Method of Volatile Detection in Lunar Regolith, Percussive Hot Cone Penetrometer Thermal Testing and Modeling

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Background – Lunar poles prospecting

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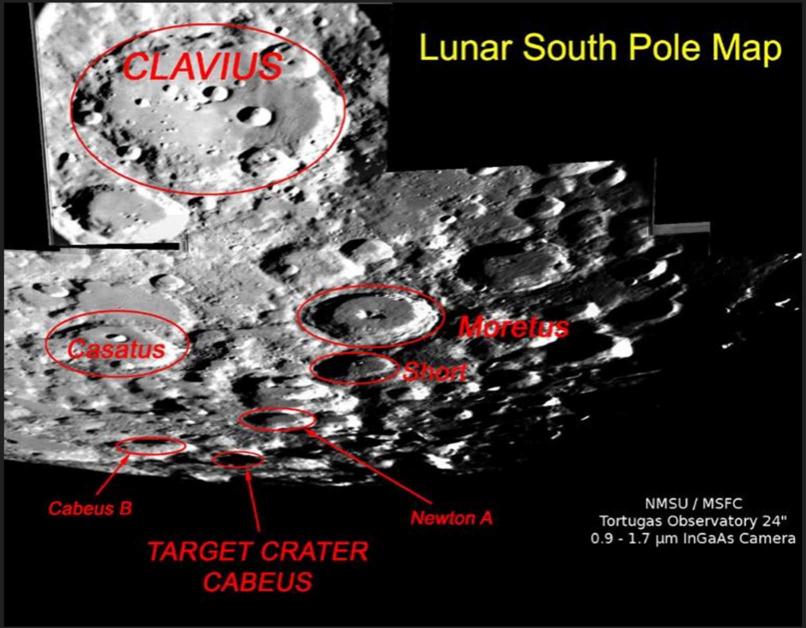


Image Credit: NMSU/MSFC Tortugas Observatory

LCROSS & LRO

- LCROSS Impact at the Cabeus crater created an ejecta plume
- Volatile compounds containing H-, C-, N-, and S-bearing species were detected (Colaprete et al., 2010; Gladstone et al., 2010)

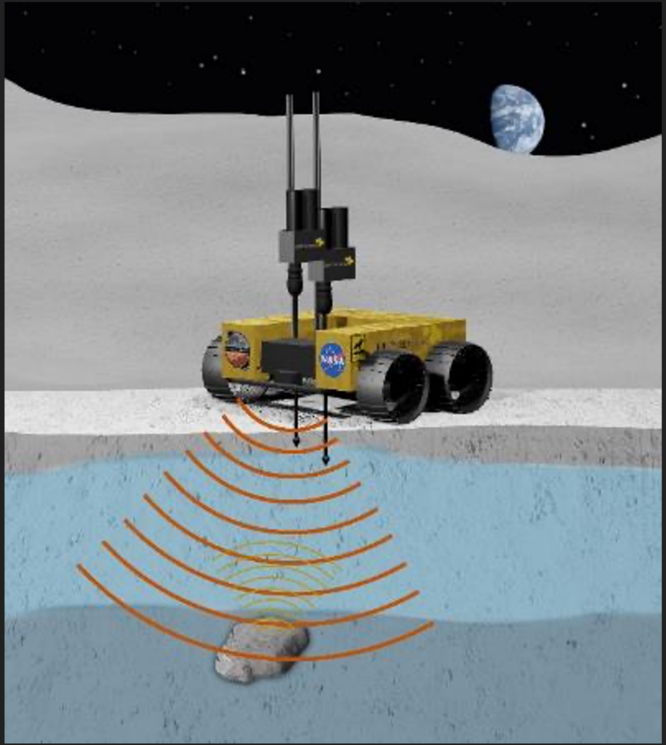
Ground Prospecting

- Provide more detailed vertical and lateral volatile distribution data for PSRs
- Only active impact experiments, ground sampling, or sample return missions from cold traps will provide detailed information about chemical compositions of lunar polar volatiles (Berezhnoy et al., 2012)

Percussive Hot Cone Penetrometer & Ground Penetrating Radar

- Percussive Hot Cone Penetrometer (PHCP)
  - Geotechnical Data
    - Cone surface pressure & load
    - Impact loads
    - Measurement of depth displacement
  - Thermal Data
    - Volatile quantity and distribution
    - Desiccated regolith properties

- Methods for validating and influencing cone design:
  - Experimental Testing – Thermal Profiles of Wet and Dry Regolith
  - Thermal Modeling – Determine sensitivity requirements



Experimental Testing – Determining Heat Affected Zone

Initial Goal of Experimental Testing Concept Layout

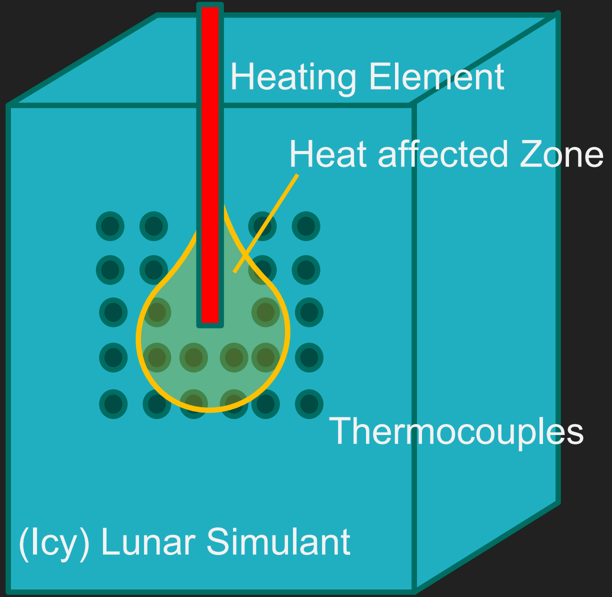


Table 1: Thermal Profiling Test Matrix 1

Sample Material and Volatile Composition	Constant Power Supplied		
	30 Watts	50 Watts	100 Watts
Dry, F-80	3	3	2
Wet 5 wt%, F-80	1	1	1
Wet 10 wt%, F-80	-	1	1
Frozen 5wt%, F-80	-	1	1
Frozen 10wt%, F-80	-	1	1
Dry, MTU-LHT-1A	1	1	1
Wet 5 wt%, MTU-LHT-1A	1	1	1
Wet 10 wt%, MTU-LHT-1A	-	1	1
Frozen 5wt%, MTU-LHT-1A	1	1	1
Frozen 10wt%, MTU-LHT-1A	-	1	1
Wet 1-2wt%, MTU-LHT-1A			
Wet 7wt%, MTU-LHT-1A	1	1	1
Frozen 1-2wt%, MTU-LHT-1A			
Frozen 7wt%, MTU-LHT-1A			

