High Temperature Microwave Dielectric Properties and Processing of JSC-1AC Lunar Simulant

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I. Abstract

Microwave heating may serve many lunar applications including heating regolith for lunar surface dust stabilization, oxygen production, building materials, and mineral refinement. The study of dielectric properties, which relate to microwave heating ability, of simulants and regoliths is needed to develop extraterrestrial microwave technologies. Microwave heating is related to dielectric constant and loss. Dielectric properties at microwave frequencies for the lunar simulant, JSC-1AC, were measured up to 1100 °C. The real and imaginary permittivity, loss tangent, and half-power depth were determined. Measurements at 2.45 GHz revealed that the loss tangent of JSC-1AC generally increased from 0.02 at 25 °C to 0.31 at 1100 °C. JSC-1AC absorbed microwave energy more efficiently as temperature increased. Microwave heating experiments confirm the sluggish heating effect of weak absorption below 250 °C, and increasingly strong absorption above 250 °C, leading to rapid heating and melting of JSC-1AC. Hybrid heating with microwave and radiant heat produced uniform materials from lunar simulant.

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II. Subject Headings

Aerospace engineering; Moon; Microwaves; Synthetic materials

III. Introduction & Background

Microwave heating has long been considered for consolidation, sintering, melting, metals refinement, and gas evolution (including oxygen, hydrogen, and helium) of regolith on the lunar surface (Allen et al. 1994a; Ruess et al. 2006). Researchers use terrestrially derived “lunar simulants” to study potential behavior of actual lunar regolith (soil). Microwave heating studies on various lunar simulants indicate general feasibility of microwave lunar regolith processing.

Microwave heating of lunar simulants and Apollo 17 lunar regolith has been performed in previous studies (Allen et al. 1994b; Meek et al. 1987; Meek et al. 1985; Taylor and Meek 2005). Simulant specimens up to the size of bricks were sintered by Meek. The microwave testing in the literature explored mostly sintering in air (Meek et al. 1986; Vaniman et al. 1986), but some examples are found using argon and hydrogen (Allen et al. 1994b). The testing atmosphere will affect the chemical and crystallographic composition as heating progresses, particularly where reactions altering transition metal oxidation states are promoted (Turkdogan et al. 1963). By processing in inert atmospheres (such as argon), or in vacuum, the partial pressure of oxygen (P_{O2}) will be reduced, which will in turn, better approximate the vacuum found at the lunar surface. Low oxygen partial pressures will thermodynamically promote lower temperature reduction of metal oxides, which may affect microwave heating. One published study involved Apollo 17 lunar soil heated in a microwave (Taylor and Meek 2005), however it was not apparent if the heating to the melting point was the result of direct microwave coupling with the regolith.
The existing microwave research on lunar simulants and regolith includes examples of heating comparisons of JSC-1 and Apollo 17 sample heating in a single mode microwave system. The single mode experiments performed by Taylor showed that the Apollo 17 materials heated faster than JSC-1 (Taylor et al. 2005; Taylor and Meek 2004), which suggests a higher dielectric loss in the regolith. Single mode systems allow high electric field concentration for heating of very small samples, but are not practical for large scale operations. In another study by the same author, microwave heating of Apollo 17 regolith in a multimode microwave system is presented (Taylor and Meek 2005); however, details of the experimental set-up and procedures such as sample size, crucible composition, microwave heating method (i.e., use of auxiliary heating), power levels, and time-temperature heating profile were excluded—all of which impact the interpretation of the results.

A study of the literature made it clear to the authors that the mechanisms of microwave heating of lunar simulants needed to be understood in a way that could be applied to actual lunar regolith. The study of microwave dielectric properties as a function of temperature will help to explain the difference in heating ability in the literature. Therefore this study focused on how microwave dielectric properties (which determine how materials heat via microwave energy) of a lunar simulant compared to microwave heating studies. This study incorporated dielectric property measurements, microwave self-heating experiments, and susceptor-assisted microwave heating experiments. This will allow comparisons through modeling of heating behavior in single and multi mode cavities, and provide a method for comparing improved lunar simulants to regolith.

