# Data Analysis Results from Cryogenic Vacuum Testing of a Percussive Hot Cone Penetrometer

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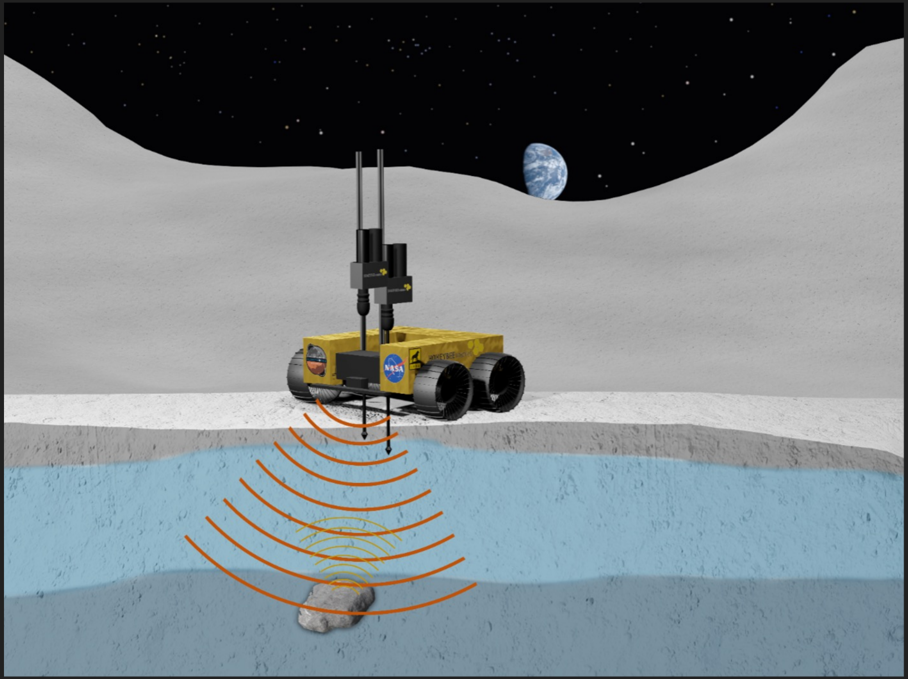
SPACE RESOURCES ROUNDTABLE

