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# The Need for High Fidelity Lunar Regolith Simulants

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# The Need for High Fidelity Lunar Regolith Simulants

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## Abstract

The case is made for the need to have high fidelity lunar regolith simulants to verify the performance of structures, mechanisms, and processes to be used on the lunar surface. Minor constituents will in some cases have major consequences. Small amounts of sulfur in the regolith can poison catalysts, and metallic iron on the surface of nano-sized dust particles may cause a dramatic increase in its toxicity. So the definition of a high fidelity simulant is application dependent. For example, *in situ* resource utilization will require high fidelity in chemistry, meaning careful attention to the minor components and phases; but some other applications, such as the abrasive effects on suit fabrics, might be relatively insensitive to minor component chemistry while abrasion of some metal components may be highly dependent on trace components. The lunar environment itself will change the surface chemistry of the simulant, so to have a high fidelity simulant it must be used in a high fidelity simulated environment to get an accurate simulation. Research must be conducted to determine how sensitive technologies will be to minor components and environmental factors before they can be dismissed as unimportant.

## Introduction

The Vision for Exploration, announced in 2004, has since been formalized by Congressional legislation as the revised U.S. Space Policy. Implementation of this policy is charged to NASA and principally carried out by the Exploration Systems Mission Directorate (ESMD). The two main programmatic elements responsible for this implementation are Constellation, which develops the space flight systems required to carry out human exploration missions, and Advanced Capabilities, which performs the technology development and associated activities required to enable human space flight system development. The Exploration Technology Development Program (ETDP) was chartered to develop enabling and enhancing technologies required by Constellation systems to allow sustainable, affordable human exploration missions. Multiple projects have been created within the ETDP to develop specific technologies, on a prioritized basis, required by these systems. Many of these projects will require lunar regolith simulants in various quantities and, at various levels of fidelity, to verify the applicability of their developed technologies.

NASA has long described the state of an emerging technology by a scale known as technology readiness levels (TRLs) (ref. 1). Table I describes these. The ETDP considers a technology development effort ready to transfer to a flight program after it has achieved TRL 6. What is required in order to bring a technology to TRL 6 is to “test in a relevant environment”. In the past, an environment relevant to the lunar surface has often meant testing the system in vacuum. In most studies vacuum has meant the technologically easy  $10^{-6}$  Torr, but sometimes this has meant almost any reduced pressure or even under an “inert” atmosphere. For example, the Apollo Lunar Roving Vehicle (LRV) wheels were tested at one-sixth gravity in a pressure of a few Torr. Given the nature of the lunar environment as we now understand it and the risks it may pose to astronaut safety and mission success, future simulations of the lunar environment must be much more comprehensive, encompassing not only the vacuum environment, but the thermal, insulative, radiation, charge, and dusty characteristics of the lunar surface as well.

A crucial component of a more comprehensive lunar simulation is a lunar simulant with a more comprehensive set of properties simulated. Lunar simulants have evolved from generic basaltic dusts early in the Apollo program to simulants that more closely mimic the bulk chemistry of the returned lunar

samples. There has also been an increasing emphasis on volcanic glass content and better control over the size and shape distribution of simulant particles. But it is increasingly recognized that the minor constituents of the lunar regolith might affect lunar surface systems to a disproportionate amount over their concentrations. In some cases these minor constituents will introduce complications, but in others the minor constituents may prove to be beneficial. There is also a growing awareness that the surface of the regolith particles may well be altered by the energetic lunar environment, and the changes in surface chemistry may have implications for such surface dependant properties as adhesion and biological activity. The objective of this paper is to explore the need for replicating the minor components and chemically activated surfaces in lunar simulants, and to advocate for a further evolution of lunar simulants to higher fidelity.

