



# MICROWAVE SINTERING: INITIAL SCALE-UP FOR LUNAR LANDING AND LAUNCH PAD CONSTRUCTION

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# Agenda



- **Overview**
  - Goals
  - Objectives
  - Partners
- **Materials**
  - Synthetic equivalents
  - Bakeout
- **Testing**
  - TGA mass spectrometry
  - Dielectric
  - Frequency
  - Sintering
- **Modeling & Analyses**
  - Microwave coupling
- **Design**
  - Magnetron
  - Solid state
- **Summary**



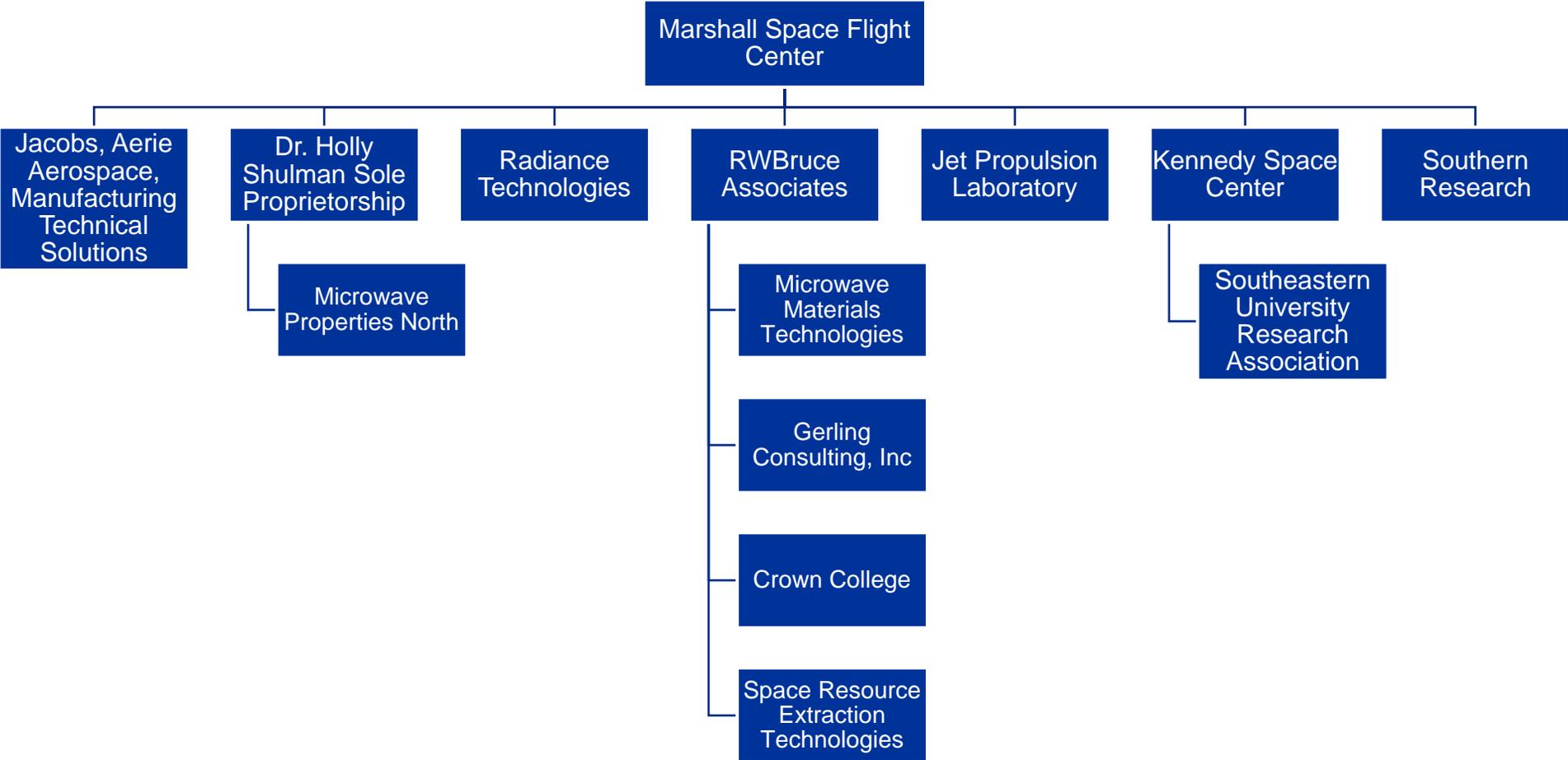
# Microwave Structure Construction Capability (MSCC) Overview



- **Goal**
  - Mature the technology and capability to emplace in-situ-based construction process on the Moon to form horizontal infrastructure elements (e.g., landing pads, roads, etc.)
- **Objectives**
  - Develop and demonstrate microwave sintering protocols/processes using lunar simulants in thermal vacuum
  - Develop microwave horn/applicator designs
  - Fabricate plates for property testing



