants: Enhanced simulants are those where a simulant producer has spent considerable effort to closely matching several lunar regolith attributes beyond what a general-purpose simulant provides. This could include enhancements in the proportions of major minerals to match a particular region on the lunar surface, the addition of agglutinate-like particles or chemically correct glass, an overall glass component that makes up about 40% of the simulant, and the presence of minor minerals such as ilmenite. Examples of this type of simulant include the NU-LHT series of lunar highlands simulants, or the newer NUW-LHT-5M lunar highlands simulant that includes synthetic glass to match the Apollo 16 glass chemistry.

3.6.4 Specialty Simulants: Specialty simulants are a small class of simulants where a very specific technical focus area drives the production of a certain simulant. These lunar simulants are typically produced and used in small amounts. Lunar simulants containing frozen volatiles to mimic ice-bearing lunar regolith at the lunar poles is an example. Another example is a simulant containing accurate agglutinate-like particles that contain nanophase iron.

3.7 Example Uses of Lunar Regolith Simulants

Below are a few examples of how simulants might be used during the development of different technologies:

3.7.1 High Temperature Processes: Mineralogy and chemistry are critical in testing technologies that involve high temperatures, such as microwave or laser sintering for additive manufacturing, oxygen or metal production via processes like molten regolith electrolysis or carbothermal reduction. For lunar highlands simulants, early work could be accommodated with a basic simulant like Greenspar, and as the technology project matures, an enhanced simulant like NUW-LHT-5M with a 40% chemically correct glass for lunar highlands would be appropriate.

3.7.2 Dust Mitigation: Particle shape, size, and glass content are important attributes when testing mechanisms, surfaces, filters, and fabrics. Typically, these simulants do not need the full PSD of the bulk lunar regolith and tend to focus on particles $\leq 100 \mu\text{m}$. General purpose simulants that contain basaltic cinders (i.e., glass) function well for this sort of testing. Some simulants labeled as a "physical simulant", such as OB-1A that contain 40% glass slag, are also appropriate. An enhanced simulant with accurately shaped agglutinates would better represent the types of particles that will be encountered on the Moon.

3.7.3 Excavation: For excavation systems, it is critical that a lunar simulant containing the full PSD of the bulk lunar regolith is used. These simulants should emulate as much as possible the "pebble- and cobble-bearing" nature of the lunar surface. Also, a large glass component should be present as the softer glass and fragile agglutinates in the lunar regolith will likely break down easier than the crystalline component, and the fine glass particles will inevitably get into excavation mechanisms.

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It should be noted that no single lunar regolith simulant will satisfy all the technology needs of a broad-based lunar exploration program. Even when developing and testing a single technology at least two very different lunar simulants should be used to determine any simulant-dependent results and to prepare the technology for the diverse terrains on the Moon. More detailed examples of use cases will be discussed in the next section.

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4.0 Picking a Simulant: Figures of Merit

Lunar regolith simulant Figures of Merit (FoM) are an “algorithm for quantifying a single characteristic of a simulant and provide a clear measure of how well a simulant and reference material compare” (Rickman et al., 2010). Apart from providing a specific quantitative measure for lunar simulants to be compared to lunar materials, FoM serve as a method for grading the fidelity of analogous materials for scientific and engineering purposes.

4.1 Figures of Merit Background

FoM values are calculated using equations that output a value between 0 (nothing like lunar regolith) and 100 (exactly like lunar regolith). Originally, the FoMs were calculated as “inner products” between unit vectors (one for a particular simulant and one for the specific lunar reference point), so when the measurements perfectly agree the formula evaluates to unity, but when they completely disagree the value is zero, and the usual case is somewhere in between (Metzger et al., 2019; see Rickman et al. 2007). Initially, four quantities were used to characterize a simulant: 1) material composition, including lithic fragments, mineral grains, glasses, agglutinates, and chemistry; 2) particle size distribution; 3) particle shape, including mean width, shape factor, aspect ratio, convexity; and 4) material density.

An example of a FoM equation for material composition (C), defined as the scaled l1 norm of the difference of two composition vectors subtracted from unity (Schrader and Rickman, 2010):

$$\begin{aligned}
 FoM &= 1 - \frac{\|W_{adjusted} (C_{adjusted\ reference} - C_{adjusted\ simulant})\|_1}{\|W_{adjusted\ C_{adjusted\ reference}}\|_1 + \|W_{adjusted\ C_{adjusted\ simulant}}\|_1} \\
 &= 1 - \frac{\sum_i W_{adjusted_i} |C_{adjusted\ reference_i} - C_{adjusted\ simulant_i}|}{\sum_i W_{adjusted_i} C_{adjusted\ reference_i} + \sum_i W_{adjusted_i} C_{adjusted\ simulant_i}}
 \end{aligned} \tag{1}$$

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

Updated calculations are based on the variation of the FoM system developed by Metzger et al. 2019, which included rewriting existing equations for each simulant property, introducing additional properties for FoM assessment, and redefining the type of mathematical models that best suit FoM calculations for specific properties. Additionally, the Johnson Space Center (JSC) Astromaterial Research and Exploration Science (ARES) Simulant Development Lab (SDL) team responsible for the FoM project has further expanded the pre-existing quantities used to describe simulants to include:

- Mineralogy
- Chemistry (oxide)
- Particle Size Distribution
- Particle Geometry (aspect ratio and form factor)
- Material Density

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- Magnetic Susceptibility
- Shear Strength (Cohesion and Angle of Internal Friction)

Equations were written as MATLAB functions to compute FoM scores for individual simulant properties. Simulant and lunar reference material data is input from excel spreadsheets – with each individual simulant being associated with a separate spreadsheet and pertinent simulant property and reference Apollo/Luna returned sample data incorporated into separate sheets within the excel document. Each comparative property function integrates the base function of individual property value ranges (e.g., the particle geometry FoM function “fomShape” is composed of the S_sphercity and S_aspectratio base functions). Previous iterations of the simulant FoM project utilized similar software tools to compute FoM algorithms, including an input editor – Excel, back-end computation – MATLAB, and front-end User Interface (UI) – Proprietary code. However, the current iteration of the FoM software was built from the ground up in MATLAB, with Excel input and output values.

Lunar regolith reference data was aggregated from numerous literary and database sources based on studies of Apollo returned samples, as well as novel measurements of lunar soils.

Table 1. Lunar regolith property reference data with data sources.

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

Simulant characterization efforts include previous studies on simulant development and property description, as well as concerted efforts focused on measurements and classification of a wide array of simulants at one time. The Johns Hopkins University Applied Physics Laboratory (JHU-APL) was responsible for several simulant assessments under the NASA Lunar Surface Innovation Initiative (LSII):

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- **2020 Lunar Simulant Assessment** – Initial study providing overview of existing commercial simulant manufacturers, their available simulant offerings, physical (PSD and particle morphology) and compositional descriptions of the simulants, and a concise comparison and evaluation of simulants.
- **2021 Lunar Simulant Assessment** – Follow up study taking a deeper dive into existing commercial simulant manufacturers and their simulant offerings. Similar properties investigated compared to 2020 assessment, but in more detail. Supply chain and quality control issues were introduced.
- **2022 Lunar Simulant Assessment** – Geotechnical focused study of commercially available simulants, measuring PSD, minimum and maximum densities, specific gravities, and shear strength of commercial simulants. In addition to commercially-available simulants, NASA/USGS materials were also characterized and evaluated.

Currently, FoM scores have been calculated for a total of 14 commercial and government-based simulants that are stored at the NASA-JSC-ARES SDL. Future iterations of FoM products will include the assessment of newly developed simulants, including NUW-LHT-5M and CSM-LHT-1G.

Table 2. List of simulants assessed with corresponding lunar region and source.

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.

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4.2 Figures of Merit Limitations

While the quantification of similarities between lunar simulants and returned samples from the Moon, via the Figures of Merit project, attempts to provide an objective reference point when assessing the relative fidelity of a particular analog material, there are inherent limitations that should be acknowledged.

First, data gathering and aggregation from a variety of sources and laboratory settings is an imperfect method when attempting to compare material properties directly. Ideally, there would be one laboratory with the capability and bandwidth of performing the same type of analysis on every simulant. However, the reality is that simulant property data comes from a variety of sources that may utilize varying instruments, techniques, and procedures to perform their measurements. This Figures of Merit (FoM) section of the User's Guide provides background information on the data gathering techniques and points to the pertinent published data when applicable. To this point, the FoM section incorporates data on simulants from published external sources, and internal NASA JSC Simulant Development Lab (SDL) characterization campaigns. These are data sources that can be referenced and are readily available at the time of publication of this version of the Simulant User's Guide (Rev. A). While there may be external groups that have simulant property data from their own research efforts, the FoM project cannot utilize the data if it is not published or made available for reference. Future revisions of the Simulant User's Guide are planned to provide updated FoM calculations, and to incorporate property data based on new published research.

Secondly, there are inherent constraints on the extent to which a measured sample is representative of a bulk material. While the Simulant Development Lab makes every effort to combat sampling bias by ensuring robust sub-sampling of the simulants that are characterized internally, it is not feasible either to measure the entirety of the material to ensure comprehensive coverage, or to do the numerous replicates needed for statistical evaluations. Additionally, we cannot control the sampling practices of other laboratories and researchers; where available, sampling strategy for external sources of simulant property data is provided. The other part of the equation falls with the processing and quality control practices adopted by the manufactures of the simulants. The property data used in the FoM calculations represents discrete sampling points tied to a specific simulant product that was available at the time of testing; changes in feedstock, processing, or any other variation of that simulant by the manufacturer usually are not captured in that data product. Finally, it is common usage for very small samples (on the order of <1 g) to represent much larger amounts of a simulant (on the order of metric tons). While sub-sampling attempts to mitigate bias, some measurement techniques (e.g., XRD for modal mineralogy, XRF for chemistry, LD/DIA for PSD and particle geometry, MS) can only be done on small sample amounts.

Thirdly, a fundamental decision has to be made on which simulant properties have to be compared to which lunar regolith properties. The FoM section of the User's Guide provides the rationale and mathematical functions on how the question of the quantifiable comparison between physical materials is addressed, but there are baseline conditions that have to be selected for the process to work. The material characteristics (i.e., mineralogy, chemistry, PSD, particle shape, bulk density, shear strength, and magnetic susceptibility) currently part of the FoM project were down selected in order to provide the maximum insight into the compositional, physical, and mechanical properties of the lunar simulants

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compared to the lunar regolith. In turn, the FoM project utilizes available lunar regolith data from a variety of literary sources to validate the simulant property data acquisition for direct comparison.

Finally, the content included is based on available data at the time of publication. There will be future simulant characterization efforts that may lead to the alteration of the existing content of this guide and there will be new simulants introduced that will need to be incorporated into future revisions. To that point, there are simulants currently available that are not included in this current iteration of the Simulant User's Guide. This has happened for several reasons, such as the timing of their development relative to the publication of this document, the availability and relative scope of the simulant, and the amount of published data on the simulant. Prime examples are simulants such as NUW-LHT-5M and CSM-LHT-1G, which have been developed and published data in close proximity to the publication of Rev. A of this document. These will be included in future iterations of the Simulant User's Guide.

4.3 Mineralogy

Understanding the comparative fidelity of the mineralogy of a lunar regolith simulant is integral in knowing the composition of the bulk granular material and crucial in activities dealing with chemical processing (e.g., ISRU and oxide/metal production), human health (e.g., radiation shielding, respiration), particle-surface interactions (e.g., plume surface interaction, dust mitigation), and particle bonding (polymer binding, sintering). The mineralogy FoM (Φ_M) is calculated using an updated version (Metzger et al., 2019) of the original composition equation by Schrader and Rickman, 2010, in which the modal mineralogy of a simulant (SM) and a lunar reference material (RM) were defined in individual vectors,

$$\vec{R}_M = (r_1, r_2, r_3, \dots, r_{N_M})^T \quad (2)$$

$$\vec{S}_M = (s_1, s_2, s_3, \dots, s_{N_M})^T \quad (3)$$

where r_i and s_i are the weight percentages of the minerals in the simulant (S_M) and a lunar reference material (R_M), and N_M is the total number of relevant minerals in both groups.

By definition of being under an l1 norm, the sum of each vector S_M and R_M must add to 1, so that Φ_M can be defined by the intersection operator $\cap$ or overlap in the mineral composition between the simulant and lunar reference material:

$$\Phi_M(\vec{S}_M, \vec{R}_M) = \|\vec{S}_M \cap \vec{R}_M\|_1 = \sum_{i=1}^{N_M} \min(s_i, r_i) \quad (4)$$

Lunar regolith reference mineralogy data was aggregated from X-ray Diffraction (XRD) analysis conducted by Taylor et al., 2019 on a total of 118 returned Apollo soil samples. Modal mineralogy

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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 mineralogy. Additionally, five general mineral groups were selected for comparison between lunar reference materials and simulants: Pyroxene, Plagioclase Feldspar, Olivine, Ilmenite, Glass (amorphous content). These general mineral groups were chosen due to their ubiquity in both Apollo sample and simulant analyses, as well as their role as majority modal constituents within both highlands (up to 100% of total modal mineralogy) and mare (up to 98% of total mineralogy) lunar regions.

Table 3. Averaged regional lunar modal mineralogy (selected mineral groups) based on Apollo returned sample XRD analysis by Taylor et al., 2019.

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

Of the 14 simulants investigated, 8 have sufficient mineralogical characterization to enable FoM calculation. Note that modal mineralogy data was measured for OB-1 and extrapolated to OB-1A – no direct mineralogical measurement of OB-1A exists. The remaining 6 uncharacterized simulants, italicized in Table 4, require additional modal mineralogy analysis. Overall, there is a need for a uniform, updated mineralogical investigation of all the listed simulants to deconstruct any variability in existing datasets. Based on existing mineralogical data for lunar simulants and the lunar reference material, mineralogy FoM (Φ_M) scores are presented in Table 5.

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Table 4. Mineralogy Figure of Merit scores.

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

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

Table 5. Lunar regolith simulant modal mineralogy (wt.%) organized by FoM-relevant mineral groups.

Simulant	Region	Agglutinates	Glass	Pyroxene	Plagioclase Feldspar	Olivine	Ilmenite	Norite	Anorthosite	Basalt	Reference
BP-1	Low-Ti Mare		0	23.7	60.7	6.2					Stoeser et al. 2010
CSM-LHT-1	Highlands				100						APL SAR 2021
CSM-LMT-1	High-Ti Mare			23	77						APL SAR 2021
GreenSpar	Highlands								90		Hudson Resources
JSC-1A	Low-Ti Mare		26.67	19.43	37.83	12.44	0.11				Schrader et al. 2008
LHS-1	Highlands		24.7	0.2		0.3	0.4		74.4		Exolith Datasheet
LMS-1	Low-Ti Mare		32	32.8		11.1	4.3		19.8		Exolith Datasheet
MLS-1	High-Ti Mare		14	33	46	7					Weiblen & Gordon 1988
NU-LHT-2M	Highlands	29.02	7.17	4.2	54.9	9.5	0.2				Schrader et al. 2009
NU-LHT-4M	Highlands	27	4.53			5.32	0.6	19.86	42.49		Wilson USGS 2020
OB-1(A*)	Highlands		45.5	2.6	46.2	5.6					Schrader et al. 2008
OPRH3N	Highlands		15	1	80					3	OPR Datasheet
OPRH4W30	Highlands	30							90	10	OPR Datasheet
OPRL2N	High-Ti Mare				10					90	OPR Datasheet

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4.4 Chemistry

Understanding the comparative fidelity of the chemistry of a lunar regolith simulant is integral in knowing the composition of the bulk granular material and crucial in activities dealing with chemical processing (e.g., ISRU and oxide/metal production), human health (e.g., radiation shielding, respiration), and particle bonding (polymer binding, sintering). The chemistry FoM (Φ_E) is calculated in a similar manner as the mineralogy FoM,

$$\Phi_E(\vec{R}_E, \vec{S}_E) = \|\vec{S}_E \cap \vec{R}_E\|_1 = \sum_{i=1}^{N_E} \min(v_i, w_i) \quad (5)$$

where $\mathbf{v}_i$ and $\mathbf{w}_i$ are the weight percentages of the oxides in the simulant ($\mathbf{S}_M$) and a lunar reference material ($\mathbf{R}_M$), and N_E is the total number of relevant oxides in both groups.

