In-Situ Measurements of Lunar Heat Flow

Marcus G. Langseth and Stephen J. Keihm
Lamont-Doherty Geological Observatory
Columbia University
Palisades, New York

During the Apollo program two successful heat-flow measurements were made in situ on the lunar surface. At the Apollo 15 site a value of 3.1×10^{-6}W/cm^2 was measured, and at the Apollo 17 site a value of 2.2×10^{-6}W/cm^2 was determined. Both measurements have uncertainty limits of $\pm$ 20 percent and have been corrected for perturbing topographic effects. The apparent difference between the observations may correlate with observed variations in the surface abundance of thorium. Comparison with earlier determinations of heat flow, using the microwave emission spectrum from the Moon, gives support to the high gradients and heat flows observed in situ.

There has long been an interest in the rate at which heat is escaping from the Moon. The Moon is a planetary-sized body that represents a significant sample of the solar system in the region of the terrestrial planets. On the other hand, the Moon is a small enough body so that there is reason to believe that during its 4.6-b.y. history it has lost a significant portion of its initial heat and, as a result, that the present heat flux mainly results from heat generated by radio isotopes in the interior to a depth of about 300 km.

Petrological and geochemical evidence gained from surface samples indicates that the Moon was radially differentiated early in its history. During this differentiation the long-lived, heat-generating isotopes of ^{238}U, ^{235}U, ^{40}K, and ^{232}Th were purged from the interior and concentrated in the outer layer of the Moon. As a result, the surface heat flow from the Moon should very nearly reflect the total abundance of isotopes in the Moon and thereby provide a valuable chemical constraint on the Moon's bulk composition.

Prior to the Apollo missions, lunar heat-flow determinations were based on Earth-based observations of thermal emissions from the Moon in the microwave band. Because of the partial transparency of lunar material to electromagnetic waves longer than 1 mm, the emission spectrum at wavelengths greater than 1 mm depends on temperatures in the subsurface. If the electrical properties of lunar soil are known, the subsurface temperature profile can be determined from the emission spectrum.

The most comprehensive effort to detect heat flow from the interior by this technique has been made by Troitsky and colleagues (refs. 1 and 2) at the Radiophysical Research Institute, Gorky, U.S.S.R. Their well-known curve, shown in figure 1, indicates an increase in brightness temperature with wavelength of about 0.6°C/cm. Using electrical and thermal properties deduced from microwave observations in the 1-mm to 3-cm range, Tikhonova and Troitsky (ref. 2) interpreted this spectral gradient in terms of a heat flow of 3×10^{-6} to 4×10^{-6}W/cm^2. Such a heat flow is approximately one-half the mean of observed heat-flow values on the Earth.

---
[1] Lamont-Doherty Geological Observatory Contribution No. 2141

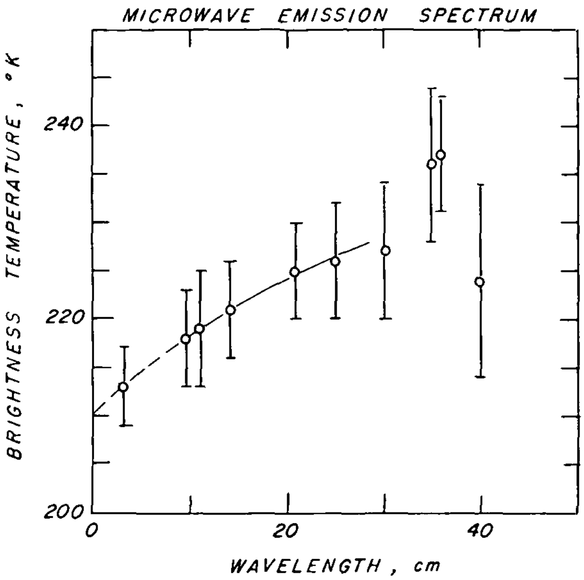

Figure 1.—*Data from microwave observations made in the Soviet Union between 1961 and 1964 using the "artificial Moon" technique (refs. 1 and 2). The plot shows microwave brightness temperature versus wavelength of the radiation.*

In-Situ Measurements During the Apollo Program

The manned lunar landings of the Apollo program provided an opportunity to make direct measurements in the lunar surface layer relevant to the heat flow through the surface. Successful measurements were made at two of the landing sites: Hadley Rille, near the edge of the Imbrium basin—visited on Apollo 15—and Taurus-Littrow, a narrow embayment on the southeastern margin of Serenitatis—visited on Apollo 17 (see figure 2).

