

MICROWAVE PROCESSING OF LUNAR SOIL

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The unique properties of lunar regolith make for the extreme coupling of the soil to microwave radiation. Space weathering of lunar regolith has produced myriads of nanophase-sized Fe⁰ grains set within silicate glass, especially on the surfaces of grains, but also within the abundant agglutinitic glass of the soil. It is possible to melt lunar soil (i.e., 1200-1500 °C) in minutes in a normal kitchen-type 2.45 GHz microwave, almost as fast as your tea-water is heated. No lunar simulants exist to study these microwave effects; in fact, previous studies of the effects of microwave radiation on lunar simulants, MLS-1 and JSC-1, have been misleading. Using real Apollo 17 soil has demonstrated the uniqueness of the interaction of microwave radiation with the soil. The applications that can be made of the microwave treatment of lunar soil for *in-situ* resource utilization (ISRU) on the Moon are unlimited.

INTRODUCTION

The chemical and physical characteristics of lunar soil, the fine fraction (<1 cm) of the lunar regolith, are at the root of the unique properties of this abundant resource on the Moon. Below, these characteristics of the lunar soil are addressed as they make the soil an effective feedstock for microwave processing. Considerations of the science of the properties of fine lunar soil, coupled with the physics of microwave radiation, form the basis for our creating processes for the microwave sintering, hot-pressing, and melting of this soil. Combining both conventional and microwave into hybrid heating can be used to form various structural and mechanical materials for use both on the Moon and in microgravity space. This will allow the effective manufacture of everything from roads on the Moon to parabolic antenna dishes for transport to near lunar orbit (e.g., L1), indeed, materials for construction in space.

SCIENCE OF LUNAR SOIL FORMATION AND CHARACTERISTICS

Lunar soil is generally fine-grained with over 95 wt% less than 1 millimeter; fifty percent is less than about 50 μm (the thickness of a human hair); and 10-20% is finer than 20 μm. The lunar-soil particle-size distribution is very broad: 'well-grade' in geotechnical engineering terms, or very poorly sorted in geological terms [1]. In addition, because of the irregular, reentrant particle shapes, the specific surface area is high: approximately 0.5 m²/g. In fact, lunar soil particles have about 8 times more surface area than 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 [2].

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Formation of Lunar Soil: The major factor in the formation of lunar soil involves micro-meteorite impacts. The rocks are broken into smaller pieces, however, additionally with formation of considerable glass (typically 40-75%) from impact-produced melting. Thereby, two competing processes are operative: comminution of larger soil particles into smaller ones, and agglutination, where silicate melt welds together soil grains into glassy aggregates [3-4]. These two competing processes complicate the formational characteristics of the soil, as shown in Figure 1. The lunar soil consists basically of the disaggregated pieces of the rock (i.e., minerals), but with a large component of impact-produced glass. Although there is some native Fe (elemental Fe⁰) in lunar rocks, the amount of native Fe⁰ in the soils is at least 10X greater than in the rocks from which the soil was formed [5-6]. At first, it was assumed that this was meteoritic metal. However, it was demonstrated that the amount of total meteoritic contamination to the soil is only about 2% at best. It was reasoned that the majority of the native Fe⁰ in the lunar soil was formed by the auto-reduction of the FeO in the silicate melts formed by micro-meteorite impacts [e.g., 7]. It is the presence of solar-wind implanted protons (hydrogen nuclei) on the surfaces of all lunar soil particles that drives the reduction. The FeO in the melt is essentially reduced to elemental Fe⁰ that homogeneously nucleates into myriads of nanophase-sized (3-33 nm) Fe⁰ (abbrev: np-Fe⁰).

This impact-generated melt quenches, thereby forming the glass which binds together the aggregates of soil particles called 'agglutinates.' Most of this fine-grained np-Fe⁰ in the agglutinitic glass is not visible with even the best optical microscope, but it gives a strong magnetic susceptibility signature to the fine fraction of lunar soil. np-Fe⁰ in the agglutinitic glass is not visible with even the best optical microscope, but it gives a strong magnetic susceptibility signature to the fine fraction of lunar soil.

Ferromagnetic resonance (FMR) is used to measure the signal from the np-Fe⁰. This value, designated as I_s, is further divided by the total FeO content of the sample in order to normalize out the differences in total iron contents of different samples. Effectively, the value *I_s/FeO designates the amount of iron in a sample that is in the native Fe⁰ state, relative to the total iron* [e.g., 8]. This value was been routinely determined on

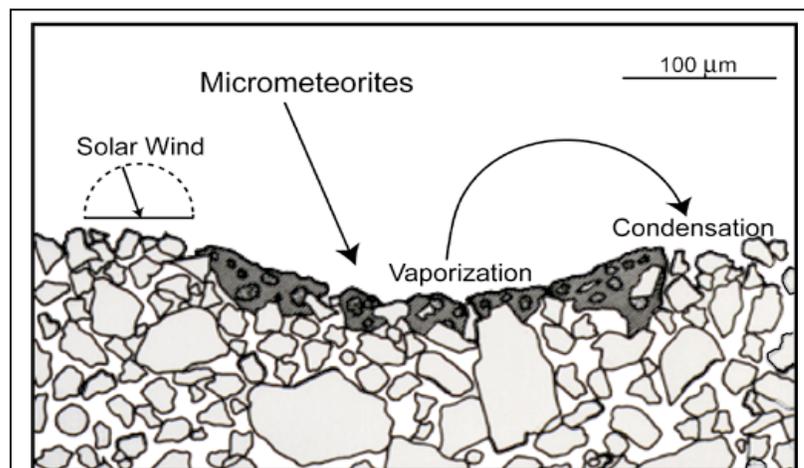


Figure 1. Schematic diagram illustrating the processes of comminution, agglutination (dark grains), and vaporization in the soil-forming processes on airless bodies [6].

