Compaction Dependent Thermal Properties of Icy Lunar Regolith in Vacuum

Travis Wavrunek, Ben Flowers, Anurag Rajan, and Paul van Susante

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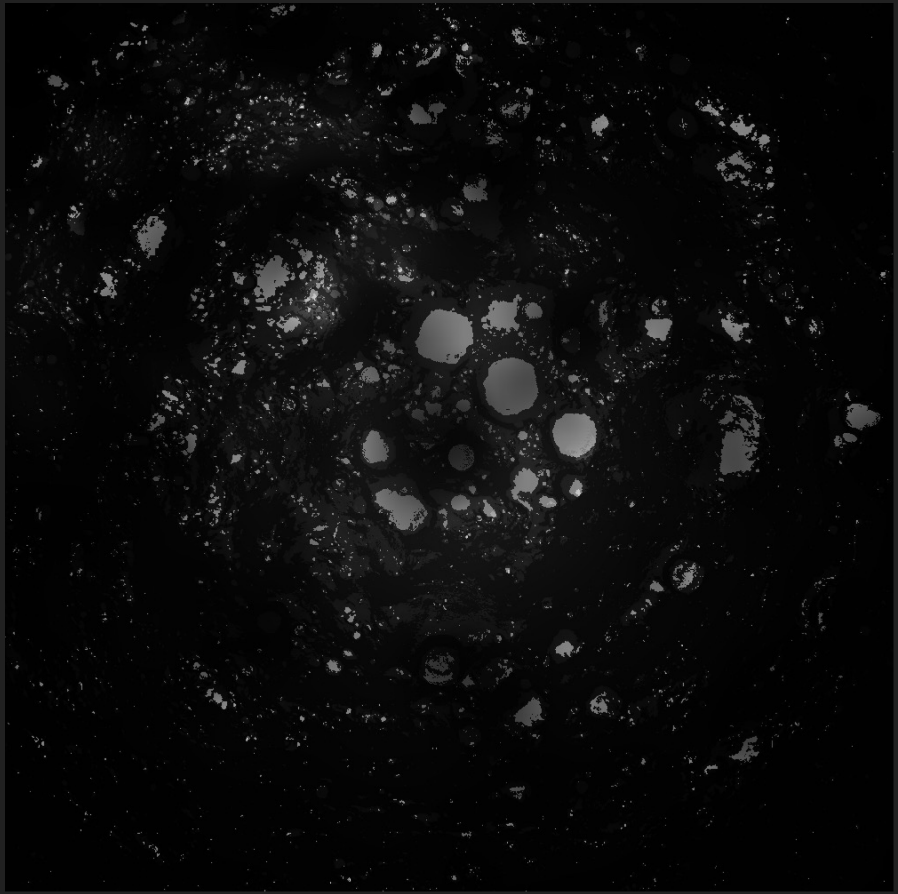
SPACE RESOURCES ROUNDTABLE

Thermal Properties of Icy Regolith

Space Resources Roundtable

- ISRU is the harnessing of local natural resources at mission destinations
- Water ice is one of the most valuable resources available on the Lunar surface
- Morphology of and location of ice bearing regolith is poorly understood

Ice Favorability Map

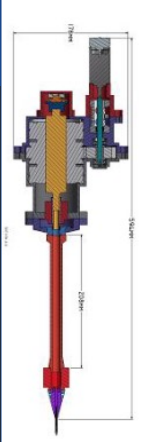


Kevin Cannon, Moon Ice Favorability Index South Pole 591mp

Thermal Prospecting - LuSTR

SPARTA-A

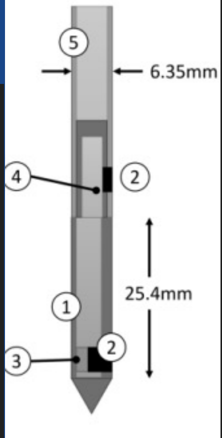
- Under Development, SPARTA measures volatiles using the line-source method and relative humidity probe
- Designed to be planet agnostic



https://ascelibrary.org/doi/epdf/10.1061/9780784484470.017

CSM Volatile Prospecting

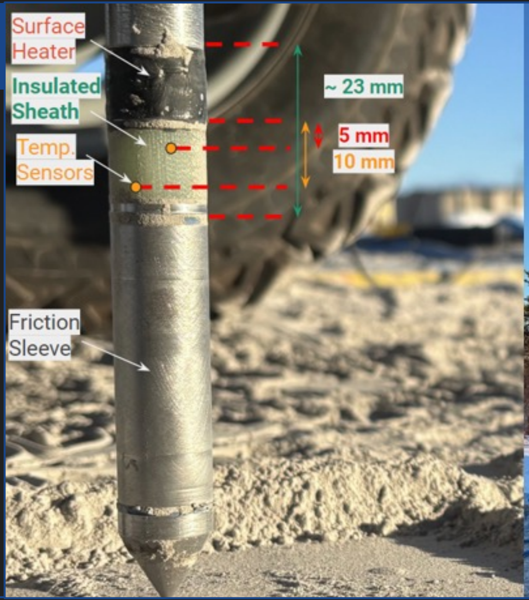
- Experiments at Colorado School of Mines use pulsed heat source and measuring cooling curves
- Reached accuracies of 1.8wt% with known compaction



https://ascelibrary.org/doi/abs/10.1061/9780784484470.035

MTU PHCP

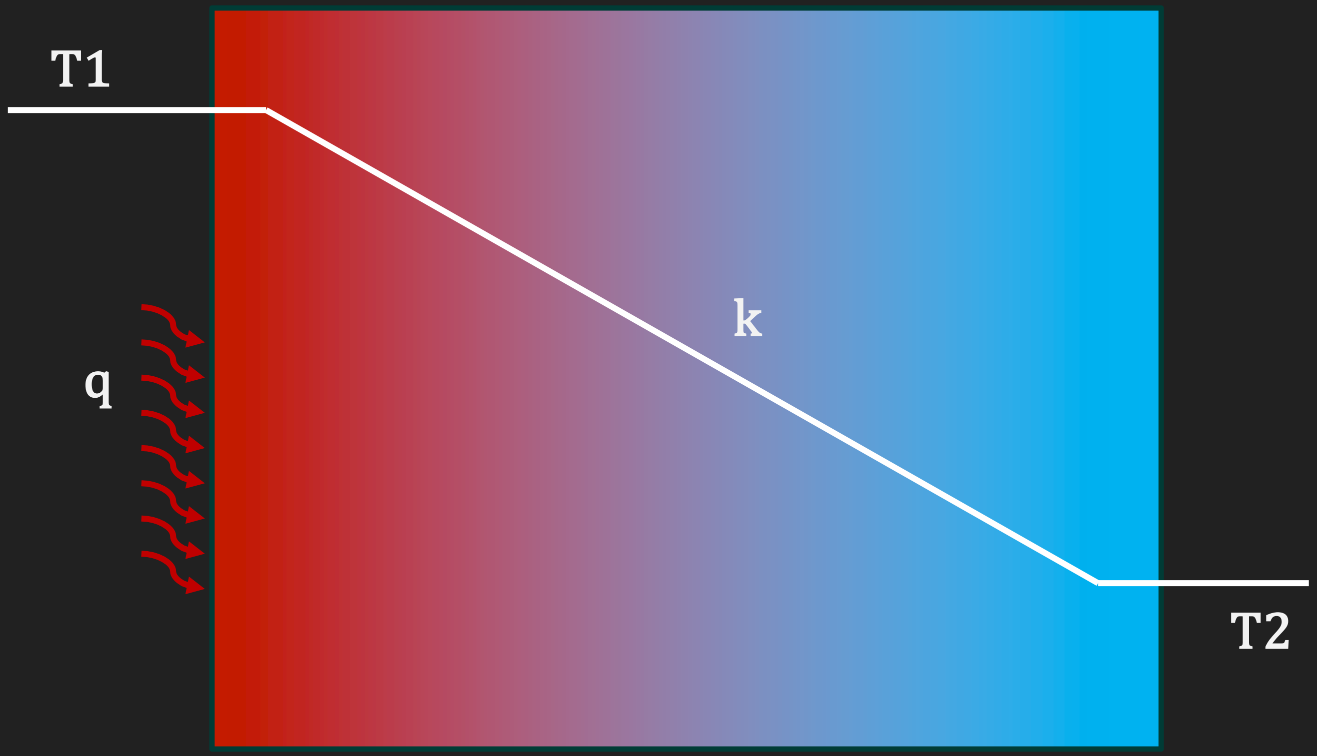
- The Percussive Hot Cone Penetrometer (PHCP) is a tool developed at MTU as part of LuSTR funding received in 2020
- Used in conjunction with a high frequency GPR
- Data collection every 10 cm up to 1m depth
- Thermal profiles are supplemented by geotechnical data to inform compaction and cohesion



