THERMAL CONDUCTIVITY OF COARSE AND FINE GRAINED SOIL MIXTURES: MEASUREMENTS AND MARS APPLICATIONS. Michael. T. Mellon[1], Christopher P. McKay[2], and John. A. Grant[3], [1]Department of Space Studies, Southwest Research Institute, Boulder, CO 80302, [2]Space Science Division, NASA Ames Research Center, Moffett Field, CA 94035, [3] Center for Earth and Planetary Studies, Smithsonian Institution, National Air and Space Museum, Washington, DC 20560.

Introduction: The thermal properties of a planetary surface are a valuable tool in probing the characteristics and structure of the regolith and bedrock.

Thermal inertia and its primary component thermal conductivity are typically derived from thermal infrared remote sensing. On Mars, low values are generally associated with fine grained particulate regolith, while high values are associated with coarse fragments and bedrock [1,2].

Often, thermal properties are translated to a characteristic particle size through the grain-size dependence of thermal conductivity at martian atmospheric pressures (see below). This effort is particularly interesting if the geologic context points to natural sorting, as with aeolian bedforms, fluvial channels, and airfall mantles.

Recent studies by the authors into the thermal properties of soils in the Antarctic Dry Valleys suggest that grain size mixtures play a significant roll.

Here we report new measurements of the thermal conductivity of soils and soil analogs at a range of pressures. We show that at terrestrial atmospheric pressure an intimate mixture of fine and coarse grained particles increases the bulk thermal conductivity over that of each component. However, the effect at martian atmospheric pressures is quite different. The bulk thermal conductivity of a mixture is intermediate but skewed toward smaller grain values at low pressures and toward larger grain values at higher martian pressures. The implications for Mars are discussed.

Previous Measurements: Previous studies of the effects of particles size on thermal conductivity at martian pressures have focused on test samples (ground rock or glass beads) with narrow size distributions [3,4]. The effects of gas pressure and density have been well characterized. Few studies have focused on broad particle size distributions or bimodal mixtures [3,5]. These studies reported that the bulk thermal conductivity follows the magnitude and pressure dependence of the large grains in the distribution at martian atmospheric pressures.

Kinetic Theory: A basic model of heat conduction through a porous soil follows from the kinetic theory of gasses and a combination of series and parallel conduction pathways [6,7]. Heat transfer through a soil occurs through grain contacts and thermal radiation, which dominate at lowest pressures, and through gas conduction which dominates at highest pressures. The transition between these extremes depends on the pore size relative to the mean free path of gas molecules. For typical soils the transition occurs at Mars atmospheric pressures, allowing for the distinction between grain sizes from remote sensing data (Figure 1).

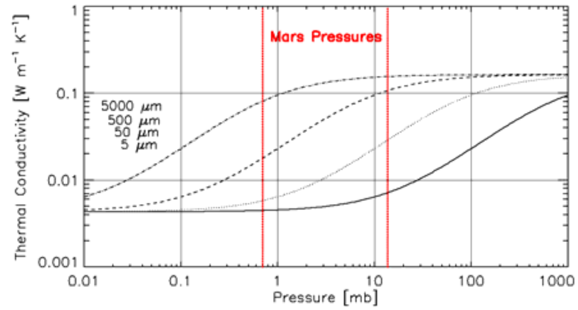

Figure 1. Theoretical thermal conductivity of a soil as a function of interstitial gas pressure (shown here for air) and soil grain size [9,10].

New Measurements: In the present study we utilized two methods for measuring thermal conductivity: i) transient heated needle (as in the previous studies); and ii) guarded heat flow. The heated needle probe offers advantages of rapid measurement and small sample size, while the guarded-heat-flow method offers high precision and uniform integration over a sample volume. Our comparison of these two methods shows that the guarded-heat-flow method performs better at low conductivity and for coarse grains Results reported here utilized the guarded-heat-flow method.

The guarded-heat-flow cell consists of two copper plate held at precisely controlled temperatures on either side of the sample. Sandwiched between the sample and each plate are heat flux transducers. In equilibrium the average heat flux and the temperature gradient are recorded and the thermal conductivity directly calculated from Fourier's law.

We tested several samples of borosilicate glass beads with narrow size distributions, mixtures of 2 mm and 63-53 μm beads in different ratios, and natural soils from the Antarctic Dry Valleys. Thermal conductivities were measured with air pressures between 0.015 mb and 840 mb.

Samples were evacuated for several days. A mean temperature of 20° C was maintained with a gradient of 7° to 12° C. Measurements were conducted at pressure increments of air up to ambient. Tests in CO_2 are planned and expected to result in slightly lower conductivities with the same trends with pressure.

Results: Figure 2 shows typical results for glass beads. The trends with pressure are similar to previous studies and agree well with kinetic theory (Figure 1).