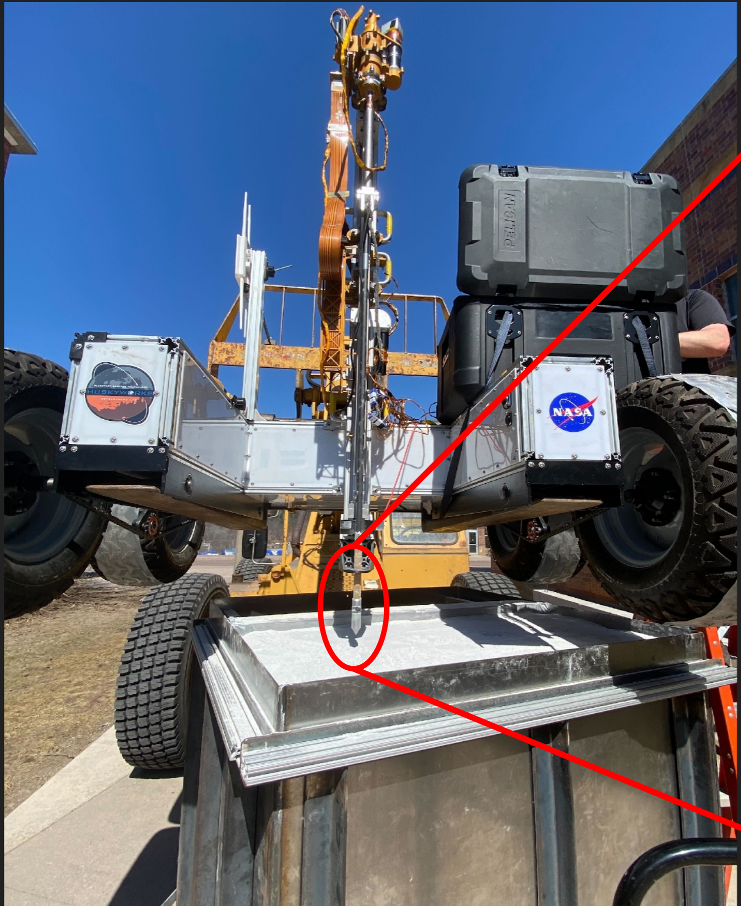
# Background – MTU LuSTR 2020 Project

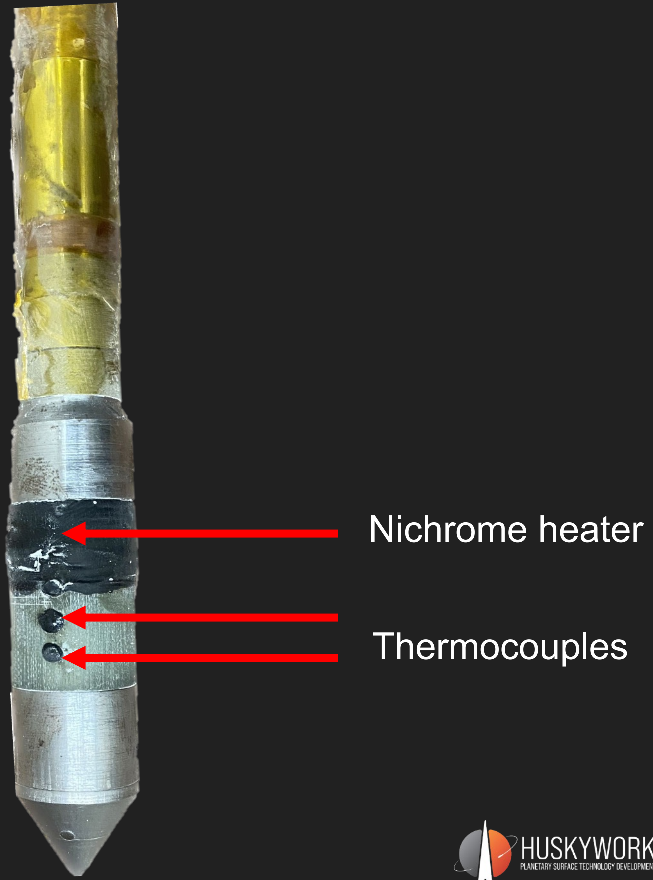
- Rover-mounted Percussive Hot Cone Penetrometer (PHCP) and Ground-Penetrating Rader (GPR) system
  - GPR: subsurface layer and ice continuity data
  - PHCP: geotechnical and volatile composition data
- Geotechnical Data
  - Cone surface pressure & load
  - Impact loads
  - Measurement of depth displacement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



# PHCP Thermal System Validation and Testing

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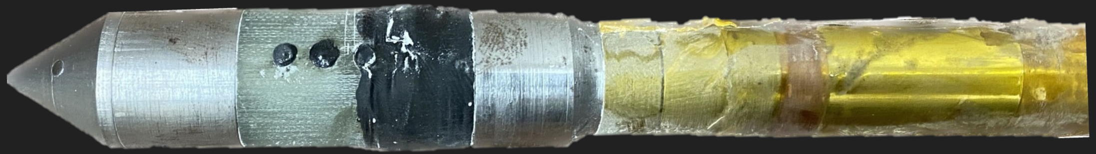


## Atmospheric Testing

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

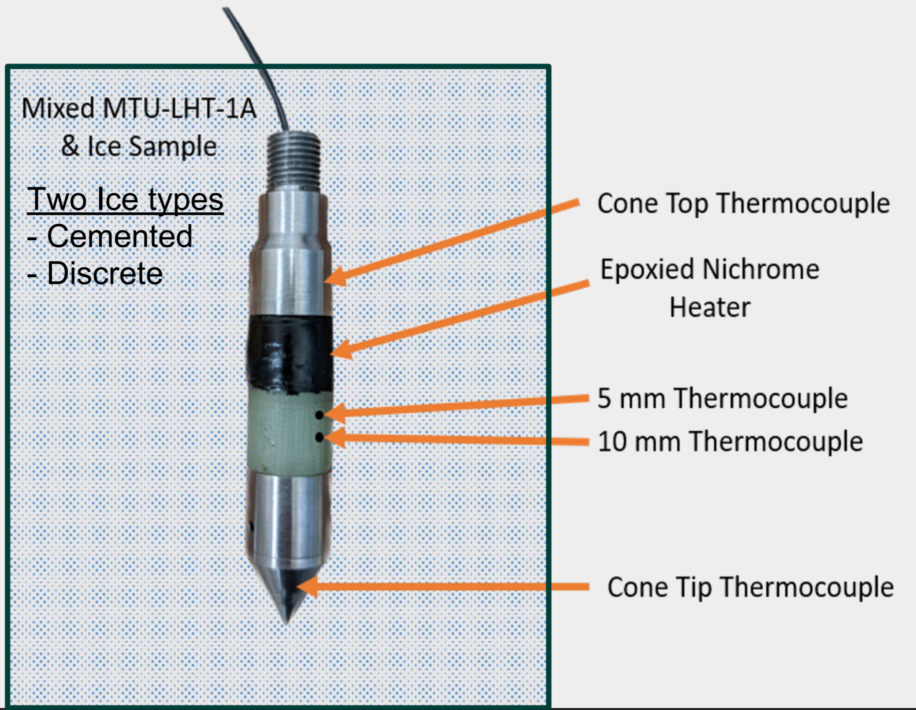
Used to establish:
- Critical thermal measurement locations
- Differences between granular & cemented icy regolith in vacuum
- How to predict water content of granular icy regolith within 1wt% using thermal data

