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The Lunar Dust Problem: From Liability to Asset

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ABSTRACT

In-Situ Resource Utilization (ISRU) of lunar materials for the establishment of an extra-terrestrial human base or settlement will involve guarding against, as well as utilizing, the ever-present, clinging, penetrating, abrasive, resource-rich, fine-grained lunar dust. The properties of the fine portion of the lunar soil (<50 μm), its dust, must be adequately addressed before any sustained presence on the Moon can be fully realized; these include: 1) *abrasiveness*, with regards to friction-bearing surfaces; 2) *pervasive nature* as coatings, on seals, gaskets, optical lens, windows, etc., 3) *gravitational settling* on all thermal and optical surfaces, such as solar cells; and 4) *physiological effects* on the tissue in human lungs. The chemical and physical properties of the fine fraction of lunar soil is at the root of the unusual properties of the dust that contribute to its deleterious effects – its *"liability".* Recent discoveries of the unique magnetic properties of lunar mare and highland soils by the senior author's Tennessee group have led to suggested solutions to the liability of the lunar dust. The soil fragments and dust grains contain myriads of adhering nano-sized (3-30 nm) Fe^0 particles, iron in its elemental form, concentrated especially in the fine, dusty fraction. The presence of this ferromagnetic Fe^0 on and in almost every grain of the fine dust-sized particles imparts an unusually high magnetic susceptibility to the particles, such that they are easily captures by a magnet. Furthermore, the presence of these nanophase Fe^0 grains imparts an unusual property to the soil for microwave energy. The microwaves couple strongly with the Fe^0 to such a degree that a sample of Apollo soil placed in an ordinary 2.45 MHz kitchen microwave will literally begin to melt before your tea-water boils. Further considerations of the properties of the fine soil are the basis for the microwave sintering/melting, hot-pressing, and extrusion of the soil to form various construction materials, in order to realize some of the *"assets"* of the soil

I. Introduction

The economic and societal rewards from exporting resource commodities from the Moon to LEO and to Earth, and potentially to Mars, as well as for use at a lunar base or settlement, would appear to be very great if not limitless. In fact, resources from the Moon can have a direct bearing on potentially reducing the cost and extending the longevity of the International Space Station (ISS) or future such stations. The ISS consumption of hydrogen, oxygen, and water can be satisfied by production of these commodities from lunar soil. For example, the production of liquid lunar oxygen (LLOX), liquid lunar hydrogen (LLH), and water involve relatively uncomplicated, well-characterized and researched processes on the Moon[1-5]. The beaming of electrical power from lunar solar cells to LEO and Earth has been examined in detail by Dave Criswell[6]. The potential of a D-^{3}He energy reactor being created and capable of using lunar ^{3}He becomes closer to reality each year, largely through the research of G.L. Kulcinski's team[7-10] at the Fusion Technology Institute (University of Wisconsin-Madison. Even placing astronomy instrumentation on the Moon and the establishment of human habitats are areas of open discussion and planning in many NASA and private circles. But, what do all of these apparent dissimilar activities have in common? *Lunar Dust.*