In addition, Figure 2 shows the result of bimodally mixed 2 mm and 53-63 μm glass beads. At high Mars pressures (low elevation) the mixtures exhibit thermal conductivities similar to that of the larger grain size alone. However, in contrast to previous studies, as the pressure decreases the conductivity is consistent with that of intermediate to smaller grain sizes alone.

Over the full pressure range it is demonstrated that the thermal conductivity of a mixture of grains follows the pressure dependence of the smaller grains, with an offset associated with the density increase (porosity reduction). This behavior can be explained as the fine grained component controlling the overall conductivity while the coarse grain inclusions act as pressure-independent thermal short circuits.

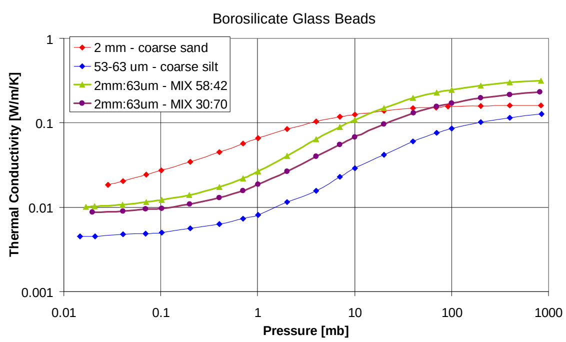

Figure 2. Measured thermal conductivity for unimodal-sized glass beads and bimodal mixtures.

Similar tests with an Antarctic soil from Linneaus Terrace in upper Wright Valley show the same overall trend with pressure as the mixed beads (Figure 3). This soil has a broad size distribution dominated by 100 μm to 1 mm grains. The overall shape of the conductivity curve is similar to that of a 100 μm unimodal grain size with an offset to higher values consistent with the mixing effect seen with glass beads.

Mars Geologic Application: A key finding for Mars is that coarse grained particles (sand, pebbles, or even cobbles) can be partly obscured by the presence of interstitial fines. This result has implications for a number of geologic contexts.

Low thermal inertia regions on Mars have been interpreted as being entirely composed of fine "dust" with a grain size of <40 μm [8]. However, our results suggest that smaller grains (e.g., μm scale like atmospheric dust [9]) mixed with sand, pebbles, or cobbles will also explain the observations (the coarser fragments may be present but partly obscured). Hence, the grain character of deposits emplaced by a wide range of processes (e.g., mass-wasting, fluvial, or glacial) may be under predicted based on measured thermal inertia, especially in higher albedo areas where significant dust is expected.

Dunes and bedforms are naturally sorted. The size of the grains, as determined from remote sensing compared with a unimodal size fraction, has been compared with models of grain saltation at Mars atmospheric pressures [10,11]. However, we find that finer dust settled into the sand interstices would reduce the thermal inertia and lead to an underestimate of grain sizes. Similarly, bedforms have been observed at high elevation in regions of low thermal inertia where individual grains sizes are thought to be too small for saltation leading to the hypothesis of saltating dust aggregates [12]. Our results imply significant sand sized grains may also be present, but thermally obscured by dust incorporated between grains at the surface.

In contrast low-elevations regions, where thermal inertias are observed to be higher, coarse grained soils may also contain substantial interstitial dust.

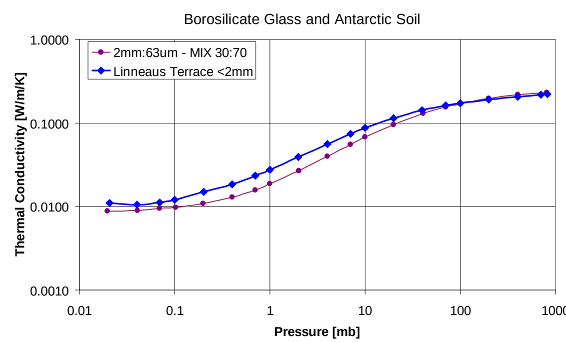

Figure 3. Mixed beads test from Figure 2 with Antarctic soil (Linneaus Terrace) superposed.

Conclusions: We have conducted new measurements of the thermal conductivity of glass beads with mixed particle sizes and natural soils. We found that:

- The guarded heat flow method works better for large grain sizes, mixed soils, and low conductivities.
- The thermal conductivity of mixed soil-grain sizes at Mars pressures is intermediate to that of the component values. The conductivity follows the pressure dependence of the smallest size fraction.
- The interpretations of low thermal inertia regions of Mars are more complex than thought. Large particles may be present in substantial quantities and partly obscured in thermal remote sensing.

References: [1] Palluconi & Kieffer, 1981; [2] Mellon et al., 2000; [3] Woodside & Messmer, 1961; [4] Presley & Christensen, 1997a; [5] Presley & Christensen, 1997b; [6] Jakosky, 1986; [7] Mellon et al., 2008; [8] Christensen, 1986; [9] Toon et al., 1977; [10] Edgett & Christensen, 1991; [11] Fenton & Mellon, 2006; [12] Bridges et al., 2010.