Cryogenic Vacuum Testing of a Heated Cone Penetrometer for Thermal Detection and Quantification of Water in Icy Lunar Regolith Simulant

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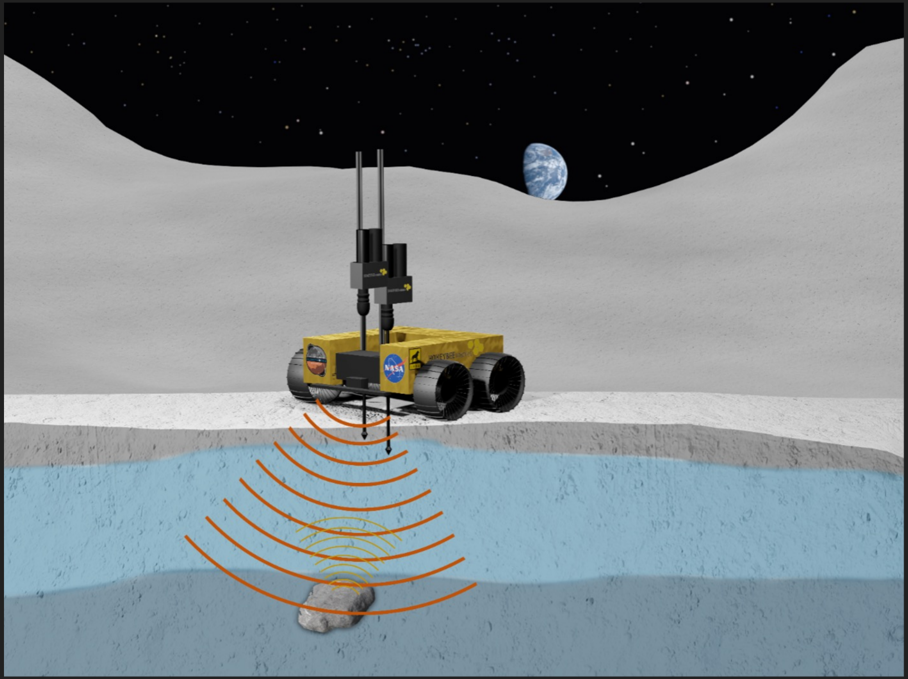
Background – MTU LuSTR 2020 Project

- Rover-mounted Percussive Hot Cone Penetrometer (PHCP) and Ground-Penetrating Rader (GPR) system
  - GPR: subsurface layer and ice continuity data
  - PHCP: geotechnical and volatile composition data
- Geotechnical Data
  - Cone surface pressure & load
  - Impact loads
  - Measurement of depth displacement
- Thermal Data
  - Volatile quantity and distribution
  - Desiccated regolith properties



Proposed prospecting instrument suite, Ground Penetrating Radar (GPR) and Percussive Hot Cone Penetrometers (PHCP)

Percussive Hot Cone Penetrometer Geotechnical and Thermal Systems

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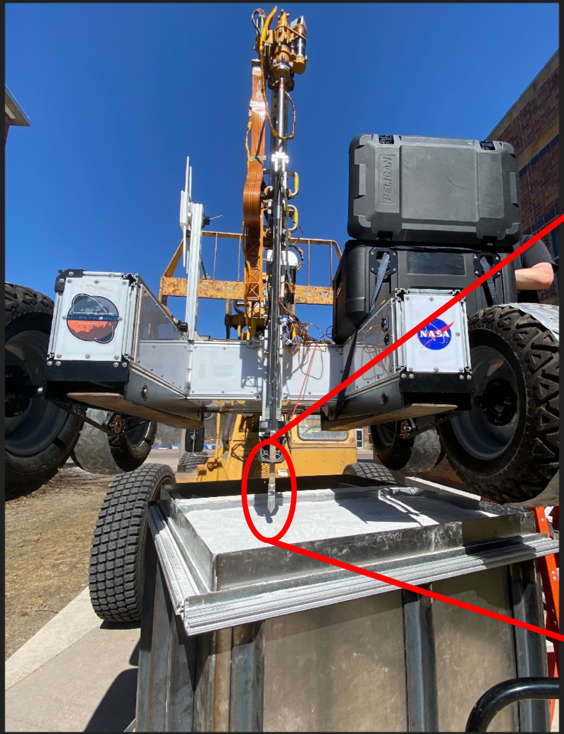