X - Recently Completed Tests

X - Upcoming Tests

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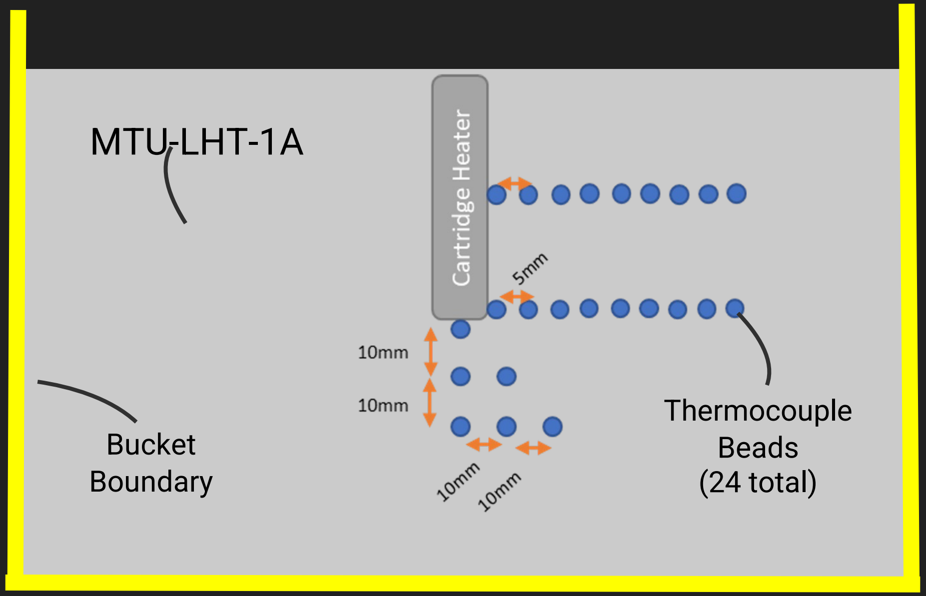
Experimental Testing – Hardware used for 1st test setup

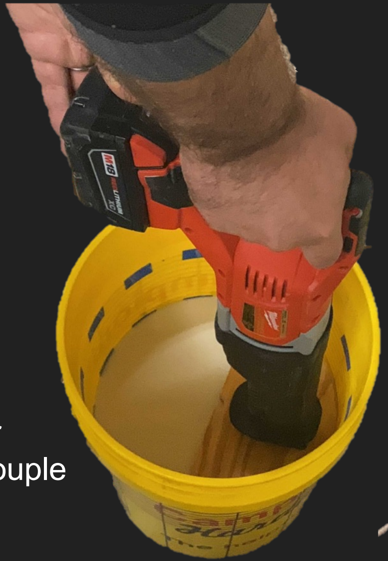
Current Test Setup Hardware:

- Ø12.7mm x 101.6 mm, 750W Cartridge heater
- (24) K-Type Thermocouples
- NI cDAQ & Microcontroller Operated Power Logger
- Modified 5-gallon bucket