At each location the astronauts buried two probes in the lunar soil to measure the temperature and thermal conductivity of the soil. At the Apollo 15 site the probes were buried to depths of 1.0 and 1.4 m; at Apollo 17 both probes were buried to a depth of 2.3 m. Each probe contains eight platinum resistance thermometers and four thermocouples which detect temperature at 11 different levels in the subsurface. Four thermometers on each probe are surrounded by heaters which can be turned on by command from Earth. These heaters are used to make in-situ determinations of thermal conductivity. The range and accuracy of measurements made by the heat-flow experiment are shown in table 1. The platinum resistance thermometers were carefully tested to demonstrate that they would retain their calibrations after experiencing the mechanical and thermal shocks of the lunar mission. Temperature data from all the thermometers are relayed to Earth every 7.2 min. At the Apollo 15 site we presently have more than 2½ yr of data and more than 1 yr of data at the Apollo 17 site.

A Summary of Results

The experiments installed on the Moon provide extensive information on the temperature and thermal properties of the lunar surface layer to a depth of 3 m, including surface temperature variations, near-surface thermal properties, subsurface temperature

Table 1.—*Heat-Flow Experiment Temperature Measurements*

Measurement	Range	Accuracy
Platinum Resistance Thermometers: Absolute Temperature	190–270 K	±0.05 K
Temperature Difference	±2 K	±0.001 K
Cable Thermocouples: Absolute Temperature	70–400 K	±0.5 K

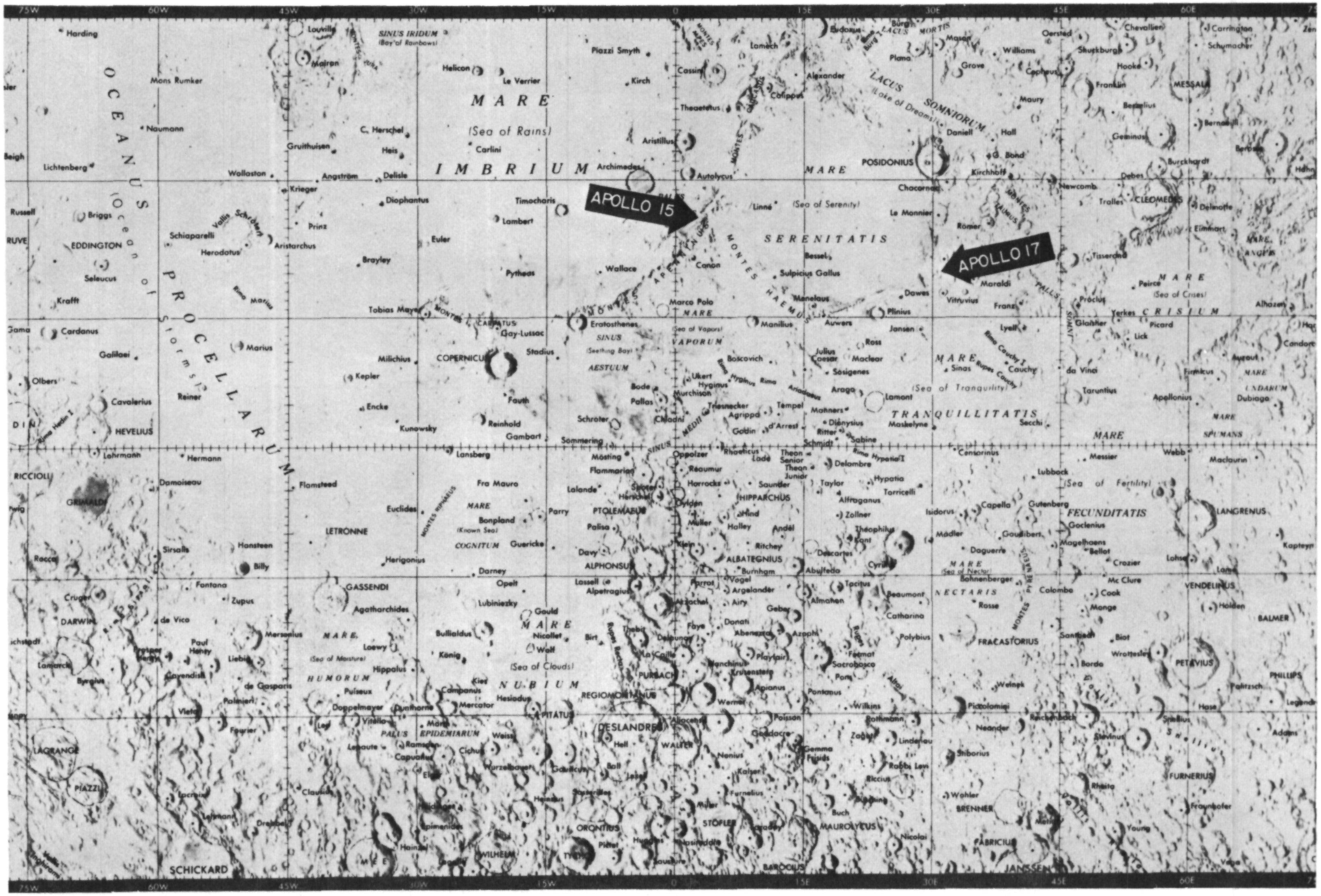

Figure 2.—*A lunar map showing the locations of the two successful heat-flow measurements.*