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PHCP Thermal System Validation and Testing

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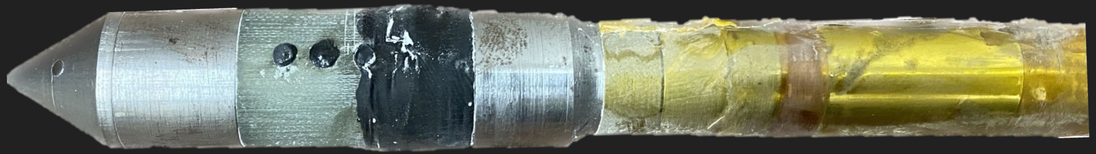


Atmospheric Testing

Used to establish:
- Size of heat-affected zone in atmosphere
- Whether phase change is visible in thermal curves
- Thermal conductivity and specific heat of MTU-LHT-1A

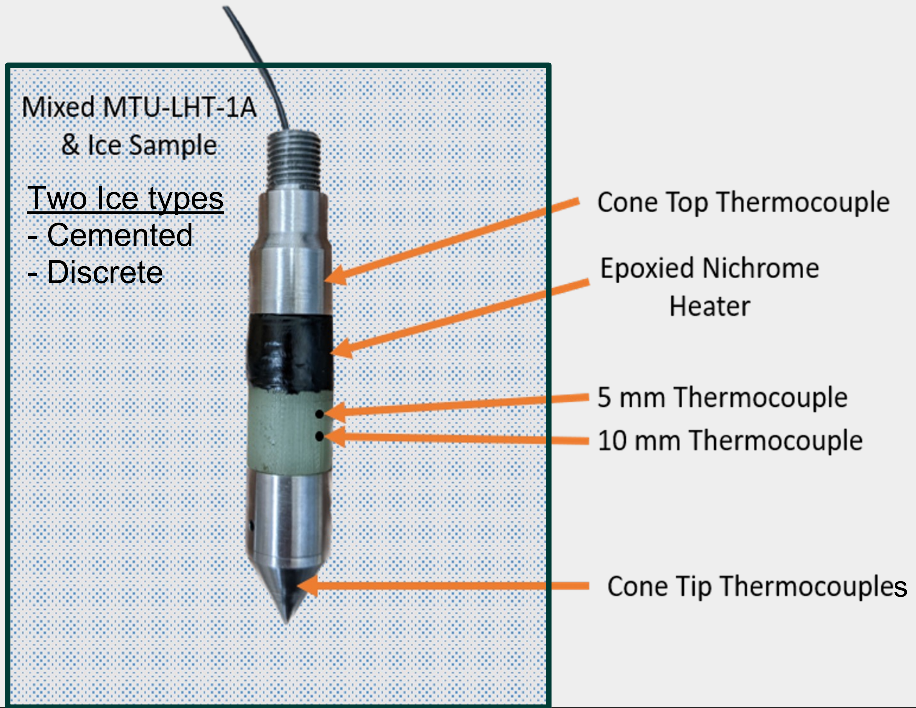
Cryogenic Vacuum Testing

Used to establish:
- Critical thermal measurement locations
- Differences between discrete and cemented icy regolith in vacuum
- Thermal properties capable of predicting water content of regolith within 1wt%

Full-system testing at Honeybee Robotics

Used to establish:
- Thermal system functionality when attached to Honeybee Trident z-stage
- Atmospheric and vacuum performance of entire system

