ASTRONAUT-DEPLOYED HEAT FLOW PROBE FOR MEASUREMENTS IN THE LUNAR SOUTH POLAR REGION. S. Nagihara[1], K. Zacny[2], and M. Grott[3], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Honeybee Robotics Altadena, CA 91001, [3]German Aerospace Center, Berlin, Germany.

Introduction: During the Apollo program, heat flow measurement was considered among the high science priorities. It was originally planned on 4 of the landing missions, but only Apollo 15 and 17 were successful [1]. The recent expert panel studies have repeatedly recommended additional heat flow measurements on future lunar-landing missions [2-4]. In order to further understand the thermal evolution of the Moon, it is important to constrain the heat flux out of the lunar mantle and the crustal contribution to the Moon's total heat budget.

The two existing heat flow data points are located ~800 km from each other in the north-central region of the near side. In addition, radiogenic heat production in the shallow subsurface there may have contributed significantly to the heat released from the surface [5, 6] at both locations.

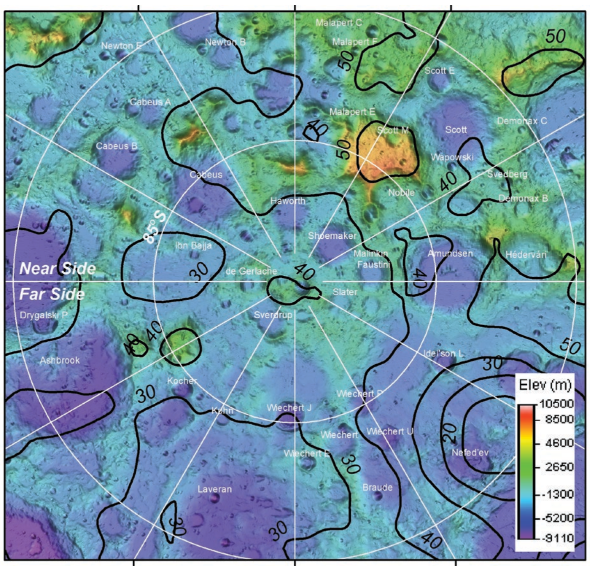

Figure 1. Shaded-relief topographic map of the lunar south polar region. The black contours are crustal thickness estimates (km) from the GRAIL mission [7]. The necessary data were obtained from [8].

Heat flow measurements in the lunar south polar region would serve as important anchor points to the global heat flow models [e.g., 6]. This region has very low concentration of heat-producing elements (U, Th, and K) in the surface regolith [9]. Within the circle of 85°S latitude, crustal thickness varies from less than 30 km to over 50 km (Fig. 1). Such geologic setting is suited for testing whether or not crustal thickness has any influence on the surface heat flow.

Additionally, thermal properties measurements in the surface and shallow subsurface regolith of this region would provide ground-truth data to the estimates derived from the Diviner lunar radiometer observations [10], and will be useful in assessing stability and distribution of the water ice in the shallow subsurface regolith of the permanently shadowed regions (PSRs).

Heat Flow Measurement Methodology: Here we focus on heat flow measurement methodology for human missions. We first summarize the one used by the Apollo astronauts [1,11], and then we discuss possible improvement for future missions.

The Apollo Heat Flow Experiment. Heat flow was obtained as the product of two separate measurements of thermal gradient and thermal conductivity of the regolith depth interval penetrated by a probe. At each of the Apollo landing site, the astronauts first drilled two hollow augers, 2.5-cm diam., made of boron-fiber glass, into the ground, roughly 10-m apart, and then inserted the thermal sensors into them (Fig. 2). After the instrument was successfully deployed and activated, the mission control took over the experiment.

The holes for installing the thermal sensors needed to be deep enough so that the thermal gradient of the regolith was not affected by the insolation cycles at the surface. The astronauts used a 450-W rotary-percussive drill and targeted 2.5-m depth for each hole. On Apollo 15, they reached only 1.4 m and 1.0 m. On Apollo 17, the astronauts were able to reach the targeted depth, thanks to the redesigned augers.

The sensor assembly consisted of two major components. The upper component consisted of an electrical cable with 4 thermocouples spaced along it with 40-cm interval. The lower component consisted of a succession of two, 2.5-cm diameter, 50-cm long, solid rod, each embedded with 4 resistance temperature detectors (RTDs) at different depths. The rod was made of fiberglass-reinforced epoxy.