TABLE I.—NASA TECHNOLOGY READINESS LEVELS

TRL	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validated in a laboratory environment
5	Component and/or breadboard validated in a relevant environment
6	System/subsystem model or prototype demonstrated in a relevant environment (ground or space)
7	System prototype demonstrated in a space environment
8	Actual system completed and flight qualified through test and demonstration (ground or space)
9	Actual system “flight proven” through successful mission operation

## Lessons Learned from Apollo

Perhaps the most instructive lessons learned from Apollo on the effects of lunar dust comes from the radiators that cooled the batteries on the LRV. These radiators were second surface mirrors with front surfaces composed of fused silica. The lunar dust has a high emittance (about 0.93), so there was little concern about the ability of the radiators to reject heat through a dust layer (ref. 2). However, the dust also has a relatively high absorptance (about 0.76), so there was concern that there would be an additional heat load from solar heating if there was a significant amount of dust on the radiators (ref. 3). These batteries had an operating range of 4 to 51 °C, and operated in an ambient environment that ranged from 24 °C, at the beginning of the mission in Apollo 16, to 64 °C at the end of Apollo 17.

The batteries were located on the front of the LRV, and so were expected to have a fair amount of dust impinging on them. Thus, the design for the battery radiators included dust covers. The plan was for the dust covers to be opened, exposing the second surface mirror radiators to cool the batteries between periods of extravehicular activity (EVA). It was anticipated that despite the precaution of the dust covers, that some dust would still find its way onto the radiators. However, a study by Jacobs, Durkee, and Harris, which utilized lunar regolith returned by Apollo 12 concluded that removing lunar dust from fused silica second surface mirrors with a nylon brush would be effective (ref. 4). This was the strategy utilized to remove the dust from the radiators on all three LRVs for Apollo 15, 16, and 17.

However, as is illustrated in figure 1, the experience on the lunar surface was very different from that which was modeled and simulated beforehand. In Apollo 15 there was good battery cool down between EVA-1 and EVA-2, but after dust found its way onto the radiators, there was essentially no cool down between EVA-2 and EVA-3 (ref. 5). Both batteries warmed to about 47 °C, about 4 °C below their maximum rated operating temperature. On Apollo 16 the batteries only cooled down 11 °C instead of the 28 °C expected, and reached their operating limit at the end of the second EVA. After the cool down

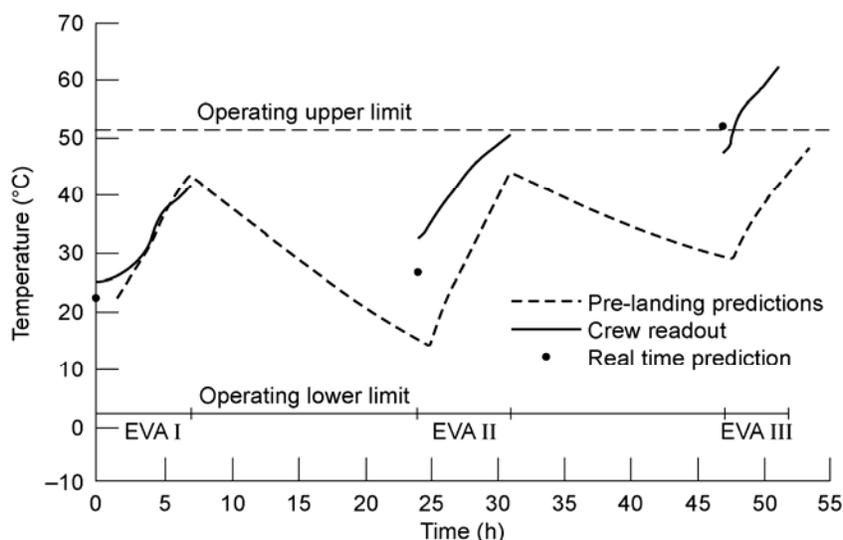


Figure 1.—Temperature Excursions in Apollo 16 LRV Battery 2.