## 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





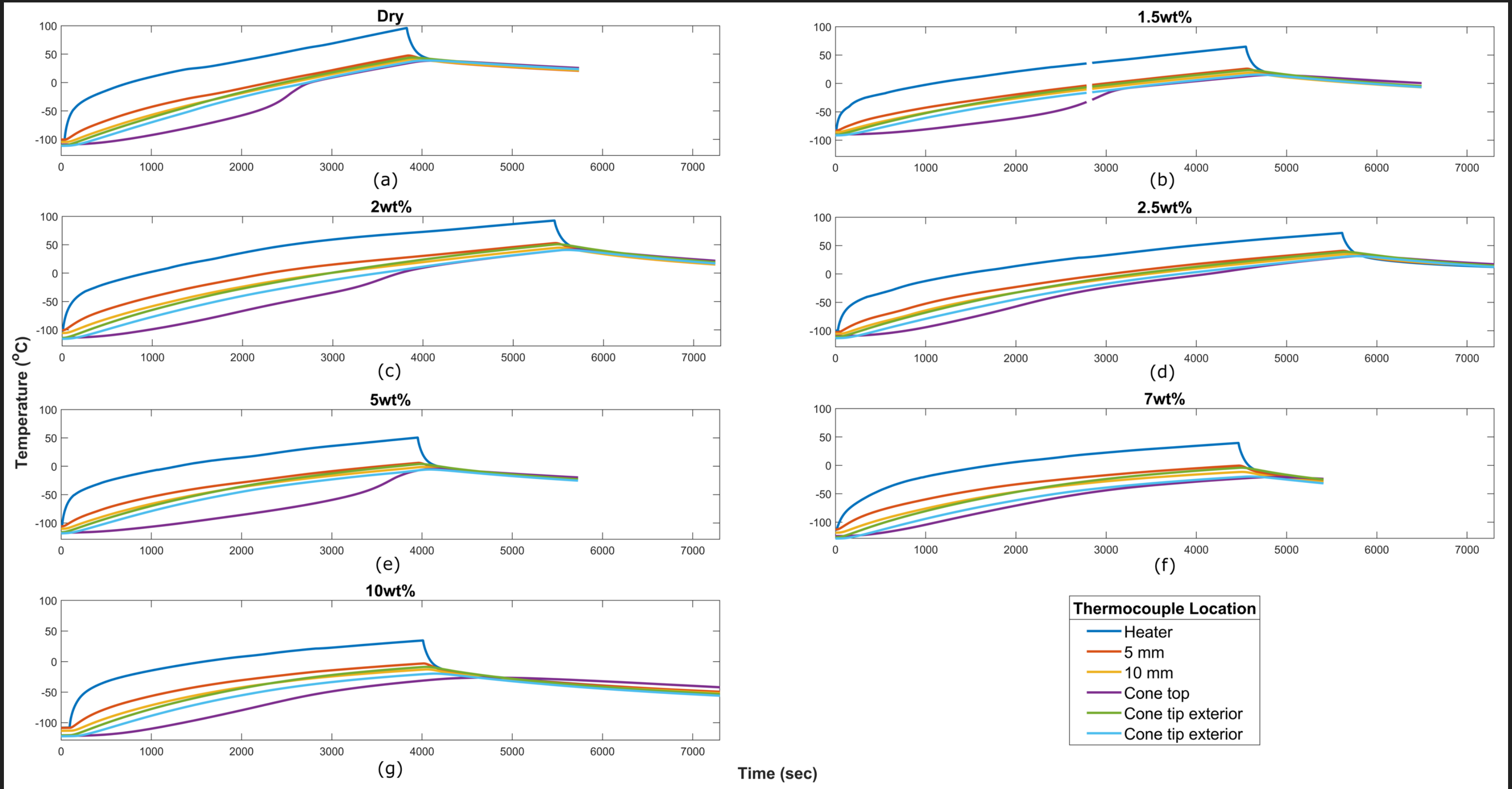

Critical features of thermal cone measurement system

| Weight Percent | Number of test replicates |
|---|---|
| 0 | 3 |
| 1.5 | 3 |
| 2 | 3 |
| 2.5 | 3 |
| 5 | 3 |
| 7 | 3 |
| 10 | 3 |

