APOLLO HEAT FLOW EXPERIMENT: IMPLICATIONS FOR LUNAR THERMOPHYSICAL PROPERTIES AND HEAT FLOW. M. White[1,2], M. A. Siegler[1,2], C. Million[3], M. St. Clair[3], [1]Planetary Science Institute, based in Dallas, TX (mnwhite@smu.edu), [2]Southern Methodist University, Dallas, TX, [3]Million Concepts

Introduction: Measurements of lunar heat flow provide valuable information for understanding 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 temperature measurements 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 (Figure 1) 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 thermal conductivity values will contribute significantly to the study of lunar heat production and future in situ measurements.

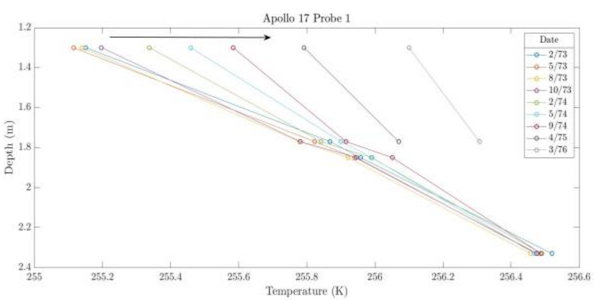

Figure 1. Temperature gradient change for Apollo 17 probe 1 through time (direction indicated by arrow). The gradient decrease is notably more pronounced closer to the surface.

Background and Data: Data from heat flow probes deployed at the Hadley Rille and Taurus-Littrow sites (Figure 2) 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 mWm^{-2} and 15 ± 2 mWm^{-2} from these sites [3] have played a significant 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 $0.9 - 1.3 \times 10^{-3}$ $Wm^{-1}K^{-1}$[3].

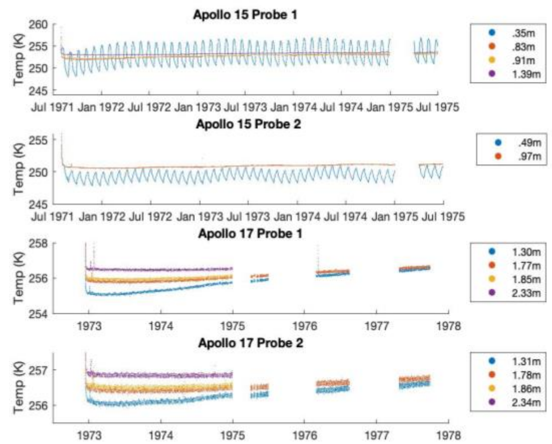

Figure 2. Improved temperature records at Apollo 15 and 17 sites including records from original investigators [3] and restored data for years 1975 to 1977 [2].

Model: To assess subsurface temperature changes and amplitudes, we developed one-, two-, and three-dimensional models using COMSOL Multiphysics (Figure 3). The comprehensive model includes the experiment probe, compacted regolith surrounding the probe, and undisturbed regolith beyond this region.

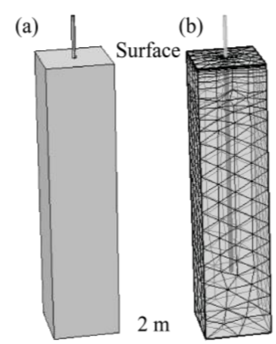

Figure 3. 3D geometry of regolith block and probe constructed in COMSOL

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

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

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 m^{-3}) is surface density, and ρ_d (~1800 kg m^{-3}) is the density at depths z≫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 3).

Results: Our preliminary results utilizing one- and two-dimensional models 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 4).

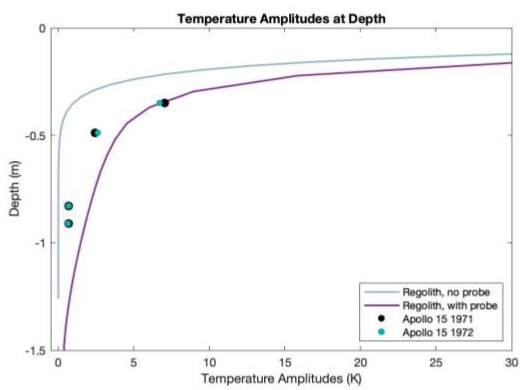

Figure 4. A comparison of temperature amplitudes of undisturbed regolith [4], regolith with the probe, and Apollo 15 HFE using a two-dimensional axial symmetric model.

More accurate three-dimensional models running comparative parameter variations are in-progress and utilize the COMSOL parametric sweep function (Figure 5). While computationally expensive, initial results support their efficacy and this method will therefore be applied to test and compare additional model parameters. We change the values of regolith density, probe conductivity, and surface albedo to cycle through specified ranges, re-

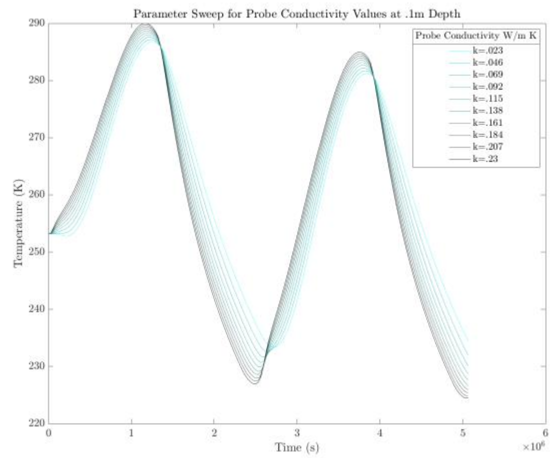

Figure 5. Example of parametric sweep of thermal conductivity of the probe.

solving the model each time to identify and evaluate the optimal properties.

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 to 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).