As with the mineralogy FoM, the overlapping value defined by the intersection operator $\cap$ is an 11-normed vector space. Lunar reference oxide chemistry data was aggregated from numerous literary sources, including Taylor, 1973; Wanke, 1973; Rhodes, 1974; Christian, 1976; Warren et al., 1978, Korotev, 1982; Papike and Simon, 1982.

The Lunar Sample Compendium (<https://curator.jsc.nasa.gov/lunar/lsc>) is an encompassing database featuring all returned Apollo and Luna sample data. 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. Additionally, eight oxides were selected for comparison between lunar reference materials and simulants: Silica (SiO_2), titania (TiO_2), alumina (Al_2O_3), ferrous/iron(II) oxide (FeO), magnesia (MgO), calcium oxide (CaO), sodium oxide (Na_2O), and potassium oxide (K_2O). 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 (>99 wt.% for both) lunar regions.

Table 6. Averaged regional lunar surface oxide chemistry (selected oxides up to 99.84 total wt.%) based on Apollo returned sample studies (see listed in text).

Apollo Bulk Chemistry (wt. %)								
Region	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O
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

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Table 7. Lunar regolith simulant bulk chemistry (wt.%) organized by FoM-relevant oxides with references and lunar regionality.

Lunar Simulant Bulk Chemistry (wt. %)										
Simulant	Region	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	Reference
BP-1	Low-Ti Mare	47.2	2.3	16.7	6.2	6.5	9.2	3.5	1.1	Stoeser et al. 2010
CSM-LHT-1	Highlands	48.0	2.9	22.9	5.7	1.9	15.9	2.6	0.0	APL SAR 2021
CSM-LMT-1	High-Ti Mare	46.9	5.1	15.1	14.0	4.1	12.2	2.7	0.0	APL SAR 2021
GreenSpar	Highlands	51.0	0.0	30.6	0.4	0.2	14.7	2.5	0.2	Wilson USGS 2020
JSC-1A	Low-Ti Mare	46.8	1.8	16.4	11.4	8.7	10.0	3.2	0.8	Wilson USGS 2020
LHS-1	Highlands	50.2	2.5	23.9	3.2	1.9	15.4	3.0	0.0	APL SAR 2021
LMS-1	Low-Ti Mare	46.9	4.5	24.2	3.2	2.4	15.2	2.8	0.0	APL SAR 2021
MLS-1	High-Ti Mare	42.8	6.8	12.1	16.3	6.2	11.1	2.2	0.2	Weiblen and Gordon 1988
NU-LHT-2M	Highlands	47.0	0.4	24.5	3.7	8.4	13.6	1.5	0.1	Wilson USGS 2020
NU-LHT-4M	Highlands	47.2	0.4	23.5	4.3	8.7	12.8	1.5	0.2	Wilson USGS 2020
OB-1(A*)	Highlands	49.7	1.5	16.8	11.8	5.8	9.7	2.5	0.7	Wilson USGS 2020
OPRH3N	Highlands	46.0	2.5	25.4	4.7	2.2	16.9	2.3	0.0	APL SAR 2021
OPRH4W30	Highlands	48.1	0.2	30.3	1.7	1.1	15.2	2.3	0.1	OPR Datasheet
OPRL2N	High-Ti Mare	46.2	5.5	16.6	12.9	2.7	12.9	3.2	0.0	APL SAR 2021

All of the listed references utilized X-ray fluorescence (XRF) in measuring the elemental composition of the lunar simulants. Steve Wilson (2020) also performed Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) to verify XRF results. The XRF instrument utilized by APL in their 2021 Simulant Annual Review study was either not able to determine potassium oxide content in the referenced simulants or the K₂O content was below the instrument's detection limit. Note that oxide chemistry data was measured for OB-1 and extrapolated to OB-1A – no direct chemistry measurement of OB-1A exists.

Based on existing oxide chemistry measurements of lunar regolith simulants and the aggregated data of lunar reference material from returned Apollo samples, the chemistry FoM (Φ_E) scores are presented in Table 8:

Table 8. Chemistry Figure of Merit scores.

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

The SDL will continue to perform analysis of the bulk chemistry of newly introduced and in-development simulants, leveraging the XRF instrumentation and laboratories within JSC ARES and JHU-APL.

4.5 Particle Size Distribution

Understanding the comparative fidelity of the Particle Size Distribution (PSD) of a lunar regolith simulant is integral in deciphering the physical nature of the bulk granular material and crucial for activities dealing with geotechnical engineering (e.g., excavation, drilling), human health (e.g., radiation shielding, respiration), particle-surface interactions (e.g., plume surface interaction, dust mitigation), and particle bonding (polymer binding, sintering). Apart from the use case scenarios, the particle size distribution of a bulk granular material can provide information on soil compressibility and strength, as well as contribute insight into the thermal conductivity, permeability (hydraulic conductivity), porosity (void ratio), optical properties, seismic properties, and depositional history of the material.

The particle size FoM (Φ_{PSD}) is defined as

$$\Phi_{\text{PSD}} = \int_0^{\infty} \min(f_S, f_R) dD \quad (6)$$

where f_S and f_R are the particle size distribution (PSD) of the simulant and lunar reference material based on mass weight (wt. %), respectively. As with the compositional FoM equations, f_S and f_R represent unit-normalized functions in an $\mathbf{1}$ -normed vector space.

Since sieving produces non-continuous, and usually non-uniform, particle size distributions, there is a need to discretize the function into N particle sizes per bounded size range. Previous iteration produced by the NASA lunar simulants team tackled the discretization issue by factoring in the range of particle diameters as defined by particle sieve screens. We have redefined the existing, discretized function:

$$\hat{\Phi}_{\text{PSD}} = \sum_{i=1}^N \min(f_i^S, f_i^R) \quad (7)$$

so that f_i^S and f_i^R represent the material weight percent values of the 25th, 50th, and 75th percentiles of the particle sizes in the simulant and lunar reference material, respectively.

Lunar reference material PSD data was aggregated from the *Lunar Soils Grain Size Catalog* (Graf, 1993). Averaged lunar PSD data was separated by lunar region, based on Apollo returned sample characterization, and broken up into the quartiles passing (25th, 50th, and 75th percentiles) for direct quantitative comparison to simulant size data. There is an on-going intra-NASA effort to digitize and reorganize the Graf (1993) to recreate existing Apollo PSDs (see Figure 13) allowing for the integration of data processing tools in analyzing the cumulative data trends (e.g., Apollo returned sample >1 mm particle size % vs. simulant grain size cutoff values).

Comparison via quartile characterization was selected as means to standardize the process of converting existing Apollo PSD data to a uniform, referenceable dataset allowing for the direct correlation to simulant data. A driving factor in the discrepancy between datasets is the multitude of varying sieving techniques utilizing disparate mesh sizes without sensible coordination or standardization amongst studies. The technological advancement in PSD characterization has also produced divergent results for contemporary simulant PSD studies in which laser diffraction (LD) and dynamic image analysis (DIA) techniques have supplanted physical sieving methods employed during Apollo sample testing.

Table 9. Averaged regional percent particle passing at 25th, 50th, and 75th percentile based on returned Apollo sample data aggregated from Graf, 1993.

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

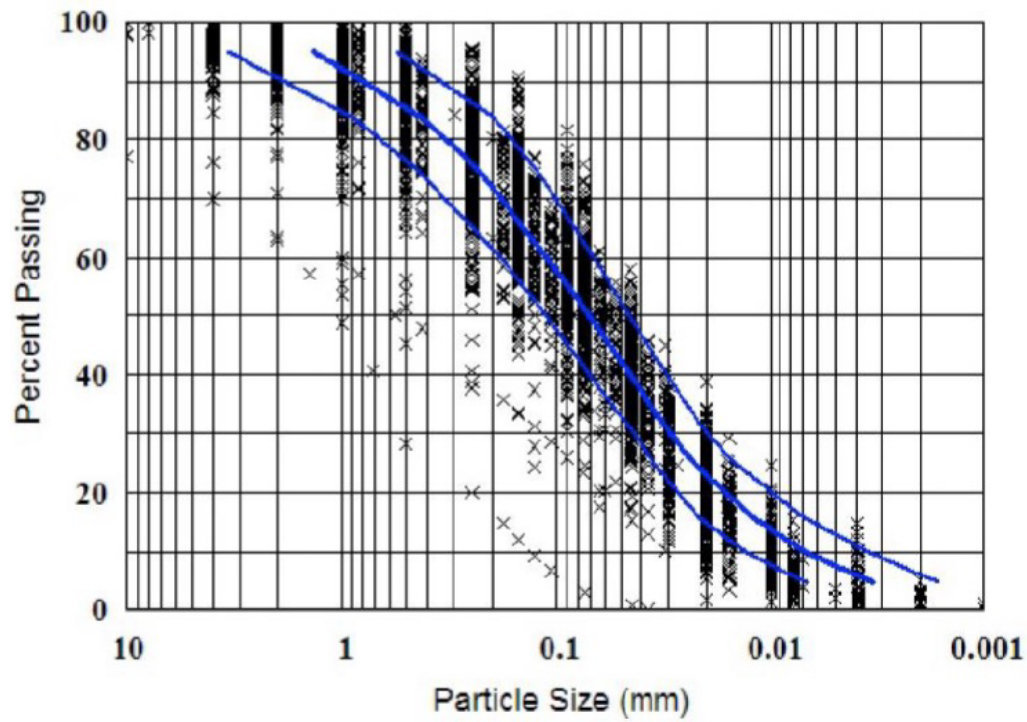


Figure 13. General particle size distribution for all Apollo returned samples (Carrier, 2003).

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Table 10. Lunar regolith simulant PSD based on % passing grains (in microns) per quartile (Q_{25} , Q_{50} , Q_{75}) with references and lunar regionality.

Lunar Simulant Particle Size Distribution (avg. Q_N in μm)					
Simulant	Region	Particle Size Distribution			Reference
		Q_{25}	Q_{50}	Q_{75}	
BP-1	Low-Ti Mare	36.4	88.4	205.0	Clark, 2021 (JSC-ARES)
CSM-LHT-1	Highlands	34.5	122.3	331.3	SDL, 2022 (JSC-ARES); APL SAR 2021
CSM-LMT-1	High-Ti Mare	40.6	140.5	360.8	SDL, 2022 (JSC-ARES); APL SAR 2021
GreenSpar (250 μm)	Highlands	37.5	78.0	141.2	Clark, 2021 (JSC-ARES)
JSC-1A	Low-Ti Mare	54.5	129.1	260.6	Clark, 2021 (JSC-ARES)
LHS-1	Highlands	38.6	85.3	165.2	SDL, 2022 (JSC-ARES); APL SAR 2021
LMS-1	Low-Ti Mare	56.2	113.3	247.1	SDL, 2022 (JSC-ARES); APL SAR 2021
MLS-1	High-Ti Mare	83.4	197.6	400.4	Clark, 2021 (JSC-ARES)
OB-1A	Highlands	68.1	138.5	417.8	Clark, 2021 (JSC-ARES)
NU-LHT-2M	Highlands	55.9	125.7	244.5	Clark, 2021 (JSC-ARES)
NU-LHT-4M	Highlands	48.1	106.7	195.9	Clark, 2021 (JSC-ARES)
OPRH3N	Highlands	15.3	36.2	84.7	APL SAR 2021
OPRH4W30	Highlands	21.5	46.9	128.4	Clark, 2021 (JSC-ARES)
OPRL2N	High-Ti Mare	16.3	36.5	82.8	APL SAR 2021

Simulant PSD data was aggregated from several studies:

- **APL SAR 2021** – PSD was determined via Dynamic Image Analysis (DIA; ISO 13322-2) by a Camsizer X2 instrument developed by Retsch Technology. As granular samples are carried by air in front of a microscope outfitted with a high-speed camera, images are captured and analyzed with the instrument's built-in image-processing algorithms. Each simulant sample PSD value is averaged across three subsample results (~100 mg per subsample).
- **Clark, 2021** – PSD was measured at the Mars, Moon, Meteorite Evolved Gas Analysis (M³EGA) laboratory at JSC ARES by Joanna Clark in 2021 (unpublished) using a MicroTrac Bluewave Particle Size Analyzer. This instrument utilizes Laser Diffraction (LD – ISO 13320-1) in which laser beams passing through granular material produce diffraction patterns representing geometrical dimensions of particles. The Clark 2021 analysis involved measuring 2-3 subsamples (~50 mL per subsample) of each simulant type.
- **SDL, 2022** – PSD was determined via a MicroTrac SYNC Particle Size and Shape Analyzer which combines Laser Diffraction (LD) and Dynamic Image Analysis (DIA). The instrument has a measurable particle threshold range between 0.01 to 4,000 microns and has the option

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for both dry and wet sample ingestion. Based on observable variations in PSD results, the SDL personnel selected wet ingestion as the operational mode for the sample characterization. Three subsamples were measured for each simulant sample (~1 g per subsample), with each subsample undergoing three measurement cycle loops.

Based on existing PSD measurements of lunar regolith simulants and the aggregated data of lunar reference material from returned Apollo samples, the particle size FoM (Φ_{PSD}) scores are presented in Table 11:

Table 11. Particle Size Figure of Merit scores.

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

The SDL will continue to perform PSD analysis of newly introduced and in-development simulants, leveraging the particle size and shape analysis instrumentation within the SDL at JSC ARES. Additionally, there was a project led by the SDL, in partnership with the University of Texas at El Paso (UTEP), to characterize the particle size distributions (following ASTM D6913, D422) of all the listed simulants and determine their Coefficients of Uniformity (C_u) and Curvature (C_c) – data available upon request.

4.6 Particle Geometry

Understanding the comparative fidelity of the particle geometry of a lunar regolith simulant is integral in knowing the physical nature of the bulk granular material and crucial in activities dealing with geotechnical engineering (e.g., excavation, drilling), human health (e.g., radiation shielding, respiration), particle-surface interactions (e.g., plume surface interaction, dust mitigation), and particle bonding (polymer binding, sintering). Apart from the use case scenarios, the particle geometry of a granular material can also provide information on soil compressibility and shear strength, as well as

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contribute insight into the thermal conductivity, permeability (hydraulic conductivity), porosity (void ratio), optical properties, seismic properties, and depositional history of the material.

The particle geometry FoM (Φ_G) is defined as the average of the linear scalar difference of two grain shape descriptors (root form factor and aspect ratio) between a lunar regolith simulant and a lunar reference material,

$$\phi_G = \frac{\sqrt{FF} + AR}{2} \quad (8)$$

in which

$$\sqrt{FF} = \max \left\{ 0, 1 - \frac{1}{w} \frac{|S_{\sqrt{FF}} - R_{\sqrt{FF}}|}{R_{\sqrt{FF}}} \right\} \quad (9)$$

and

$$AR = \max \left\{ 0, 1 - \frac{1}{w} \frac{|S_{AR} - R_{AR}|}{R_{AR}} \right\} \quad (10)$$

where $S_{\sqrt{FF}}$ and $R_{\sqrt{FF}}$ define the simulant and lunar reference material root form factor, respectively, S_{AR} and R_{AR} define the simulant and lunar reference material aspect ratio, respectively, and w is a scale factor ($0 < w < 1$) that shows how far the simulant's root form factor/aspect ratio can be from a lunar reference material's root form factor/aspect ratio before testing with the simulant becomes devoid of value. Here, we use $w = 0.5$ to create a 50% threshold value for nominal testing conditions; any value over threshold constitutes off-nominal or “no value” for testing purposes, with a linear increase in value as error reduction approaches 0% (modified from Metzger et al., 2019).

