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

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Introduction: Evidence of water ice and other volatiles around the lunar poles in permanently shaded regions (PSR) has been confirmed by analyzing the results of the LCROSS impact plume. [1] Although the existence of volatiles like H_2O, CO_2, SO_2, CH_4, and others have been confirmed and quantified from orbit and by studying the impact plume from the LCROSS impact site, detailed sampling of lunar PSRs has not yet been done. Active ground sampling will be needed to improve our understanding of the distribution and quantity of volatiles present in the lunar regolith. This knowledge will be critical in achieving NASA's strategic goals of scientific discoveries, extended human presence on the moon, and sustainable long-term exploration, development and utilization.

Primary methods for sampling the lunar surface in PSR include drilling and core sampling. However, the mechanisms utilized for drilling are prone to excessive wear over time. One method of collecting geotechnical data on Earth utilizes dynamic cone penetrometers. Funding through NASA's LuSTR 2020 initiative has allowed the Planetary Surface Technology Development Lab (PSTDL) at Michigan Technological University (MTU) to explore and design an integrated method of volatile detection and geotechnical sampling using a percussive hot cone penetrometer (PHCP). To inform the design and development of the PHCP, experimental tests were conducted to characterize expected behavior of heat conduction in dry, wet and icy regolith simulant. In tandem with these experimental tests, thermal modeling and simulations were generated to investigate the effects of different cone material properties on the observable thermal behavior. Both the experimental testing and thermal modeling & simulation are discussed further in addition to the current thermal cone design.

Thermal Profile Testing: Thermal properties of the lunar regolith simulant MTU-LHT-1A, produced by the PSTDL, had yet to be characterized. A simple test setup was designed using a 5-gallon bucket, 14-gauge type-K thermocouples, a 21W/cm^2 cartridge heater, and an AC power logging data acquisition system (DAQ) to begin characterizing the propagation of heat through MTU-LHT-1A. (Figure 1)

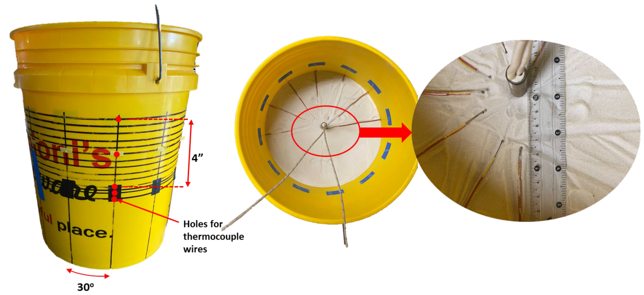

Figure 1: Modified 5-gallon bucket and thermocouple placement relative to the heater

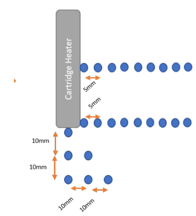

Figure 2: Cross section of the thermocouple placement relative to the cartridge heater

Dry, 5wt%, and 10wt% wet regolith samples were tested by compacting layers of regolith and embedding thermocouples at specific depth and 5mm incremental distances from the surface of the submerged cartridge heater. (Figure 2) Constant power levels; 30 Watts, 50 Watts, and 100 Watts were used as a method of controlling the energy input to the heater for various tests. These tests allow determination of differences in rates of heat transfer and sizes of heat affected zones for samples with different moisture contents. Figure 3 below shows the results of 9 different tests comparing the change in temperature over time of regolith simulant mixed with 5wt% water at various distances to the heated surface for three different power levels. Testing was also performed on frozen (cemented) regolith, dry, with 5wt% and 10wt% water to observe the thermal behaviors during solid to liquid to gas phase change.