Outline of cryogenic vacuum thermal cone test campaign

# Results: Thermal Curves






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

# Results: Explanatory Variables

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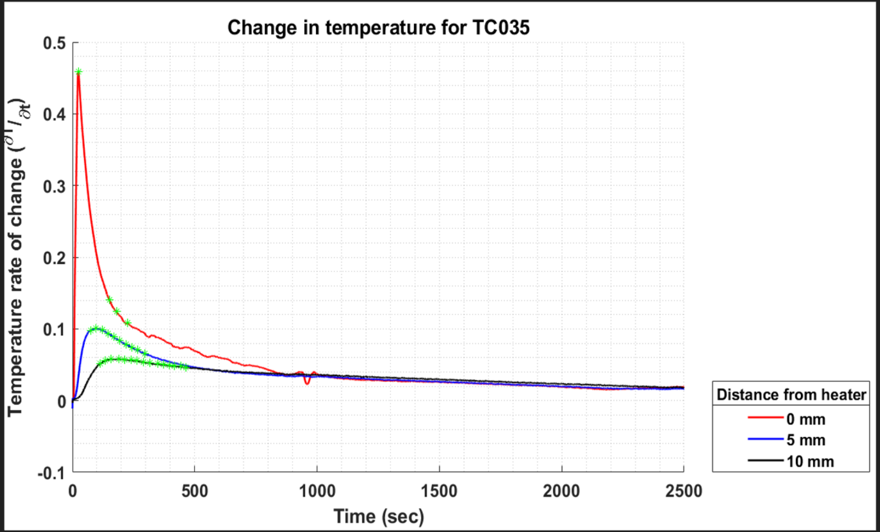
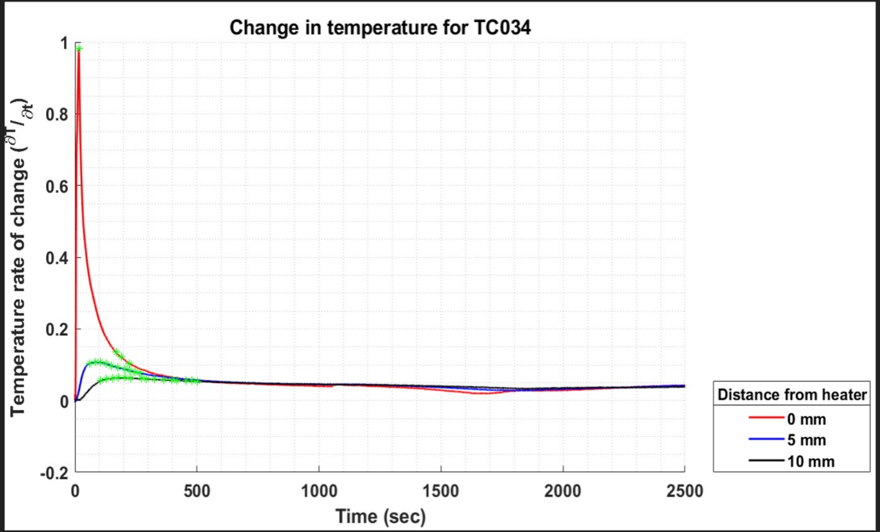
Goal: create correlational model that can predict the granular ice content of icy regolith within 1wt% using the thermal data

- Visual information from thermal curves alone does not contain enough information to quantify water ice
- Additional explanatory variables to consider:
  - Rate of temperature change
  - System heat capacity in 10˚C intervals
  - Bulk density

# Explanatory Variables: Maximum Rate of Temperature Change

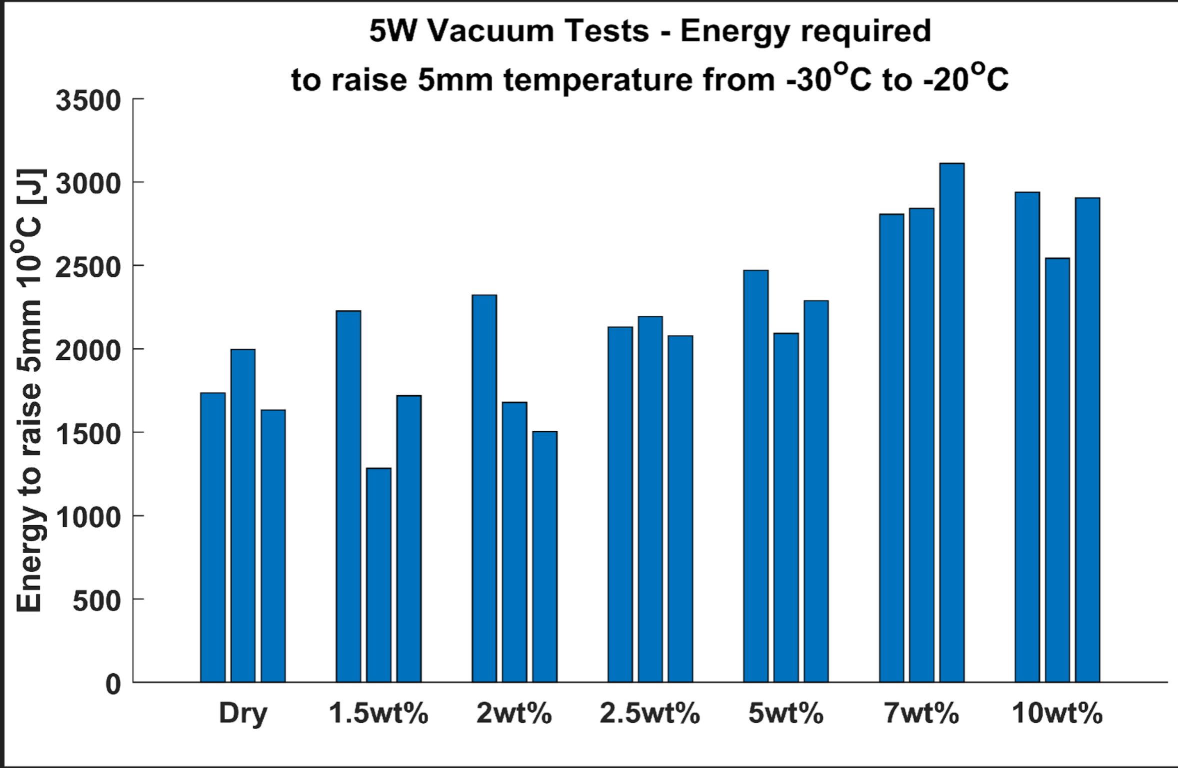



Rate of temperature change vs time for a **7wt% test**. The maximum rate of temperature change at the heater surface is 0.46˚C/sec.




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.

