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Development of a Microwave Facility for Processing Lunar Regolith

M. Barmatz, C. Hays
Jet Propulsion Laboratory

T.T. Meek
University of Tennessee

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Presentation

- Historical Background
  - Unique properties of the lunar regolith
  - Previous studies of microwave processing
- Roadmap for Evaluating Microwave Heating
  - Determine regolith source of exceptional absorption
    - Proposed approach to develop realistic simulant
  - Evaluate of Microwave Heating Approaches
    - Proposed softening technique
    - Perform heating studies and property measurements
  - Designs for Prototype Lunar Facility
- Concluding Remarks

Historical Background

- Fabrication of a Lunar Base on the Moon
  - Astronauts will need building material for their lunar base and other technological and scientific activities
  - Cost of transporting materials to the Moon are staggering (~ $80K/kg)
  - Advantageous to use lunar regolith for construction needs
- Unusual Regolith Properties
  - Moon has no atmosphere
  - Space weathering on cosmological time scales, e.g., micrometeorite impacts and reduction processes produced a unique fine-grain lunar regolith
  - Major question is how to best process the regolith
  - Initial studies suggests that the volumetric heating capability of microwaves may be ideally suited for processing the regolith

Historical Background

- Initial microwaves studies
  - Apollo missions (1969-1972) returned some lunar soil for study
  - Simulants of the lunar regolith (MLS-1, JSC-1) were made for extensive studies
  - Initial microwave studies by Professor Meek and co-workers showed good energy absorption by simulants
    - T.T. Meek, D.T. Vaniman, F. Cocks, and R.A.Wright, Lunar Bases and Space Activities in the 21st Century, 479 (1986)
  - A preliminary test on Apollo return regolith showed significantly better microwave absorption than in simulants. Why?
  - Early explanations for the exceptional absorption were centered around the presence of mobile defects associated with broken bonds produced by micrometeorite impacts

Historical Background

- Recent microwave studies
  - Extensive characterization of Apollo lunar samples has recently revealed the presence of elemental, nanophase iron (np-Fe^0) that can enhance microwave absorption
    - L.A. Taylor, H.H Schmitt, W.D. Carrier, III, and M. Nakagawa, AIAA, Proc. 1st Space Exploration Conf., Orlando, CD ROM 2043 (2005)
    - L.A. Taylor and T.T. Meek, J. Aerosp. Eng., **18**, 188 (2005)
  - Model for formation of np-Fe^0 is not fully developed
  - Microwave enhancement is due to the fact that the nanophase iron size is comparable to the skin depth of the microwaves in metals (~ 1 micron at 2.45 GHz)
  - However, there is only a very small amount of nanophase iron present in the regolith and there still is a debate whether this is the main cause of the exceptional microwave absorption

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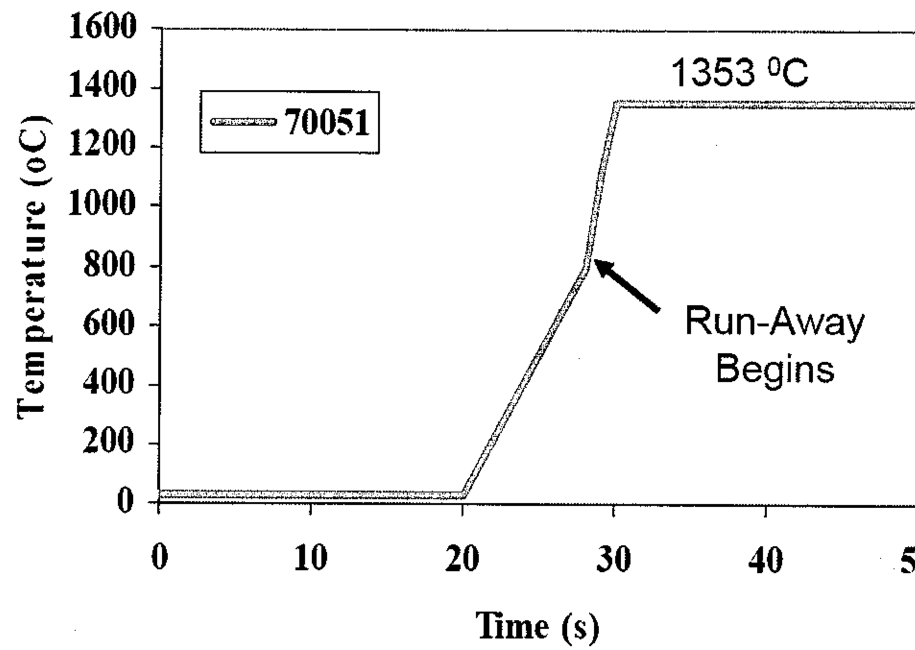
Historical Background

