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Apollo 13 Lunar Heat Flow Experiment

Direct measurement of the heat escaping from the lunar interior will be made during Apollo 13.

M. G. Langseth, Jr., A. E. Wechsler, E. M. Drake, G. Simmons, S. P. Clark, Jr., and J. Chute, Jr.

On the Apollo 13 mission, the astronauts will set in place a heat flow experiment—part of the Apollo Lunar Surface Experiments Package (ALSEP)—to measure the steady-state heat flow through the lunar surface. This experiment will provide the first direct measurement of the rate at which the moon's interior is losing energy to outer space.

For planetary bodies as large as the earth and the moon, both energy retained from initial formation and energy generated by interior processes contribute to the net surface heat flow. The initial interior temperature distribution of these bodies is in part determined by the fraction of gravitational energy retained during accretion. Also, if the earth and moon were formed soon after the creation of the heavier elements, then the decay of short-lived isotopes could have contributed significantly to the initial temperature. The principal continuing process generating heat within planets is the decay of the long-lived radioisotopes of uranium, thorium, and potassium. Because of the smaller size of the moon, it is probable that it has lost a greater percentage of its initial heat than has the earth. Consequently, surface heat flow results from heat sources distributed throughout a greater percentage of the moon's volume than the earth's, and therefore could yield more information about the moon's internal constitution than terrestrial measures yield about the earth.

The limitations on equipment weight and astronaut extravehicular time demand that the heat flow measurement be made at shallow depths. The feasibility of making a valid measurement depends to a large extent on the rapid attenuation with depth of the extreme surface temperature variations. This rapid attenuation is due to the very low thermal diffusivity of the lunar regolith (*1*). Nevertheless, at practical measuring depths (3 meters) thermal gradients due to heat flow from the interior will be superimposed on a transient temperature field that includes significant contributions from other sources. Special temperature sensors and techniques for the measurement of thermal conductivity had to be developed to meet the stringent range, resolution, and stability required for an accurate measurement of the heat flux from the interior in the lunar surface layer.

The measurement of heat flow in the lunar soil consists of independent determination of the steady-state vertical temperature gradient

$$\frac{dT}{dz}$$

and the effective thermal conductivity K of the material across which the gradient is measured. The heat flux per unit area $\vec{Q}$ is related to these quantities by the conduction equation:

$$\vec{Q} = -K\frac{dT}{dz}$$

These measurements will be made with slender probes 1 meter long placed at the bottom of two 3-meter boreholes separated by about 10 meters (Fig. 1). An astronaut will make the boreholes by driving a fiberglass tube (2.5 centimeters in diameter) into the lunar surface with a drill (Fig. 2). These probes will be used to make two measurements of temperature gradient and four of thermal conductivity in each borehole. The purpose of making multiple measurements is to detect local subsurface

Drs. Langseth and Chute are research associates at Lamont-Doherty Geological Observatory of Columbia University. Drs. Wechsler and Drake are staff members of Arthur D. Little, Inc., Cambridge, Massachusetts. Dr. Simmons is a professor at Massachusetts Institute of Technology, and Dr. Clark is a professor at Yale University.

Table 1. Parameters of heat flow measurement. The probe has three operating modes. In mode 1, the normal operating mode, temperatures and temperature differences are monitored by sensors on both probes and in the probe cables. One complete set of measurements is made every 7.25 minutes. In mode 2, the mode for measuring thermal conductivity over the lower portion of the range of anticipated lunar values, a selected heater is energized at 0.002 watt, and temperature response of a concentric sensor is monitored at about 3-minute intervals. In mode 3, the mode for measuring thermal conductivity over the higher portion of the anticipated range of lunar values, a heater is energized at 0.5 watt, and temperature response is monitored at 1-minute intervals at a sensor 10 centimeters away.