Cryogenic Vacuum Thermal Cone Testing Overview



Critical features of thermal cone measurement system

Weight Percent	Number of discrete ice replicates	Number of cemented ice replicates
0	3	3
1.5	3	0
2	3	3
2.5	3	1
5	3	1
7	3	0
10	3	1*

Outline of cryogenic vacuum thermal cone test campaign

Cryogenic Vacuum Thermal Cone Testing – Sample Preparation

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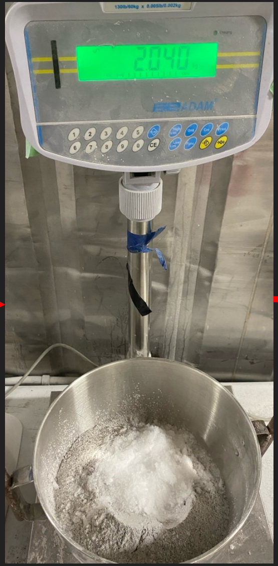
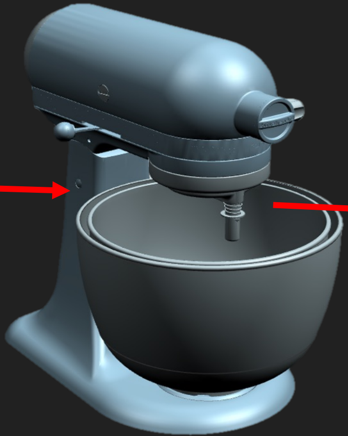
1. Measure 2kg of regolith

2. Measure out ice content (wt%)



3. Combine ice and regolith



4. Mix until homogenous

5. Compact and repeat until box is full

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Cryogenic Vacuum Thermal Cone Testing – Test Procedure

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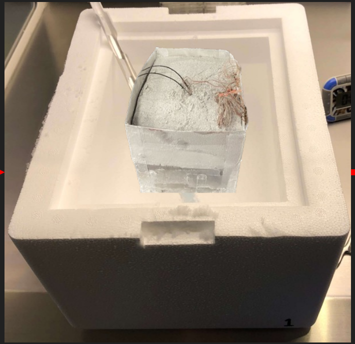
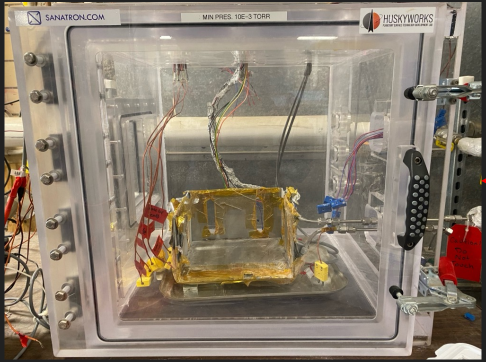
Regolith sample in -80˚C freezer



Regolith sample submerged in liquid nitrogen bath



Acrylic vacuum chamber with aluminum liquid nitrogen cooled shroud

Measured Variable	Measurement Instrument
Cone top temperature	40 gage type K thermocouple
Cone tip temperature	40 gage type K thermocouple
Heater temperature	40 gage type K thermocouple
5mm and 10mm from heater temperature	30 gage type T thermocouple
Vacuum chamber pressure	Workerbee convection gauge
Power supply to heater	Hanmatek DC power supply & Visual studio software

Outline of all measured variables and their measurement devices. Unless otherwise specified, all data was recorded using an NI DAQ chassis and Labview at a sampling frequency of 1Hz