all soil samples and many brecciated rocks since the early '70s continuing on to today, virtually all measurements performed by Dr. Richard Morris at Johnson Space Center. The value of I_s/FeO has been determined to be largely a function of the abundance of agglutinitic particles in a soil, at least for the $>45 \mu m$ fraction. Because the abundance of agglutinates is reasoned to increase with a soil's exposure to space weathering at the lunar surface, this I_s/FeO value has been taken, for the $<250 \mu m$ size fraction, as the **maturity index** for lunar soil. **Immature** soils have I_s/FeO values of 0-30, **Submature** from 30 to 60, **Mature** above 60, somewhat arbitrary divisions, but accepted by all lunar soil investigators [9-10].

Agglutinitic Glass versus Grain Size and Maturity: It has been demonstrated [11] that for a given mare soil, **the abundances of agglutinitic glass increase significantly with decreasing grain size**, as evidenced by the I_s/FeO values that increase with decreasing grain size. Recall that the maturity index, I_s/FeO , is an indication of the amount of $np-Fe^0$. As shown by Taylor et al. [12-13] in a study of selected mare soils and illustrated in Fig. 2, the percentage increase in agglutinitic glass, from larger grain sizes to the smaller size fractions, is only on the order of 10-15%, whereas the I_s/FeO changes 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 strongly suggestive of the presence of another source of nanophase Fe^0 , in addition to that in the agglutinitic glass**.

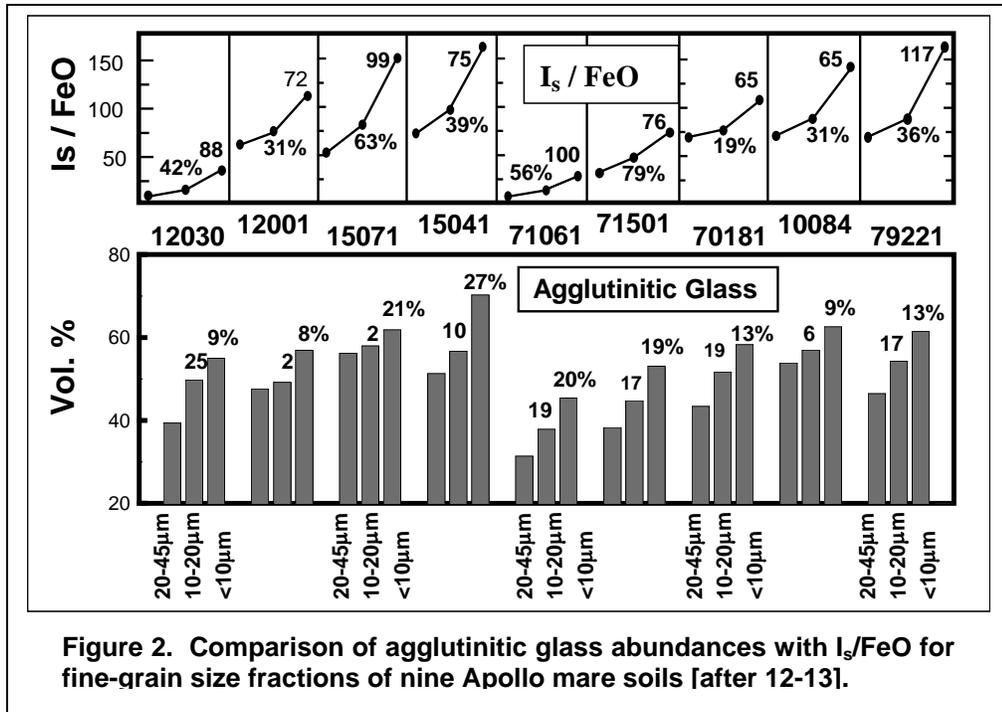


Figure 2. Comparison of agglutinitic glass abundances with I_s/FeO for fine-grain size fractions of nine Apollo mare soils [after 12-13].

Recent discoveries [e.g., 14-17] have been made of another major source of $np-Fe^0$ present in thin patinas ($<1 \mu m$) on the surfaces of many lunar soil particles. Most of this $np-Fe^0$ formed by deposition of vapor also produced by the abundant and intense micrometeorite impacts. A smaller portion may have formed by radiation damage [18].

However, the exact mechanism of formation of the Fe^0 , although not well understood, was predicted long ago by Hapke et al. [19].

Surface-Related Nanophase Fe^0 : The thesis on vapor-deposited patinas [e.g., 15, 20-21] has also found supporting evidence in our recent studies [e.g., 12-13, 22-24]. The BSE and X-ray maps shown in Figure 3 show that even plagioclase grains ($\text{CaAl}_2\text{Si}_2\text{O}_8 - \text{NaAlSi}_3\text{O}_8$) contain thin rims with appreciable Fe contents. The other mineral grains also contain Fe-rich rims, but the sensitivity of the $\text{FeK}\alpha$ map in Figure 3 is not sufficient to show this. It would appear that ***the presence of nanophase Fe^0 in the vapor-deposited patinas (rims) on virtually all grains of a mature soil provides the additional and abundant source for the greatly increased I_s/FeO values***, and as a side-note, causes the severe complications in the reflectance spectra of the Moon [20, 25-27].