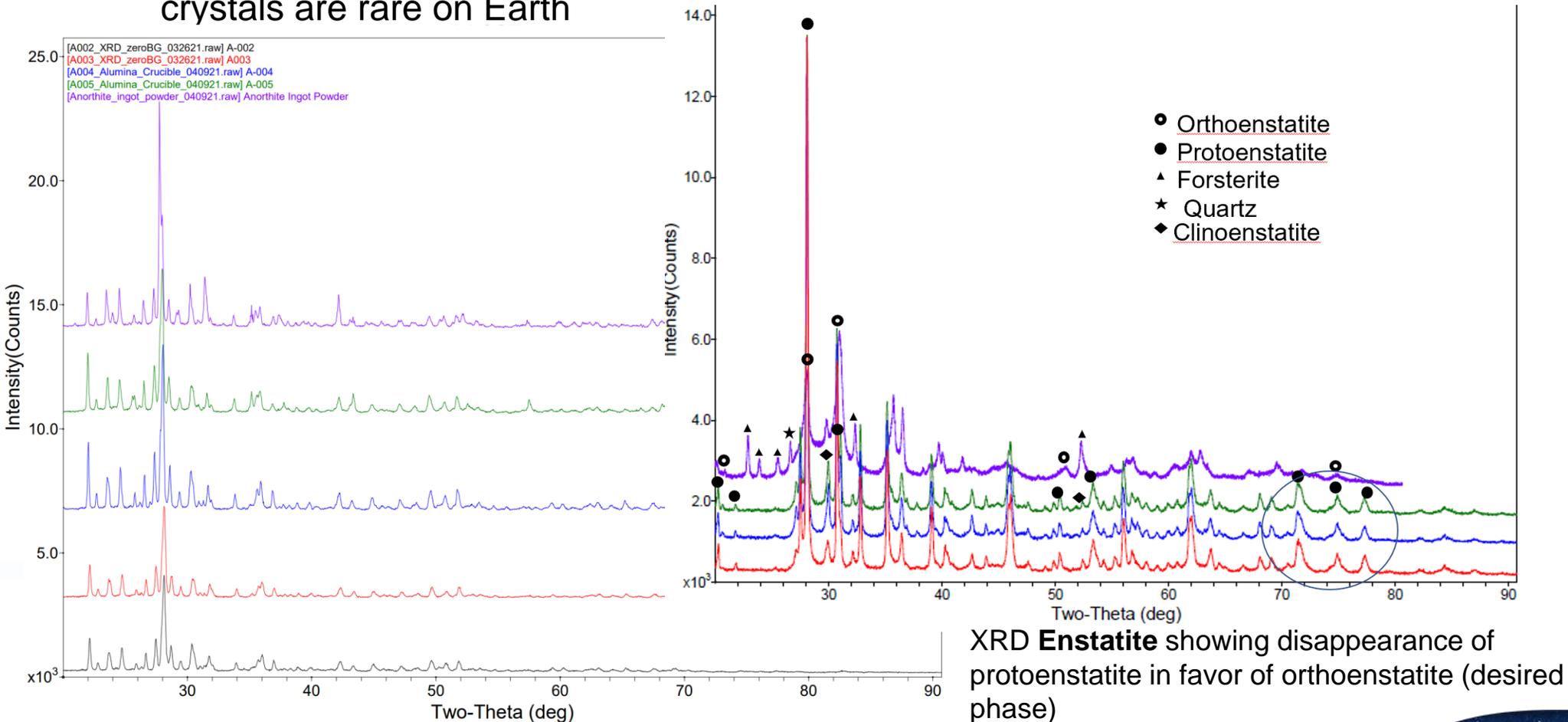
# MSCC Partners



# Synthetic Mineral Equivalents

- **Scalable methods identified**

- Anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ) Common plagioclase mineral on the moon, rare on Earth
- Diopside ( $\text{MgCaSi}_2\text{O}_6$ ) Common clinopyroxene mineral, however typically found in solid solutions on Earth
- Enstatite ( $\text{MgSiO}_3$ ) Common orthopyroxene mineral, however isolated pure crystals are rare on Earth



XRD **Anorthite** from a variety of scalable process methods

XRD **Enstatite** showing disappearance of protoenstatite in favor of orthoenstatite (desired phase)

Fabrication & testing done at Alfred University

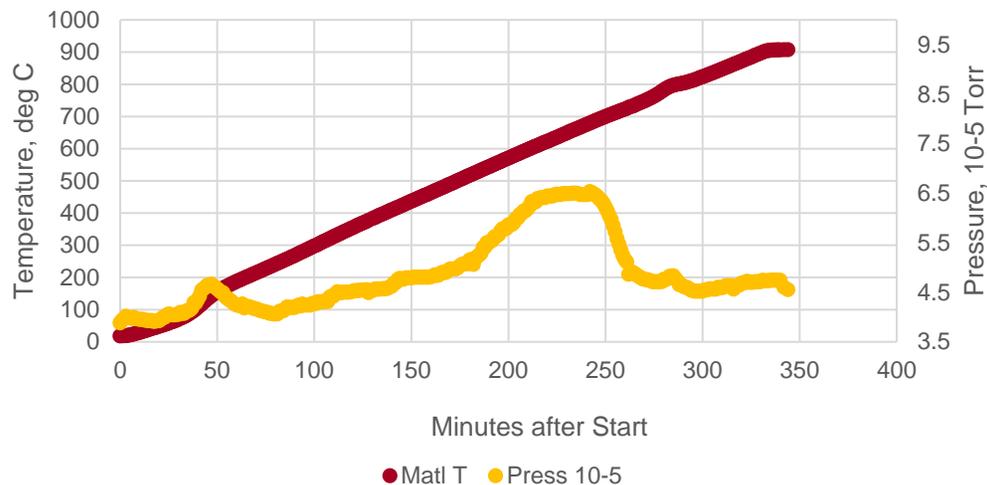


# Bakeout

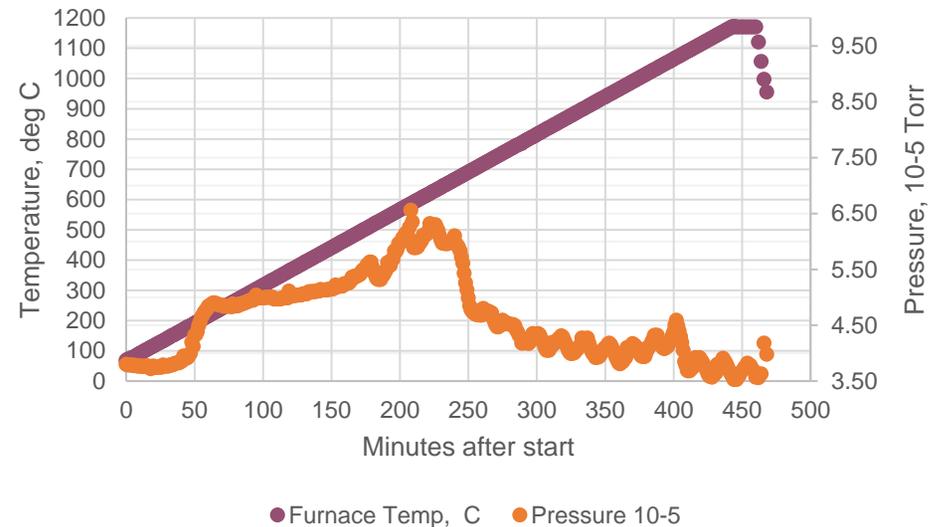


- **Objective: Determine optimal bakeout temperature and time to remove non-lunar material**
- Inert and vacuum heat treating with radiant furnace to various temperatures
- Testing to examine what comes off and what is left behind
  - Microscopy, particle size analysis, Thermal Gravimetric Analyses (TGA)-Fourier Transform Infrared, TGA with Mass Spec, Vacuum TGA, Liquid Nitrogen trap, etc.