period, at the beginning of the third EVA the batteries had only cooled about 2 °C. At the end of the third EVA the temperature had exceeded the maximum rated survival temperature, as shown in figure 1 (ref. 6). The battery temperature profile on Apollo 17 was similar to that of Apollo 16 and after a little more than 4 hr into the third EVA the batteries exceeded their maximum operating temperature. By 6 hr, the batteries had reached their maximum survival temperature (ref. 7). Apparently, lunar dust under lunar surface conditions is much more adherent than under the terrestrial simulation conditions chosen by Jacobs, Durkee, and Harris. It was inferred that the finest fraction of the dust was not removed by brushing, and solar absorption by these particles accounted for the drop in radiator performance. Since solar heat load is proportional to the fractional coverage, this fine fraction soon covered most of the surface and dominated heat transfer. The lesson here is that the simulation of the lunar environment must be of high fidelity, more than just a simple vacuum chamber, if accurate results are to be obtained.

### Current Lunar Regolith Simulants

Since the total amount of lunar regolith brought to the Earth is only about 380 kg (ref. 8), in order to test the durability of systems to dust in the lunar environment, lunar dust simulants will generally be employed in ground verification tests. Several simulants (table II) have been developed since this activity was started for the Apollo program (ref. 9). These have varied in their composition, particle size distribution, and particle shape.

TABLE II.—LUNAR REGOLITH SIMULANTS

	Basaltic dust		1967
MLS-1	Minnesota Lunar Simulant (mare)	Mare	1988
MLS-2	Minnesota Lunar Simulant (highlands)	Highlands	
JSC-1	NASA baseline simulant (mare)	Mare	1993
FJS-1	Japanese mare simulant with ilmenite	Mare	1998
MKS-1	Japanese mare simulant with ilmenite	Mare	1998
JSC-1A	Mimic of JSC-1	Mare	2006
OB-1	Canadian highlands simulant	Highlands	2007
NU-LHT	NASA/USGS Lunar Highlands Simulant	Highlands	2008
CAS-1	Chinese Academy of Science mare simulant	Mare	---

Which of these simulants, if indeed any of them, is of high enough fidelity to provide a “relevant” environment, in the TRL 6 sense of the term? Rather than do a side-by-side comparison of currently available simulants, it seems rather more productive to address the question *ab initio*. That is, what are the characteristics a high fidelity lunar simulant should possess?

To answer the question in the TRL 6 sense logically leads to the conclusion that the answer depends on the application to be tested. As an example, in order to test out a system that is meant to produce oxygen from lunar regolith, that simulant must have the same fraction of oxygen producing minerals as the regolith. For the hydrogen reduction of ilmenite process the simulant should thus contain up to 16 percent ilmenite to match the high titanium lunar soils that would be the feedstock (ref. 10). In early development testing, simulant with more ilmenite or even pure ilmenite could be used, but for the TRL 6 test, it should be present only in the amounts expected to be encountered on the lunar surface.

If the technology being developed is a system to remove dust from radiator surfaces, the ilmenite fraction may be less important. But for this application the simulant must closely mimic the size and shape distributions of the dust fraction (smaller than 20  $\mu\text{m}$ ) as these will be the most difficult particles to remove, and size and shape are critical to adhesion. In addition to size and shape, hardness, surface chemistry and electrostatic properties are important to adhesion as well.

Not only must a high fidelity simulant have the correct fractions of the component of interest, but also the correct fraction of interfering materials. It was recently reported that an oxygen generating reactor was badly corroded after use because of the presence of minute quantities of fluorine in the lunar simulant used as a feedstock (ref. 11). This result compels an examination of fluorine levels both in the lunar regolith and simulants. Is this an interference that must be planned for, or did the simulant contain higher levels of fluorine than would be expected in lunar regolith? Or perhaps the action of the fluorine was increased by reaction with water in the simulant, which would not be expected in lunar soils.

A fundamental question that must be answered at the onset of any technology development program is, “How good is good enough?” This question is important for both the fidelity of the technology demonstrator, and for the environment in which it will be tested. In the early stages the fidelity might be quite low. In the initial tests of an excavator, digging in beach sand will provide much useful design information. But by the TRL 6 trials, only regolith simulant with the correct geotechnical properties under vacuum and perhaps low gravity conditions will validate the technology. The test conditions will in all likelihood be complex.