Magnetic Separation of Lunar Soil Particles: Several studies have been performed 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 [4, 28-30]. Using a Frantz Isodynamic Separator, specifically calibrated for susceptibility measurements, Taylor and Oder [31] studied various size fractions of hi-Ti and low-Ti mare soils, as well as some from the highlands. They were able to successfully

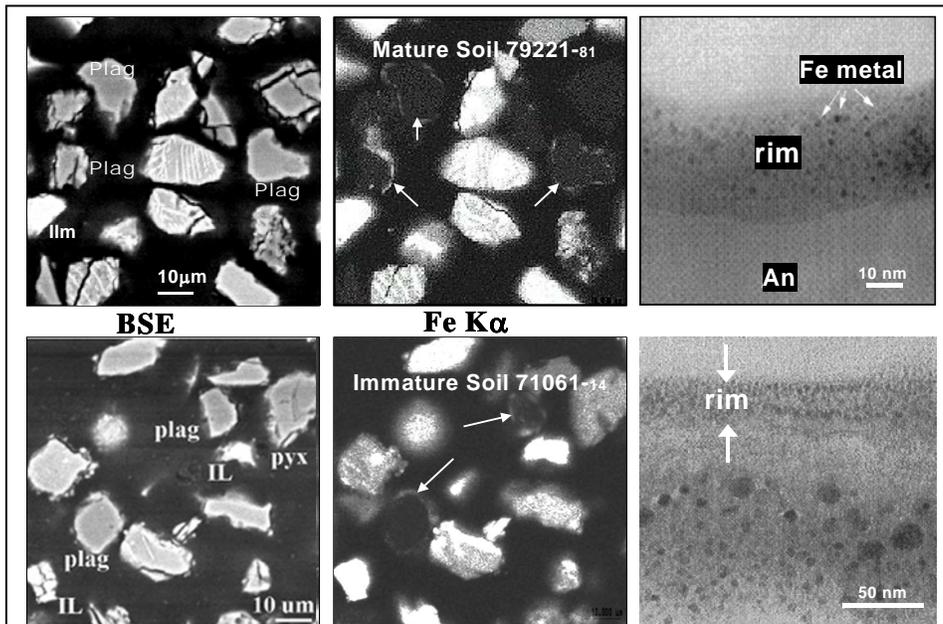


Figure 3. Back-scattered electron images (BSE), $\text{FeK}\alpha$ X-ray maps, and TEM photos of particles from mare soils. The BSE image is a factor of the average atomic number of each phase; the $\text{FeK}\alpha$ X-ray map shows slight rims of Fe about the plagioclase grains, which do not contain appreciable Fe (<0.3%); and the TEM photos show the nature of the vapor-deposited rims of typical lunar grains that contain np- Fe^0 within a thin layer of SiO_2 -rich glass [16, 20, 23-24]. Note that the lower-right photo is that of an agglutinate where the differences in the relative sizes of the np- Fe^0 are clearly visible, with the vapor-deposited Fe^0 in the rim.

beneficiate the soil particles with decreasing efficiency as grain size decreased, down to 45-20 μm . With sizes $<20 \mu\text{m}$, they determined that separation was not possible. It appeared that 'clumping' of these fine-sized grains was responsible. It was suspected that this fine-grain size was probably hygroscopic, causing the clumping. It is now apparent that this size fraction behaved as if virtually all the particles had relatively higher magnetic susceptibilities than the coarser particles. In retrospect, this behavior is now explainable, with our new knowledge, that each of these fine grains contains a surface patina of ferromagnetic nanophase Fe^0 .

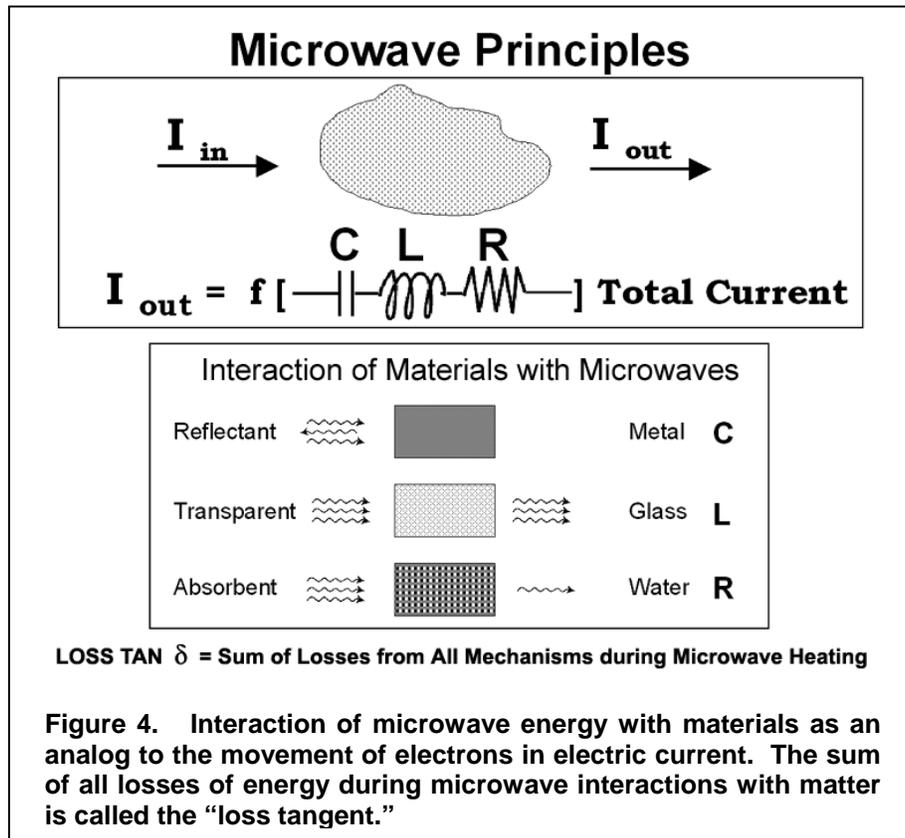
Physical Setting of the Nanophase Fe^0 : Recent experimentation with the $<10 \mu\text{m}$ fraction of mature hi-Ti mare soil 79221 [32] has shown that a strong hand magnet will easily attract practically all the grains, even those that are plagioclase, but have a thin patina of np- Fe^0 . This fine fraction, along with the high-magnetic-susceptibility agglutinitic glasses from coarser sizes, can be easily beneficiated from the lunar soil to make a feedstock for microwave processing. On a micro-scale, the np- Fe^0 both on the particle surfaces as well as in the agglutinitic glasses are effectively minute grains of a conductor each separated from the next by dielectric silicate glass, as discussed in detail below.