900 C Max Temperature Thermal Pretreatment  
JSC-1A



1200 C Max Temp Thermal Pretreatment of JSC-1A

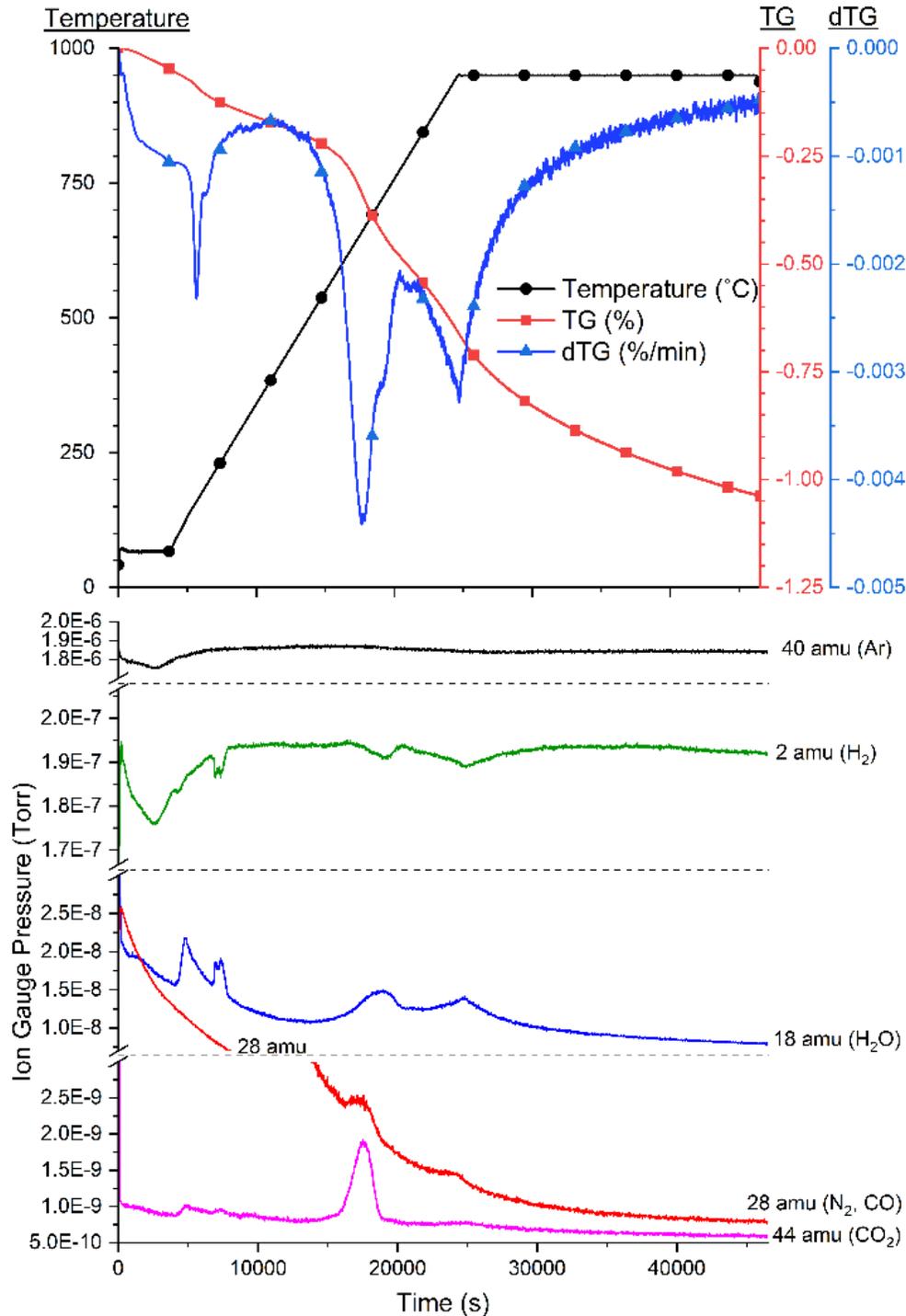


Comparison of temperature/pressure changes during JSC-1A pretreatment tests (JPL)





