National Aeronautics and Space Administration

# 3D Microwave Print Head Approach for Processing Lunar and Mars Regolith

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## Motivation:

NASA is evaluating various methods to process lunar and Mars regolith in preparation for future missions. We have performed earlier studies [1-3] to understand the mechanism associated with the lunar regolith's excellent absorption of microwave energy that is useful for microwave processing. Using an upgraded microwave heating facility we have shown that the previously observed [4] enhanced heating is a consequence of the microwave volumetric heating of the samples. This enhanced heating effect was observed in both highland and mare lunar simulants. We have also demonstrated that this enhance heating effect occurs in the Mojave Mars Simulant (MMS). Volumetric heating leads to more efficient heating of the interior of the sample compared to the sample surface. This situation arises because the sample surface radiates energy while the heat produced in the interior only slowly dissipates due to thermal conduction to the surface. This effect can produce a significant temperature gradient leading to sintering or melting in the sample interior. Now that we understand how to control the cause of the sintering and melting we have the ability to develop a 3D microwave print head facility for processing lunar and Mars regolith in the future.

## Approach:

We performed a microwave heating study to determine the optimum heating parameters and to understand the internal melting process. All studied samples were initially outgassed at 200ºC for 3 hours and the sample density was determined before and after being heated. A 200-Watt TWT microwave amplifier was used to excite our waveguide cavity in a $TE_{104}$ mode at 2.45 GHz to heat a sample. The sample to be processed was placed in a quartz holder positioned within the wave-guide cavity at an electric field maximum. There are two distinguishing feature of this heating facility; a frequency tracker continually tracks the resonant frequency during heating to maximize the electric field strength in the cavity, and an impedance tracker continually adjusts the coupling between the power source and cavity to maintain critical (maximum) coupling into the cavity.

## Measurements and Analyses:

We initially addressed the concern that the enhanced heating effect could be associated with a chemical interaction with oxygen in the surrounding atmosphere. To test this concern we repeated our heating measurements on a lunar JSC-2A simulant with a nitrogen atmosphere surrounding the cavity. The resultant heating profile was essentially the same as when heating in earth's atmosphere. The remaining studies were then performed using earth's atmosphere. Our microwave heating facility was controlled by a LabVIEW program. Figure 1 shows a fast heating run to a set temperature of 600ºC using the new LabVIEW program. With this system we were also able to quickly heat a Mars simulant sample to a surface temperature of 435ºC as shown in Fig. 2. This figure also shows the cooling rate when the microwave power was turned off. When lunar or Mars samples were heated to a higher (surface) temperature of ~700ºC they would completely melt as shown in Fig. 3. Chemical analyses and optical microscopy were performed on various JSC-2A samples heated in our microwave facility. Elemental analysis was performed using a Horiba Model XGT-5000 X-Ray Fluorescence Microscope (µXRF). Powdered samples (some before heating and others after heating) were analyzed using Diffuse Reflectance Infrared Fourier Transform (DRIFT) spectroscopy. Micro-Raman spectroscopy was performed with a Bruker Senterra system equipped with a 532nm laser. In addition, Thermal Analysis using a TA Instruments Q Series Differential Scanning Calorimeter (DSC) and Thermogravimetric Analysis (TGA) system were performed.

Microwave processed simulants, heated to 500 – 600ºC, were roughly spherical, with a powdery outer surface. A sample heated to ~ 600ºC was cleaved into roughly two hemispheres and micro-photographed. A picture of this cleaved sample is shown in Fig. 4. There are three zones: 1) the surface powder that was mainly left in the vial, 2) the grainy, sintered outer rind and 3) the glassy interior that shows a smooth melted glass appearing region with voids. Micro-Raman spectroscopy and FTIR analysis of the bulk material was consistent with mixed plagioclase feldspar, Ca-pyroxene, olivine, and basalt glass. The DSC of the unprocessed simulant did not show any phase change or sintering up to 550ºC. The surface powder was placed in the TGA and heated to 1000ºC and this resulted in a sintered (fused), rind like appearance suggesting that the rind in the microwave heated sample could have reached 1000ºC! Micro-Raman and micro-XRF measurements showed that the interior glass regions were more uniform point-to-point that was indicative of melting and mixing. Bulk FTIR spectra of the melted sample center showed a difference in the Si-O bonds as the silicates combine in solution.