Here, $\sqrt{FF}$ is the root form factor characterizing a particle as a ratio between area (A) and perimeter (P) calculated as

$$FF = \frac{4\pi A}{P^2} \quad (11)$$

thus,

$$\sqrt{FF} = \frac{2\sqrt{\pi A}}{P} \quad (12)$$

and AR represents the aspect ratio, defined as the quotient of minimum linear size (B) by maximum linear size (L), or min and max Feret diameter measured for all orientations ($d_{F,min}$ and $d_{F,max}$) so that,

$$AR = \frac{B}{L} \quad (13)$$

Root form factor ($\sqrt{FF}$) and Aspect Ratio (AR) were down selected as integral representative particle shape parameters following cluster and correlation analysis performed by Hentschel and Page (2003), which showed that the square root of the form factor and aspect ratio allowed for efficient particle shape description using a reduced set of parameters. AR is sensitive to the elongation of a particle's shape, while $\sqrt{FF}$ is a descriptor that is sensitive to boundary irregularities or the ruggedness profile of a grain (Hentschel and Page, 2003).

Lunar reference material particle geometry data was measured directly by a MicroTrac SYNC Particle Size and Shape Analyzer at the Colorado School of Mines by Sarah (nee Deitrick) Walker and Kevin Cannon (unpublished). The SDL has the same version of the MicroTrac SYNC instrument, that was referenced in the particle size FoM section of this chapter detailing the instrument and operational specifications. The shape parameters of four lunar samples were characterized by laser diffraction (LD) and dynamic image analysis (DIA): 10084, 15601, 64501, 67461. It is estimated that each sample run on the MicroTrac SYNC instrument produced shape data on anywhere between 50,000 to 200,000 individual particles (Walker, personal communication 08/28/2023). For direct comparison purposes, $\sqrt{FF}$ and AR values were averaged for each measured Apollo sample to create a bulk reference point for each shape descriptor (Table 12):

Table 12. Averaged AR and Root Form Factor values for Apollo samples measured by Cannon and Walker, 2021.

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

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Table 13. Lunar regolith simulant particle geometry (Image and AR) values with references and lunar regionality:

Lunar Simulant Particle Geometry Bulk Values				
Simulant	Region	AR	$\sqrt{FF}$	Reference
BP-1	Low-Ti Mare	0.67	0.93	SDL, 2022 (JSC-ARES)
CSM-LHT-1	Highlands	0.66	0.92	SDL, 2022 (JSC-ARES)
CSM-LMT-1	High-Ti Mare	0.56	0.84	APL SAR 2021
GreenSpar	Highlands	0.62	0.90	SDL, 2022 (JSC-ARES)
JSC-1A	Low-Ti Mare	0.66	0.93	SDL, 2022 (JSC-ARES)
LHS-1	Highlands	0.61	0.90	SDL, 2022 (JSC-ARES)
LMS-1	Low-Ti Mare	0.49	0.87	APL SAR 2021
MLS-1	High-Ti Mare	0.64	0.91	SDL, 2022 (JSC-ARES)
NU-LHT-2M	Highlands	0.63	0.91	SDL, 2022 (JSC-ARES)
NU-LHT-4M	Highlands	0.62	0.91	SDL, 2022 (JSC-ARES)
OB-1A	Highlands	0.59	0.89	SDL, 2022 (JSC-ARES)
OPRH3N	Highlands	0.63	0.90	SDL, 2022 (JSC-ARES)
OPRH4W30	Highlands	0.61	0.90	SDL, 2022 (JSC-ARES)
OPRL2N	High-Ti Mare	0.63	0.91	SDL, 2022 (JSC-ARES)

Simulant shape data was aggregated from several studies:

- **APL SAR 2021** – Particle Geometry was determined via Dynamic Image Analysis (DIA; ISO 13322-2) by a Camsizer X2 instrument developed by Retsch Technology. As granular samples are carried by air in front of a microscope outfitted with a high-speed camera, images are captured and analyzed with the instrument's built-in image-processing algorithms. Each simulant sample particle shape descriptor value is averaged across three subsample results (~100 mg per subsample).
- **SDL, 2022** – Particle geometry was determined via a MicroTrac SYNC Particle Size and Shape Analyzer which combines Laser Diffraction (LD) and Dynamic Image Analysis (DIA). The instrument has a measurable particle threshold range between 0.01 to 4,000 microns and has the option for both dry and wet sample ingestion. Based on observable variations in particle shape results, the SDL personnel selected wet ingestion as the operational mode for the sample characterization. Three subsamples were measured for each simulant sample (~1 g per subsample), with each subsample undergoing three measurement cycle loops.

Based on existing particle shape measurements of lunar regolith simulants and the aggregated data of lunar reference material from returned Apollo samples, the particle geometry FoM (Φ_G) scores are presented in Table 14:

Table 14. Particle Geometry Figure of Merit scores.

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

The SDL shall continue to perform particle shape analysis of newly introduced and in-development simulants, leveraging the particle size and shape analysis instrumentation within the SDL at JSC ARES. Additionally, the SDL will be performing novel measurements of additional Apollo lunar samples (10084, 15041, 65901, 67701, and 68501) to increase the existing high fidelity 2D characterization of returned samples of various maturity levels.

4.7 Density

Understanding the comparative fidelity of the density of a lunar regolith simulant is integral in knowing the physical nature of the bulk granular material and crucial in activities dealing with geotechnical engineering (e.g., excavation, drilling), human health (e.g., radiation shielding, respiration), particle-surface interactions (e.g., plume surface interaction, dust mitigation), and particle bonding (polymer binding, sintering). Apart from the use case scenarios, the density of a granular material can provide information on the bearing capacity, slope stability, seismic wave velocity, electrical resistivity, thermal conductivity, and depth of penetration of ionizing radiation of the material.

The material density FoM (Φ_G) is defined as the linear scalar difference of averaged ρ -values between a lunar regolith simulant and a lunar reference point

$$\phi_D = \max \left\{ 0, 1 - \frac{1}{w} \frac{|\rho_S - \rho_R|}{\rho_R} \right\} \quad (14)$$

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where ρ_S and ρ_R represent the average of the minimum and maximum densities of a lunar simulant and a lunar reference material, respectively, and w is a scale factor ($0 < w < 1$) that shows how far the simulant's ρ -value can be from a lunar reference material's ρ -value before testing with the simulant becomes devoid of value. Here, we use $w = 0.5$ to create a 50% threshold value for nominal testing conditions; any value over threshold constitutes off-nominal or “no value” for testing purposes, with a linear increase in value as error reduction approaches 0% (modified from Metzger et al., 2019).

Lunar reference density data was aggregated from numerous literary sources, including 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.

Table 15. Averaged Image and Image values (in g/cm³) for lunar regolith samples.

Lunar Regolith Density values (g/cm ³)			
Mission	$\rho(\min)$	$\rho(\max)$	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

Table 16. Averaged ρ_{min} and ρ_{max} values (in g/cm³) for lunar regolith simulants.

Lunar Simulant Density Values (in g/cm ³)				
Simulant	Region	$\rho_{(min)}$	$\rho_{(max)}$	Reference
BP-1	Low-Ti Mare	1.43	1.86	Suescun-Flores et al., 2015
CSM-LHT-1	Highlands	1.50	1.90	SDL, 2023 (JSC-ARES)
CSM-LMT-1	High-Ti Mare	1.50	1.76	APL SAR 2022
GreenSpar	Highlands			
JSC-1A	Low-Ti Mare	1.57	2.03	Zeng et al., 2010
LHS-1	Highlands	1.38	1.56	APL SAR 2022
LMS-1	Low-Ti Mare	1.58	1.73	APL SAR 2023
MLS-1	High-Ti Mare	1.59	2.09	Perkins, 1991; Perkins & Madson, 1996; Batiste & Sture, 2008
NU-LHT-2M	Highlands	1.37	2.06	Zeng et al., 2010
NU-LHT-4M	Highlands	1.50	1.63	APL SAR 2022
OB-1A	Highlands	1.51	1.63	APL SAR 2022
OPRH3N	Highlands	1.32	1.50	APL SAR 2022
OPRH4W30	Highlands			
OPRL2N	High-Ti Mare	1.31	1.54	APL SAR 2022

The compaction methodology for ρ_{max} characterization of granular material is highly impactful on the produced density values. For the APL SAR 2022, minimum and maximum densities were determined in laboratory settings at ambient pressures with air or nitrogen environments via a modified proctor mold and aluminum cylinder set up. In the summer of 2023, a set of density characterizations were performed by the SDL of the CSM-LHT-1 simulant using a vibratory table in line with ASTM standards D4253 and D4254.

Based on existing density measurements of lunar regolith simulants and the aggregated data of lunar reference material from Apollo and Lunakhod samples, the material density FoM (Φ_D) scores are presented in Table 17:

Table 17. Density Figure of Merit scores.

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

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

There was a 2023 project led by the SDL, in partnership with the University of Texas at El Paso, to perform extensive density characterization of all the listed simulant via varying compaction methods, including impact (ASTM D1557), vibration (D4253,4) and 1-D static pressure (ASTM D2435) – data available upon request. Furthermore, the SDL will continue performing ρ_{min} and ρ_{max} measurements following ASTM 4253,4 on any future or in-development commercial simulants. Additionally, the SDL is planning on leveraging computed tomography techniques developed within the ARES division at NASA JSC to scan vertical profiles of simulant packages as a means to measure packing density and porosity via correlation of void spaces on cross-sectional images.

4.8 Shear Strength – Cohesion (c) and Angle of Internal Friction (ϕ^0)

Understanding the comparative fidelity of the shear strength (Cohesion and Angle of Internal Friction) of a lunar regolith simulant is integral in knowing the physical and mechanical nature of the bulk granular material and crucial in activities dealing with geotechnical engineering, such as excavation, drilling, terramechanics, and surface construction. Apart from the use case scenarios, the shear strength of a granular material can also provide information on the compressibility, bearing capacity, slope stability, and trafficability of the material.

The shear strength FoM (Φ_{ss}) is defined as the average of the linear scalar difference of two shear strength descriptors (Cohesion and Angle of Internal Friction) between a lunar regolith simulant and a lunar reference material,

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$$\phi_{SS} = \frac{C + \phi^{\circ}}{2} \quad (15)$$

in which

$$C = \max \left\{ 0, 1 - \frac{1}{w} \frac{|S_C - R_C|}{R_C} \right\} \quad (16)$$

and

$$\phi^{\circ} = \max \left\{ 0, 1 - \frac{1}{w} \frac{|S_{\phi^{\circ}} - R_{\phi^{\circ}}|}{R_{\phi^{\circ}}} \right\} \quad (17)$$

where S_C and R_C define the simulant and lunar reference material cohesion value, respectively, $S_{\phi^{\circ}}$ and $R_{\phi^{\circ}}$ define the simulant and lunar reference material angle of internal friction (AoIF), respectively, and w is a scale factor that shows how far the simulant's cohesion/AoIF can be from a lunar reference material's cohesion/AoIF values before testing with the simulant becomes devoid of value. Here, we use $w = 2.5$ to create a threshold value for nominal testing conditions; any value over threshold constitutes off-nominal or “no value” for testing purposes, with a linear increase in value as error reduction approaches 0% (modified from Metzger et al., 2019).

Soil shear strength can most simply be defined by the Mohr-Coulomb failure criterion,

$$\tau = \sigma \tan(\phi) + C \quad (18)$$

where τ is the shear strength in kPa; σ is the normal stress in kPa; C is the cohesion in kPa expressed as the intercept of the failure envelope with the τ axis; and ϕ is the angle of internal friction where $\tan(\phi)$ represents the slope of the failure envelope.

Practically, we can define a cohesive component (C) that is independent of applied stress,

$$C = y - \text{intercept on the } \sigma - \tau \text{ plane} \quad (19)$$

and a frictional component (ϕ°) that is directly proportional to the normal stress (σ)

$$\phi^0 = \tan^{-1} \left(\frac{\tau_{\max} - c}{\sigma_N} \right) \tag{20}$$

Lunar reference material shear strength data was modified from Carrier et al., 1999 with values outlined in Table 18 below:

Table 18. Lunar regolith Cohesion and Angle of Internal Friction values modified from Carrier et al., 1999.

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

To facilitate direct comparison between simulants and lunar samples, the range of cohesion and AoIF values per depth range was averaged out to create a singular reference data point to be incorporated into the Φ_{ss} FoM calculation.

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Table 19. Cohesion (in kPa) and AoIF (in degrees) values for lunar regolith simulants with references and associated regionality.

Lunar Simulant Shear Strength Values						
Simulant	Region	C (kPa)		ϕ°		Reference
		Avg.	Range	Avg.	Range	
BP-1	Low-Ti Mare	1.0	0-2.0	45.0	39.0-51.0	Suescun-Flores et al. 2015
CSM-LHT-1	Highlands	12.0		32.0		APL SAR 2022
CSM-LMT-1	High-Ti Mare	12.0		36.0		APL SAR 2022
GreenSpar	Highlands	n/a		n/a		
JSC-1A	Low-Ti Mare	1.7	1.4-2.4	44.9	42.9-48.8	McKay 1994, Arslan et al., 2010
LHS-1	Highlands	11.0		35.0		APL SAR 2022
LMS-1	Low-Ti Mare	10.0		37.0		APL SAR 2022
MLS-1	High-Ti Mare	0.8	0.1-1.5	51.7	41.4-62.3	Perkins, 1991; Perkins & Madson, 1996; Batiste & Sture, 2008
NU-LHT-2M	Highlands	n/a		n/a		
NU-LHT-4M	Highlands	8.0		38.0		APL SAR 2022
OB-1A	Highlands	15.0		35.0		APL SAR 2022
OPRH3N	Highlands	12.0		36.0		APL SAR 2022
OPRH4W30	Highlands	n/a		n/a		
OPRL2N	High-Ti Mare	7.0		40.0		APL SAR 2022

As with density FoM outputs, the shear strength parameters are reliant on the modes of compaction, as well as the relative density values. The 2022 APL Simulant Assessment team performed direct shear measurements via a GeoTac Digishear machine under ambient conditions with 3 different confining stresses per sample at 500, 1500, and 3000 lbs/ft² and a lateral movement of 0.1 inches per minute up to a maximum displacement of 0.25 inches.

Based on existing shear strength measurements of lunar regolith simulants and the aggregated data of lunar reference material from Apollo and Lunakhod samples, the shear strength FoM (Φ_{ss}) scores are presented in Table 20:

Table 20. Shear strength Figure of Merit scores.

Shear Strength Figures of Merit	
<i>Simulant</i>	<i>Score</i>
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

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

There was a 2023 project led by the SDL, in partnership with the University of Texas at El Paso, to perform extensive direct shear characterization of all the listed simulant via varying compaction methods, including impact (ASTM D1557), vibration (D4253,4) and 1-D static pressure (ASTM D2435) – data available upon request. In addition to measuring the cohesion and AoIF parameters, UTEP also characterized the angle of dilatation (Ψ^0) for all the listed simulants. Furthermore, the mechanical property testing was performed under three different relative density regimes and three different strain rates (0.015, 0.075, and 0.300 in/min). Lastly, the SDL will perform in-house direct shear measurements, following ASTM D3080, on any future or in-development commercial simulants via a Gilson HM-382 Digital Pneumatic Direct Shear Machine.

