

## IMPORTANT CONSIDERATIONS FOR LUNAR SOIL SIMULANTS

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### ABSTRACT

Lunar samples are not readily available for In-Situ Resource Utilization (ISRU) studies, necessary for preparations for a return to the Moon with landers, robots, and astronauts. Lunar soil simulants have been produced as substitutes for the real thing; BUT how good are they? JSC-1 and 1A were produced only to approximate the geotechnical properties of lunar soil, with its natural glassy component. This welded volcanic tuff is neither highlands- or maria-like in composition, being at best only half-way between in FeO content, and is only typical of a 2-3 % by area of the lunar surface. Indeed, JSC-1A has the wrong mineralogy [e.g., it has no ilmenite, yet has been used for hydrogen reduction of ilmenite, as well as for as feedstock for several other oxygen-production and ISRU processes.] And largely because of the blessings of NASA in the production of JSC-1, similar lunar simulants have been effectively duplicated by other nations (e.g., China, Japan). The Minnesota Lunar Simulant (MLS-1) was a reasonable hi-Ti mare soil simulant in composition, yet has been abandoned by NASA.

When NASA MSFC got into the lunar simulant business, lunar soil experts repeatedly advised that “one size does not fit all”, meaning that each lunar soil simulant should only be used for very specific purposes. But the education of the engineering community has not been sufficient such that “*high-quality studies are still being performed on the wrong simulants*”. Also, lunar soil simulants are being produced supposedly with certain properties, which are in reality definitely not proper lunar simulants. For example, simulants with nanophase metallic Fe are far from being similar to lunar soils; JSC-1A made with nanophase Fe has an order of magnitude more nanophase magnetite than metallic Fe, so what good is this product? Indeed, most people questioned are not really sure what or why they are trying to simulate nanophase Fe: magnetic susceptibility? Dielectric properties? Toxicity?

A review of the unique properties of lunar samples required for studies in engineering and applied sciences (exclusive of biology) is conducted here. This naturally leads to an evaluation of current simulants and the requirements for simulants that must accurately reflect *all* properties of lunar soils. If not possible to synthesize suitable materials, it may be necessary to use the soils from the Apollo lunar sample collection.

## INTRODUCTION

Since the first return of lunar rocks and soils to Earth in July, 1969, and recognition of the precious nature of these national treasures, there has been a continuous need for lunar regolith simulants for many engineering studies. Noticing that many types of homemade simulants were used by individual groups, the lunar simulant working group (at Space 92) identified the need for large quantities of well-accepted simulants for use in a wide range of studies. Hence, the birth of JSC-1 simulant in the US (McKay et al., 1994). Japan shortly thereafter produced their simulants for mare soils (Kanamori et al., 1998). Since then, the demand of lunar regolith simulant diminished, but was recently revived. With the incentive of returning humans to the Moon and setting up a lunar outpost, the demand for suitable simulants intensified. Since JSC-1 supply was exhausted, the lunar regolith working group (2005) advised production of new lunar regolith simulants and provided funds to different groups for constructing these. In 2008-2009, five soil simulants were produced worldwide. This paper discusses and reviews the unique properties of lunar soils, the principle motivations that the scientific/engineering properties must be address, and how the concept of “One Size Fits All” may be good for K-Mart shoppers, but does not address the needs for lunar simulants.

## UNIQUE LUNAR SOIL PROPERTIES

Lunar soils were made from lunar rocks via physical and chemical processes involving constant bombardment by meteorite and micrometeorite, solar-wind, and galactic cosmic rays. As a result, lunar soils differ from terrestrial rocks and soils in almost every aspect. Particle size and shape, specific gravities, and the glass content of lunar soils can be successfully approximated by most of lunar soil simulants if care is taken to calibrate the simulant against lunar soil. Other properties that have been largely overlooked in the production of lunar soil simulants, but are important in engineering, in-situ resource utilization (ISRU), and toxicity applications are elaborated below.

