HEAT FLOW PROBE DEPLOYMENT OPTIONS FOR THE INTERNATIONAL LUNAR NETWORK MISSIONS. S. Nagihara[1], K. Zacny[2], P. T. Taylor[3], M. B. Milam[3], E. Mumm[2], M. Maksymuk[2], P. Fink[2], and W. Henrnandez[2], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Honeybee Robotics Spacecraft Mechanism Corp., New York, NY 10001, (zacny@honeybeerobotics.com), [3]Goddard Space Flight Center, Greenbelt, MD 20771.

Introduction: Knowledge of the Moon's thermal structure is fundamental in understanding its origin and internal compositional variation, both of which are intertwined with the origin of the Earth and the rest of the solar system (*NASA Strategic Goal 3C*). The flow of heat that originates from the lunar interior can be measured, and serves as a constraint to the thermal structure. That is why heat flow measurements were conducted during the Apollo missions [1] and are considered high priority for the International Lunar Network (ILN) missions planned in the next decade [2].

Heat flow is determined from two sets of measurements made in the subsurface: the thermal gradient in, and the thermal conductivity of, the depth interval of interest. A cylindrical probe is inserted into the subsurface for carrying out these measurements (Fig. 1). A heat flow probe typically contains a series of temperature sensors placed along its length. Temperature measurements obtained at different depths down the probe yield the thermal gradient. The probe also contains an electrical heater wire run along its length. After the thermal gradient has been determined, the wire emits heat into the surrounding regolith formation. The temperature sensors monitor how quickly or slowly the heat dissipates away from the probe at their depths. The information is used to calculate the thermal conductivity of the regolith [3-4].

The shallow subsurface temperature of the Moon is strongly influenced by the diurnal, annual, and precessional fluctuations of the insolation [1, 5-6]. Therefore, the best way to measure the internal heat flow is to insert the probe to a depth beyond the reach of the surface fluctuation. In order to avoid the 18.6-year-cycle precessions effect, the probe must reach 5- to 7-m depth [6-7].

Constraints and Options for Heat Flow Probe Deployment: A heat flow probe may be deployed in a number of ways on the Moon. However, for the ILN, very few options would fully meet both the constraints imposed by the small lander and the scientific objective of measuring the internal heat flow. For example, a mole can be an ideal tool for subsurface access for lander missions by meeting the mass and power constraints, but it is unlikely that it would reach the desired depth of 5 to 7 m into lunar regolith solely by internal hammering of the small mass. In addition, the hole dug by the mole would have variable diameters down the hole, and thus would not achieve good physical contact between the thermal sensor and the well bore formation [8].

In order to assure good data quality, the heat flow instrumentation on the ILN lander would require some of type of drilling capability. In order to minimize the mass, we will make the probe strong enough to serve also as the drill string. That way, the lander will not need separate systems for drilling and for lowering the probe into the hole. In addition, the drill string that is left behind will ensure good physical contact with the well bore. In order to minimize the electrical power requirement, we will use a pneumatic drill system, driven by leftover of the compressed helium gas of the propulsion system for soft-landing the lander. Pneumatic drilling systems are not only simpler in operation (and in turn more robust) than electro-mechanical systems but also are lighter.

Rotary Drilling vs. Percussive Hammering: There are two general approaches in penetrating the heat flow probe to the desired depth: rotary and percussive. There can be a hybrid of the two. For example, the Apollo astronauts used a ~400-Watt rotary-percussive drill. The biggest problem encountered by the Apollo 15 astronauts was poorly designed auger flutes, which limited the depth to only ~1.7 m. With redesigned bore stems, Apollo 16 and 17 reached their target depth of 2.5 m. Even then, drilling was proved to be most strenuous part of the EVA, and if given the choice, astronauts would prefer a robotic system to do the job [H. Schmitt, Per. Comm.].

Although the rotary-percussive drilling approach to penetrating lunar regolith was proven effective during the Apollo experiments, we believe that a pure percussive approach will make the heat flow probe deployment simpler for robotic landers. The percussive penetrometer uses high-frequency and low-energy impacts to penetrate the regolith. When a rod is inserted into regolith, the resistance to insertion comes from two sources: regolith being displaced/crushed ahead of the probe and regolith sliding against the rod as it is being inserted. (The latter is referred to as sleeve friction.) The combination of high-frequency and low-energy percussive impacting reduces both types of resistance forces. The regolith ahead of the pointed tip of a penetrometer becomes displaced, packed, and crushed due to the vibration. This allows deep penetration. Simultaneously, the regolith rubbing against the penetrometer surface continuously vibrates and reduces the sleeve friction.