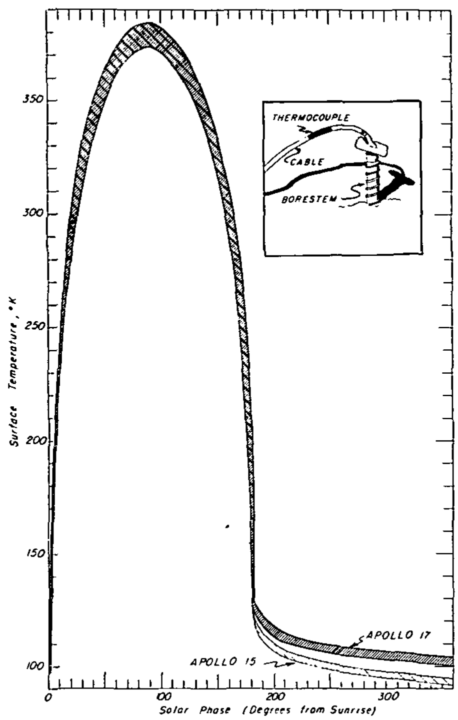

Figure 3.—*The calculated surface temperature throughout a lunation based on the temperature of a thermocouple inside a cable (see inset) which is exposed above the surface.*

variations, and thermal conductivity. All of this information is essential to understand the total heat budget near the lunar surface and the contribution of the flux from the interior.

SURFACE TEMPERATURE VARIATIONS

Measurements by thermocouples in cables above the lunar surface provide information on the surface temperature variation. The cable is in radiative equilibrium with the lunar surface, except during times when the temperature is changing rapidly, as during an eclipse or at terminator crossing. The lunar surface temperature can be readily computed from laws governing thermal radiation. In figure 3 we show the surface temperature variation at the Apollo 17 site during a complete lunation. During lunar day, the temperature deductions have large errors because of uncertainties in the amount of solar radiation reflected from the lunar surface, but at night the errors are small. Similarly, surface temperatures can be deduced quite accurately from thermocouple data during the umbral phase of an eclipse.

In a manner similar to the classical methods of Wesselink (ref. 3) and Jaeger (ref. 4), the cool-down of the surface after sundown and during an eclipse can be used to deduce the thermal properties of the regolith to a depth of about 15 cm. For analysis of the in-situ data we use a thermal model that includes many layers with thermal properties that vary with depth and temperature. To explain the observed temperature variations at lunar night and during an eclipse, the conductivity and density must vary with depth. The variations of density and conductivity shown in figure 4 will explain the surface temperature variations during the lunar night almost exactly, but these de-

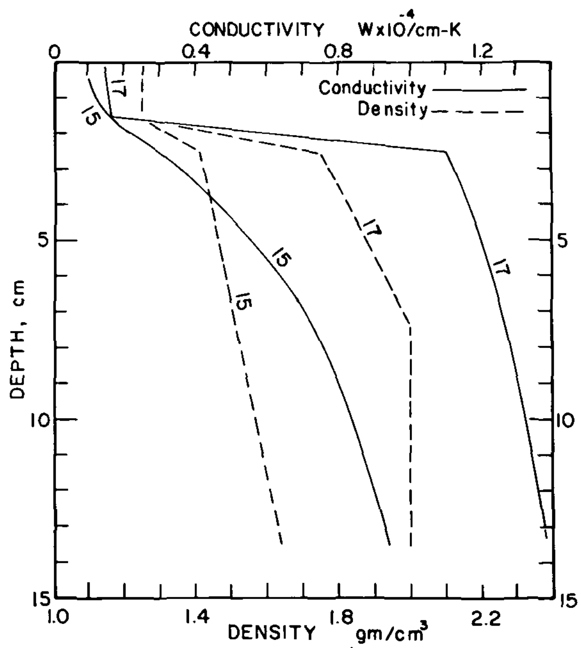

Figure 4.—*Profiles of thermal conductivity and density, with depth in the lunar regolith that will explain the observed surface temperature variations shown in figure 3. Conductivity values shown are those appropriate to the mean temperature at each depth.*

duced profiles are not necessarily unique. Two features of the profiles shown are essential to explain the data:

1. The upper 1 to 2 cm must have an extremely low thermal conductivity, and this conductivity must be temperature-dependent. The conductivity at the mean surface temperature (216 K) is approximately 1.5 × 10^{-5}W/cm-K, which is in good agreement with measurements on returned lunar fines.
2. At a depth of about 2 cm, the conductivity must increase greatly to values 5 to 7 times greater than the surface value.