Icy Regolith and Thermal Conductivity

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p} \nabla^2 T$$

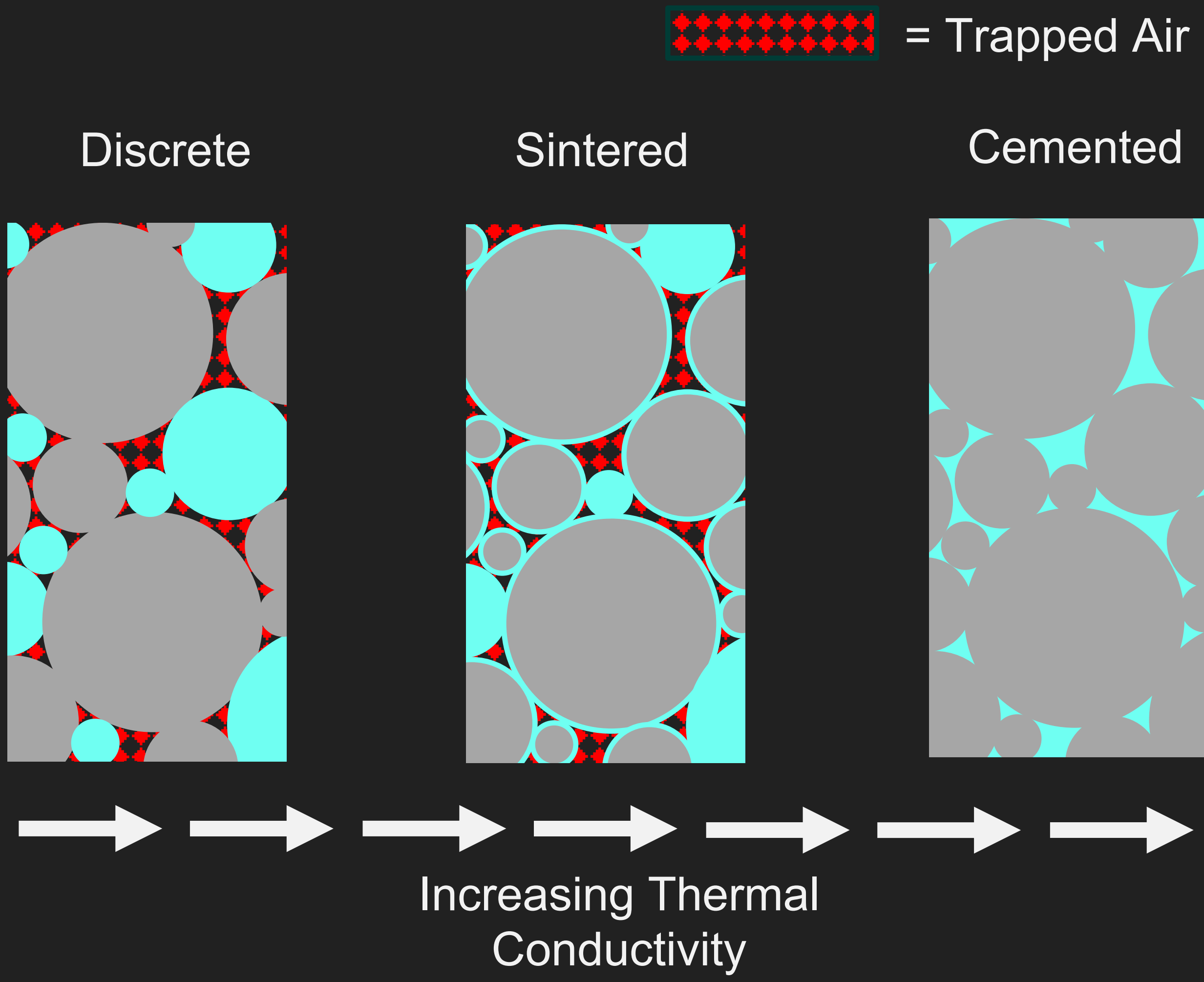
T = Temperature
T = Time
k = Thermal Conductivity
ρ = Density
C_p = Heat Capacity



Thermal Conduction Paths

Ice Formations

- No ground-truth data on form of lunar ice deposits
- Possible formations of water ice have been proposed
- Two of most interest in our testing are cemented ice and discrete ice
    - Valuable for testing as they can be manufactured in large homogenous quantities
    - Valuable for analysis as they represent the two extremes of thermal conductivity and strength



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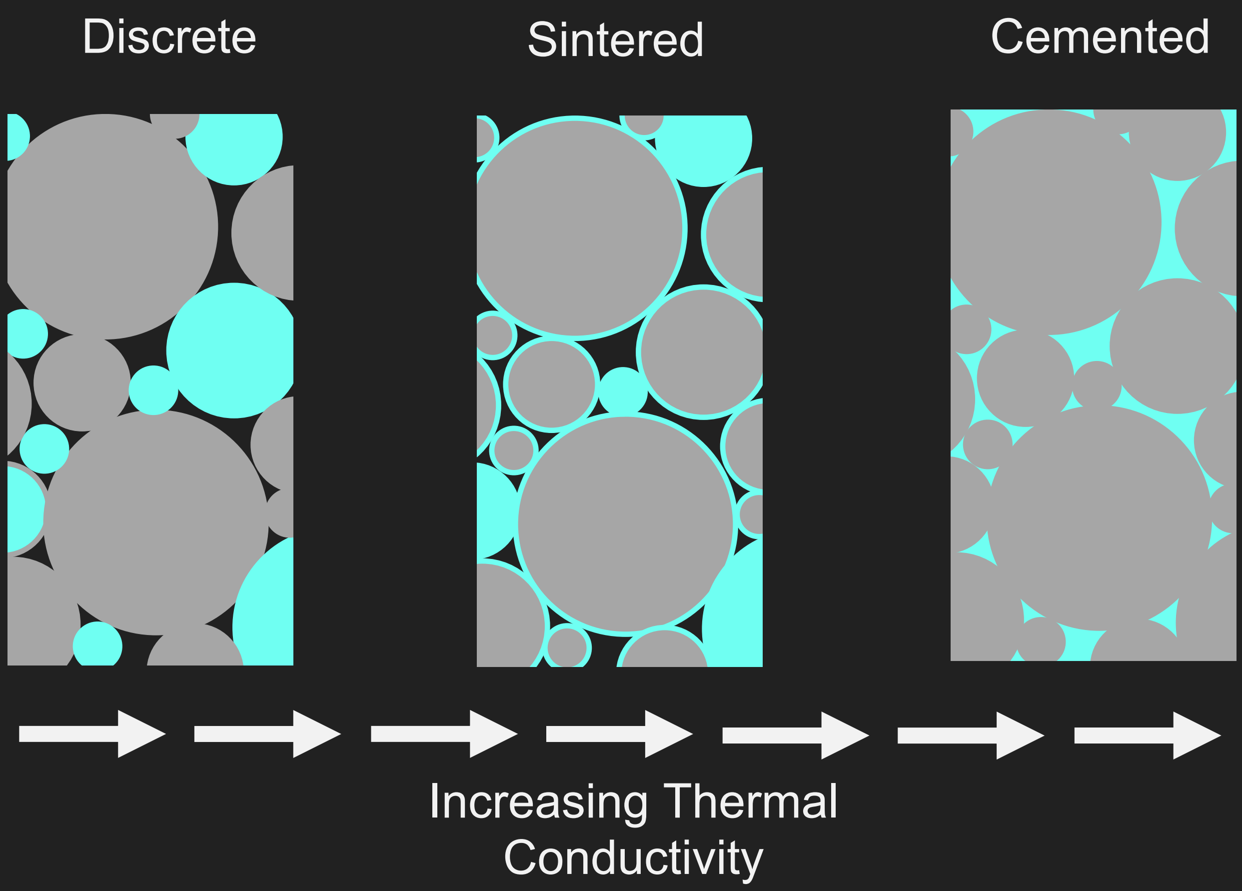
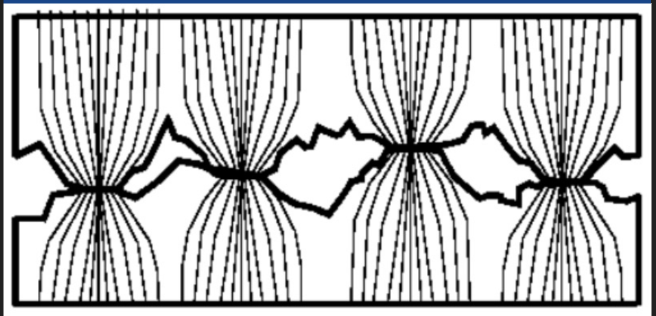