The presence of extensive amounts of np- Fe^0 on virtually all surfaces of soil grains is particularly advantageous where the grain-size of a soil fraction is small (e.g., $<45 \mu\text{m}$), since the surface to volume ratio is largest. It will be possible to easily shape and form the soil and to sinter it slightly by "hot pressing." The np- Fe^0 will ripen and grow during this process, thereby adding significantly to the adhesion and strength of the aggregates. In addition, the np- Fe^0 is located within a silicate glass, which being inherently unstable, will readily create additional fusion of the particles to each other. Indeed, as discussed below, the presence of this thin rim of np- Fe^0 on each grain can facilitate the formation of a fine-scale melt at the surface of these grains, thereby producing a glass binder – i.e., 'a transient liquid-phase sintering.' The discovery of the abundance of this nanophase native Fe^0 on the surface of lunar soil grains provides unique properties to lunar soil that make it an ideal feedstock for microwave processing.

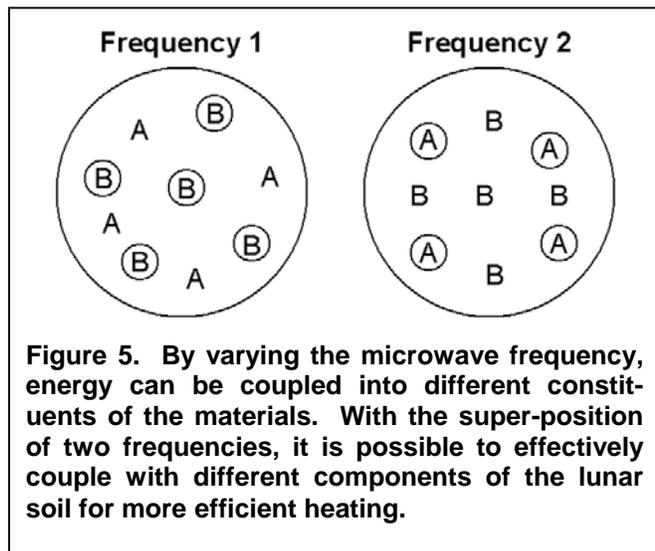
MICROWAVE ENERGY

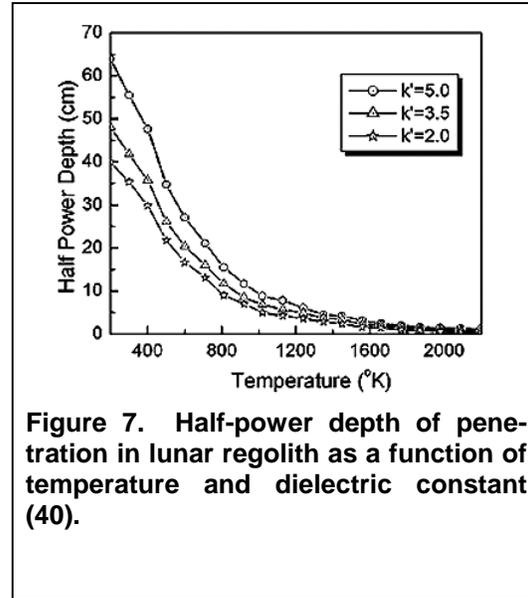
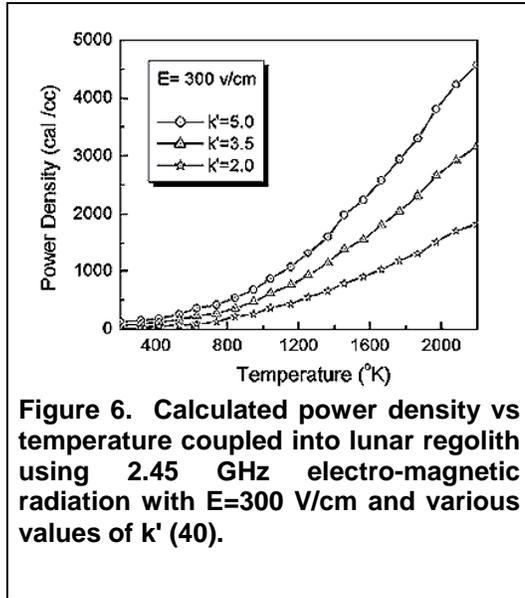
Principles: The microwave part of the electromagnetic spectrum corresponds to frequencies between 300 MHz and 300 GHz [33-35]. However, most research and industrial activities involve microwaves only at 2.45 GHz and 915 MHz frequencies. Based on their microwave interaction, most materials can be classified into three categories – opaque, transparent, and absorbers. Bulk metals are opaque to microwave and are good reflectors (Fig. 4). Most other materials are either transparent or absorb microwaves to varying degrees at ambient temperatures, depending on the frequency of the microwave radiation.