In order to develop a 3D microwave print head facility, the existing 2.45 GHz microwave facility will be modified to incorporate a quartz tube running vertically through the cavity. A modeling study will determine the optimum location for the tube given the size of the sample and an estimate of the temperature dependence of its dielectric constant. Given this information, a new 2.45 GHz waveguide cavity will be built. Excitation of a $TE_{10n}$ waveguide cavity mode will provide the heating power and the sample surface temperature will be monitored using a non-contact pyrometer. A LabVIEW program will record the sample surface temperature and microwave parameters (forward power, reverse power, H-field strength, and resonant frequency) during the heating process. A simulant sample will be slowly fed through the quartz tube and heated past its melting point to enhance the flow rate. Melted simulant will flow out the bottom of the tube into various molds simulating forming a wall or paving a road. Power, flow rate, and tube diameter will be varied to optimize performance. Lunar highland and mare simulants as well as Mars soil simulants will be evaluated.

Once the operating parameters for controlled melting are determined in the 2.45 GHz facility, a larger scaled-up version will be designed for use with an existing STMD Co-Robotic System such as the ATHLETE [5] robotic system. Figure 5 shows a schematic of this future 3D microwave print head facility. This microwave heating approach could also be adapted for other (ISRU) activities such as extracting consumables for human life-support systems.

## References:

[1] Barmatz, M., Steinfeld, D., Begley, S.B., Winterhalter, D., and Allen, C., (2011) LPS XXXXII, Abstract #104

[2] Barmatz, M., Steinfeld, D., Winterhalter, D., Rickman, D. Gustafson, R., Butts, D., and Weinstein, M., (2012) LPS XXXXIII, Abstract #1050.

[3] Barmatz, M., Steinfeld, D., Winterhalter, D., Rickman, and Weinstein, M., (2013) LPS XXXXIV, Abstract #1223.

[4] Taylor, L.A., and Meek, T.T., (2005) J. Aerosp. Eng. 18, 188-196.

[5] Howe, A.S., Wilcox, B., McQuin, C., Townsend, J., Rieber, R., Barmatz, M., and Leichty, J., (2013) AIAA2013-5437, AIAA Space 2013 Conference & Exhibition. San Diego, California, USA.

## Graphs, Photos, and Schematics:

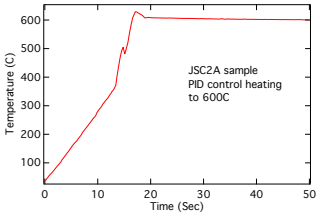


**Figure 1.** JSC-2A sample dielectric heating curve using new LabVIEW program

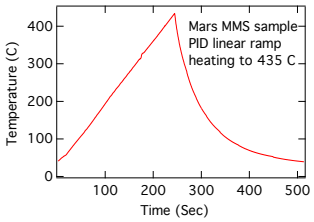


**Figure 2**. Dielectric heating and cooling curve for Mojave Mars Simulant (MMS) using a 100ºC per minute linear ramp rate

**Figure 3.** Melted JSC-2A sample in quartz holder after being heated to 700ºC

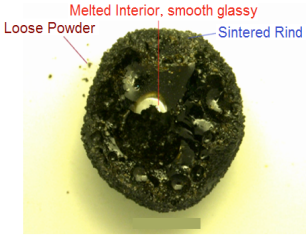


**Figure 4.** Photo of interior of a cleaved JSC-2A sample after being heated to ~ 600ºC

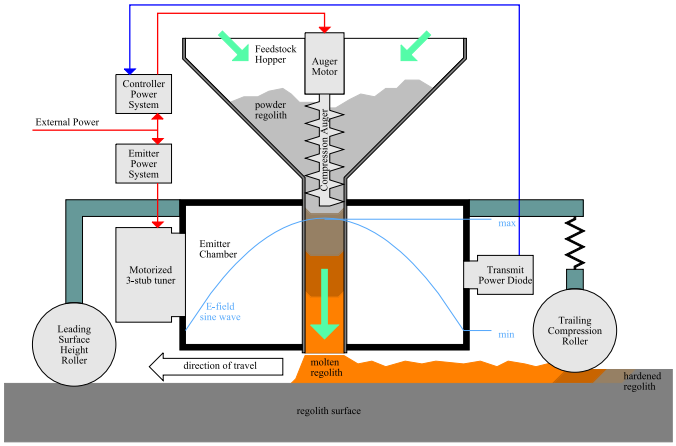


**Figure 5**. Schematic of 3D microwave print head concept

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