All these activities on the lunar surface involve utilizing or guarding against the ever-present, clinging, abrasive, resource-rich, fine-grained lunar dust. In fact, the deleterious effects of the lunar dust [defn: fine portion of the lunar soil, herein defined as <50 μm] became apparent with the first lunar excursion (EVA) by Neil Armstrong and Buzz Aldrin during the Apollo 11 Mission and the return of the first lunar samples. The various rocks and soil samples were placed in "rock boxes." These were sealed at 10^{-12} torr on the Moon, only to be found to be at 1 atmosphere when opened in the Lunar Receiving Lab (LRL) at Johnson Space Center in Houston. [Author L.A. Taylor was in the LRL at that time.] The presence of the 'clinging' lunar dust had made the indium, knife-edge seals fail. This dust was so pervasive that no lunar rock boxes from any of the 6 Apollo missions to the Moon ever maintained their lunar vacuum -- they all leaked. Additionally, pressurization of the lunar module used more oxygen after the initial opening of the hatch in order to offset the leaks from the poor seal on closing. The astronauts' suits had considerable dust embedded in their outer fabric, after each EVA, which could not be brushed off. Bearings between the suit gloves and arms and the helmet and neck were visibly scratched around their circumference (no significant increase in leak rate was noted, however.). The inside of the Lunar Module (LM) was temporarily "full of dust," including the atmosphere that the astronauts breathed, as related by Apollo 17 astronaut Harrison H. Schmitt, a co-author of this paper. This cabin dust settled quickly, but was noted again when the LM became weightless after ascent from the Moon before being filtered out by lithium hydroxide (LiOH), carbon dioxide filters. Brushes were used before reentering the LM, but with little effect other than to fatigue the astronauts arms and fingers. Wet wipes were used in the Lunar Module with good effect to clean bearings and visors, and an inefficient vacuum cleaner was employed in the Command Module. The cameras that the astronauts used suffered from lunar dust on the lens, a situation that was tolerated rather than solved. Another example of the deleterious effects of lunar dust involved the friction caused by the extremely abrasive nature of the lunar soil. This dust was responsible for wearing through portions of the outside fabric layers of gloves and lower legs of the astronauts' suits. This extreme abrasiveness of lunar dust must be addressed by engineering design studies before there can be adequate cost analysis for "*in-situ* resource utilization" or other activities on the Moon. Picture the large arrays of solar cells and reflective thermal control surfaces covered with fine layers of dust, reducing their efficiency. The presence of dust on the delicate optical instrumentation of the astronomers and astrophysicists also will need to be countered, although no degradation of laser reflector corner cubes after 35-40 years has been reported. This dust makes up 40-50% of the lunar regolith (soil). Also, recall that the movement and adherence of all particles on the Moon is greatly enhanced by the 1/6-G environment, the hard vacuum, and the extreme dryness that leads to static electricity between soil particles. Some characteristics of the dust lead to significant losses of solar-wind volatile resources merely due to agitation during sample handling[11].

Lunar dust properties that must be addressed before any commercial presence on the Moon can be fully evaluated are: 1) abrasiveness and penetration, with regards to friction-bearing surfaces; 2) pervasive nature as coatings, on seals, gaskets, optical lens, windows, *et cetera*; 3) settling on all thermal and optical surfaces, such as solar cells; and 4) physiological effects on humans, especially with respect to the lungs, lymph system, and heart.

The chemical and physical properties of the fine fraction of the lunar soil – the dust – is at the root of the unusual properties of the dust that contributes to its deleterious effects – its "liability." Armed with a sufficiently detailed knowledge of these fine particles, it should be possible to address and remedy the above-mentioned dust problems. Below, the unique properties of the lunar soil that we already know are addressed. Recent findings have led to the suggested solutions to the liability of the lunar dust. Further considerations of the properties of fine soil form the basis for creating a process of hot-pressing and microwave sintering/melting to form various construction materials on the Moon, in order to realize some of the "assets" of the soil. Microwave heating in-situ or nearly in-situ also may mitigate the problem of volatile losses due to agitation. In fact, the properties of fine portion of the lunar soil, the dust, and many of the principles discussed in this paper are the basis for patents (pending) by senior-author L.A. Taylor and the University of Tennessee for remediation and ISRU of the "Lunar Dust Problem." In this paper, we will outline our proposed approach to this dust endeavor, based upon previous scientific/engineering knowledge derived from extensive studies of Apollo regolith and its finer fraction (<1 cm), the soil.

II. Science of Lunar Soil

Lunar soil is dusty; typically, over 95% is finer than 1 millimeter; about fifty percent is finer than 60 μm (the thickness of a human hair); and 10-20% is finer than 20 microns. The lunar soil particle-size distribution is very broad: 'well-graded' in geotechnical engineering terms, or very poorly sorted in geological terms. In addition, because of the irregular, reentrant particle shapes, the specific surface area is high: approximately 0.5 m^2/g. In fact, lunar soil particles have about 8 times as much surface area as an assemblage of spheres with the equivalent particle size distribution. As a result of both of these factors, lunar soil particles do not pack together as efficiently as, for example, uniform spheres. Even when lunar soil is packed extremely tightly (by a combination of compression and shaking), the porosity is roughly 40 to 50% -- high by terrestrial standards[12].