As many homemakers have experienced, solid, non-porous metal readily reflects and effectively 'shorts out' the microwaves. However, that same metal in a powdered form – effectively conductors separated by dielectric (particles and air) – will absorb microwaves at room temperature and will be heated effectively and rapidly [36]. This principle has led to a patent by Meek et al, wherein Cu powder was lightly oxidized forming thin dielectric rims such that the conductive Cu grains were effectively separated by the dielectric CuO [37-38]. Even when compressed into forms, the individual Cu cores of the grains are separated by the dielectric. It is primarily this ***principle of metal separated by a dielectric glass*** that will be expounded on below.



The heating that occurs in a microwave field depends on the local dielectric properties. For a simple monolithic material, the model is straight-forward. However, as the number of phases increase, the model increases in complexity. Due to the differences in dielectric characteristics in a composite substance, each phase couples differently with the microwave energy thereby developing local temperature conditions (inhomogeneities) in the material. It is possible to have solid-state sintering of particles and development of local melt pockets, as well. Once a liquid phase is developed, then thermodynamic equilibrium and nucleation kinetics must be considered. Exactly how the electromagnetic field affects these thermo and kinetic factors



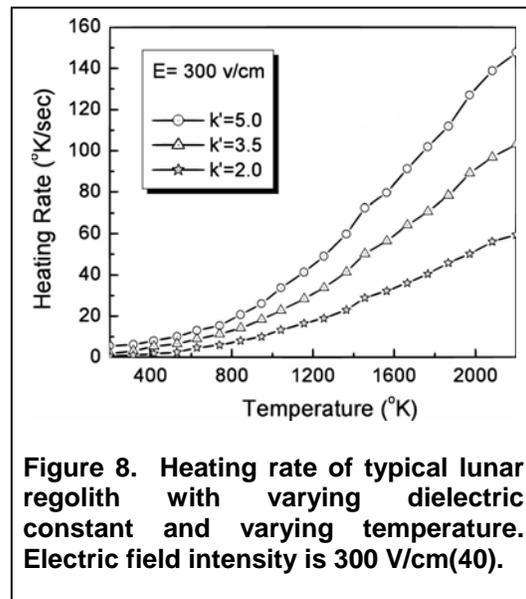


becomes ever-more complicated. But the combination of solid-state and liquid-phase sintering can result in better mechanical properties. This has been coined “transient liquid-phase sintering.”

Specific frequencies ‘couple’ with particular materials such that they cause substantial heating. In fact, as shown in Figure 5, it is possible to have multiple microwave frequencies such that the energy can be coupled into different constituents of a given material. Such a situation is not simple to establish, especially for a multi-component material such as the lunar soil, but our preliminary modeling has shown that it is theoretically possible.

Modeling for the sintering of a dielectric in a microwave field involves the interactions of the electromagnetic radiation with matter and can be approximated by use of three basic components: **Power Density; Half-Power Depth; Heating Rate.** These characterize how a material, such as a ceramic, will heat in an electromagnetic field. An initial analysis of these properties for the lunar soil was performed by Meek [39] and Meek et al. [40-41]. The power deposited per unit volume into a dielectric media by an electromagnetic field is: $P = KfE^2k'\tan \delta$, where P = power per unit volume; K = constant; f = frequency of radiation; E = electric-field intensity; k' = relative dielectric constant; and $\tan \delta$ = loss tangent.

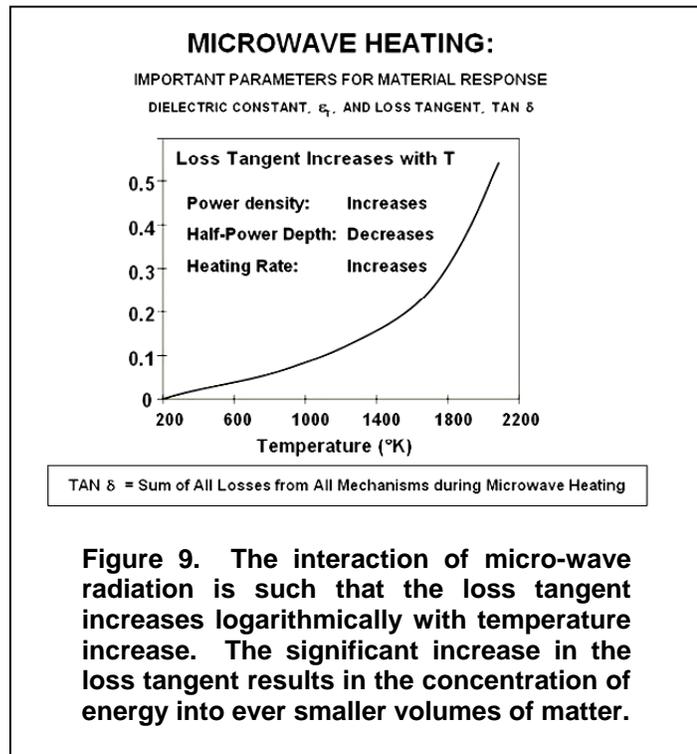
Dielectric properties and loss tangent data were obtained from the literature and used



in construction of Figures 6-9 [41-45]. Figure 6 shows the power density deposited into lunar regolith for varying regolith dielectric constant and for an electric field intensity of 300V/cm.