4.9 Magnetic Susceptibility (X)

Understanding the comparative fidelity of the magnetic susceptibility (MS) of a lunar regolith simulant is integral in knowing the physical nature of the bulk granular material and crucial in activities dealing with particle-surface interactions, such as dust mitigation and plume surface interactions.

The magnetic susceptibility FoM (Φ_{MS}) is defined as the average of the logarithmic scalar difference of magnetic susceptibility (MS) values between a lunar regolith simulant and a lunar reference material,

$$\Phi_{MS} = \max \left\{ 0, 1 - \frac{|\log_{10} \chi^S - \log_{10} \chi^R|}{\log_{10} w} \right\} \quad (21)$$

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where χ_S and χ_R are the **MS** values (in $10^{-9}\text{m}^3/\text{kg}$) of a lunar simulant and the lunar reference material, respectively, and w is a scale factor that shows how far the simulant's **MS** can be from a lunar reference material's **MS** values before testing with the simulant becomes devoid of value. Here, we use $w = 5$ to create a threshold value for nominal testing conditions; any value over threshold constitutes off-nominal or “no value” for testing purposes, with a linear increase in value as error reduction approaches 0% (modified from Metzger et al., 2019).

Lunar reference MS data was averaged from direct measurements of Apollo samples performed by Rochette et al., 2010 with the values outlined in Table 21 below.

Table 21. Averaged Magnetic Susceptibility values modified from Rochette et al., 2010.

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

Table 22. Simulant magnetic susceptibility values with references and associated regionalities.

Lunar Simulant MS Values ($\log(\chi)$ with χ in $10^{-9}\text{m}^3/\text{kg}$)			
Simulant	Region	MS	Reference
BP-1	Low-Ti Mare	3.73	SDL, 2023 (JSC-ARES)
CSM-LHT-1	Highlands	2.98	SDL, 2023 (JSC-ARES)
CSM-LMT-1	High-Ti Mare	3.48	SDL, 2023 (JSC-ARES)
GreenSpar	Highlands	0.95	SDL, 2023 (JSC-ARES)
JSC-1A	Low-Ti Mare	3.38	SDL, 2023 (JSC-ARES)
LHS-1	Highlands	3.08	SDL, 2023 (JSC-ARES)
LMS-1	Low-Ti Mare	3.43	SDL, 2023 (JSC-ARES)
MLS-1	High-Ti Mare	4.01	SDL, 2023 (JSC-ARES)
NU-LHT-2M	Highlands	3.03	SDL, 2023 (JSC-ARES)
NU-LHT-4M	Highlands	2.86	SDL, 2023 (JSC-ARES)
OB-1A	Highlands	3.22	SDL, 2023 (JSC-ARES)
OPRH3N	Highlands	n/a	
OPRH4W30	Highlands	n/a	
OPRL2N	High-Ti Mare	3.65	SDL, 2023 (JSC-ARES)

MS measurements were performed in the SDL via a Bartington Instruments MS2/MS3 system. Readings were averaged over 3 subsample runs utilizing both low ($0.465\text{ kHz} \pm 1\%$) and high ($4.65\text{ kHz} \pm 1\%$) operational frequencies with an applied field of $250\text{ }\mu\text{T}$ peak $\pm 10\%$ and a calibration accuracy of 1% (using a 10 ml calibration sample).

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Based on existing MS measurements of lunar regolith simulants and the aggregated data of lunar reference material from Apollo and Lunakhod samples, the magnetic susceptibility FoM (Φ_{MS}) scores are presented in Table 23.

Table 23. Magnetic Susceptibility Figure of Merit scores.

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

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

The SDL will continue to perform MS analysis of newly introduced and in-development simulants, leveraging the Bartington Instruments MS2/3 instrumentation within the SDL at JSC ARES.

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4.10 Figures of Merit Summary Chart

Table 24. Simulant Figure of Merit summary chart.

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”.

4.11 Ongoing and Future Work

The goal of the FoM project is to provide an objective metric for available lunar regolith simulants that can be iterated on to encompass future granular analog material development. New simulants will be characterized based on existing FoM property requirements and FoM scores will be calculated appropriately and published in future revisions of the Simulant User’s Guide. The FoM project can be expanded on in the future to include additional parameters for direct comparison to lunar regolith, as long as there is existing lunar sample data or new measurements can be made on representative lunar samples using similar methodologies. Some examples of parameters being considered for future iterations of FoM revisions include electric conductivity, thermal conductivity, and optical properties such as emissivity, absorptivity, solar reflectance, etc.

The SDL at NASA JSC ARES is working with the X-Ray Core Facility at The University of Texas at El Paso (UTEP) for X-ray Diffraction (XRD) analysis, including mineral phase characterization through Rietveld refinement, of all the simulants listed throughout this guide. Additionally, UTEP is performing a geotechnical study of lunar simulants, including the characterization of:

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- Physical and Textural properties
 - Specific Gravity (G_s) following ASTM D854
 - Particle Size Distribution (PSD) following ASTM D6913, D422 and defining:
 - Coefficient of Uniformity (C_u)
 - Coefficient of Curvature (C_c)
 - Density Measurements, including:
 - Maximum Dry Density (γ_{max}) via varying compaction methods, such as:
 - Impact (ASTM D1557)
 - Vibration (ASTM D4253)
 - 1-D Static Pressure (ASTM D2435)
 - Minimum Relative Density (γ_{min}) following ASTM D4254
 - Mechanical properties
 - Direct Shear Test following ASTM D3080 to determine:
 - Angle of internal friction (ϕ°)
 - Angle of dilatation (Ψ°)
 - Cohesion (C)
 - Shear strength parameters will be characterized under 3 different:
 - Relative density levels (based on selected compaction methodology)
 - Compaction methods (Impact, Vibration, 1-D Static pressure)
 - Strain rates (0.015, 0.075, 0.300 in/min)

The SDL will continue performing in-house simulant characterization, leveraging the instrument suite available within NASA JSC ARES laboratories, as well as the capabilities of the SDL itself. Pertinent ARES research labs can provide mineralogical characterization via X-ray Diffraction (XRD) and measurement of the elemental composition via X-ray Fluorescence (XRF) in the XRD laboratory. Internally, the SDL has capability to perform particle size and shape characterization via the MicroTrac SYNC instrument and the Keyence VHX-7000 Digital Microscope, magnetic Susceptibility measurements via the Bartington Instruments MS2/3 System, shear strength (cohesion and AoIF) analysis via the Gilson Digital Pneumatic Direct Shear Machine and a HM-504A pocket vane shear, and varying compaction methodology characterization via a vibratory table and a Gilson HM-580 Mechanical Soil Compactor.

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5.0 Working Safely with Lunar Simulants

5.1 Silica Background

“It remains for me to speak of the ailments and accidents of miners, and of the methods by which they can guard against these, for we should always devote more care to maintaining our health, that we may freely perform our bodily functions, than to making profits. Of the illnesses, some affect the joints, others attack the lungs, some the eyes, and finally some are fatal to men.”

-Georgius Agricola

De Re Metallica, Translated from the First Latin Edition of 1556

5.2 Silicate Minerals

Minerals are naturally occurring, solid, inorganic elements or compounds, with a definite chemical composition and an ordered atomic structure (i.e., crystalline). The absence of an ordered crystalline structure differentiates amorphous solids, such as glasses, from minerals. Minerals are grouped into classes based on their chemical composition. There are 8 mineral groups including: native metals, oxides, sulfides, sulfates, halides, carbonates, phosphates, and silicates.

Silicates, minerals that are composed predominantly of silicon and oxygen, are the most abundant mineral constituent in both lunar and terrestrial rocks. The basic structural building block of all silicates is the silicon tetrahedron, $(\text{SiO}_4)^{4-}$, which consists of one central silicon atom (Si^{4+}) bound covalently to four oxygen atoms (O^{2-}) to form a four-sided pyramid (Figure 14). The resulting silicon tetrahedron structure carries a net charge of -4, which allows for several bonding configurations with the tetrahedra structure to result (i.e., tetrahedra may link to one, two, three, or all four oxygen atoms of another tetrahedra to form a new structure).

These distinct structural configurations are classified as isolated (nesosilicates), paired (sorosilicates), ring (cyclosilicates), single or double chain (inosilicates), sheet (phyllosilicates), and framework (tectosilicate) silicates (Figure 15). Common rock-forming silicate minerals include plagioclase and alkali feldspars (tectosilicates), pyroxenes (single chain inosilicates), olivine (nesosilicate), quartz (tectosilicate), clays (phyllosilicates), micas (phyllosilicates), and amphiboles (double chain inosilicate). Approximately 92% of the Earth's crust (including both continental and oceanic crust) is composed of silicate minerals. The estimated modal mineralogy of the Earth's crust is 39% plagioclase feldspar, 12% alkali feldspar, 12% quartz, 11% pyroxenes, 5% amphiboles, 5% micas, 5% clays, 3% other silicates, 8% nonsilicate minerals (Ronov and Yaroshevsky, 1969).

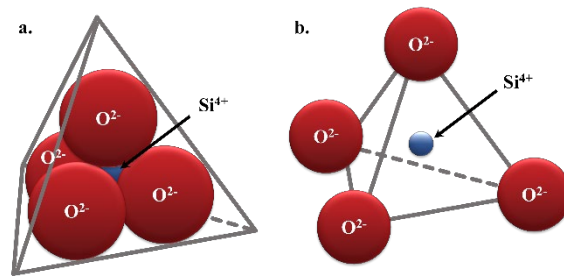


Figure 14. Illustration of silicon-oxygen tetrahedrons: the building blocks of silicate minerals. Shown left (a): Ball model of silicon-oxygen tetrahedron. Shown right (b): expanded view of silicon-oxygen tetrahedron. Oxygen atoms are shown in red while silicon atoms are shown in blue. Note that oxygen atoms occupy the corners of the tetrahedron with a single silicon atom occupying the center of the structure.

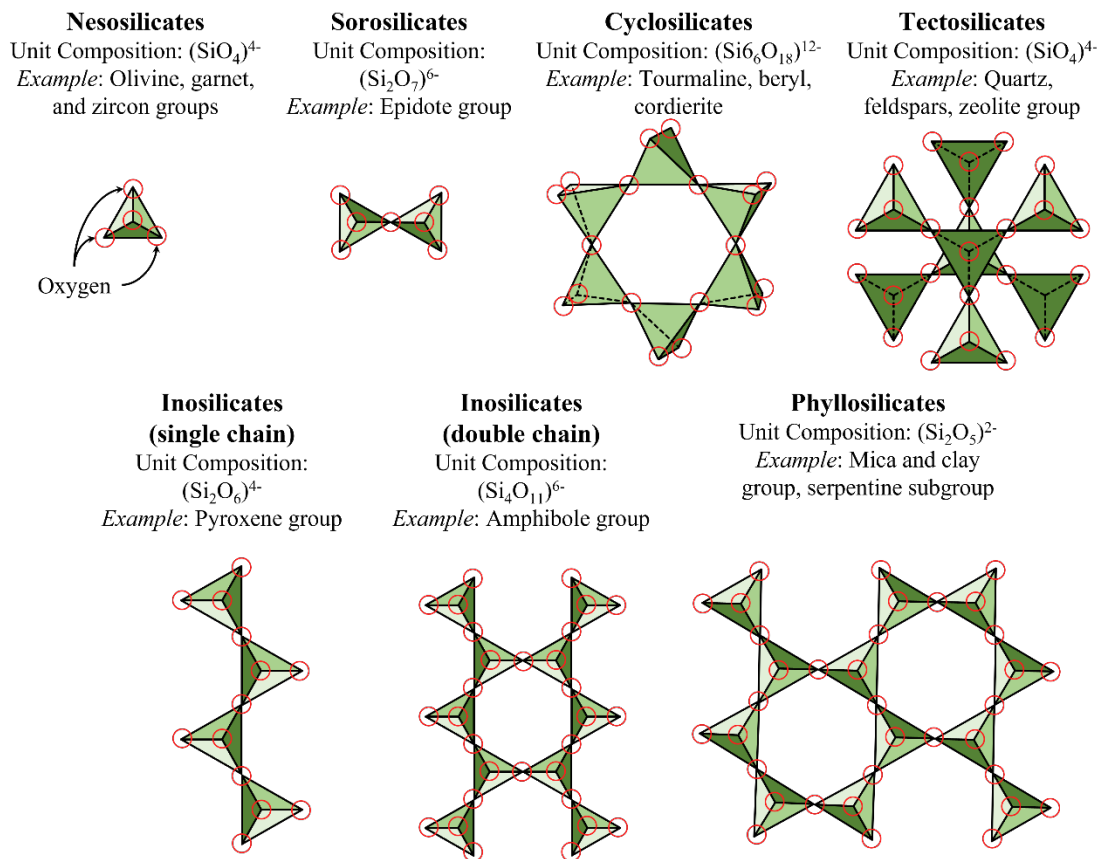


Figure 15. Illustration of the eight structural configurations of silicate minerals. Oxygen atoms are denoted with a red, open circle.

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Lunar mineralogy is dominated by plagioclase feldspar $(\text{Ca,Na})(\text{Al,Si})_4\text{O}_8$, pyroxene $(\text{Ca,Fe,Mg})_2\text{Si}_2\text{O}_6$, and olivine $(\text{Mg,Fe})_2\text{SiO}_4$. On the other hand, potassium feldspar $(\text{KAlSi}_3\text{O}_8)$ and silica minerals (SiO_2 ; silicon dioxide), though common on Earth, are far less abundant on the Moon (Heiken et al., 1991). Further, although silica minerals (SiO_2) are rare on the Moon, the rocks used to create lunar simulants are derived from silica-bearing terrestrial (Earth) sources. Therefore, simulants derived from terrestrial feedstock materials may contain some fraction of crystalline silica.

5.3 Silica (SiO_2) Minerals

Crystalline silica (SiO_2 unbonded to other elements) occurs naturally in several mineralogical forms (or polymorphs) as α , β **quartz**; α , β 1, β 2 **tridymite**; α , β **cristobalite**; coesite; and stishovite (Figure 16). Varietal names of crystalline silica include agate, chalcedony, chert, flint, jasper, novaculite, quartzite, sandstone, silica sand, and tripoli (IARC, 1997). At ambient pressure and temperature conditions, α -quartz is the thermodynamically stable form of crystalline silica; all other silica polymorphs exist metastability at the Earth's surface (IARC, 1997). In addition to its thermodynamic stability, quartz also exhibits resistance to both chemical and mechanical weathering. As such, quartz is ubiquitous in the near-surface geologic environment (i.e., quartz composes 12% of the Earth's crust).

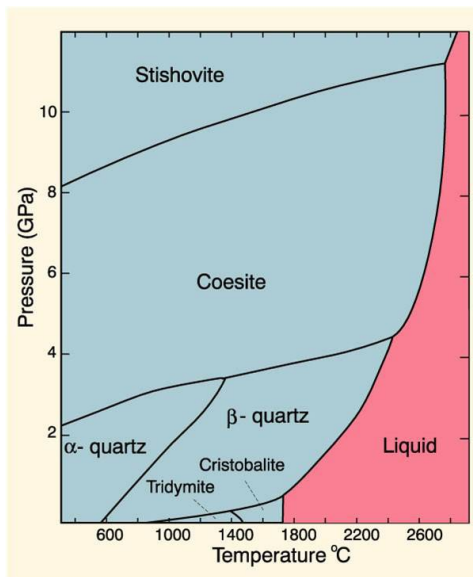


Figure 16. Taken after Winter (2010); used with permission. Equilibrium pressure-temperature (P - T) phase diagram for SiO_2 . Note that under typical conditions, only one SiO_2 phase is stable at any given P - T regime (i.e., blue shaded regions). However, under certain P - T conditions, multiple silica phases may coexist together. At phase boundaries (e.g., boundary between stishovite and coesite), two SiO_2 phases coexist together at equilibrium. While at triple point junctions (e.g., intersection between coesite, α -quartz, and β -quartz), three SiO_2 phases coexist together at equilibrium.