**Reduced Nature:** The magmatic systems on the Moon have crystallized their rocks in systems with a paucity of free oxygen (partial pressure of  $O_2$  or fugacity of  $O_2$ ), such that metallic iron, that is Fe in its zero-valance state –  $Fe^0$  – is a stable mineral that occurs in all lunar rocks. Therefore, the lunar soil contains this metallic Fe as a component, in addition to the meteoritic FeNi metal from impactors. Besides this highly reduced form of Fe, all remaining Fe is present as  $Fe^{2+}$ . None of this Fe is present in its highly oxidized form –  $Fe^{3+}$ , whereas minerals formed on Earth almost always contain  $Fe^{3+}$ . As a result, apparently similar minerals (e.g., ilmenite) on the Earth and the Moon have quite different magnetic and chemical properties. For example, Taylor & Oder (1991) performed ilmenite beneficiation studies on several Apollo soils, in which they performed quantitative magnetic measurements of the minerals in different size-fractions (e.g., 90-125  $\mu m$ ). Contrary to what would be assumed by most terrestrial geologists, lunar ilmenite has about the same magnetic susceptibility as pyroxene, whereas terrestrial ilmenite is extremely magnetic, largely

because of the presence of  $\text{Fe}^{3+}$  and intergrown magnetite, both absent from the Moon. The beneficiation of lunar ilmenite by magnetics is not feasible.

**Nanophase Fe:** It has been known for over 40 years that all lunar rocks and soils contain metallic Fe as a stable component (review by Taylor and Cirlin, 1984). The majority of this metallic Fe is present as nanophase (np)-size grains, mostly dispersed in the glass of impact-produced agglutinates - aggregates of minerals and rock fragments held together by quenched impact-melt glass. These np-Fe particles were originally called “single-domain” Fe with sizes of 3-33 nm because they possess single-domain magnetic properties. An early model proposed that the formation of the np-metallic Fe in abundant agglutinitic glass involved the auto-reduction of impact-produced melts in the soil by solar-wind implanted protons ( $\text{H}^+$ ) (Housley et al., 1973). They also determined that the majority of the single-domain, np-metallic Fe in agglutinitic glass by size is  $<20$  nm. However, this model did not explain the homogeneous nucleation and growth of the Fe dispersed equally within the glass, nor the apparent lack of detectable  $\text{H}_2\text{O}$ , which should have formed by the reduction of the ‘FeO’ in the melt by the hydrogen. Nevertheless, this auto-reduction formation was considered logical and reasonable for over two decades.

It was only more recently that much of np-Fe was determined to be largely a direct function of space weathering (Keller and McKay, 1993, 1997). The micrometeorite-induced impact melt of the lunar soil does not simply reach its melting point (1200-1400  $^{\circ}\text{C}$ ); it can far exceed this, reaching temperatures  $>2000$ -3000  $^{\circ}\text{C}$ , such that the boiling point is exceeded, whereby some of the more-volatile components are vaporized (e.g.,  $\text{Na}_2\text{O}$ ,  $\text{FeO}$ ,  $\text{SiO}_2$ ). These compounds then dissociate further forming  $\text{Fe}^0$ ,  $\text{SiO}^{+2}$ ,  $\text{Si}^0$ , etc. These vapors subsequently permeate the soil and become deposited as rims on most grains and consist of silica-rich glass, containing myriads of suspended np-Fe particles (e.g., Taylor et al., 2001a, b). These amorphous glass rinds, being brittle, are readily chipped off by ensuing micrometeorite impacts and accumulated in the fine-grained glassy portion of the soil. Slightly larger impacts that melt the soil selectively melt this glass with its np-Fe. The Fe grain size “ripens” somewhat in size producing slightly larger metallic Fe particles, still suspended in glass. Further examples of this amorphous glass with np-Fe have been documented by several other investigations (Wentworth et al., 1999; Pieters et al., 2000; Noble et al., 2001, 2007; Taylor et al., 2001 a,b). Indeed, verification of this vaporization process was discovered in the presence of Fe-Si metallic alloys (Anand et al., 2004), including  $\text{Fe}_2\text{Si}$  – the mineral, hapkeite, named after Prof. Bruce Hapke of the Univ. of Pittsburgh, who proposed the importance of this vapor-deposition process  $>30$  years ago (Hapke et al., 1975). It is this np-Fe in the amorphous glass on the rims of most grains in a mature lunar soil, as well as in the agglutinitic glass, which so drastically affects the spectral reflectance of lunar soil (e.g., Pieters et al., 2002).

