LUNAR GLOBAL HEAT FLOW MAPPING WITH A REUSABLE LANDER DEPLOYED FROM THE DEEP SPACE GATEWAY SPACECRAFT. S. Nagihara[1], K. Zacny[2], P. Chu[2], and W. S. Kiefer[3], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Honeybee Robotics, Pasadena, CA 91103, [3]Lunar and Planetary Institute, Houston, TX 77058.

Introduction: Measurements of the heat flow originating from the interior of the Moon help us better understand its thermal evolution and the differentiation history of the lunar crust and mantle [e.g., 1]. During the Apollo program, heat flow measurements were considered high priority and planned on 4 of the landing missions (Apollo 13, 15, 16, and 17). The successful measurements obtained at the Apollo 15 and 17 sites (21 mW/m^2 and 16 mW/m^2, respectively) [2], along with the data from the gamma-ray spectrometer onboard Lunar Prospector [3], lead to the hypothesis that the Procellarum KREEP terrane is hotter than the surrounding areas because of the relative abundance of heat-producing elements, K, Th, and U in its crust [4].

Even though surface distribution of these heat-producing elements has been mapped globally, their vertical distribution is unknown. It is likely that their abundance decreases with depth into deeper crust. In addition, there is considerable geographic variation in lunar crustal thickness (10 to 80 km) as revealed by the GRAIL mission [5]. A thicker portion of the lunar crust may produce more radiogenic heat than a thinner portion.

In order to understand the Moon's internal thermal regime further, we need to more tightly constrain the crust's contribution to the Moon's total heat budget. To achieve that goal, additional heat flow measurements are desired at locations of varying crustal thickness and abundance of heat-producing elements. We believe that the *Deep Space Gateway* (DSG) can be utilized to quickly obtain heat flow data at many locations on the Moon.

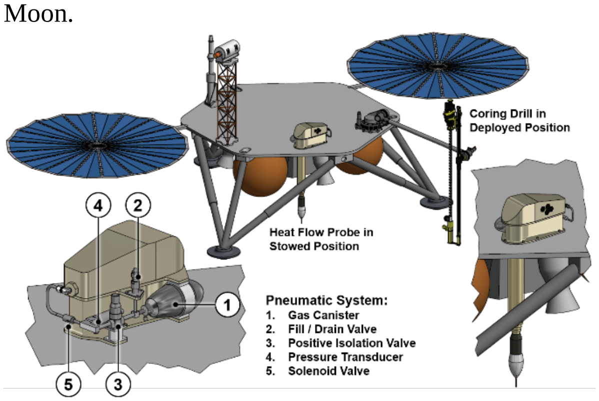

Figure 1. Conceptual drawings of the heat flow instrumentation (with the probe stowed) mounted on a reusable lander, deployed from the *Deep Space Gateway* spacecraft.

Proposed Experiment: We propose to equip the DSG spacecraft with a reusable lander that can shuttle to and from the lunar surface. The heat flow instrument is mounted on the platform of the lander (Fig. 1). Here, we envision a small lander carrying two or three instruments and a geologic sampling tool. It is solar-powered, and also serves as the communication link between the payload and the DSG spacecraft. On each deployment to the lunar surface, the DSG crew navigates the spacecraft and keeps a station above the locality targeted for a heat flow measurement. The lander touches down and stays there for 2 to 3 earth-days and completes all the necessary measurements and sampling. The instruments and tools are operated either by the DSG crew or the Earth-based personnel. When the lander returns to the DSG spacecraft, the crew services the payload instruments and prepares for next deployment. Spare sets of instruments are kept on the DSG spacecraft.

Heat Flow Instrumentation: In recent years, our group has been developing a compact, modular heat flow instrumentation specifically for robotic lunar-landing missions [6]. Our current prototype is at Technical Readiness Level (TRL) 5. The entire system weighs ~2 kg. It is mounted on a lander's platform and designed to penetrate >3 m into regolith, well below the thermal skin depth of the Moon. It uses a pneumatic system for excavating a hole into regolith. The penetrating cone emits gas jets and blows away regolith particles ahead of it, while the deplolyment mechanism on the lander extends the telescoping tube and pushes the cone downward (Fig. 2).