The dearth of knowledge regarding microwave interactions with real lunar regolith and the tightly controlled availability of lunar regolith present a critical challenge. The current lunar simulants were not designed to mimic high frequency electrical and magnetic properties, which dictate microwave behavior.
To meet this challenge, dielectric properties of simulants, and also lunar regolith, can be measured and applied to computational models of microwave heating.

Microwave heating is caused by frictional processes related to dielectric mechanisms. Dielectric properties are the primary factor in determining the microwave heating characteristics of materials. Dielectric property measurement requires less than 1 gram of sample, and may be feasible for existing terrestrial lunar regolith stock. Meanwhile, larger scale microwave heating testing of simulant can be used to demonstrate the technical concepts of in-situ lunar regolith manipulation.

Lunar simulants were designed to approximate certain property sets, such as mechanical properties, particle size and shape, or mineralogical make up, however no lunar simulant truly approximates real lunar regolith. In fact, the mineral composition of the moon varies across the surface much like on Earth (Olhoeft and Strangway 1975). Therefore even the “best” lunar simulant will only simulate regolith from one area on the moon.

The natural variability of lunar mineralogy, as presented by Olhoeft, indicates that variability exists in the dielectric properties of regolith (Olhoeft and Strangway 1975; Olhoeft et al. 1973). Dielectric properties are composition and temperature dependant. The natural mineralogical variability will cause variation in the dielectric properties, and therefore on microwave processing, in different locations on the lunar surface. It is possible that these variations will require small adjustments in the microwave power or process time. At this stage, it is not known if standard lunar simulants will adequately represent the dielectric properties of lunar regolith. Researchers have discussed the development of higher-fidelity lunar simulants e.g., by simulating the glass-nano iron coating found on most lunar regolith, however, this step may not be necessary. The applicability of standard lunar simulants can first be determined by 1) measuring the dielectric properties of a range of regolith types and lunar simulants, 2) making
comparisons by modeling the microwave heating behavior, and 3) performing accurate microwave heating studies of lunar simulants.

**Microwave dielectric properties**

A literature review of existing microwave and dielectric property work on lunar regolith and simulants revealed that while much work was done in the 1970s on dielectric properties of Apollo regoliths by Johnson Space Center, Lockheed Martin, and Georgia Institute of Technology, there was no specific study of microwave dielectrics as a function of temperature up to the melting point (Bassett and Shackelford 1972; Olhoeft and Strangway 1975; Olhoeft et al. 1973). In fact, high-temperature microwave dielectric measurement techniques were not developed until the early 1990s by Hutcheon and Mouris at Atomic Energy of Canada Ltd, Chalk River Labs (Hutcheon et al. 1992).

Today, methods exist for obtaining dielectric property data up to high temperatures (1400 °C), which allows for prediction and understanding of how regolith will heat in microwave fields. This data is critical to develop generalized, yet accurate modeling of microwave systems for lunar paving (open microwave source), brick production (contained microwave source), or heating in oxygen production reactors (which often have agitation of the regolith). This data will also be useful to eventually compare the dielectric behavior of regolith simulants to real lunar regoliths.

Dielectric permittivity and loss determines the microwave heating of materials, across the range of processing temperatures. If these properties are known, microwave absorption can be determined, and modeling can be used to design a system for heating the materials. If a material is transparent (non-heating) to microwaves at low temperature, but absorbing of microwaves (heating) at higher temperatures, then a supplemental heat source, such as susceptors or heating elements, can be added to the system to provide the heat at low temperatures. At higher temperatures, the supplemental source can be removed
(e.g., turned off) if no longer needed, or remain on, to promote greater temperature uniformity. The dielectric property data reveals the microwave heating trends for the material, facilitating the design of high efficiency systems, which is critical for lunar applications.

**Microwave self-heating and microwave assisted heating**

Experimental studies of microwave heating vary between those that rely solely on microwave energy to heat a material (microwave-only or pure-microwave heating), and those techniques that employ a susceptor or conventional heat to assist at low temperatures or to provide more uniform heating (Gaustad et al. 2005; Shulman 2008). The method of microwave heating employed is critical to fully understand the implications of microwave heating on a particular material or process. For example, a material heated with the assistance of susceptors, whether external susceptors or a susceptor crucible, will be heated quickly using microwave energy, regardless of whether the material itself couples well. Also, susceptors, as strong absorbers, decrease the microwave power that is available to be absorbed by the sample. Therefore, susceptor materials strongly influence the results of microwave heating trials, and obfuscate the direct microwave heating effect in the sample material. Without knowing if tests were conducted with or without susceptors, it is difficult to analyze the results of some previous studies in microwave heating. Studying both microwave only and susceptor assisted heating is important as each method may have advantages depending on the specific heating application.

**Other lunar regolith processing methods**

The literature reveals competing techniques for lunar soil stabilization—(1) sintering via a solar concentrator heat source, (2) heat or UV-curable polymers conducted by Hintze, et. al., at NASA Kennedy Space Center (Hintze et al. 2009), and (3) fabricating lunar concrete (Ruess et al. 2006).
A solar concentrator is attractive as a passive heating device. Solar concentrators have been shown to densify lunar simulant surface up to 6 mm deep in fixed position, or only 1-2 mm deep in a rastering mode (Hintze et al. 2009). Thicker structures required additional layers to build up bulk. A solar concentrator has low power requirements, relying only on correct positioning with the sun and focus at the target area. Serious difficulties to the implementation of this technology, however, include (a) small spot size (1 in²), (b) limited penetration depth of heat, and (c) the need for sophisticated positioning controls, mirrors, and lenses required to maintain the desired focal spot location relative to the movement of the sun and the solar concentrator. Further, the possible build up of lunar dust on the lenses and mirrors (Gaier 2005), will reduce solar concentrator efficiency. A combination of a solar collector and microwave energy may be the best solution, as solar can overcome the low dielectric loss at low temperature, which is an issue for the microwave heating.

The polymer-stabilization methods are attractive with low-heat curing. UV-curing polymers may cure directly from sunlight (Hintze et al. 2009). However, all polymers must be manufactured on Earth and transported to the moon, making large-area stabilization difficult to sustain due to heavy reliance on transportation.

Ruess, et. al, of the University of Stuttgart and Rutgers University, proposed “lunar concrete” made from beneficiated high calcium lunar rock (Ruess et al. 2006). Cement, however, requires significant water resources which are not readily available on the moon, though the recent Chandrayaan-1 and LCROSS expeditions revealed significant water ice at the lunar poles (Dino 2009; Page September 24, 2009). Ruess suggests fabricating water on the moon by combining extracted oxygen and hydrogen from lunar soils, and processing rock into calcium oxide for the cement. Virtually all cement on Earth is made from biologically created calcium carbonate (limestone). The apparent lack of water, free-calcium minerals like limestone, and the infrastructure required to produce both the needed lime (CaO) and water, make
lunar concrete impractical for near term use. In comparison, a microwave heating process requires only solar energy and batteries to supply power, and it uses only the existing lunar regolith to fabricate structures.

IV. Experimental Procedure

Dielectric property measurements

JSC-1AC, a lunar mare simulant, was selected for dielectric property and microwave heating experiments. JSC-1AC is similar to lunar simulant JSC-1A, but contains coarse particles with sizes between 1 and 5 mm. The JSC-1AC simulant used in this study was a gray-brown powder composed chemically of primarily (>5% each) silica, alumina, magnesia, calcia, ferrous oxide, and ferric oxide (Rickman et al. 2007; Schrader et al. 2010). The main mineral phases present are plagioclase feldspar, basaltic glass, olivine and calcium pyroxene.

Two pellets totaling 267 mg of JSC-1AC were pressed to 2.09 ± 0.15 g/cc density for dielectric testing. Dielectric measurements were performed by Microwave Properties North (Deep River, Ontario) using a high temperature cavity perturbation technique.

The samples were continuously purged with ultra-high purity argon to avoid reactions with oxygen that would alter the simulant chemistry relative to the inert environment found on the moon. The pellets were cycled twice from room temperature to 1100 °C, with the dielectric properties measured in 50 °C steps on heat up, and 200 °C steps on cooling. The real (\(\varepsilon'\)) and imaginary (\(\varepsilon''\)) permittivity were calculated from frequency and quality factor shifts that were measured using a network analyzer (Mouris and Hutcheon). Parameters useful in microwave heating analysis, tan \(\delta\) (ratio of \(\varepsilon''/\varepsilon'\)) and half-power depth (\(D_{HP}\)) were calculated from the measured values.
Microwave heating tests

Samples of JSC-1AC lunar simulant were heated in alumina crucibles by microwave energy. Alumina was selected because it does not significantly absorb microwave energy or produce radiant heat in the temperature range tested. All experiments were conducted using 2.45 GHz microwave energy. Heating rates were controlled by adjusting the microwave power level. Tests were stopped once the set point temperature was reached.

Low power microwave heating of JSC-1AC lunar simulant was conducted with ThermWave 1.3 microwave furnaces (Research Microwave Systems) at NASA Kennedy Space Center and Ceralink. Alumina crucibles were used to hold 50 g samples of JSC-1AC, which were then placed in a microwave transparent thermal package (3.25” ID, 2.25” H). Silicon carbide susceptors (Gaustad et al. 2005) were included in one experiment to compare against the self-heating behavior of the simulant. Air temperature inside the furnace was measured every 20 seconds with a type S thermocouple approximately 1 cm above the simulant. The internal and external temperature of the sample was measured after heating was completed. The external temperature was measured with an infrared thermometer pointed at the surface of the sample. The internal temperature of the sample was measured by inserting a thermocouple into the center of the sample.

Higher power microwave heating tests were conducted with a 3 kW Autowave microwave vacuum-furnace (CPI, Beverly, MA). The chamber was evacuated to 0.1 torr and backfilled to 760 torr with ultrahigh purity argon. In this system, temperature was measured with a K-type thermocouple 1 cm from the side of the alumina crucible, and a 2-color optical pyrometer (Raytek model MR1SBSF, 700-1800 °C range) observing the opposite side of the crucible through a hole in the insulation.
V. Results & Discussion

Dielectric property results

Dielectric properties of JSC-1AC were measured at 2.45 GHz. The properties were measured on heating and cooling of the material. Results are shown in Figure 1. The loss tangent increases, and the half power depth decreases, above 200 °C. In general, this behavior is true of most materials. Microwave heating rate increases as the temperature of the material increases. The change in the dielectric loss from heating to cooling indicated that an irreversible transition (phase change, glass transition, or reaction) occurred between 800 and 1000 °C (Figure 1A), most likely relating to densification of the simulant due to sintering or even melting. Since dielectrics are materials properties (related to composition, crystal structure, and defect structure), they can be correlated to phase changes in the material.

Testing demonstrated a significant correlation between the dielectric properties and microwave heating rate of JSC-1AC. This was an expected result, consistent with an extensive body of work on dielectric properties and microwave heating of materials (Fischer 1997; Goodson 1997; Shulman et al. 2007). Dielectric property testing is an important tool for predicting microwave heating behavior of materials. The results also revealed that the half-power penetration depth of microwaves into lunar simulant JSC-1AC (at 2.45 GHz, the most common frequency) decreases significantly from >25 cm at 25°C, to 1.3 cm at 1100 °C (Figure 1B). The dielectric property results indicate that once preheated to 300°C, JSC-1AC should heat rapidly, with high efficiency near the surface of a deep bed of JSC-1AC.
Figure 1. A) Graph of real permittivity ($\varepsilon'$) and dielectric loss ($\varepsilon''$), as a function of temperature for JSC-1AC, at 2.45 GHz. The dielectric loss curve shows the data measured on heating and cooling. B) Graph of Half-Power Depth and loss tangent ($\tan \delta$, the ratio of $\varepsilon''$ to $\varepsilon'$), as a function of temperature for JSC-1AC, at 2.45 GHz. The low Half-Power Depth of JSC-1AC at elevated temperatures (above 600 °C) indicates preferential microwave heating and solidification (sintering or melting) at the surface (25 mm to 100 mm).

**Low power microwave self heating tests**

Microwave testing was performed to determine how microwave heating rates changed at different microwave power levels and over different heating durations. Low power tests enabled heating studies to occur without significant risk of thermal runaway (i.e., melting) of the JSC-1A. This information can be used to design the most efficient process for sintering simulant or for heating in high temperature oxygen production reactors.

Several experiments were performed at 720 W, for heating times of 5, 10, 15, 20, and 40 minutes. In these experiments, the temperature was monitored during the test by a thermocouple in the air above the
sample. At the end of the experiments, a pyrometer measurement was made on the surface of the powder, and the internal temperature of the powder was measured using a thermocouple.

The temperatures measured from 5 to 20 minutes are plotted in Figure 2. The heating rate gradually decreased, with the internal temperature of the powder reaching just below 200 °C. The internal temperature of the powder was higher than the surface or the surrounding air, indicating that the heat was being produced within the simulant powder. Simulant powder temperatures were significantly higher than the air temperature, even at the surface. The decrease in heating rate near 200 °C was supported by the decrease in dielectric loss measured from room temperature to 250 °C.

In the 40 minute experiment, Figure 3, the heating ability of the simulant appeared to increase again, with the total temperature rise doubling that observed in the 20 minute experiment. This result correlated with the increase of dielectric loss observed above 250 °C.

![Figure 2](image)

**Figure 2.** Graphs of JSC-1A internal temperature (thermocouple after microwave heating), surface temperature (optical pyrometer), and air temperature (thermocouple during microwave heating) for the 720 W microwave power level. Measurements were made on separate experiments heated for 5, 10, 15, and 20 minutes each.
High power microwave self heating tests

The low power heating tests showed that a well insulated sample of JSC-1AC, experiences a substantial heating rate decrease from room temperature to approximately 200 °C – and an increase of heating rate above 200 °C. This corresponded with the loss tangent minimum near 200 °C. The higher power microwave tests described below demonstrated that with sufficient microwave energy, the 200 °C loss minimum can be overcome, leading to rapid efficient heating to the sintering and melting temperatures of the simulant.

Additional microwave self-heating experiments were performed on JSC-1AC using a higher power, 3 kW microwave system in an inert argon atmosphere. The testing showed that the simulant heated very slowly from room temperature to approximately 200 °C, similar to the low power experiments. Above 200 °C, however, the heating accelerated to well over 100 °C/minute. An optical pyrometer, capable of reading temperature above 700 °C, indicated that the alumina crucible temperature was significantly greater than

Figure 3. Graph of internal JSC-1AC sample temperature from 720 W microwave power tests showing decreased heating rate to 200 °C, with evidence of increased heating rate at higher temperatures, as the dielectric loss increased.
the atmosphere temperature near the simulant (Figure 4). The internal temperature of the molten simulant was likely higher, based a cross section of the simulant after heating, which showed clearly molten regions, as shown in Figure 5.

![Graph of JSC-1AC microwave self heating](image)

**Figure 4.** Graph of JSC-1AC microwave self heating in the 3 kW CPI Autowave system. Low heating rates, averaging 6 °C/min were maintained up to 200 °C. Without changing the power level further, the heating rate shifted dramatically above 200 °C, to rates in excess of 100 °C/min. The pyrometer measurements, which started reading at approximately 900 °C, showed that the simulant was significantly hotter than the atmosphere measured by the thermocouple.

A clear demarcation was observed between the inner molten simulant and outer sintered simulant (Figure 5). The melting point of the simulant is 1100-1120 °C, which provides an estimate for the temperature at the demarcation. The molten regions of the simulant cooled into a glassy material with an obsidian-like appearance. Fracture surfaces of the molten material indicated a glassy material by way of the fracture patterns observed. The surface of the simulant in contact with the argon atmosphere, at the top outer edge of the simulant was still loose powder, indicating significantly lower temperature. The bubbles are likely to be a combination of trapped argon and outgassing.
Figure 5. Photograph of lunar simulant JSC-1AC after heating with microwave only. A) shows cut surface of the completely molten glassy phase. B) shows a smooth fracture surfaces of the glassy phase. C) indicates the demarcation between the glassy phases (believed to have reached temperature above the liquidus of the simulant), and the partially melted/liquid-sintered outer shell (which reached temperatures between the solidus and liquidus). The outer zone likely was composed of a mixture of solids and liquid at its maximum temperature, while the visible boundary was at the liquidus temperature. D) Shows a large void under the cap of the simulant. The cap sintered, but did not fully melt as a result of surface cooling. The surface tension of the melt was great enough to prevent the bubble from collapsing.

