DEVELOPMENT OF COMPACT, MODULAR LUNAR HEAT FLOW PROBES. 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: The heat flow measurements conducted during the Apollo 15 and 17 missions [1] yielded constraints to the internal thermal structure of the Moon as well as lessons for similar experiments to be conducted on future lunar missions. The heat released through the solid surface of the Moon (and any other planetary body) is obtained as a product of the thermal conductivity and the vertical thermal gradient of the depth interval penetrated by the probe. Heat flux through the surface regolith fluctuates with time, however, in sync with the insolation. In order to detect the heat flow from the lunar interior, a probe must reach depths below the influence of the insolation. Recent re-analysis of the Apollo heat flow data suggest that probes for future lunar missions should penetrate to at least 3-m depth into lunar regolith, ~0.6 m deeper than the Apollo probes were able to reach [2,3]. Another study found that the rotary-percussive drilling technique compacted the regolith around the wellbore and contributed to the erroneous *in-situ* thermal conductivity measurements on the Apollo missions [4].

Additional lunar heat flow measurements in the future would be useful for constraining the spatial variation in thermal structure of the Moon. Such experiments are recommended by the latest Decadal Survey [5], and will complement the findings from NASA's recent GRAIL and LRO /DIVINER missions.

Here we report our latest efforts in developing a compact, modular heat flow probe system that can be accommodated into various forms of robotic and human lunar-landing missions (Fig. 1). Because it is a compact system and uses little power, it can be easily accommodated to small landers. It would be ideal for future missions such as NASA's Resource Prospector, JAXA's Selene II, and Russian Luna 27 and 29. The system is also well suited for human lunar missions such as Golden Spike. Because the system is easily portable and semi-autonomous, its deployment requires very little time and effort by the astronauts. Once the astronauts have set it up on the lunar surface, actual deployment of the probe into lunar regolith can be controlled remotely from the earth. It is essentially a set-it-and-forget-it system from the astronauts' point of view.

Compact, 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). It uses a pneumatic excavation mechanism and requires little electrical power [6]. 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) and meets the requirements set by recent studies [3]. Reaching the 3-m depth with a low-power, low-mass system is a major technological challenge. For example, driving a 3-m long probe into the ground by a rotary or percussive drill, as it was done on the Apollo missions, would make a system several times heavier and require more power than our system. An internal hammering mechanism such as moles, planned for the InSight mission [7], would be as light-weight as our instrument, but may lack the excavation capability necessary for reaching the target 3-m depth. In addition, any of these percussive techniques would compact the regolith around the wellbore, while it advances to greater depths. Therefore, it would suffer from the same problem the Apollo experiments encountered in *in-situ* thermal conductivity measurements.

Our pneumatic excavation system utilizes a glass fiber composite stem which winds out of a reel and pushes its conical tip into the regolith (Figs. 2 and 3). Simultaneously, Helium gas jets, emitted from the cone tip, blow away regolith from the bottom of the hole. 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 (Figs. 3 and 4). During a deployment, when the penetrating cone reaches one of the depths targeted for a thermal conductivity measurement, it stops excavating, 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 particulate 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 [8] for thermal conductivity measurement. The probe emits heat with a constant rate and monitors its temperature increase with time. Thermal conductivity of the regolith around the probe is very close to being inversely proportional to the natural logarithm of the rate of temperature rise. The actual mathematical relationship can be obtained by experiments in a vacuum chamber using regolith stimulant such as JSC-1A.

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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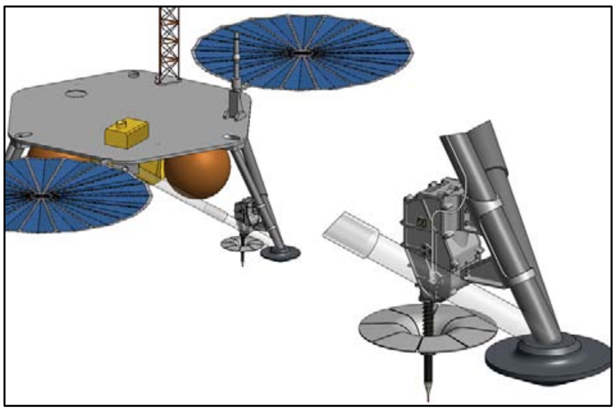

Figure 1: A conceptual drawing of the proposed heat flow system attached to a leg of a lunar lander.

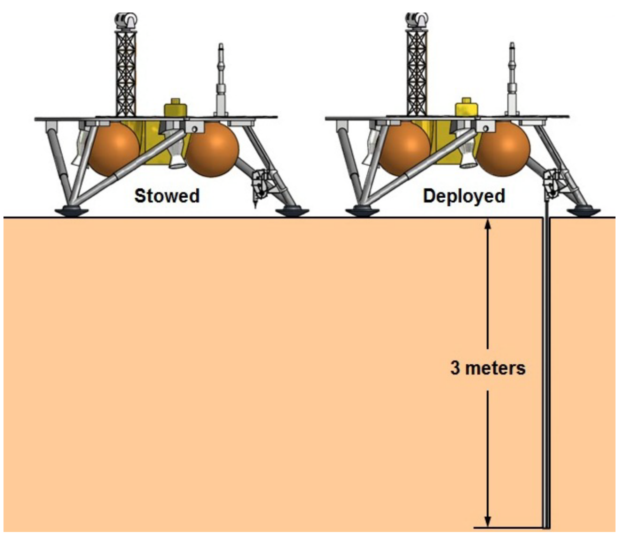

Figure 2: The heat flow probe in stowed (left) and deployed (right) configurations.

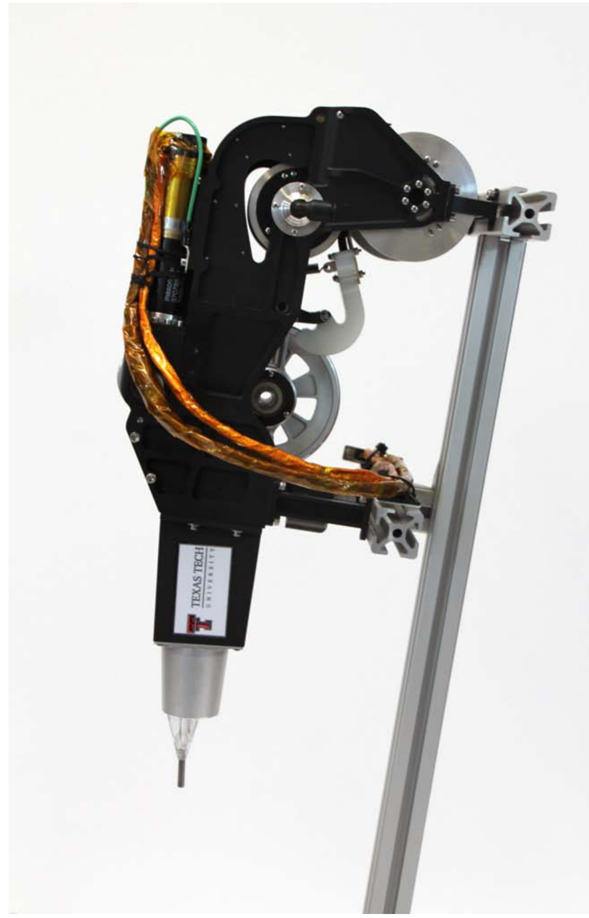

Figure 3: A photograph of the latest prototype of the heat flow system in a stowed configuration.

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

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