OPTIONS FOR HEAT FLOW PROBE DEPLOYMENT ON ROBOTIC LUNAR MISSIONS. S. Nagihara1, K. Zacny2, D. Kim2, M. Hedlund2, and G. Paulsen2, 1Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), 2Honeybee Robotics, Pasadena, CA 91103.

Introduction: Heat flow measurements are considered one of the top priorities for future lunar-landing missions [1]. A panel of scientists has recently recommended NASA that heat flow probes on such missions penetrate at least 3 m into the lunar regolith [2]. The target depth is greater than reached during the Apollo Heat Flow Experiment (2.4 m) [3].

Heat flow is obtained as a product of two separate measurements of the thermal gradient and the thermal conductivity of the depth interval penetrated by the probe. The common strategy among the heat flow probes proposed/developed for robotic planetary missions [e.g., 4-6] is to measure temperature and thermal conductivity of the regolith by stopping at different depths, as the probe penetrates into the subsurface.

Here we discuss two approaches for deploying heat flow probes into the lunar subsurface and reach the targeted 3-m depth.

Percussive Penetration: NASA’s InSight mission to be launched in 2018 will deploy a heat flow probe that uses a mole in penetrating into the regolith on Mars [6]. A mole is a device that uses the momentum of internal hammering in wedging itself into the ground. The mole developed for InSight comes in a cylinder of ~30-cm length and ~2.5-cm diameter. The mole itself also acts a thermal conductivity probe. For measuring the thermal gradient, the mole tows a tether embedded with temperature sensors, as it penetrates deeper into the regolith.

A mole advances by hammering and compacting the soil/regolith ahead of it. The impact energy of the mole’s internal hammering is only ∼0.5 J/blow for InSight [7]. Thus it is limited in its ability to penetrate into regolith that is already well compacted. Porosity of lunar regolith decreases sharply with depth. At ∼20-cm depth, its relative density reaches 100% [8]. If the InSight mole were to be deployed on the Moon, it may not reach 3-m depth.

As an alternative to the mole, we have considered a system based on a percussive penetrometer (Fig. 1). In this design, an external hammering head is attached to a lander’s platform. A solid rod (made of glass fiber) transfers the impact energy to the penetrometer attached to the lower end. The rod comes in 30-cm sections. It is extended one section at a time, as the penetrometer makes its way into the subsurface. The rod sections are stowed on a carousel. The penetrometer pulls a thermal tether similar to the one used by InSight for the thermal gradient measurement. The penetrometer duals as the thermal conductivity probe.

This design has two advantages over a mole-based system. First, it can penetrate deeper, because the external hammer can deliver stronger impact blows (>5 J/blow vs. ∼0.5 J/blow). The penetrometer body (8-cm length and 1-cm diameter) is considerably smaller than the mole, and that also helps with the penetration. The diameter and in turn the probe’s projected area, in particular has the biggest impact on penetration. The area ratio of the mole to the new probe is 6:1. If this is combined with the hammer energy, the new probe generates 60 times greater pressure per unit area than the mole. In lab tests using well compacted JSC-1A lunar regolith simulant (relative density 90+%) placed in a 0.9-m deep container in vacuum, the penetrometer took only few tens of seconds in reaching the bottom.

Second, the penetrometer, because of its smaller size, needs much less time and power in making thermal conductivity measurement. A thermal conductivity probe for in-situ measurement emits heat from its body and monitors how quickly the heat dissipates into the surrounding soil/regolith. The time required for heating is roughly proportional to the diameter of the probe squared and inversely proportional to the thermal conductivity of the material [9]. For InSight, it is expected that the 2.5-cm diameter mole would be heated for 24
hours per measurement [6] in Mars regolith, which is expected to be nearly 10 times as thermally conductive as lunar regolith. Lab tests using our smaller penetrometer shows that less than 1 hour of heating may yield adequate sensitivity (Fig. 2).

The external percussive approach also has a major disadvantage: it is several times more massive than the mole-based system. The use of solid rod and the carousel adds significantly to the total mass. In addition, there is an inherent problem in percussive approaches in general: it compacts the regolith around the probe and alters its thermal property as a result [10-11].

Pneumatic Subsurface Excavation: An alternative to the percussive penetration is to excavate a hole into the regolith and insert a probe. That would avoid the problem of compacting and altering the thermal properties of the regolith. We believe that the pneumatic excavation technique [4-5] is optimal in balancing the excavation capability and mass saving. Our prototype of the pneumatic heat flow probe (Fig. 3) spools out a glass fiber composite stem downward. The stem then forms a hollow cylinder of ~1.5-cm diameter. It pushes the penetrating cone into the regolith, while gas jets, emitted from the cone tip, blow away loosened material. Removing material from the bottom of the excavated hole allows the stem to advance deeper with minimal thrust. A short (~1.5 cm), thin (~2-mm diameter) thermal probe attached to the cone tip measures temperatures and thermal conductivities of the regolith by stopping at different depths on the way down. During each stop, to measure the thermal conductivity of undisturbed regolith, the probe shuts off the gas jet, pushes the needle probe into the bottom-hole regolith, and heats it for 30 minutes. After the probe reaches the targeted, 3-m depth, the temperature sensors embedded on the fully extended stem monitor long-term stability of the thermal gradient. Our current prototype weighs less than 2 kg, comparable to the mole-based system on InSight.

Figure 2. A compilation of heating test results for the penetrometer using JSC-1A lunar regolith simulants in a range of thermal conductivities.

Figure 3. Left: The latest prototype of the pneumatic heat flow probe with the stem stowed. Right: Schematics of the major components of the heat flow probe.


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