The simulant community is coming to consensus that the best approach to high fidelity simulants is to use materials, to the extent possible, of similar composition, size distribution, shape distribution, and bulk density as lunar regolith. An effort is underway under the leadership of the NASA Marshall Space Flight Center to quantify the properties of simulants with respect to standard materials using standard figures of merit (ref. 12). Although the methodology is applicable to any reference material, ultimately simulants must be compared to lunar regolith.

The composition of the regolith samples returned from the six Apollo sites and the two Luna sites have been studied in great detail. These are summarized in the Lunar Sourcebook (ref. 13), and numerous other references. From these studies it is known that about 65 to 90 percent of the regolith is composed of silicate minerals. The largest component is made of plagioclase feldspars  $[(\text{Ca-Na})(\text{AlSi})_4\text{O}_8]$ , followed by pyroxenes  $[(\text{Ca-Fe-Mg})\text{Si}_{12}\text{O}_6]$  and olivine  $[(\text{Mg-Fe})_2\text{SiO}_4]$ . The composition of any high fidelity simulant should similarly be dominated by these minerals. Oxide minerals such as ilmenite  $[(\text{Mg-Fe})\text{TiO}_3]$  and spinels  $[\text{FeCr}_2\text{O}_4, \text{FeTiO}_4, \text{FeAl}_2\text{O}_4, \text{MgTiO}_4]$  are present as well. Although the spinels occur in only trace amounts, they are extremely hard and may be important in abrasion tests. Ilmenite has been found in mare basalts in concentrations as high as 20 percent, but only about 0.5 percent in the highlands. Volcanic and impact glasses can make up from about 7 to 30 percent of the regolith. In addition there are small amounts of native metals  $[\text{Fe}^0, \text{Ni}^0, \text{Co}^0]$ ; phosphate minerals, primarily whitlockite  $(\text{Ca}_3(\text{PO}_4)_2)$ ; and sulfur, primarily in the form of troilite  $[\text{FeS}]$ . Some soils contain small amounts of material high in potassium (generally much less abundant on the Moon than on Earth), rare Earth elements, and phosphorus (KREEP). In addition there are about 100 other minerals present in trace amounts, some of which have not been seen terrestrially. Whether these minor components are required

for a particular high fidelity simulant depends on whether they affect the process or technology being developed. The sensitivity to such minor components must be determined before the TRL 6 trials are carried out, so as to determine whether they must be included in the test simulant.

Lunar simulants are made from terrestrial rock and minerals, and some common components of terrestrial rock are rare or absent in lunar materials. Potassium feldspars [(K-Al)Si<sub>3</sub>O<sub>8</sub>] and silica [SiO<sub>2</sub>] though abundant in terrestrial rock, are rare in the lunar samples. Absent on the Moon (at least in the equatorial regions) because they contain water are micas, clays, and amphiboles. These minerals should likewise be absent from lunar simulants.

## **Minor Components of the Lunar Regolith**

Besides the bulk mineralogy, three classes of minor components not found terrestrially are found in lunar samples which may have major effects on processes and technologies. These are widely regarded as components that must be present in any high fidelity simulant. These are also regarded as important enough that several government and private laboratories are engaged in ways to produce them.

The first of these are lunar agglutinates. Actually, these can hardly be considered a minor component as they can make up as much as 60 percent of some lunar soils (ref. 14). Agglutinates are formed by the impact of micrometeoroids on the lunar surface. These particles measure just micrometers in size, and are vaporized in the Earth's atmosphere, but impact the Moon. A log-linear extrapolation from Christiansen's model leads to the conclusion that about fifty 10 μm size meteoroids per square meter may fall per day on the lunar surface (ref. 15). When a micrometeoroid strikes the lunar surface at a speed of tens of kilometers per second, the subsequent energy release results in impact melting of the upper layer of regolith. In addition to melting some volatiles, implanted solar wind particles (H and He), are released giving the resulting glass a frothy appearance. Iron is also vaporized, but quickly recondenses and forms deposits on surrounding particles. The molten rock also seeps down into the regolith and binds fine particles together in the melt glass.

