Data Analysis Results from Cryogenic Vacuum Testing of a Percussive Hot Cone Penetrometer. E. L. Zimmermann[1], G. B. Johnson[2], P. J. van Susante[3], J. S. Allen[4], T. C. Eisele[5]. [1,2,3,4]Dept. of Mechanical and Aerospace Engineering, Michigan Technological University 1400 Townsend Drive, Houghton, MI 49931. [5]Dept. of Chemical Engineering, Michigan Technological University 1400 Townsend Drive, Houghton, MI 49931 (contact: pjvansus@mtu.edu).

Introduction: Recent observations of the lunar surface have established the widespread presence of water ice within the top 1 mm of lunar regolith [1]. Surface water concentration estimations range from less than 30 ppm to 560 ppm in the lunar midlatitudes and poles, respectively [2] [3], but water concentrations below the first 1 mm of the lunar surface are largely unknown. However, analysis of the LCROSS impact site has suggested that permanently shaded regions of the moon may contain a water concentration up to 7.9% by mass within the first 1 m of regolith [4]. In order to detect and quantify water within the first 1 m of regolith, the Planetary Surface Technology Development Lab (PSTDL) at Michigan Technological University developed the Percussive Hot Cone Penetrometer (PHCP), a cone penetrometer that features a nichrome heater and set of thermocouples for in-situ thermal volatile detection (Fig. 1). The PHCP was tested in cryogenic vacuum conditions with granular icy regolith mixtures containing ice concentrations of 1.5 – 10wt%. The goal of this testing was to determine whether the PHCP thermal volatile detection system is capable of estimating the ice content of icy regolith within ±1 wt%.

Methods:

PHCP and Testing Overview: The PHCP thermal volatile detection system consists of a nichrome heater epoxied about the middle of the cone head and 6 thermocouples placed along the length of the cone head (Fig. 1). Two of the thermocouples are placed within an insulative G-10 sheath 5mm and 10mm below the heater. Three thermocouples were taped to the exterior of the cone head at the top, tip, and heater locations. The last thermocouple was embedded into the inside tip of the cone head (Fig. 1).

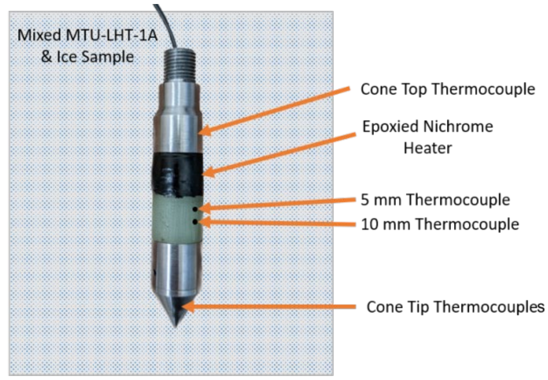

Fig. 1. *MTU PHCP with annotated thermocouple and heater locations*

All thermal volatile detection tests were conducted in compacted granular icy MTU-LHT-1A lunar regolith simulant [5]. The following concentrations of ice (weight percent) were tested throughout the project: 0, 1.5, 2, 2.5, 2.5, 5, 7, and 10 percent. Three replicates of each weight percent were run for a total of 21 tests. All test samples were prepared at -4.4°C and then further cooled to -110°C with a liquid Nitrogen bath. During testing, the vacuum chamber pressure was kept below 50mTorr and a constant power supply of 5 Watts was supplied to the nichrome heater. Power was supplied to the heater for 1.5 hours or until the heater surface reached 100°C. The following data was logged and recorded until 30 minutes after the heater was turned off: temperature data from all 6 cone head thermocouples, vacuum chamber pressure data from a convection vacuum gauge, and the power being supplied to the heater by the power supply.

Sample Preparation: Each sample was prepared by mixing MTU-LHT-1A regolith simulant with discrete, shaved ice particles with particle diameters ranging from less than 425 μm to 600 μm. Each sample was prepared in a space where everything is kept at -4.4°C in 2 kg layers. For each layer, 2 kg of pre-cooled simulant was measured out using a 2 g-accuracy scale while the ice content was measured using a 0.1g-accuracy scale. The simulant and ice shavings were combined using a stand mixer. Once each layer was homogenously mixed, it was transferred from the mixer to a 8.75in x 7.625in x 8.25in aluminum box and compacted. This mixing and compacting process was repeated until the sample reached an approximate height of 8in within the box, resulting in bulk densities ranging from 0.94g/cc to 1.85g/cc, depending on the weight percent ice content of the sample. The finished sample was transferred to a -80°C freezer where it would remain for a minimum of 12 hours prior to testing. The cone was manually percussed into each discrete ice sample before testing.