THE NEAR-SURFACE MEAN TEMPERATURE GRADIENT

One of the most interesting features of the subsurface temperature measurements is the very large difference in mean temperature (i.e., the temperature averaged over one lunation) between the surface and depths of a few centimeters. At the Apollo 15 site the mean temperature 35 cm below the surface is 45 K higher than at the surface; the difference at the Apollo 17 site is 40 K. This large increase in mean temperature is due primarily to the temperature dependence of thermal conductivity in the top 1 to 2 cm, which results from the nonlinear behavior of radiative heat transfer. These large differences require that the ratio of the radiative component to conductive component at 350 K be about 2 to 3. Figure 5, from Keihm and Langseth (ref. 5), shows the variation of mean temperature and the amplitude and phase of variations of lunation period with depth in the regolith, based on the models shown in figure 4.

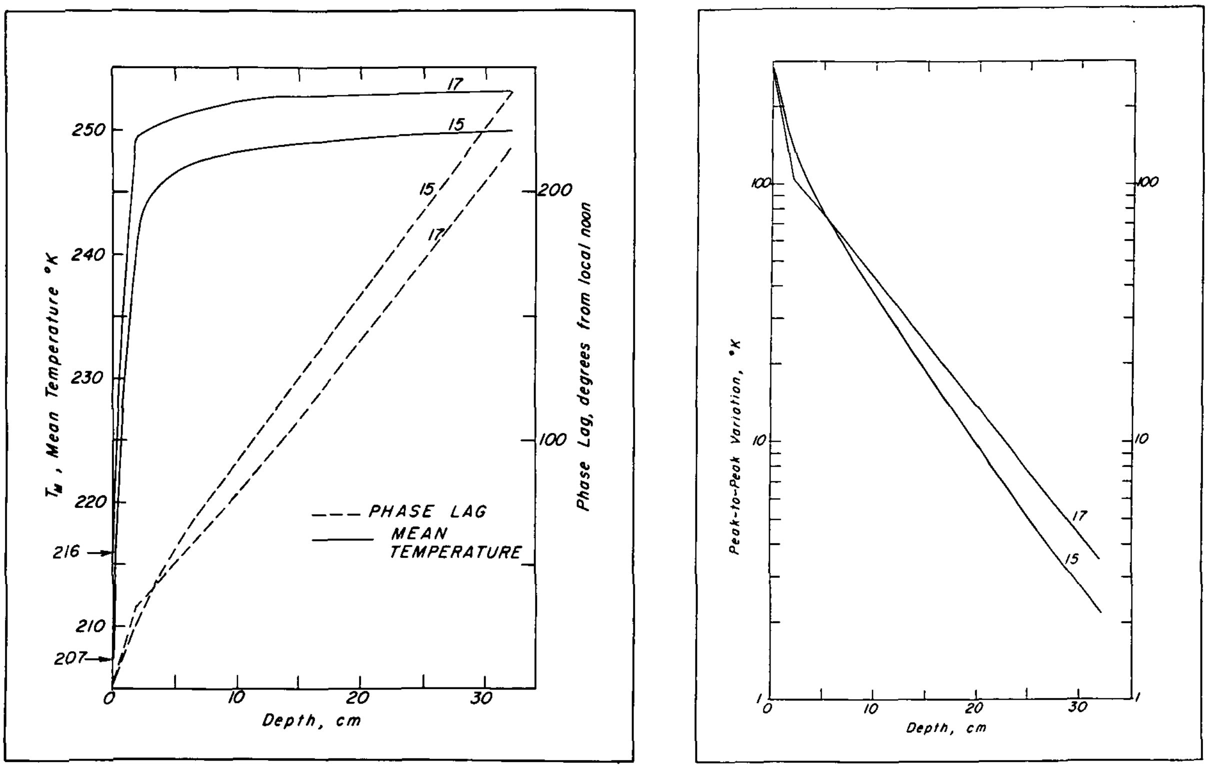

Figure 5.—*In the right plot, the expected peak-to-peak monthly variation of temperature as a function of depth. The left-hand plot shows mean temperature and phase lag of the monthly variation versus depth. These results are based on the conductivity and density models shown in figure 4.*

Subsurface Temperature Profiles

The probes are inserted inside the hollow fiberglass tubing which is drilled into the lunar soil. Figure 6 shows Charles Duke, an Apollo 16 astronaut, drilling one of the heat-flow holes. Figure 7 shows the temperature history of one of the probes after insertion into the tube. The probes require approximately 1 month to reach within a few thousandths of a degree of thermal equilibrium with the surrounding regolith. The thermometers buried below 80-cm depths do not see any perceptible variation due to the monthly temperature cycle, and temperature gradients should reflect heat flowing from the lunar crust. The temperature profiles at four of the probes are shown in figure 8. Very small corrections have been added to these data to account for thermal shunting effects of the fiberglass tubes and probes, so that these profiles should represent true undisturbed regolith temperatures.

