A COMPACT IN-SITU THERMAL CONDUCTIVITY PROBE AS PART OF A LUNAR REGOLITH EXCAVATION SYSTEM. S. Nagihara[1], K. Zacny[2], M. Hedlund[2], and P. T. Taylor[3], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Honeybee Robotics, Pasadena, CA 91103, [3]Goddard Space Flight Center, Greenbelt, MD 20711.

Introduction: Geothermal heat flow measurements are a high priority for the future lunar geophysical network missions recommended by the latest Decadal Survey [1] and previously the International Lunar Network [2]. Because the lander for such a mission will be relatively small, the heat flow instrumentation must be a low-mass and low-power system, while it needs to measure both thermal gradient and thermal conductivity of the regolith penetrated. It also needs to be capable of excavating a deep enough hole (~3 m, [2]) to avoid the effect of potential long-term changes of the surface thermal environment [3, 4]. It would probably be impossible to meet the low-power, low-mass requirements, if a heat flow instrument on such a mission utilized a long (> 3-m) probe driven into the ground by a rotary or percussive drill.

The recently developed 'proboscis' excavation system [5] can largely meet the low-power, low-mass, and the depth requirements. The excavation system utilizes a stem which winds out of a pneumatically driven reel and pushes its conical tip into the regolith. Simultaneously, gas jets, emitted from the cone tip, loosen and blow away the soil (Fig. 1). Lab tests have demonstrated that the proboscis system has much greater excavation capability than other previously proposed low-power, low-mass systems such as the mole internal hammering system. Here we report on the design of the thermal conductivity probe that is going to be attached to the penetrating cone of the proboscis system.

The New *In-situ* Thermal Conductivity Probe for the Proboscis Excavation System: A typical thermal conductivity probe used for terrestrial soil samples (the so-called 'needle probe') consists of a thin metal tube of ~2-mm diameter and ~5-cm length, which contains a linear electric heater along its length and a temperature sensor (e.g., thermistor) at its center. When the probe is inserted into the soil, it heats up and monitors the temperature increase [6]. The measurement theory requires that the length of the probe is much longer than its diameter and that the probe is made of highly conductive material. In such a configuration, one can assume that the heat diffuses away through the soil dominantly in the radial direction from a line heat source, and that temperature of the probe is always the same as that of the soil in contact with the probe. Then, the thermal conductivity can be an algebraic function of the heat input and the logarithmic rate of the temperature rise.

The new thermal conductivity probe for the proboscis excavation system is attached to the tip of the penetrating cone (Fig. 1). In order not to diminish the excavation efficiency, the probe is short (1- to 1.5-cm). The probe has a diameter of 3-mm in order to insure good thermal contact with powdery regolith materials in vacuum, and for mechanical strength. The short needle contains a platinum wire-wound resistance temperature detector (RTD), and a thin heater wire which wraps around the cylindrical ceramic casing of the RTD. During a deployment, when the penetrating cone reaches one of the depths targeted for thermal conductivity measurement, it stops blowing gas, and the stem pushes the short probe into the yet-to-be excavated, undisturbed bottom-hole soil. Then, it begins heating and monitors the temperature rise. When, the measurement is complete, the system resumes excavation.

Obviously, the length/diameter ratio of the short needle is not large enough to allow direct application of the standard needle probe technique. In determining thermal conductivity, it is necessary to construct a theoretical heat transfer model of the instrumentation and perform simulations of the heating experiment. Such simulations using a somewhat simplified heat transfer model show that the new system should be able to resolve the thermal conductivity of regolith within ~0.003 W/mK with a total heater power of as little as 0.05 W, provided that the temperature measurement yields ~0.1-K resolution (Fig. 2).

Discussion and Conclusions: Prior to the present study, two types of compact *in-situ* thermal conductivity systems were proposed for low-mass lunar robotic missions. One is a button-shaped device containing a heater-RTD assembly, imbedded in the casing of a bullet-shaped penetrator (0.8-m length and 0.15-m diameter) dropped from a Lunar-orbiting spacecraft [7]. The other is a heater-RTD assembly built into a 'mole' self-hammering system deployed from a lander. For thermal conductivity measurement, either the casing of the mole itself (typically, ~0.3-m length and ~2-cm diameter) or a separate instrument housing of a similar size pulled by the mole, acts as the heat source [8,9].