Lunar rocks, from which the soil was formed, crystallized under such low partial pressures of oxygen (fugacity) that native iron (Fe^0) formed as one of the stable mineral phases in the lunar igneous rocks – e.g., mare basalts[13]. During analyses of Apollo samples, the startling observation was made that the amount native Fe^0 in the lunar soils is about 10X greater than in the rocks from which the soils were derived[14]. At first, it was assumed that this 'extra' Fe metal was from meteoritic sources. However, it was demonstrated that the amount of meteoritic contamination to the soil is only 1% at best, and the meteoritic Fe would be only a small fraction of that. We were to learn of an entirely different type of weathering process than occurs on Earth. It seems that the majority of the native Fe^0 in the lunar soil was formed by *the auto-reduction of the FeO in silicate melts and vapors,* as these were formed by micrometeorite impacts of the silicate minerals in the lunar soil. This reduction was caused by the abundance of solar-wind-implanted hydrogen on and near the surface of every soil particle. This effectively caused the FeO in the impact melt to be reduced to elemental Fe^0 that became supersaturated and *nucleated homogeneously to produce myriads of nanophase-sized (3-33 nm)* Fe^0 particles (abbr: np-Fe^0). This melt quenched, thereby forming the glass that binds together the aggregates of soil particles called 'agglutinates.' Most of this fine-grained np-Fe^0 in the agglutinitic glass is not visible even with the best optical microscope. However, it is the formation and presence of this np-Fe^0 that is at the heart of both the deleterious and beneficial properties of the lunar soil.

A. Formation of Lunar Soil

The major weathering and erosional factors in the formation of lunar soil involve micrometeorite impacts. Larger soil particles are *comminuted* to finer ones; silicate glass, formed by some impacts, welds together soil grains into glassy *aggregates* called agglutinates. These two competing processes complicate the formational characteristics of the soil. Recently, we have become aware of yet another set of processes that significantly affect lunar soils[15-18]. These involve the additional formation of *surface-correlated nanophase* Fe^0, resulting from impact-induced vaporization and subsequent deposition of Fe- and Si-rich patinas on most soil particles[17-19], as well as sputter-deposited contributions[20]. The average grain size of this nanophase Fe^0 is substantially less that that in agglutinitic glass such that it causes the major portion of space weathering effects that negatively affect reflectance spectra[16,17,21].

