APOLLO HEAT FLOW EXPERIMENTS: LESSONS LEARNED FOR FUTURE LUNAR-LANDING MISSIONS. S. Nagihara[1], W. S. Kiefer[2], P. T. Taylor[3], D. R. Williams[3], and Y. Nakamura[4], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Lunar and Planetary Institute, Houston, TX 77058, [3]Goddard Space Flight Center, Greenbelt, MD 20711, [4]Institute for Geophysics, University of Texas at Austin, Austin, TX 78758.

Introduction: Heat flow probes were deployed successfully as part of the Apollo Lunar Surface Experiment Package (ALSEP) at the Apollo 15 and 17 landing sites [1]. The heat flow value obtained for the Apollo 15 site (21 mW/m^2) was greater than the one for the Apollo 17 site (16 mW/m^2). Later, data from the gamma-ray spectrometers onboard the Lunar Prospector [2] and Kaguya missions [3] showed that the surface of the Procellarum KREEP terrane (PKT), which includes the Apollo 15 site, is more abundant in heat-producing elements, K, Th, and U than the rest of the lunar surface (Fig. 1). These observations lead to the hypothesis that heat flow in the PKT is higher than in the surrounding areas due to the higher concentration of the heat-producing elements in its crust [4].

There have been no additional heat flow measurements on the Moon since Apollo 17 in 1972, but some robotic lunar-landing missions are being planned for the near future. The teams competing for Google's *Lunar X-prize* are in their final stage of preparation. NASA may also send spacecraft to the Moon in response to President Trump's directive of last December to send humans back to the Moon. Some future missions, such as the *Resource Prospector* [5], *Deepspace Gateway*, and the *Lunar Geophysical Network* [6], are already under consideration. With an anticipation that some of these future lunar missions will carry out heat flow measurements, here we present recommendations for additional measurement sites and the methodology based on the lessons learned from the Apollo and more recent lunar missions.

Sites for Future Heat Flow Measurements: Even though the lunar surface has been mapped globally in terms of its abundance of heat-producing elements [2,3], their subsurface vertical distribution is unknown. Based on our current knowledge of the thermal evolution of the Moon [7], we expect that the elements are more heavily concentrated in the crust than in the mantle. We also expect that, within the crust, the elemental concentration may decrease with depth. The crust's contribution to the Moon's total heat budget is still relatively unknown, and that has been a major hindrance in the effort to further constrain the thermal structure of the interior.

For future robotic lunar-landing missions, we propose that heat flow measurements be made in areas where the lunar crust is known to be very thin and also outside the PKT. Crustal heat production in such areas should be minimal, and thus heat flow measurements there should yield values close to the flow originating from the mantle. One might argue that the measurements reported at the Apollo 17 site serve such a purpose, but that area is likely underlain by Th-rich ejecta from the PKT basins and craters [8]. Further, the Apollo 17 site was located in a valley in a transition zone between highland and maria. The heat flow through the lunar surface there may have been affected by the sharp lithologic variation in the regolith and the underlying crust [9]. For future measurements, we suggest sites further away from the PKT on the flat central floor of mare basins, such as Mare Crisium and Mare Nectaris (Fig. 1). Crustal thickness in these basins is less than 10 km in their central parts, according to the estimates from the GRAIL mission [10]. Heat flow measurement sites should be at least 100 km from the basin rim in order to avoid the aforementioned edge effect.

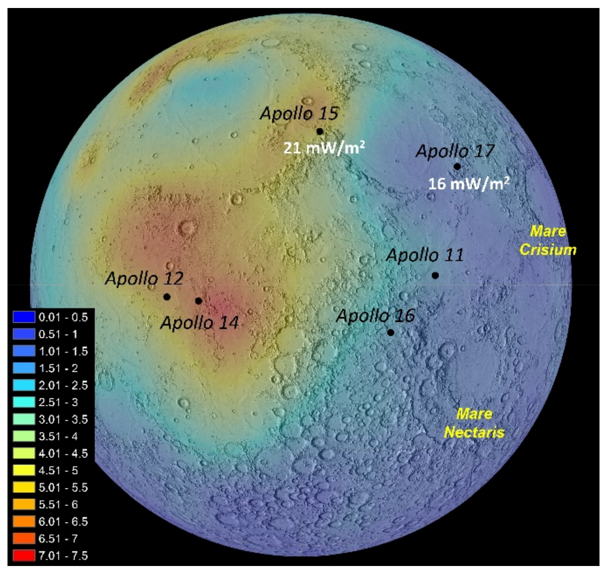

Figure 1. The Apollo landing sites are indicated on the map of surface thorium distribution obtained from the Kaguya Gamma-ray Spectrometer [3]. The heat flow values for the Apollo 15 and 17 sites are also shown. The locations of Mare Crisium and Mare Nectaris are also indicated. The color scale shows Th in ppm.