Regolith

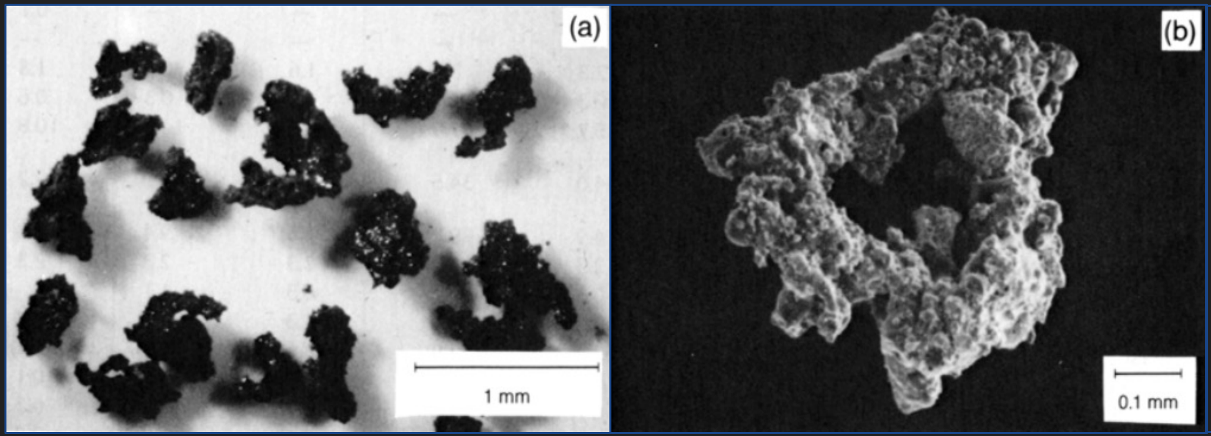
Lunar Regolith In-Situ Measurements

- During Apollo 15 and Apollo 17, astronauts investigated the thermal conductivity of subsurface regolith.
- Thermal conductivity values were found to be very low
  - Subsurface regolith having a conductivity of $0.9 - 1.3 \times 10^{-2} \frac{W}{m\ K}$
  - Comparing to solid basalt having a conductivity of $\sim 2.7 \frac{W}{m}$
- The drastic difference is primarily due to poor contact resistance between regolith particles, exasperated by lack of intestinal air in vacuum

Particle Contact



https://arc.aiaa.org/doi/10.2514/1.2664



Images of regolith agglutinates from Lunar Source Book
(a) optical microscope photo from Apollo 11
(b) electron photomicrograph of Apollo 11 agglutinate

https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter07.pdf

MTU Line-Source Setup

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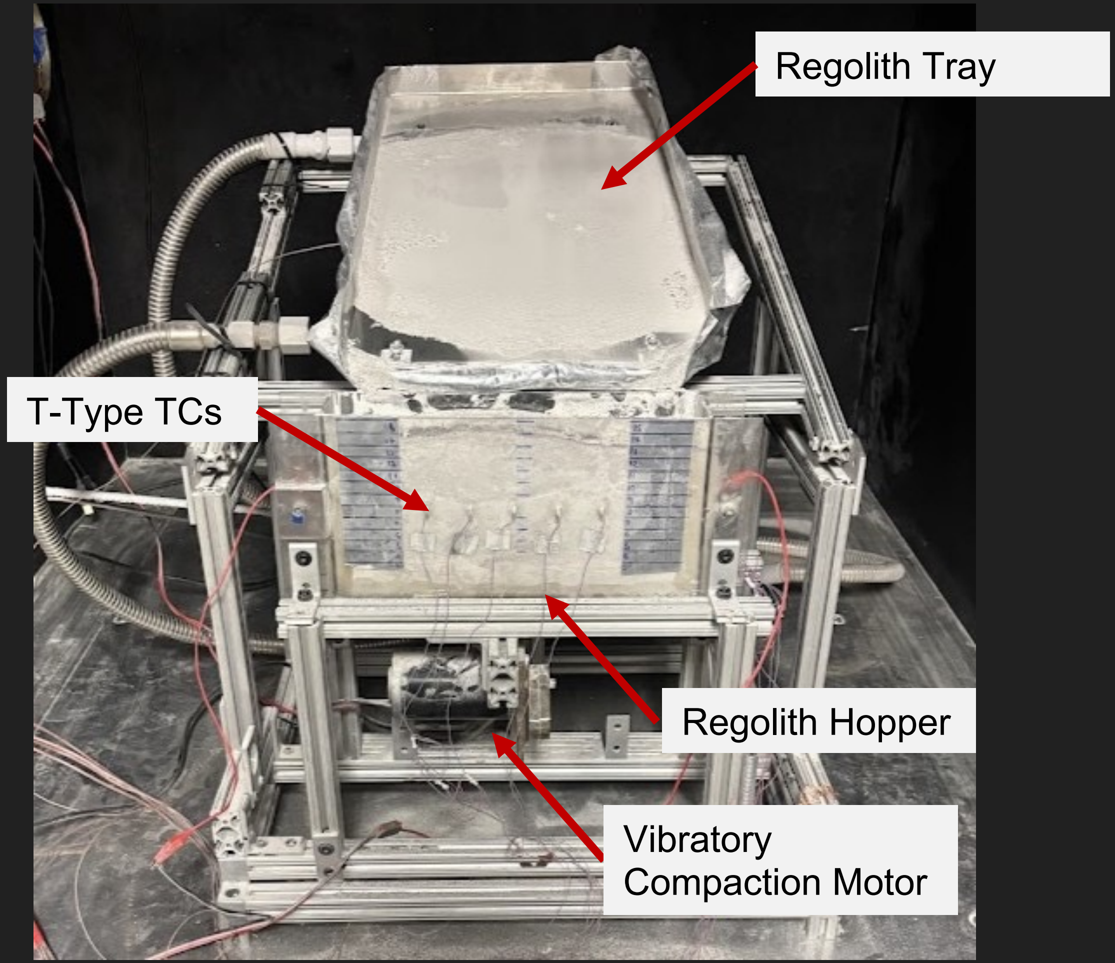
Purpose

- Method of determining thermal properties of lunar regolith
- Regolith is poured into a hopper containing a hot wire heat source and compacted
- Thermocouples at fixed distances record temperature profiles



Test Campaign

Testing Overview

- Test campaign investigated discrete icy regolith at multiple compactions
- Ambient pressure tests to use as a baseline of comparison

Test		Ambient Pressure			Vacuum Pressure		
Dry Regolith	Low Compaction: <1.5 g/cm3	0 wt%			0 wt%		
	Med. Compaction:	0 wt%			0 wt%		
	High Compaction: >1.7 g/cm3	0 wt%			0 wt%		
Discrete Icy Regolith	Low Compaction: Porosity > 0.5	1.5 wt%	3 wt%	6 wt%	1.5 wt%	3 wt%	6 wt%
	High Compaction: Porosity < 0.5	1.5 wt%	3 wt%	6 wt%	1.5 wt%	3 wt%	6 wt%

Test Procedure

Shaved ice and cold regolith are mixed to desired wt%

Sample is chilled in LN2 bath for 2 hours (~-170 C)

Regolith is loaded and spread on dumping tray

DTVAC brought to pressure, shroud temperature along sublimation curve

Regolith is dumped into Hopper once DTVAC pressure reaches 0.1 mTorr

Vibratory compaction to desired compaction level

Constant power supplied to wire heat source for 2 hours

Post test compaction measurements

Sample Preparation

Test Procedure

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Shaved ice and cold regolith are mixed to desired wt%

Sample is chilled in LN2 bath for 2 hours (~-170 C)

Regolith is loaded and spread on dumping tray

DTVAC brought to pressure, shroud temperature along sublimation curve

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Vibratory compaction to desired compaction level

Constant power supplied to wire heat source for 2 hours

Post test compaction measurements

Precooling Sample

Test Procedure

Shaved ice and cold regolith are mixed to desired wt%

Sample is chilled in LN2 bath for 2 hours (~-170 C)

Regolith is loaded and spread on dumping tray

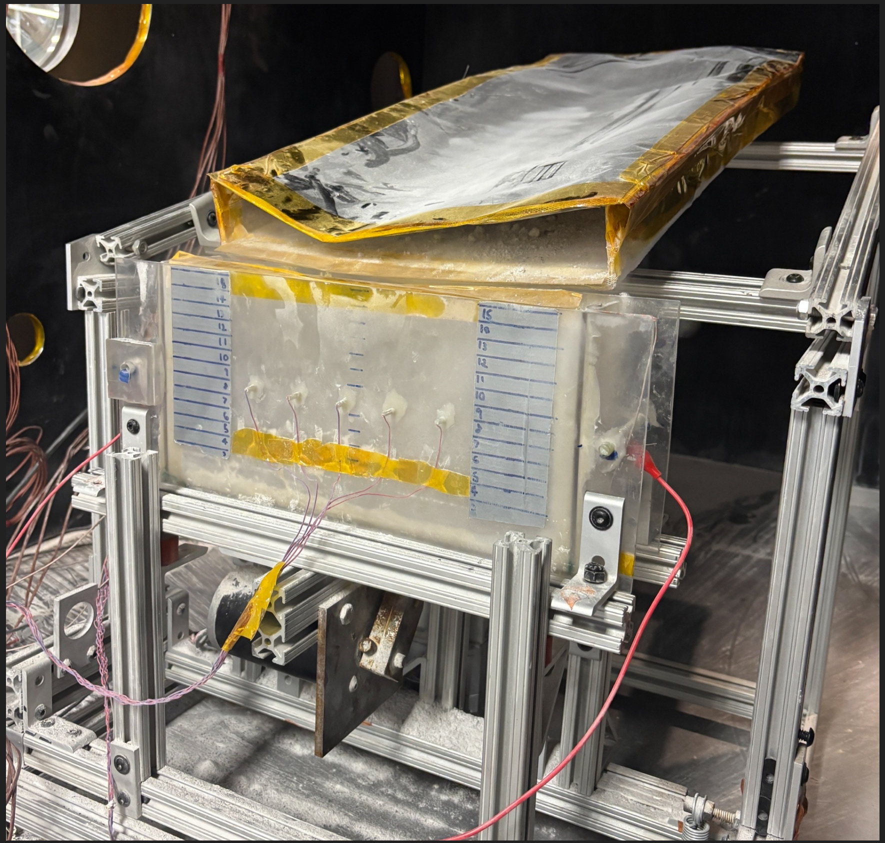
DTVAC brought to pressure, shroud temperature along sublimation curve