The next expression allows us to determine the depth into the dielectric material where the power is half its value at the surface. This is called the half-power depth and is defined as: $H = 3\lambda_0 / [8.68\pi k' \tan \delta]$, where λ_0 = wavelength of incident radiation; k' = relative dielectric constant; and $\tan \delta$ = loss tangent. Figure 7 shows how the half-power depth of penetration, "H", varies as a function of regolith dielectric constant and temperature. The last equation used in this modeling gives an approximate rate of temperature increase in a dielectric media that is heated in an electromagnetic field. This is only approximate because it does not include heat losses due to conduction, convection, radiation, or change of state. It is: $\Delta T \approx 8 \times 10^{-12} f E^2 k' \tan \delta / \rho C_p$, where ΔT = heating rate in °C/min; f = frequency; E = electric-field intensity; k' = relative dielectric constant; and $\tan \delta$ = loss tangent; ρ = density of material; & C_p = heat capacity. Figure 8 shows how lunar regolith will heat in a microwave field as a function of soil dielectric properties in an applied electric field of 300 V/cm.

From this heating model, it is apparent that for an applied frequency of 2.45 GHz (~10⁻⁶ eV photon energy) at 500 K and for a regolith with a k' of 5, the power density is approximately 250 cal/cc. Initially, heating is dominated by the applied electric field, "E". Power density increases with the square of the electric-field intensity E . As temperature increases, a critical temperature is reached at which the dielectric loss $\tan \delta$ becomes of primary importance in the ability to deposit energy into the material. As shown in Figure 7, the amount of energy deposited per unit volume increases as temperature increases. Figure 8, however, shows that as temperature increases, the half-power depth of penetration decreases. Initially at low temperature, 2.45 GHz microwave energy is easily deposited into a regolith depth of approximately 65 cm for a material dielectric constant of 3.5. At this depth, the power density is one-half that at the surface of the soil. As is apparent from Figure 8, the half-power depth of penetration decreases as temperature increases. This decrease is again a function of $\tan \delta$. As $\tan \delta$ increases, H decreases. The shape of the half-power depth curve is the inverse of the power density curve. In order to increase H , microwave radiation of a longer wavelength (lower frequency) should be used. Recognizing that low frequency (2.45 GHz) microwave heating occurs pre-



dominately as dielectric heating and then becomes dominated by the dielectric loss of the material, the rate of temperature rise starts off slowly, but increases at a rate that is influenced by the dielectric loss of the regolith. The shape of the heating curve is also influenced by the loss tangent of the soil. As regolith temperature increases, the volume of material being heated decreases due to the decrease in H . This is not of primary importance because the initial volume is heated so rapidly that by the time the half-power depth decreases appreciably, the soil is already sintered. Figure 9 shows the heating rate of lunar regolith as a function of soil dielectric constant and an applied electric field intensity of 300V/cm. As regolith temperature increases, the rate of temperature rise ΔT increases. At a regolith temperature of 1000 °C. the heating rate of a soil with a dielectric constant of 5 is approximately 50 °C per second. By increasing “E”, the heating rate can be markedly increased and sintering of the regolith can be accomplished very rapidly.

With a homogeneous distribution of two materials of contrasting dielectric constants in a composite, the lowest dielectric phase will have the highest electric field intensity. As sintering ensues, the density of this area increases in an attempt for the radiation to homogenize the dielectric constant. But as this occurs, more and more power is deposited into the lower-density regions with the lower dielectric phase. Another way to look at this is: Once dense regions begin to form, the microwave field will begin to decouple from these regions and couple more strongly to the regions of low density and low dielectric constant. The net goal of the microwave field is to create a material with a uniform dielectric constant.

Dynamics of Microwave Heating: Inspection of the equations above provides insight into the effects of microwave energy as temperature increases. Figure 9 shows the effects of temperature on the ‘loss tangent’ term, $\tan \delta$, that is of major importance here. In the equations for the Power Density and Heating Rate, the $\tan \delta$ term is in the numerator, with the result that both the Power Density and Heating Rate increase dramatically as temperature increases; however, the Half-Power Depth, where the loss tangent is in the denominator, decreases. These effects are at the center of the microwave heating – i.e., the power of the microwave energy becomes ever-more concentrated into a smaller volume as temperature increases. With this net effect, it is imperative that the frequency of radiation and the electric-field intensity be properly balanced such that the heating does go into a “run away mode”, which is not easily controlled.