**Magnetic Properties:** Despite the small amounts of np-Fe ( $<1$  wt%) in most lunar soils, it bestows properties that are important for ISRU and toxicity investigations and their associated engineering experiments. As emphasized by Taylor et al. (2005, 2009), the presence of a thin ( $\sim 100$  nm) rind of glass containing np-Fe on virtually all particles of a mature soil does not affect large particles appreciably, but the  $<50$   $\mu\text{m}$  size fraction of typical mare soil can be attracted and picked up by a simple hand magnet. With the recognition of this fantastic magnetic

property for almost 50 % of the soil, there have been many designs produced for dust mitigation strategies (e.g., Eimer and Taylor, 2007a).

After the establishment of the major magnetic susceptibility of the fine portion of the lunar soil due to the np-Fe, the senior author of this paper, with a strange curiosity, placed some real Apollo lunar soil in a microwave oven. As subsequently elaborated on by Taylor and Meek (2005), “Lunar soil placed in your kitchen microwave oven will melt at 1200-1400 °C, BEFORE your tea-water will boil.” With this discovery of the ability of lunar soil to couple so well with normal frequencies (2.45 GHz) of microwave energy, and a subsequent patent, numerous lunar applications have been forth-coming. For example, a lunar paver has been designed that can be used to effectively make a landing pad on the Moon for rockets, as well as the construction of roads, habitats, radio-telescopes, radiation shields, heat for oxygen production or melting water-ice in permanently shadowed craters, etc. Several of these techniques will mitigate against the ever-present problems of lunar dust for astronomy, solar-cell efficiency, black-body effect of dust coverings, etc.

**Glass and Agglutinates:** A major component of lunar soils (30-60 %) is impact-formed glass either in splash glass or as major portions of agglutinates. As one of the main components (the major component in mature lunar soil, McKay et al., 1991; Basu et al., 1996), fragile and crushable agglutinates exert significant control on the geotechnical and mechanical properties of lunar soils. Agglutinates typically consist of many vesicles ranging from nm to um size, enhancing the reactive surface area of agglutinate. Last and most important, all agglutinitic glasses contain myriads of np-Fe particles suspended in glass without touching each other, which impart a relatively high magnetic susceptibility to the agglutinitic glass (Taylor and Oder, 1991).

**Lunar Dust:** With the awareness of many problems posed by the pervasive lunar dust, it becomes apparent that the toxicity of lunar dust needs to be addressed before prolonged human settlement on the Moon (Gaier, 2005; Taylor et al., 2005). The lunar dust is the fine portion of lunar soil, which can become airborne in any pressurized environment, e.g., lunar module. Studies on mineralogy of lunar soils by Taylor et al. (2001a, 2001b, 2001c, 2003, 2009) have shown that lunar soils contain increasing agglutinitic glass with decreasing grain size, suggesting lunar dust dominantly consists of the np-Fe rich glass. Given its small size and its highly reactive nature, these minute metal particles could pose threats to human safety (c.f., Liu et al., 2007, 2008a,b; Park et al., 2006a, 2008; Gaier, 2008; Wallace et al., 2009). For toxic studies, np-Fe bearing lunar dust simulants are needed. No natural rocks and soils on Earth have any equivalents to the chemical and physical properties of lunar agglutinates. Therefore, materials with similar abundance and chemistry (i.e., np-metallic iron) to lunar agglutinates need to be added to simulants for engineering, ISRU, and toxicity investigations.

The mining and transportation of lunar soil on the Moon will stir up lots of dust that will be elevated into the exosphere and create serious problems for everything from astronomical observations to coatings on astronaut's suits. Dust mitigation methods are needed to minimize the dust interference of human activities on the Moon. With this in mind and as outlined by Taylor and Taylor (2009), a Lunar Soil MAagnetic Collector (LSMAC) was designed and tested. This is basically a

version of a ‘leaf sucker’, so common in the Fall here on Earth, except that it consists of a tube made of circular magnets that are activated serially (cf., a MAG-LEV train). The lunar soil and especially the dust, are drawn into this tube and is a version of what might be termed a “soil sucker” for a better name (Eimer and Taylor, 2007b).

