HEAT FLOW PROBE FOR SHORT-DURATION LUNAR MISSIONS ON SMALL LANDERS. S. Nagihara[1], P. Ngo[2], L. Sanasarian[2], V. Sanigepalli[2], and K. Zacny[2], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Honeybee Robotics, Pasadena, CA 91103.

Introduction: During the Apollo program, heat flow measurements were considered among the high science priorities, and were planned on 4 of the landing missions. Only Apollo 15 and 17 were successful in obtaining the measurements [1]. Additional heat flow measurements at strategic locations are necessary in further understanding their relationship with other geologic observations such as surface abundance of heat-producing elements [2] and crustal thickness [3].

NASA, through its new Commercial Lunar Surface Payloads (CLPS) program, is planning multiple lander missions starting in the early 2020s. This provides the lunar science community opportunities to acquire data at multiple locations on the Moon. However, commercial landers on the CLPS missions will be relatively small with limited payload capacity, and they are not expected to survive lunar nights. Here we describe the new lunar heat flow probe we are developing for such short-duration missions with limited payload capacity.

Measurement Methodology: *Previous Methodologies.* Heat flow is obtained as the product of the thermal gradient and the thermal conductivity of the regolith/rock depth interval penetrated by a probe. For future lunar missions, a panel of scientists recommended 3 m as the target penetration depth [4] in order to avoid the thermal waves associated with the insolation cycles. On the Apollo 17 mission, the astronauts were able to penetrate 2.4 m into lunar regolith using a rotary-percussive drill [1]. On the CLPS missions, such a drill would exceed the lander's mass and power limits.

The heat flow probe on the InSight mission (HP^3) uses a low-mass, low-power alternative to the conventional drill [5]. HP^3 uses a 'mole', a cylindrical device that uses the momentum from internal hammering in penetrating into soil. The one built for HP^3 is about 40-cm long and 2.5-cm diameter, and weighs less than 1 kg. However, the mole advances very slowly into the subsurface. For InSight mission, it is expected to take ~70 sols in reaching 3-m depth into Mars regolith, stopping 3 to 4 sols every ~50 cm to make necessary thermal measurements. Therefore, the mole would not meet the time constraint of the CLPS missions, while it is within the mass and power limits.

New Methodology. The new heat flow probe we are developing for the CLPS missions is tentatively named Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER). It weights ~1 kg and of shoe-box size with its probe stowed. LISTER is a modular system, and it can be attached to the lander's leg or mounted on the deck (Fig. 1). It uses a pneumatic excavation system in quickly penetrating 3 m into lunar regolith [6]. It is expected to complete all the necessary thermal measurements within 10 hours. Power consumption is less than 10 W even during the peak times. LISTER meets all of the mass, power, and time requirements of the CLPS missions.

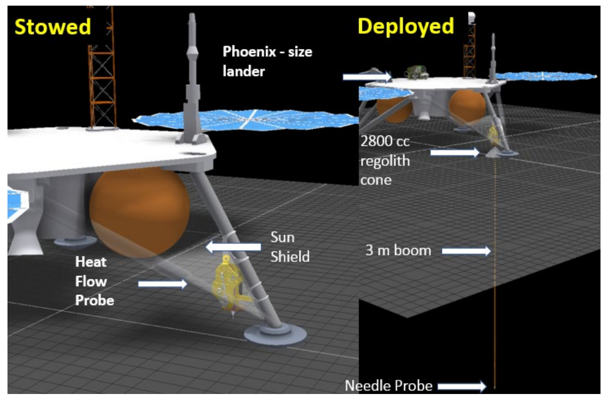

Figure 1. A schematic diagram showing LISTER attached to a Phoenix-size lander's leg with the probe stowed (left) and deployed (right).

LISTER's deployment mechanism spools out a boom made of Kapton and fiberglass (Fig. 2). On the way out of the mechanism, the flat boom becomes a hollow, ~2-cm wide, cylindrical column for mechanical strength. The penetrating cone at the leading edge of the boom advances by the combination of the spooling and a gas jet, fed through the boom and emitted from the cone tip, blowing away regolith particles.

A short (~2 cm), thin (2 mm diameter) needle sensor is attached to the tip of the penetrating cone (Fig. 3). The cone-sensor assembly makes multiple stops at pre-targeted depths on the way deeper into the regolith. At each stop, the gas jet shuts off, the needle sensor is pushed into the yet-to-be-excavated, undisturbed regolith at the bottom of the hole, and it makes temperature and thermal conductivity measurements in less than an hour. Five or 6 sets of measurements with ~0.5-m depth intervals can be obtained in 10 hours or less.