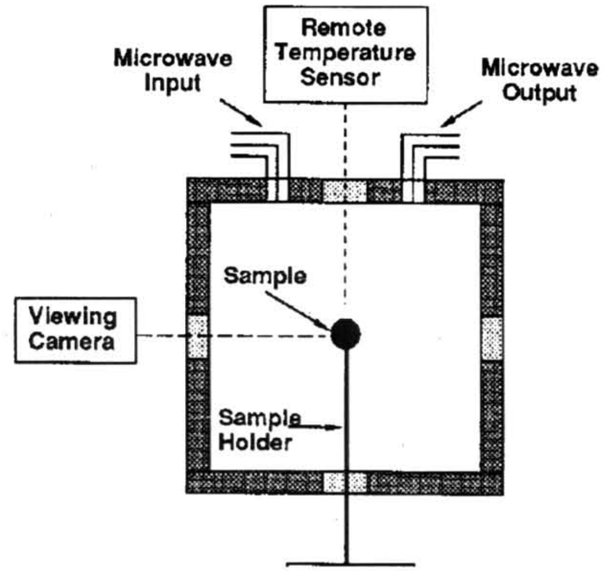
- Recent Regolith Heating Tests (Prof. Larry Taylor)
  - The heating properties of a simulant and Apollo lunar sample were compared
  - Comparison clearly shows improved heating in lunar regolith confirming earlier finding
  - However, still need to determine source of improvement (nanophase iron, mobile defects)

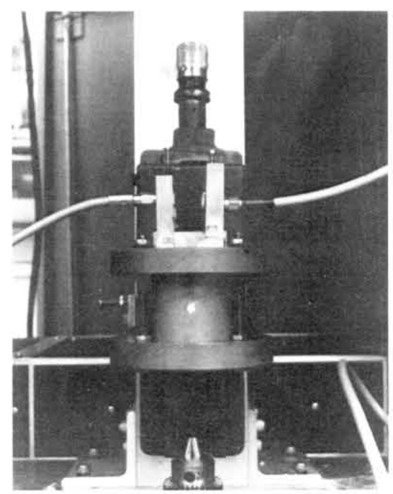
2.45 GHz Wave-Guide	Pellet Size (mm)	Beam Power (watts)	Time to Reaction (sec)	Maximum Temp (°C)
Apollo 17 70051 (<45 μm)	6 X 6	**250**	**20**	**1353**
JSC-1A (<50 μm)	6 X 6	**500**	**55**	**1215**



Determination of Absorption Source

- Single Mode Cavity Approach
  - Can perform controlled heating studies to easily determine which composition heats most efficiently
  - Can obtain the loss tangent ($\tan\delta = \varepsilon''/\varepsilon'$) versus temperature from measurements of the real (ε') and imaginary (ε'') parts of dielectric constant
  - Perform measurements on samples of differing composition ($\leq$ 500 C)
- What samples to use?
  - Lunar regolith or simulants