THERMAL CONDUCTIVITY

Thermal conductivity of the regolith can be deduced from three different effects. First, and most important, were measurements made by in-situ experiments. The effects of heaters turned on for a period of 36 hours at low power were measured. From

Figure 6.—*An astronaut drilling sections of fiberglass tubing into the Moon for the heat-flow probes.*

the rate of rise of temperature after 20 hours it is possible to determine the conductivity. Second, the initial cool-down of the probes from high temperatures permits determination of conductivity based on the initial energy input into the hole. Cool-down estimates can be made at all the gradient sensors, i.e., at eight different depths in each hole. Third, temperature variations with a monthly period penetrate to approximately 80 cm, and the annual variation of surface temperature is felt at all depths. The attenuation of these variations with depth depends in part on the thermal conductivity of the surrounding material. However, because of radiative transfer along the fiberglass tubing, the attenuation data are difficult to interpret. Our analysis requires a thermal conductivity between 1 and 2 $\times$ 10^{-4}W/cm-K to reproduce the attenuation observed. The conductivities measured by the first two techniques are shown versus depth in figure 9. We note that the thermal conductivity of the lunar soil lies between 1.4 and 3.0 $\times$ 10^{-4}W/cm-K; this is approximately a factor of 10 higher than the conductivity at the surface. The increase of conductivity at about a 2-cm depth appears to be mainly

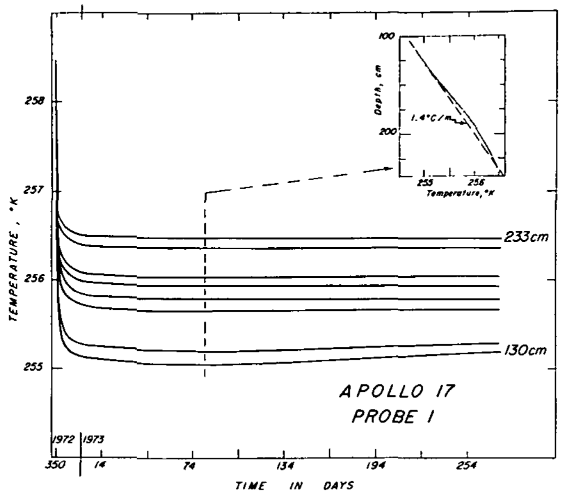

Figure 7.—*The 10-month temperature history of eight thermometers on one of the probes at the Apollo 17 site. The inset shows the temperature depth profile after 75 days.*

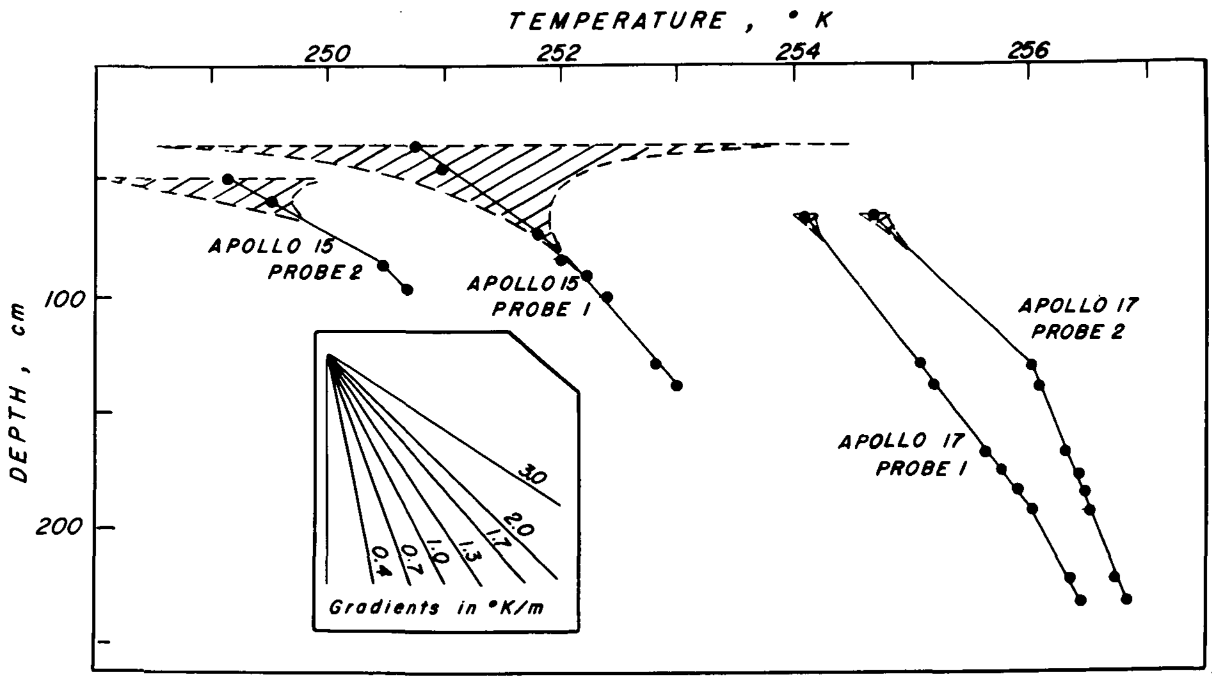

Figure 8.—*Temperature depth curves for the four lunar heat-flow measurements. The hatched areas above 70 cm are the envelopes of monthly variations.*