Parameter	Temperature difference (°K)*	Absolute temperature (°K)	Thermal conductivity
	Lower 1 meter of borehole		
Range	± 2 and ± 20	200 to 250	2×10^{-6} to 4×10^{-3} watt/cm°K
Accuracy	± 0.002 and 0.020	± 0.1	20%
	Upper 2 meters of borehole		
Range		90 to 350	
Accuracy		± 1	

* The experiment measures temperature difference at two sensitivities with a ratio of 10 to 1.

inhomogeneities and to monitor thermal transients propagating downward from the surface.

Conductivity measurements will be completed during the first 45 days of operation, whereas temperature-gradient measurements will be made at frequent intervals for a period of at least 1 year.

The Temperature and Physical Properties of the Regolith

Since the lunar surface debris layer plays such an important role in this experiment, it is pertinent to review briefly our knowledge of its surface temperature and physical characteristics. The surface temperature varies from 90°K just before lunar dawn to nearly 400°K at lunar noon, and the average temperature is probably in the range 210° to 240°K (*2*). This diurnal cycle is modulated by an annual variation of about 2°K that results from the eccentricity of the earth-moon orbit about the sun. These variations propagate into the subsurface but are attenuated exponentially with depth. In a homogeneous material the sinusoidal components of temperature variations decrease as $T_0 \exp(-\beta z)$, where T_0 is the amplitude of the sinusoidal component at the surface and z is the depth. The coefficient β is equal to $\sqrt{\pi/\alpha P}$, where α is the diffusivity and P is the period. The maximum subsurface heat flows induced by the diurnal and the annual cycles of temperature as a function of conductivity at depths 1, 2, and 3 meters below the surface are shown in Fig. 3, where they are compared with the expected range of heat flow from the moon's interior. To calculate the values plotted in Fig. 3, we assumed the subsurface to be homogeneous and heat flow to be by conduction only.

The rapid cooling of the lunar surface during an eclipse (*3*) was an early indication of the very low average thermal conductivity of the lunar surface material. This apparently low conductivity was the earliest evidence that the moon is extensively covered by a layer of fine rock powder, since laboratory measurements of evacuated powders gave values of conductivity in the right range, 10^{-5} to 10^{-4} watt per centimeter per Kelvin degree, to explain the data obtained during eclipse (*4*). Conductivity measurements made on an Apollo 11 lunar soil sample, with a density of 1.265 grams per cubic centimeter, gave a value of 1.71×10^{-5} watt/cm °K at 205°K (*5*).

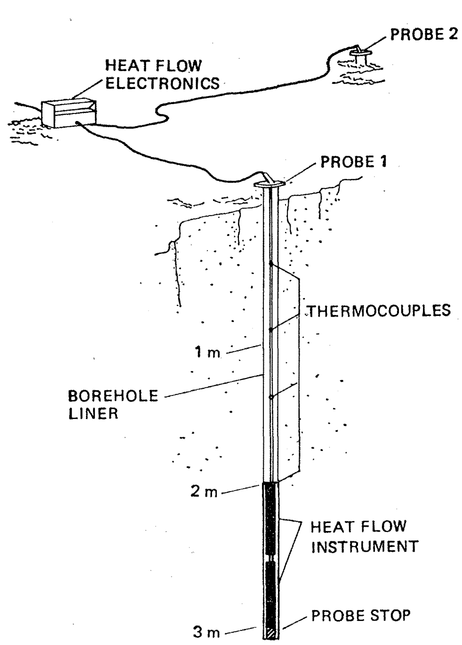

Fig. 1. The heat flow experiment as it may appear in the lunar surface.

The mechanical properties observed by the Surveyor and Apollo missions show that the compaction of the debris layer increases with depth in the upper several centimeters. This increase in density may be accompanied by an increase in conductivity. Fountain and West (*6*) showed a typical increase of conductivity by a factor of 3 for an increase in density from 0.8 to 1.5 grams per cubic centimeter. From these results we conservatively estimate the maximum possible value of conductivity for the fine regolith material in situ to be 10^{-3} watt/cm °K.