# Explanatory Variables: Heat Capacity




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

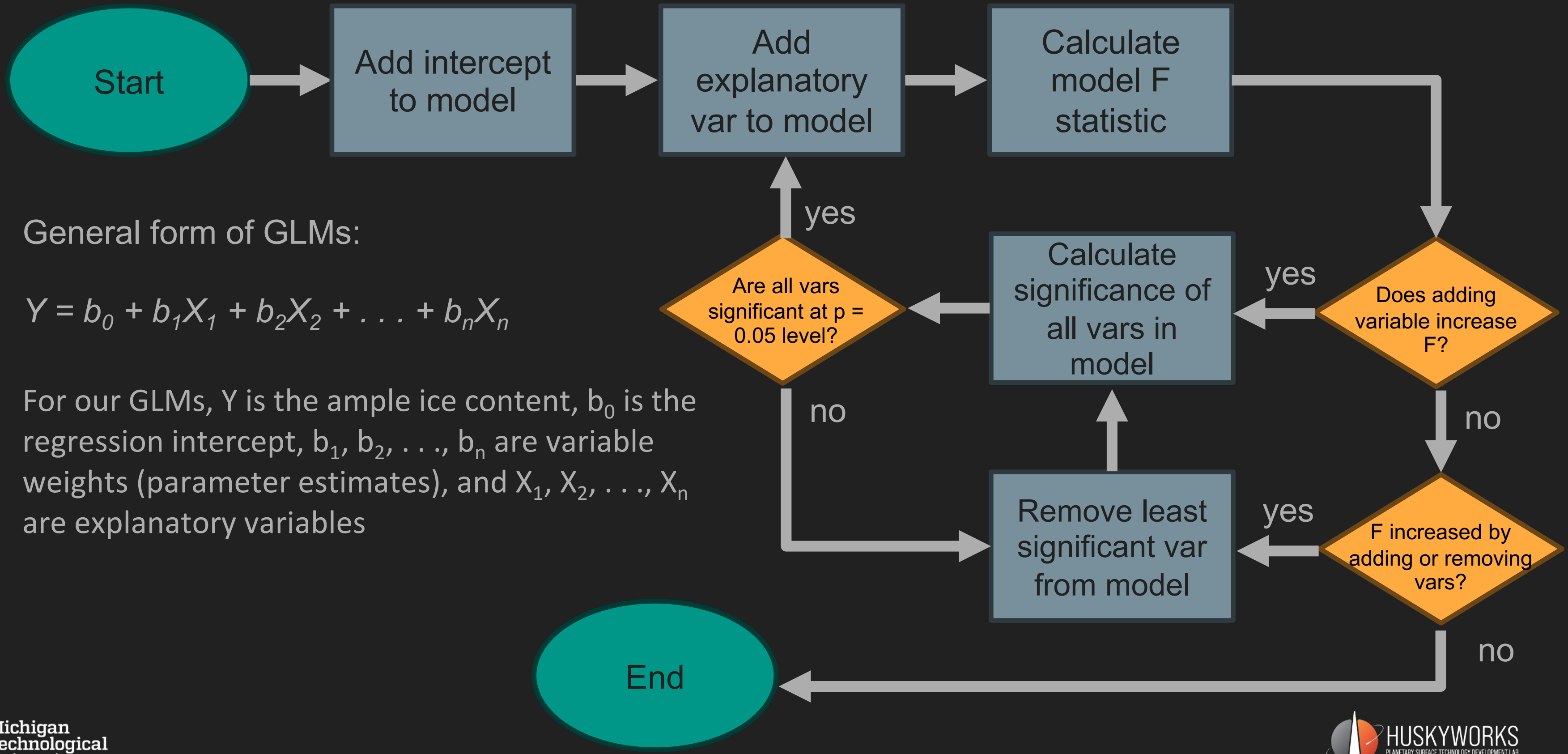
* note: Range of experiment -110 °C to max 100 °C

# Correlating Explanatory Variables to Sample Ice Content

- Method for creating correlation: General Linear Model (GLM) regression
  - Can handle non-normal distributions
  - Broadly applicable model
  - Statistical Analysis Software (SAS)
- Three GLMs
  - Minimize variable pool
  - Add variables to pool until model meets desired prediction performance
  - Stepwise elimination

# Model Variable Selection via Stepwise Elimination






General form of GLMs:

$$Y = b_0 + b_1X_1 + b_2X_2 + . . . + b_nX_n$$

For our GLMs, Y is the ample ice content, $b_0$ is the regression intercept, $b_1$, $b_2$, . . ., $b_n$ are variable weights (parameter estimates), and $X_1$, $X_2$, . . ., $X_n$ are explanatory variables

# Regression Model Variable Pools

- GLM 1: Thermal variables
- GLM 2: Thermal variables + bulk density
- GLM 3: Thermal variables + bulk density + thermal-bulk density interaction terms

| GLM | Explanatory Variable Pool |
|---|---|
| 1 | Max. rate of temp. change, heat capacity from -80°C to 10°C in 10°C intervals |
| 2 | Max. rate of temp. change, heat capacity from -80°C to 10°C in 10°C intervals, sample bulk density |
| 3 | Max. rate of temp. change, heat capacity from -80°C to 10°C in 10°C intervals, sample bulk density, thermal-bulk density interactions terms |