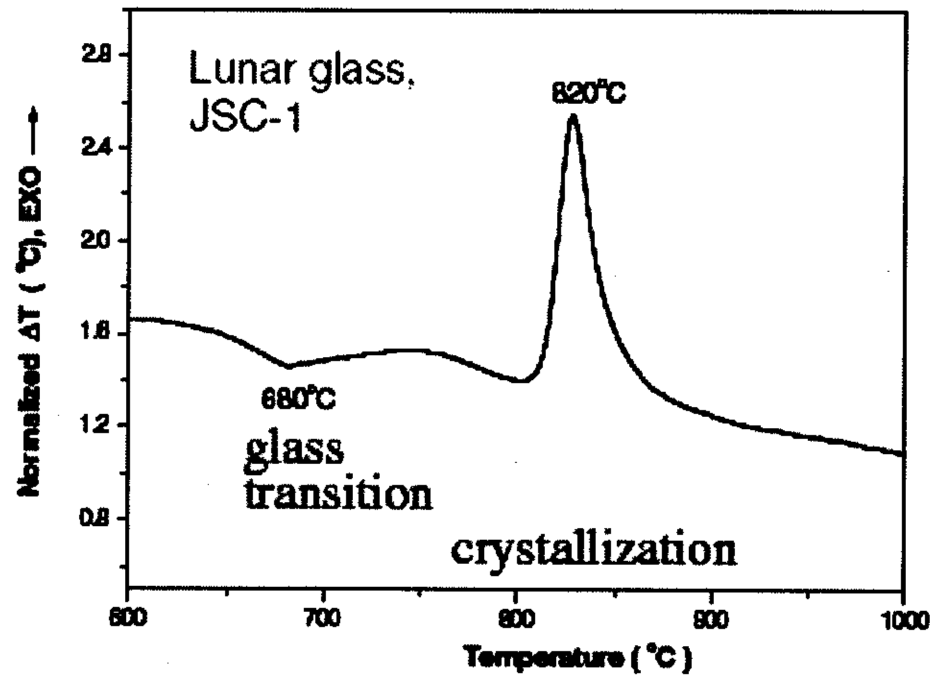




Properties of Lunar Regolith

- Composition of Lunar Regolith
  - The lunar regolith consists mostly of glasses (SiO_2, Al_2O_3, CaO, MgO, FeO, Fe_2O_3) that have melting temperatures in the range T_m = 1200 - 1400 C
  - The lunar simulant glasses have a glass transition temperature, T_g = 680 C and crystallization temperature, T_x = 820 C

Differential Thermal Analysis (DTA) curve for lunar simulant (JSC-1) - from C.S. Ray *et al.*, MSFC, 2004



Determination of Absorption Source

- Lunar Regolith
  - Small amounts of lunar regolith can be obtained for study
  - With enough regolith material, could attempt to modify the amount of nanophase iron (using a magnet) or the mobile defects to produce samples with different compositions for testing
- Simulants of Lunar Regolith
  - New basic simulant compositions now being prepared at Marshall Space Flight Center will not contain nanophase iron or mobile defects
  - Enhance these new simulants to obtain a more realistic representation of the lunar regolith
  - Ion implantation methods can introduce mobile defects and volatiles (H^+, O^{2-}) into a basic simulant composition, and other methods can introduce np-Fe^0
  - Compare the microwave heating capability of nanophase iron-enhanced simulant to mobile defect-enhanced simulant

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Determination of Absorption Source

- Novel Softening Approach
  - We propose a method to produce nanophase iron using a rapid solidification method
  - In this approach, a simulant containing nanophase iron particulates is formed by melt-spinning (~ 10^5 K/sec) or injection casting (~ 10^2 - 10^4 K/sec) under a controlled atmosphere
  - These processes are comparable to those that result in the formation of agglutinitic glassy regolith