The site for the Apollo 13 landing is the Fra Mauro formation (at about 3° south latitude and 17° west longitude). This site is on a broad region of subdued topography just north of the large, flat-floored crater, Fra Mauro. This area has an average elevation slightly greater than that of the surrounding mare and is not easily classified as either highland or mare. It has many ridges and troughs aligned roughly north-south, which are thought to have been formed by the ejecta from the great impact that formed the circular Imbrium Basin (*7*). Local topography of the landing site is shown by Orbiter III photography at a scale down to 3 meters. The local thickness of the debris layer can be judged from the morphology of fresh craters and from the depth of craters where blocks of solid rock occur in the surrounding ejecta blanket. In the vicinity of the landing site there are several fresh craters; however, only craters larger than 100 meters in diameter and greater than 15 meters deep have blocks in the floor or on the surrounding ejecta blanket. The thickness of the regolith at the Fra Mauro site, based on this evidence, is apparently greater than 15 meters.

One of the difficulties in interpreting heat flow measurements in the shallow lunar subsurface is the effect that heterogeneity of the regolith has on the temperature field. The cratering process, which pulverizes and deepens the regolith, will lead to a highly irregular and fractured contact between the fine debris and the denser substratum. In addition, the more energetic impacts scatter fragments of denser rock onto the surface. Both the irregular interface between the regolith and substrate and large blocks of higher conductivity rock in the debris layer can produce large local distortions in the temperature field by refraction of the heat flow.

Heat Flow Experiment System

The major components of the experiment (Fig. 1) are the heat flow probes (*8*), the electronics (*9*), and the lunar surface drill (*10*). The electronics system that provides control, monitoring, and data processing of the experiment is contained in a separate, thermally controlled box on the lunar surface. The electronics package is connected to the ALSEP central station which provides power for the experiment and transmits the data to earth. The heat flow experiment measurement parameters are listed in Table 1.

Heat Flow Probes

Each heat flow probe consists of two identical measuring sections, 50 centimeters long (Fig. 4), each of which contains a "gradient" sensor bridge, a "ring" sensor bridge, and two heaters. These bridges are mounted in a thin-walled filament-wound epoxy fiberglass cylindrical shell designed for both mechanical strength and low thermal conductance. The gradient bridges provide the primary measurements of temperature and temperature difference (*11*). Each bridge consists of four platinum resistors of approximately 500 ohms (Fig. 5A; R_1, R_2, R_3, and R_4). Adjacent arms of the bridge are located in sensors at opposite ends of the 50-centimeter epoxy fiberglass probe sheath; consequently, output of the gradient bridge is a measure of the temperature difference between the two sensor locations. Bridge resistance is a measure of the average temperature of the two gradient sensors.

The ring bridges, designed for temperature difference measurements about 10 centimeters from the heaters, are also comprised of four 500-ohm platinum resistors and are used in thermal conductivity experiments. These sensors are smaller and lighter than the gradient sensors, but their wiring arrangement is identical. In addition to measurement of thermal conductivity, these bridges can provide auxiliary measurements of temperature differences.

Gradient and ring bridges were randomly selected during manufacture and were calibrated bimonthly for a period of 1 year to establish their stability. The rates of drift of three gradient bridges proved to be less than 0.001°K per year. The maximum drift of two ring bridges was 0.026°K per year; however, the sensitivity, which must remain stable to permit accurate short-term temperature measurements for the conductivity experiment, varied by only 0.02 percent during the year. To achieve this stability, special techniques were developed to mount the platinum elements so that they are free of strain.

The gradient bridges were calibrated at 42 points and the ring bridges at 14 points throughout their operating range to achieve the desired temperature and temperature difference accuracy and resolution with standards traceable to those of the National Bureau of Standards. The standard deviation for the total number of calibration points on all bridges was about 0.0004°K—very much within the required accuracy.

A cable 10 meters long connects each probe to the electronics system. Four calibrated Chromel-constantan thermocouples are located in the cable at distances of 0, 65, 115, and 165 centimeters, respectively, from the top of the probe. The reference junction of the thermocouple is embedded in an isothermal block located in the electronics box. The temperature of the reference junction is measured with a resistance bridge consisting of two platinum elements and two elements with temperature coefficients of zero. When the probe is emplaced, the thermocouples will be in the upper portion of the borehole (see Fig. 1) and will be used to measure temperature transients propagating downward from the lunar surface.