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Non-crystalline (amorphous) forms of silica exist naturally as well, and include opal, biogenic silica, diatomaceous earth, biogenic silica fibers, and vitreous silica (volcanic glasses) (IARC, 1997). Varietal names of non-crystalline silica include diatomaceous earth, diatomite, kieselguhr, and tripolite (IARC, 1997). Note that under elevated heating conditions, amorphous silica phases can be converted to crystalline silica phases (e.g., the high-temperature process of manufacturing silica bricks can transform amorphous silica to cristobalite or tridymite) (Leung et al., 2012).

5.4 Crystalline Silica Content in Simulants

Simulants are geologically complex materials that are developed to represent the physical and/or compositional characteristics of a planetary surface (e.g., a naturally occurring soil or regolith). There are dozens of commercially available simulants that have been developed over the years; each simulant exhibits unique physical, chemical, and mineralogical characteristics. Simulants are derived from either natural or synthetic sources (i.e., “feedstocks”) of glass, minerals, and rocks. These feedstock components are processed by crushing, pulverizing, melting, etc., and then combined in the appropriate proportions to represent a particular site, surface, or region (e.g., Lunar Highlands Regolith).

As noted above, it is important to highlight that feedstock sources (e.g., rocks) may contain silica-bearing minerals in them (e.g., quartz). As such, simulants that are produced from those same feedstock sources may then also contain some fraction of crystalline silica in them, too. Further, the handling and processing of materials which contain large-sized particles of crystalline silica (i.e., $> 100 \mu\text{m}$) may lead to the generation of respirable crystalline silica particles (i.e., $< 10 \mu\text{m}$).

There is a long history of NASA and other facilities using various simulants, and planetary samples, without personal protective equipment and without recognized problems. In most cases these uses were not prolonged and typically small in quantity. As NASA and others have increased simulants uses (small and large facilities), as we prepare for human planetary surface operations, and as regulatory requirements increase, we continue to emphasize proper Safety and Health (S&H) controls to ensure risk and exposures are kept to a minimum.

Table 25 summarizes total percent crystalline and respirable silica contents in select planetary simulants and feedstock materials. These simulants, depending on their chemistry, mineralogy, and physical characteristics (e.g., particle size distribution, particle geometry) represent a potential hazard to employees who may work directly with, or in the vicinity of, any testbed containing simulants. The information provided will assist the simulant user and their organization to properly design, construct, and conduct safe and healthy operations which do not expose the user or bystanders above applicable regulatory (Occupational Safety and Health Administration [OSHA]) or adopted (NASA/American Conference of Governmental Industrial Hygienists [ACGIH]) exposure limits.

These requirements also apply to organizations and users who conduct operations with non-specific (chemistry, mineralogy) surface planetary simulants (e.g., beach/silica sand, volcanic rock, soils) used in a specific facility to approximate a working surface.

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Table 25. Summary of Total Percent Crystalline and Respirable Silica Contents in Select Planetary Simulants and Feedstock Components.

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)

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Martian Simulant	*Total Percent Crystalline Silica (wt%)	†Percent Passing (<10 µm) Respirable Fraction	Total Respirable Crystalline Silica (wt%)	Analysis Source
Fillite	4.52	2.0	0.09	§ (2023)
JSC Mars-1	0.49	1.1	0.01	§ (2023)
JSC Rocknest Mars Soil Simulant	0.5	20	0.1	§ (2023)
JPL Mojave Mars Simulant (MMS)	0.24	20.5	0.05	§ (2023)
M90	4.19	0.2	0.01	§ (2023)
*	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.			

Note that this guide can only provide general guidance related to worker protection when using simulants. Evaluating exposure can be complex and there are formally defined methods for doing so. This guide recommends discussion with local health and safety personnel to accurately evaluate risk in doing specific operations with specific simulants.

Further, risk of exposure to crystalline silica in simulants is highly dependent on the simulant itself and how that simulant is stored, handled, and processed by the end user(s). Individuals are advised to work closely with their local Safety and Occupational Health office when simulants are involved to accurately assess the level of risk that is associated with their specific use-case scenario. All identified risks must be addressed and either eliminated or minimized by developing workplace and engineering controls. Length of testing and frequency of testing will all factor into the risk of exposure when using simulants.

5.5 Potential Hazards from Simulants

Simulants represent both acute (injury) and chronic (illness) safety and health hazards. Before starting work in any laboratory that you are unfamiliar with, you are required to first review the laboratory's hazard analysis (HA). Pay particular attention to the controls that are listed in the HA. The Safety Data Sheet (SDS) of the material you are going to be working with should be the second item you review. While the SDS will provide exposure controls, it is important to remember the manufacturer or distributor is not going to know how you will be using the material and therefore makes the exposure controls as conservative as possible to minimize liability. These controls should be used as a guide. A facility or test-specific hazard analysis and discussion with local Health and Safety Experts and Laboratory Personnel can determine appropriate controls based upon potential hazards of the operation.

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5.5.1 Injury

Slips trips and falls: Walking and working surfaces – Loose material outside of the actual containment and/or test area has the potential to cause slips, trips and falls when found on walking surfaces. In most workplaces, more than half of the injuries are caused by slips, trips, and falls, which are often caused by foreign materials and/or objects on walking surfaces. Loose material on benchtops can contaminate equipment that is not part of a test or experiment. Care should be taken to ensure materials remain in their intended location. Work areas should be frequently cleaned, wet wiped and/or HEPA Vacuumed, and appropriate footwear should always be used when working around these materials.

Irritant (Eye): Loose simulants and simulant grains can cause painful eye injury when simulant grains are rubbed across the eye surface. This typically occurs when contact is made from hand transfer and by airborne materials. Appropriate eye PPE, glasses and/or goggles, will be necessary depending on the physical characteristics of the simulant.

Pulmonary: Some of the acute symptoms of exposure include coughing, breathing difficulty, wheezing, decreased pulmonary function, irritated eyes. This will primarily be a concern for sensitive individuals and is not a concern for most personnel.

5.5.2 Illness

Simulants represent a significant number of chemical and mineral constituents. Chronic inhalation of respirable (<10 microns), particulates can lead to pneumoconiosis, a subgroup of lung disease. This includes Silicosis and Asbestosis and Black Lung (coal). These are most often associated with occupations involving the inhalation of mineral dusts and occur, in most cases, following years of heavy, unregulated, exposures.

The primary exposure concerns to personnel using simulants include crystalline silica (SiO₂: Quartz, Cristobalite, and Tridymite) and Particulates Not Otherwise Regulated (PNOR) or Total Dust. Of these, crystalline silica represents the greatest potential for illness and disease and is regulated under the OSHA general industry and construction standards, 29 CFR 1910. 1053 and 29 CFR 1926. 1153. Crystalline silica can become airborne when workers chip, cut, drill, or grind objects that contain silica.

Acute silicosis occurs following a few months, to as long as two years, after exposure to very high concentrations of crystalline silica. Symptoms of acute silicosis include severe disabling shortness of breath, weakness, and weight loss. NASA's S&H requirements and culture ensures that exposures shall be kept below applicable standards which will protect employees from this chronic illness.

Chronic or classic silicosis is the most common form of silicosis. It occurs after 15-20 years of moderate to low exposures to crystalline silica. Symptoms include shortness of breath upon exercise and clinical signs of poor oxygen/carbon dioxide exchange. Later symptoms in the late stage of the disease include fatigue, extreme shortness of breath, chest pain, and/or respiratory failure.

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While these chronic conditions are listed, they are a result of very high exposures over long periods of time. NASA's S&H requirements and culture ensures that exposures shall be kept below applicable standards which will protect employees from this chronic illness.

Also of note, all simulants used for planetary surface simulation are kept indoors and in a very dry condition. This is normal for the lunar and mars environment, however not as common on Earth where wetting is a common and simple method for reducing exposure to respirable silica and for controlling dust. This represents some challenges to developers. Further discussion exposure hazards and applicable OSHA and other regulatory standards is found below.

5.6 Exposure Hazards, Crystalline Silica, PNOR, Control

In June of 2018 OSHA, 29 CFR 1910.1053, began enforcing silica standards for general industry and Construction. OSHA set a permissible exposure limit (PEL) of no greater than 0.05 mg/m^3 ($50 \text{ }\mu\text{g/m}^3$) of respirable crystalline silica, calculated as an 8-hour time-weighted average (TWA). NASA has implemented a stricter requirement based on the ACGIH. No NASA employee shall be exposed to an airborne concentration of respirable crystalline silica in excess of 0.025 mg/m^3 ($25 \text{ }\mu\text{g/m}^3$) TWA, this level is also the OSHA Action Level (AL) in which some OSHA requirements become mandatory. When monitoring shows exposures are below the AL, there are no further requirements for the employer to complete. When the exposure monitoring shows an exposure above the AL but below the PEL, scheduled monitoring must be completed every six months. When exposures are above the PEL, scheduled monitoring must be completed every three months. Employees must be notified of their results within fifteen working days after the exposure assessment is completed by safety and occupational health personnel. Further requirements of the OSHA standard do not apply when exposures are below the action level. Medical surveillance is only required when employees are exposed to crystalline silica at or above the action level for more than thirty days per year.

OHSA has set a limit of 15 mg/m^3 (Total) and 5 mg/m^3 (Respirable) calculated as an 8-hour TWA for Particulates Not Otherwise Regulated (PNOR). The respective employer is responsible for ensuring proper S&H evaluation and controls are in place and for applying applicable exposure limits. There may be additional exposure limits applicable to the work location and specific material being used. Consult your local S&H Professional for guidance. There are several controls which can be implemented for employee protection.

5.6.1 NIOSH Hierarchy of Controls

The National Institute for Occupational Safety and Health has established the "Hierarchy of Controls, a method of identifying and ranking safeguards to protect workers from hazards (Figure 17). They are arranged from the most effective to the least effective methods and include elimination, substitution, engineering controls, administrative controls, and personal protective equipment. Using this system, we discuss the control of the silica and PNOR/Dust/Particulates. While some of these controls may be possible when designing facilities using simulants, the nature of planetary surface testing and the need for specific simulants may preclude the use of some of these control methods, such as elimination/substitution and engineering controls (wetting).

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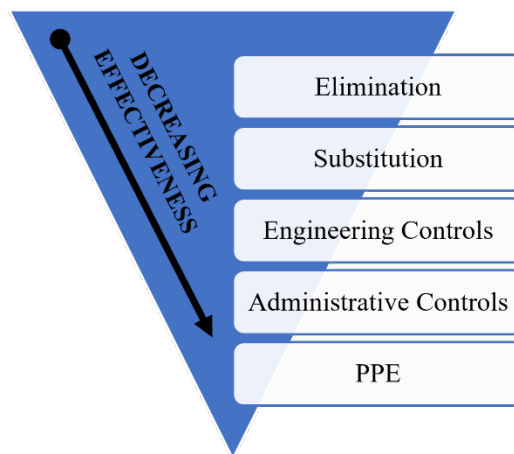


Figure 17. NIOSH Hierarchy of Controls.

5.6.1.1 Engineering Controls

The most effective form of protection from silica and PNOR exposure is removing or isolating the silica at the point where it is made. When working with lunar simulants, the first line of defense would be to eliminate the hazard altogether, by substituting the silica containing lunar simulant with a less hazardous material. This is not always feasible, and in the cases where a substitution cannot be made, basic engineering controls should be implemented. The three major types of engineering controls for silica dust are (1) wet methods (2) vacuum dust collection systems and (3) isolation.

Wet methods involve using water or a foam to keep dust down and out of the air. While wet methods may be acceptable for simulant clean up, they may not be acceptable during transfer of materials and operating testing facilities. Vacuum dust collection systems remove dust at the point where it is made. Isolation separates the employee from the silica dust. Other examples of engineering controls include, but are not limited to: using local exhaust ventilation to control the level of dust (e.g., test cell ceiling exhaust – ensure that there is a clear rooftop exhaust exclusion zone, lab hoods, air filtering devices with HEPA filters); containing or isolating the activity and restricting access (e.g., minimize the number of individuals potentially exposed; there should be no bystanders during high-risk activities); use of portable HEPA vacuums to capture dust at the source or on horizontal surfaces; and covering of ancillary equipment to prevent contamination. Engineering controls are designed to protect everyone in the area, not just a single person.

5.6.1.2 Safe Work Practices

The second most effective type of protection is safe work practices. This involves completing tasks in ways that reduce dust exposure. Safe work practices should be implemented when handling simulants. The first safe work practice that should be implemented is ensuring that the engineering controls are working properly (e.g., by checking the ventilation system). Any engineering controls which are not working should be immediately addressed. Some safe work practices include: the use of water to minimize dust generation when possible/applicable; prohibiting dry sweeping/brushing and use of

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compressed air to clean surfaces; wet wiping/mopping of horizontal surfaces; prohibiting eating and drinking in the lab; washing of hands and face prior to leaving the worksite and prior to eating or drinking; slowly transferring simulants from one container to the next (do not pour dust materials quickly, slower is better); leaving contaminated bags and clothing undisturbed (e.g., do not shake contaminated bags/clothing; use of wet methods when grinding, drilling, and cutting silica-containing materials when possible; and proper use of Personal Protective Equipment (PPE). Dust-generating tasks should always be scheduled when other employees will not be around. Like engineering controls, safe work practices should be designed to protect everyone in the area.

5.6.1.3 Administrative Controls

Administrative controls include documentation, signage, limiting worker exposure time, and training of all personnel. Any laboratory which uses silica-containing materials should have a properly written exposure control plan signed off by the safety committee. This document should contain background information, instructions for the control plan usage, clearly defined roles, and responsibilities (Occupational Health, Supervisors, Lab Manager, Workers, Visitors, etc.), risk table with respiratory risk category and required exposure controls, respirator risk category and minimum protection respirator type, as well as any supporting documents.

Any products containing silica should be clearly labeled as such. It is the manufacturer's responsibility to label all products that contain more than 0.1% silica; however, it is the employer and user's responsibility to ensure that the label is not removed or defaced. In addition, when required by the OSHA standard, proper signage must be posted outside the restricted test area indicating a silica hazard is present and that respiratory protection is required.

5.6.1.4 Personal Protective Equipment

Personal Protective Equipment (PPE) will be based on the following: task being performed, previous monitoring for similar tasks, and conditions with which the task is being performed. PPE may include respiratory protection, protective clothing, gloves, and/or safety glasses or goggles. Respiratory protection may be as simple as a disposable filtering facepiece respirator to a powered air purifying respirator (PAPR) with a high efficiency particulate air (HEPA) filter.

No matter the PPE requirements, good personal hygiene should be always used. Wash your hands before eating lunch or smoking. Wash your hands before leaving the lab or directly after leaving. Do not eat on any work surface in the lab. Drinks should have a closable lid.

5.7 Simulant Hazard Communication

The Hazard Communication Standard (HCS), 29 CFR 1910.1200 (h), requires all employers to provide information and training to their employees about the hazardous chemicals to which they may be exposed at the time of their initial assignment and whenever a new hazard is introduced into their work area.

To this end, NASA and the JSC Astromaterials Simulant Development Lab (SDL) has developed and provided, or required the manufacturer to develop and provide, Safety Data Sheets, SDS (formally

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MSDS) for all of the simulants that they manage. SDSs can be provided upon request. These SDS are compliant with the recently mandated Global Harmonization System (GHS) classification system. However, some of the SDSs for these simulants do not adequately note or describe the significant differences between OSHA regulated Crystalline Silica (Quartz, Cristobalite, and Tridymite) and less toxic “silicate” minerals. The user should understand and consider these significant differences in toxicity and regulatory requirements as they plan and execute simulant use.