Regolith is dumped into Hopper once DTVAC pressure reaches 0.1 mTorr

Vibratory compaction to desired compaction level

Constant power supplied to wire heat source for 2 hours

Post test compaction measurements



Regolith Loaded into DTVAC

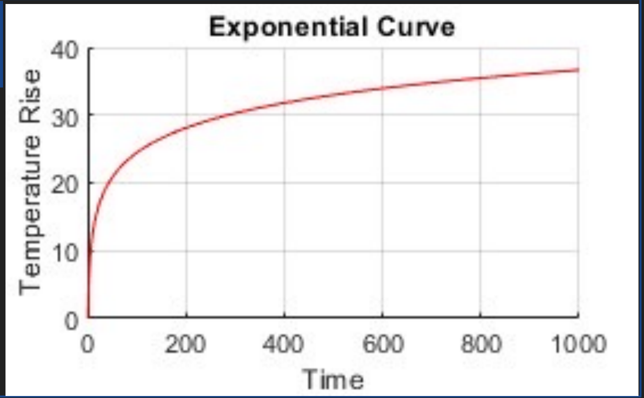
Line Source Testing

- Line-Source procedure is often used to find thermal conductivity of insulating materials
- With collected thermal curves, conductivity can be found various methods
- After a period of time, temperature rise can be approximated as an exponential growth

Exponential Fit

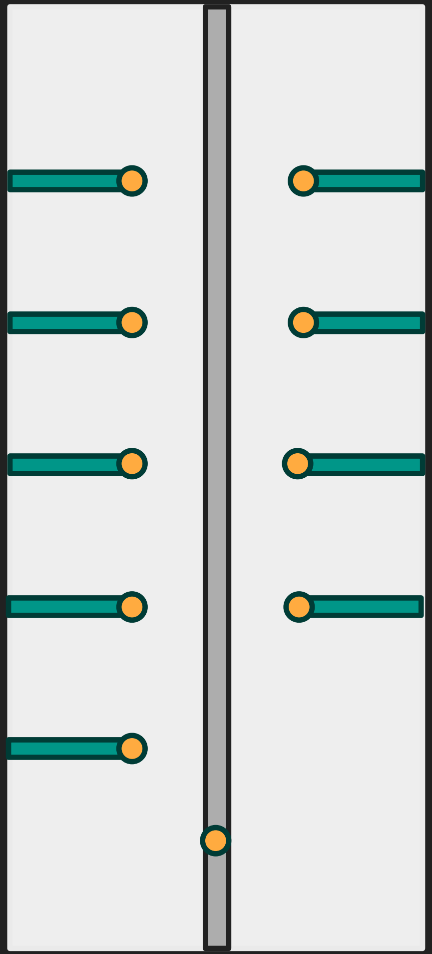
$$T = s \ln t + b \qquad k = \frac{q}{4\pi s}$$

Carslaw Jaeger

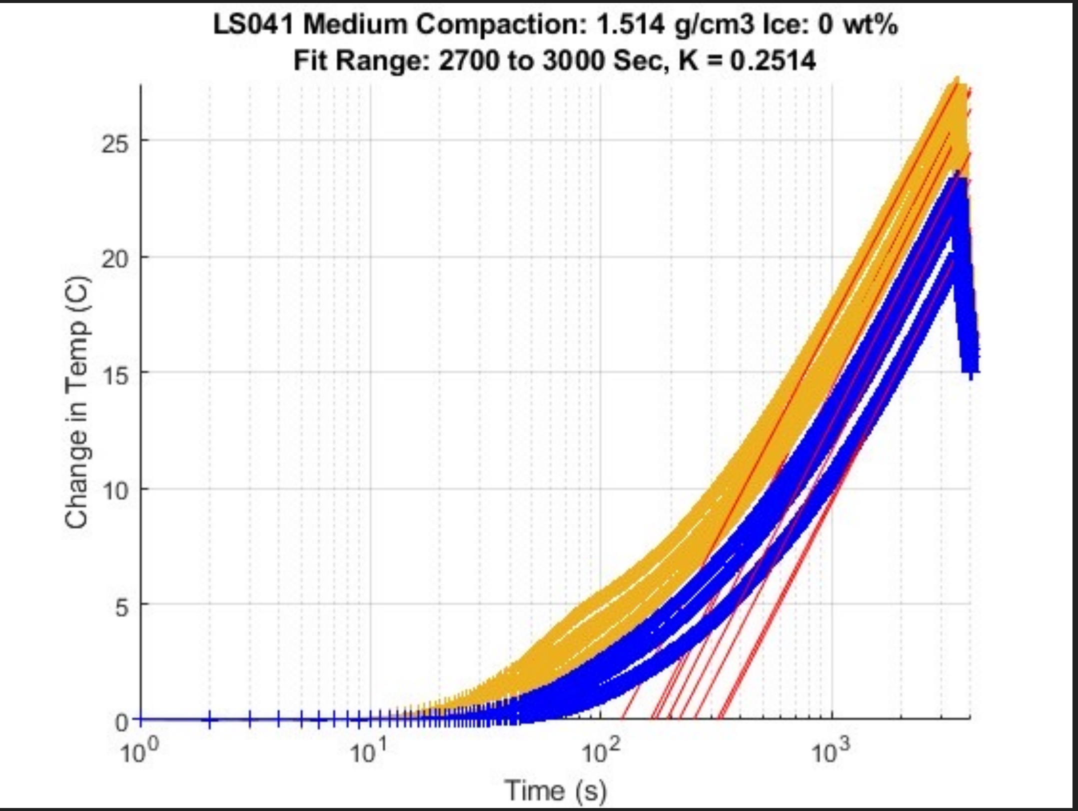


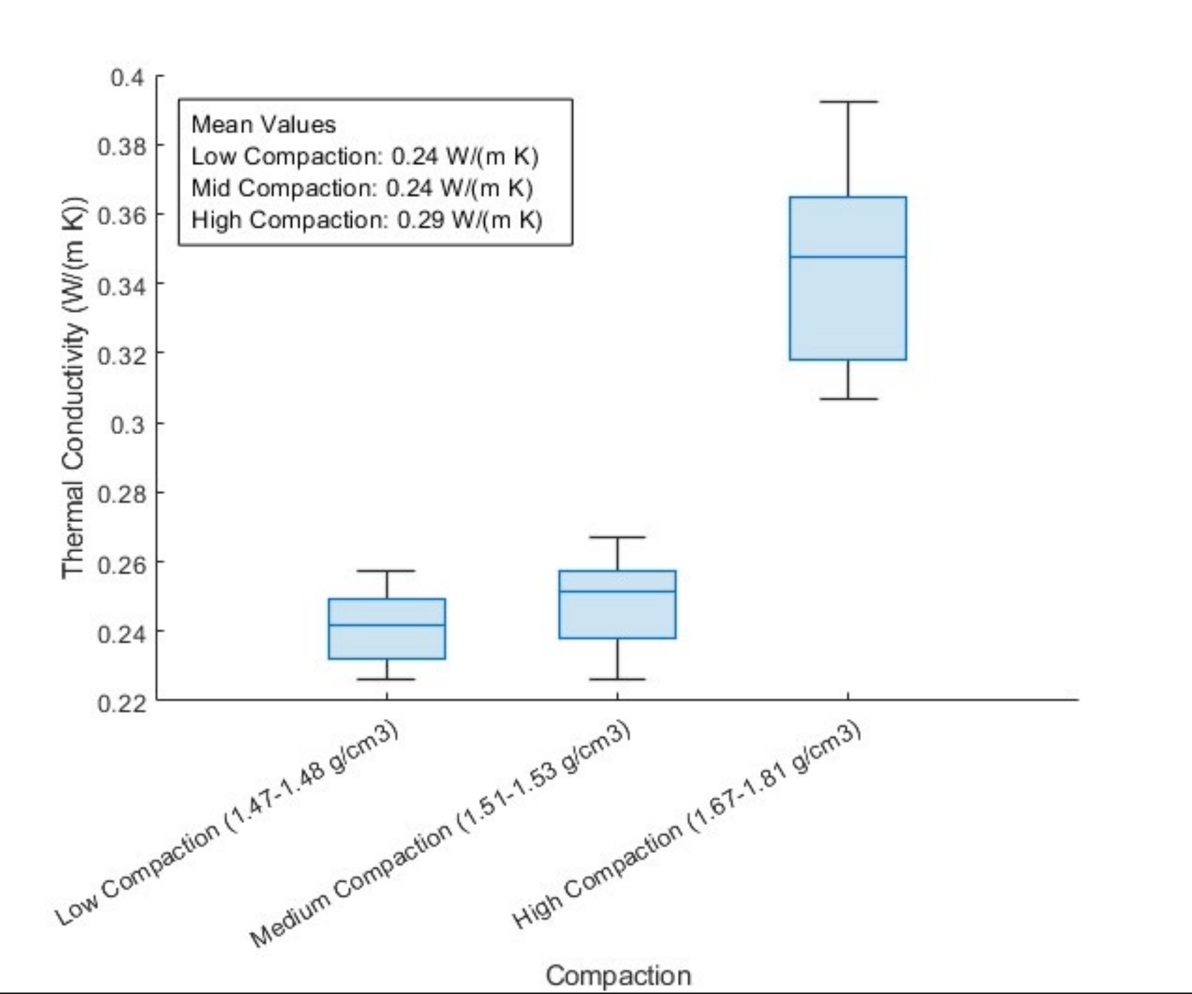
T = Temperature
C_p = Heat Capacity
q = Heat/Length
T = Time
k = Thermal Conductivity
ρ = Bulk Density

