

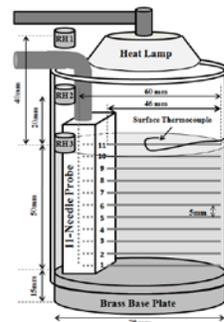
**LABORATORY MEASUREMENTS OF THERMAL PROPERTIES OF MARTIAN PERMAFROST ANALOGS.** M. A. Siegler<sup>1</sup>, O. Aharonson<sup>2</sup>, and N. Schorghofer<sup>3</sup>, <sup>1</sup>UCLA, Department of Earth and Space Sciences, <sup>2</sup>California Institute of Technology, Department of Geologic and Planetary Sciences, <sup>3</sup>University of Hawaii, Institute of Astronomy.

**Introduction:** Thermal properties of icy regolith on Mars have generally been extrapolated from theory or measurements of terrestrial permafrost. In a series of laboratory experiments, we measure thermal conductivity, thermal diffusivity, and heat capacity of icy regolith created by vapor deposition under Martian atmospheric conditions. We find ice deposited in this manner, which may be common on Mars (and present on the Moon), has a thermal conductivity that increases roughly linearly with volumetric ice content. We find a best fit linear trend for conductivity,  $\lambda_{icy}$ , of  $\lambda_{icy} = 0.811\phi F + \lambda_{dry}$  where  $\phi$  is the dry regolith porosity and  $F$  is the volumetric ice-filling fraction, or about 81% that of a linear mixing trend between dry regolith and ice. We describe the observed microphysical structure of ice responsible for these thermal properties, which displaces interstitial gases, traps bubbles and bridges non-neighboring grains.

**Background and Experimental Setup:** Here we describe a set of thermal properties measurements performed in a unique laboratory set up at the Caltech Icelab. The basis of this experiment has been reported in previous studies [1] and involves the deposition of water vapor into a sub-freezing regolith simulant in low pressure (6mbar) CO<sub>2</sub> atmosphere. The regolith simulant, 500  $\mu\text{m}$  glass spheres, is kept under a relatively strong thermal gradient ranging from 268K at the surface to ~200K at 5cm depth. As water vapor enters the vacuum chamber, it deposits within the pore space of simulant at depths where temperatures fall below those required for saturation. Water vapor densities are maintained such that the surface remains nearly ice free, while an ice table forms at roughly 1cm depth.

Understanding the physical and thermal properties of vapor-derived ice is an important factor in examining the response of subsurface ice to Martian climate variation [8, 2].

We instrumented the apparatus with an 11-needle thermal properties probe. As seen in Figure 1, the needles, each 1mm in diameter, lie horizontally through the 5cm regolith simulant at 0.5cm intervals. Each needle contains a resistive wire heater and a thermocouple. The heater is briefly pulsed (~10 seconds) and heat loss and exchange between neighboring needles is monitored by the thermocouples. The amplitude and rate of temperature change at a source needle or its neighbor will be modified by the thermal diffusivity and heat capacity of the surrounding medium [9].



**Figure 1: Schematic drawing of the 11-needle thermal properties probe within a 5cm deep sample.**

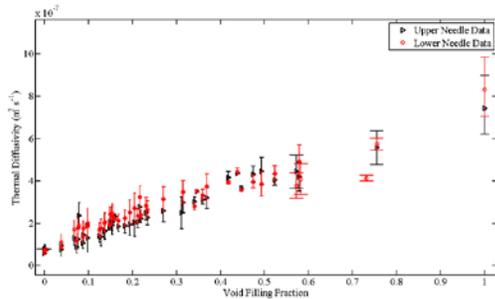
There is a rich history of literature in soil and material science fields on applying such measured heat pulses to derive thermal properties. Past laboratory work using the heated line-source technique on dry regolith has been widely used in interpreting Martian regolith grain size from remote observations [3]. Recently, a similar heated needle device, the Thermal and Electrical Conductivity Probe (TECP) operated aboard the Mars Phoenix lander. Unfortunately, ice saturated soils found at the landing site proved too cohesive to insert the TECP needles.

**Experimental results:** As ice deposits in-situ about the needles in the experiment, we have been able to measure ice content up to relatively high pore filling fraction. Roughly twenty deposition experiments of increasing duration were run. Needle-derived properties are associated with gravimetrically measured ice content. However, pore constriction by ice limits us to maximum volumetric filling fractions of roughly 80%. The 100% filling fraction measurements in Figures 2 and 4 were found by freezing beads saturated in liquid water from the bottom up under 6mbar ambient conditions.