# TGA + Mass Spectroscopy

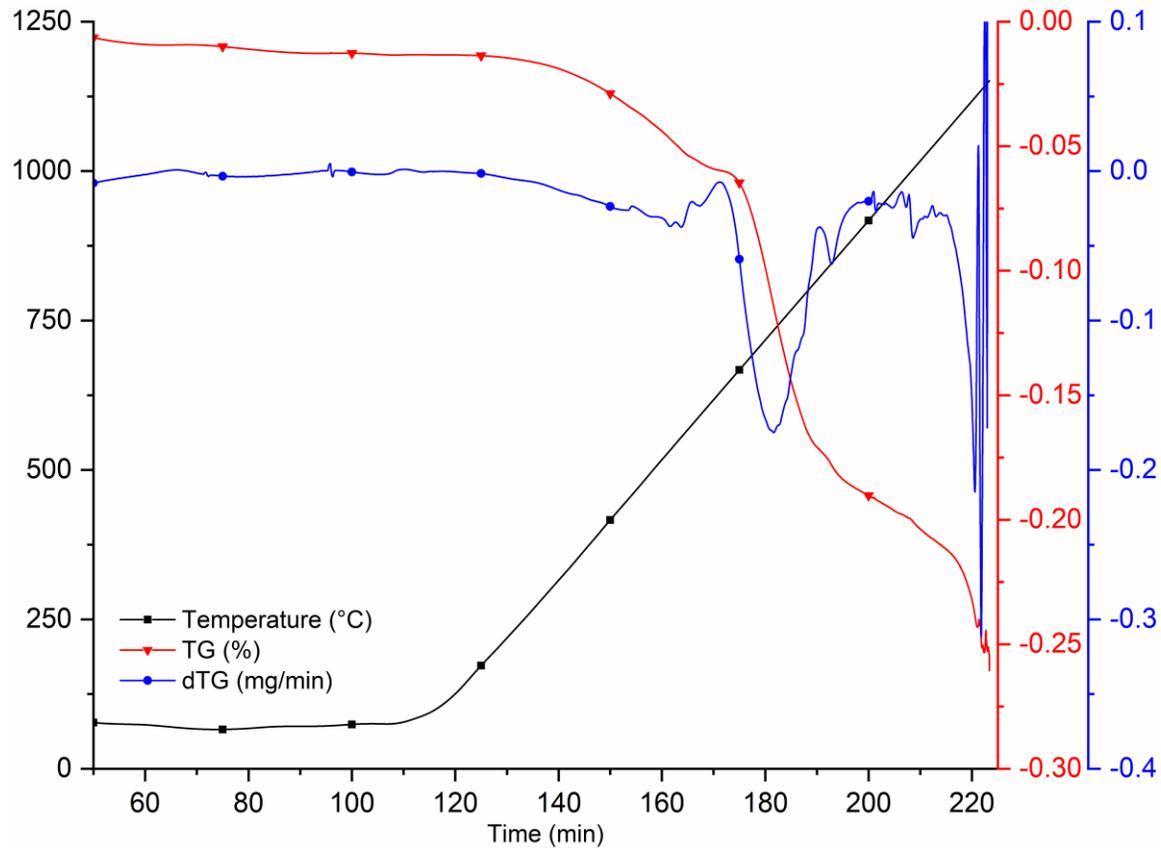


- JSC 1A in Ar/5H<sub>2</sub> gas flow
- MS captures outgassing events:
  - ~100°C: H<sub>2</sub>O
  - ~700°C: CO<sub>2</sub>
- 950°C and higher: H<sub>2</sub>O – oxide reduction

Testing done at MSFC



# Vacuum TGA Testing

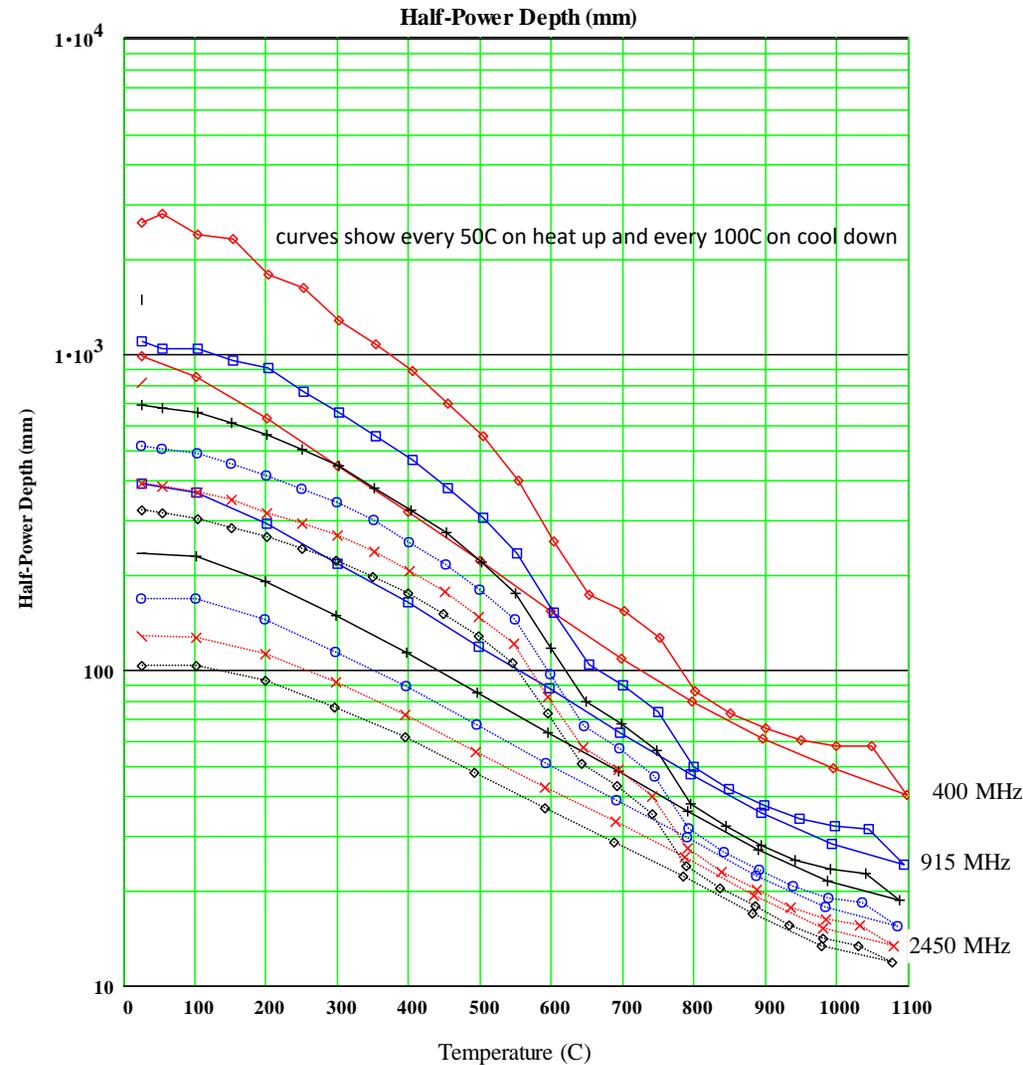
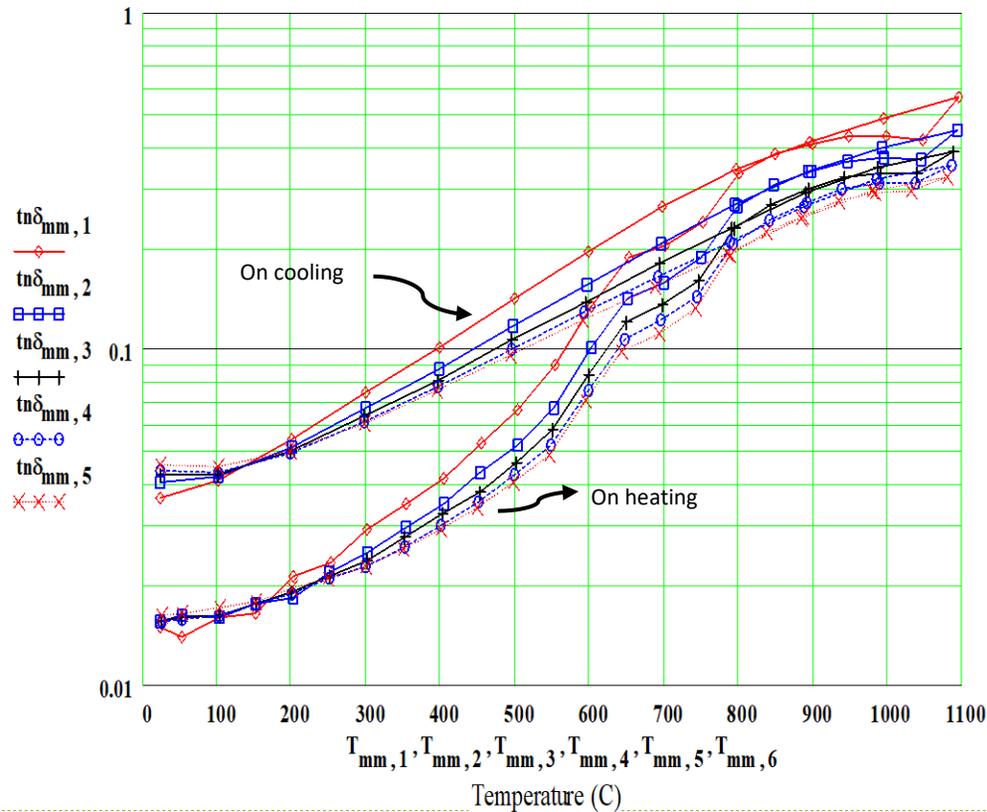