Each bridge is energized with bipolar excitation pulse of 8 volts which lasts 2.6 milliseconds. The short duration of this pulse limits self-heating of the platinum elements, and the bipolar technique eliminates errors due to offsetting

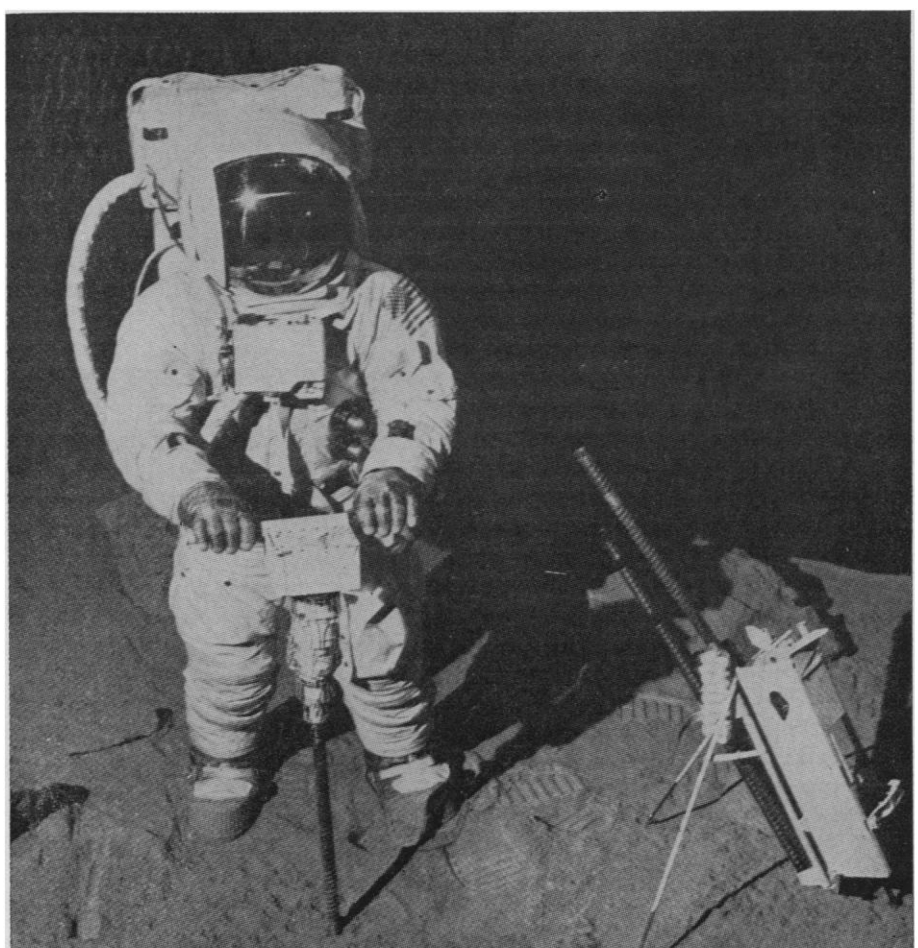

Fig. 2. The lunar surface drill during space-suited tests at the Martin Marietta Corporation. A ½-horsepower electric motor in the power head delivers rotary and percussive energy to the drill stem. The motor is powered by silver-zinc batteries with a capacity of 300 watt-hours at 24 volts. The drill rod used to make the heat flow holes consists of interconnecting sections, each 50 centimeters long, of tubular fiberglass reinforced with boron filaments.

voltages. Furthermore, as the ratio of bridge-imbalance voltage to excitation voltage is used in interpretation of data, and each is measured sequentially with the same amplifier, any error due to changes in the amplifier gain is eliminated.

Determination of Thermal Conductivity

Three independent approaches will be used to determine thermal conductivity, and the accuracy of each depends on the thermal properties of the regolith. First, eight measurements of thermal conductivity in situ will be made by activating the heaters at the ends of each probe section. Second, thermal diffusivity will be determined from measurements of the attenuation and rate of propagation downward of the periodic variations of surface temperature. Lastly, as additional verification, subsurface samples from a nearby borehole will be returned to earth for laboratory measurements of thermal properties.

