APOLLO HEAT FLOW EXPERIMENT: IMPLICATIONS FOR LUNAR THERMOPHYSICAL PROPERTIES AND HEAT FLOW.

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Introduction: Measurements of lunar heat flow provide valuable information for our understanding of the Moon's internal structure, composition, and evolution. Recently expanded and improved data [1,2] from the Apollo 15 and 17 Heat Flow Experiment (HFE) provide the only available in situ lunar temperatures to date. Existing analysis and interpretations of the HFE data present an opportunity for reinvestigation as notable uncertainty is associated with the derived values of lunar regolith thermal conductivity and corresponding heat flow. The presence of a decreasing thermal gradient over time and temperature amplitudes larger than those predicted by models using LRO Diviner-derived thermophysical properties [4] highlights a need for thorough reexamination. A critical evaluation of measured subsurface temperature amplitudes and subsequently determined in situ thermal conductivity values will contribute significantly to the study of lunar heat production and future in situ measurements.

Background and Data: Data from heat flow probes deployed at the Hadley Rille and Taurus-Littrow sites (Figure 1) during Apollo 15 and 17 provide temperature measurements at depths below the lunar surface down to 1.7 m and 2.5 m, respectively [3]. Subsurface temperatures were used to calculate regolith thermal properties and corresponding heat flow values [3]. Heat flow measurements of 21 ± 3 $\mathrm{mWm^{-2}}$ and 15 ± 2 $\mathrm{mWm^{-2}}$ from these sites [3] have played a major role in evaluations of the thermal state of the Moon. A linear factor in the heat flow calculation, regolith thermal conductivity estimates currently lie within the range of $0.9 - 1.3 \times 10^{-3}\ \mathrm{Wm^{-1}K^{-1}}$[3].

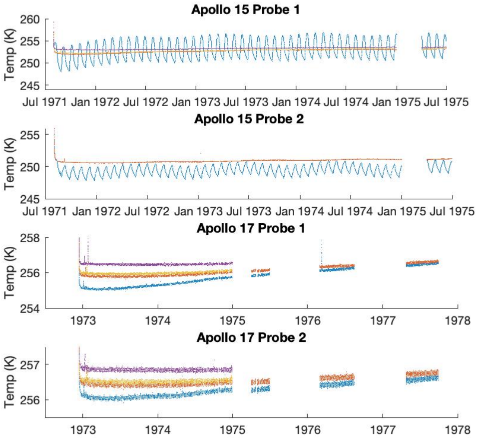

Figure 1. Improved temperature records at Apollo 15 and 17 sites including records from original investigators [3] and restored data for years 1975 to 1977 [2].

Model: To assess subsurface temperature changes and amplitudes, we developed a two-dimensional axisymmetric model using COMSOL Multiphysics (Figure 2). The comprehensive model includes the experiment probe, compacted regolith surrounding the probe, and undisturbed regolith beyond this region.

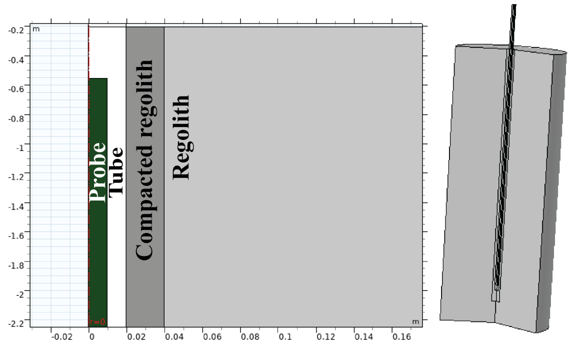

Figure 2. Model geometry for the Apollo HFE using cylindrical symmetry.

Variation of temperature (T) with time (t) and depth (z) is described as

$$\rho c_p \frac{\delta T}{\delta t} = \frac{\delta}{\delta z}(K\frac{\delta T}{\delta z})$$

where ρ is density, c_p is specific heat, and K is thermal conductivity. The model assumes increasing regolith density and conductivity with depth, matching Apollo core sample observations [5]. The relationship between density and depth for the lunar regolith is modeled by

$$\rho(z) = \rho_d - (\rho_d - \rho_s)e^{-z/H}$$

where z is depth below the surface, ρ_s (~1100 kg $\mathrm{m^{-3}}$) is surface density, and ρ_d (~1800 kg $\mathrm{m^{-3}}$) is density at depths $z \gg H$-parameter [3]. Thermophysical properties for the probe and tube are set according to documented estimates [6]. We aim to model three primary scenarios to understand the discrepancy between observed and current regolith model-predicted temperature amplitudes:

(1) *An undisturbed area of lunar regolith* with global thermophysical regolith properties determined using LRO Diviner.

(2) *The probe and tube* surrounded by undisturbed regolith.

(3) *The probe, tube, and surrounding compacted regolith* with undisturbed regolith outside the compacted domain (Figure 2).

Results: Our preliminary results suggest that temperature amplitudes at depth are controlled in part by the probe. While a strictly regolith model fails to produce sufficient temperature amplitudes, a probe-inclusive model exhibits amplitudes comparable to HFE data (Figure 3).

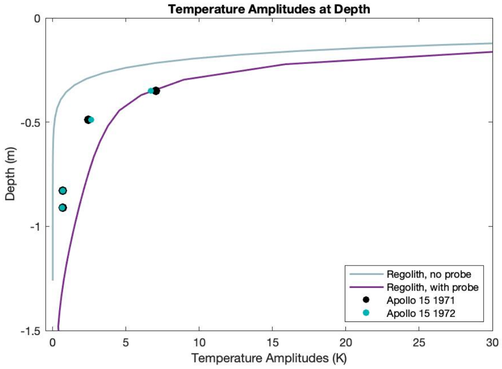

Figure 3. A comparison of temperature amplitudes of undisturbed regolith [4], regolith with the probe, and Apollo 15 HFE.

Because previous derivations of lunar thermophysical parameters did not account for the contribution of the probe [3], adjustments to currently accepted values for Apollo 15 and 17 sites may be appropriate. These potential changes have notable implications for our understanding of the thermal state of the Moon, emphasizing the importance of a more precise estimate. Future work includes refining the probe model and conductivity and evaluating the role of regolith compaction.

In addition to temperature amplitudes, modeling efforts will address the observed long-term subsurface temperature drift and decreasing thermal gradient in HFE data. Subsurface temperatures notably increase over the experiment timeline with those closest to the surface experiencing the largest degrees of warming. This drift in thermal gradient could alter present heat flow estimates and will be addressed using the model outlined above. Model considerations for the multiyear subsurface warming will include effects of the probe, astronaut-induced changes to thermophysical regolith properties, and the Moon’s 18.6 year orbital precession period. Our comprehensive analysis of these issues ultimately aims provide a better understanding of lunar thermophysical parameters and heat flow.

References: [1] St. Clair et al. (2019) LPI Contrib. No. 2151. [2] Nagihara et al. (2018) JGR Planets, 123 (5): 1125–39. [3] Lengseth et al. (1976) LPSC (Vol. 7, pp. 3143-3171). [4] Hayne et al. (2017) JGR Planets, 122 (12): 2371–2400. [5] Keihm & Langseth (1973) LPSC (Vol. 4, pp. 2503). [6] Grott, M., J. Knollenberg, and C. Krause. 2010. *JGR,* 115 (E11).