As noted in Section 5.4, JSC Astromaterials SDL provides Table 25 on the crystalline silica content of each of their simulants. The table summarizes total percent crystalline and respirable silica contents in select planetary simulants. Note that these data serve as a guide to bring awareness to those interested in working with simulants. Variations in total percent crystalline and respirable silica content in simulants may occur because of batch differences in simulants and sampling size bias (e.g., measured data from milligrams of one sample are used to extrapolate the characteristics an entire batch of simulant).

5.8 Workplace Monitoring

Exposure monitoring is the only method to determine your occupational exposure to crystalline silica. Exposure monitoring consists of either personal and/or area monitoring. Samples are sent to an independent accredited laboratory for analysis.

JSC Occupational Health has been working with the JSC-SDL to conduct silica and PNOR monitoring during various testing scenarios. Results from these tests can be found in Table 26. To date (August 20th, 2024) all exposures have been below the OSHA PEL and Action Level for crystalline silica and well below the PEL for Particulates Not Otherwise Regulated.

Further information on other sites using simulants can be found on the Office of the Chief Health and Medical Officer Occupational Health Center Regolith SharePoint Site:

- <https://nasa.sharepoint.com/sites/ohp/SitePages/Simulants.aspx>

You may have to request access to this page from the Office of the Chief Health and Medical Office to access this page.

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Table 26. Silica and PNOR monitoring completed in the Simulant Development Lab, NASA-JSC.

Date	Task	Simulant	Task Time	Crystalline Silica 8-hr TWA Result	Respirable Particulates Not Otherwise Regulated 8-hr TWA
February 2023	Simulant Tumbling	LHS-1	289 minutes	<4.09 $\mu\text{g}/\text{m}^3$	<0.039 mg/m^3
February 2023	Simulant Tumbling	LHS-1	289 minutes	<3.97 $\mu\text{g}/\text{m}^3$	0.078 mg/m^3
March 2023	LDES Simulant Testing	NU-LHT-4M	175 minutes	<4.67 $\mu\text{g}/\text{m}^3$	<0.043 mg/m^3
March 2023	LDES Simulant Testing	NU-LHT-4M	169 minutes	<4.19 $\mu\text{g}/\text{m}^3$	<0.042 mg/m^3
March 2023	LDES Simulant Testing	NU-LHT-4M	173 minutes	<4.14 $\mu\text{g}/\text{m}^3$	<0.043 mg/m^3
April 2023	Vacuum Testing	CSM-LHT-1 JSC-1A LHS-1D	232 minutes	4.5 $\mu\text{g}/\text{m}^3$	0.21 mg/m^3
May 2023	Small Rock Crusher	Tephra	118 minutes	8.36 $\mu\text{g}/\text{m}^3$	0.54 mg/m^3
June 2023	Vacuum Testing	CSM-LHT-1 JSC-1A LHS-1D	125 minutes	<6.1 $\mu\text{g}/\text{m}^3$	0.18 mg/m^3
June 2023	Vacuum Testing	CSM-LHT-1 JSC-1A LHS-1D	123 minutes	9.2 $\mu\text{g}/\text{m}^3$	0.36 mg/m^3
September 2023	Small Rock Crusher	Synthetic Anorthite	169 minutes	<4.1 $\mu\text{g}/\text{m}^3$	0.10 mg/m^3
September 2023	Small Rock Crusher	Synthetic Anorthite	165 minutes	<4.2 $\mu\text{g}/\text{m}^3$	0.04 mg/m^3
November 2023	Transfer of BP-1 from bulk containers	BP-1	71 minutes	<5.22 $\mu\text{g}/\text{m}^3$	0.09 mg/m^3

OSHA Permissible Exposure Limit PEL

- Crystalline Silica: 50 micrograms/ m^3 8-hour TWA
- Particulates Not Otherwise Regulated (PNOR)
 - Total PNOR: 15 milligrams/ m^3 8-hour TWA
 - Respirable PNOR: 5 milligrams/ m^3 8-hour TWA

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5.9 NASA Facilities Utilizing Lunar Simulants

5.9.1 Johnson Space Center (JSC) / SDL Requirements

The Johnson Space Center in Houston, Texas SDL a multifunction collaborative lab space that supports the analysis, curation, development, distribution, and testing of planetary simulants (Lunar and Martian) and granular materials (Figure 18). The SDL provides a dynamic working space where science (characterization of physical simulant properties) and engineering (tools, gloves and suit materials, dust mitigation, robotic prototypes) experiments can be conducted using testbeds of simulants. The lab currently houses over 30 metric tons of planetary simulants and feedstock materials. Additionally, the SDL is furnished with a wide array of equipment and tools used to process simulants (including bulk simulant and feedstock materials such as rocks) along with a key selection of analytical instruments which are used to characterize these materials. As noted, they maintain SDS for all simulants.



Figure 18. Photographs of the Simulant Development Lab at the Johnson Space Center. Shown left: photograph of active testing lab, part of the SDL. Shown right: Particle Size Analyzer and Digital Microscope housed within the SDL's analytical suite.

Currently, only full-time employees involved in simulant handling, distribution and testing are required to be respirator qualified and utilize respiratory protection when working in the facility. Respirators are provided to those affected employees.

For visiting engineers and scientists, exposure monitoring during a variety of testing scenarios and using different simulants has shown that none of the activities result in silica exposures above the OSHA Action Level of 25 micrograms/cubic meter (Table 26). Employees are also required to meet OSHA hazard communication requirements, but other than silica awareness, there are not any locations meeting the definition of a regulated area under the OSHA Silica standard in the SDL.

Visiting scientist and engineers conducting testing may choose to utilize respiratory protection under the OSHA Voluntary Respiratory Use, 29 CFR 1910.134 Appendix D. Voluntary respirator users must meet the requirements of this section to use respirators in the SDL.

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Check with the JSC SDL for Current S&H requirements before traveling to and/or testing at the SDL. You and your organization are responsible for understanding and meeting their S&H requirements.

5.9.2 Kennedy Space Center (KSC)

Kennedy Space Center in Cape Canaveral, Florida is the home of Swamp Works. Swamp Works was established in 2012 and is a facility devoted to innovation and leveraging skills and capabilities across KSC (Figure 19). Today, Swamp Works focuses on granular mechanics and regolith operations (GMRO), applied chemistry, electrostatics and surface physics, advanced materials and systems, applied physics, and corrosion technology. The GMRO Lab is located within the main Swamp Works building at KSC and combines theoretical and experimental granular mechanics with applied robotics to operate with the soil on other planetary bodies like the Moon. In addition to GMRO, KSC also built a Hazard Field near the north end of the Space Shuttle's runway. The Hazard Field is a landscape of simulated craters and boulders in sandy regolith.

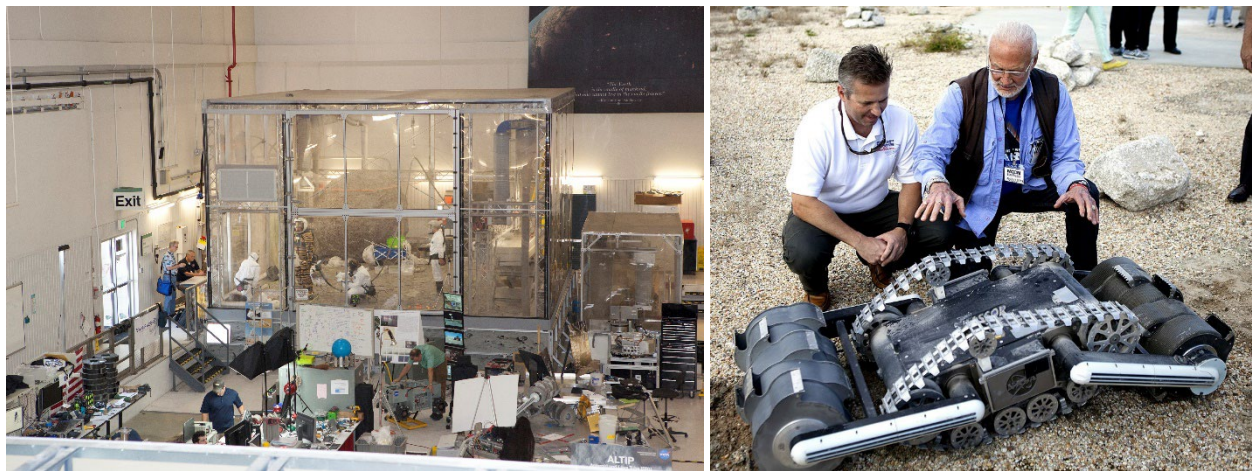


Figure 19. Photographs of Swamp Works at the Kennedy Space Center: Shown left: A view inside the Swamp Works facility highlighting the enclosed regolith test bin. Shown right: Rob Mueller, co-founder of Swamp Works, together with Apollo 11 astronaut Buzz Aldrin discussing the RASSOR robot developed by Swamp Works for space mining applications.

“Rather than the transportation of getting into space, Swamp Works is mainly concerned with what you do when you get there,” Mueller said. “That requires innovation of new technologies, and Swamp Works encourages that innovation.” (NASA 2023).

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5.9.3 Glenn Research Center (GRC)

Glenn Research Center in Cleveland, Ohio is the home of the Simulate Lunar OPERations (SLOPE) facility and the Excavation Lab (Figure 20 and Figure 21). The SLOPE facility serves to provide controlled test conditions to evaluate the tractive performance and power consumption of roving vehicles on lunar terrain. Because the lab is indoors, the facility has stable temperature and humidity levels which limits variability in soil conditions, but also requires strict hazard controls and health monitoring due to silica containing simulants like GRC-1 and GRC-3.

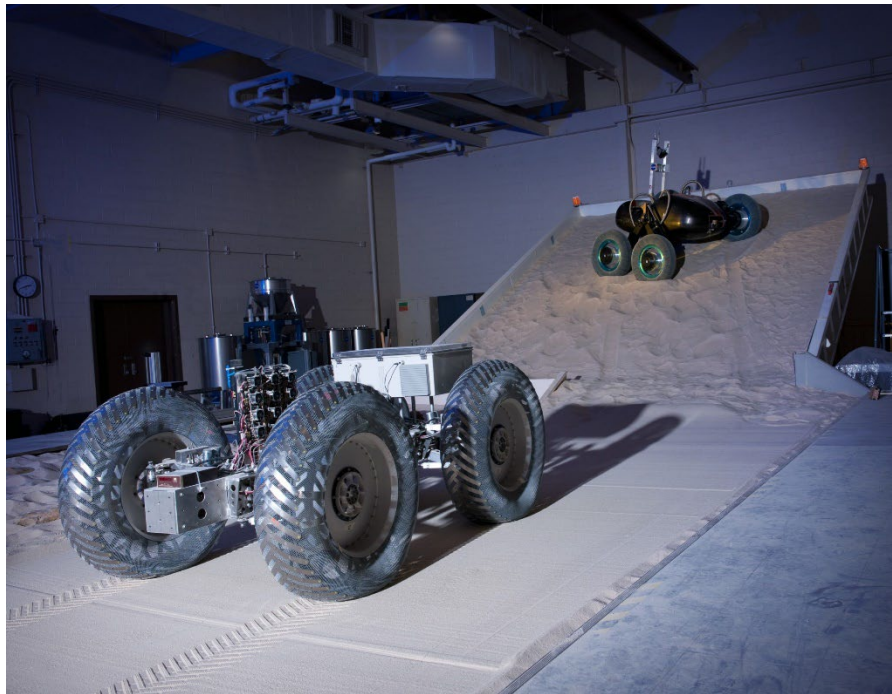


Figure 20. Photograph of the SLOPE facility at the Glenn Research Center.

The Excavation Lab houses the Advanced Planetary EXcavator (APEX), a heavy-duty 4 degree-of-freedom robotic arm capable of excavating from multiple adjacent soil bins. Excavation tools can be lowered to desired digging depths and driven at controlled rates on pre-programmed paths while digging forces are measured using a 6-axis load cell. Similar to the SLOPE facility, this lab requires many engineering controls and health monitoring. A dust enclosure with HEPA filter air exchange surrounds the APEX and soil bins to protect operators from respiratory hazards. Examples of required PPE for as related to Tasks and Risk Category (Tier 0-IV) for various simulant related activities conducted at GRC can be found in Table 27.



Figure 21. Examples of tasks in the SLOPE facility or Excavation Lab and their associate risk categories are listed in Table 27 for reference.

Table 27. Required PPE as related to Tasks and Risk Category (Tier 0-IV).

Task	Risk Category	Required PPE
SLOPE soil preparation	Tier IV	PAPR, boot covers, disposable pants/coveralls
SLOPE sink tank testing	Tier IV	PAPR, boot covers, disposable pants/coveralls
Bulk loading of simulants	Tier III	PAPR, boot covers, disposable pants/coveralls, sealed eye protection
SLOPE rover testing	Tier II	Half-mask, boot covers, disposable pants/coveralls
Mixing simulant with cement mixer	Tier II	Half-mask, boot covers, disposable pants/coveralls
Dry sieving	Tier II	Half-mask, boot covers, disposable pants/coveralls
General cleaning	Tier I	Half-mask, HEPA vacuum clothing
TREC testing	Tier 0	None
Ultrasonic soil penetration	Tier 0	None

5.9.4 Other Regolith Simulant Facilities Available to NASA and Its Partners

Additional NASA Centers (e.g., Marshall Space Flight Center) and Federally Funded Research and Development Centers (e.g., the Jet Propulsion Laboratory) have terrain fields, indoor simulant facilities, dirty thermal vacuum chambers, etc., with specific simulant usage controls that will be captured in future versions of this User's Guide.

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There are specific S&H requirements, PPE, training, etc., to work in each of these active test facilities. The requirements are based upon the potential hazards and controls and of the specific simulant materials. If you are traveling to one of these existing facilities check with operators to ensure that you have and can meet all current S&H requirements at the facility. Some examples of requirements for above noted facilities are attached to this guide.

When developing new facilities or conducting testing it is highly recommended that S&H personnel get involved in the design stage of test and or facility development. By using standard engineering controls, the user can decrease the need for PPE for users and operators.

5.10 Conclusion

While it is the responsibility of the employer to ensure a safe workplace, it is the responsibility of the employee to do the following: Not in order of priority or process.

- Ensure early and engaged involvement in your organizations activities to develop simulant use facilities. Involve local S&H professionals in design, construction and test readiness.
- Use the NIOSH Hierarchy of controls to determine and set S&H requirements.
- Gain awareness of the crystalline silica and respirable silica contents of planetary simulants Abide by HCS and GHS hazard warning labeling requirements found in the SDS for Simulants.
- Understand that coarse-grained (non-respirable) size fractions may be broken down to respirable size fractions ($<10\text{ }\mu\text{m}$) through mechanical processing (e.g., crushing, grinding, pulverizing forces).
- Label all simulants that contain $>0.1\%$ crystalline silica by weight or volume with the appropriate hazard warning labels.
- Read, understand, and adhere to the controls set out in the Silica Exposure Control Plan if applicable.
- Use the assigned personal protective equipment (PPE) in an effective and safe manner.
- Minimize dust generation during testing activities.
- Complete required training, medical surveillance, and respirator fit testing when required.
- Report any exposure incidents or any signs or symptoms of illness from silica exposure to employee's supervisor or the Occupational Health Organization.