Measurements using the single needle technique determines only the convolved quantity of thermal conductivity. As these measurements are effected by soil properties in all directions, anisotropic ice distribution in the medium can also strongly affect derived quantities.

Measuring the dissipation of the heat pulse at both the heated and neighboring needles allows separate determination of thermal diffusivity and heat capacity. The heat flux is measured in the plane of the needles, allowing for determination thermal properties in the vertical (along thermal gradient) direction. This mea-

surement showed that thermal diffusivity had a clear, roughly linear increase with volumetric pore filling, seen in Figure 2.



**Figure 2: Thermal diffusivity as a function of volumetric ice content.**

**Interpretations and supporting data:** This linear trend implies that ice deposition geometry in pore spaces does not vary dramatically as a function of ice content. This differs from previous theory [4] which assumed ice first forms at grain contact points, causing a dramatic increase in thermal conductivity at low ice contents. This process, called sintering, occurs due to a vapor density gradient which drives deposition toward a point of inward curvature [5].

The fact that we do not see the dramatic rise in thermal conductivity implies grain sintering is not the primary mode of vapor deposition. We suggest the process is overwhelmed by the competing vapor density gradient caused by the presence of microscale thermal gradients between neighboring grains. Microscopic examination of initial ice deposition (images from an 11 hour run shown here) confirms that ice first deposits in long tendrils, connecting semi-distant grains, rather than sintering adjacent grains.

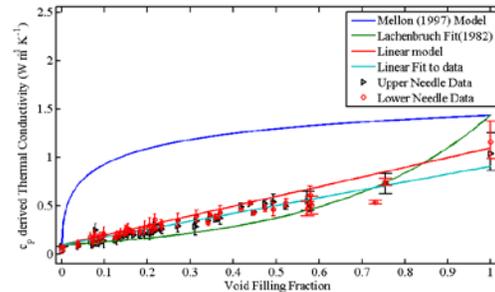


**Figure 3: Ice tendril structures formed during an 11 hour experimental run. The beads are 500-600 $\mu$ m for scale.**

The motive force behind this unexpected deposition seems to lie in the presence of local temperature gradients. These gradients can exist due to the limited conductive pathway between grains touching at only a small point in a low density atmosphere.

As saturation vapor density is exponentially dependent on temperature, even moderate local gradients can dominate over the effects from grain curvature. The resulting structure does not cause the rapid increase in cross sectional area available for solid heat conduction that results from grain sintering [1, 6].

Heat capacity also varies directly with volume filling (when corrected to a standard temperature), leading to a linear trend in thermal conductivity. We find a best fit linear trend for conductivity,  $\lambda_{icy}$ , of  $\lambda_{icy}=0.811\phi F+\lambda_{dry}$  where  $\phi$  the dry regolith porosity and  $F$  is the volumetric ice-filling fraction (and heat capacity is corrected to 263K), or about 81% that of a linear combination between dry regolith and ice.



**Figure 4: Thermal conductivity as a function of volumetric ice content (corrected to 263K) as compared to models.**

Figure 4 compiles this data with the sintering model, a linear mixing model, and a model fit to measurements of frozen terrestrial permafrost samples [7].

Under Martian conditions, ice will, as in the experiment, be driven into the regolith by thermal gradients [8, 1]. These gradients will be expressed on small scales similar to those observed here, prohibiting grain sintering and causing initial structures similar to those we observe. However, unlike the experiment, diurnal and seasonal oscillations in temperature may allow ice to redistribute to form sintered structures. Experiments underway at the Caltech Icelab aim to address this question.

**References:** [1] Hudson, T.L. *et al.* (2009) *JGR 114*, E01002. [2] Schorghofer, N., and O. Aharonson (2005) *JGR 110*, E05003. [3] Presley, M. A., and P. R. Christensen (1997b) *JGR 102*(E4), 9221–9229. [4] Mellon, M. T. *et al.* (1997) *JGR 102*(E8), 19,357–19,369. [5] Hobbs, P. V. and Mason, B. J. (1964) *Philosophical Magazine*, 9:98, 181-197 [6] Piqueux, S. and P. R. Christensen (2009) *JGR 114*, E09006. [7] Lachenbruch *et al.* (1982) *JGR 87*, 9301-9316. [8] Mellon, M. T. and Jakosky, B. M. (1993) *JGR 98*, 3345-3364. [9] Bristow, K. L. *et al.* (1994) *Soil Soc. Am. J.* 58, 1288-1294.