There are two types of in situ thermal conductivity experiments. For conductivities less than 5×10^{-4} watt/cm °K (the lower range of conductivity), the experiment will be performed by energizing a heater at a power level of 0.002 watt and monitoring temperature rise at the gradient sensor beneath the heater. The other gradient sensor in the bridge, 50 centimeters away and unaffected by the heater, will serve as a reference. The temperature rise at the gradient sensor is related to the thermal conductivity of the lunar surroundings, the ambient temperature, the conductance of the borehole casing, and the thermal coupling between the heater and the other probe components. The relation of the temperature rise at the gradient sensor to the conductivity of the surrounding lunar material is shown in Fig. 6A for an ambient temperature of 205°K at the bottom heater on the upper probe section.

For thermal conductivities greater than 2×10^{-4} watt/cm °K, a heater is energized at 0.5 watt, and temperature response is measured at the ring sensor located 10 centimeters away. After about 3 hours, transients related to heat-transfer effects in the probe become small, and the rate of change of ring sensor temperature is related to the thermal conductivity of the surrounding material (Fig. 6B).

Interpretation of Measurements in Terms of Local Heat Flow

Although the probes and casing are designed to have low thermal conductance, the emplaced equipment will cause some shunting of the heat flux in the low-conductivity regolith. An extensive test program was conducted to relate measurements of temperature differences by the probes to a known gradient along an aluminum tube. The combined effects of the high thermal resistance of the radiation gap between the probe and the aluminum tube and the shunting of the probe body cause the measured difference to be about 4 to 7 percent lower than that over the adjacent section of the aluminum tube. The results of these tests were used to relate temperature difference, ΔT_{probe}, measured with the gradient bridges to temperature difference, ΔT_{tube}, along the aluminum tube by a relation of the form:

$$\frac{\Delta T_{\text{probe}}}{\Delta T_{\text{tube}}} = A + BT$$

where T is the ambient temperature. Typical values are $A \cong 0.9$ and $B \cong 0.0003 °\text{K}^{-1}$. These results may be used

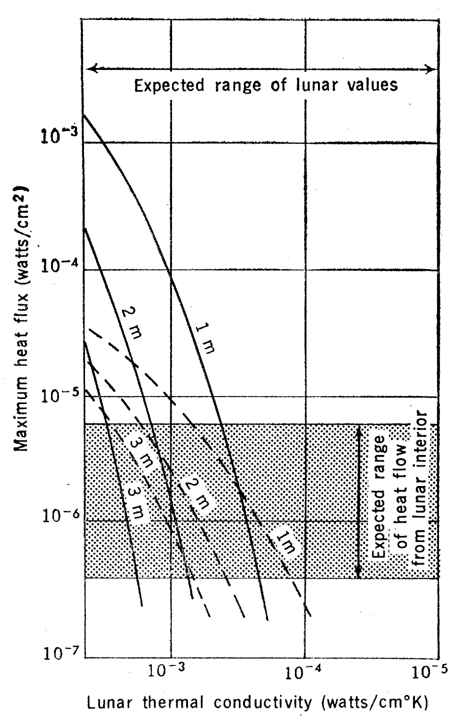

Fig. 3. The maximum amplitude of the periodic heat flow induced by the lunation and annual cycle at 1, 2, and 3 meters below the surface of the regolith is shown as a function of thermal conductivity. Solid line, diurnal wave (first harmonic); dashed line, annual wave. Numbers on curves represent depth below surface.

to interpret measurements of temperature differences by the bridges on the moon in terms of the temperature gradients along the borehole.

The shunting effect of the borehole casing will depend on the conductivity of the lunar material. For lunar regolith conductivities of the order of 10^{-5} watt/cm °K the ratio of casing to soil conductivities is about 100. However, the ratio length to diameter of the casing is also about 100, so that, even for this large contrast in conductivity, the shunting effect reduces the gradient by only a few percent.