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6.0 Test Preparation with Simulants

6.1 Background

6.1.1 Historical Perspectives and Early Development Work in Simulant Testing

Since the Apollo and Luna exploration programs, engineers and scientists have studied the regolith in its environment and attempted to replicate beds of similar materials to serve as testing grounds. The development program of the Lunar Rover Vehicle (LRV) included extensive experimentation of wheel designs in a wide variety of simulant materials prepared as testbeds using the limited knowledge available at the time. The return of regolith core and rock samples by the early Apollo missions greatly increased this knowledge through the interpretation of in-situ measurements and laboratory testing that yielded a much more comprehensive picture of the nature of the regolith and its properties within its environment (Heiken et al., 1991; Jolliff et al., 2018). This knowledge led to the search for terrestrial rock materials with greater geologic similitude to the collected lunar materials and their use in new hardware tests and processes. Over the years, much of the effort was placed on the selection of simulant materials and their production in sufficient quantities with consistent quality. Internal NASA efforts during the Constellation program led to users' guides to serve as references that discuss the importance of lunar technology programs to use a set of recommended simulant materials and have access to common knowledge about the handling, and preparation of simulant materials for testing (Sibille et al., 2006; Schrader et al., 2010). More recently, NASA published testing standards for hardware exposed to planetary dust environments as NASA-STD-1008 which documents specific recommended protocols for NASA hardware testing (John, 2021). This users guide provides complementary information to NASA-STD-1008 with current best practices for users involved in testing hardware at different TRL levels, particularly around simulant preparation for various testing environment and test characteristics.

6.1.2 Regolith Simulant Preparation: Test Requirements and Methodology

Most lunar regolith simulants available in large quantities consist of mixtures of terrestrial mineral and rock materials sourced at specific geologic deposits on Earth that are accessible for mining. This fact results in a fundamental difference between these materials and lunar regolith: they were formed and changed over time by different processes and forces. This results in simulant materials that are similar in their geology and their mineralogy to specific lunar regolith while they also differ by the presence of terrestrially weathered minerals such as hydrates, sulfates, or clay minerals, and other formed minerals with inclusions that are not or rarely present in lunar materials. On the other hand, lunar regolith contains unique constituents that may be present at certain locations, regions or globally that are not found in terrestrial natural materials: glass-mineral agglutinates, reduced iron at submicron scale, solar wind-implanted ions and derived molecules, pyroclastic glass, impact features at mm and micron scales, and absence of any hydro-altered surfaces and minerals. In addition, the lunar environment itself plays a major role in producing unique characteristics of the physical state of the regolith such as photoelectrically charged surfaces that change with exposure to solar illumination, unaltered mineral surfaces at the molecular scale where van der Waals forces dominate, and high angle of repose in the absence of atmospheric pressure.

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6.2 Test Classification with Regolith Simulant

6.2.1 *Ambient Terrestrial Conditions*

Many tests are performed under terrestrial ambient conditions to obtain preliminary data and/or to enable the scale-up and maturation of hardware before transitioning to vacuum and higher-fidelity simulated lunar conditions. These terrestrial environments range from enclosed regolith beds in climate-controlled laboratories to outside field test ranges in a variety of seasonal weather conditions. Such tests may include surface mobility, subsurface penetrating work, surface handling of regolith and sensor testing for surface and subsurface measurements. Most of the lunar materials simulants available at the publication time of this guide exhibit a total average of 0.5 wt.% of water of which ~ 0.2 wt.% represents physi-adsorbed water at equilibrium in climate-controlled rooms. This latter value should be verified for each simulant batch being used as it varies significantly between simulants and between batches if the source materials or the processing are changed by the vendor. Quantitative measurements are underway on a comprehensive list of simulants and are expected to be published soon. Users are strongly encouraged to obtain their own measurements before testing and report them in publications. In ambient laboratory conditions, dry regolith will re-adsorb water from the environment at varying rates depending on the simulant. It is therefore important to perform initial comparative tests with small amounts of dried simulant and non-dried simulant to identify the effect of the physi-adsorbed water on the test outcomes. Users should select appropriate desiccation techniques and heating conditions discussed in Section 6.3.1 of this guide.

6.2.1.A *Mechanical Operations and Sensor Testing*

6.2.1.A.(i) *Particle Size Distributions*

The vast majority of “full-PSD” simulants available at time of publication exhibit particle size distributions with an upper limit of 1 mm. This widely accepted limit is an artifact that originated with the initial PSD measurements of Apollo core samples that establish this upper limit that accounts for 90% of the volume of the samples (McKay et al., 1991). McKay et al. cautions that the upper fractions between 1 mm and 1 cm should be included to represent the lunar regolith while the 1 cm particles admittedly constitute the arbitrary upper size limit. The actual particle composition of the lunar surface material obviously includes larger particles ranging from pebbles to rocks that depend on location on the lunar surface. Regolith near large young crater rims contain a larger portion of rocks than areas with few craters or with small older craters for example. Recent work by Kovtun et al. re-examined the catalogued data of Apollo 16 soil samples and revealed that the PSD of surface material of these lunar highlands’ regolith extended to 80 mm, identified as the maximum sample clast size (Kovtun, 2024.) Table 28 displays the resulting distribution of particle size by clast and Figure 22 exhibits the complete PSD of the Apollo 16 surface material from Kovtun, 2024. This recent information is important for many regolith handling technologies and systems and will be complemented by similar studies on other samples in the future. At this time, it is recommended that hardware that interacts with regolith mechanically should ultimately be tested in simulants that include representative particle size fractions from 10 mm to 80 mm that represent the lunar highland regions considered for their deployment.

Table 28. Particle size average % content and associated clast nomenclature for Apollo 16 surface samples (Kovtun, 2024).

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 %

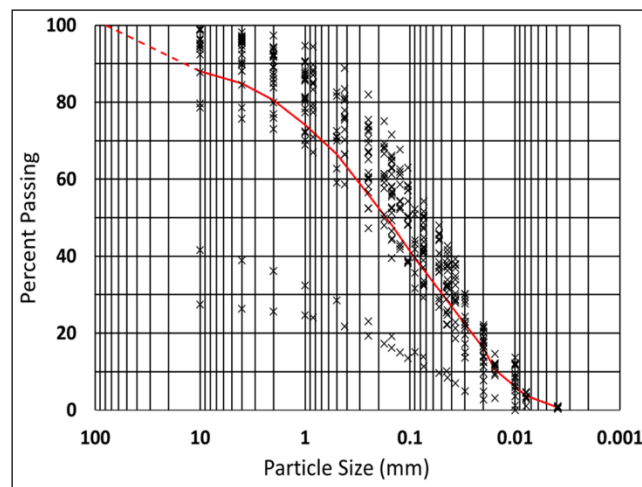


Figure 22. Lunar soil particle size distribution for Apollo 16 surface samples taken from Morris et al. (1983), Graf (1993), and JSC's Lunar Sample and Photo Catalog. Red line represents average distribution, dotted redline shows projection out to maximum sample clast size (~ 8 cm) to show the entirety of the PSD.

Particle Aspect Ratio and Form Factor (sphericity) are factors that affect flow behavior of simulant materials during mechanical tests. Many technology development paths for lunar and Mars surface hardware begin with tests in ambient terrestrial conditions using simulants available to the technologists at a cost afforded by their budget. It is therefore important to examine the implications of the choice of simulant on the value of the test results and the conclusions drawn for the tested design. Simulants that are selected solely for mechanical tests and physical sensor tests are sometimes labeled “low fidelity” materials because they are not selected to represent chemical composition and sometimes even have non-representative mineralogy when compared to lunar regolith. While this approach appears reasonable for many early development tests, it is highly recommended to select simulant materials whose specific physical characteristics such as full PSD, shape and angularity approximate closely those of lunar regolith. It is strongly recommended to evaluate each simulant being considered using published figures of merit in Section 4 of this document. It is also important to be cognizant that tests designed to mature mechanical hardware beyond early phases of development should include “higher fidelity” physical simulants to challenge the technology adequately for the

achievement of the targeted TRL. This approach also aids in avoiding redesign costs later in the development phases.

6.2.1.A.(ii) *Bed layering and compaction*

Current knowledge of the depth profile of lunar regolith does not confirm the presence of distinct layers of material with sharp increments in bulk density while density increases with depth (Carrier et al., 1991, 2003). The practice of creating layers of simulant at different densities arise from the need to approximate this gradual increase with depth and to measure the performance of penetrating instruments against increasingly compacted regolith with accuracy. It is important to perform bulk density measurements or estimates at the relevant depths of the regolith bed where changes in density occur during the creation of the bed to account for this defining parameter accurately during test data analysis. In addition, the preparation of regolith testbed should strive to achieve shear strength values similar to those of lunar surface material as well as their dependence on depth. Connelly and Carrier pointed out that the absence of cratering under the effects of Apollo landers' engine exhaust plumes indicates increasing shear strength below the surface (Figure 23), and this also impacts drilling, excavation, and other mining operations as well as ultimate bearing capacity (Connelly and Carrier, 2023).

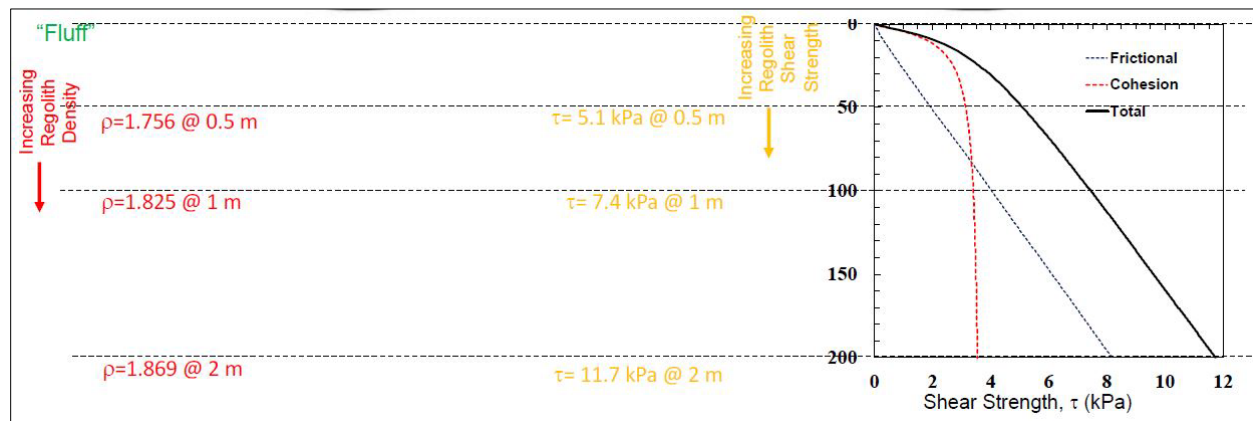


Figure 23. Dependence of lunar regolith density and shear strength with depth below surface for intercrater areas (Connelly and Carrier, 2023).

Key recommendations:

- Regolith simulants used in ambient condition mechanical testing should be stored dry in a location with active humidity control. If this is not possible, the simulant should be desiccated using methods listed in Section 6.3.1.
- Select simulants with known PSD that extend to 80 mm in size when possible, with particle shape characteristics that make it possible to approximate the lunar shear strength profile as a function of depth. The PSD should be reported for test data interpretation.

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- Bulk density and relative density of simulant material should be measured or estimated for all tests, including as a function of depth when compaction methods are used to create a density profile.

6.2.1.B Extractive processing testing

Many ISRU projects aim to extract components of interest from the bulk regolith through processing in a variety of chemical, physical, and thermal conditions. In some tests, the regolith is simply loaded in the system as the source material without any requirements on achieving a final aspect such as a flat bed, a compacted column. In other cases, these requirements exist, and they are akin to those of mechanical testing operations in the previous section.

The selection of simulants for extractive processing tests requires added considerations from those used in mechanical testing because mineralogy and chemical compositions become prevalent factors during testing. The mineralogical mixture of a simulant defines in large part its chemical composition and it becomes the first factor to consider. However, the abundance of major and minor chemical constituents will depend on the geology of terrestrial deposits from which rocks are sourced to manufacture the simulant. In addition, it is very important to obtain mineralogy and chemical composition data, including that of minor and trace constituents that are specific to the production lot of the purchased simulant. Variability in source materials occurs regularly during the production of simulants and the frequency of change varies from vendor to vendor and most vendors can provide such data for each production lot. Minor and trace constituents that are both the result of geologic formation and weathering alterations can become particularly important for certain processes and some are detailed in the sections below.

6.2.1.B.(i) Low Temperatures

The temperature range qualified as “low” in this document is below 100° C and applies to both the regolith simulant during testing and the processing temperature. Some tests aim at extracting water and other volatiles from simulant that are initially at sub-freezing or even cryogenic temperatures. As stated in Section 6.2.1 lunar regolith simulants currently available are often contaminated with adsorbed water and humid air from transportation and previous testing. In the case of low temperature testing, the simulant may have been previously used with ice. In all cases, it is strongly recommended that the simulant be thoroughly dried using the methods described in Section 6.3.1 prior to emplacement in the test environment to ensure that the initial state of the simulant is baselined to a reference condition.

The low processing temperatures typically allow the selection of simulants that may contain terrestrial weathering compounds that will not be thermally released from the minerals. However, careful consideration must be given to the release of such contamination during chemical processing conditions if the extraction is performed in a reacting medium and/or using electrolytic processes. In such cases, the recommended practice is to pre-process the simulant to remove compounds that would not be found in lunar materials. Examples of such removal methods are described in Section 6.3.2.

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6.2.1.B.(ii) High Temperatures

High temperature processing of regolith requires specific knowledge of the chemical composition of the minerals and their availability to the reactions involved. It is therefore important to identify the presence of components that would not be found in lunar materials and can participate in the processing reactions. These components are likely to affect measured yields, and some may react with test hardware and detectors and cause damage. One example is the presence of Cl and F in some simulants that form acidic effluents in reduction reactions of regolith by hydrogen. In addition, experimentation with high temperature processing of regolith in ambient conditions increases the potential of forming oxidation products that would not be formed under lunar conditions. In some cases, oxidation reactions may involve minor components of the complex mineral compositions in simulants that affect yields or lead to the formation of unwanted by-products in the final product. The use of inert atmospheres is often advised to eliminate unwanted reactions in ambient pressure processing tests. In addition, preparation of the selected simulant may be required to remove unwanted impurities such as weathered components by reaction in a reducing environment or calcination/pyrolysis as required.

Key recommendations:

- Obtain full chemical composition data of regolith simulants being considered including minor and trace components to anticipate process reactions at high temperatures.
- 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.

6.2.2 Vacuum Conditions

6.2.2.A Mechanical Operations and Sensor Testing

6.2.2.A.(i) Dry Regolith Tests

Using regolith simulant in a vacuum chamber presents several unique challenges. Not only does the particulate matter poses a risk to the vacuum chamber hardware (pumps and instruments), but the regolith simulant also itself tends to off-gas violently during the pump down process. At laboratory room temperature, the physi-adsorbed water on regolith particles evolves at pressures below 20 torr. This results in soil movement, including spouts that result in airborne particles, that disturbs the compaction and preparation of the soil bed. Several publications have discussed these behaviors in small and large-scale soil beds (Kleinhenz and Wilkinson, 2012). The off-gas disturbances can be mitigated by regulating the pump rates to keep the pressure decay very slow. The exact rates and pressure ranges vary based on the soil bed condition, but circumstantial data about off-gassing are reported in later sections.

Correspondingly, chamber evacuation will result in the removal of moisture from the regolith simulant although this ambient temperature desiccation is limited, and pre-test desiccation is recommended using methods listed in Section 6.3.1.