# Regression Results

- GLMs were evaluated based on their prediction performance
- Criteria for “good” model fit: adjusted $R^2 >= 0.9$ and RMSE <= 1wt%

| GLM | Explanatory Variable Pool | Adj. $R^2$ | RMSE (wt%) |
|---|---|---|---|
| 1 | Max. rate of temp. change, heat capacity from -80°C to 10°C in 10°C intervals | 0.63 | 1.92 |
| 2 | Max. rate of temp. change, heat capacity from -80°C to 10°C in 10°C intervals, sample bulk density | 0.79 | 1.47 |
| 3 | Max. rate of temp. change, heat capacity from -80°C to 10°C in 10°C intervals, sample bulk density, thermal-bulk density interactions terms | 0.93 | 0.83 |

# A Closer Look at GLM 3

GLM 3: $\text{Ice wt\%} = -1.75 + 0.075*a - 0.105*b + 0.045*c - 0.172*d + 0.166*e$

| Symbol | Corresponding Variable | Description |
|---|---|---|
| a | $C_{p(-40\_-30)}*\rho_b$ | Interaction term between system heat capacity from -40°C to -30°C and bulk density |
| b | $C_{p(0\_10)}*\rho_b$ | Interaction term between system heat capacity from 0°C to 10°C and bulk density |
| c | $C_{p(-70\_-60)}$ | System heat capacity from -70°C to -60°C |
| d | $C_{p(-50\_-40)}$ | System heat capacity from -50°C to -40°C |
| e | $C_{p(0\_10)}$ | System heat capacity from 0°C to 10°C |

Need thermal range of -70°C to 10°C and need to know bulk density

# GLM 3 Sensitivity Analysis

- How precise do bulk density measurements need to be?
- Randomly added or subtracted uncertainty values to original bulk density data and re-ran regression
    - 0.05 g/cc
    - 0.1 g/cc
    - 0.15 g/cc
    - 0.2 g/cc

| Test # | Measured Bulk Density (g/cc) | Randomly add or subtract | Bulk Density w/additional uncertainty (g/cc) |
|---|---|---|---|
| 1 | 1.54 | -0.05 | 1.49 |
| 2 | 1.49 | -0.05 | 1.44 |
| 3 | 1.4 | +0.05 | 1.45 |
| 4 | 1.81 | +0.05 | 1.86 |
| 5 | 1.32 | -0.05 | 1.27 |

Rerun regression with "uncertain" values, retrieve $R^2$ and RMSE values

# GLM 3 Sensitivity Analysis Results

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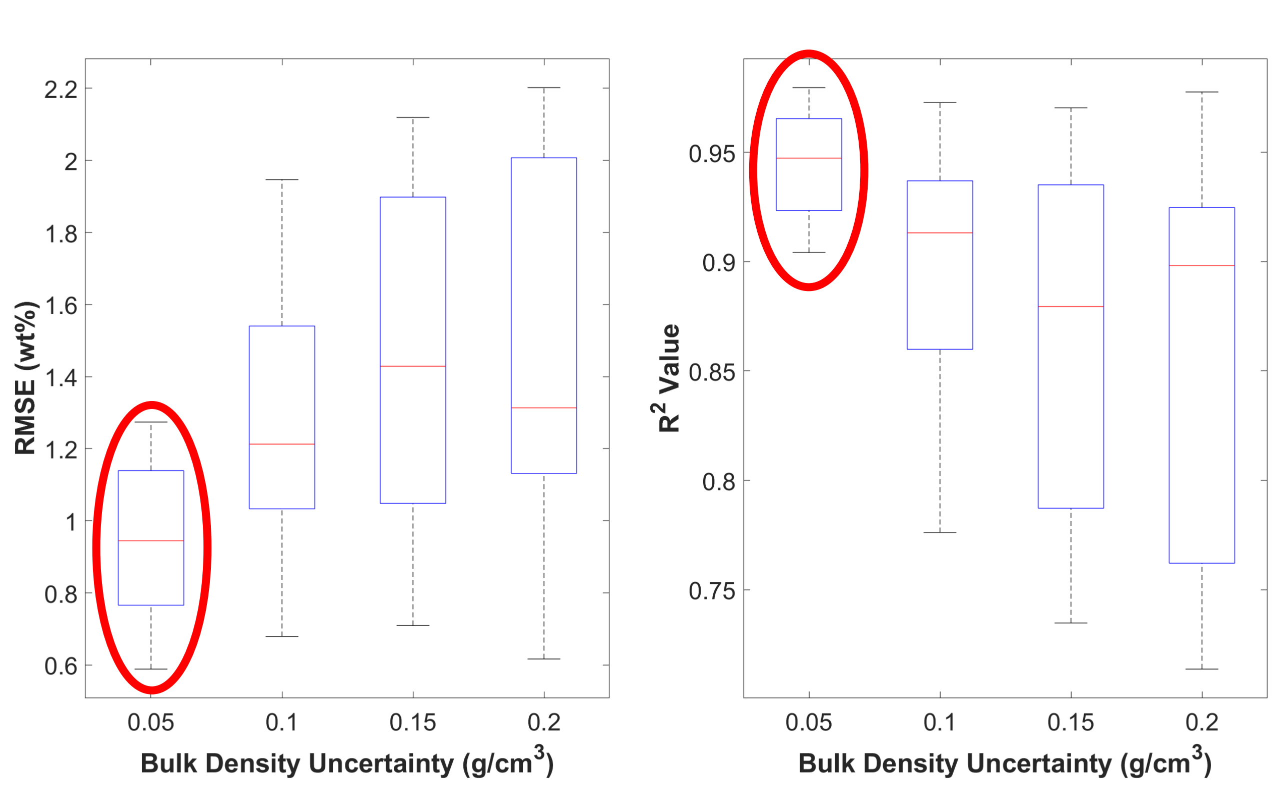
Low is good