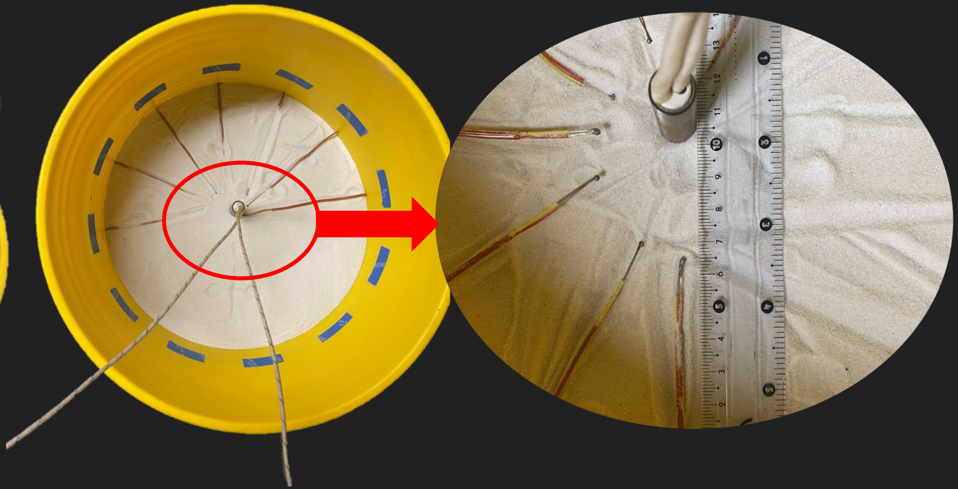


Experimental Testing – Test Setup Procedure

Modified 5-gallon bucket

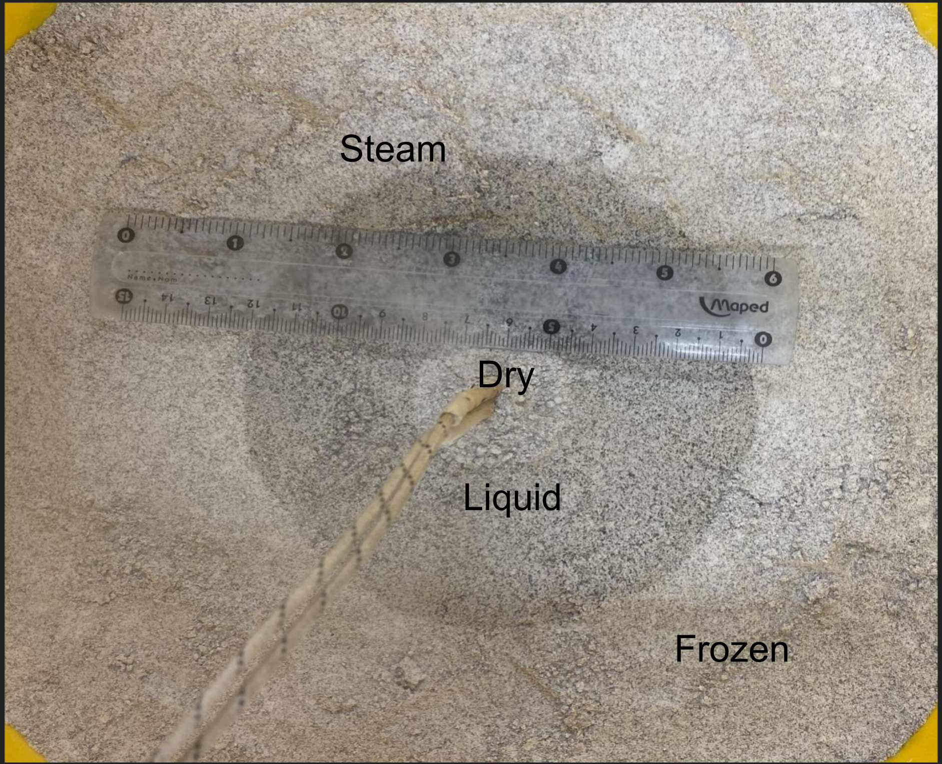


Vibratory compaction or Consistent compressive compaction



Heater and relative thermocouple spacing

Experimental Testing – Test Observations



Frozen 10wt% Water & MTU-LHT-1A @ Constant 100 Watts

Experimental Testing – Dry MTU-LHT-1A Test Results

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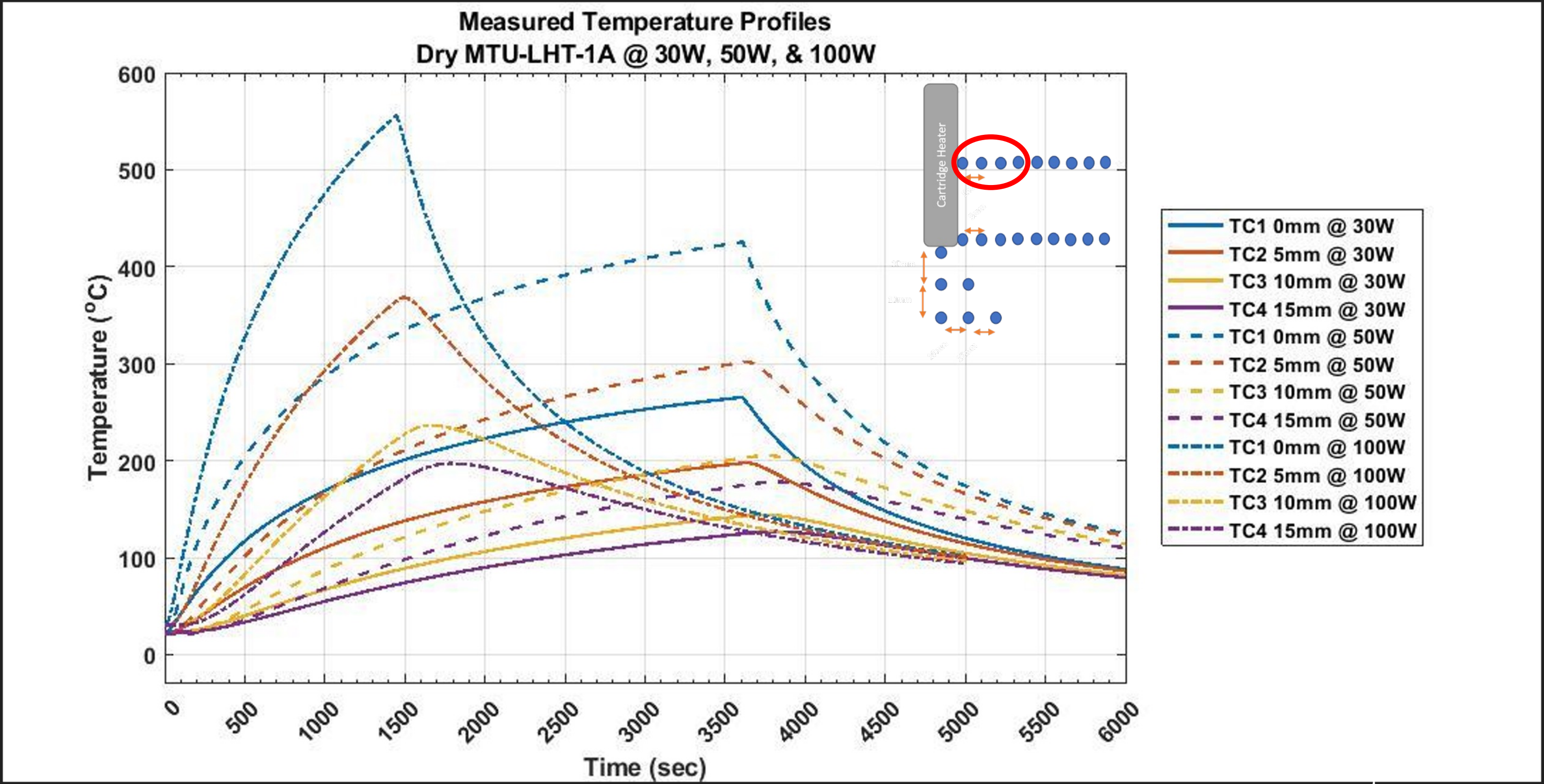
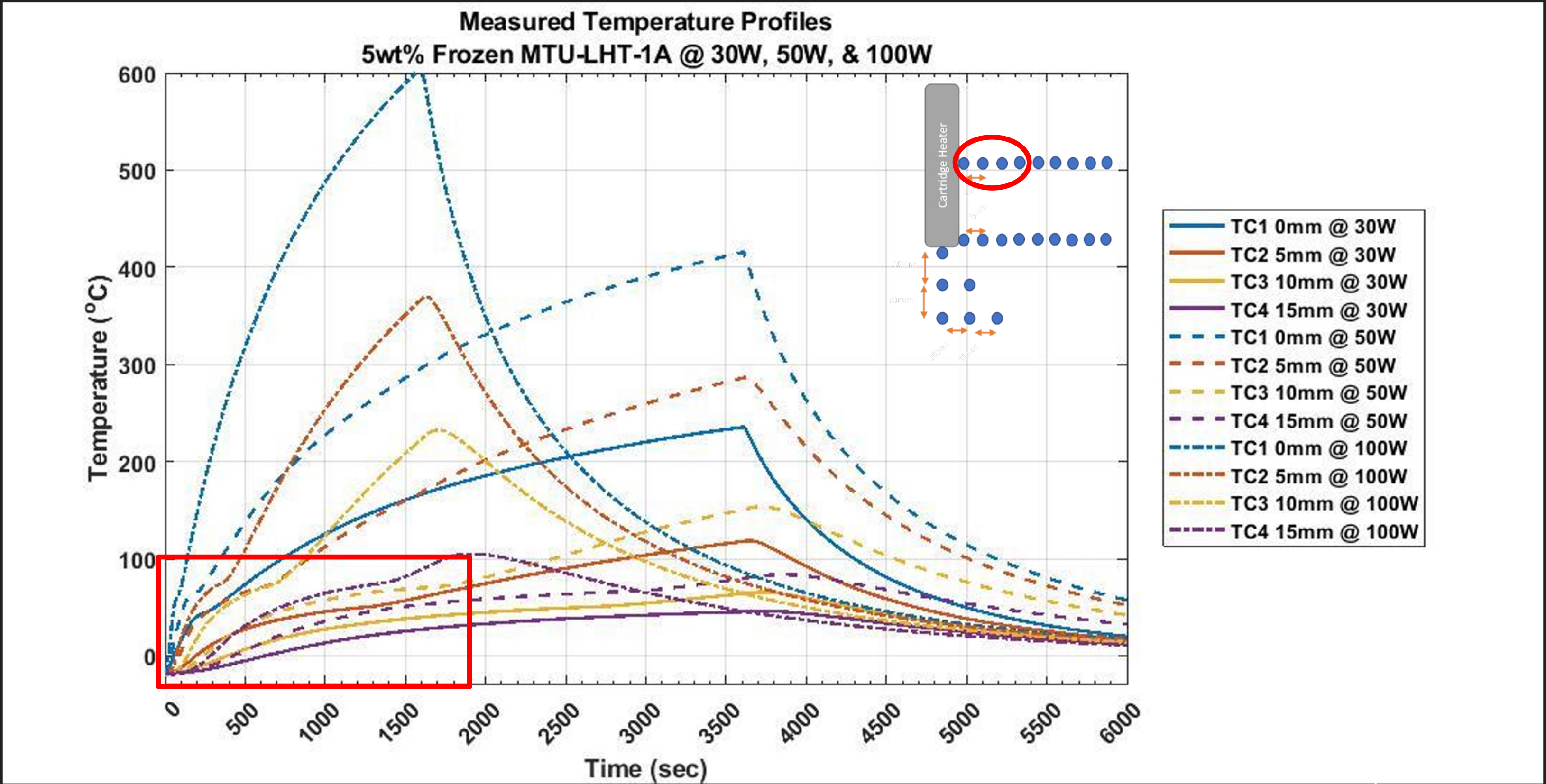
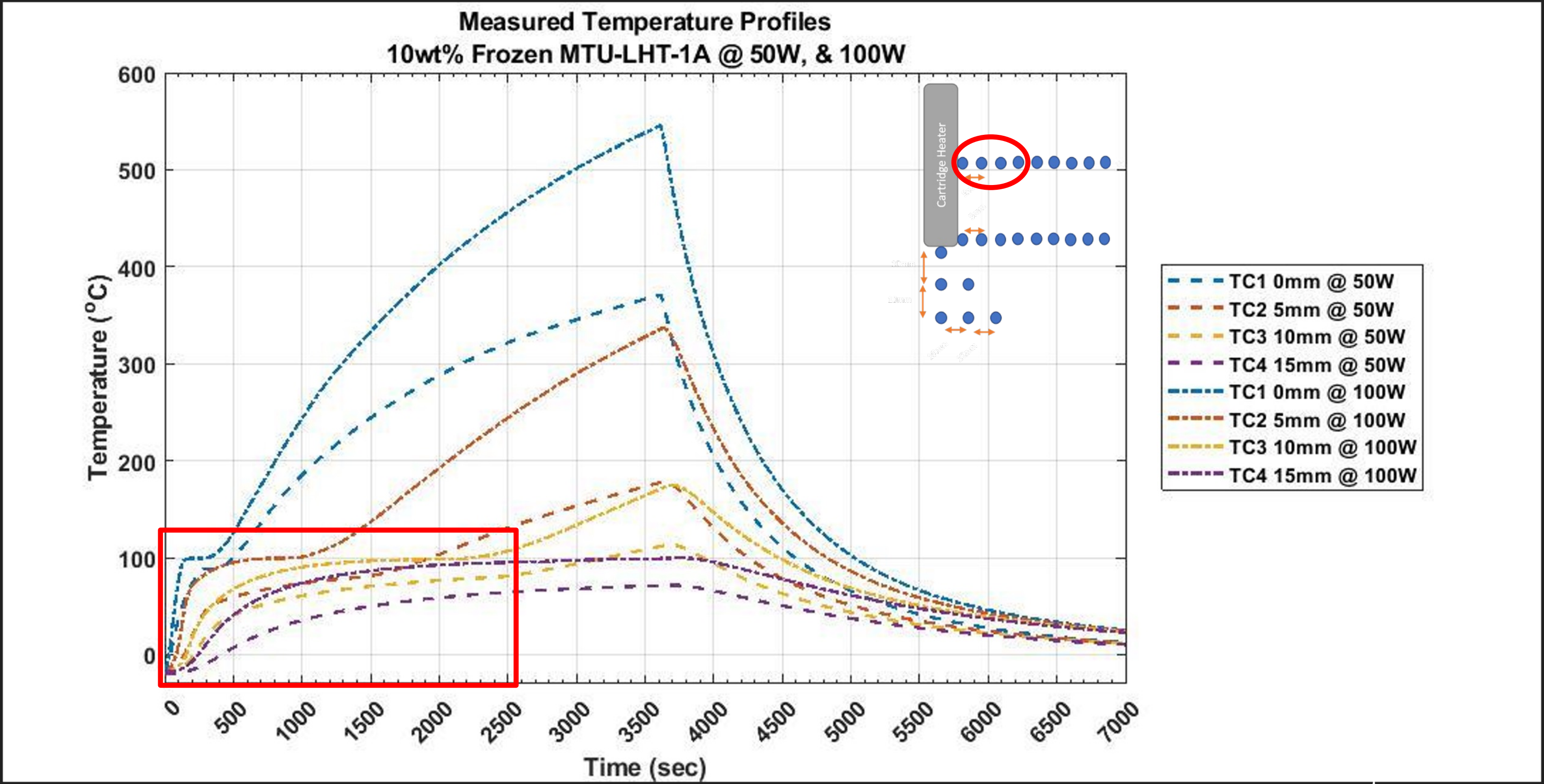