**No Hydrated Alteration:** Lunar soil lacks any clay or hydrated alteration minerals, which are ubiquitous in rocks and soils on Earth. Rocks on earth, being exposed to Earth’s atmosphere and hydrosphere, experienced variable degrees of weathering so that they all contain small but measurable amounts of clay minerals (minerals with abundant OH and HOH) and other volatile-bearing minerals (e.g., pyrrhotite,  $Fe_{1-x}S$ ). It is customary in the chemical analyses to perform an LOI – Loss On Ignition – by placing a portion of the soil at 950-1000 °C, with weighing before and after. This LOI is mainly water, with lesser amounts of  $CO_2$ ,  $SO_2$ ,  $Cl_2$ , etc. Most of lunar soil simulants were prepared by air-drying the raw materials, which cannot efficiently remove these volatile contaminations. Therefore, oxygen and water production experiments using these simulants may significantly overestimate the production rate. Several investigations of hydrogen reduction of JSC-1A have supposedly formed  $H_2O$ , when indeed, it is the inherent volatiles in the simulant that have been released (JSC-1A has an LOI of 0.5-1.2 wt%; FJS-1 has ~0.5 wt% water).

## **LUNAR SOIL SIMULANTS: STRENGTH AND WEAKNESSES**

Since the Apollo missions, several lunar soil simulants have been manufactured and utilized for engineering, science, and medical experiments. All simulants reasonably re-produce the bulk chemistry (e.g.,  $MgO$ ,  $FeO$ ,  $Al_2O_3$ ) of lunar soils, except for  $Na_2O$ , which is extremely depleted in lunar soils (Figure 1). If carefully prepared and thoroughly tested, the particle size of simulants can be manufactured to be close to lunar soils. Below, we review the history and development of several of these lunar soil simulants, and address some of their pros and cons.

**MLS-1:** The first lunar soil simulant was manufactured in 1969 by Prof. Paul Weiblen at the University of Minnesota (MLS-1) and handed out as key-ring holders at the Apollo 12 conference in January of 1970. MLS-1 was made by crushing and sizing a high-Ti basaltic hornfels from a quarry in Duluth, MN (Weiblen and Gordon, 1988; Weiblen et al., 1990). It had a composition that was similar to the contingency soil sample, 10084, collected by Neil Armstrong during Apollo 11. MLS-1 was ground to a similar grain size as 10084. It lacked one of the major components of lunar soils, namely impact-produced glass, in the form of agglutinates. However, this was solved by dropping crushed MLS-1 through a 30 ft. tall plasma furnace, which melted the particles that then quenched to glass. This glass was then added to MLS-1 and a closer approximation to lunar soil was attained. But, the glass was not a good approximation to the lunar agglutinates, which are very fragile and crushable. However, the major problem with MLS-1 was the lack of consistency in particle size distribution and the overall bulk chemical composition. In addition, MLS-1 was entirely different in mineralogy, with plentiful Ti-magnetite. This stimulant is already out of stock.