High is good

Left: Bulk density uncertainty vs RMSE for GLM 3 sensitivity analysis. Right: Bulk density uncertainty vs $R^2$

# Conclusions & Future Work

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**Main takeaway: The PHCP can predict the granular ice content of icy regolith within ± 1wt% in cryogenic vacuum conditions if the bulk density is known within 0.05 g/cc.**

Avenues for future work:

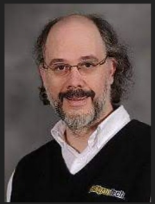
- Cross-validate correlation on HBR vacuum data
- Test with other/additional simulants
- Create correlations for non-water volatiles in cryogenic vacuum conditions
    - CO2
    - Methane
    - Methanol
    - Ethylene
- Thermal modeling

# Acknowledgements



## PSTDL LuSTR Thermal Team

Dr. Paul van Susante, PI



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# Questions?

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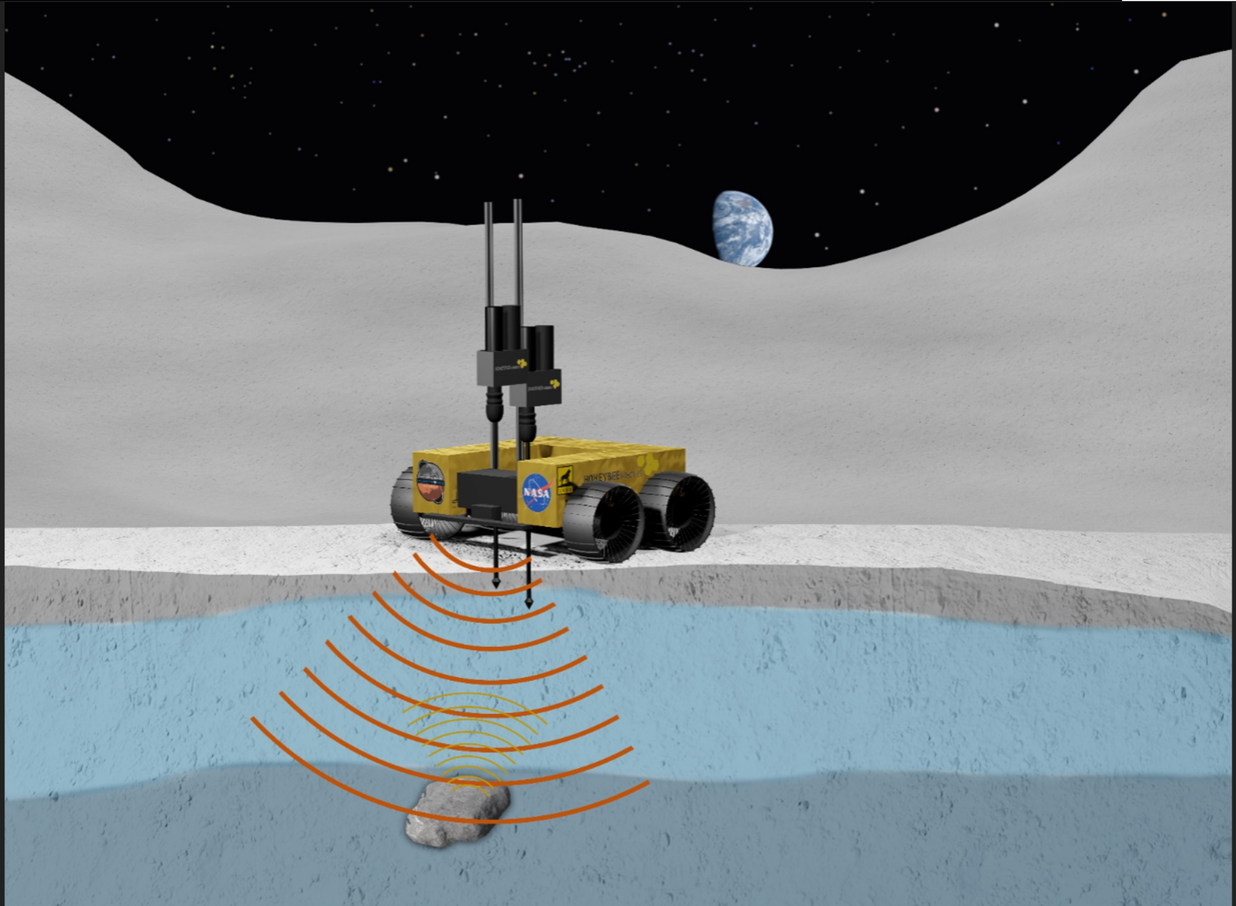

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# Supplementary Slide: Sample Preparation