Melt Spinning

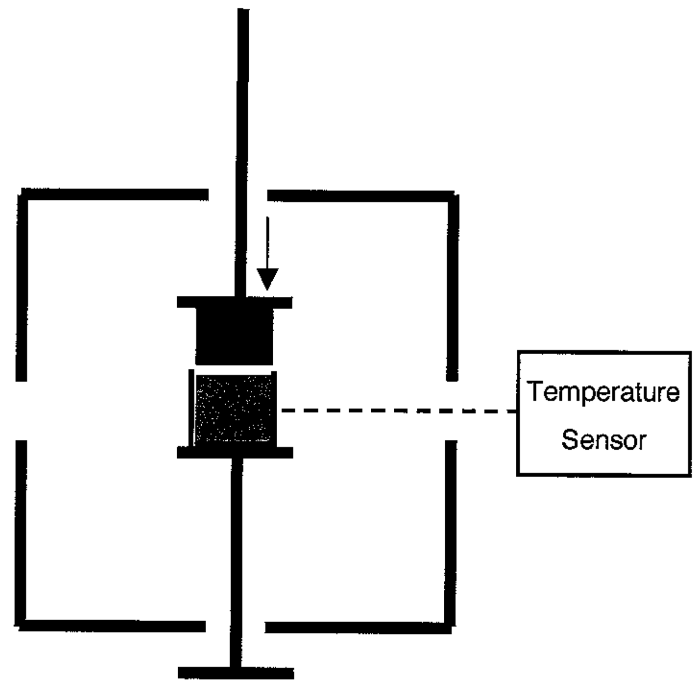
Injection Casting

Sintering and Softening Techniques

- Sintering and Softening Techniques
  - The most common approach to produce building blocks is to initiate sintering by heating a material to near its melting temperature, T_m
  - An alternative approach, that we propose, is to heat the regolith under compression to temperatures between the agglutinitic glassy phase, glass transition temperature, T_g, and crystallization temperature, T_x, i.e., into the supercooled liquid region (SLR), $\Delta T = (T_x - T_g)$
    - In this temperature region, the viscosity of the glass is significantly decreased allowing the sample to soften and flow under pressure
    - This SLR region is several hundreds of degrees below T_m
    - If the compaction associated with this softening is sufficient, it could significantly reduce the time and energy associated with the compaction process

Evaluation of Microwave Processing

- Microwave Heating Studies
  - Use the best absorbing simulant composition (nanophase iron, mobile defects or combination) for further microwave studies
  - Initial compaction studies will be performed with small samples (several grams) using a 300 W, TWT amplifier at frequencies between 2 to 4 GHz
  - Processing temperatures will be between the supercooled liquid region and melting
  - Some samples will be under pressure during heating to determine degree of enhancement in compaction



Microwave Hot-Press Technique

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Evaluation of Microwave Processing

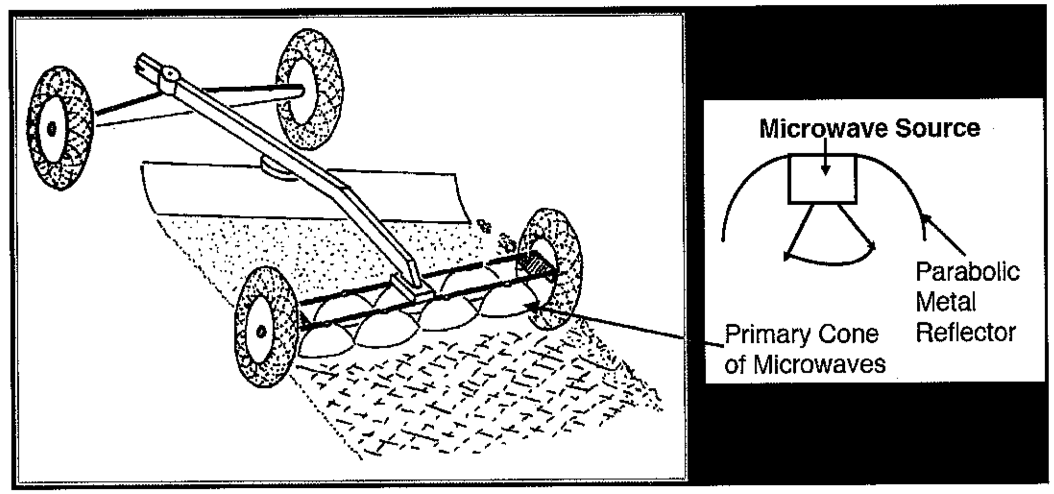
- Thermal and Mechanical Studies
  - Thermal and mechanical properties of microwave compacted simulant samples will then be measured and compared
  - Measurements will include sample density, and glass transition, crystallization, and melting temperatures
  - Sample microstructure will be determined from optical and scanning electron microscope studies
  - Also sample compressive strength and Vicker's microhardness will be obtained
  - The results of these studies should provide the optimum microwave processing parameters for compaction of small samples

Evaluation of Microwave Processing

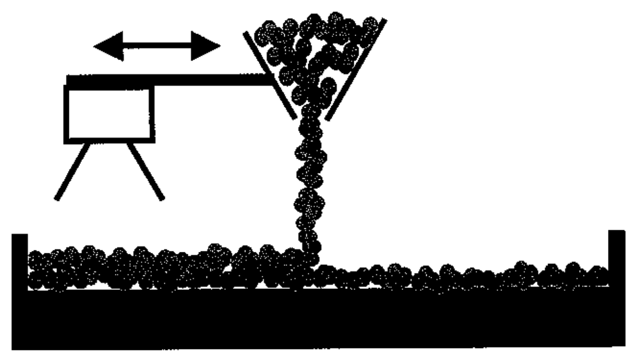
- Higher Power Microwave Heating Studies
  - Once an optimum set of heating parameters are found, larger simulant samples will be processed using high powered 2.45 GHz magnetron systems
  - The results of these new heating studies will be compared to earlier results to see how the processing parameters change with larger samples
- Lunar Regolith Studies
  - Apollo samples will be tested under the same optimum heating conditions found from the simulant studies
  - These tests will validate that the simulants used are a good representation of the regolith composition