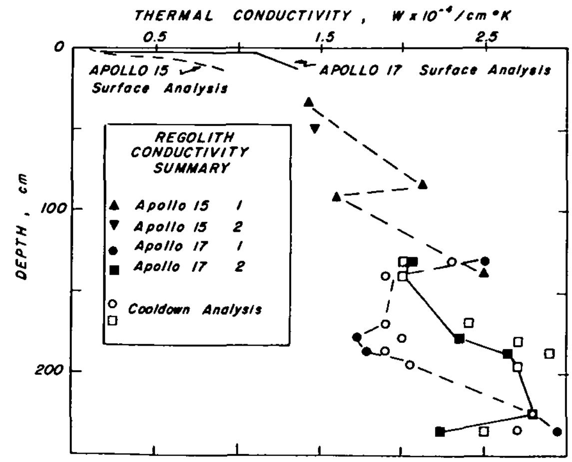

Figure 9.—*A summary of thermal conductivity determinations at the heat-flow site. At the top of the plot the lines are the same as in figure 4. Deeper points are results of in-situ measurements and analysis of probe cool-down data.*

due to a large increase in the soil compaction and grain boundary contacts with depth. It is likely that at this 2-cm depth the disruptive effects of micrometeorite bombardment give way to compactive effects. Conductivity values for regolith fines as high as 2×10^{-4} W/cm-K have not been duplicated in the laboratory, and further tests of highly compacted lunar soil should be made.

HEAT FLOW IN SITU

When the conductivity and gradient observations are combined, the heat-flow values shown in table 2 result. The best value of heat flow at the Hadley Rille site is 3.1×10^{-6}W/cm^2 and at Taurus-Littrow 2.8×10^{-6}W/cm^2.

Temperature measurements at probe 2 at the Apollo 17 site require special attention (see fig. 8). The profile indicates a very large decrease in gradient with depth at 130 cm which, because the conductivity is relatively uniform, must reflect a change in heat flow with depth. Also, the heat flow in the lower part of the hole, about 1.9 W/cm^2, is considerably lower than that at the other two locations. These results suggest that heat flow is locally disturbed, perhaps by a large rock buried very near where the probe is emplaced. The heat flow, using the temperatures at 67 and 234 cm, gives a heat flow of 2.5×10^{-6}W/cm^2, which is in reasonable agreement with the value at probe 1.

Possible Disturbance to the Heat Flow

How representative are the measurements of the average heat loss from the Moon? The answer to this question depends on whether there are significant regional and local disturbances. Certain disturbing effects, such as that of local topography, can be estimated and corrected for.

The amounts of radioisotopes in the crust may be anomalous in the region where the heat-flow observations are made. We have orbital data on the distribution of thorium and uranium on the surface that can be applied to this problem.

Table 2.—*Summary of Lunar Heat-Flow Results*

	Gradient K/m	Conductivity W x 10^{-4}/cm K	Heat Flow W x 10^{-6}/cm^2
Apollo 15			
Probe 1	1.75	1.78	3.1
Apollo 17			
Probe 1	1.36	2.06	2.8
Probe 2	1.30	2.00	2.5

NOTE: The estimated error of heat-flow determination is ±20 percent.

Other effects, such as thermal conductivity contrasts in the subsurface which can refract the heat-flow lines, are not directly observable, but geological observations can be used as a guide for assuming subsurface conductivity geometries. From these assumptions an appreciation of whether the measurements are anomalous may be obtained.

TOPOGRAPHY

Significant disturbances of heat flow will occur in the vicinity of craters having a diameter-to-depth ratio of 6 or less. The dominant effect of such craters is to increase the heat flow just outside the crater rim due to the slightly higher mean temperature in the crater floor. In the upper part of figure 10 we show the heat-flow anomaly over a crater with a diameter-to-depth ratio of 6 as a function of radius. It can be seen that the anomaly decreases very rapidly with distance from the rim. By and large the astronauts were successful in setting up the experiment far from craters larger than 1 m in diameter. At the Apollo 17 site, topographic maps show three craters which we estimate have a combined effect that increases the heat flow by 0.3 W/cm². That is, a correction of about −10 percent should be applied to the Taurus-Littrow values for the effect of craters. At the Hadley Rille site there were no craters in the vicinity of the probes which would have a significant effect on the heat flow. Consequently, no correction has been applied.

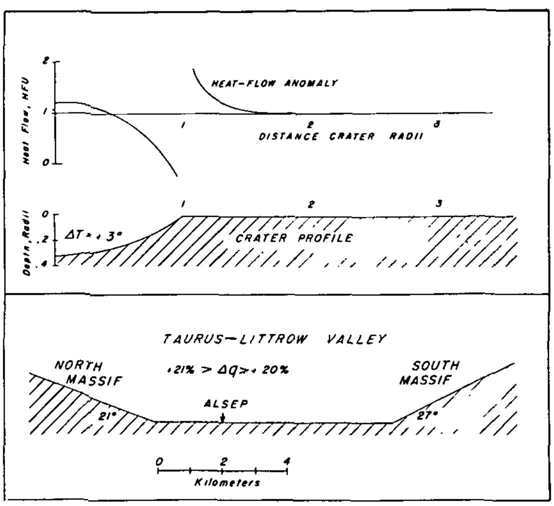

Figure 10.—*In the upper part of the figure, the heat-flow anomaly expected over a crater with an aspect ratio of 1.6. The lower part shows schematically a cross section of Taurus-Littrow and the estimated effect on the heat flow,* Δq.