Heat flow is obtained as a product of two separate measurements of thermal gradient and thermal conductivity of the regolith interval penetrated. The instrumentation acquires these measurements by performing a stop-and-go operation on the way down to the 3-m depth. A short, needle-shaped probe (~2-cm long, ~2-mm diameter) is attached to the tip of the penetrating cone. The needle contains a temperature sensor (resistance temperature detector) and a heater wire. During the hole excavation, when the penetrating cone reaches a depth targeted for thermal measurements, it stops blowing gas. Then, the deployment mechanism mounted on the lander pushes the needle probe into the regolith at the bottom of the hole. Temperature of the regolith is recorded as the frictional heat of the needle penetration gradually dissipates. Soon afterwards, the probe utilizes the so-call 'hot-wire' technique and measures the thermal conductivity of the regolith [7]. Compared with the probes used for the Apollo Heat Flow Experiment [2], our needle sensor requires much less time (< 1 hour) for thermal conductivity measurement, because of its thin diameter (2.5 cm vs. 2 mm).

We expect one set of temperature and thermal conductivity measurements to be completed in less than 1 hour. Stopping every 0.3 - 0.5 m into the subsurface, we expect to complete the entire heat flow measurement operation in less than 12 hours. The progress of the operation can be monitored by cameras mounted on the lander and is controlled by the crew on the DSG spacecraft or the Earth.

When measurements at the maximum target depth are finished, the deployment mechanism reverses and retracts the probe. Gas jets are used to loosen and blow-away regolith particles that have partially filled the hole above the penetrating cone. If the probe becomes stuck in the hole, the deployment system can detach the subsurface portion of the instrumentation.

Resource Requirement: The heat flow instrumentation is compact, about the size of a shoe box with the probe stowed, and weights ~2 kg (Fig. 1). Power and energy usage is expected to be less than 10 W and 10 Whr, respectively, even during peak times. A small amount (~100 g) of compressed (~400 kPa) helium gas is needed for the pneumatic system, and it may be shared with the lander's propulsion system. The gas must be recharged by the crew when the lander returns to the spacecraft.

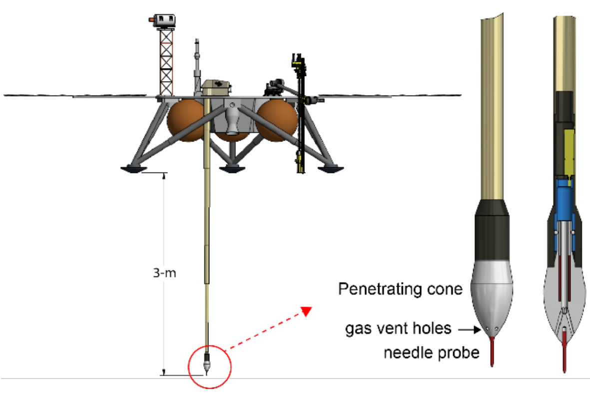

Figure 2. Conceptual drawings of the heat flow instrumentation fully deployed into the subsurface regolith.

Operation and maintenance of the instrumentation are not expect to take up much of the crew's time. Our heat flow instrumentation is a modular system. If one unit is damaged during a deployment, the crew can swap it with another one with little time, when the lander returns to the DSG spacecraft. By keeping multiple units on the spacecraft, the crew simply sends damaged units to the Earth for repair whenever convenient. When heat flow measurement is conducted on the near side of the Moon, the Earth-based personnel can take over the operation entirely, and that frees up the DSG crew's time. For operations on the far side, the DSG crew may need to take control of the instrumentation.

Proposed Landing Sites: Measuring the Moon's global heat flow distribution requires measurements at a variety of locations, but each measurement requires only an earth-day or less on the lunar surface. That makes heat flow measurements an ideal application of a reusable lander based at the DSG. Important measurement locations include regions of both very thin crust (e.g., central Mare Crisium, Mare Orientale, or Mare Moscoviense, far from the basin rim) and regions of feldspathic highland terrane of varying crustal thickness on both the near side and far side. In addition, landing sites in the center of the Procellarum KREEP terrane and on the floor of the South Pole-Aitken basin are also desirable [8].

Reusable Lander as Shared Resource: We consider the reusable lander required for the heat flow experiment as a resource that can be shared by many other ground-based operations. Because the heat flow instrumentation is compact and light, it leaves plenty of room for other payloads. A geologic sampling or coring tool may be one of such other payloads that can share the lander (Fig. 1). Finally, the reusable lander enables us to conduct a variety of ground-based experiments and operations on the Moon without having to land human-crewed spacecrafts.

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