Concepts for a Scaled-Up Lunar Facility

- Magnetron Array
  - Early proposal (1986)
  - Lunar rover could pull bank of magnetrons to heat or sinter the regolith
  - The fused material could be left in place as a roadbed or surfaced area or cut into building blocks
  - This approach needs a large energy source

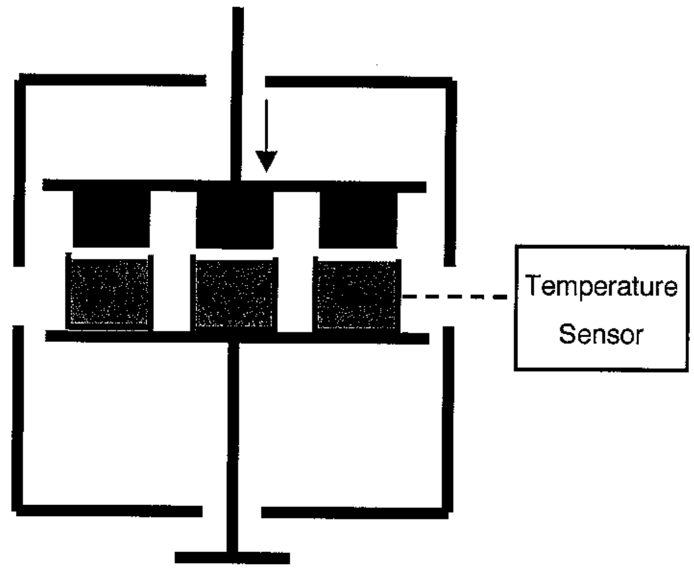


- Magnetron Assembly Line
  - Regolith could be placed into crucibles and heated in a microwave oven to form many building blocks
  - The regolith could be compressed under pressure or just sintered

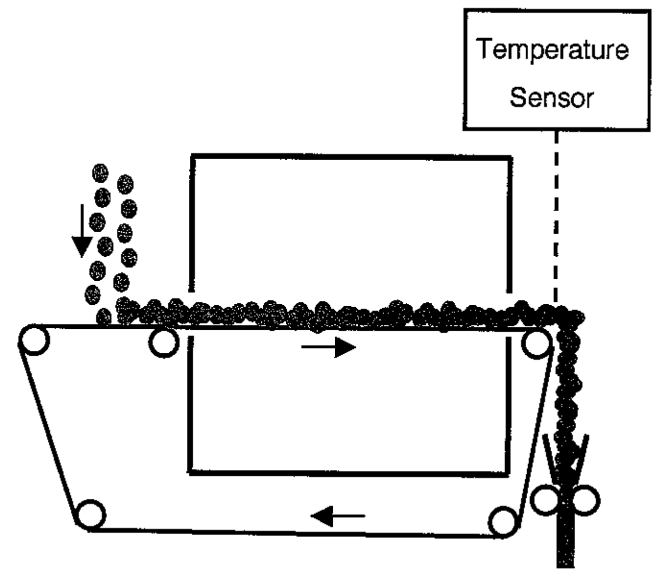


Concepts for a Scaled-Up Lunar Facility

- Batch Processing
  - Regolith could be placed into crucibles and heated in a microwave oven to form many building blocks
  - The regolith could be compressed under pressure or just sintered



- Continuous Processing
  - A more advanced design could use a conveyor belt to continuously process the regolith in a microwave oven
  - The heated and softened soil would then be rolled into a uniform sheet for use in various construction projects



Concluding Remarks

- Roadmap for Developing a Lunar Microwave Facility
  - We have presented an approach to determine the source of the enhanced microwave heating
  - A set of microwave heating studies are proposed for a specially designed realistic simulant to determine optimum processing parameters
    - Apollo lunar soil will be used to validate the heating features found for the simulant
  - We have also introduced several possible designs for a future lunar microwave processing facility
    - Once a design is chosen, a prototype unit will be built and tested to demonstrate the production of realistic building blocks
- Future Lunar Facility
  - In the future when sufficient funds become available, a microwave facility for processing regolith *on the lunar surface* will be ready to be built