EXPERIMENTATION WITH LUNAR SIMULANTS

As should be apparent from the above discussion, there are no “lunar simulants” that have the specific properties of $np\text{-Fe}^0$ such that they may be used for microwave heating and sintering experiments. Two major lunar simulants exist: MLS-1 and JSC-1. The Minnesota lunar simulant (MLS-1) consists of crushed high-Ti diabase (basalt) from Duluth that has been crushed so as to approximately duplicate the particle-size distribution of Apollo 11 lunar soil. Portions of this crushed rock have been melted to simulate the large glass components of lunar soil. However, it must be realized that this Minnesota rock was chosen for a simulant only because it had high-Ti content and general composition similar to Apollo 11 soil 10084. Its mineral chemistries were near that of the lunar phases, but they contain large amounts of Fe^{3+} , entirely atypical of lunar. However, these lunar simulants have been studied extensively by microwave processing [e.g., 46-51], with no unexpected results.

Sintering Progress of Powder Particles By Microwave Energy

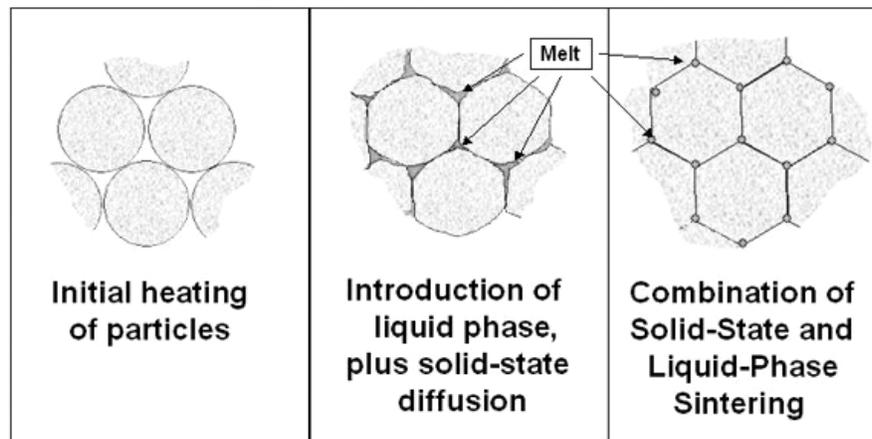


Figure 10. Diagrammatic representation of the progressive sintering of lunar soil (left to right). It is the development of the “transient liquid phase” that is promoted by the surficial nanophase Fe^0 . It is evident that this coupling with the microwave radiation creates temperatures far in excess of that present in the centers of the minerals.

It is the large amounts of agglutinitic glass, typically >50%, that make the lunar soil so unusual compared with any terrestrial analogs. This was the impetus that caused the Johnson Space Center to establish lunar simulant JSC-1. This is a crushed volcanic tuff that consists of a large percentage of glass shards and angular grains that more closely approximates the physical abrasive properties of lunar soil, but not its chemistry. Thus, the two main lunar simulants used by scientists and engineers worldwide only have some particular properties which are similar to lunar soil. This is not widely appreciated. However, there is presently no lunar soil simulant that has the nanophase Fe^0 properties that make experimentation with microwave radiation realistic to any degree. However, we are fortunate to have been allocated some Apollo 17 soil by NASA.

Sintering of Lunar Simulants: Microwave heating experiments of lunar soil, conducted by co-author Tom Meek and his colleagues [40-41, 52], were found to be extremely difficult to decipher because they did not know about the presence of the abundant nanophase Fe^0 . Instead, they attempted to interpret the sintering experiments in light of solar-wind radiation defects on the surfaces of the grains. They also speculated that the mineral ilmenite (FeTiO_3), abundant in some of the mare soils, was causing some of the heating [53]. But the distinct differences in microwave effects between the actual lunar soil and ‘apparently representative’ lunar simulants were not understood. As presented below, we now appreciate the cause for the unique behavior of lunar soil with microwave radiation, and it cannot be emphasized enough that this is an unusual property for any naturally occurring material.

As discussed above, the surfaces of most lunar soil particles consist of a thin ($<1 \mu\text{m}$) rind of nanophase Fe^0 (metallic Fe; 3-30 nm) in a matrix of high-silica glass. Here we have Fe metal, that is a conductor and opaque to microwaves, within a glass that is basically electrically insulating (dielectric) and near transparent to microwaves at room temperature. But when heated above a certain critical temperature, T_C , the glass will begin to absorb and couple more effectively with microwave radiation. At elevated temperatures, the transparent glass becomes microwave-absorbing, as well as the nanophase Fe^0 , greatly enhancing the interaction of the system with microwaves. But, even with these considerations, lunar soils contain glasses of different compositions, and probably T_C values, and will present added complexities to the successful modeling of microwave interactions.

Microwave Melting Along Grain Boundaries of Mare Soil

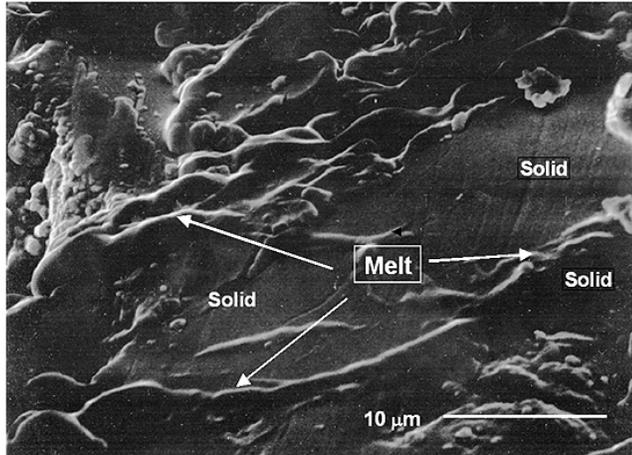


Figure 11. SEM photo of the surface of lunar soil grains after sintering with 2.45 GHz microwave radiation. Note the presence of a melt phase (now glass) along grain boundaries. Although the 'measured temperature' of the charge was $<900 \text{ }^\circ\text{C}$, the temperature necessary to produce the melt along the grain boundaries was $>1200 \text{ }^\circ\text{C}$.

