THE APOLLO THERMAL CONDUCTIVITY EXPERIMENT REVISITED.

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Introduction: Lunar heat flow is a fundamental parameter characterizing the thermal state of the Moon and it is directly connected to processes like volcanism and tectonism which we observe on the lunar surface. Lunar heat flow has been measured at two sites during the Apollo 15 and 17 missions, and values of 21 and 16 mW m^{-2} have been obtained [1]. However, these values carry significant uncertainties due to the large uncertainty connected to the in-situ determination of the regolith's thermal conductivity.

In the Apollo experiments, regolith thermal conductivity k was determined using four different approaches [2][3]: (1) Carrying out active heating experiments. (2) Monitoring the thermal reequilibration of the borestem as a function of time after initial insertion of the probes. (3) Evaluating the decay of the periodic temperature perturbation induced by the annual temperature wave as a function of depth. (4) Analysing the propagation of Astronaut induced thermal disturbances as a function of depth.

Of these approaches, (1) and (2) gave broadly consistent results, with k ranging from 0.0141 to 0.0295 W m^{-1} K^{-1}, depending on probe location and depth. On the other hand, (3) and (4) also yielded consistent results, but in the range 0.009 to 0.013 W m^{-1} K^{-1}. Furthermore, it was found that the regolith's thermophysical properties vary only little with depth, contrary to the results obtained using methods (1) and (2). It was concluded at that time that the values obtained by methods (3) and (4) were more reliable, because the small volumes sampled by methods (1) and (2) may have been thermally altered during the drilling process [1].

Modeling: The approach followed by the Apollo active heating experiment was similar to the standard line heat source method for thermal conductivity determination and relied on the controlled injection of heat into the probed medium and interpretation of the temperature rise at the heater as a function of time. However, the complicated measurement setup impeded a straight-forward inversion of the obtained self-heating curves and a detailed finite difference model had to be used to invert the data in a two step process [3]: (1) The slope of the temperature rise ΔT vs. $\ln(t)$ was fitted for large times $t > 1000$ min to obtain the thermal conductivity k of the regolith. (2) The amplitude of ΔT was fitted by adjusting the thermal contact resistance H between probe and regolith.

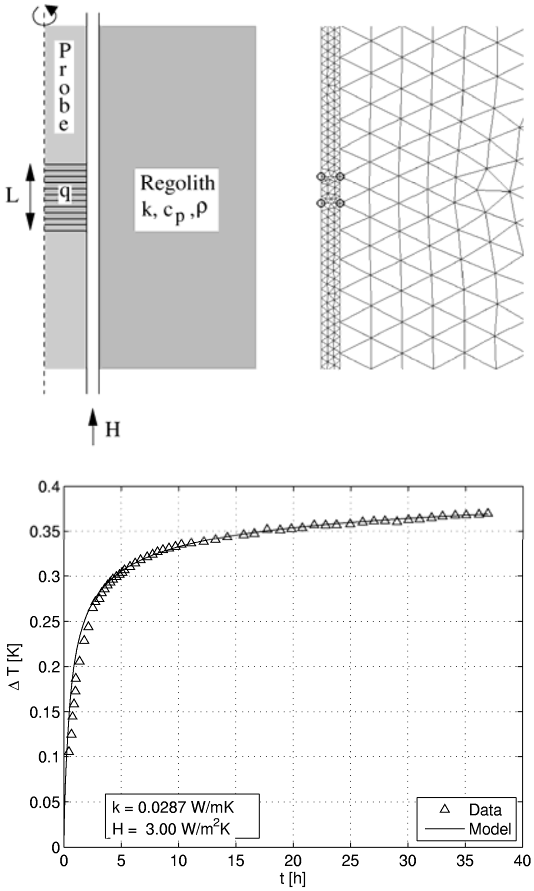

Figure 1: (Top) Schematics and grid of the finite element model used to invert the Apollo active heating experiment data. (Bottom) Data from an Apollo 17 heating experiment (scanned) and nominal model fit.

Note that although interpretation of the data was made difficult by diversion of the injected heat in the axial direction, the estimated total conductance of the borestem is only $7 \cdot 10^{-5}$ W K^{-1} per meter. This is equivalent to a copper cross section of only 0.18 mm^2, i.e., not particularly high.

The largest uncertainty associated with the above data inversion technique is the knowledge of the thermophysical properties of the probe itself [3]. Therefore, we have build a simple finite element model to test the sensitivity of the Apollo inversion method on probe properties. As heating experiment data was unavailable in electronic form, data had to be scanned from [3]. Furthermore, we have tested the influence of regolith compaction on the obtained results.

The model setup is sketched in Fig. 1 and encompasses the probe stem with a nominal heat capacity of 750 J kg^{-1} K^{-1} and thermal conductivity of 0.23 W m^{-1} K^{-1} [2]. The 1.7 cm long heater is energized at 0.002 W [2] and the temperature rise at its center is recorded. The reglith heat capacity was set to 670 J kg^{-1} K^{-1} [1] and its density to 1800 kg m^{-3}. The bottom panel of Fig.1 shows the fit of the nominal model to the Apollo data, where a thermal contact conductance of 3 W m^{-2} K^{-1} has been assumed. The best fit thermal conductivity is 0.0287 W m^{-1} K^{-1}.