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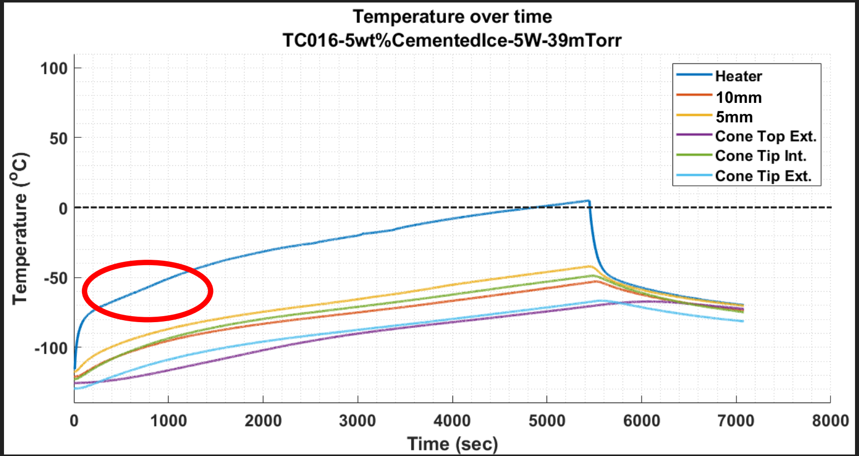
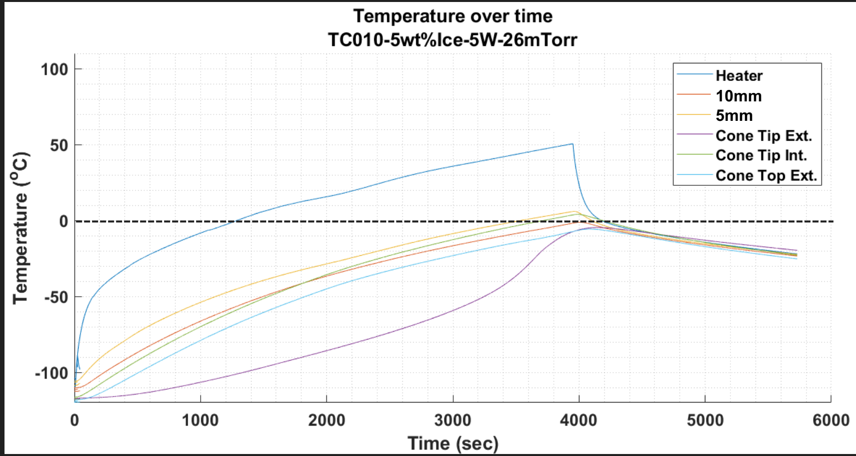
Results: Thermal Curves

Cemented Ice Sample



Thermal curves of a 5wt% cemented ice test. Note the slight inflection at -55C that could indicate phase change.

Discrete Ice Sample



Thermal curves of a 5wt% discrete ice test. No noticeable inflection is seen in the curve.