EXPERIMENTATION WITH REAL LUNAR SOIL

Experimentation on microwave sintering and melting of lunar soil involves several complex considerations. Our furnace was designed for the use of either microwave radiation alone or the hybrid heating using the addition of

conventional heating elements as well. One of the major problems in microwave experiments is determining the real temperature of the sample. An average temperature of a material can be obtained by an optical pyrometer or use of shielded thermocouples. But, as demonstrated by Meek et al. [54], temperature gradients on the orders of hundreds of degrees can exist on a micro-scale. In fact, this is thought to be the factor causing the production of a "transient liquid phase" during sintering, as depicted schematically in Figure 10. This production of the "transient liquid phase" is well demonstrated by a photomicrograph of one of our experiments with Apollo lunar soil, as shown in Fig. 11. Note the melt (now glass) formed along grain boundaries. In addition, the actual shape of the body being radiated affects the local heating rates significantly; the microwave frequency can play a major role in the production of temperature gradients that develop in the body; therefore, achieving sufficiently uniform heating is not straight-forward. Couple this with the multi-phase nature of the lunar soil.

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, 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 *tremendous energy savings*.

Table 1. BENEFITS OF MICROWAVE OVER CONVENTIONAL HEATING.

- **Rapid Heating Rates [1000⁰/min]**
- **High Temperatures [2000⁰C]**
- **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**

PRODUCTS FROM MICROWAVE PROCESSING OF LUNAR SOIL

It is not difficult to conceive of applications of microwave processing of lunar soil for a multitude of products. Figure 12 depicts “*a road-paving wagon*” to be pulled over the lunar surface, consisting of a front blade for minor smoothing of the regolith, with two rows of magnetrons in the back. The first row of magnetrons is set in power and frequency such that the half-power depth will assure that the soil beneath the wagon will be solidly sintered to a depth of 0.5 meters. The second row is set such that the magnetrons will completely melt the uppermost 3-5 cm of the soil, which will crystallize to glass as the wagon passes on. In addition, as this wagon passes along it will heat up and thereby *release most of the solar-wind particles* within the soil, most notably hydrogen, helium, carbon, and nitrogen. An apparatus should obviously be constructed on here in order to capture these valuable elements. As emphasized by Taylor and Kulcinski [55], the value of helium-3 for the generation of clean, non-radioactive fusion energy may well be the savior of the human race in this 21st century.

Sintering of pre-formed blocks of soil can be used *to form solid bricks* for various construction purposes (e.g., igloos). An impact crater might be selected and smoothed out to a parabolic shape. Subsequent microwave treatment of the surface could *produce an antenna dish*, complete with a smooth glass surface. Or, this dish might be cut into sections for movement and reassembly to another location – e.g., a station at L₁ orbit? 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*. The variety of possible applications awaits only *an overly active imagination* [56].

CONCLUSION

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., MS-1; JS-1, etc.). Each simulant has properties “like” but not identical to the lunar soil. In particular, the ubiquitous presence of nanophase Fe⁰ (3-10

LUNAR SOIL PROCESSING & PRODUCTS

SINTERING and MELTING

Creating Smooth-Sintered to Glassy Surfaces on the Moon

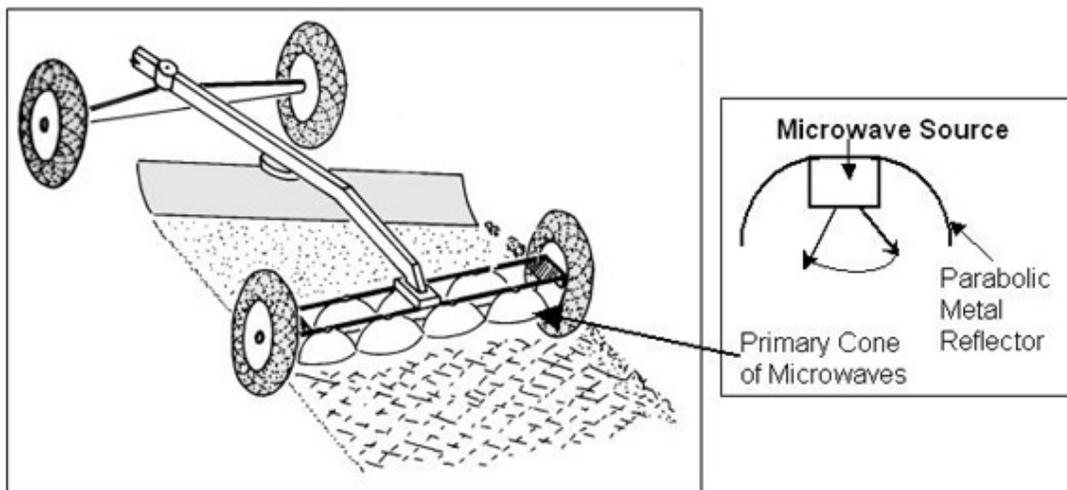


Figure 12. Cartoon of a “Lunar Road-Paving Wagon” with two sets of magnetrons that can be set to various frequencies and power in order to effectively sinter/melt the lunar soil, thereby constructing a trafficable road (US 101).

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, and 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.

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