Temperature distributions measured with the heat flow probes represent a summation of many effects. To detect the desired lunar heat flow component, we must identify precisely all other components of equivalent or greater magnitude associated with both the thermal flux in the undisturbed lunar surface layer and the thermal perturbations introduced by emplacement of the instrument.

Because of the periodicity of the diurnal and annual thermal waves that propagate downward through the surface layer, their effects can be identified and eliminated from the data either analytically or by averaging over a complete cycle. The thermocouples in the upper 2 meters of the borehole provide information on attenuation and phase shift of the thermal waves, which in turn indicates the thermal diffusivity of the upper surface material. The 1-year observation period will allow detection of all major subsurface transients.

Local variation of thermal flux may arise from the presence of isolated rocks either in the shallow subsurface or on the surface near the experiment site, from lateral thermal conductivity variations, from surface topography, and from variations of absorptance and emittance over the lunar surface. The distortions due to surface effects can be estimated from photographs of the location. Subsurface effects can be evaluated only by the spatial sampling provided by the two separate probes and multiple sensing points along each probe.

Flux transients are introduced by heat generated during drilling and by subsequent equilibration of the probe and casing to local temperatures. These transients may either be identified and described analytically or be allowed to decay before [accurate] measurement of heat flow is initiated. Components of

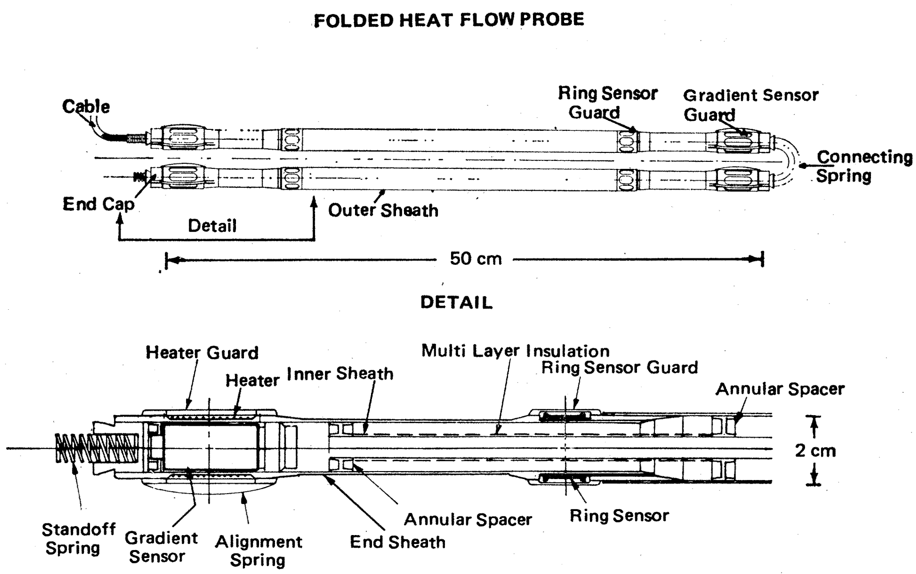

Fig. 4. (Top) The heat flow probe, which consists of two tandem 50-centimeter sections, is shown with the sections folded as they are in their flight package. (Bottom) A detailed drawing of one end of a probe section shows the arrangement of sensors and heaters.

flux due to alteration of the heat balance at the lunar surface caused by disturbance of the thermal parameters of the surface material may be more troublesome. Local alteration of absorptance, emittance, and possibly thermal conductivity around the top of the borehole by footprints or debris will slightly modify the average surface temperature of the disturbed area, which will result in a downward-propagating temperature wave that will eventually sweep past the probe. This transient wave may be identified as it moves past the thermocouples and bridges. Only if the lunar surface material has a relatively high conductivity will this transient reach the lowest meter of the hole during the yearlong observation period.

Is a Single Measurement Representative?

A successful experiment will yield a measurement of the local steady-state heat flow from the subsurface below the Fra Mauro formation. We must then determine whether the value is representative of the moon's average heat flow. This question cannot be answered definitely until we have a few measurements from other locations on the moon to determine the variability of surface heat flow.