Methods of Identifying Ice Content in Icy Regolith

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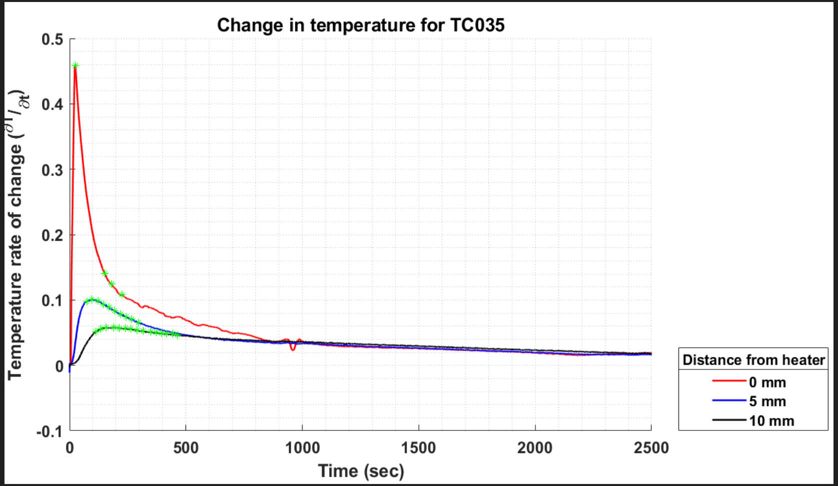
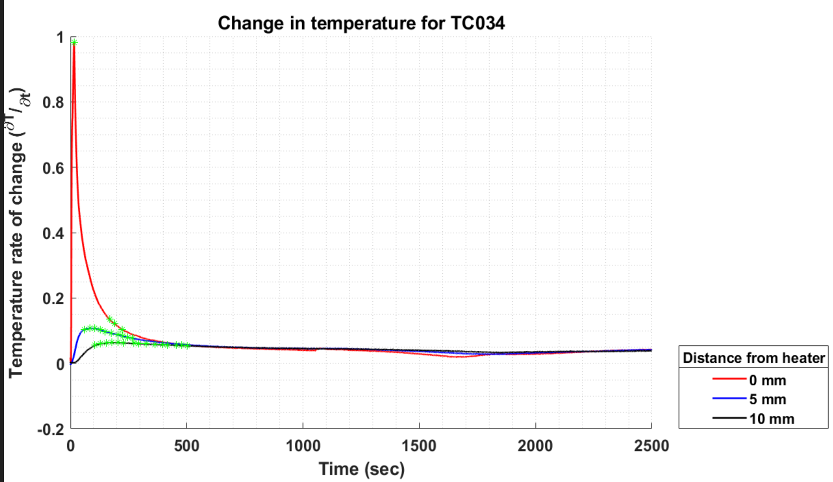
- Thermal curves alone do not contain enough information to quantify water ice
  - Highly dependent on bulk density of regolith (geotechnical measurement)
- Alternative indicator variables to consider:
  - Rate of temperature change during testing
  - Energy required to raise the sample's temperature by 10˚C
  - Differential Scanning Calorimetry (DSC)
- Goal: create correlational model that is capable of predicting the water content of icy regolith within 1wt%

Determining Ice Content Based on Rate of Temperature Change

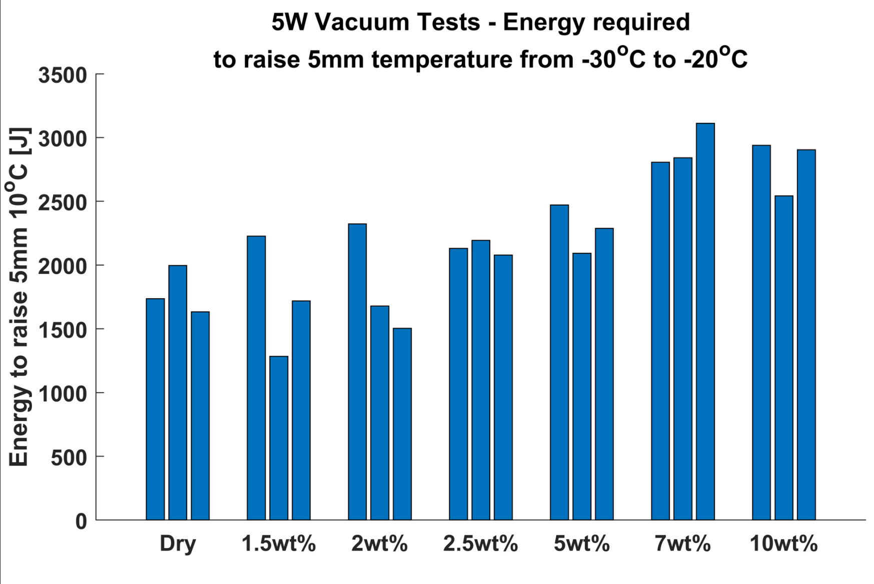


Rate of temperature change vs time for a **7wt% test**. The maximum rate of temperature change at the heater surface is 0.46˚C/sec.