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6.2.2.A.(ii) Ice-bearing Regolith Tests

Most published tests with ice-bearing regolith simulants in vacuum conditions have been performed with simulants that were frozen with pre-determined amounts of water before being introduced in the vacuum environment. Methods of preparing the regolith simulant, including moisture addition and compaction are found in detail in multiple references (Kleinhenz and Linne, 2013). In this study, the moisture doped regolith simulant was cryogenically frozen in a vacuum environment. Lacking a good method for measuring soil moisture content, in-situ and in a vacuum, the simulant was sampled pre- and post- vacuum to determine desiccation during exposure. This approach is feasible for most laboratories that do not have access to a system capable of producing the ice within the regolith bed under vacuum conditions. It is important to note that the pre-vacuum preparation method will result in a significant difference in the amount of ice present in the regolith between the preparation and the equilibrium state under vacuum before the test begins. This was documented by Kleinhenz et al. (2013) with pre- and post-vacuum sampling of the ice-bearing regolith beds for 3 different simulants. Their results show a decrease in moisture content by an average of 1% regardless of the initial concentration value and significant desiccation of the upper layers of the bed to depths of 20 cm by as much as 50% of the initial moisture value. Recent work by Johnson and Dreyer (2024) examined the mechanisms that lead to the formation of more porous ice-regolith mixtures that can be created in laboratory and may represent geological conditions for such lunar materials. The two test preparations documented above each represent the plausible range of lunar ice-regolith mixed materials that present different challenges for mechanical hardware during testing and are important to consider in designing such tests.

Key recommendations:

- Desiccation of regolith simulants prior to vacuum testing is recommended for tests 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 simulant materials should be prepared in vacuum when possible and their degradation measured or estimated when they are prepared in ambient condition prior to test.

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6.2.2.B Extractive Processing Testing

All considerations described in the section on terrestrial condition testing apply here. Vacuum processing of mineral mixtures adds another level of complexity and new factors to consider for both the choice of simulant and the methods to prepare it.

6.2.2.B.(i) Low Temperatures

Low pressure conditions enhance volatilization of water from ice when the material receives heat from the hardware operations and/or the selected extractive process. Sublimation rates become non-negligible when the test conditions depart from the ultra-high vacuum levels expected in lunar Permanently Shadowed Regions (PSRs) (Piquette et al., 2017). The co-existence of water ice and other volatile molecules in PSR materials was confirmed by the LCROSS measurements (Colaprete et al., 2010) but current data does not indicate whether all these components are within the ice structure thus making it difficult to create representative simulants for such materials. These findings also point to the need for careful selection of the simulant to be used to avoid the presence of non-lunar phases that can produce additional volatiles during extractive processing. If this is not possible, the removal of such unwanted components in the simulant may be warranted using either calcination or reduction methods to prepare the simulant prior to mixing with water ice. The inclusion of other molecules in the manufactured ice should also be based on the current state of knowledge in lunar science.

6.2.2.B.(ii) High Temperatures

Several minerals and impurities that are not found in lunar regolith are very often present in terrestrially sourced regolith simulants and these components evolve, react, and thermally decompose. Gas species such as H₂O, NO, H₂S, CO₂, SO₂, SO₃, HCl, HF have been reported in detail by mass spectrometry under vacuum (Figure 24) by Petkov and Voecks and attributed to a series of thermally activated processes (Petkov, 2023). The evolution of physisorbed water, the dehydration of hydrates, and the reaction of major non-lunar phases (sulfates, carbonates) are common to all terrestrially sourced simulants while lesser-represented components (nitrates, fluorites, chlorites, etc.) are found in some. These complex thermal processes have important impacts for high-temperature tests under low pressures. The associated mass loss during thermal processing ranges from 0.5 to 1% and lead to the generation of a gas stream of complex composition that may be reactive with hardware components such as valves, lines, and pumps. It also leads to physical changes in the processed simulant such as the creation of large and multiple trapped gas inclusions at moderate temperatures (Figure 25) and their eventual release when the simulant is fully molten with low viscosity.

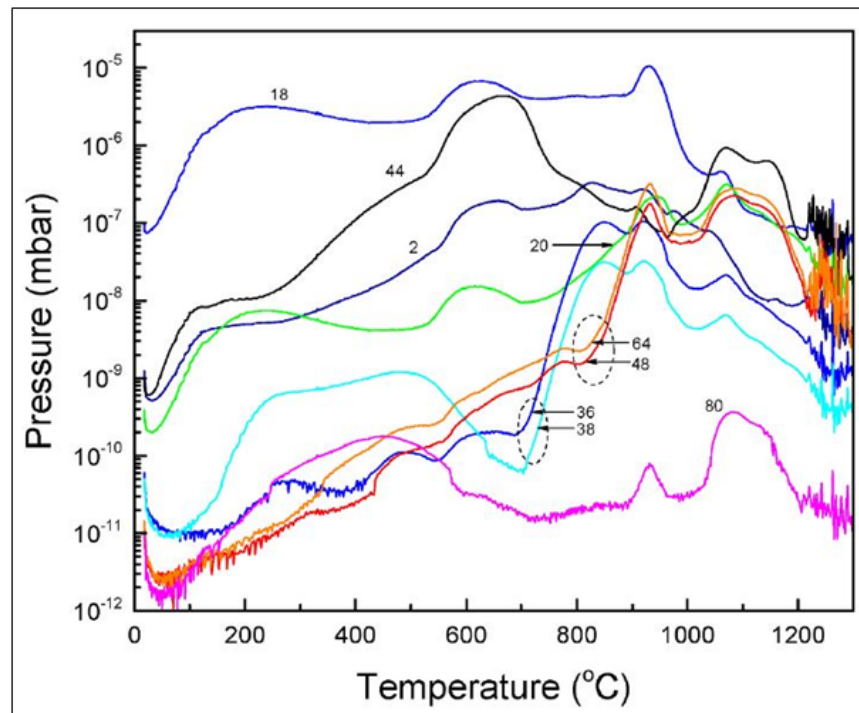


Figure 24. Selected mass spectra traces of evolved species from simulant CSM-LHT-1G as a function of temperature. m/z numerical labels identify H_2 (2), H_2O (18), CO_2 (44), SO_2 (48, 64), SO_3 (80), HF (20), and HCl (36, 38) (Petkov and Voecks, 2023).



Figure 25. Vacuum sintered sample of CSM-LHT-1G displaying voids created by trapped gas during process.

Key recommendations:

- The selection of regolith simulants for extractive process testing under vacuum should be based on high quality characterization data of volatile components for the range of testing conditions.
- The presence of unwanted components (i.e., non-lunar phases) in the selected simulant may require their removal by appropriate thermochemical processing and further characterization prior to testing.

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6.3 Simulant Preparation Methods

As discussed previously, the test objectives and requirements influence the need and selection of specific preparation steps and methods. Nevertheless, several preparation steps are recommended for all types of tests with regolith simulants. Simulant materials must be stored under conditions that minimize or eliminate contact with moist air to avoid water intake and possible weathering over time. This is easily accomplished for small quantities in air-conditioned rooms and sealed containers while large (multi-tonne) regolith outdoor test fields require impermeable coverings and active dehumidification when possible. The preservation of the PSD of the simulant throughout the regolith test volume is an important objective for any test preparation. The PSD of simulant materials does not remain the same throughout the material during transport and subsequent storage in containers due to the upward migration of larger more buoyant particles enabled by vibrations, resulting in size segregation of the stored material. Stored simulant should be homogenized by rolling and overturning the storage containers many times prior to sampling fractions of the material or use of the total amount. Lastly, simulants are subject to physical change even during tests during which they are not destroyed or undergo phase change. Repeated friction against hardware, mixing with contaminants, and loss of fine particles are among such alterations, and it is recommended to measure the PSD of previously used simulant materials prior to re-use and potential contamination should be tracked and recorded by test conductors.

6.3.1 Desiccation

Conceptually, one of the major objectives of simulant preparation for testing is to remove contaminants that are relevant to the test, with moisture being the primary one in almost all cases. Lunar regolith and simulants exhibit similarly low thermal conductivity which limits the effectiveness of bulk drying methods applied to large amount of these materials. NASA-STD-1008 recommends specific protocols for NASA tests the following drying temperature ranges to remove the different types of water from most simulants and achieve the desired level of desiccation for a given test: Physi-adsorbed water (110 °C for 12 hours), surface-bound water (200 °C for 24 hours) in dry circulating air or inert gas ovens; structural water bound in the crystal structure of the minerals represents only 1-2% of the total water but leads to significant reactivity in high temperature processing. It can be removed between 450 °C and 750 °C depending on the simulant under reducing conditions (UHP Argon with 4% H₂) to prevent oxidation of Fe-bearing silicates (Wilkerson, 2023.) Similar removal of structural water has been reported by heating simulant at 10⁻⁵ torr. The selection of a regolith desiccation method will depend on the simulant (including its initial water content and desorption and absorption characteristics), the test environment, and the processing parameters of the regolith operation, and the TRL of the intended test. This guide focuses on the practical aspects of desiccation as important factors to consider for users based on the scale and the objectives of their test campaign.

The capacity of simulant materials to absorb water and their resulting water content vary depending on the weathering processes and their geologic origin that shape them. All of them exhibit some degree of hygroscopicity that requires desiccation to eliminate the surficial water that would not be found in lunar regolith. It is recommended that regolith simulants be desiccated at 200 °C in dry circulating air

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for 2-3 hours (or 110 °C for 12 hours per NASA-STD-1008) to remove the surficial water. This is practical for many test preparations involving a few 10s kg of simulant material but becomes less so when 100s or 1000 kg of material need to be desiccated. Efficient methods employed industrially with granular materials exist that can be applied to regolith such as percolation of heated dry air or other gas through a regolith bed with moisture trapping. Bed fluidization can also be employed but is not typically necessary but may accelerate the desiccation process overall especially for quantities on the order of 2-20 kg.

Circulating air desiccation is also an efficient method that is scalable for large quantities. It is employed by the Planetary Surface Technology Development Laboratory (PSTD L) at Michigan Technological University to dry quantities on the order of 1000 kg (1 t) (Van Susante, 2024). Air is heated and circulated at 62.8 °C over trays of simulant arranged in stacked racks in a closed container allowing for surface drying of the simulant in one large batch. The PSTD L method desiccates simulant for at least 24 hours on standard baking sheets in thin, evenly distributed layers of no more than five centimeters (5 cm) in thickness. This process ensures that the entirety of the material is desiccated relatively quickly compared to being stored only in buckets in controlled atmosphere.

6.3.2 Impurity Removal

Desiccation methods described in Section 6.3.1 remove adsorbed water and other low vapor pressure volatile components. The removal of organic impurities from a simulant is often achieved by calcination at moderate temperatures (300-600 °C) in oxygen-rich environment. The removal of other major non-lunar components found in simulants such as sulfates, carbonates produced by weathering mechanisms can be performed with varying success through their reduction in environments such as He/H₂ mixtures at temperatures up to 800-900 °C.

6.3.3 Freezing

Recent experimental projects have resulted in several preparation methods that need to be considered to obtain ice-regolith materials that represent a range of test conditions. Planetary scientists continue their investigations into the possible formation mechanisms of these icy mixtures in the lunar environment and on other planetary bodies and the creation of such mechanisms remain speculative and elusive in the laboratory to produce materials in sufficient quantities for testing.

Methods for obtaining ice-regolith mixtures range from simple mix-and-freeze techniques in ambient conditions to in-vacuo condensation techniques for water and volatile molecules to obtain inferred lunar shadowed craters concentrations. The mixing of water and simulants in various proportions followed by freezing before test has been employed by many investigators (Gertsch, Kleinhenz, Meurisse, and others) and result in homogenous materials that exhibit very high compression strength and toughness. These properties have often been sought to represent challenging conditions for drilling and excavation tests. However, they produce materials in which pure ice fill the pores of the material structure which may not represent many lunar materials. Recent investigations have demonstrated the sintering of the ice-regolith mixture under mechanical pressure and shown the creation of materials with moderate strength and higher porosity that may be more presentative of geologic formation

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mechanisms (Johnson and Dreyer, 2024). This sintered icy regolith is made by crushing ice at -20 °C in a wall-in freezer. The granular ice is mixed with regolith that has been at the same temperature for a day. The mixture is then processed to become sintered or used as-is to produce a non-consolidated simulant.

6.3.4 Bed Preparation (Layering, Compaction)

The method employed to create a regolith testbed should be selected based on the test objectives and the conditions that must be achieved as discussed in previous sections. The use of desiccated simulant and the recorded measurements of bulk density achieved as a function of depth are recommended for all preparations. The detailed methodology employed by Van Susante (2024) provide a well-documented set of steps to prepare a deep regolith test volume with repeatable consistency in ambient conditions. Grading of deposited simulant layers followed by vibratory compaction and volume and mass measurements can be adapted to obtain desired density profiles versus depth. A regolith testbed for vacuum testing can be prepared using a similar approach in a container prior to moving it into the vacuum chamber. Alternatively, the empty test container can also be evacuated first in the vacuum chamber and the layers of regolith can be emplaced with hoppers and graders and compacted to obtain the desired values under vacuum. This method shortens pumping times and avoids disturbance of the regolith caused by fast pumping rates but it requires additional regolith handling hardware with automation and calibration of the compaction method to achieve the desired relative density since measurements under vacuum may not be possible. The latter method may not be necessary for low TRL experimentation but should be considered to test hardware in regolith conditions that exhibit strength values expected under vacuum conditions as reported by Johnson et al. (Johnson, 1973).

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Appendix A

Acronym List

ACGIH	American Conference of Governmental Industrial Hygienist
AL	Action Level
AoIF	Angle of Internal Friction
APEX	Advanced Planetary EXcavator
AR	Aspect Ratio
ARES	Astromaterial Research and Exploration Science
ASTM	American Standard of Testing and Materials
CLPS	Commercial Lunar Payload Services
COTS	Commercial Orbital Transportation Services
CRS	Commercial Resupply Services
CSM	Colorado School of Mines
DIA	Dynamic Image Analysis
DREAM2	Dynamic Response of the Environments at Asteroids, the Moon, and moons of Mars
FMR	Ferromagnetic Resonance
FoM	Figure of Merit
GHS	Global Harmonization System
GMRO	Granular mechanics and regolith operations
GRC	Glenn Research Center
HA	Hazard Analysis
HCS	Hazard Communication Standard
HEPA	High Efficiency Particulate Air [Filter]
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
ISRU	In-situ Resource Utilization
ISS	International Space Station
JHU-APL	Johns Hopkins University Applied Physics Lab
JSC	Johnson Space Center
KSC	Kennedy Space Center
LD	Laser Diffraction
LROC	Lunar Reconnaissance Orbiter Camera
LRV	Lunar Roving Vehicle
LSII	Lunar Surface Innovation Initiative
M ³ EGA	Mars, Moon, Meteorite Evolved Gas Analysis
MS	Magnetic Susceptibility
MSC	Manned Spacecraft Center
MSDS	Material Data Safety Sheet

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MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NIOSH	National Institute for Occupational Safety and Health
NRC	National Research Council
OPR	Off Planet Research
ORBITEC	Orbital Technologies Corporation
OSHA	Occupational Safety and Health Administration
PAPR	Powered air purifying respirator
PEL	Permissible exposure limit
PNOR	Particulates Not Otherwise Regulated
PPE	Personal protective equipment
PSD	Particle Size Distribution
PSI	Plume Surface Interaction
PSTD	Planetary Surface Technology Development Laboratory
P-T	Pressure-temperature
S&H	Safety and Health
SAR	Simulant Assessment Report
SBIR	Small Business Innovative Research
SDL	Simulant Development Laboratory
SDS	Safety Datasheet
SEI	Space Exploration Initiative
SLOPE	Simulate Lunar OPERations
SRT	Space Resource Technologies
SSERVI	Solar System Exploration Research Virtual Institute
TRL	Technology Readiness level
TWA	Time-weighted average
UHP	Ultra High Purity
UI	User Interface
USGS	United States Geological Survey
UTEP	University of Texas El Paso
xEVAS	Exploration Extravehicular Activity Services
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence