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

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I.   Abstract (150-175 words)

Microwave heating has many potential lunar applications including sintering regolith for lunar surface stabilization and heating regolith for various oxygen production reactors. The microwave properties of lunar simulants must be understood so this technology can be applied to lunar operations. Dielectric properties at microwave frequencies for a common lunar simulant, JSC-1AC, were measured up to 1100 °C, which is approximately the melting point. The experimentally determined dielectric properties included real and imaginary permittivity (ε', ε''), loss tangent (tan δ), and half-power depth, the distance at which a material absorbs 50% of incident microwave energy. Measurements at 2.45 GHz revealed tan δ of JSC-1A increases from 0.02 at 25 °C to 0.31 at 1100 °C. The corresponding half-power depth decreases from a peak of 286 mm at 110 °C, to 13 mm at 1100 °C. These data indicate that JSC-1AC becomes more absorbing, and thus a better microwave heater as temperature increases. A half-power depth maximum at 100-200 °C presents a barrier to direct microwave heating at low temperatures. Microwave heating experiments confirm the sluggish heating effect of weak absorption below 200 °C, and increasingly strong absorption above 200 °C, leading to rapid heating and melting of JSC-1AC.

II.   Subject Headings (4-8 from ASCE list)
   a. **Aerospace engineering**
   b. **Moon**
   c. **Microwaves**
   d. **Synthetic materials**

III.   Introduction & Background

Researchers use terrestrially derived "lunar simulants" to study potential behavior of actual lunar regolith (soil). Lunar simulants were designed to approximate certain property sets, such as mechanical properties, particle size and shape, or mineralogical make up. While no lunar simulant fully approximates real lunar regolith, it should be noted that the mineral composition of the moon varies across the surface much like on the Earth. Therefore even the "best" lunar simulant will only simulate regolith from one area on the moon. 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. Microwave heating

1

studies on various simulants indicate general feasibility of microwave lunar regolith processing. One published study actually involved Apollo 17 lunar soil heated in a microwave[1], however it was not apparent if the heating to the melting point was the result of direct microwave coupling with the regolith.

Microwave heating of lunar simulants and Apollo 17 regolith has been performed in previous studies[1-3]. Specimens up to the size of bricks were sintered by Meek. The microwave testing in the literature appears to be primarily performed in air, which impacts the chemistry of the materials being heated. Atmosphere affects the chemical and crystallographic composition as heating progresses, particularly when reactions altering transition metal oxidation states (especially Fe, Ti) are promoted. 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.

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[4], 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[1]; however, details of the experimental set-up and procedures such as sample size, crucible composition, microwave heating method (ie., use of auxiliary heating), power levels, and time-temperature heating profile were excluded – all of which impact the interpretation of the results. The study of microwave dielectric properties as a function of temperature will help to explain the difference in heating ability in the literature. 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 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. Therefore this study focused on how microwave dielectric properties (which determine how materials heat via microwave energy) of the lunar simulants compared to microwave heating studies. This study incorporated dielectric property measurements, microwave self-heating experiments, and susceptor-assisted microwave heating experiments.

The dearth of knowledge of actual microwave performance of real lunar regolith, and the continued interest in this technology, presents a critical challenge to mitigate the lack of lunar regolith with the use of simulants. The simulants were not designed to simulate regolith microwave (ie., high frequency electrical and magnetic) properties. To meet this challenge, dielectric properties of simulants, and also lunar regolith, can be measured and applied to computational models of microwave heating. 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.

The natural variability of lunar mineralogy, as presented by Olhoeft, indicates that variability exists in the dielectric properties of regolith[5, 6]. Dielectric properties are composition and temperature dependant. The natural mineralogical variability will cause variation in the dielectric properties, and therefore on 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 also 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 patina found to coat 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[5-7]. 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[8].

Today, methods exist for obtaining dielectric property data up to high temperatures (1400-1500 °C), which allows for prediction and understanding of how regolith will heat in microwave fields. It is understood that lunar soil may have large variations in composition and density, both of which will affect dielectric properties. 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 compare the dielectric behavior of regolith simulants to real lunar regolith.

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 if no longer needed, or remain in place 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[9, 10]. 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 suscepting crucible, will surely 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, suscepting materials strongly influence the results of microwave heating trials, and obfuscate the direct microwave heating effect in the sample material. Without knowing whether 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[11], and (3) fabricating lunar concrete[12].

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[11]. Thicker structures required additional layers to build up bulk. It has low power requirements, relying only on correct positioning with the sun and focus at the sintering target area. Serious difficulties to the implementation of this technology, however, include (a) small spot size (1 in^2), (b) the limited penetration depth of heat from the solar concentrator, 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[13], will reduce solar concentrator efficiency.

The polymer-stabilization methods are attractive with low-heat curing. UV-curing polymers may cure directly from sunlight[11]. 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[12]. 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[14, 15]. 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. 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[16]. The main mineral phases present are plagioclase feldspar, basaltic glass, olivine and calcium pyroxene.

For dielectric property measurement, two pellets totaling 267 mg of JSC-1AC were pressed to 2.09 ± 0.15 g/cc density for testing 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 (ε') and imaginary (ε'') permittivity were calculated from frequency and quality factor shifts that were measured using a network analyzer[17]. Parameters useful in microwave heating analysis, tan δ (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 microwave experiments. All tests were conducted using 2.45 GHz microwave energy. Heating rates were controlled by adjusting the microwave power level. Power levels were varied throughout each run, given in (Table 2). Tests were stopped once the set point temperature was reached. Simulant was loaded into alumina crucibles.

Low power microwave heating of JSC-1AC lunar simulant was conducted with ThermWave 1.3 microwave furnaces (Research Microwave Systems) at NASA 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 (Research Microwave Systems) 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 during heating 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.

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. 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 heating rate of JSC-1AC. This was an expected result, consistent with an extensive body of work on microwave heating 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.
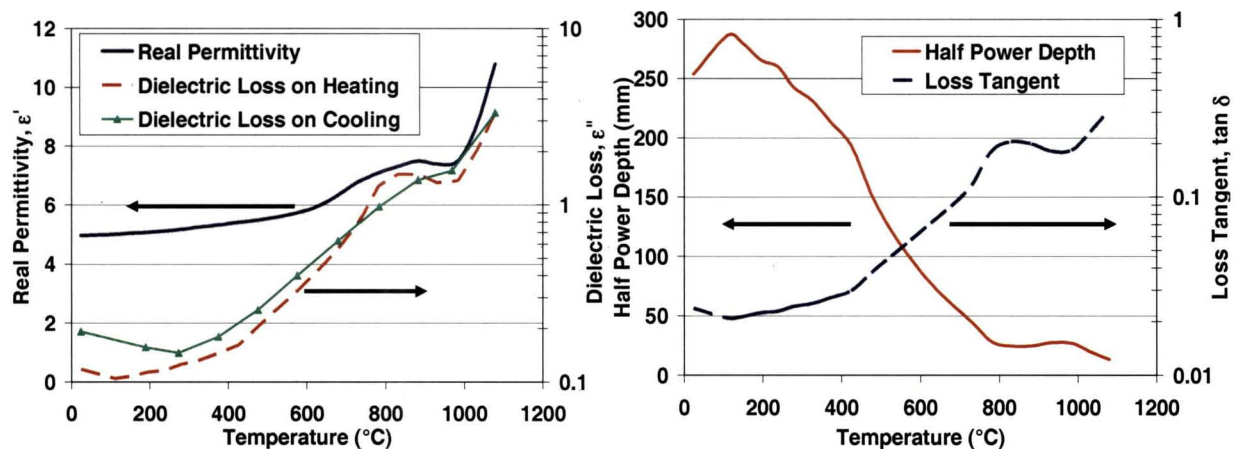

Figure 1. A) Graph of real permittivity (ε') and dielectric loss (ε''), as a function of temperature for JSC-1AC, at 2.45 GHz. The dielectric loss curve shows the data measured on heating and cooling. **B)** Graph of Half-Power Depth and loss tangent (tan δ, the ratio of ε'' to ε'), as a function of 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.

6

Low power microwave self heating tests

Microwave testing was done to determine how microwave heating rates changed at different microwave power levels and over different heating durations. This information can be used to help design the most efficient process for sintering simulant or for heating in high temperature oxygen production reactors.

Heating was conducted for 5, 10, 15 or 20 minute duration runs starting from room temperature at 20%, 40% and 60% microwave power levels (100% ≈ 1000 W). An additional time series was done with the first 5 minutes at 60% microwave power and the remaining time at 80% power. This was done to prevent arcing at low temperatures and high power. At the end of each run the internal and external temperature of the sample was measured. The change in temperature was calculated at 5 minute intervals by subtracting the final temperature of a given run by the final temperature of the next shortest run. Since the air temperature followed the same heating rate for each run, it was assumed that the internal and external sample temperatures were the same for the longer runs as they were at the end of the shorter. For example, for the 20 minute test, the sample temperature at 5, 10 and 15 minutes were assumed to be the same as the temperatures measured at the end of those shorter tests. This assumption was supported by a previous study showing sufficient repeatability to allow accurate modeling of microwave heating in the same type of system (Research Microwave Systems ThermWave 1.3)[18].

At low power levels (20 and 40%), the heating rate was relatively constant for the 20 minute duration. For the higher power levels the heating rates decreased as the internal temperature approached 200 °C. This demonstrated that the microwave heating ability of the simulant was decreasing up to 200 °C, as predicted by the dielectric properties. Figures 2 and 3 suggest that the material should undergo a minimum in the effectiveness of heating at temperatures between 150-200 °C. This is especially true for the sample run at 80% power. The lower power tests appeared to still be heating after 20 minutes, but had not reached high enough temperatures to experience the same decline in microwave heating ability.

One run was performed at 80% power for 40 minutes (Figure 4Figure 4). The internal temperature at the end of this run was 365 °C, indicating that there was a 166 °C change in temperature in the second 20 minutes of the run, as compared to a 178 °C change for the first 20 minutes. This large temperature gain is considerably larger than the 40 °C change that would be expected based on linear extrapolation of the 15 – 20 minute interval, and indicated that the material must have heated more efficiently at the higher temperatures. This was expected based on the loss tangent measurements.
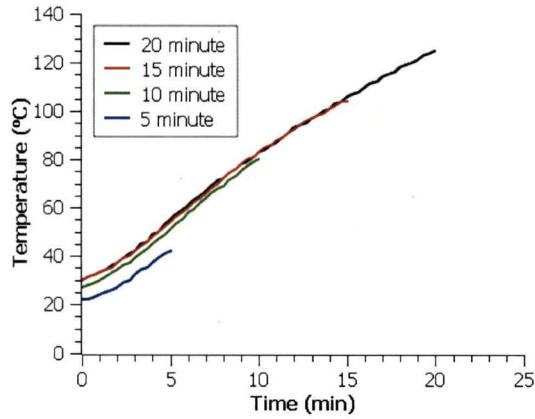
Figure 2. Air temperature during 5, 10, 15 and 20 minute heating cycles, at 60% power, showing repeatibility. These heating profiles were used to create the data points shown in Figure 3.
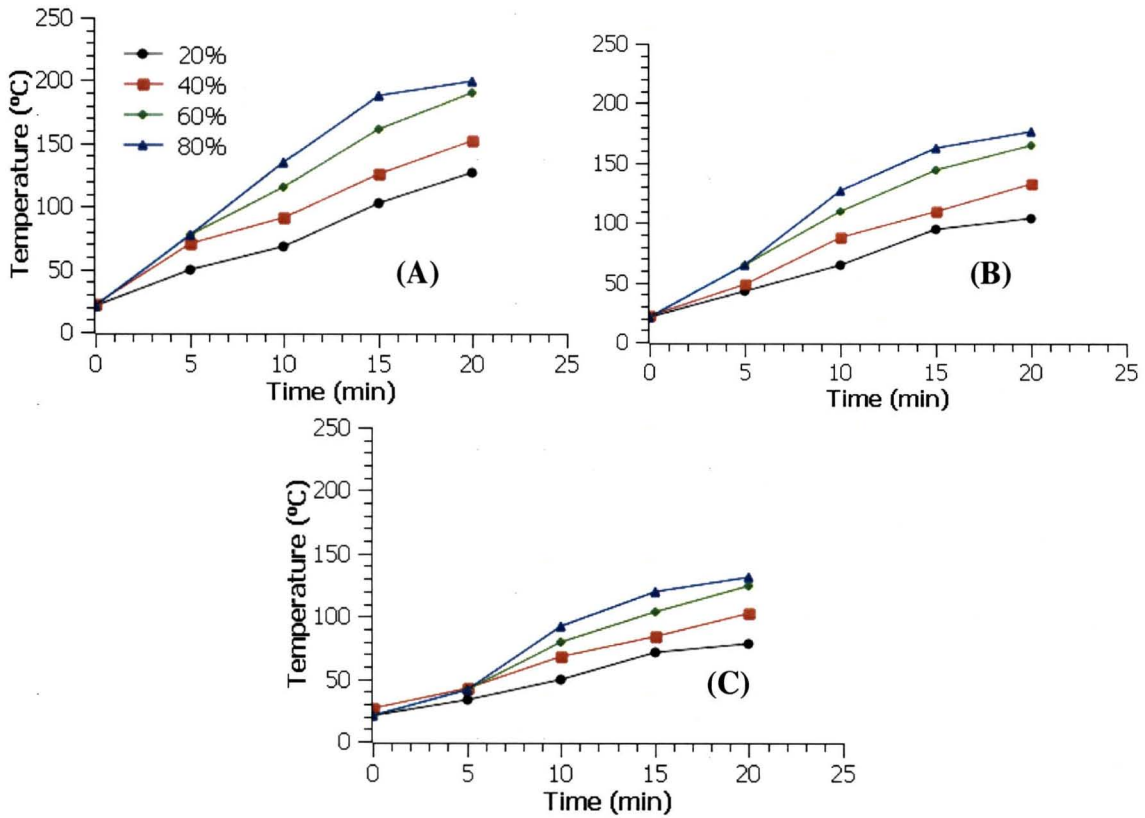

Figure 3. Graphs of A) internal temperature (thermocouple), B) surface temperature (optical pyrometer), and C) air temperature (thermocouple) for each power level in the low power ThermWave 1.3 microwave system.
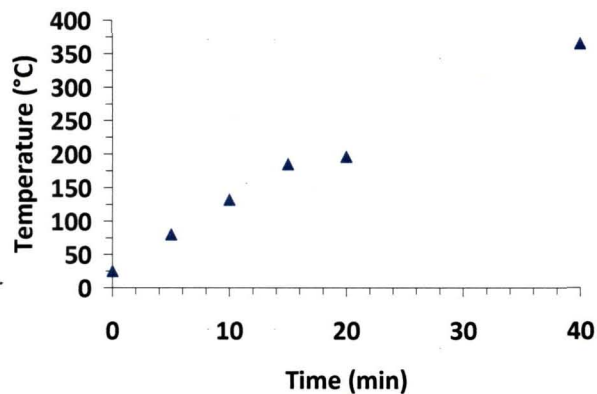
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Figure 4. Graph of internal JSC-1AC sample temperature from 80% microwave power tests showing decreased heating rate to 200 °C, and evidence for increasing heating rate above 200 °C.

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 180 °C, similar to the low power experiments. Above 180 °C, however, heating accelerated to well over 100 °C/minute. Direct measurements by pyrometer of the alumina crucible indicated that 1100 °C was reached within 10 minutes of the atmosphere near the sample reaching 200 °C (Figure 5Figure 5). The internal temperature of the molten simulant was likely higher, based on the results in Figure 3Figure 3.
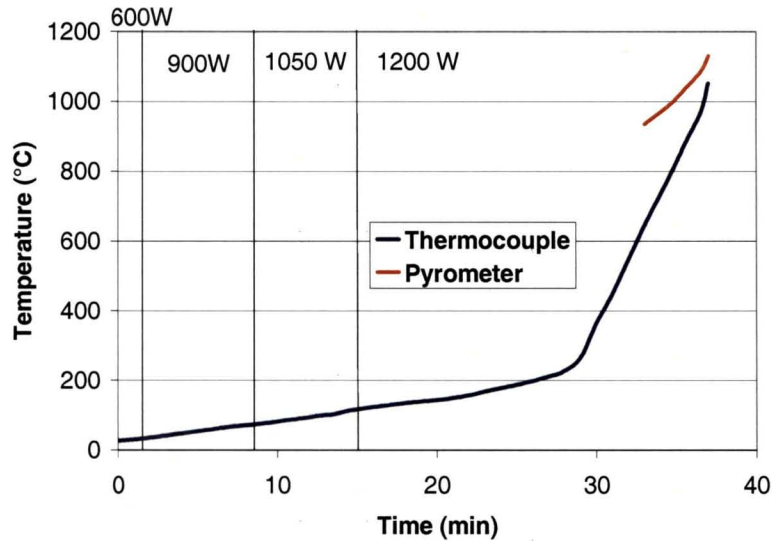
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Figure 5. Graph of JSC-1AC microwave self heating in the 3 kW CPI Autowave system. Low heating rates, averaging 6 °C/min were maintained up to 200 °C. Without changing the power level further, the heating rate shifted dramatically above 200 °C, to rates in excess of 100 °C/min. The pyrometer measurements, which kicked in at high temperature show 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 6Figure 6**Error! Reference source not found.**). 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 the clear presence of Wallner lines, wake hackle, and mist hackle. 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.
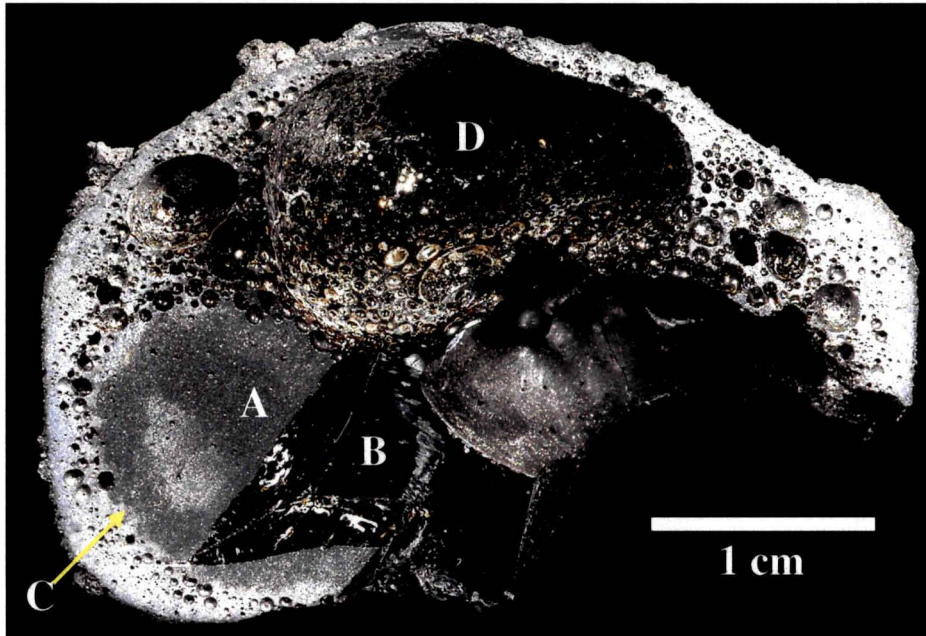
Figure 6. Photograph of lunar simulant JSC-1AC after heating with microwave only. A) shows cut surface of the completely molten glassy phase. B) shows a smooth fracture surfaces of the glassy phase. C) indicates the demarcation between the glassy phases (believed to have reached temperature above the liquidus of the simulant), and the partially melted/sintered outer shell (believed to have reached temperature 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 point. D) shows a large void under the cap of the simulant. The sintered, but not molten, cap indicated that the top surface did not fully melt, and that the surface tension of the melt was high 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 7Figure 7. 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 to avoid the thermal runaway 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 roundness of the pores indicated that the simulant melted, see Figure 8Figure 8**Error! Reference source not found.**. 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.
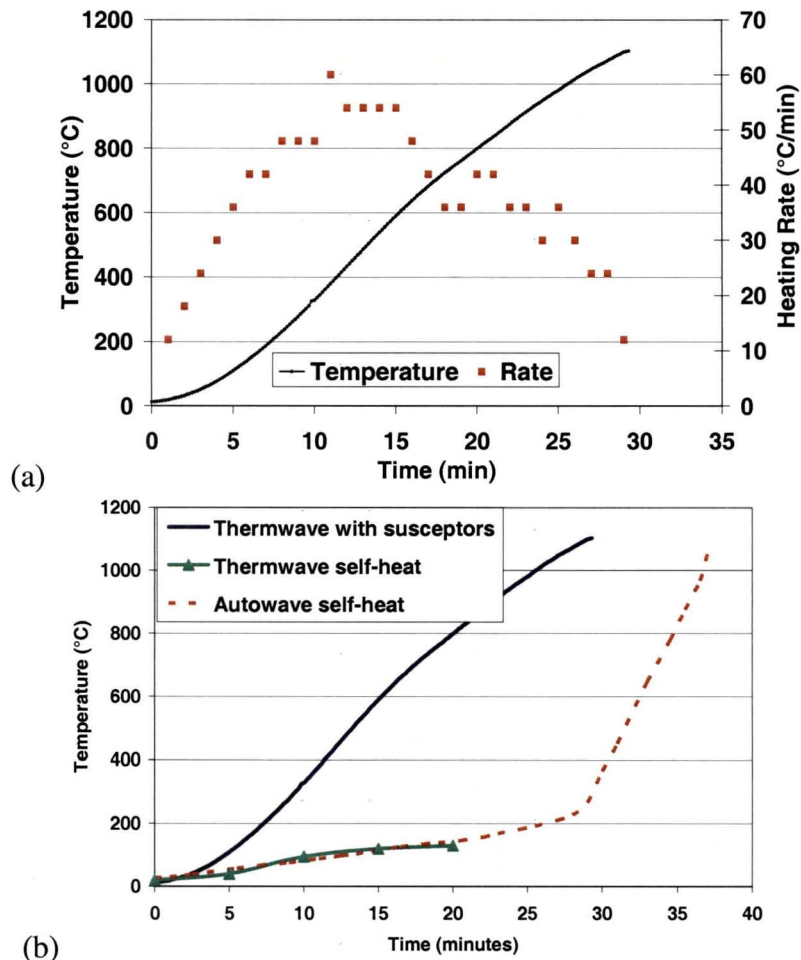

(a)

(b)

Figure 7. (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 ThermWave and Autowave microwave self-heating experiments with the susceptor assisted heating. The total process time with susceptors was faster, using a lower power microwave system, and produced a more uniform product.
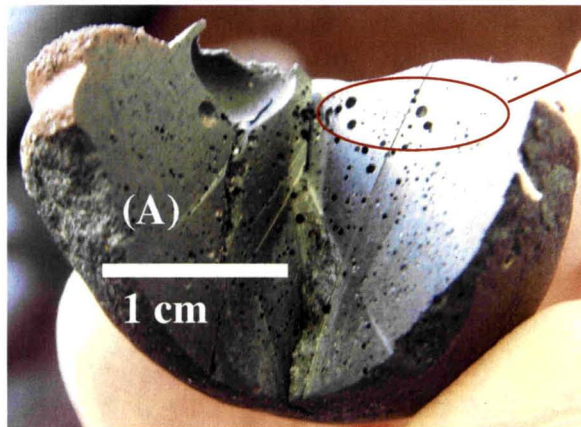
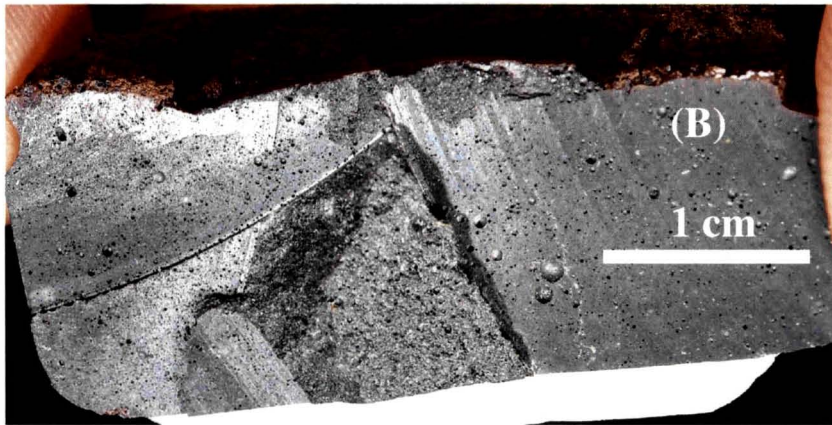~ 1 mm pores located near top surface

Figure 8. 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 (ie., 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 over 200 °C by another heat source such as radiant heaters or microwave activated susceptors. On the lunar surface, this need may be heightened by the lower starting temperature of -100 to -50 °C for the regolith, depending on the sub-zero dielectric properties. 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.

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. For in situ utilization of regolith to produce lunar bricks, microwave heating balanced with a radiant heat source is likely to prove highly efficient.
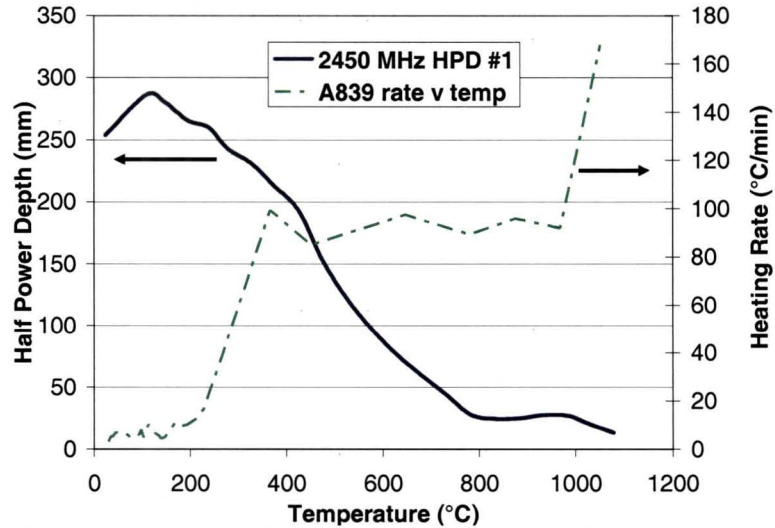
Figure 9. Plot of the Half-power Depth and the observed heating rat in the high-power microwave self-heating test, of JSC-1AC at 2.45 GHz. The plot shows that heating rate increased significantly as Half-Power Depth decreased (ie. microwave absorption increased).

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 pyrometer reading 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 10Figure 10). That compared with only 267 kJ to heat from an atmosphere temperature of ~250 °C, to 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 route 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.
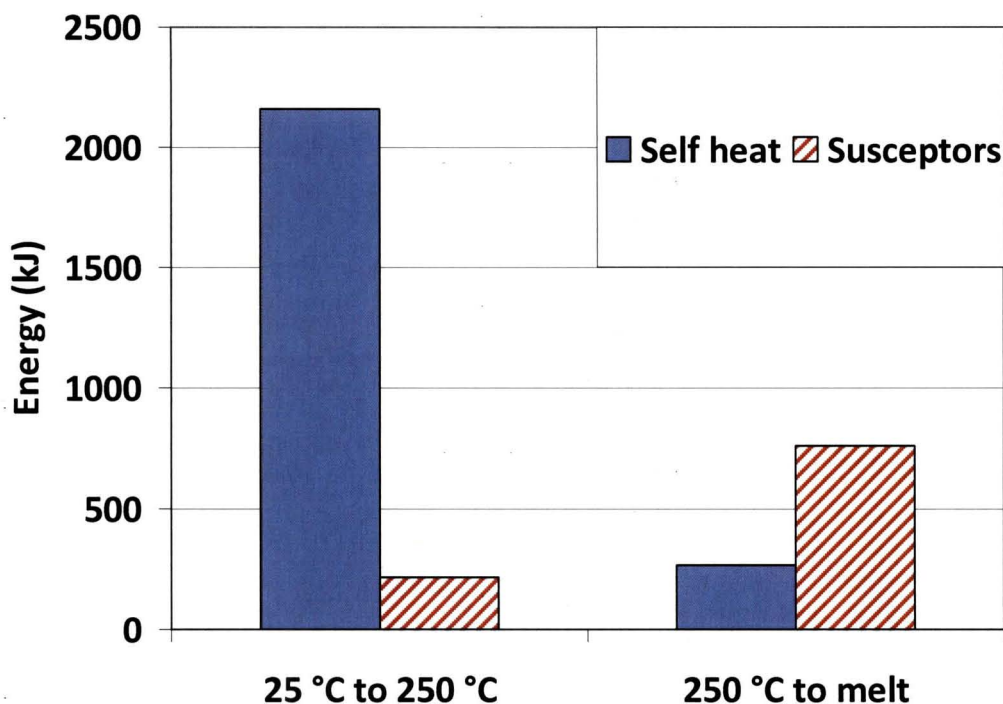
Figure 10. Graph of the microwave energy required for heating JSC-1AC, with and without susceptors, from 25 °C to 250 °C, andfrom 250 °C to melting. The data indicates that self heating is very inefficient up to 250 °C, but becomes very efficient above 250 °C, as the dielectric loss increases, and the 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.

Future application of this study
The dielectric data produced in this study will allow future simulations of JSC-1AC heating to be constructed 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. High temperature dielectric properties of actual lunar regolith will show how well existing simulants replicate the dielectric properties of their lunar archetypes. Existing simulants can be used (as assumedly less than desirable replicates) allowing for development of models and proof of concept for microwave heating in lunar exploration and resource exploitation.

VI.   Summary and Conclusions

Microwave heating of the lunar simulant JSC-1AC is possible from room temperature without the use of secondary heating via susceptors or radiant heat. However, below ~400 °C, microwave-only heating was highly inefficient. Above ~400 °C, microwave only heating became extremely efficient for bringing the JSC-1A up to sintering and melting temperatures. The dielectric properties of the lunar simulant JSC-1AC were measured and correlated to the observed microwave heating ability. Microwave heating experiments using pure microwave heating and susceptor assisted heating were performed to compare to the dielectric properties. The dielectric properties correlated well with the microwave-only heating. 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. 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.

VII.   Acknowledgements

VIII.   Notations

ε'	Real dielectric permittivity (dielectric constant)
ε''	Imaginary dielectric permittivity (dielectric loss)
Tan δ	Loss tangent, Ratio of ε'' to ε'
D_{HP}	Half-power depth

IX.   References

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