Lessons Learned from the Apollo Heat Flow Experiment: The Apollo heat flow probes operated from their times of deployment at the Apollo 15 (July 1971) and the Apollo 17 (December 1972) sites through September 1977 [11]. However, at the conclusion of the Apollo program, the data were analyzed only through December 1974 [1]. The heat flow experiment data from 1975 to 1977 had not been archived with the National Space Science Data Center. Recently, major portions of the 1975 – 1977 heat flow data have been restored from the original archival data tapes for the ALSEP experiments and the ALSEP Performance Summary Reports [12-13].

The Apollo experiment determined the heat flow at each site as a product of two separate measurements of thermal gradient in, and thermal conductivity of, the regolith interval penetrated by the probe [1]. The original investigators of the experiment noticed that temperatures at depths well below the thermal skin depth of ~1 m were gradually increasing, even after the thermal effect of drilling holes and installing the probes has diminished. For example, Figure 2 shows the records for the three of the temperature sensors installed at depths greater than 1 m for the full duration of the observation at the Apollo 17 site (1972 – 1977). At this site, thermal gradient decreased by ~70% from the beginning to the end. The experiment at the Apollo 15 site yielded similar results.

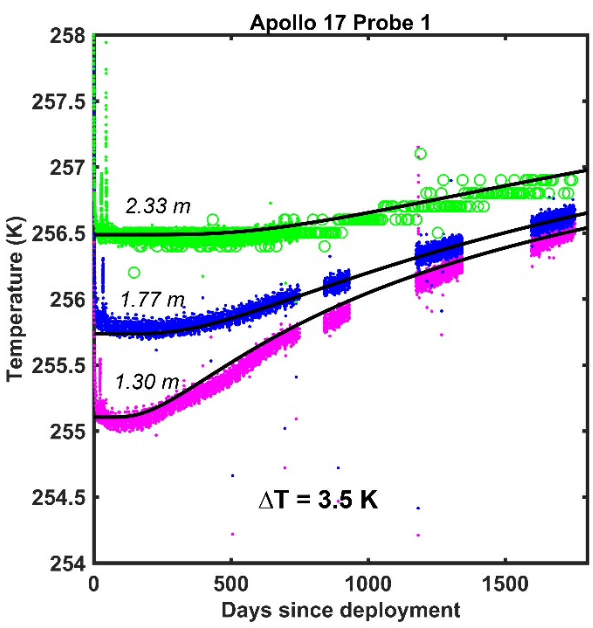

Figure 2. Color dots show the subsurface temperature records at 1.30-, 1.77-, and 2.33-m depths observed by the Apollo 17 Heat Flow Probe 1 for the full duration of the experiment. The black, solid lines are model predictions for an abrupt surface warming by 3.5 K.

In recent years, possible causes of the long-term subsurface warming have been debated [14-16]. The manner in which the warming occurred suggests that temperature of the surface increased rather abruptly by 1.5 K - 3.5 K at the time of the probe deployment, and the warming gradually propagated downwards (Fig. 2). That can be shown by a simple analytical heat conduction model [17]. We suggest that the astronauts' activities in the vicinity changed thermal or photometric property of the surface regolith, and that caused it to absorb more solar heat. Some photos of the ALSEP deployment sites show darkening of the surface regolith. In our estimation, a less than 0.05 reduction in albedo would result in the large enough increase in surface temperature.

Conclusions: One of the important lessons from the Apollo experience is that activities related to the deployment of heat flow probes and the presence of the spacecraft in the vicinity may alter the surface heat balance of the area [18]. Fortunately, it takes time for these surface changes to seriously alter the subsurface thermal setting below the skin depth. Therefore, heat flow measurements on future missions should quickly deploy the instruments and complete necessary measurements. How the surface changes affect the subsurface thermal setting should also be carefully evaluated. As for possible sites for additional measurements, we suggest central locations in major mare basins away from the PKT. Measurements in such locations would yield the best estimates of the mantle heat flow, and they would be useful for constraining the thermal structure of the deep interior.

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