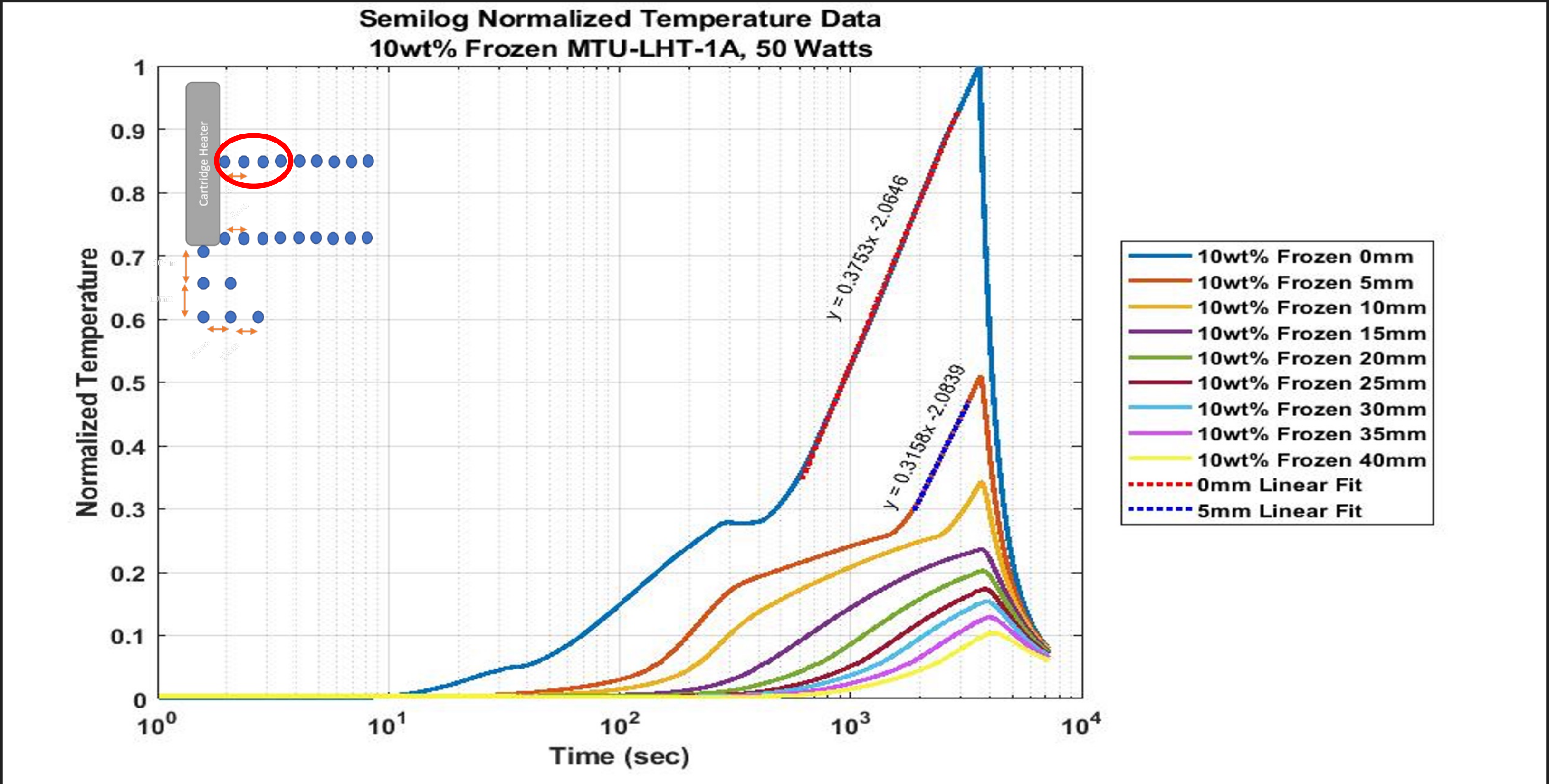
Experimental Testing – 5wt%, MTU-LHT-1A Test Results