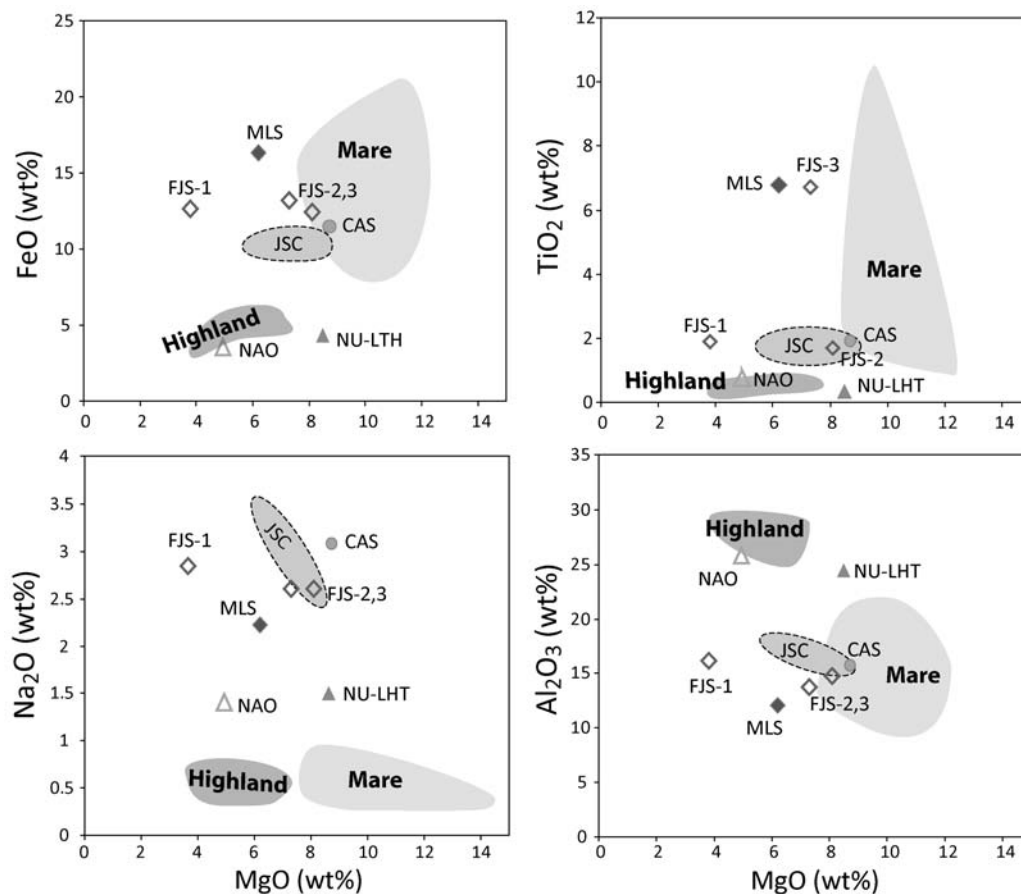


Figure 1. Bulk chemistry of lunar soil and lunar soil simulants. Compositions of lunar soils were taken from Handbook of Lunar Soils (Morris et al., 1983).

**JSC-1:** It was decided in the early '90s that the lunar soil simulant situation had gotten to a critical point, with misuse of several homemade simulants by engineers desperate for something to measure. A special workshop on lunar regolith simulants was held at the Space 92 meeting in Albuquerque. As a result of this, it was decided to produce a lunar soil simulant using a volcanic tuff/ash mined just north of Flagstaff, AZ. This new simulant, with its abundant volcanic glass (~49 wt%; Hill et al., 2007), was originally meant to be used mainly for mechanical engineering purposes. But in the publication of McKay et al. (1994) that documented this product, *it was stated that virtually all its properties fell within the ranges of lunar mare samples*. This statement was probably the single factor that has confused the scientific and engineering community for the ensuing 15 years. Although this simulant does have a bulk chemistry that resembles some Apollo 14 soils, the Apollo 14 mission was not in a mare, and is atypical of the maria of the Moon, and dissimilar from almost all soils from Apollo 11, 12, 15, and 17. The confusion over the compositional properties of JSC-1 led many investigators to assume that it was a typical mare soil simulant, although it has no ilmenite, something common to all mare soils. And it has been used as the simulant for the study of hydrogen reduction of ilmenite, among several other studies for which JSC-1 was inappropriate. This

simulant was dispersed by JSC free-of-charge, and 15 tons of this lunar soil simulant was gone within several years.

**FJS-#:** Three types of mare soil simulants were developed in Japan and produced by Shimizu Corp. (Kanamori et al., 1998). FJS-1 was crushed from basaltic lavas from Mt. Fuji, Japan. Compared to lunar soils, FJS-1 contains lower MgO (Figure 1). Therefore, FJS-2 and FJS-3 were produced by mixing FJS-1 with olivine, and with olivine and ilmenite, respectively, to simulate Apollo 14 and 11 soils. Mechanical properties of FJS-1 simulant were tested by Kanamori et al. (1998), which reasonably agree with those of lunar soils. All three types contain about 0.5 wt% H<sub>2</sub>O as reported by Kanamori et al. (1998). The mineral constituents of these simulants have not been reported. Therefore, it is unclear whether these simulants have abundant glass. No np-Fe was added to these simulants. Although it is good for certain mechanical properties, FJS-1 is not suitable for any in-situ resource utilization investigations such as water production by hydrogen reduction (Yoshida et al., 2000, Sueyoshi et al., 2008) because its chemistry differs from most lunar soils.