In penetrating lunar regolith, the tool may also run into a buried rock. Carrier [9] estimates that the probability of running into a rock with a diameter twice or greater than that of the penetrometer cone (2cm or less) in 5- to 10-m depth is only 1% to 2%. The same study also predicts that smaller rocks can be pushed aside by the drill/penetrometer because of the high regolith porosity (~40%).

For the ILN missions, we prefer a top-drive percussive hammer system to rotary approach in terms of simplicity in operation, lower mass, simpler design, and lower power.

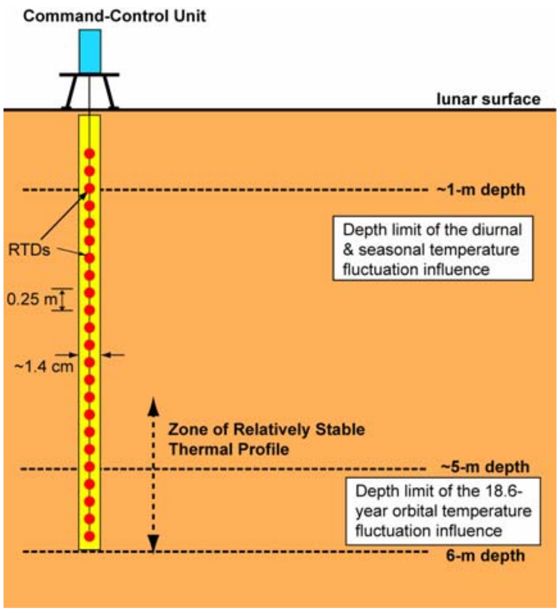

Fig. 1 A schematic diagram showing the depth penetrated by the heat flow probe (yellow column), the positions of the temperature sensors (red circles), and their relations to the depths of influence of the surface temperature fluctuations of varying periods. RTD is resistance temperature detector.

Percussive System with Carousel Deployment: The system we envision for the ILN missions consists of a long heat flow probe split into 0.5-m sections and arranged on a carousel, and a hammering actuator for 'pounding' heat flow probe into the ground (Fig. 2). The probe is essentially the 'drill' string. The deployment would proceed in the following manner. 1) Hammer the first 0.5-m probe section into the ground. 2) Lined up the second 0.5-m section and join it to the first one in the ground. 3) Hammer the joined probe further into the ground. 4) Line up the 3rd section and repeat hammering. The percussive head will be powered by a pneumatic system.

A percussive penetration system of similar configuration has already been tested and yielded promising results. In a lab experiment using well compacted JSC-1A lunar stimulant with penetration resistance of 11MPa (roughly 6 times that of the in-situ lunar regolith), the percussive system with various probe diameters reached the bottom of the sample container (0.7-m depth) in 10 – 140 seconds. In addition, the same percussive system was able to drive a 10-m-long pipe into regolith-like materials (finely crushed diabase) within 3 to 6 minutes in a recent field test conducted outside of the Goddard Space Flight Center [10].

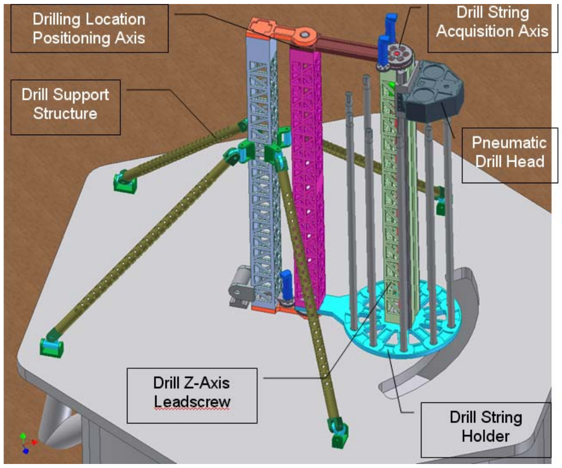

Fig. 2 A schematic diagram showing the main mechanical components of the heat flow deployment system.

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