Below this high temperature region there is an impact shock wave. This shock wave can distort crystal lattices and even fracture the regolith particles, resulting in small sharp shards (comminution). This process has continued for billions of years, such that micrometeoroids strike areas that have been struck many times before. The regolith has thus been subjected to many cycles of agglutination—vaporization—comminution. Such “space weathering” of the soils has happened longer in some areas resulting in some soils being more “mature” than others. The ratio of vapor deposited Fe<sup>0</sup> to Fe<sup>2+</sup> (Fe<sup>0</sup>/FeO) is commonly used as a quantitative measure of soil maturity (ref. 16).

The properties of agglutinates are quite different from mineral grains. They are part mineral, part glass, with many pores in the glassy regions formed by escaping volatiles when the glass is molten. (These are sometimes referred to as “frothy agglutinates”.) This means they have irregular shapes, very high surface area, low density, and low strength. The complex and irregular shapes may enable them to more easily embed in fabric materials than conventional fracture particles. Van de Waals forces between the agglutinates and smooth surfaces may be lower because of smaller contact area. However, electrostatic forces may be higher because the charge distribution will not be evenly distributed, as is seen in irregularly shaped copier toner particles (ref. 17). Agglutinates are mechanically more fragile than mineral grains and so will support less stress. Their complex shapes will also impede flow. Because of agglutinate fragility, tests which mechanically work the simulant may break it down to the point where it may need to be replaced on a regular basis to maintain the integrity of the test. This effect may also have been observed during the Apollo missions when it was noted that the more they tracked over an area, the deeper the loose dust seemed to get (ref. 18).

Much progress has been made recently in the fabrication of artificial agglutinates. Generally these are formed by rapidly heating fine particles either in plasmas or in high intensity lasers followed by rapid cooling (ref. 19). The morphology of these artificial agglutinates is remarkably similar to the lunar agglutinates and some even contain Fe<sup>0</sup> in a similar form. It is anticipated that these will become commercially available in the near future.

A related material found in conjunction with the agglutinates is metallic iron. Iron vapor produced during micrometeoroid impact condenses out and re-deposits onto the surrounding regolith grains. Much of the deposition is in the form of spheroidal Fe<sup>0</sup> particles a few nanometers to over a hundred nanometers in size. These are often trapped in a “rind” of silica-rich glass which coats their surfaces (ref. 20) though some is deposited as a surface layer. Some of the vaporized iron comes from nickel-iron type meteoroids, and so contains a few percent of nickel metal and some amount of cobalt metal as well (ref. 21). To date little has been done to determine how the Ni<sup>0</sup> and Co<sup>0</sup> affect the nanophase Fe<sup>0</sup> properties.

There has been much speculation about how this nanophase iron affects the properties of the dust. The smallest grains are superparamagnetic, and the larger ones ferromagnetic (ref. 22). This has given rise to the proposal to remove the smallest dust particles from surfaces using “magnetic brushes” (ref. 23). This would be most effective for the smallest dust grains since they have the highest surface area to mass ratios and so the highest fractional Fe<sup>0</sup> content. These are also the particles which are in general the most difficult to remove because their adhesion forces are strong relative to their inertial masses. It has also been reported that the nanophase iron enhances the microwave absorption by the dust to the extent that it may be sintered with only a modest input of energy (ref. 24). On the more problematic side, some of the dust grains are small enough (tens of nanometers) to pass through the lungs directly to the blood stream (ref. 25). If those particles contain Fe<sup>0</sup> on their surfaces, they may trigger serious toxic effects (ref. 26). Even if the nanophase Fe<sup>0</sup> is encapsulated in a glassy rind, the thin silica layer can be dissolved in the bloodstream and other biological fluids releasing the toxic Fe<sup>0</sup> (ref. 27).