JSC-1A TGA in Vacuum with 200C Bakeout (MSFC)

- Thermal conductivity, frequency, permittivity, dielectric, TGA inert and vacuum, microscopy, etc. also being conducted



# Dielectric Properties: JSC-1A (Heating and Cooling)



Dielectric Loss Tangent as a Function of Temperature and Frequency

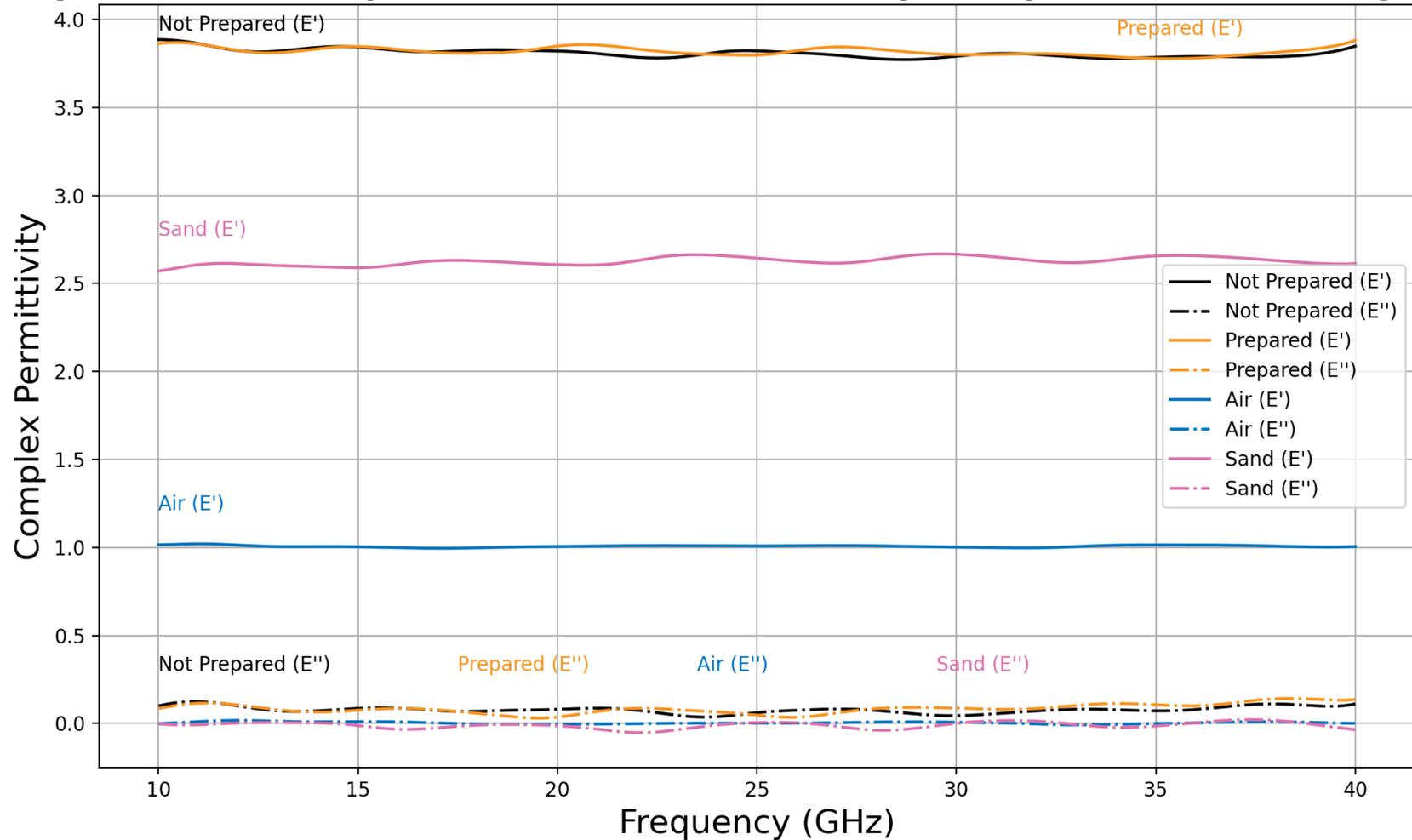
Penetration Depth as a Function of Temperature and Frequency