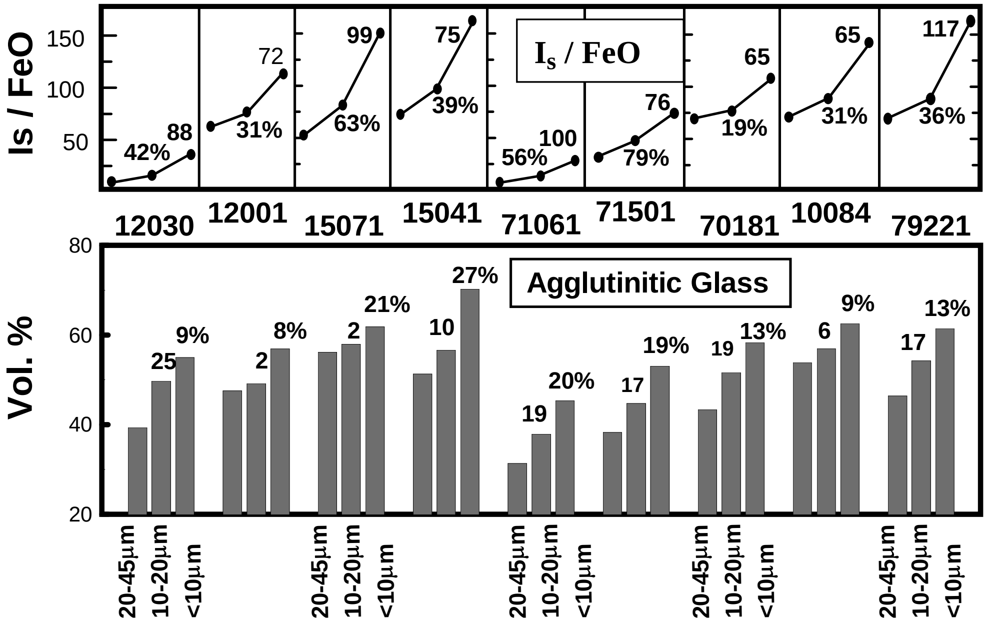

FIGURE 1. Note the change in agglutinitic glass as one goes from a coarser size to a finer size. Likewise for the I_S/FeO values. The agglutinitic glass contents increase gradually, whereas the I_S/FeO values increase dramatically and greatly. Modified after Taylor et al.[27] .

B. Agglutinitic Glass versus Grain Size and Maturity

The amount of np-Fe^0 in a lunar soil is measured by FerroMagnetic Residence (FMR) and designated as “I$_s$”. In order to quantify the amount of iron in a sample that is present as np-Fe^0, this value is divided by the total FeO content of the soil fraction under investigation[22-23]. *The value of “I$_s$/FeO” is used as* ***the maturity index for all lunar soils.*** This value effectively shows the amount of np-Fe^0 that has been formed by the weathering processes, which is a function of the amount of agglutinates in the soil, which increases with exposure time at the surface of the Moon.

Due to the fragile and brittle nature of these glassy aggregates, the agglutinates are readily crushed. It has been demonstrated recently, by quantitative digital-image analysis, that for a given mare soil, *the abundance of agglutinitic glass increases significantly with decreasing grain size*, as also evidenced by the I$_s$ /FeO values, which increase with decreasing grain size. As shown in Figure 1 by Taylor[17-18] and by Taylor et al.[24-27], the percentage increase in agglutinitic glass, from the larger grain sizes to the smaller size fractions is only on the order of 10-15%, whereas the I$_s$ /FeO values change by about 100%. That is, *with a decrease in grain size, the change in agglutinitic glass content is relatively small compared with the change in I$_s$/FeO.* This logically leads to the conclusion that **the large increase in I$_s$/FeO is direct proof of the presence of another source of nanophase Fe^0**, in addition to the agglutinitic glass.

C. Surface-Correlated Nanophase Fe

The thesis on vapor-deposited patinas[18] has also found supporting evidence in several subsequent studies[16-17,19,28]. ***The presence of nanophase Fe^0 in the vapor-deposited patinas (rims) on virtually all grains of a mature soil provides an additional and abundant source for the greatly increased I$_s$/FeO values*** **(Fig. 2).** In fact, for grain sizes of lunar soils <50 μm, the amount of np-Fe^0 on the surfaces is large, possibly equal to that in the agglutinitic glass in these fine grain sizes. The brownish patinas are clearly observable on the walls of large, exposed vesicles in melt breccias, as observed by author H. H. Schmitt at Apollo 17 Station 6, and are temporarily removed locally by micrometeorite impacts.