Experimental Testing – 10wt%, MTU-LHT-1A Test Results



Experimental Testing – Visualizing Test Results

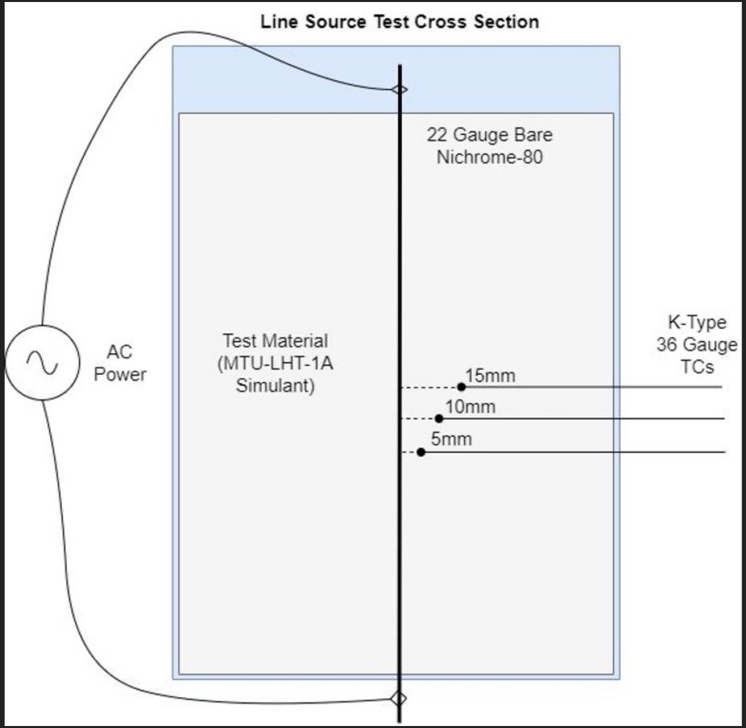


Thermal Properties of Lunar Subsurface Environment

- Physical properties impacting PCHP's thermal response
  - Level of regolith compaction/relative density
  - Saturation and distribution of volatiles
  - Cone geometry and materials
  - Contact resistance
  - Temperature dependency of thermal properties
  - Mass transfer (phase change of volatiles)
  - Volatile state (Physisorbed, Chemisorbed, or Bulk)
- Various forms and steps of modeling needed to understand these properties
  - Dry regolith properties will eliminate unknowns during testing with volatiles
  - Once water is understood, other volatiles will be added to models

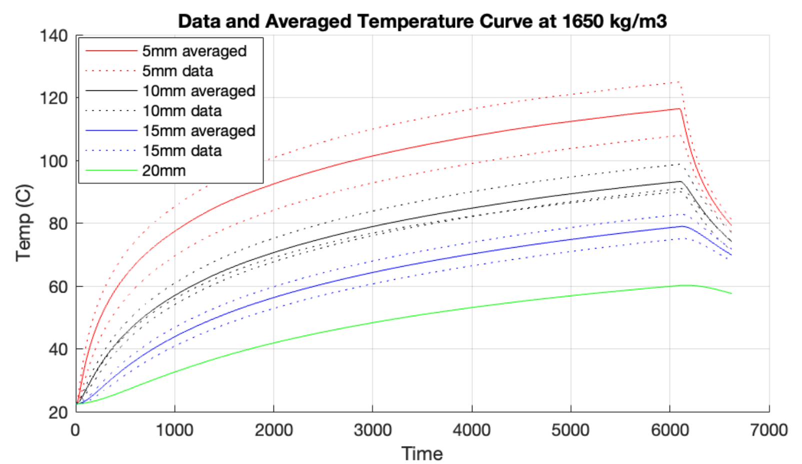
Line-Source Testing–Overview

- Line-source model represents simplified solution
  - 1D radial heat equation in semi-infinite domain
  - Nichrome wire acts as line heat source
- Thermocouples at 5 mm, 10 mm, 15 mm, and 20 mm
- Effective thermal properties found using non-linear least-squares optimizer
  - Solution from Carslaw and Jaeger 1959

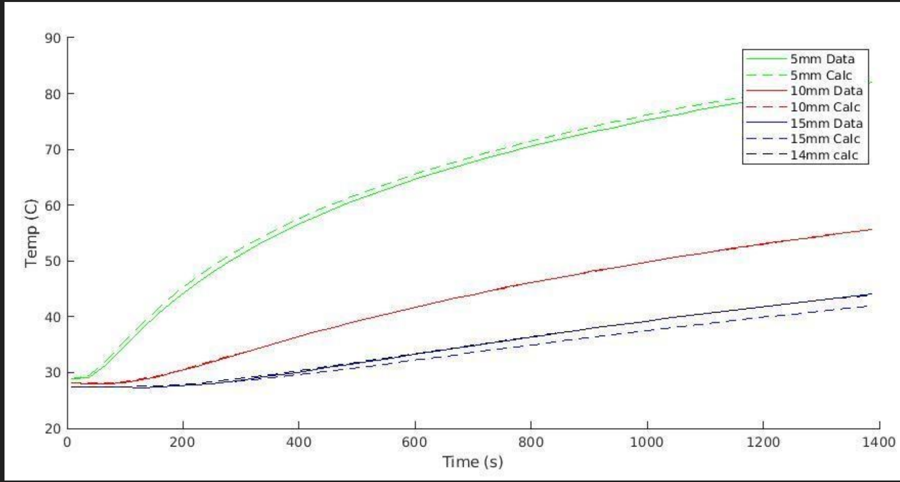


Line-Source Testing – Compaction

- Compaction testing is in progress
  - Thermal conductivity and specific heat as a factor of compaction and temperature
  - Using Dry MTU-LHT-1A