A platinum resistance temperature detector is used as the temperature sensor. For the thermal conductivity measurement, the needle heats up for 30 minutes and monitors the temperature rise over time [7].

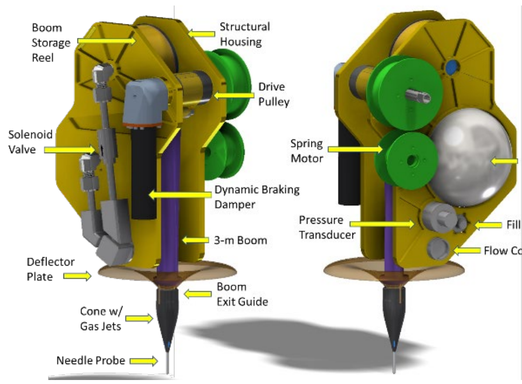

Figure 2. Schematics of the deployment mechanism of LISTER.

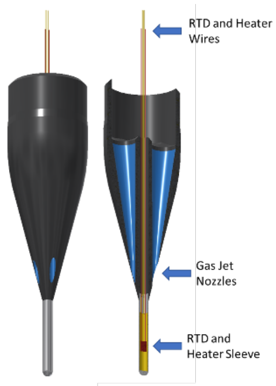

Figure 3. Diagram and cutaway view of the penetrating cone and the cone-tip needle probe.

Avoiding surface-originated thermal noise by rapid deployment and measurements. The surface operation of the CLPS missions is expected to take place during a lunar day. Temperature of the lunar surface during the operation may be tens of Kelvins greater than that of the subsurface where LISTER makes thermal measurements. In order to minimize the day-time heat and insolation from affecting the subsurface thermal measurements, LISTER is placed under a heat shield (Fig. 1). In order to further thermally isolate the subsurface temperature sensor from the lander, we use low-thermal-conductivity materials for the boom. Further, the needle sensor itself has a low heat capacity and can quickly thermally equilibrate with the surrounding regolith upon insertion.

Landing a spacecraft also alters the thermal environment of the lunar surface. However, because of the low thermal conductivity of the lunar regolith, it would be several months before the surface changes begin to affect regolith temperature below 1-m depth [8]. LISTER would complete all the necessary subsurface measurements well before that.

Laboratory Tests: We have conducted a number of laboratory tests on our current prototype using the JSC-1a lunar simulant. The in-situ thermal conductivity measurement capability of the cone-tip sensor has already been tested successfully on our earlier prototype in a vacuum chamber [7]. For the deployment mechanism, we already confirmed the ability to flow gas through the flattened, coiled boom to the probe cone with pressures sufficient for pneumatic excavation. We are currently refining the mechanism to achieve 30- to 40-N weight-on-bit (WOB) force.

We are also conducting tests to determine the range of gas flow rates optimal for excavation without disturbing the bottom-hole regolith ahead of the needle probe. In our recent test, we filled a ~50-cm-deep bin with JSC-1a simulant with a thin (~2 cm) layer of fluorescent powders, placed ~13-cm below the surface (Fig. 4). In 1 atm, we pneumatically penetrated an aluminum tube slowly with a dummy cone-needle assembly. The forward progress of the tube was visually monitored. Our goal was for the needle to reach the fluorescent layer before the layer is disturbed by the gas jet. Disturbance of the layer was detected when fluorescent particles appeared on the surface around the tube. We stopped excavation upon the first appearance of the fluorescent particles.

By repeating penetration tests using a different gas flow rate each time, we determined that at 11 SLPM flow rate or less, the needle reached the top of the fluorescent layer before it was disturbed. Future penetration tests will be conducted in a vacuum chamber.

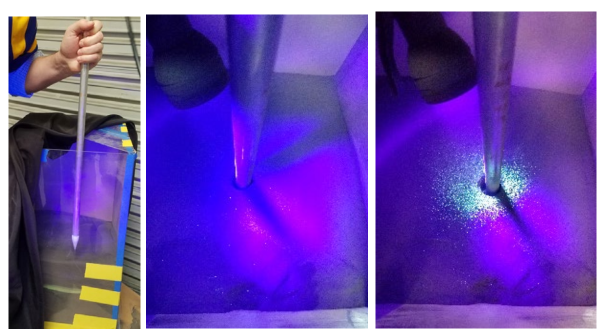

Figure 4. Regolith simulant disturbance test setup (left) and the surface before (middle) and after fluorescent layer disturbance (right).

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