View From Above



Thermal Conductivity of Dry MTU-LHT-1A



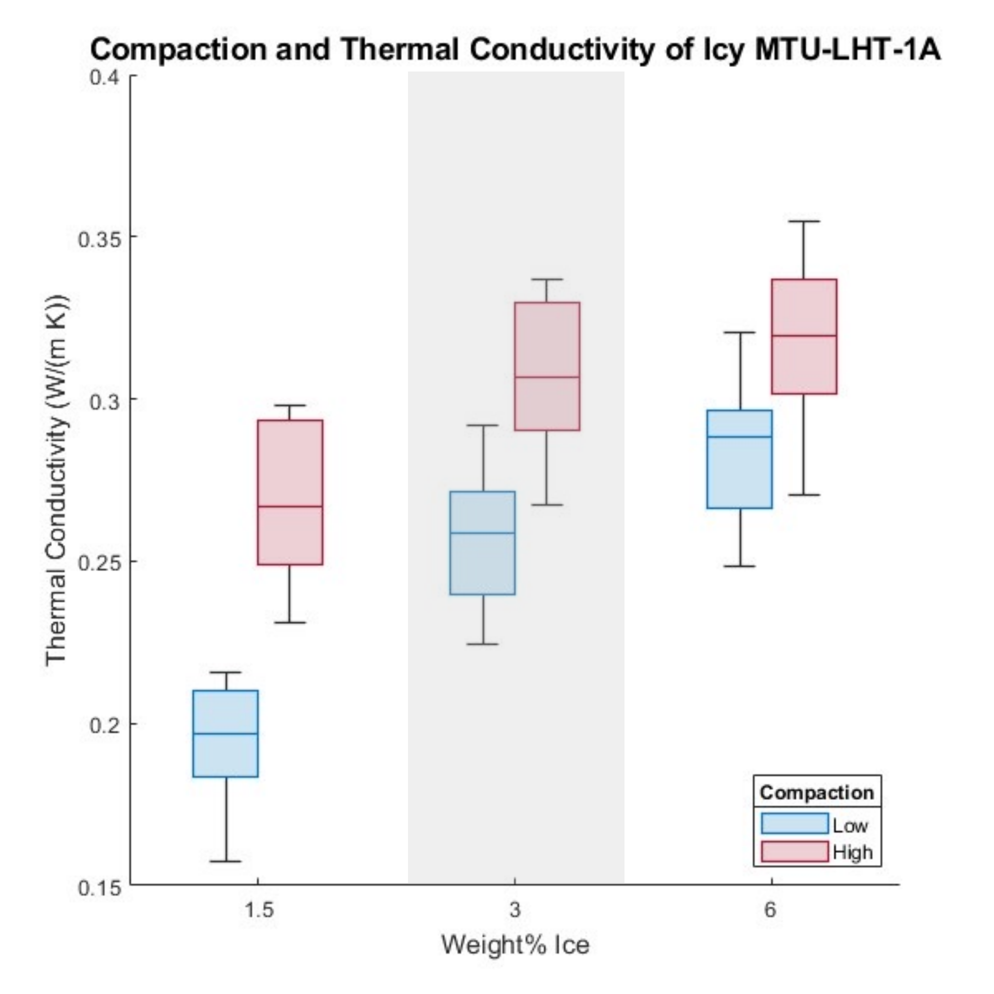


- Exponential fit curve (red line) is fit to linear portion of temperature profiles (yellow/blue lines)

Atmospheric Icy Compaction

Temperature	Pressure
-25 to -15 C	1 atm

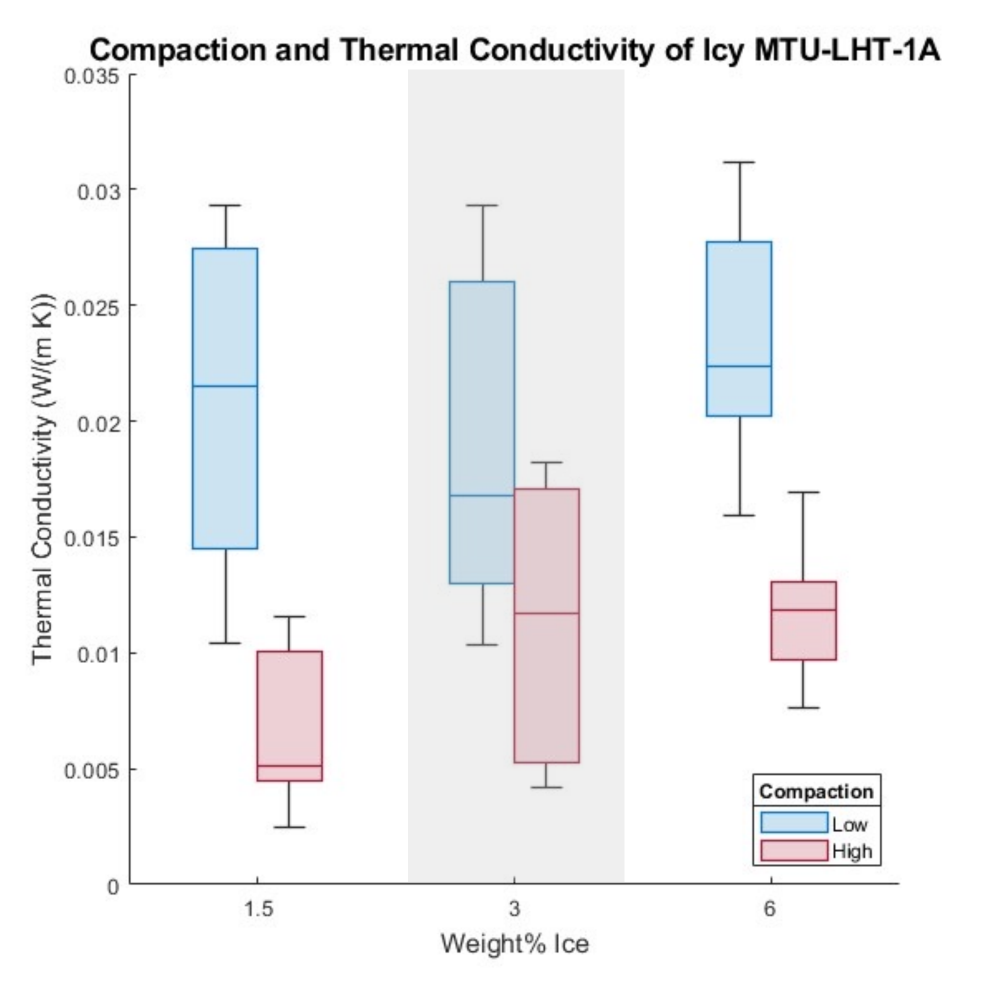
Compaction Goal	Weight % Water Ice	Bulk Density	Porosity	Mean k (W/m K)
High	1.5	1.533	0.49	0.268
	3	1539	0.47	0.307
	6	1415	0.48	0.318
Low	1.5	1248	0.58	0.194
	3	1143	0.6	0.257
	6	1168	0.57	0.284