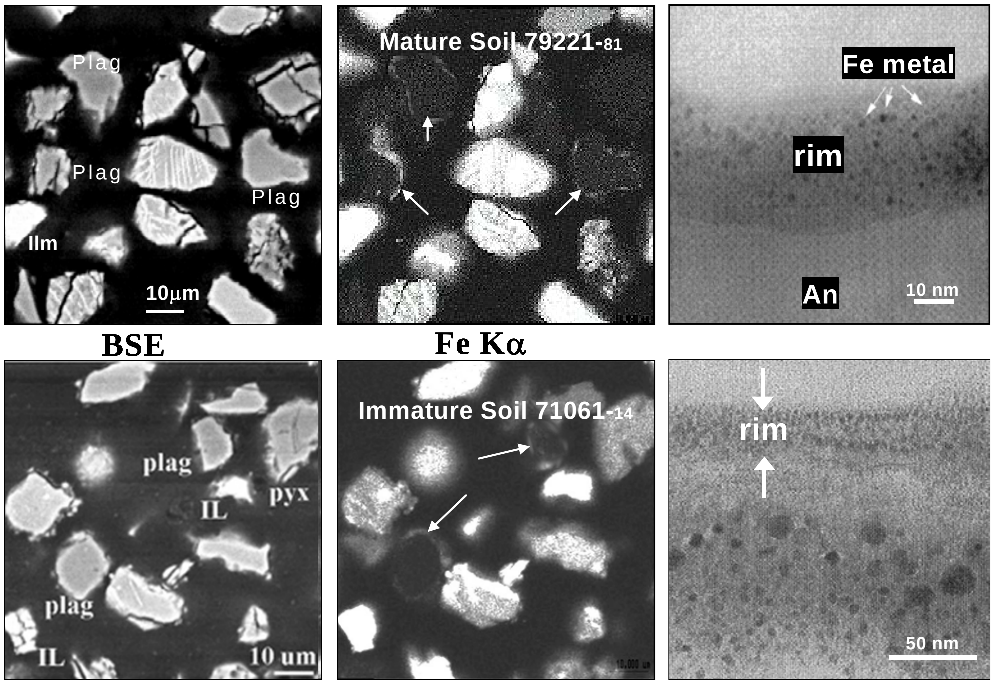

FIGURE 2. *Note the plagioclase grains ($CaAl_2Si_2O_8$) in the Back-Scattered Electron (BSE) image (left). In the Fe X-ray map (center), a thin Fe rim is present on these plagioclase grains, giving them a significant bulk magnetic susceptibility. Both mature (79221) and immature (71061) soils have vapor-deposited coatings on rims of most grains. The TEM images (right) show the fine-grained nature of the nanophase Fe^0 on the plagioclase (An) grains. Modified after Pieters et al.[16].*

D. Magnetic Separation of Lunar Soil Particles:

Taylor and Oder[29] and Oder and Taylor[30] performed studies on lunar soils in order to determine the optimum conditions for the beneficiation of soil components for *in-situ* resource utilization (ISRU) at a lunar base or settlement. Using a Frantz Isodynamic Separator, specifically calibrated for susceptibility measurements, they studied various size fractions of hi-Ti and low-Ti mare soils, as well as soils from the highlands. They were able to successfully beneficiate soil particles in the 90-150 μm size range. But the efficiency of the magnetic separation decreased with smaller grain sizes, down to about 45 μm. With smaller size fractions, real separation and beneficiation were not considered feasible at that time. It appeared that 'clumping' of these fine-grained particles was responsible and the susceptibilities were all high, with no effective diamagnetic splits possible. This was not of importance at that time, since it was the coarser particle sizes that were the focus of their studies. In retrospect, it is apparent that these <50 μm size fractions behaved as if virtually most of the particles had relatively higher magnetic susceptibilities than the coarser particles. In fact, this behavior is now explainable, with our new knowledge, in that each of these fine-sized grains contains a surface patina of ferromagnetic nanophase Fe^0.

Recent experimentation by the senior author with the 10-20 μm fraction of mature hi-Ti mare soil, 79221, has shown that a hand magnet will easily attract practically all the grains, even those that are plagioclase with a thin patina of np-Fe^0. According to Taylor[18], this fine fraction, along with the high-magnetic susceptibility agglutinitic glasses from coarser sizes, can be easily beneficiated from the lunar soil to make a good feedstock for conventional, microwave, or hybrid-heating "hot pressing" with sintering/melting. This feedstock would consist of glass and fine-grained soil particles with abundant np-Fe^0 both in and on the glass, as well as on the surfaces of individual mineral grains.

III. Dust Abatement

Below, we will address considerations and suggestions for the abatement of lunar dust and then demonstrate that the same unique properties that aid the effective management of the dust can also prove extremely beneficial for ISRU purposes.

