COMPACT, MODULAR HEAT FLOW PROBES FOR LUNAR LANDERS.

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Introduction: Measurement of heat released from the lunar intertior is important in understanding the Moon's structure, composition, and origin [1, 2]. Heat flow is obtained as a product of the thermal conductivity and the vertical temperature gradient in the regolith. Apollo 15 and 17 recorded heat flow measurements [2]. More measurements in the future would reveal geographic variation of heat flow across the lunar surface, and they will complement the findings from NASA's recent GRAIL and LRO /DIVINER missions.

We are currently developing a compact, modular heat-flow system that can be accommodated into various forms of robotic and human lunar-landing missions (Fig. 1). For example, JAXA's Selene II, and Russian Luna 27 and 29 scheduled for 2017 and 2020, respectively, could accommodate our heat flow system. Other flight opportunities may be materialized by the privately funded Google Lunar X-Prize and Golden Spike.

The New Modular Heat Flow System: The new heat flow system is compact and light-weight (~ 2 kg in total), and it can be attached to any stable, landed platform (Fig. 1). In addition, it uses a pneumatic excavation mechanism and requires little electrical power [3]. The modular, compact, low-mass and low-power nature of the system makes it easily adaptable to a variety of missions.

The new system is designed to reach 3-m depth into lunar regolith (Fig. 2). This depth has been considered necessary for future lunar heat flow measurements in order to avoid the effects of long-term temporal changes in lunar surface thermal environment [4]. Such changes may be due to the 18.6-year-cylcle lunar precession [5, 6], or may be initiated by presence of the lander itself [7]. Reaching the 3-m depth with a low-power, low-mass system is a technological challenge. For example, driving a 3-m long probe into the ground by a rotary or percussive drill would make a system several times heavier and require more power than our system. In contract, an internal hammering mechanism such as moles [8] would be as light-weight as our instrument, but may lack the excavation capability necessary for reaching the target depth. Our pneumatic approach may be one of the very limited options for achieving all the technical requirements.

The pneumatic excavation system utilizes a glass fiber composite stem which winds out of a reel and pushes its conical tip into the regolith (Fig. 3). Simultaneously, Helium gas jets, emitted from the cone tip, remove the regolith. The material for the stem is chosen for its mechanical strength and low thermal conductivity.

Attached to the tip of the penetrating cone is a probe for *in-situ* thermal conductivity measurement (Fig. 4). During a deployment, when the penetrating cone reaches one of the depths targeted for a thermal conductivity measurement, it stops operating, 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.

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 [9] 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):

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

where the coefficient C is proportional to Q and inversely proportional to the thermal conductivity. This constant can be constrained by lab calibration experiments [10].

In monitoring the stability of regolith temperature up and down the hole, which is necessary in obtaining the thermal gradient, we embed a series of RTDs along the stem with an 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.

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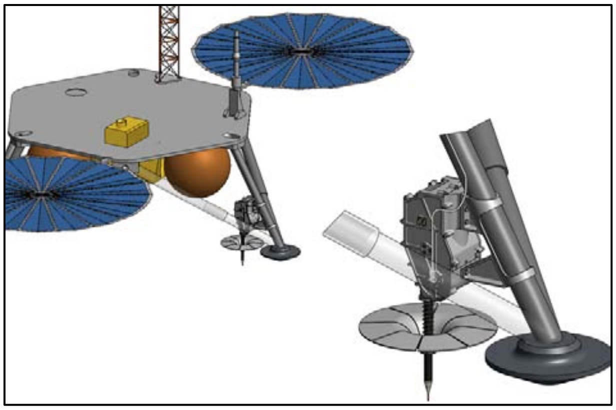

Figure 1: A conceptual drawing of the proposed heat flow system attached to a leg of a lunar lander.

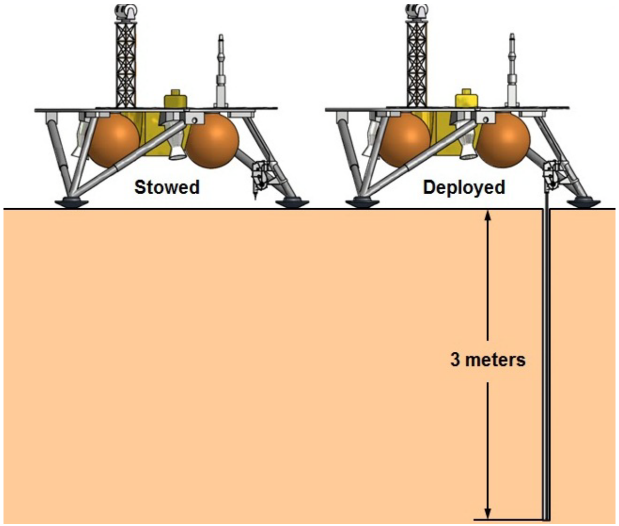

Figure 2: The heat flow probe in stowed (left) and deployed (right) configurations.

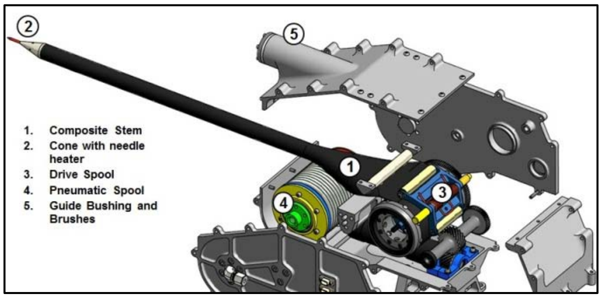

Figure 3: More detailed schematics of the major components of the heat flow system.

Figure 4: A photograph of the prototype of the cone tip and thermal conductivity.

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