In terms of accuracy of thermal conductivity measurement, all of these approaches, including that of the present study, have problems, mainly because their sensor configurations deviate from that of the standard needle probe. In addition, temperature measured by the probe is heavily influenced by that of the instrument body to which the sensor is built/attached. The instrument body has a much larger heat capacity and thermal inertia than the sensor assembly. As the sensor heats up, a significant portion of the energy is absorbed by the instrument body, which responds more slowly to the heating than the sensor unit does. Accuracy of the thermal conductivity determination, therefore, heavily relies on having a very accurate heat transport model of the instrumentation, which must be thoroughly tested by lab experiments. It is also highly desirable that the probe has a low heat capacity and is thermally isolated from the rest of the instrument body.

We believe that the short probe design of the present study is advantageous over the two previously proposed penetrator- and mole-based systems in four aspects. First, the thermal inertia of the short needle probe is much less than the other two built into the body of a penetrator or a mole. Therefore, it senses the temperature of the soil more accurately and responds more quickly to temperature changes of the soil. Second, the short needle probe has a heat capacity much less than that of the body of the penetrator/mole, and thus does not require as much heater power in making a thermal conductivity measurement. Third, the short needle probe system causes less mechanical disturbance to the part of the soil in contact with the sensor than the penetrator (free-falling into the regolith) and the mole (hammering and compacting the soil) do. Finally, the proboscis excavation system has already been demonstrated to easily reach ~1-m depth (the bottom of the test chamber) in experiments using well compacted JSC-1A lunar stimulant [5].

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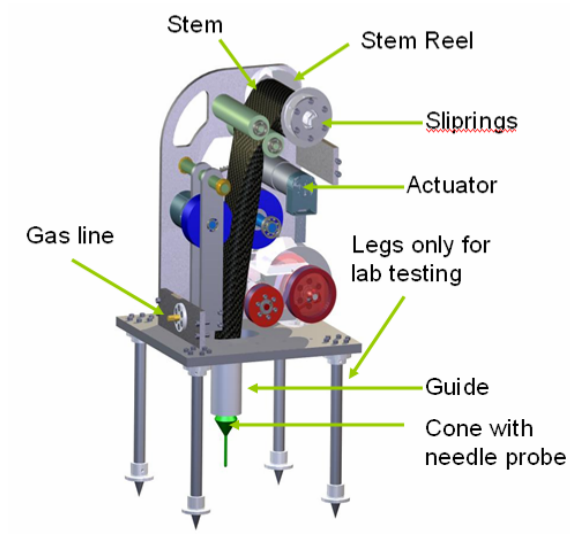

Figure 1. A schematic diagram of the proboscis excavation system and the short needle probe attached to the tip of the penetrating cone.

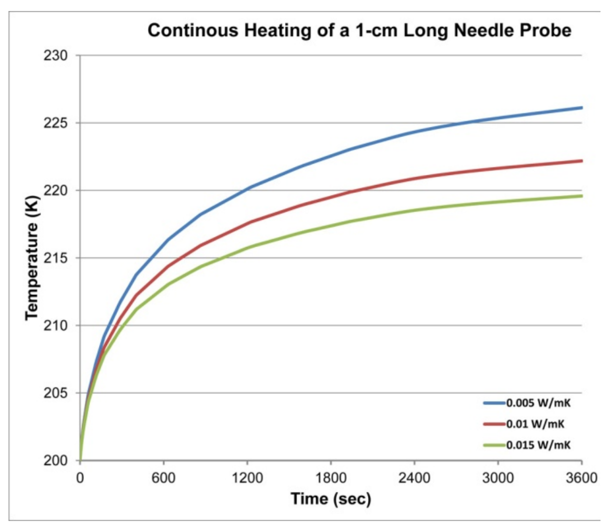

Figure 2. Model predictions of the temperature increase of a 1-cm long probe in response to continuous heating of 0.05 W for regolith thermal conductivities of 0.005 W/mK (blue), 0.01 W/mK (red), and 0.015 W/mK (green).