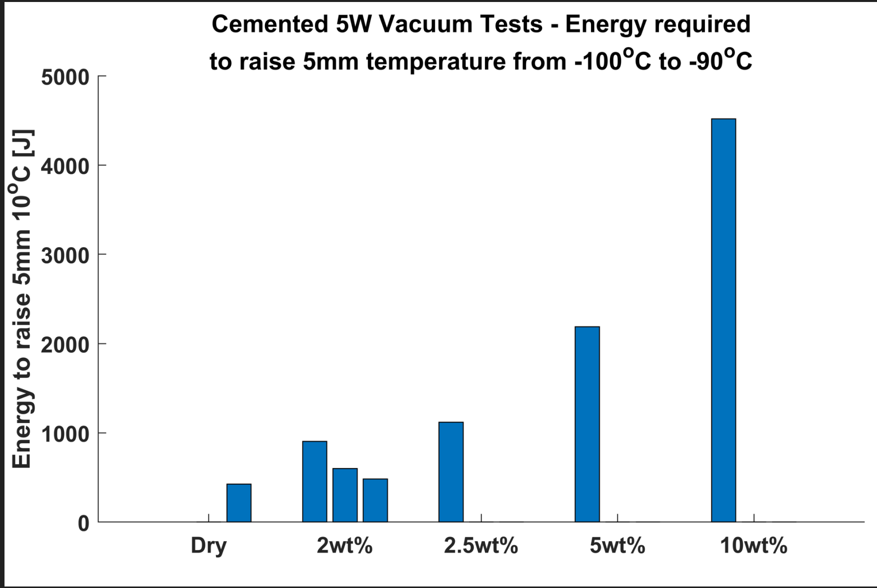


Rate of temperature change vs time for a **dry test**. The maximum rate of temperature change at the heater surface is approximately 0.98˚C/sec.

Determining Ice Content Based on Energy Required to Raise Sample Temperature



Energy required to raise discrete ice tests from -30˚C to -20˚C, separated by weight percent



Energy required to raise cemented ice tests from -100˚C to -90˚C, separated by weight percent

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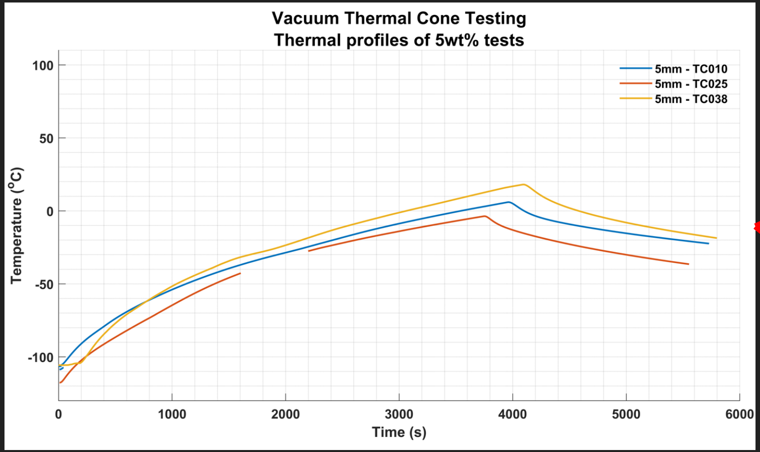
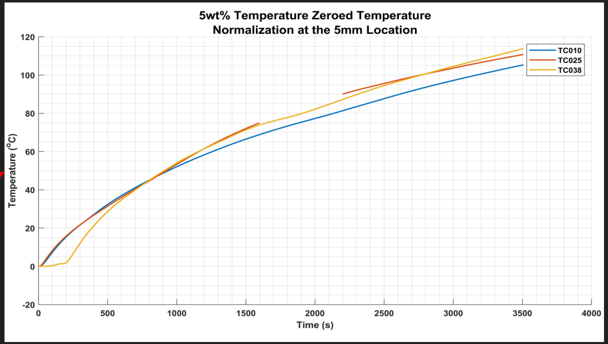
Determining Ice Content with DSC: Pre-Processing