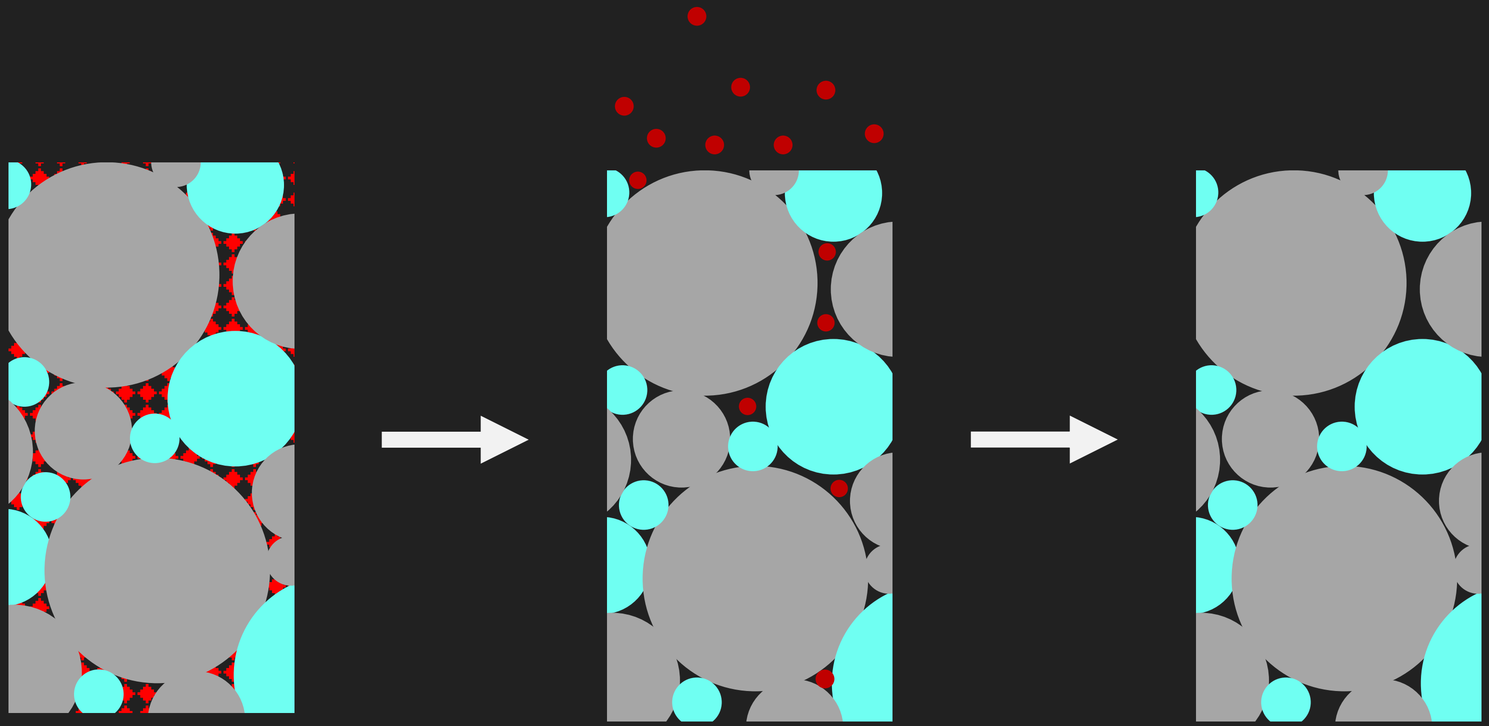
Vacuum Data

Temperature	Pressure
-60 to -30 C	<0.1 mTorr

Compaction Goal	Weight % Water Ice	Bulk Density	Porosity	Mean k (W/m K)
High	1.5	1.355	0.49	0.0067
	3	1.464	0.47	0.0113
	6	1.14	0.48	0.0117
Low	1.5	1.139	0.58	0.0208
	3	1.157	0.6	0.0189
	6	1.015	0.57	0.0235



Trapped Air in Regolith



Regolith pre-dump into hopper
Extremely low permeability traps air

Post Dumping
Even after dumping into hopper, some trapped air may remain

Post Compaction
Vibratory compaction fluidizes simulant and allows trapped air to escape

Results compared to real regolith

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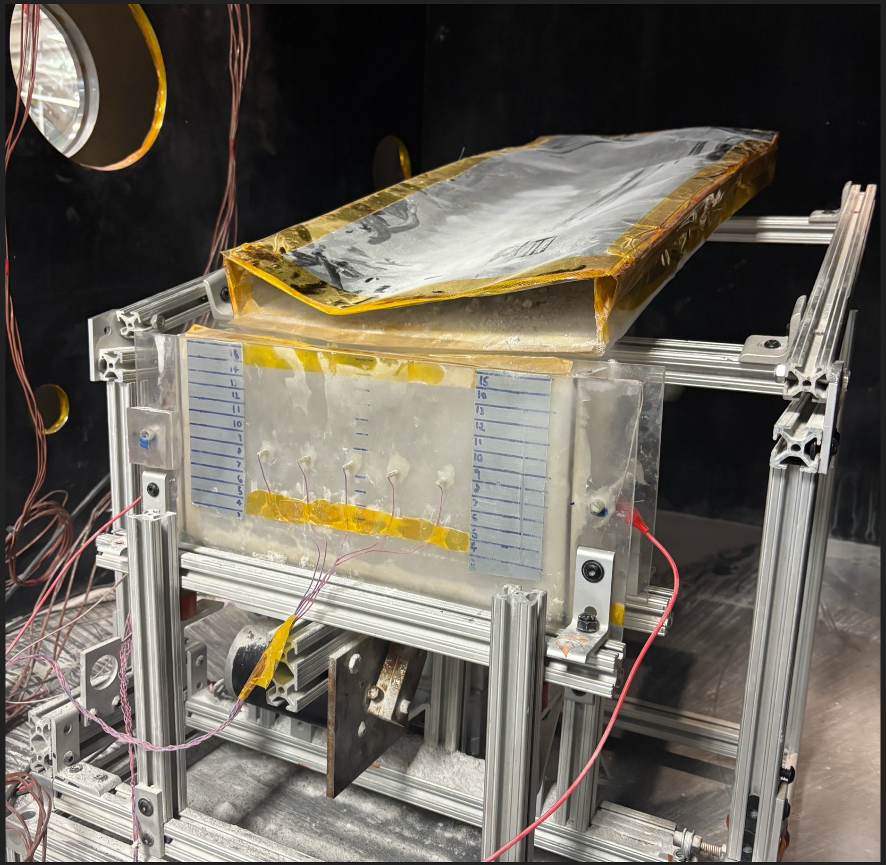
Measurement	Ice Content wt%	Compaction (g/cm3)	Conductivity W/(m K)	Source
Ambient Pressure				
JSC Ambient	0	1.68	0.196	Yuan (2011)
MTU Ambient	0	1.51 - 1.8	0.26-0.37	This Study
MTU Discrete Icy	1.5 - 6	1.14 - 1.54	0.19 - 0.31	
Vacuum Pressure				
Apollo Probes	0	50-250 cm lunar depth	0.009 – 0.013	Langseth (1976)
JSC Vacuum	0	1.69 - 1.89	0.0019 - 0.031	Sakatani (2018)
	0	1.70	0.0037	Hütter (2011)
MTU Vacuum	0	1.4 - 1.68	0.036	This Study
MTU Vacuum Discrete Icy	1.5 - 6	1.01 – 1.46	0.007 – 0.37	

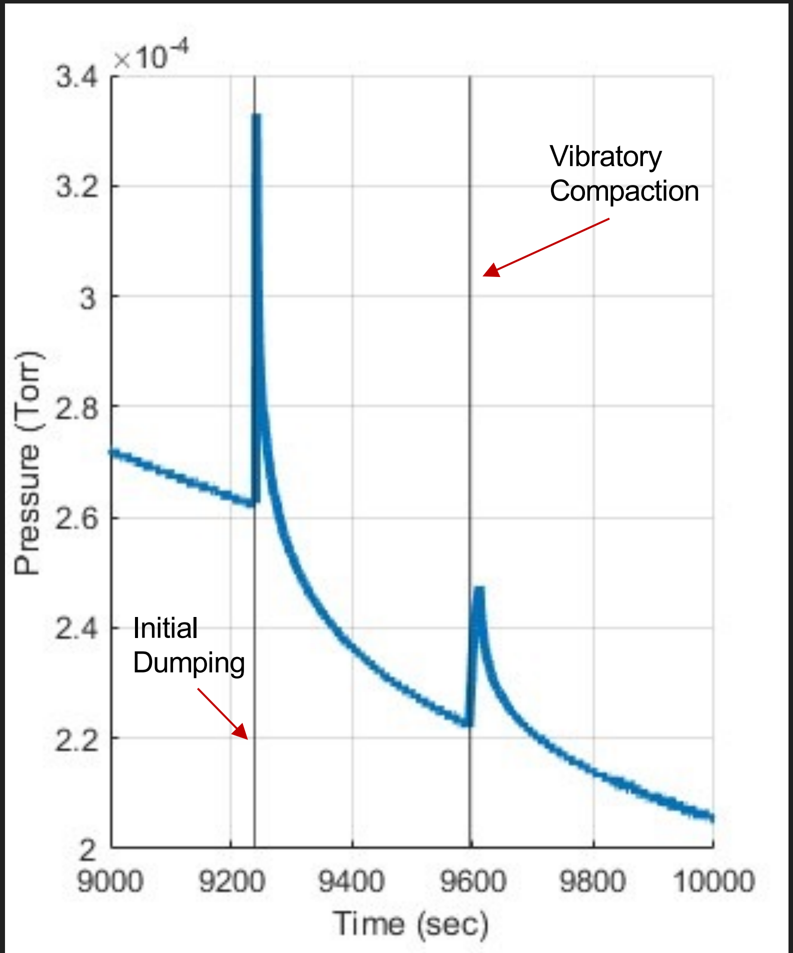
Overview and Conclusions

- Trend of conductivity increasing with bulk density and water ice is clear in ambient pressure freezer tests
- Vacuum Chamber testing did not follow expected trends. Lots of possible reasons
  - Trapped air in regolith
  - Different starting temperatures
  - Pressure differences in testing
- Discrete ice has conductivities near that of dry regolith
- Testing icy regolith in vacuum presents design and procedural challenges