**JSC-1A:** In January, 2004, President Bush proclaimed that the United States would return humans to the Moon, in preparation for going on to Mars, and beyond. It instantly became paramount that the engineering community had much to accomplish before this return, particularly learning how to “live-off-the-land”, with In-Situ Resource Utilization (ISRU) taking on a major role. Hence, the immediate need for more lunar soil simulant. The senior author of this paper, as part of a Lunar Dust Program at the Colorado School of Mines, contracted with Dr. James Carter, producer of JSC-1, to deliver more of this same simulant, now called JSC-1A to Golden, CO. After the Lunar Simulant Workshop in January, 2005, ORITEC, through an SBIR contract, had Carter produce 15 tons of this “new” JSC-1A for free distribution to all NASA-funded researchers working on ISRU projects. Some of the JSC-1A was further milled and sieved to produce 1 ton of JSC-1Af (average particle size 27 μm) and 1 ton of JSC-1AC (<5 mm). As a clone of JSC-1, the geotechnical properties of JSC-1A have not been tested thoroughly. In addition, JSC-1A does not have agglutinates and np-Fe, although attempts have been made to simulate the np-Fe. As with its predecessor, JSC-1, this JSC-1A has continued to be used and misused by many.

**CAS-1:** This Chinese simulant was produced to mimic Apollo 14 soil 14163, which is essentially a duplicate of JSC-1. The feedstock is a volcanic scoria with 20-40 vol% of glass from Sihai pyroclastics from Jinlongdingzi Volcano, China (Zheng et al., 2009). The scoria was crushed to produce the desired grain size. CAS-1 is a good duplicate of JSC-1 in terms of bulk chemistry. The mineral abundance in CAS-1 has not been reported. Similar to JSC-1, CAS-1 does not contain agglutinates nor np-Fe. It may be used as a good simulant for its geotechnical properties. It is unclear if this simulant is under production.

**NAO-1:** This Chinese simulant was produced by Li et al. (2009) to mimic Apollo 16 highland soil. Feedstock was a Qunni gabbro from Tibet. Plagioclase (An<sub>95</sub>) was picked from the gabbro and subsequently melted at 1550 °C to form glass, which was mixed with the gabbro to produce compositions similar to the average values of Apollo 16 soils. The mixture was then milled to <100 μm. The reported specific gravity of this stimulant is 2.92 g/cc, similar to JSC-1. The mean and median

particle sizes of NAO-1 are 53-81 and 41-61  $\mu\text{m}$ , similar to Apollo 17 soils. The chemistry of plagioclase and bulk chemistry of NAO-1 are good approximate of highland soils. However, this stimulant has yet to be produced in bulk quantities. The morphology and abundance of glass and their relationship with grain size are unknown. Similar to other simulants, np-Fe was not simulated in NAO-1.

**NU-LHT-#:** Starting with the lunar soil simulant workshop in January, 2005, Marshall Space Flight Center (MSFC) became the overseers of lunar soil simulants, as well as the producers, through collaboration with the United States Geological Survey (USGS). After over 4 years of beaucoup \$\$\$, they have produced at least one lunar simulant, a soil simulant for the highland terrains of the Moon – NU-LHT – of various designs (1M, 2M). NU-LHT is made from rocks (norite, anorthosite, orthopyroxenite, peridotite, and noritic mill Waste) from the Stillwater layered intrusion, southwestern Montana and from Twin Sister dunite, Washington (Lowers et al., 2008). An agglutinate component was produced by plasma melting of mill sand from the Stillwater complex and added to the bulk stimulant. Minor components include chromite, fluoroapatite, and synthetic whitlockite. The abundance of each component has not been reported. Lowers et al. (2008) specified that the abundance of agglutinates for NU-LHT decreases with decreasing grain size, which is opposite to that in lunar soils. In addition, np-Fe was not simulated in NU-LHT simulants. NU-LHT highland simulants are the best that now exist. However, considerable more funds are being spent with “SBIR companies” attempting to produce lunar simulants with different properties – e.g., np-metallic Fe.