Heat treat was 500C Argon



# JSC-1A Frequency Testing at Ambient Conditions

## Complex Permittivity of Materials without Acrylic Layers (Inversion Algorithm)



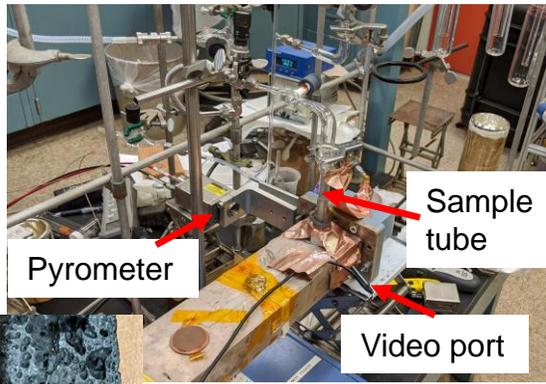
The prepared and unprepared samples are JSC-1A. The Prepared samples have been baked out at 200°C for 8 hours and stored in vacuum jars for transport to the testing site. The Unprepared samples were used as received.

Testing done through Radiance Technologies

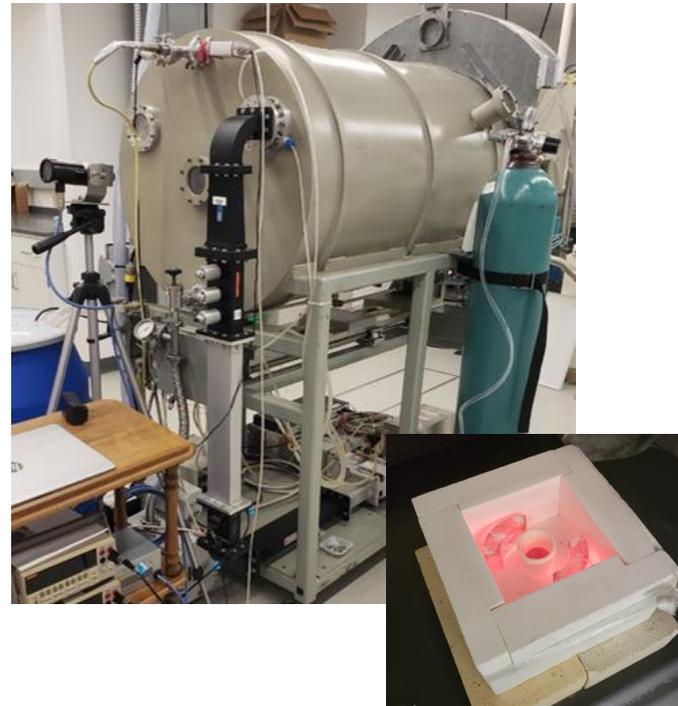


# Microwave Sintering

- Objectives
  - Gain understanding of the heating profile, uniformity, and depth of penetration of the microwaves into the regolith
  - Determine and develop optimized energy efficient process
    - Volume sintered per hour from -200C to sintering temperature, accounting for porosity
    - Mitigating thermal runaway



Small-scale Thermal Vacuum (TVAC) chamber with 200W microwave system. Sintered sample was done in vacuum. (JPL)



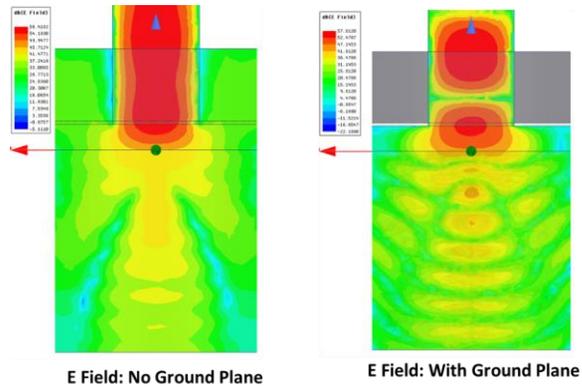
2' diameter inert atmosphere chamber with 3kW microwave system (Alfred University)