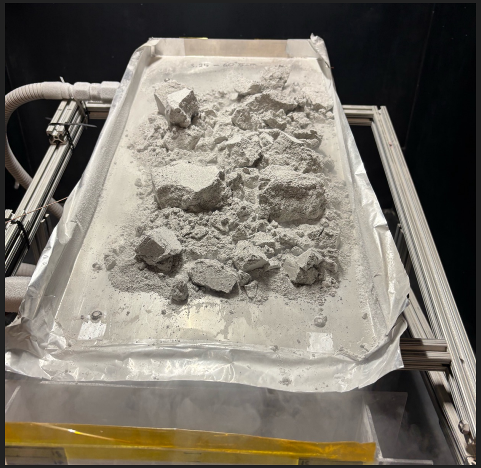


Icy Regolith Thermal Vacuum Testing

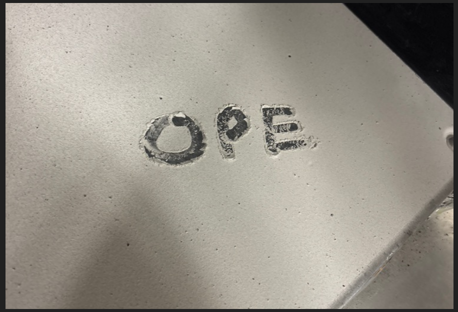
Pressure Spikes During Dumping



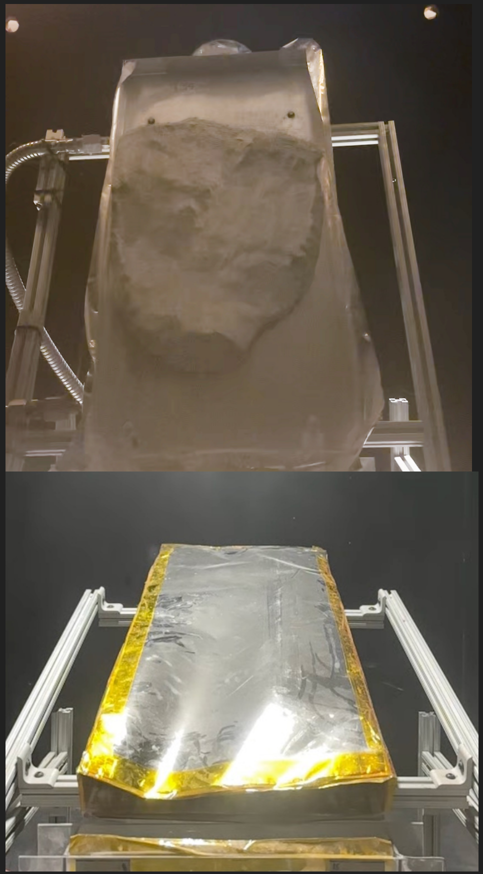
Regolith clumping



Regolith jetting due to sublimation

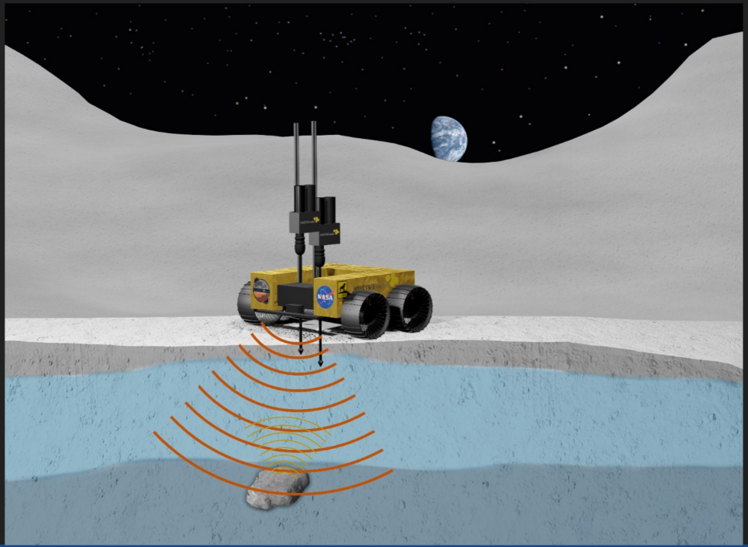


Icy regolith freezing to tray

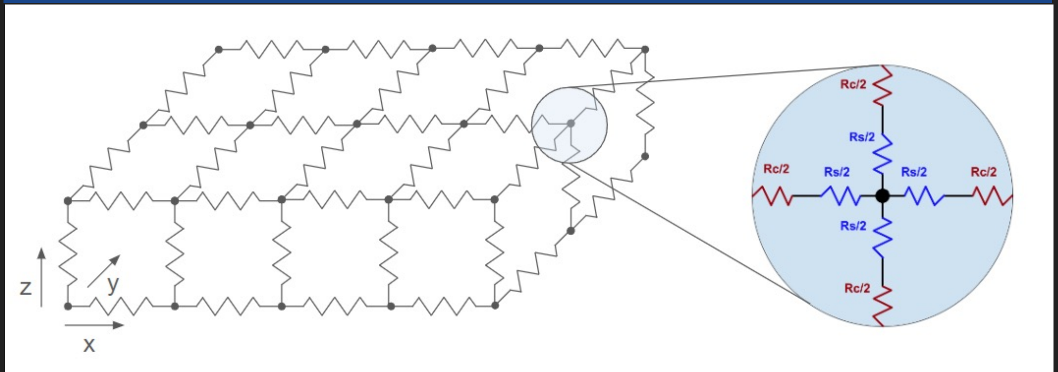


Future Work

- Further investigation into vacuum low compaction results
  - Testing procedural changes to further reduce trapped air
- Testing of cemented regolith conductivities
  - Trapped air further a concern
  - Is there significant changes in conductivity between vacuum and ambient pressure
- Predictive model
  - Model to predict thermal conductivity of icy regolith mixtures and how compaction changes these values



Network Model - Visualization



Acknowledgments

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PSTDL LuSTR Thermal Modeling

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Questions?