Susceptor-assisted microwave heating tests

Susceptor-assisted heating of JSC-1AC produced more uniformly consolidated simulant samples in less total time than the self-heating experiments. The heating profile with susceptors is shown in Figure 6. The microwave power level was gradually increased from ~300 W to ~800 W to maintain a relatively constant heating rate, to avoid arcing at low temperatures, and the non-uniform heating observed in the self-heating tests. The susceptor heated simulant had dramatic structural differences from the microwave-only samples. A pie shaped section of the microwaved simulant revealed a relatively uniform cross section, with a large round pore in the upper center, and several smaller spherical pores throughout the consolidated simulant. The pores ranged up to 1 mm in the bulk of the material, while a surface bubble
measured ~7 mm. The bubbles of the pores indicated that the simulant melted, see Figure 7. Near the sintering and melting temperature, the susceptors provided radiant heat to improve the uniformity of heat in the simulant. This prevented the “thermal runaway” condition where part of the simulant sample fully melted, while other regions were only sintered. The more uniform temperature, without hotspots, and slower cooling rates as a result of the presence of the hot susceptors, contributed to the lack of macroscopic glassy regions.

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{figure6a.png}
\caption{(a) Graph of the heating profile and heating rate for susceptor assisted microwave heating of lunar simulant. (b) Graph comparing air-temperature heating profiles from low power ThermWave and high power Autowave microwave self-heating experiments with the low power susceptor assisted heating.}
\end{figure}
The total process time with susceptors was faster, using a lower power microwave system, and produced a more uniform product.

![Image](A)

![Image](B)

**Figure 7.** Photographs of susceptor assist heated JSC-1A after firing to 1100 °C. A) Lower average heating rate of 31 °C/min and B) higher average heating rate of 37 °C/min resulting in fewer retained bubbles.

**Correlation of dielectric properties (half power) and heating rate**

The half power depths for JSC-1AC, suggest that the powder would weakly absorb microwave energy below 200 °C. Upon exceeding 200 °C, the rapidly increasing tan δ, and decreasing half power depth suggest that the material should begin to heat well. With mitigation of heat losses (i.e., by using thermal insulation), the JSC-1AC would be predicted to reach the sintering or melting temperatures required using microwave energy.
In practice, the microwave self-heating of 39 g of JSC-1AC in an alumina crucible, demonstrated a slow heating rate up to ~200 °C, of 4-8 °C/min. Above 200 °C, the heating rate accelerated to nearly 100 °C/min. These temperatures were measured with a thermocouple placed 1 cm from the side of the crucible, and therefore represent a lag from the actual temperature of the simulant. Regardless, the heating rates observed are indicative of a dramatic shift in the microwave absorption of JSC-1AC, correlated with a decrease in the 2.45 GHz microwave half-power depth.

This testing indicates that microwave heating of lunar simulant JSC-1AC will greatly benefit from a pre-heat to 250 °C by another heat source such as radiant heaters or microwave activated susceptors. Lunar regolith would also benefit from preheating, if it has similar temperature dependent dielectric changes. On the lunar surface, this need may be heightened by potentially lower starting temperatures, down to -180 °C for the regolith in shadowed regions or during night, depending on the sub-zero dielectric properties. During lunar daytime, lunar surface temperatures up to 100 °C will reduce the heat energy needed to preheat soil (Heiken et al. 1991).

Dramatically different microstructures and heating patterns were achieved with microwave only vs. susceptor assisted microwave heating. Despite similar total run times, the microwave-only samples exhibited molten, glassy cores with large voids, surrounded by sintered material, and loose powder at the outside of the crucibles. This resembled a “thermal runaway” condition, where the microwave energy was preferentially absorbed by the hotter, higher loss inner portion of the sample. The surface of the samples experienced greater heat loss, remaining cooler with lower dielectric loss. Therefore less microwave energy was available to heat the cooler surface. This surface effect is likely to be present regardless of the lunar regoliths dielectric properties. The material directly on the surface will always be cooler because of radiative heat loss.
The susceptor assisted runs produced more uniformly consolidated structures. The susceptors served to balance the thermal profile in the sample, causing the microwave absorption to be more uniform throughout the sample. This prevented excessive heat generation in one region, and avoided the melting observed in microwave self-heating.

The behavior observed in microwave heating within a crucible placed in a well insulated thermal package is likely to differ greatly from heating open ground for lunar paving. Results from this study indicate that for in situ utilization of regolith to produce lunar bricks, microwave heating balanced with a radiant heat source is likely to prove highly efficient.

![Figure 8](image)

**Figure 8.** Plot of the Half-power Depth and the observed heating rate in the high-power microwave self-heating test, of JSC-1AC at 2.45 GHz. The plot shows that heating rate increased significantly as Half-Power Depth decreased (i.e. microwave absorption increased).

**Energy efficiency of microwave heating**

The microwave self-heating process achieved a thermocouple reading of 1050 °C (atmosphere 1 cm from crucible), which occurred at a surface temperature (pyrometer) of 1193 °C, and possibly a higher internal sample temperature, based on the glassy core and sintered shell appearance of the sample after heating.
The total process energy consumption was 2427 kJ, of which 2160 kJ (89%) was used just to heat to an atmosphere temperature of ~250 °C (Figure 9). That compared with only 267 kJ to heat from an atmosphere temperature of ~250 °C, to the point of melting the simulant powder core. The increased efficiency of heating as a result of decreasing half-power depth, provides further evidence for optimizing microwave heating by using preheating via susceptors or a non-microwave heat source to over 200 °C. By comparison, when susceptors were used to heat an equal sized sample of JSC-1AC, only 220 kJ of microwave energy were required to achieve 250 °C atmosphere temperature.

![Figure 9](image_url)

**Figure 9.** Graph of the microwave energy required for heating JSC-1AC, with and without susceptors, from 25 °C to 250 °C, and from 250 °C to melting. The data indicates that self heating is very inefficient up to 250 °C, but becomes efficient above 250 °C, as the dielectric loss increases, and the material heats. When efficient susceptors are used, the initial heat up is very fast, however the need to heat the additional mass of susceptors using the microwave energy made the 250 °C-to-melt range less efficient when susceptors were used. These results suggest that a hybrid method, in which radiant heat is applied up to 250 °C, and then removed, would be the most energy efficient way to heat JSC-1AC.

**VI. Summary and Conclusions**

In this study, the dielectric properties of the lunar simulant JSC-1AC were measured and the predicted heating behavior correlated to the observed experimental microwave-only heating. The dielectric
properties correlated well with the microwave-only heating. Both the measured and observed results showed that direct heating of JSC-1AC is possible from room temperature, however, below 200 °C the heating is sluggish and inefficient. At temperatures above 200 °C, the stimulant couples efficiently and self heats for sintering and melting.

Experimental studies using microwave and secondary radiant heating (susceptors) were also carried out. In the susceptor heating case, the heating profile appeared to be dominated by the susceptors, which heated far better than the simulant at low temperatures. The findings of this study indicate that a combination of microwave energy balanced with a radiant heat source is likely to provide the most efficient heating for lunar solidification.

Further studies of dielectric properties, including testing of actual regolith, and the development of models utilizing the data to simulate microwave heating scenarios will greatly advance the knowledge base for lunar implementation of microwave heating.

**Future application of this study**

The dielectric data produced in this study will allow future simulations of JSC-1AC heating to be performed and microwave processes to be optimized for time and energy efficiency. This will further demonstrate the applicability of microwave heating to the lunar environment, by allowing relatively easy simulation of lunar environment, whose conditions are non-trivial to duplicate for study on Earth. The transfer of a model from lunar simulant to lunar regolith will be as simple as exchanging the dielectric properties of each material. The measurement of high temperature dielectric properties of actual lunar regolith is extremely important and should be performed. High temperature dielectric properties of actual lunar regolith will show how well existing simulants replicate the dielectric properties of their lunar archetypes. The processing challenges that occur when using lunar simulants are likely to still exist with
lunar regolith, even though the dielectric properties differ. Existing simulants can be used allowing for
development of models and proof of concept for microwave processes in lunar exploration and resource
exploitation.

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VIII. Notations
\( \varepsilon' \)  
Real dielectric permittivity (dielectric constant)

\( \varepsilon'' \)  
Imaginary dielectric permittivity (dielectric loss)

\( \tan \delta \)  
Loss tangent, Ratio of \( \varepsilon'' \) to \( \varepsilon' \)

\( D_{HP} \)  
Half-power depth

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