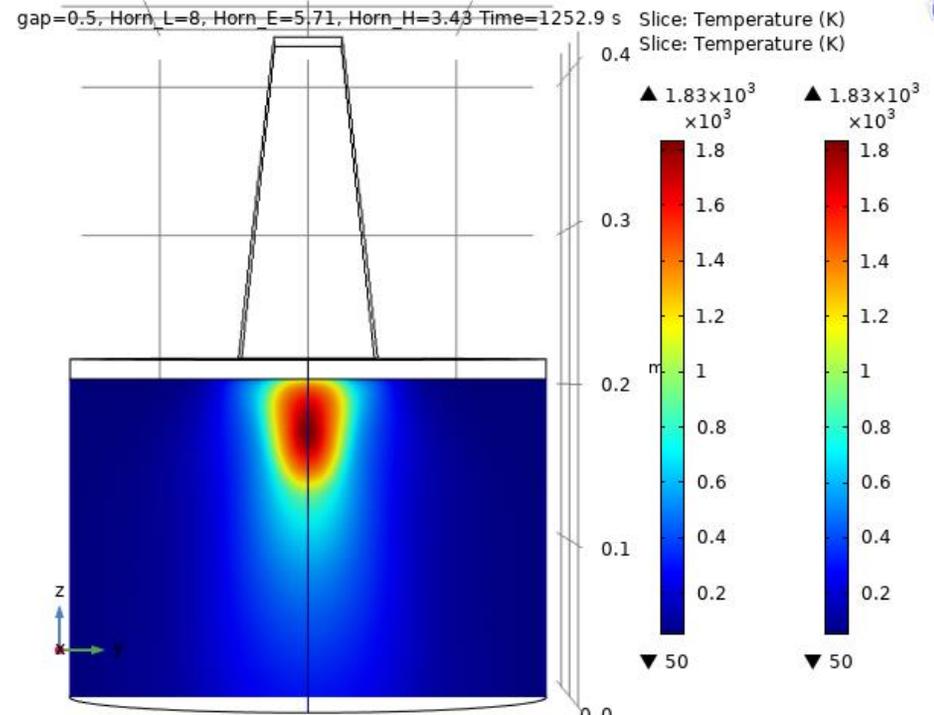
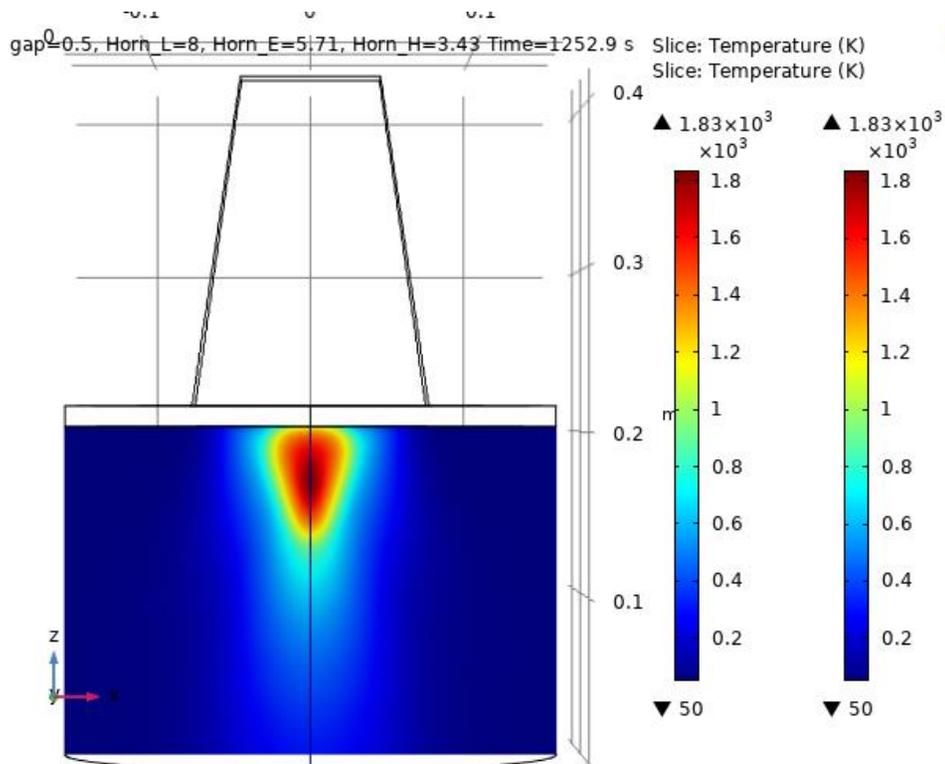
4' diameter TVAC chamber with 2kW microwave system and various horn configurations. Sintered sample was done in air. (MSFC)



# Microwave Coupling with JSC-1A



Open-Ended Waveguide Launcher With and Without Ground Plane via HFSS (JPL)

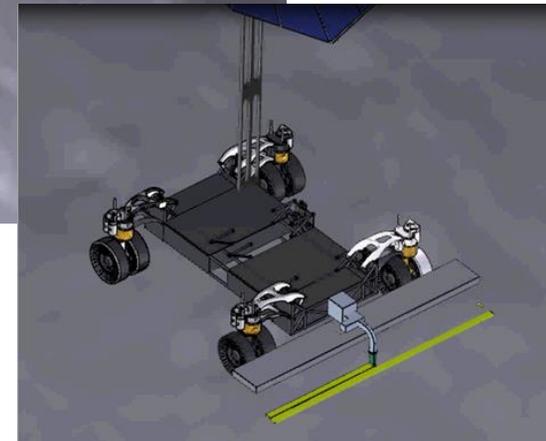
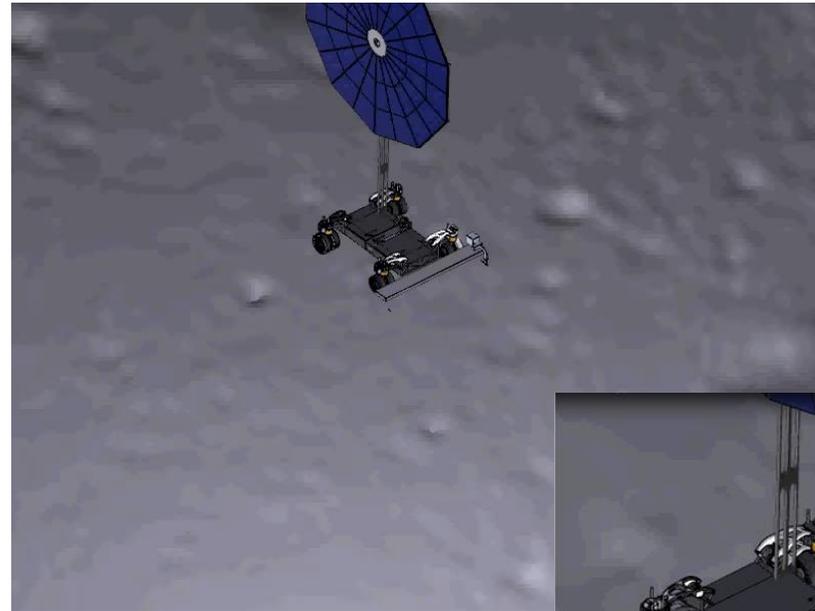
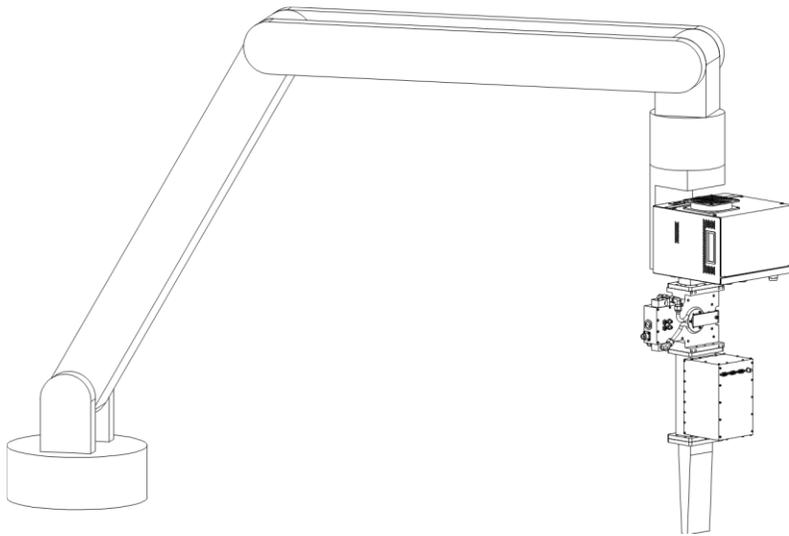