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Additional Material

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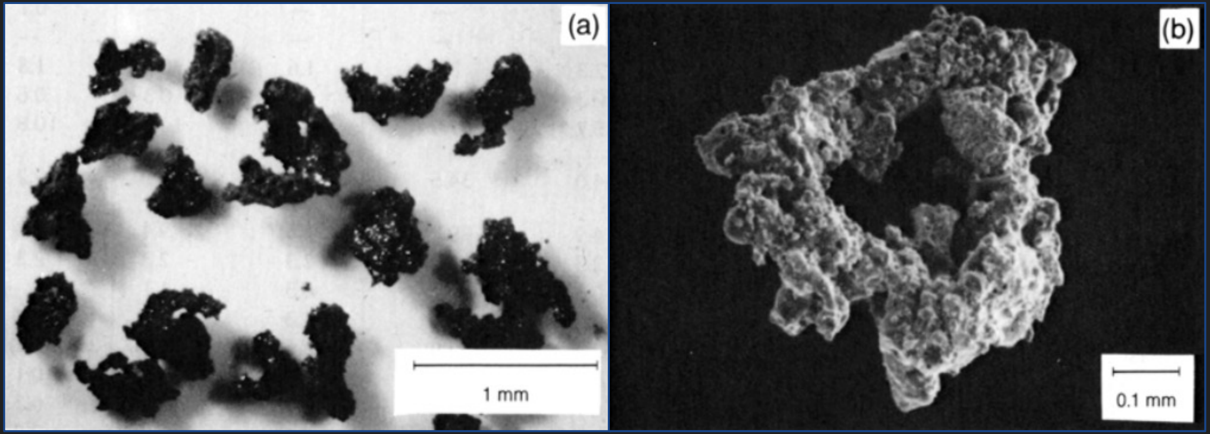
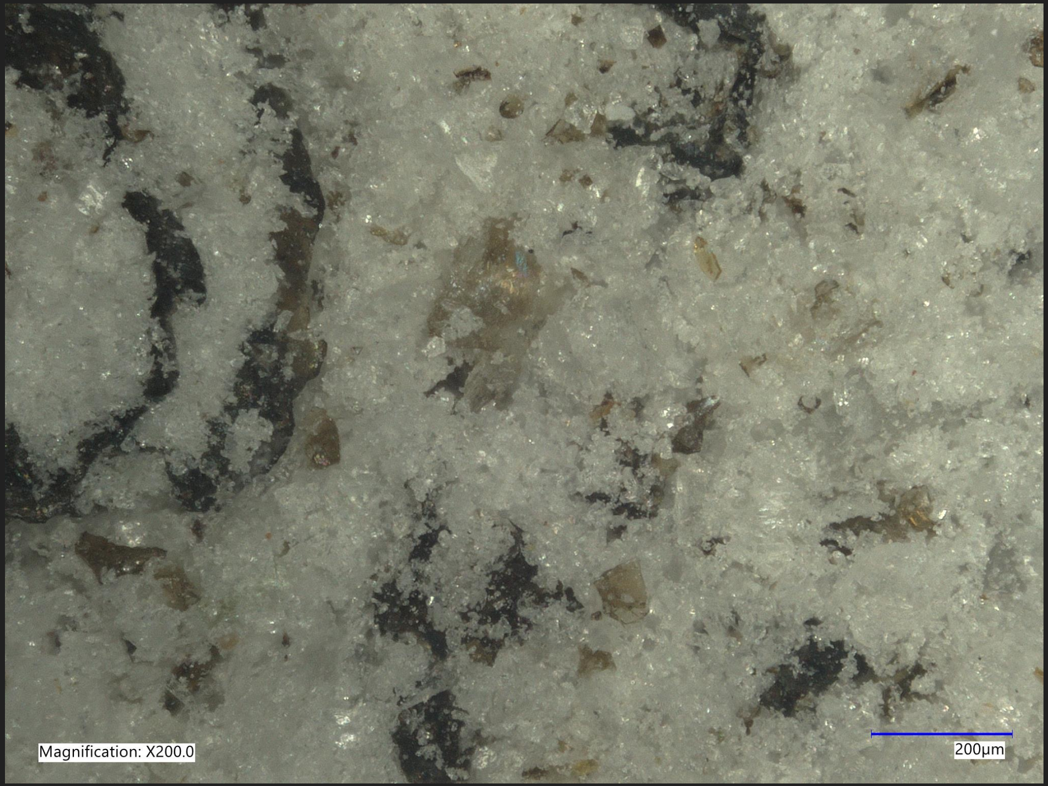
MTU-LHT-1A

Lunar Regolith

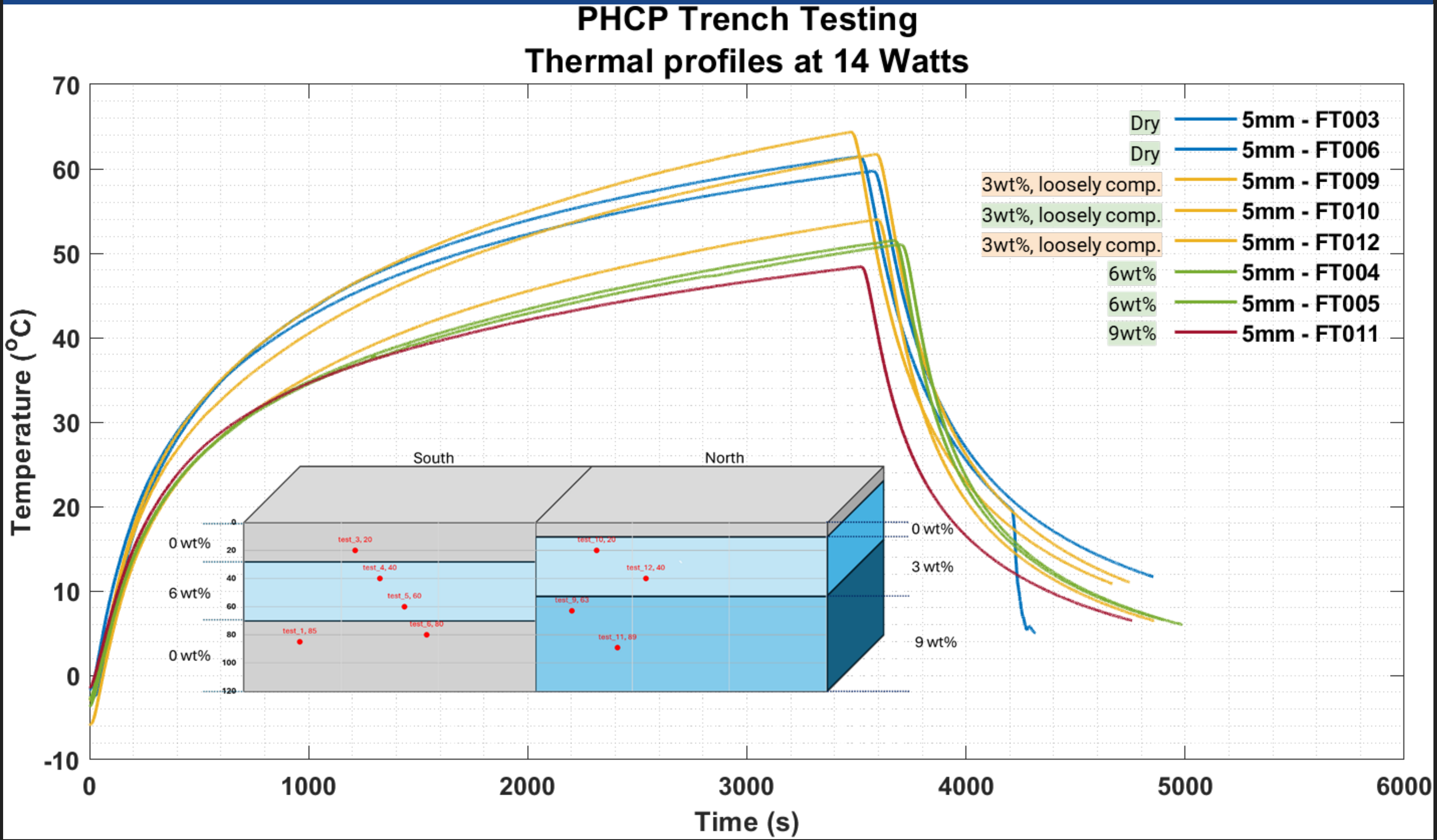


MTU-LHT-1A

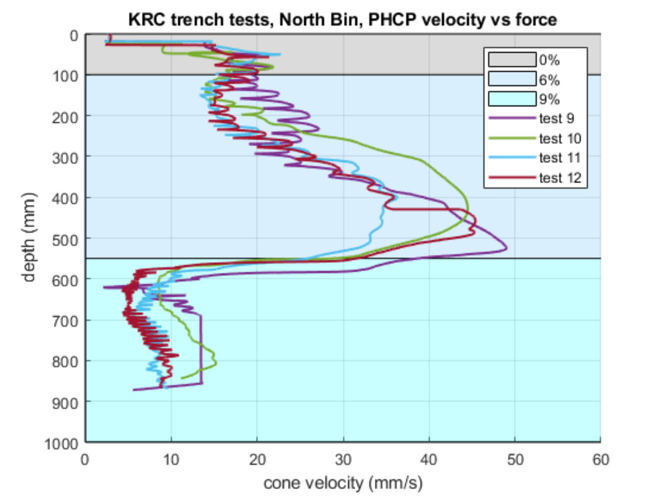


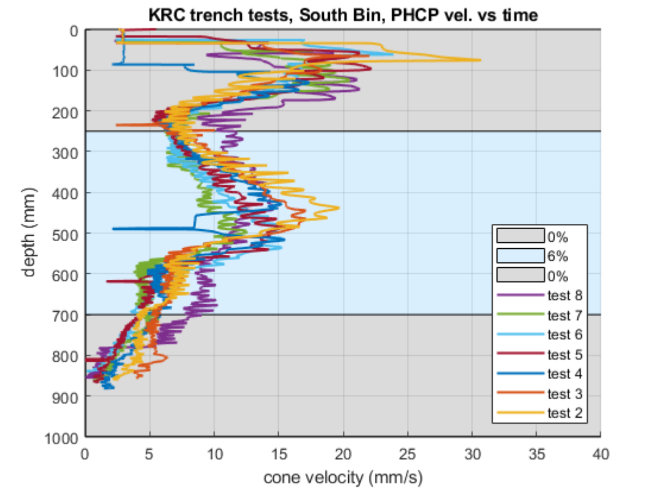
Trench Testing

Thermal Data



Geotech Data





Previous Testing