The relatively large amounts of np-Fe^0, particularly in the <50 μm portion of the lunar soils, provides the effective means for the elimination of dust from many surfaces, where it would have deleterious effects – e.g., on solar cells, seals, lens, windows, even in breathing air[28]. When discussing the discovery of the high magnetic susceptibility for the lunar dust, Harrison Schmitt said to the senior author, "Just think what a brush with magnets attached would have done for us on the Moon."

A. Magnetic Handling of Lunar Soils:

The ferromagnetic properties of the dust portion of the lunar regolith present special challenges and opportunities for dust mitigation, as well as handling, processing, and beneficiating lunar soil for recovery and manufacture of useful products. For example, it may be extremely desirable to segregate the lunar soil into different size fractions at an early stage of processing. Sieving or cycloning such a material would be the usual process on Earth, but these methods normally require a water slurry, which is probably not practical on the Moon, although a "gas slurry" may be. Particles in the fine-fraction of the lunar soil are magnetic [described above], but normal magnetic separation is impractical, because the material just clumps together[29]. New, less conventional techniques must be investigated as part of an air-filtering system at a lunar base or fluidization during processing for volatile extraction.

There is another technique, called "high-gradient magnetic separation" that should be applicable here. In this method, the material to be segregated is passed through an open matrix of metallic material (such as steel wool) inside a powerful magnet. The matrix creates locally high gradients in the magnetic field, which attract and trap fine particles in the approximate size range of the wire diameter of the matrix, while allowing coarser particles to pass through (note that this is the *opposite* of sieving). By having different matrices, it is possible to segregate the raw material into different size fractions. When the matrix material is "saturated", the magnetic field is turned off, or the matrix is mechanically removed, and the particles fall off. Normally high-gradient magnetic separation is done in a water slurry, such as in the kaolin industry, which annually processes many millions of tons of clay. However, because there is no atmosphere on the Moon, it may be possible to process the soil without a working fluid. This same technique of high-gradient magnetic separation, using a steel-wool matrix, is being investigated as part of an air-filtering system at a lunar base.

B. Lunar Dust Inhalation:

It would seem almost unnecessary to state that a detailed study of the effects of lunar dust upon human physiology is paramount. The objective of a necessary *in vitro* study would be to determine whether lunar dust can elicit an acute inflammatory response in rat alveolar macrophages, monocytes, and neutrophils. An acute inflammatory response would reflect that the cells bound the moon dust and ingested them, and were capable of eliminating them by apoptosis.

Unlike silica, there is a paucity of information on the biohazards of moon dust in a literature search of PubMed. Although moon dust consists of minerals and glasses with several major-elemental contents, it may be more like amorphous silica, such as glass or fibrous glass, which has not been shown to be fibrogenic. However, it is entirely possible that the extremely fine-soil particles may cause a fibrogenic reaction, pass into the blood stream, or enter the lymphatic system. To our knowledge, no research has been conducted on the effects of lunar dust on humans using real lunar samples, but only with grossly inadequate lunar soil simulant. It could be beneficial to this end if NASA would procure agreements with living lunar astronauts, and local jurisdictions, for specialized autopsies of their respiratory systems at the time of death.

IV. Lunar Dust For ISRU

It is apparent that the in-situ resource utilization of the fine fractions of the lunar soil, some 50% by mass of the regolith, holds great potential for most lunar material needs, which have been the subjects of numerous studies. The solar-wind content of a given lunar soil is >80% within the dust, being largely a function of grain surface. The dust is the place to go for maximum recovery of hydrogen, helium, etc. from embedded solar-wind particles. The abundance of glass in the different size fractions of the soil increases dramatically in the dust portions, reaching amounts >>50%, up to 80%. It is this glass content that aids the sintering of soil to form bricks, etc. A recent discovery of the effects of microwave energy upon the unique properties of lunar dust by Taylor and Meek[31] is among the latest factors to be incorporated into the ISRU of lunar regolith.