Data Analysis: Generalized linear model (GLM) regression was used to create and fit models for ice content prediction. Three GLMs were constructed to evaluate the significance of various regressor variables in predicting ice content. These models used wt% ice as the dependent variable and included several regressor variables that varied by model. The correlation and accuracy of each model was assessed with its adjusted R^2 and root means squared error (RMSE), respectively. A bulk density sensitivity analysis was run on the GLM 3 to evaluate maximum bulk density estimation uncertainty that the model could withstand while maintaining an R^2 value > 0.9 and an RMSE < 1wt% ice.

Results: GLM 1 only included thermal regressor variables and was the least accurate model with an adjusted R^2 value of 0.63 and an RMSE of 1.92wt%. GLM 2's regressors consisted of thermal variables as well as the sample bulk density. The adjusted R^2 and RMSE values for GLM 2 were 0.79 and 1.47wt%, respectively. GLM 3's regressor variables included thermal variables, sample bulk density, and interaction terms between each thermal variable and the sample bulk density. GLM 3 was the most accurate model with an adjusted R^2 value of 0.93 and an RMSE of 0.83wt%. Table 2 shows the adjusted R^2 and RMSE values of each GLM for comparison. Bulk density sensitivity analysis of GLM 3 revealed that the model could only maintain R^2 > 0.9 and RMSE < 1wt% if the sample bulk density remained within ±0.05 g/cm^3 (Fig. 2).

Table 1. *Regressors, Adjusted R^2, and RMSE values for GLM 1 – 3.*

GLM	Regressors	Adj. R^2	RMSE (wt%)
1	Thermal vars	0.63	1.92
2	Thermal vars + bulk density	0.79	1.47
3	Thermal vars + bulk density + interactions	0.93	0.83

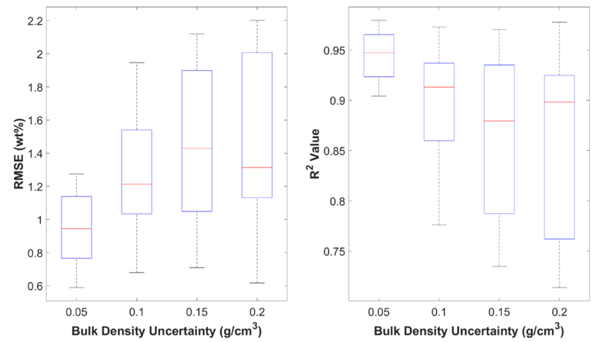

Fig. 2. *Left: Boxplot of bulk density uncertainty vs RMSE for GLM 3 bulk density sensitvity analysis. Right: Boxplot of bulk density uncertainty vs R^2 for GLM 3 bulk density sensitivity analysis.*

Discussion & Conclusions: The PHCP thermal volatile detection system is able to detect the granular ice concentration of icy regolith mixtures within ±1wt% if the bulk density of the mixture is known within ±0.05 g/cm^3. This result highlights the significant relationship between regolith bulk density and heat transfer properties, and demonstrates that thermal heating data alone is not sufficient to estimate the volatile concentrations present within granular icy regolith mixtures. Work is ongoing to assess the PCHP's bulk density estimation precision. Future work will apply GLM 3 to PHCP thermal vacuum data acquired from Honeybee Robotics' facilities.

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[1] S. Li and R. E. Milliken, "Water on the surface of the Moon as seen by the Moon Mineralogy Mapper: Distribution, abundance, and origins," *Sci. Adv.*, vol. 3, no. 9, p. e1701471, Sep. 2017, doi: 10.1126/sciadv.1701471. [2] H. Lin *et al.*, "In situ detection of water on the Moon by the Chang'E-5 lander," *Sci. Adv.*, vol. 8, no. 1, p. eabl9174, Jan. 2022, doi: 10.1126/sciadv.abl9174. [3] Y. Xu *et al.*, "High abundance of solar wind-derived water in lunar soils from the middle latitude," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 119, no. 51, p. e2214395119, doi: 10.1073/pnas.2214395119. [4] P. D. Strycker *et al.*, "Characterization of the LCROSS impact plume from a ground-based imaging detection," *Nat. Commun.*, vol. 4, no. 1, p. 2620, Oct. 2013, doi: 10.1038/ncomms3620. [5] C. Carey and P. Van Susante, "Michigan Technological Universities' Lunar Highland Simulant MTU-LHT-1A," in *Session 4 - Individual Poster Presentations*, Golden, CO, Jun. 2022. [Online]. Available: https://isruinfo.com/public/index.php?page=srr_22#SRR_22_1