Much effort has gone into fabricating nanophase iron particles. Two separate proprietary processes have been developed at NASA Glenn which incorporate Fe<sup>0</sup> into a glass rind on the surface of dust grains. These will be detailed in future reports. Some of the agglutinate production processes referred to above also incorporate nanophase Fe<sup>0</sup>. It will be particularly important to include nanophase Fe<sup>0</sup>-doped simulant in toxicological studies, and in developing those technologies which propose to take advantage of either the increased microwave absorbance or magnetic properties. Some resource extraction catalysts may also be sensitive to Fe<sup>0</sup> poisoning. High temperature processing could also result in the formation of iron carbonyl (or analogous nickel carbonyl or cobalt carbonyl) which must be handled carefully because of their extreme toxicity.

Another minor component of the lunar soil is sulfur. The major mineral it is found in on the Moon is troilite (FeS). Nearly all lunar regolith samples contained troilite in compositions ranging up to 1 percent (ref. 28). Troilite is rare on the Earth because some of the Fe<sup>2+</sup> is usually oxidized to Fe<sup>3+</sup>, resulting in the mixed oxidation state mineral pyrrhotite. Small amounts of NiS and CoS are probably found in the lunar regolith as well as the result of gardening of metallic nickel-iron meteoritic fragments in the presence of troilite.

FeS will react during high temperature regolith processing to form hydrogen sulfide (H<sub>2</sub>S) and sulfur dioxide (SO<sub>2</sub>) gases. The sulfur, in whatever form it takes, must be removed in the early stages of regolith processing. It cannot be allowed to pollute breathable oxygen because both H<sub>2</sub>S and SO<sub>2</sub> are toxic. It can also poison catalytic surfaces such as the Fischer-Tropsch catalysts proposed for reforming methane from hydrogen and carbon dioxide or PEM fuel cell catalysts. Similarly, sulfides can react with most noble metal catalysts, rendering them ineffective (ref. 29). The reactivity of FeS may also be used, however, as a resource. For example, many authors have studied the use of FeS to filter out toxic metals from impure water using a cation exchange mechanism. Sulfur compounds have also been proposed as a binder in concrete made from lunar regolith (ref. 30). There may well be other uses for the FeS or elemental sulfur separated from regolith during processing.

## **Effects of the Lunar Environment on the Regolith**

Lunar simulant under terrestrial conditions will not necessarily mimic lunar regolith under lunar conditions. In fact, lunar regolith will not react the same under terrestrial conditions as it will under lunar conditions. The environment of the Earth is humid, oxidizing and relatively protected from high energy radiation by the Earth’s magnetic field and atmosphere. In contrast, the lunar environment is dry,

chemically reducing, and constantly bombarded by high energy electromagnetic and particle radiation. The surface chemistry of any material will be different in these two environments.

The lunar environment is expected to “activate” the surfaces of the regolith particles. Activation includes any process that enhanced the chemical reactivity of the surface. These processes include excitation of the electronic state of an atom, removal of electrons from the surface, or displacement of atoms from their equilibrium lattice positions. Passivation is the process of relaxation of atoms back to the ground state. These processes include collisions with foreign bodies, the emission of radiation, or radiationless relaxation processes.

An activated surface has a relatively large fraction of its surface atoms in activated states. Activated states can result from three basic mechanisms. The first is the ejection of electrons from the surface by light in the ultraviolet or x-ray regions (0.01 to 300 nm wavelengths) resulting in free radicals, that is, atoms with unpaired electrons. These are usually chemically unstable and will react with the first atomic collision after they are formed. The second is the sputtering of atoms off of the surface, which often results in the remaining surface atoms having “dangling bonds”, or unsatisfied valence shells. These are also very chemically reactive. Third, high energy collisions can result in crystal lattice defects, with atomic displacements which can lead to highly strained structures. These highly strained structures are also chemically very reactive.

Work by Sternovsky et al., found that the work function (energy to extract an electron from the surface) of the lunar regolith can be expected to be about 5.8 eV (ref. 31). Typical mineral bonds have energies that range from 3 to 9 eV. Thus any radiation, either electromagnetic or particle, that can impart more than about 3 eV has the potential to activate a surface atom. This implies that light with a wavelength less than 400 nm can break mineral bonds, and light with a wavelength less than 200 nm can ionize surface atoms. This includes a substantial portion of the solar electromagnetic output which falls on the Moon but is filtered out by the atmosphere of Earth.