Line-Source Testing – Results

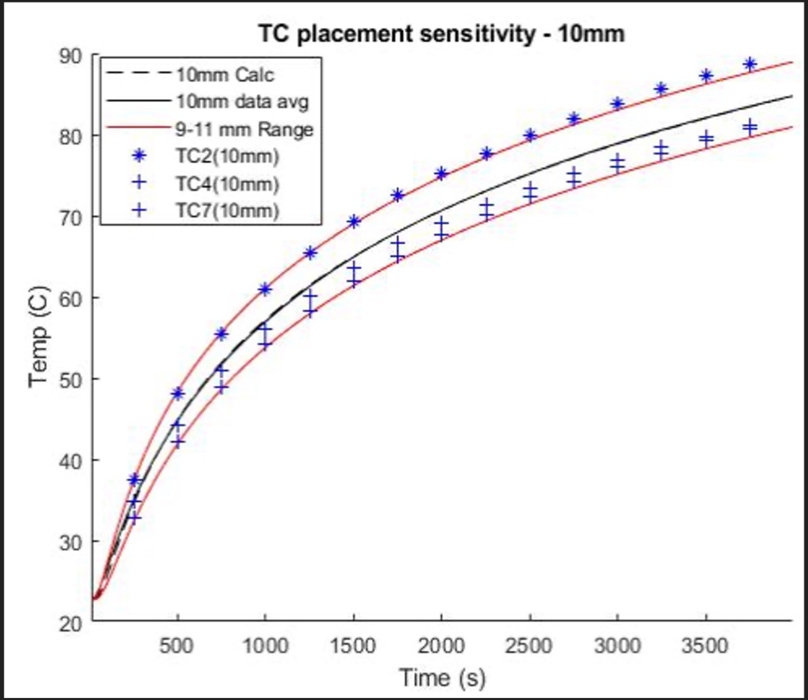


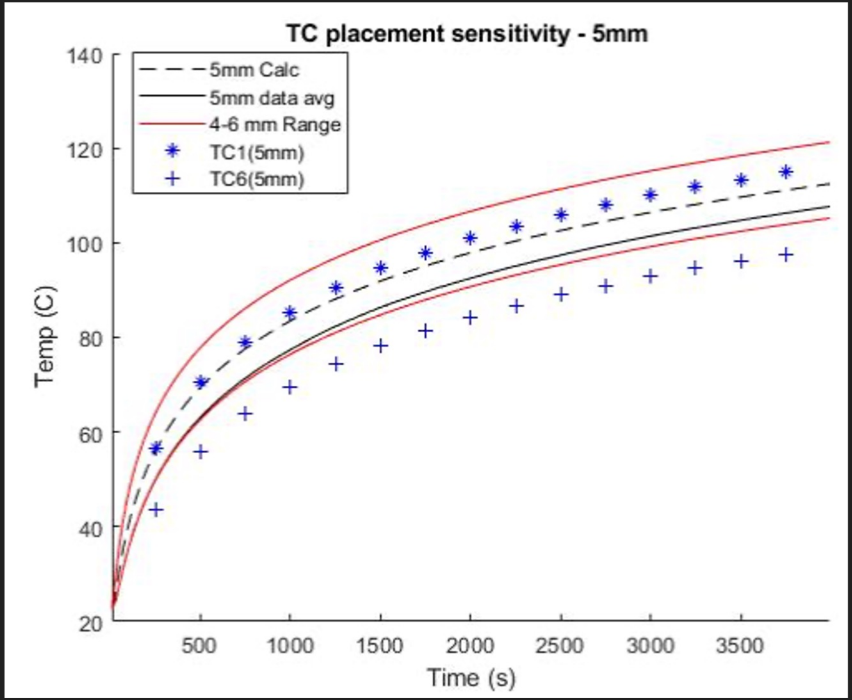
Thermal Conductivity = 0.341 W/m*C
Thermal Diffusivity = 9.75e-8 m^2/s

TC Location	R^2	Max Error	Average Error
5 mm	0.99583	1.1452 °C	0.9688 °C
10 mm	0.99995	0.1683 °C	0.0054 °C
15 mm	0.94227	2.1316 °C	1.0920 °C
*14 mm	0.99946	0.2432 °C	0.0669 °C

- Optimizer results match well with experimental data and comparable to JSC-1A in ambient tests
- Error is attributed to thermocouple misplacement

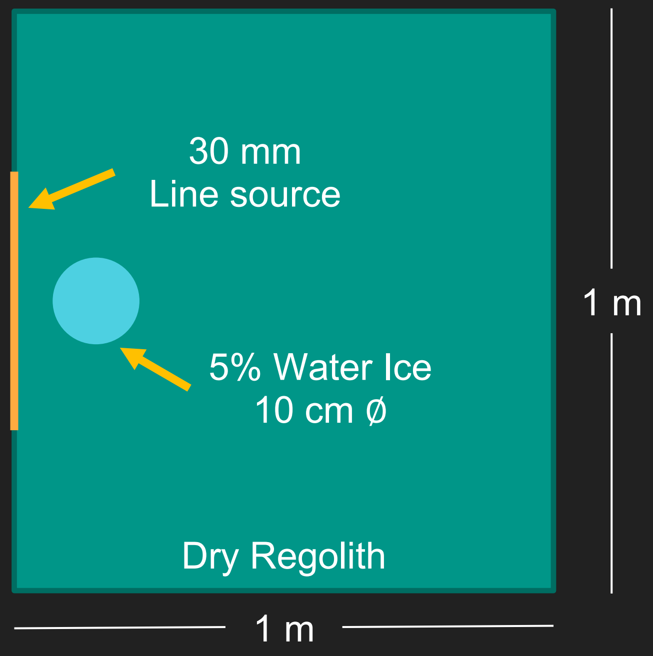
Line-Source Testing – TC Placement Error





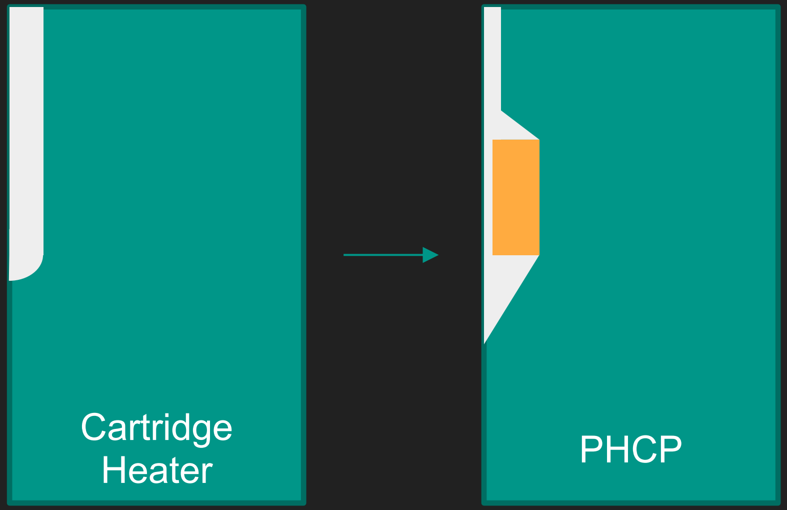
Line Source Modeling – Preliminary Phase Change