At Hadley Rille both the rille and the Apennine Front will affect the heat flow, but in opposite ways. Both effects are on the order of 5 percent and, thus, appear to be self-cancelling. Therefore, it appears that the best value for the heat flow at Hadley Rille is the uncorrected value, 3.1×10^{-6}W/cm², with an estimated uncertainty of ± 20 percent.

The massifs that bound the Taurus-Littrow Valley on the north and south have a significant effect on the heat flow. We have estimated the correction to be applied using a method developed by Lachenbruch (ref. 6). The valley is modeled as shown at the bottom of figure 10. Based on this model, we estimate that a correction of −15 to −20 percent should be applied to the Apollo 17 measurement. Applying all corrections, the best value for heat flow in the Taurus-Littrow region is 2.2×10^{-6}W/cm², with an estimated uncertainty of ± 20 percent.

SURFACE RADIOACTIVITY

When topographic effects are taken into account, the heat flow at Taurus-Littrow is 25 to 30 percent lower than at Hadley Rille. The results of the orbiting gamma-ray experiment reported by Metzger (ref. 7) gave evidence of substantial variations in radioactive elements on the surface. One of the regions with the highest concentrations in radioactivity is the Hadley Rille area of Mare Imbrium. There the counts per second are about twice those at Taurus-Littrow and three to four times those observed over much of the lunar farside. The difference in heat flow between these two sites may therefore reflect a real variation in radioactive heat production in the lunar crust. A similar correlation between surface heat flow and radioactive heat production of surface rocks is observed on the Earth. A most significant implication is that two in-situ measurements may overestimate global heat flow, especially if the results of the gamma-ray experiment over the farside and nearside highlands are representative, since the observed concentrations of radioactive isotopes are much lower there.

POSSIBLE SUBSURFACE EFFECTS

Both sites where the heat-flow experiments were installed are at the margins of large mascon basins. These basins have been flooded by basaltic lavas early in the Moon's history. As a result, it is possible that a conductivity contrast exists between the mare basalt and the underlying basin floor and adjacent highlands. It is not likely that the bulk conductivity of the basalt will be as high as that measured on returned solid samples. The active seismic experiments by Kovach and Watkins (ref. 8) indicate that these flows are highly fractured. Extensive fracturing of rocks in vacuum will decrease their conductivity appreciably. It may be possible to entertain a conductivity contrast of mare fill material to underlying basin floor material of 10.

Our observations, located at the margin of basins, may see an edge effect as a consequence of this contrast. If they lie within the basin as the Apollo 15 site appears to, an edge effect heat-flow anomaly would add to the observed heat flow. If, on the other hand, the observation is outside the basin rim as might be the case at Taurus-Littrow, the observed heat flow would be disturbed toward lower values. Uncertainties do not at this time permit an accurate assessment of disturbance due to buried contacts between rocks of different thermal conductivity. The best estimate of the size of such an effect is by comparison with other estimates of heat flow from the Moon; e.g., those made from Earth-based microwave measurements.

Comparison With Earth-Based Microwave Measurements

To compare our measurements with microwave measurements, we return to the set of measurements of lunar brightness temperature between 3 and 70 cm made by Troitsky and colleagues. Waves from 5 to 20 cm are emitted from depths comparable to those measured by the heat-flow experiment. We will compare the spectral gradient in this band of wavelengths with that expected from a lunar surface layer, having the temperatures and thermal properties we measured in situ. The greatest uncertainty in such a comparison is the value of the power absorption length, l_e, of electromagnetic waves. In figure 11 we show the microwave data compared with theoretical results using different absorption lengths. The model has the parameters given in the table at the top of the figure. The lowermost curve has a power absorption length that is a function of λ, i.e., $l_e = 5.8\ \gamma^{1.48}$, which is an empiri-