A. Microwave Sintering/Melting of Lunar Soils for Construction Materials.

It has been demonstrated by Taylor and Meek[31] that microwave energy can couple to a high degree with the nanophase-sized metallic Fe in the glass of the lunar soil to generate temperatures >1000 ^{o}C within a few minutes. This unexpected discovery opens the door for innumerable applications for the ISRU of lunar soil, although net cost studies that include power generation have yet to be done. For example, microwave melting and selective phase melting of lunar materials could also be used either in the preparation of ceramic materials with simplified geometries (e.g. bricks) and with custom-tailored microstructures, or for the direct preparation of hermetic walls in underground structures. It is also important to note that heating lunar regolith via microwave radiation may be a an effective technique of collecting solar-wind implanted gases, such as hydrogen and helium-3, with high net efficiency. In addition, a 2-meter-wide microwave unit moving over the lunar soil could effectively produce a "paved road" consisting of sintered/melted soil. Processing of pre-molded soil can *produce strong structural components*. Melting of the mare low-viscosity soil for *blowing glass wool or pulling of glass fibers*. Due largely to the presence of np-Fe^0 in lunar soil, the advantages of using microwave radiation for processing are immense.

Table 1. Benefits of Microwave over Conventional Heating.

- Rapid Heating Rates [1000^0/min]
- High Temperatures [2000^0C]
- Enhanced Reaction Rates {Faster Diffusion Rates]
- Faster Sintering Kinetics [Shorter Sintering Times]
- Lower Sintering Temperature [Energy Savings]
- Taylored Microstructures [Improved Mechanical Properties]
- Considerably Reduced Processing Time
- Process Simplicity
- Less Labor

B. Microwave versus Conventional Heating

Due largely to the presence of np-Fe^0 in lunar soil, the advantages of using microwave radiation for processing are immense. As listed in Table 1[31], a comparison against normal conventional heating (large resistance-driven) shows that microwave heating of lunar soil has many distinct perks, the bottom line of which is that of *large energy savings for the ISRU activities on the Moon.*

V. Summary

The problem of lunar dust is not well-appreciated, but is of paramount importance for any considerations of commercialization of the Moon relative to resource recovery, engineering design, operational procedures planning, and occupational medical practice. The liabilities from lunar dust can be mitigated and potentially eliminated by using the unique features of the ferromagnetic np-Fe^o in the agglutinitic glass and importantly, in the vapor-deposited coatings on virtually all mineral and glass phases in the lunar soil.

With the beneficiation of the fine portions of the lunar soils, it will be possible to form various structural and mechanical products by hot-pressing and sintering, both by normal heat treatment and by microwave processing. It also may be possible to efficiently extract solar wind volatiles from regolith fines by such processing.

The lunar soil is the best material for immediate use for ISRU purposes in the immediate vicinity of and on the Moon. However, studying the precise properties of the fine fraction of the lunar soil, the portion of particular interest here, is not possible with any known lunar soil analog (e.g., MLS-1; JSC-1, etc.). Each simulant has properties "like" but not identical to the lunar soil. In particular, the ubiquitous presence of nanophase Fe^0 (3-10 nm) in the glass of the soil and present on the surfaces of almost all grains is such a fine-scale feature that it is virtually impossible to duplicate exactly with a simulant. Fortunately, we have the necessary lunar soil (with NASA permission for ISRU purposes) to investigate the coupling of nanophase elemental Fe in and on the soil particles and have performed preliminary experiments with the soil. The 80 grams of Apollo 17 soil that has been allocated to the senior author, Larry Taylor, is the only real feedstock with which to study the microwave sintering of lunar soil. This has been amply indicated in the discussion above of the unique properties of the lunar soil that make all lunar soil simulants insufficient for the proposed studies.

Acknowledgments

This paper is dedicated to the scientists and engineers, astronauts and support personnel, and all persons making up the "lunatics" who have been continuously preparing [i.e., >30 years] for a return to the Moon and establish of a human settlement. It has been a long wait, but now is the time.

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