DESIGNING HEAT FLOW EXPERIMENTS FOR FUTURE LUNAR MISSIONS. S. Nagihara[1], P.T. Taylor[2], M.B. Milam[2], P.D. Lowman[2], and Y. Nakamura[3], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Goddard Space Flight Center, Greenbelt, MD 20771, [3]Institute for Geophysics, University of Texas at Austin, Austin, TX 78713.

Introduction: A number of robotic and human missions to the moon are proposed for the next decade. Some of these missions will probably include measurements of endogenic heat flow from the lunar interior. Here we discuss what improvements that could be made over the previous measurements carried out for the Apollo program.

The Apollo Heat Flow Experiments: Heat flow is obtained as a product of the thermal gradient and the thermal conductivity of the geologic interval of interest. During the Apollo program, heat flow instruments were installed at the Apollo 15 (1971) and 17 (1972) sites. At each site, two holes were drilled with ~10-m separation and instruments were deployed in both. They successfully operated for ~6 years and recorded subsurface temperature distribution, its time fluctuation, and *in-situ* thermal conductivities down to 1.6- to 2.3-m depths [1,2].

Because diurnal and annual fluctuations of the surface temperature influenced the depth range where the sensors were installed, long-term observations are necessary in obtaining the thermal gradient representative of the heat flow from the lunar interior by theoretically removing the transient signals. Langseth et al. [3] determined the heat flow at the 2 sites (21 mW/m^2 at Apollo 15 and 16 mW/m^2 at Apollo 17) using data collected up to 1974. They did not use the in-situ thermal conductivity data in their determination of the heat flow values. Instead, they derived average thermal conductivities of the regolith columns penetrated by the sensors by modeling the process of diurnal and annual temperature signals propagating downward. There was a discrepancy between the *in-situ* and the model-derived thermal conductivity values with the former being 10% to 100% greater. Cause of the discrepancy was not fully resolved at that time.

More recently, re-examination of the entire temperature record from the Apollo heat flow instruments have been conducted by some research groups [4,5]. They found a long-term surface temperature fluctuation trend which is attributable to the 18.6-year orbital precession of the moon. If the thermal gradients at the two Apollo landing sites were fully adjusted to account for the long-term transient effect, heat flow values there may be 1/3 of what Langseth et al. [3] obtained.

Depth and Duration of Sensor Deployment for Future Missions: Simple mathematical heat conduction models can show that the 18.6-year surface temperature fluctuation penetrates to ~5-m depth into lunar regolith (Fig. 1). Because the Apollo data were obtained at relatively shallow depths (1.6 to 2.3 m) for durations (~6 years) much shorter than the precession-controlled period of the surface temperature fluctuation, it is difficult to accurately remove the transient noise from the data. For future missions, it is desired that temperature sensors reach at least 6- to 7-m depths, where temperature distribution should be fairly stable and yield the steady-state thermal gradient. Mission preparations should include development of technologies for drilling to such depths. If deep drilling is not feasible, the instrumentation should be deployed for two decades or more so that the data can be fully corrected for the long-term surface temperature fluctuation.

In-situ Thermal Conductivity Measurement: Various data from the Apollo program suggest that the lunar regolith is heterogeneous in thermal conductivity [3,6]. Thermal conductivity increases with depth by 40% to 60% from the surface to ~2-m depth. It can also vary considerably between different sites. Its texture, more specifically, how tightly the grains are packed, heavily influences the thermal conductivity. In obtaining the heat flow at any particular site on the moon, it is essential that both temperature and *in-situ* thermal conductivity be measured with a relatively high depth resolution (20-cm or shorter intervals). Because accuracy of the *in-situ* thermal conductivity measurement is important in preparing for future missions, we should further investigate the cause of the discrepancy between the *in-situ* and the model-derived thermal conductivities, which Langseth et al. [3] observed.

The *in-situ* thermal conductivity measurement technique used for the Apollo instruments is an adaptation of the so-called "needle probe" technique, which is commonly used for measurements on unconsolidated soil and sediment samples on earth [7]. In this technique, typically, a thin (< 2-mm diameter) probe is inserted into the medium of interest, and releases heat with a known, constant rate. Thermal conductivity of the medium is determined from the manner temperature of the probe rises with time. The measurement theory assumes that the probe is an infinitely long, line heat source, and makes the problem one-dimensional in the cylindrical coordinate system. The temperature rise due to the heating (ΔT) is then expressed as:

$$\Delta T = \frac{Q}{4\pi k}\ln(t) + const\,, \qquad (1)$$

where Q is the rate of heat injection (W/m) to the medium, k is the thermal conductivity (W/m·K), and t is the time of heating (sec.). The thermal conductivity can be obtained from the slope of a plot of ΔT versus $\ln(t)$.