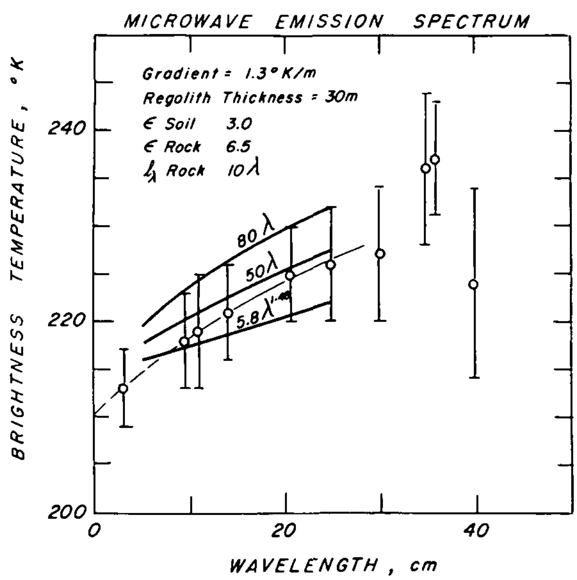

Figure 11.—*The data shown in figure 1, compared with theoretical emission spectra based on the thermal properties models at the Apollo 15 site. Three different relations between absorption length and wavelength were used and are noted on the curves.*

cal fit to the experimental results. This relation produces a good fit to radiotelescopic observations of the attenuation of the variations of microwaves over a monthly period in the range from 1 mm to 3.2 cm. The result is an increase in brightness temperature that fits within the error bars but is a poor fit to the observed spectral gradient. The temperature gradient in the lunar surface layer would have to be larger to better fit the microwave data using this relation. The middle curve corresponds to an l_e of 50λ, which is near the mean of values reported by Gold et al. (ref. 9), based on measurements of lunar samples at a wavelength of 68 cm. The best fit to the spectral gradient would be obtained for an l_e of 80λ. The principal result of this comparison at this point in our knowledge is that gradients of 1.3°C/m or higher, as observed in situ, are supported by microwave observations. The heat flows deduced by Tikhonova and Troitsky from 2.9×10^{-6} W/cm^2 to 4×10^{-6}W/cm^2 are in close agreement with our results.

Future Work

Several lines of future work can be proposed. First, more laboratory measurements of the electromagnetic power absorption length of lunar fines in the wave band from 5 to 20 cm would greatly improve the comparisons made above. Second, further Earth-based measurements of microwave emissions in the wavelength range from 5 to 30 cm would be extremely valuable. Measurements with sufficient resolution to detect variations in emission spectra over the lunar disk would be especially significant. Third, other in-situ measurements in highland regions, using an automated lander, would be extremely important. Finally, microwave observations from lunar orbit could possibly map heat flow variation over the entire Moon.

Acknowledgment

Columbia University's participation in the Lunar Heat-Flow Program was made possible through NASA contract NAS 9–6037. The experiment would not have been possible without the efforts of many people at the Bendix Aerospace Systems Division, Ann Arbor, Mich.; Arthur D. Little, Inc., Cambridge, Mass.; Martin Marietta Corporation, Denver, Colo.; Gulton Industries, Inc., Albuquerque, N. Mex.; and Rosemount Engineering Co., Minneapolis, Minn. The assistance of John Chute, Jr., and K. Peters in the analysis of the data is gratefully acknowledged. The drafting and manuscript were patiently done by A. Trefzer.

References

1. KROTIKOV, V. D., AND V. S. TROITSKY, Detecting Heat Flow From the Interior of the Moon. *Soviet Astron.*, Vol. 7, No. 6, 1964, pp. 822–826.
2. TIKHONOVA, T. V., AND V. S. TROITSKY, Effect of Heat From Within the Moon on its Radio Emission for the Case of Lunar Properties Which Vary With Depth. *Soviet Astron.*, Vol. 13, No. 1, 1969, pp. 120–128.
3. WESSELINK, A. F., Heat Conductivity and Nature of the Lunar Surface Material. *Bull. Astron. Inst. of Netherlands*, Vol. 10, 1948, p. 351.
4. JAEGER, J. C., The Surface Temperature of the Moon. *Australian J. Phys.*, Vol. 6, 1953, p. 10.
5. KEIHM, S. J., AND M. G. LANGSETH, JR., Surface Brightness Temperatures at the Apollo 17 Heat Flow Site: Thermal Conductivity of the Upper 15 cm of Regolith. *Proc. Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta*, Supplement 4, Vol. 3, 1973, pp. 2503–2513.
6. LACHENBRUCK, A. H., Rapid Estimate of the Topographic Disturbance to Surficial Thermal Gradients. *Rev. Geophys.*, Vol. 6, No. 3, 1968, pp. 365–400.
7. METZGER, A. E., J. I. TROMBKA, L. E. PETERSON, R. C. REEDY, AND J. R. ARNOLD, Lunar Surface Radioactivity: Preliminary Results of the Apollo 15 and Apollo 16 Gamma Ray Spectrometer Experiments. *Science*, Vol. 179, 1973, pp. 800–803.
8. KOVACH, R. L., AND J. S. WATKINS, The Velocity Structure of the Lunar Crust. *The Moon*, Vol. 7, 1973, pp. 63–75.
9. GOLD, T., E. BILSON, AND M. YERBURY, Grain Size Analysis and High-Frequency Electrical Properties of Apollo 15 and 16 Samples. *Lunar Science*, Vol. IV, Lunar Science Institute, Houston, 1973, pp. 293–295.