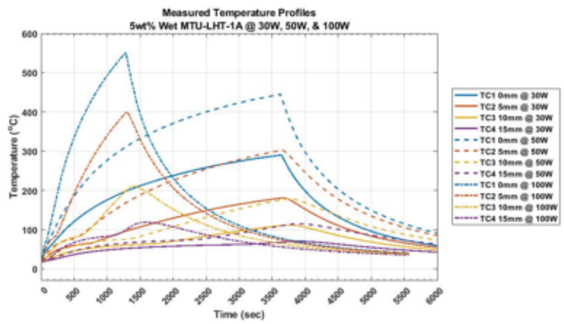

Figure 3: Measured temperatures at the heater midpoint layer. 0, 5, 10, & 15 mm distances from the heater's surface. Three constant power level tests, 30, 50, & 100 Watts each with 5wt% water

To conduct experimental thermal testing on samples with other volatile inclusions like CO_2, SO_2, and CH_4, a new test setup had to be designed. This new experimental setup will need to cool and maintain cryogenic (LN_2) sample temperatures to achieve liquid or solid phase volatiles. To achieve this, a vacuum vessel with a pre-aligned heater and thermocouples will be submerged in a liquid nitrogen bath. Active LN_2 cooling will also be utilized in the mixing of MTU-LHT-1A and other volatiles. Final designs for this test setup have been created and construction is in progress.

Thermal Modeling of Dry Simulant: In addition to the thermal profiling of MTU-LHT-1A with the cartridge heater, testing is in progress using a line-source test setup. This alternative test setup (Figure 4) provides well understood boundary conditions and can be modeled as an axisymmetric 1D geometry.

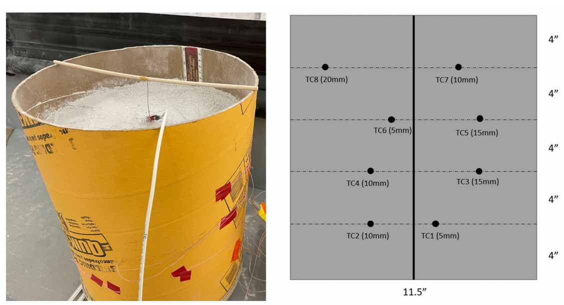

Figure 4: Line Source Configuration for Thermal Properties at Different Compactions

The line-source test setup is composed of a 11.5" diameter cardboard cylinder with 16" of compacted regolith was developed. Additionally, thermocouples were fixed in place by taught fishing line to keep them in position (+-1mm) during compaction. A 22-gauge nichrome wire was used as the line heat source with 40-gauge thermocouples spaced at 5mm intervals. This cylinder replaces a 5-gallon bucket used previously and allows for more accurate layer-wise compaction to achieve specific bulk densities (relative compaction) due to the uniform diameter. The data from these tests is then curve fit to provide temperature and compaction dependent effective thermal conductivity and diffusivity values for the regolith simulant at ambient pressure.

Thermal Cone Design: The thermal profiling and modeling informs the design of the thermal section of the PHCP as well as geotechnical considerations. The PHCP will act similarly to the cartridge heater, consisting of a constant power source with temperature sensors on the cone surface. To detect volatile inclusions as low as 1 weight percent, a constant power level and sensitive temperature sensors need to be selected to achieve these requirements. The preliminary design (Figure 5) takes into consideration, the expected temperature range, abrasion resistance needed to survive in the lunar environment, and thermal conductivity to minimize the interference of the rest of the PHCP.

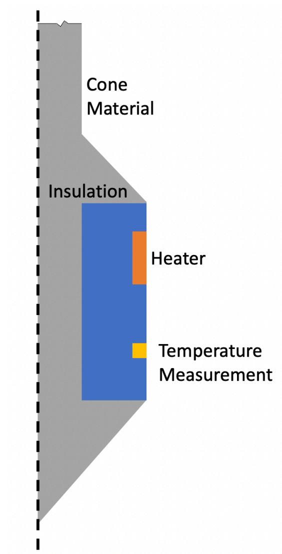

Figure 5: Preliminary Thermal Design of PHCP

Thermal modeling of the probe is ongoing and will inform the material selection and temperature measurement sensitivity needed.

References

[1] G. Johnson, T. Wavrunek, A. Rajan, P. J. van Susante, T. Eisele, and J. S. Allen, "Method for Thermal Modeling and Volatile Measurement of Lunar Regolith," presented at the ASCE Earth and Space 2022, Denver, Colorado USA, Apr. 2022.