Figure 2, adapted from Wilson, et al., shows the particle radiation flux density and energy emitted by the Sun into the vicinity of the Moon (ref. 32). A typical mineral crystal will have about  $10^{15}$  atoms/cm<sup>2</sup> of surface (shown as a “\*” in the figure). Extrapolation of the solar wind protons to that value leads to the conclusion that a solar wind proton will strike a surface atom carrying a keV or more of energy each (24 hr) day. Similarly, it will interact with a 1 MeV solar storm proton only about once per millennia, a 100 MeV proton, and a GeV cosmic ray about once every 100 million years. The solar wind protons may have several collisions before they come to rest, and will often become implanted, as evidenced by their release as hydrogen gas from the Apollo samples (ref. 33). These high energy particles may also sputter atoms from the surfaces of the particle, resulting in dangling bonds and lattice dislocations.

The previously discussed micrometeoroid flux on the Moon results in high energy collisions with the regolith, and each collision will result in the fracture of a large number of particles. The surfaces of freshly ground minerals are characterized by the presence of highly reactive free radicals (ref. 34), and since the regolith was formed by impact fracture, they probably form on the lunar surface as well. These fracture surfaces often include “shock structures” which include dislocations and dangling bonds which will be chemically active. Thermal excursions which can be as large as 300 K near the equator will induce thermal stresses which may create new dislocations and fracture surfaces.

So there are many processes to activate particle surfaces. There are not, however, many passivation mechanisms. Under the rarified atmosphere (really a ballistic exosphere) with pressures of  $10^{-12}$  Torr on the day side and  $10^{-14}$  Torr on the night side, there are very few collisions with gaseous atoms that have a chance to relax the active site. Such atoms as do collide will have such low collisional energy that few will be able to heal a lattice defect. As a result, passivation in the lunar environment is expected to be a very slow process.

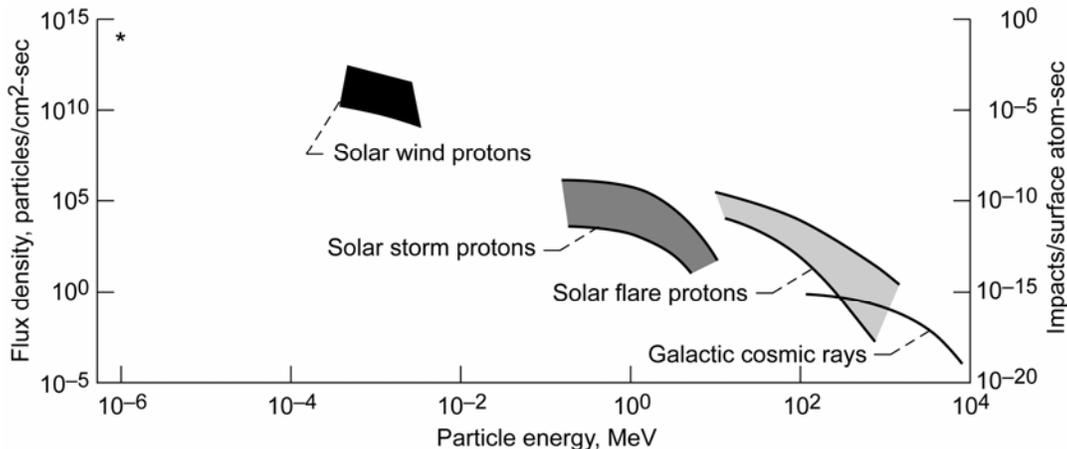


Figure 2.—Impacts per lunar surface atom per second for energetic radiation. Typical density of atoms in a crystal and their binding energy is shown by the “\*”. (Adapted from Wilson, et al. (ref. 25))