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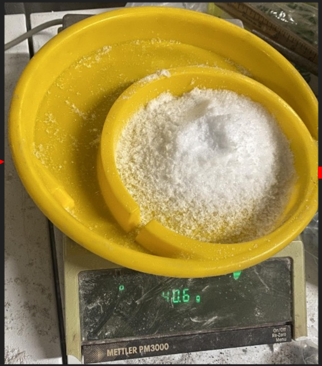
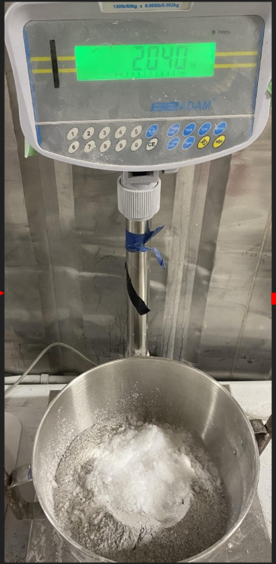
1. Measure 2kg of regolith




2. Measure out ice content (wt%)



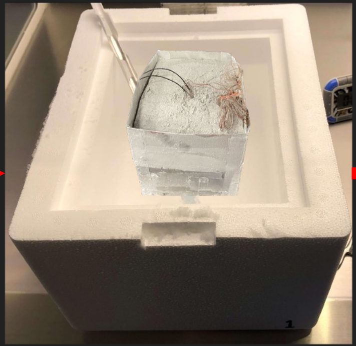

3. Combine ice and regolith

4. Mix until homogenous

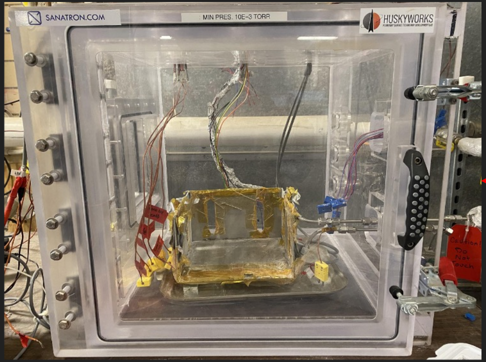
5. Compact and repeat until box is full

# Supplementary Slide: Sample Preparation

Regolith sample in -80˚C freezer



Regolith sample submerged in liquid nitrogen bath




Acrylic vacuum chamber with aluminum liquid nitrogen 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 & opensource power logger |

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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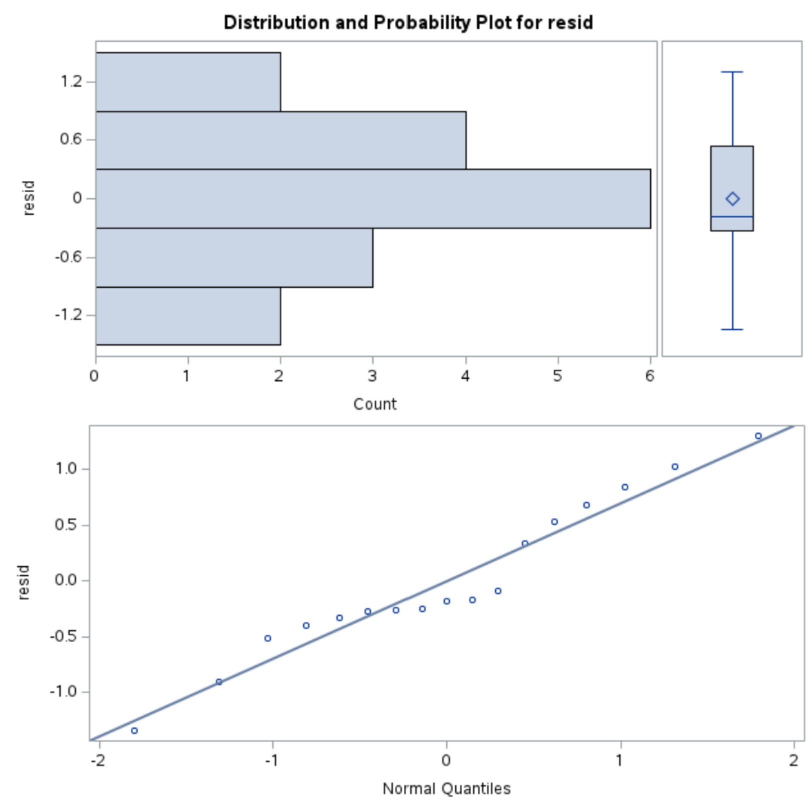
# Supplementary Slide: Model Assumptions




| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 2.213706079 | 1.02104787 | 2.17 | 0.0553 |
| MaxTempRa*Trial50_02 | -0.181885931 | 0.14458308 | -1.26 | 0.2370 |
| Trial50_0*Energy_40_ | -0.000630760 | 0.00075318 | -0.84 | 0.4219 |
| Trial50_0*Energy_0_1 | 0.000337615 | 0.00055674 | 0.61 | 0.5578 |
| Energy_70_60C | -0.002580793 | 0.00201300 | -1.28 | 0.2287 |
| Energy_50_40C | 0.002212410 | 0.00211837 | 1.04 | 0.3209 |
| Energy_0_10C | -0.000533096 | 0.00083754 | -0.64 | 0.5387 |