- 2D axisymmetric line source model
  - Developed in COMSOL
  - 2 phase (ice and vapor)
  - Water vapor transport
- Phase change model will aid in understanding of how different forms of ice will impact response
- Future modeling will investigate impact of additional volatile species



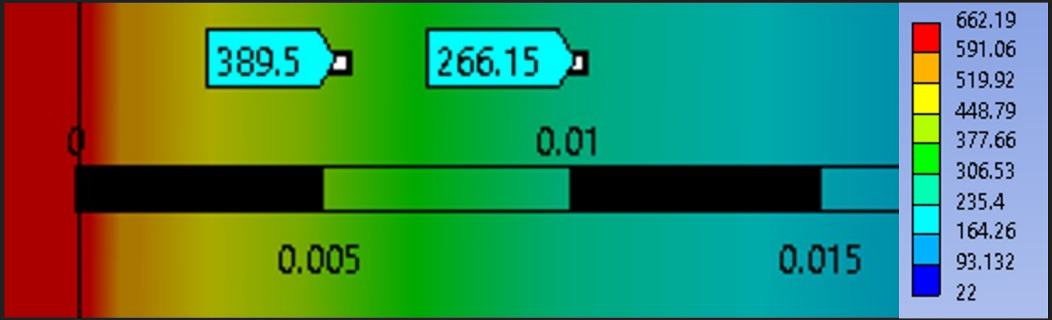
PHCP Geometry – Model Validation

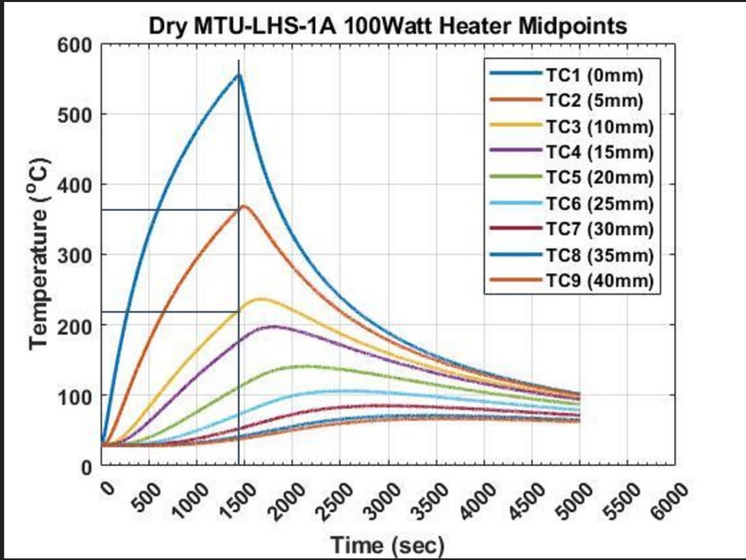
- Determining the thermal response of PHCP is required for developing a design to meet specifications
    - Accuracy of sensors needed to measure 1 wt%± of volatiles ± 0.1 wt%
    - Temperature range of materials needed
    - Input power to reach phase change temperatures
- Model validation of cartridge heater
- Ansys modeling of PHCP proposed geometry



PHCP Geometry – Cartridge Heater validation

- Model of cartridge heater to validate methodology for heat transfer in regolith
- Results show close similarity to experimental data
- Error within expected bounds of error from thermocouple misplacement (±1mm)





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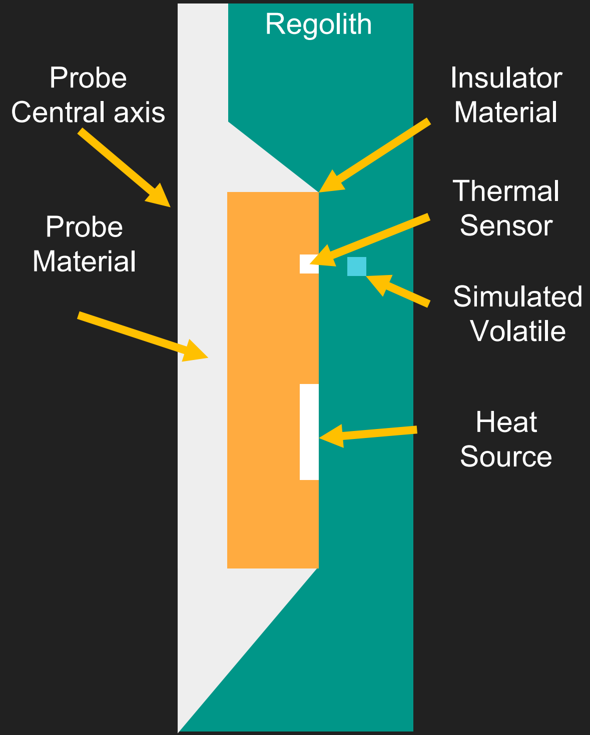
PHCP Geometry – Preliminary Modeling



- Thermal model based of off cone geometry
  - Stainless steel probe material
  - G10 composite as insulative material
  - Water ice simulated as time activated heat sink
- Location of TC is subject to change, but this mounting style removes placement error seen previously
- Simulated volatile will change in species and concentration to determine sensitivity of system

Testing Going Forward – Additional Volatiles Test Setup

Table 1: Volatiles being considered for testing. Extracted from LCROSS data (Colaprete et al. 2010)

Volatile Species	Target Temperature (Tripple Point)
H_2O - Water	< 0 °C
CO_2 - Carbon Dioxide	< -56 °C
CH_4 - Methane	< -182 °C
C_2H_4 - Ethylene	< -169 °C
CH_3OH - Methanol	< -98 °C
SO_2 - Sulfur Dioxide	< -75 °C