There is also some experimental evidence that the regolith exists in an activated state. Grossman measured the cohesion in a porous friable microbreccia in Apollo 11 sample 10065-33 in a vacuum of  $7 \times 10^{-10}$  Torr (ref. 35). Upon cleaving the sample the cohesion between the two pieces was measured to be  $8 \times 10^{-3}$  N. After just four minutes the cohesion dropped to  $2 \times 10^{-3}$  N, and within 15 minutes the forces were too weak to be measurable. This may be due to quenching of activated sites by gas molecules. Although tested at  $10^{-10}$  Torr, the pressure is still two to four orders of magnitude higher than lunar pressures.

Further evidence of regolith activation comes from the Apollo records. Several astronauts remarked that when they first took their helmets off after being on the lunar surface that the lunar dust had a pungent odor, often described as the smell of burnt gunpowder. This smell can be the result of olfactory cells responding to free radicals, such as  $\text{NO}_x$  (which is a stable free radical) which has a pungent odor as well. Further, the lunar curator reported at the Biological Effects of Lunar Dust Workshop in 2005 that “the gunpowder smell went away in a few hours” (ref. 36). This would be consistent with the passivation of free radicals on the particle surface.

## Conclusions and Recommendations

High fidelity lunar regolith simulants will be required to verify the performance of structures and mechanisms to be used on the lunar surface. Minor constituents will in some cases have major effects on the adhesion, abrasion, and toxicity of the lunar dust, thus the definition of a high fidelity simulant is application dependent. The lunar environment itself will change the surface chemistry of the simulant, so a high fidelity simulant must be used in a high fidelity simulated environment to get an accurate simulation. Research must be conducted to determine how sensitive technologies will be to minor components and environmental factors before they can be dismissed as unimportant.

Keeping in mind that the definition of a high-fidelity simulant is application dependant, it is recommended that the steps outlined in table III be considered when choosing or formulating a simulant to test that particular application. First, a careful consideration of how the minor components of the lunar regolith, principally those noted above, could affect the performance of a particular component or subsystem must be made. The performance could be degraded or enhanced. Second, how will the environment alter the surface composition or reactivity of the regolith, particularly the dust, and will that impact the component or subsystem? If the impact may be significant, how will the enhanced reactivity be replicated or accounted for in the simulation. Third, how will the properties of the regolith evolve over

time? Friable particles may be comminuted, and activated particles may generate secondary chemical species or may be pacified.

It is clear that the longer astronauts and the systems they use are exposed to the lunar regolith, the better the interactions between them must be understood if risks to astronaut safety and mission success are to be reduced to an acceptable level. An important part of the risk reduction process is to be able to accurately simulate the affects of regolith on people and systems. And an accurate simulation depends on have a high fidelity lunar regolith simulant, one that contains all relevant minor constituents and surface energy states.

TABLE III.—RECOMMENDATIONS

Identification of application-dependent contributing minor components
Identification of application dependent interfering minor components
Analysis of how properties might change during the mission (i.e., crushing of friable agglutinates)
Identification of surface activation mechanisms
Replication of surface activation states

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<b>14. ABSTRACT</b> The case is made for the need to have high fidelity lunar regolith simulants to verify the performance of structures, mechanisms, and processes to be used on the lunar surface. Minor constituents will in some cases have major consequences. Small amounts of sulfur in the regolith can poison catalysts, and metallic iron on the surface of nano-sized dust particles may cause a dramatic increase in its toxicity. So the definition of a high fidelity simulant is application-dependent. For example, in situ resource utilization will require high fidelity in chemistry, meaning careful attention to the minor components and phases; but some other applications, such as the abrasive effects on suit fabrics, might be relatively insensitive to minor component chemistry while abrasion of some metal components may be highly dependent on trace components. The lunar environment itself will change the surface chemistry of the simulant, so to have a high fidelity simulant it must be used in a high fidelity simulated environment to get an accurate simulation. Research must be conducted to determine how sensitive technologies will be to minor components and environmental factors before they can be dismissed as unimportant.					
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