COMSOL analysis of microwave heating with a horn and 0.5" gap between horn and simulant bed (MSFC).



# Design

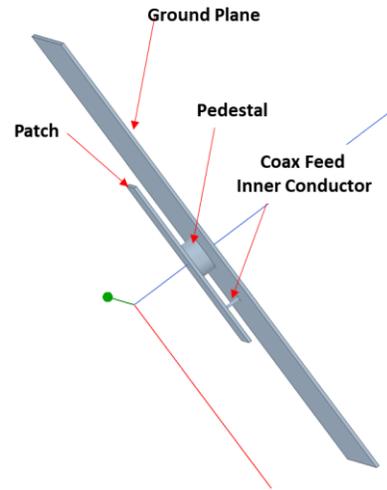
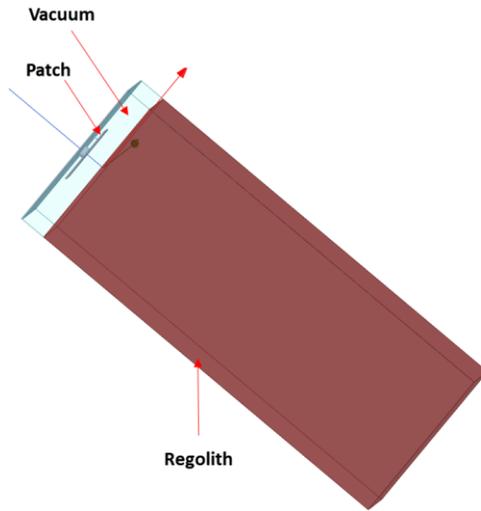
- Microwave source (magnetron, solid state)
- Thermal management system
- High temperature applicator that can work continuously in a lunar environment while exposed to an 1100C radiant surface and volatiles



Various options being considered  
(Gerling Consulting left image and MSFC right image/video).

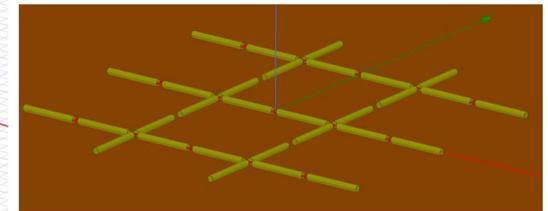
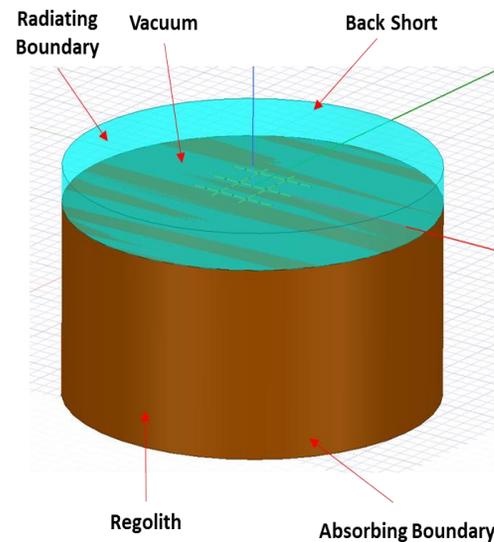


# Solid State Design



All-Metal Patch Array Element

Close-Packed Dipole Array for Regolith Sintering

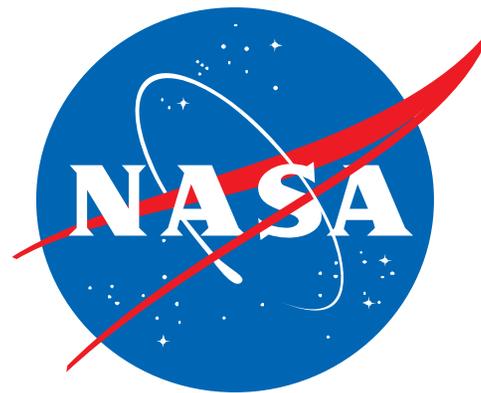


# Summary



- **Fabricating synthetic minerals to characterize constituent materials**
- **Defining bakeout cycle for simulants**
- **Characterizing simulant to support processing protocols development**
- **Conducting microwave sintering experiments at multiple locations with different capabilities to develop sintering protocols and provide inputs to con-ops**
- **Conducting microwave coupling analyses at multiple locations and using different software**
- **Pursuing various design configurations and microwave sources**





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