The 2.55-cm diameter Apollo probe was not a line heat source. It had short (2-cm long), isolated sections wrapped with resistance heater wires [1,2]. The geometrical configuration was quite different from what was assumed by the measurement theory. Langseth and others [2] realized this, but they suggested that the 1-D approximation was adequate, and applied Eq. 1 to the temperature records of the heated sections.

Here we show simple simulation results comparing two probes of a same diameter (2.55 cm) with different heater configurations (Fig. 2). One generates heat only along a short (2-cm), isolated section (i.e., analogous to the Apollo probe) and the other generates heat all along its length. All the other parameters, including the thermal conductivity of regolith (0.02 W/m·K), are the same between the two cases. One can observe that the former yields a smaller temperature rise in a given time period than the latter. Application of Eq. 1 to the former would result in an over-estimate of the regolith thermal conductivity. This may at least partially explain the fact that the *in-situ* thermal conductivity values obtained for the Apollo probe were consistently greater than the model-derived values.

Long-term Heating vs. Pulse Heating: Because the probe injects additional heat to the surrounding regolith, the temperature records obtained during thermal conductivity measurements are not particularly useful for extracting any cyclicity associated with the surface environmental changes. The heater section of the Apollo probe injected ~250 J of heat over a period of 30 to 40 hours in each thermal conductivity measurement. It took additional tens of hours before the injected heat fully dissipated. The time required for thermal conductivity measurement should be shortened for future missions. It is worth considering use of the so-called pulse heating technique [8], which injects less amount of heat in a much shorter period of time. This technique was developed after the Apollo program and is now widely used for terrestrial measurements.

References: [1] M.G. Langseth et al. (1972) *Apollo 15 Preliminary Science Report*, NASA, Sec. 11. [2] M.G. Langseth et al. (1973) *Apollo 17 Preliminary Science Report*, NASA, Sec. 9. [3] M.G Langseth. et al. (1976) *LPS VII*, 3143-3171. [4] M.A.Wieczorek and S. Huang (2006) *LPS XXXVII*, abstract #1682. [5] Y. Saito et al. (2007) *LPS XXXVIII*, abstract #2197. [6] C.J. Cremers (1975) *JGR*, 80, 4466-4470. [7] R.P. Von Herzen and A.E. Maxwell (1959) *JGR*, 64, 1557-1563. [8] C.R.B. Lister (1979) *Geophys. J. Royal Atr. Soc.* 57, 451

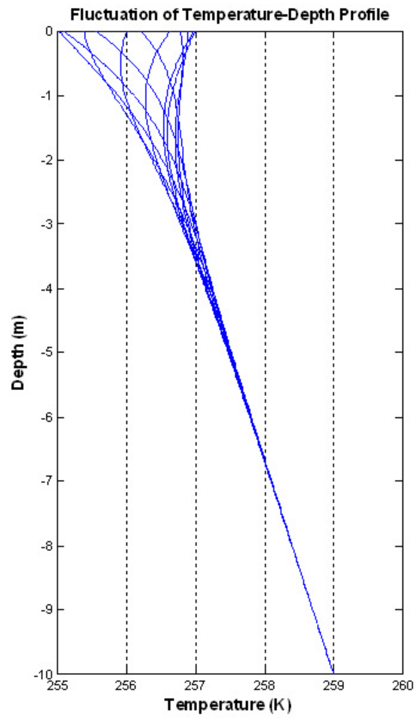

Fig. 1 A model showing temperature fluctuation through the regolith column in response to a sinusoidal surface temperature changes of 18.6-year period and 1-K amplitude. Thermal gradient and thermal diffusivity of regolith are assumed to be 0.3 K/m and 1×10^{-8} m^2/s, respectively.

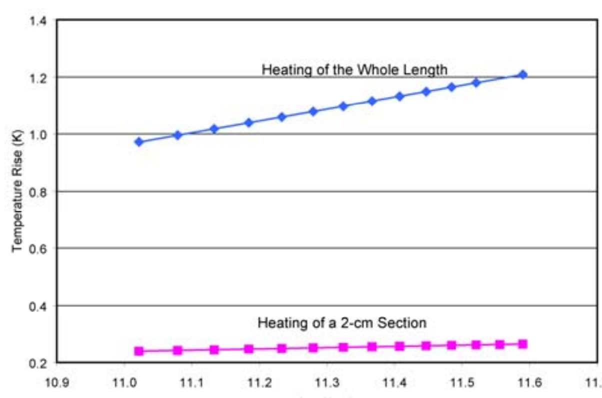

Fig. 2 ΔT versus ln (t) plots for two probe models: one generating heat along a 2-cm section (pink) and the other genering heat all along its length (blue).