The RTDs and thermocouples placed at multiple depths yielded the thermal gradient. After the installation, it took 100 to 200 earth days for the sensor assembly to thermally equilibrate with the surrounding regolith. The long equilibration time was due to factors such as the epoxy rods being initially much hotter (heated by the Sun) than the subsurface regolith, frictional heat from the drilling, and the low thermal conductivity of the regolith. In addition, conductive coupling between the RTDs embedded in the epoxy rods and the regolith was poor [12]. There was contact resistance between the epoxy rod and the casing. There were also many small gaps between the casing and the regolith at various parts of the hole.

In measuring thermal conductivity in-situ, the investigators [1] adapted the so-called 'hot wire' method by applying heat at short sections of the epoxy rod.

Figure 2. Apollo 15 commander David Scott inserting the thermal sensors to one of the boreholes, where the borestem is extruded. The drill is also shown next to the borestem (*Apollo Lunar Surface Journal*, https://www.hq.nasa.gov/alsj/main.html).

New Probes for the Artemis Missions. Because regolith in some parts of the south polar region may be partially filled with ice, we believe that rotary-percussive or percussive drilling is the simplest and sound approach for drilling holes. The Apollo 17 heat flow experiment showed that the 2.5-m hole depth was sufficient for heat flow measurement. In addition, the Apollo 17 neutron probe experiment [13] showed that ~3-m deep holes left behind from coring operations did not collapse, and thus do not require casing for installing instrumentation downhole later.

Based on these lessons learned, here we propose a new design for the thermal sensor assembly, which eliminates the problem of poor conductive coupling.

The new design stems out of one of the robotic probe deployment options we considered earlier [14]. RTDs are connected by cables and coiled inside a telescoping tube, which extends from 0.4-m length to ~3-m length. Once a hole has been excavated, an astronaut places the tube in the bottom of the hole. As the astronaut pulls up the tube, it extends up the hole. Inside the extending tube, the sensor string uncoils itself. Once the tube has fully extended, the astronaut pulls the tube out of the hole, simultaneously, each RTD, loaded with a leaf-spring, anchors itself to the wall of the hole. Thus, the RTDs are in direct contact with the regolith.

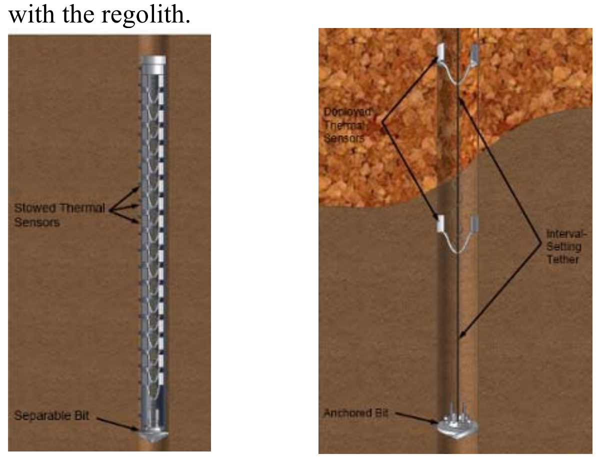

Figure 3. Conceptional drawings for the new thermal sensor assembly with the tube slowed (left) and the RTDs anchored inside the hole (right) [14].

Table 1 gives notional estimates for the key parameters for spacecraft accommodation and crew interactions for the new design.

Table 1: Estimates on the resources needed

Parameter	**Estimate**
Mass (w/o electronics)	1 kg
Size	2 cm in diam**.** x 40 cm long
Power	0 W to deploy, < 10 W for data acquisition
Deployment time	< 1 hour

References: [1] Langseth M. G. et al. (1976) *LSC, 7,* 3143-3171. [2] Nat. Academy Sci. (2007) *The Scientific Context for the Exploration of the Moon,* 121 p. [3] Cohen, B. A., et al. (2009) *ILN Final Report*, 45 p. [4] Lunar Exploration Analysis Group (2017) *Advancing Science of the Moon*, 69 p. [5] Wieczorek M. A. and Phillips R. J. (2000) *JGR, 105*, 20417-20430. [6] Siegler, M. A. and Smrekar S. E. (2014) *JGR-Planets, 119*, 1-17. [7] Wieczorek M. A. et al. (2013) *Science, 339*, 671-675. [8] Hare T. et al. (2014) *LPSC XLV*, #2487. [9] Lawrence D. J. et al. (2000) *JGR, 105*, 20307-20331. [10] Williams J.-P. et al. (2019) *JGR-Planets, 124*, 2505-2521. [11] Nagihara S. et al. (2018) *JGR-Planets, 123,* 1125-1139. [12] Grott M. et al. (2010) *JGR-Planets, 115,* E11005. [13] Woolum D. S. et al (1973) *Apollo 17 Prelim. Sc. Rept.* 18:1-12. [14] Zacny K. et al. (2009) *LPSC XL,* #1070.