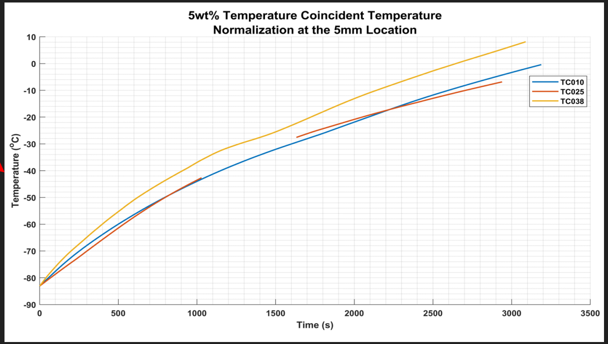
Subtract initial temperature

Start all data sets at maximum initial temperature

"Zeroed" Data



"Coincident" Data



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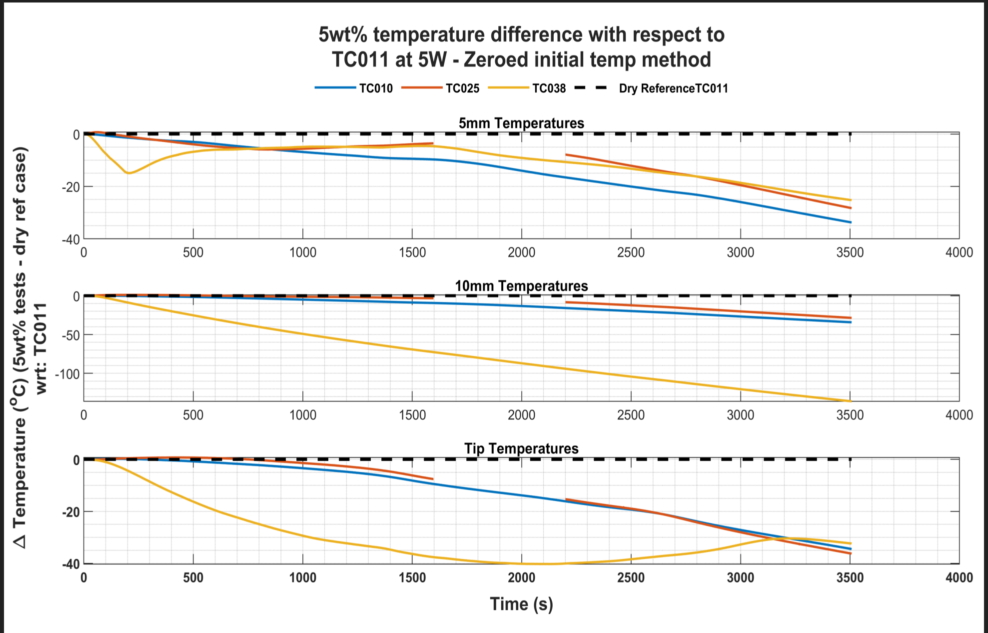
Determining Ice Content with DSC

- Traditional DSC: two cones, compare simultaneous measurements
- Our approach: One cone tested in two samples, then compare results from separate measurements



Conclusions & Future Work

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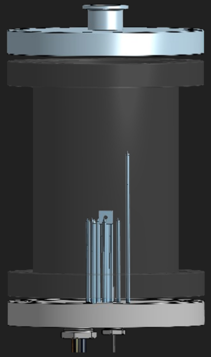
Conclusions

- Thermal curves alone are not sufficient to quantify ice content of lunar regolith in vacuum
- There are additional metrics that can be used to predict ice content from thermal testing

Future Work

- Characterize thermal behavior of non-water volatiles in cryogenic vacuum conditions
  - CO_2
  - Methane
  - Methanol
  - Ethylene
  - SO_2



Cryogenic vacuum vessel design

Cryogenic vacuum vessel fabrication progress

Acknowledgements

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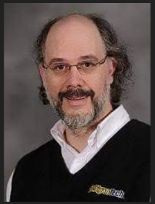
PSTDL LuSTR Thermal Team

Dr. Paul van Susante, Faculty Advisor



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George Johnson, Research Engineer

Travis Wavrunek, PhD Student

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