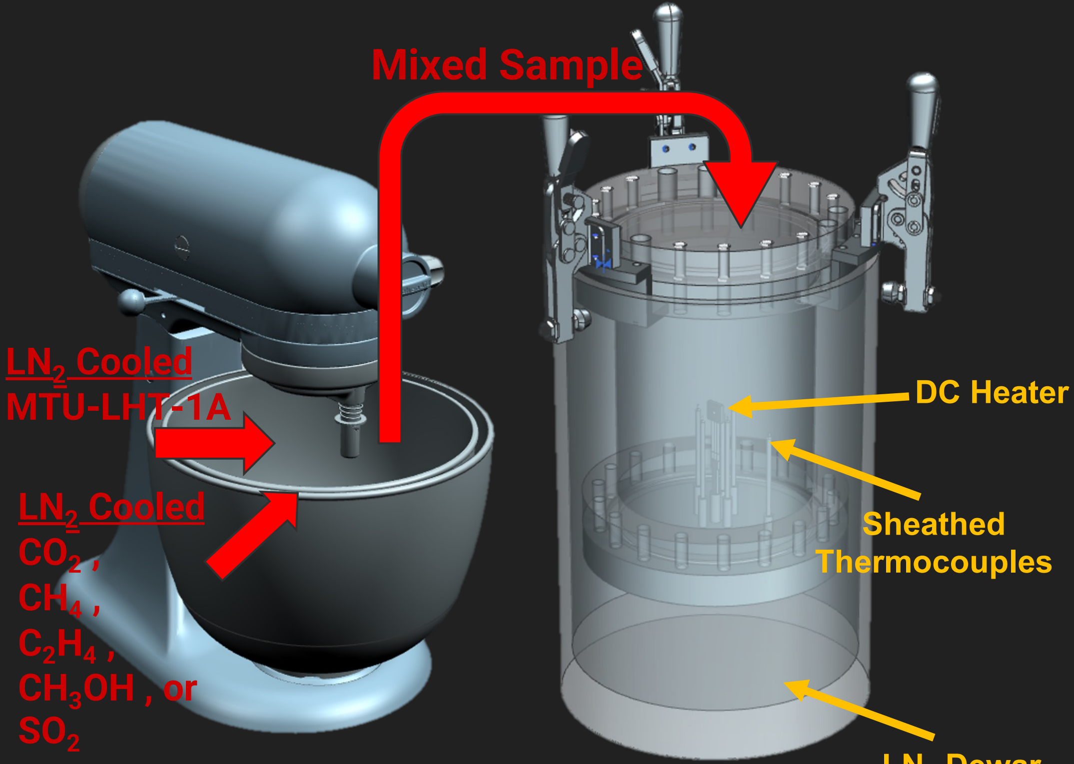
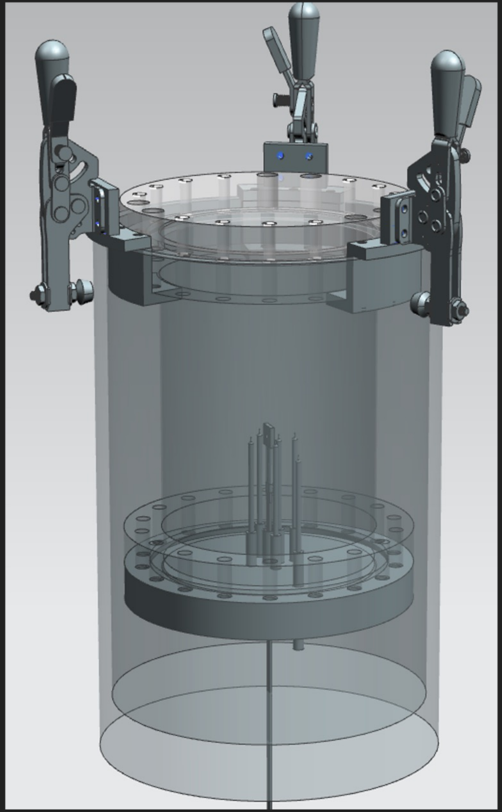
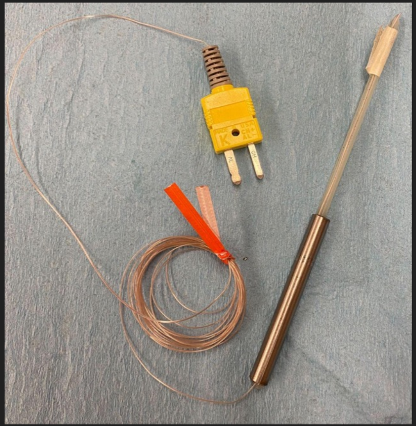


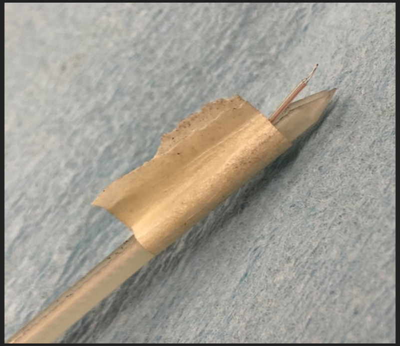
Figure 1: Actively Cooled Mixing of Volatiles and MTU-LHT-1A. Transferred Mixed Sample to Test Vessel in a LN_2 Bath

Testing Going Forward – Test Setup Current Progress



- Polycarbonate Lid
- Stainless Steel Tube Feedthrough Pieces
- G10 Sheaths for 40-gauge Type-K Thermocouples





Acknowledgements

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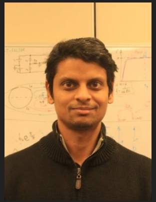
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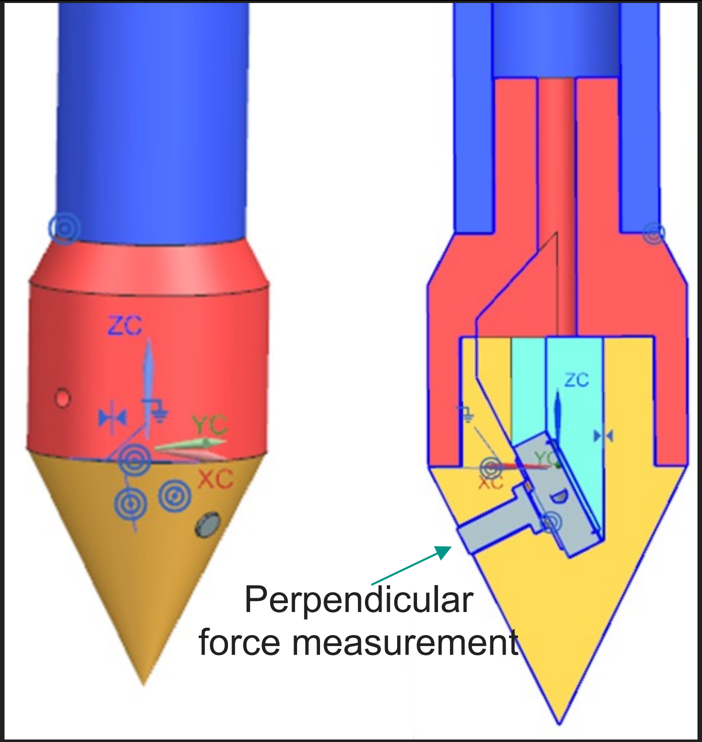
Geotechnical instrumentation



20 mm
diameter

Piezo Electric
Load cell

Phase Change

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$$\frac{\partial}{\partial t}(\emptyset\rho_v) + \nabla.(\rho_v \boldsymbol{u}_v) - \nabla.[D\nabla\rho_v)] = Q_v$$

$$\boldsymbol{u}_v = \frac{k}{\mu_v}\nabla P_v$$

$$(\rho C_p)_{eff}\frac{\partial T}{\partial t} + \rho_v C_{p,v}\boldsymbol{u}_v.\nabla T - \nabla.[k_{eff}\nabla T] = Q_s + Q_L$$