**OB-1:** This is a lunar highland soil simulant developed by NORCAT/EVC as a root simulant (Richard et al., 2007; Battler and Spray, 2009). The feedstock is the Shawmere anorthosite from Ontario, Canada, which was then mixed with an olivine slag with an unknown origin. The average composition of plagioclase is  $\text{An}_{78}$ . The olivine slag is composed of purely  $\text{Fe}_2\text{SiO}_4$ . The bulk chemistry of OB-1 and its mineral abundances have not been reported. Battler and Spray (2009) recommended its use for drilling, abrasion and wear applications. OB-1 does not contain np-Fe simulant.

#### **NEED FOR NANOPHASE METALLIC FE IN SIMULANT:**

As discussed above, none of the commercially available lunar soil simulants produced to date contain np-Fe. Attempts have been made to produce np-Fe in JSC-1A. However, results are far from being similar to lunar soils: JSC-1A made with np-Fe has an order of magnitude more nanophase magnetite than metallic Fe, so what good is this product? Why would anyone use JSC-1A as a feedstock to make np-Fe when it already contains plenty of nanophase-sized magnetite? The answer lies in the lack of knowledge of the real lunar soil and an appreciation for single-domain Fe.

Indeed, most people questioned are not really sure what or why they are trying to simulate np-Fe: magnetic susceptibility? Dielectric properties? Toxicity? But, if NASA wants it, by gosh, it must be important. *Lunar-like simulations of np-Fe in silica-rich glass have successfully been produced in the size range observed in vapor-deposited glass coatings and in agglutinitic glass ONLY by Liu et al. (2007) and Noble et al. (2007).* These materials also contain similar magnetic properties to



lunar soils (Liu et al., 2007). Although two-component materials were synthesized in Liu et al. (2007) and Noble et al. (2007), the technique by Liu et al. (2007) has the potential of adaption for more realistic compositions and for generating thin coatings similar to vapor-deposited glass coatings on lunar soil particles. All other np-Fe simulants on the market or in manufacture as of now are not even close to lunar in characteristics. Yet they are out there now for incorrect applications to engineering endeavors.

When NASA MSFC got into the lunar simulant business, lunar soil experts repeatedly advised that “one size does not fit all”, meaning that each lunar soil simulant should only be used for very specific purposes. But the education of the engineering community has not been sufficient such that “*high-quality studies are still being performed on the wrong simulants*”. Lunar soil simulants are being produced supposedly with certain properties, which are in reality definitely not proper lunar simulants. We strongly feel that a warning statement in bold letters should be printed on the label of each lunar soil simulant to read: **THIS LUNAR SOIL SIMULANT SHOULD NOT BE USED FOR ANY ENGINEERING ENDEAVORS WITHOUT THOROUGH LUNAR SCIENCE CONSIDERATIONS!**

### **CONCLUDING REMARKS**

The real engineering needs for lunar samples is quite small, IF the proper lunar regolith simulants were to be produced. However, such simulant production has not always been made with the input of knowledgeable lunar soil experts. This is exemplified by the engineering studies that found bastardized uses for JSC-1 and JSC-1A.

Many of the properties of lunar regolith are not easy to duplicate. For example, with the increased interest in np-metallic Fe, one would naturally ask, “What properties of this unique lunar feature are being duplicated?” This is where the discussion should be centered, NOT on “Let’s make some because an SBIR and/or NASA have an AO [Announcement of Opportunity] out for some np-Fe-bearing simulant!”

The needs for the Apollo samples versus the possibility of producing simulants is the resounding theme of this paper. This naturally leads to an evaluation of the requirements for lunar soil simulants. If not possible to synthesize, it may be necessary to use the soils from the Apollo lunar sample collection.

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