Results: We have varied the probe thermal conductiviy k_s, heat capacity c_p and contact conductance H to estimate the robostness of the inverted thermal conductiviy values. Varying H between 1.5 and 6 W m^{-2} K^{-1} was found to have a negligible influence (<2 %). The results of varying c_p and k_s are summarized in Fig. 2a. Varying these parameters within a factor of two results in best fit conductiviy estimates that differ by <25%, but probe thermal properties were probably known much better than this generous range. Also, heat dissipation along the electrical connection wires inside the probe was found to be negligible.

To test the influence of regolith compaction on the results, we included a cylindrical region of regolith with increased thermal conductivity k_{com} close to the borestem. The maximum compacted conductivity k_{com} = 0.035 W m^{-1} K^{-1} was estimated by assuming 100% relative density and linearly extrapolating k according to the data by [5]. Furthermore k_{com} was scaled for the maximum stress that allows for an open borehole. Results of the calculations are summarized in Fig. 2b, where the background thermal conductivity was set to 0.0116 W m^{-1} K^{-1}, the value obtained by method (3) above. The best fit thermal conductivity k ist given as a function of the radius of the compacted region d. To obtain a thermal conductivity of 0.0287 W m^{-1} K^{-1} the disrupted region close to the borestem needs to extend 7 cm into the regolith. This implies a significant disruption of the ambient regolith by the rotary-percussion action of the drill.

To sample more undisturbed regolith, the heating experiment's duration would need to be significantly increased. Increasing the heating time to 336 h (half a lunation) resulted in a best fit thermal conductivity of 0.015 W m^{-1} K^{-1}. This would be marginally practical, but would nevertheless overestimate k by 30 %.

Conclusions: The setup of the Apollo active heating experiment hampered a straight-forward data inversion due to the small size of the heater and the relatively high axis thermal conductivity of the probe. However, our sensitivity analysis suggests that the obtained results are robust.

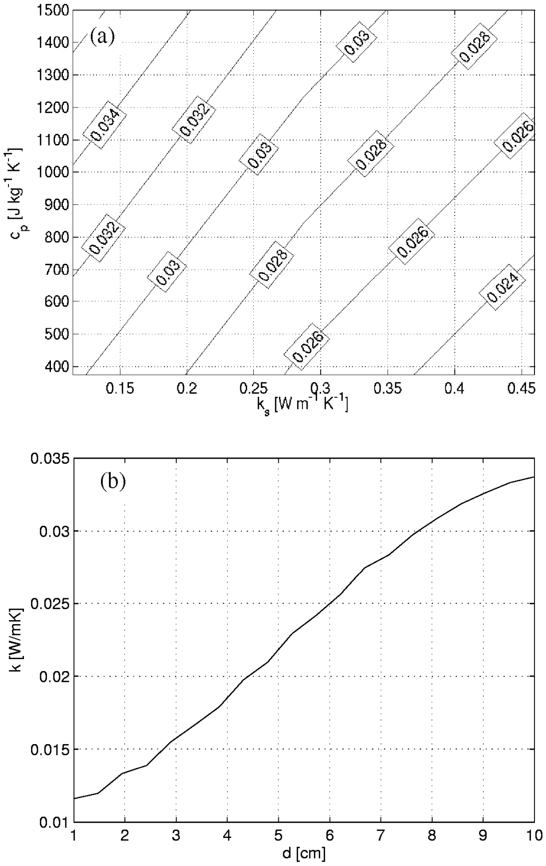

Figure 2: (a) Contour plot of the change of the obtained thermal conductivity with respect to the nominal thermal conductivity of 0.0285 W m^{-1} K^{-1} in percent as a function of borestem heat capacity c_p and thermal conductivity k_s. (b) Best fit thermal conductivity k obtained by fitting the slope of a simulated heating curve for different radii of the compacted region d. Background thermal conductivity is 0.0116 W m^{-1} K^{-1}.

The discordance between results obtained using different methods must be attributed to a massive disruption of regolith within many centimetres of the borehole, as originally concluded by [1]. Future thermal conductivity experiments should take care to both minimise regolith disturbance and maximise heating time to obtain representative results.

References: [1] M.G. Langseth et al., *Lunar Science Conference*, 7th, 3143-3171, 1976. [2] M.G. Langseth et al. (1972), *Apollo 15: Preliminary Science Report*, NASA SP-289, Chapter 11. [3] M.G. Langseth et al. (1973), *Apollo 17: Preliminary Science Report*, NASA SP-330, Chapter 9. [4] M.G. Langseth et al. (1972), The Moon, 4, 390. [5] K. Horai, *PEPI*, 27, 60-71, 1981.