

A COMPACT, DEEP-PENETRATING HEAT FLOW PROBE FOR SMALL LUNAR LANDERS. S. Nagihara¹, K. Zacny², M. Hedlund², and P. T. Taylor³, ¹Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), ²Honeybee Robotics, Pasadena, CA 91103, ³Goddard Space Flight Center, Greenbelt, MD 20711.

Introduction: Heat flow released from a planetary surface is obtained as a product of two separate measurements of the thermal gradient and the thermal conductivity of the vertical soil/rock/regolith interval penetrated by the instrument. Heat flow measurement is considered a high priority for the lunar geophysical network mission recommended by the latest Decadal Survey [1]. It may also be deployed on other lunar missions such as JAXA's Selene2 scheduled to launch in 2017 or Russian Luna 27 and 29 scheduled to launch in 2017 and 2020, respectively. Other flight opportunities may be available through the Google Lunar X-Prize teams.

To insure high quality data, the heat flow instrument must be placed in a hole deep enough to avoid the effects of long-term temporal changes in lunar surface thermal environment. Such changes may be due to the 18.6-year-cycle lunar precession [2, 3], or may be initiated by presence of the lander itself [4]. A panel of scientists have recently recommended that a heat flow instrument for future lunar missions should penetrate a minimum of 3 m into the regolith in measuring both thermal gradient and thermal conductivity [5]. Additionally, the instrument itself should have minimal impact on the subsurface thermal regime, and it must be a low-mass and low-power system to fit on a small lander. It would be very difficult to meet the mass and power constraints, if the instrument utilizes a long (> 3 m) probe driven into the ground by a rotary or percussive drill.

Here we report progress in our efforts to develop a new, compact heat flow instrumentation that meets all of these science and engineering requirements for future lunar lander missions.

The Excavation System: Some researchers have previously proposed a lunar heat flow probe tethered behind a mole [6] or embedded in the mole itself [7]. A mole is a compact device that wedges itself into planetary regolith by utilizing the momentum generated by internal hammering. These researchers recommend such a mole-based heat flow system on small lander missions to the Moon and Mars, mainly because it should weigh little (< 2 kg) and requires little power. However, lunar regolith below ~20-cm depth is highly compacted and cohesive [8]. The relative density at such depths reaches 100%. One cannot compact such regolith further without altering the size and the shape of the grains. There are only two ways for a probe to

advance in such a condition. The first is to loosen the regolith materials and remove them from the hole. The second is for the device to crush/pulverize the regolith *in situ*, re-compact it, and wedge itself further in (i.e., to exceed the bearing pressure of the overburden regolith). There is no other way. A mole-based system does neither, and hence is not likely to reach the targeted 3-m into lunar regolith.

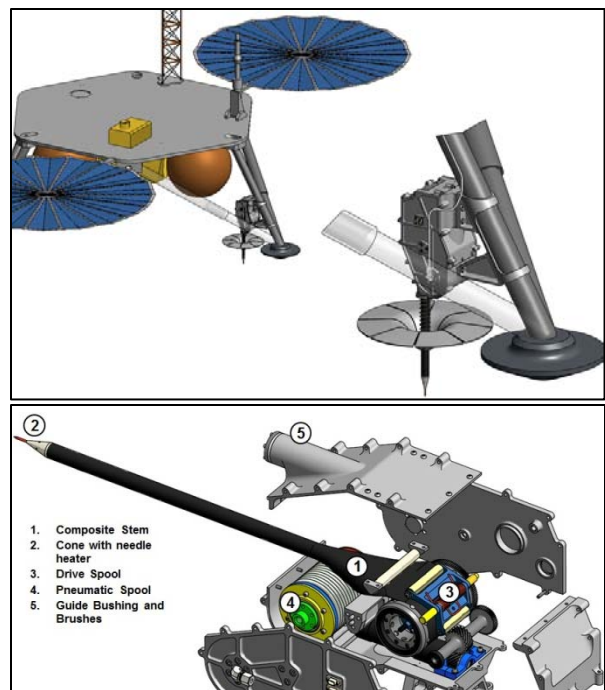


Figure 1: Top: A conceptual drawing of the proposed heat flow instrumentation attached to a leg of a lunar lander. Bottom: More detailed schematics of the major components of the heat flow system.

Our recently developed pneumatic excavation system loosens and remove the regolith [9]. The excavation system utilizes a stem which winds out of a reel and pushes its conical tip into the regolith (Fig. 1). Simultaneously, gas jets, emitted from the cone tip, loosen and blow away the regolith materials. In its current design, the stem is primarily made of glass fiber for its mechanical strength and relatively low thermal conductivity. Helium gas is used for the jet, because it is commonly available for planetary landers in pressurizing the propellant tank. Lab tests using an earlier model in a vacuum chamber have shown that

only 8 gram of Helium gas is required for excavating 0.6 m in 22 seconds [10]. The near-vacuum environment maximizes the mechanical force of the gas jet.

Thermal Measurement Systems: Attached to the tip of the penetrating cone is a probe for *in-situ* thermal conductivity measurement (Fig. 2). 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 regolith. When the measurement is complete, the system resumes excavation.



Figure 2: Photographs of the prototype thermal conductivity probe (top) and the RTD used for the probe (bottom) A quarter is shown for the scale.

The *in-situ* thermal conductivity probe consists of a short (~1 cm) metal tube containing a resistance temperature detector (RTD) wrapped in a coil of heater wire. In its current design, the probe has a diameter of 2-mm in order to insure good thermal contact with powdery regolith materials in lunar vacuum, and for mechanical strength. The penetrating cone is made of a low-conductivity plastic in order to thermally insulate the probe from the rest of the instrument.

We use a variant of the ‘needle probe’ method [11] for thermal conductivity measurement. The probe emits heat (Q) with a constant rate and its temperature (T) increases linearly with the natural logarithm of the total heating time (t):

$$T = C \ln t + T_0 \quad (1),$$

where the coefficient C is proportional to Q and inversely proportional to the thermal conductivity. This constant can be constrained by lab calibration experiments [12].

The thermal conductivity probe can also be used to measure regolith temperature prior to heating, as it makes stops on the way down, and it can monitor long-term stability of temperature at the bottom of the hole.

In monitoring the stability of regolith temperature at shallower depths, we embed a series of RTDs along the stem with equal spacing of ~30 cm. Once the probe is fully deployed to the target depth, the regolith around the hole, overtime, reestablishes thermal equilibrium at the depths unaffected by the insolation. If the stem is made of materials of low thermal conductivity whose properties are well known, it is possible to estimate the downhole variation of regolith temperature based on the temperatures sensed at the RTDs, as shown previously for the tethered thermal sensors for a mole-based heat flow system [6].

Conclusions: Our current effort focuses on merging the excavation and the thermal systems into a single prototype unit and test it at technical readiness level (TRL) 5/6. In its current configuration, the entire system weighs ~1.5 kg. This should be able to meet the mass and power constraints for most small landers for future lunar missions.

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