THE HEAT FLOW PROBE FOR THE COMMERCIAL LUNAR PAYLOAD SERVICES PROGRAM OF NASA.

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Introduction: NASA, through its Commercial Lunar Payload Services (CLPS) program, is planning multiple robotic lander missions to the Moon starting in the 2021. Here we describe the heat flow probe selected as a payload for one of these missions planned in 2022.

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], as recommended by a number of recent expert panel studies [4-6].

The CLPS program is expected to maintain a cadence of 2 flights per year. This provides the lunar science community opportunities to potentially acquire data (including heat flow) at multiple locations on the Moon relatively quickly. However, commercial landers on the CLPS missions will be relatively small with limited payload capacity, and they are not expected to survive lunar nights. Actual time for scientific operation on the lunar surface will therefore be limited to 7 to 10 earth days per flight on most of these missions. The heat flow probe selected for the CLPS program is expected to acquire all the necessary measurements within one earth day.

Measurement Methodology: Heat flow is obtained as the product of the thermal gradient and the thermal conductivity of the regolith depth interval penetrated by a probe. For future lunar missions, 3 m has been recommended 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 new heat flow probe being developed for the CLPS mission is named Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER). It weighs ~4.6 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 underbelly (Fig. 1).

LISTER uses a pneumatic excavation system in quickly penetrating into lunar regolith [7]. Its 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, ~1-cm diameter, cylindrical column for mechanical strength. The penetrating cone at the leading edge of the boom advances by the combination of the spooling and gas jets, fed through the boom and emitted from the cone tip, blowing away regolith particles.

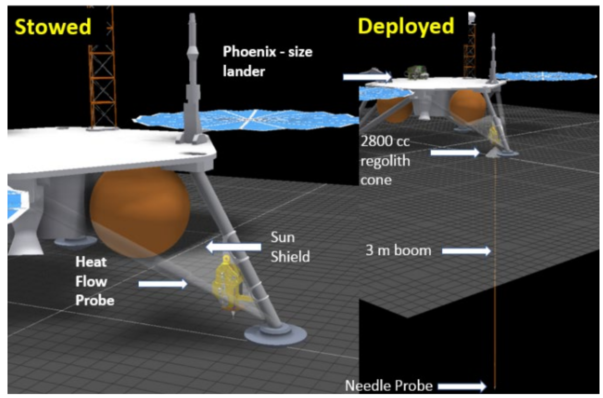

Figure 1. A schematic diagram showing LISTER attached to a lander's leg with the probe stowed (left) and deployed (right).

A short (~2 cm), thin (2-mm diameter) needle sensor is attached to the tip of the penetrating cone (Fig. 2). The cone-sensor assembly makes multiple stops at pre-targeted depths on the way deeper into the regolith. At each stop, the gas jets shut 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. A platinum resistance temperature detector is used as the temperature sensor. After insertion to the regolith, the needle sensor passively monitors the temperature for 30 to 60 minutes as it thermally equilibrates with the surrounding. Afterwards, the needle heats up for 30 minutes and monitors the temperature rise over time. Thermal conductivity is determined from the rate of warming [8].

Five or six sets of such thermal measurements with ~0.5-m depth intervals will be obtained down to 2- to 3-m depth in one earth day.

Surface operations for the CLPS missions will take place during a lunar day. Temperature of the lunar surface during the LISTER operation may be tens of Kelvins greater than that of the subsurface where thermal measurements are made. In order to minimize the daytime heat and insolation from affecting the subsurface thermal measurements, LISTER is placed under a sun 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.

The Advantage of the Rapid Deployment and Measurements: The Apollo heat flow data show that the thermal wave associated with seasonal insolation fluctuation reaches at least 1.5-m depth [1]. The 3-m target penetration depth was recommended [4] so that necessary thermal measurements can be made within the deep enough regolith interval to avoid the thermal wave.

Besides the insolation cycles, landing of a spacecraft may alter the thermal environment of the lunar surface in many ways. For example, the lander's jets blow away some of the loose regolith particles and may alter the photometric properties (e.g., albedo) of the surface. In addition, the lander would cast a shadow, where there was none previously. These changes in the surface boundary condition gradually propagate downward as thermal noise. However, because of the low thermal conductivity of the lunar regolith, it would be several months before the noise begins to affect regolith temperature below 1-m depth [9]. LISTER would complete all the necessary subsurface measurements well before that.

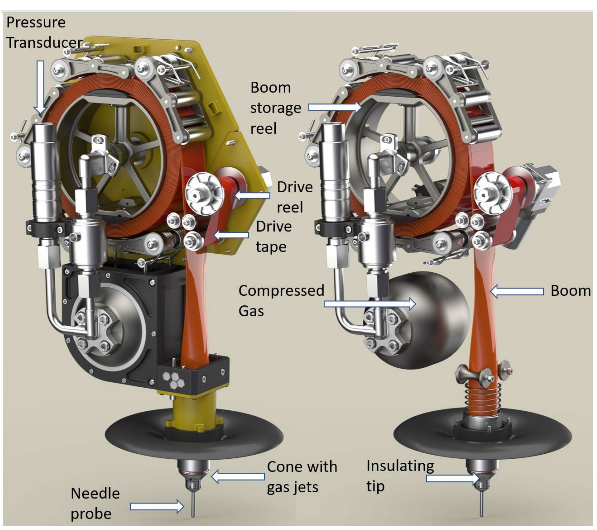

Figure 2. Schematics of the deployment mechanism of LISTER.

Laboratory Testing and Design Refinement: 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 [8]. We are currently evaluating penetration performance of LISTER on various lunar regolith simulants (JSC-1A for maria, NU-LHT-2M for highlands, and BP-1 multipurpose) to further improve the excavation efficiency of the gas jet. Based on these test results, we make improvements to the design of the boom and the deployment mechanism. For example, rather than using the Kapton-fiberglass boom itself as the gas conduit, lining the boom with thin, tubes dedicated to gas flow (Fig. 4) dramatically improves the excavation performance. In addition, the manner in which gas emits from the cone influences the penetration performance, and we are making refinements to the cone design as well.

Figure 4. Left: the boom of the current prototype fully extended. Right: the new boom design line with thin tubes for gas flow.

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