On earth the surface heat flow varies by two orders of magnitude (*12*), but it is now clear that the heat flow differs greatly from the mean value, about 6×10^{-6} watt per square centimeter, only in tectonically active regions. Far from these regions heat flow values are nearly encompassed by the range 3.7×10^{-6} to 9.0×10^{-6} watt per square centimeter. These variations can be explained in terms of the movements of the earth's lithosphere (*13*) and variation of radioisotope abundance in the continental crust (*14*). On the moon the gross surface morphology is dominated by large impact craters and local volcanism with little evidence for currently active tectonic belts. The samples returned on Apollo 11 (*15*) indicate that some differentiation has occurred but that the radioisotopes have not been as intensively concentrated as on earth. Therefore, these two principal sources of variation of terrestrial heat flow are probably not significant on the moon.

One source of variation that may be significant on the moon is lateral change in thermal conductivity extending to several tens of kilometers. Compressibility measurements of Apollo 11 sample 10017 as a function of confining pressure indicate that it retains some porosity to pressures of about 2 kilobars (*16*). This behavior is attributed to the extreme dryness of the lunar rocks (*16*). On the moon pressures of 2 kilobars are reached at depths of 30 to 35 kilo-

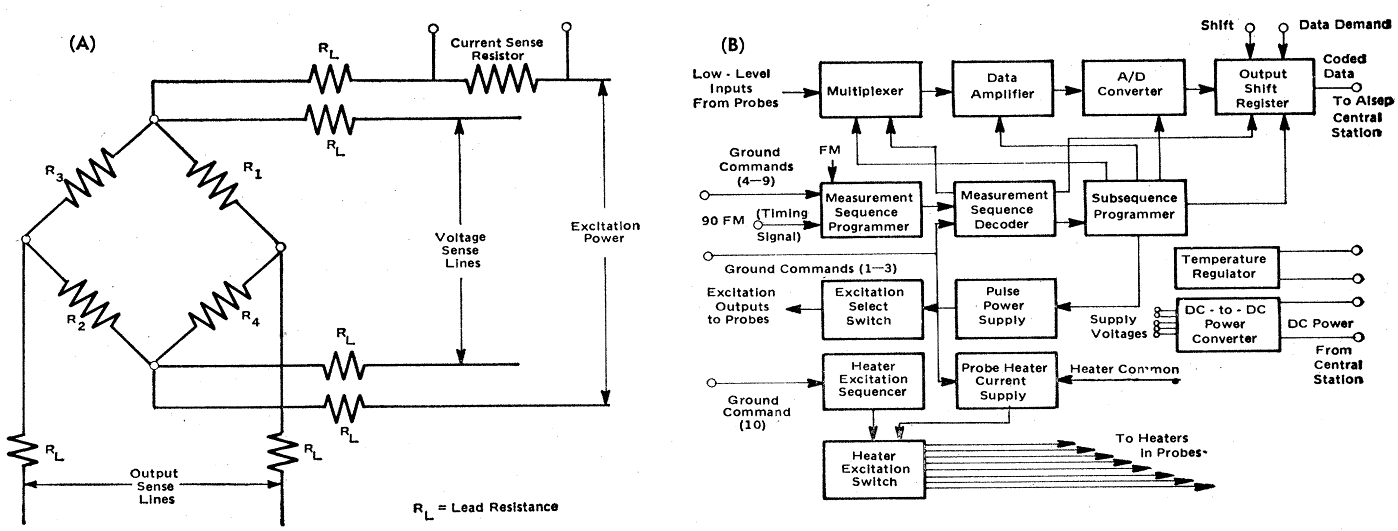

Fig. 5. Schematics of the heat flow experiment measurement system. (A) Configuration of gradient and ring sensor bridges. All bridge resistive elements are platinum wires that are interconnected with Evanohm wire. (B) Block diagram of the heat flow experiment electronics system. The circuitry is contained in a thermally controlled box on the lunar surface separate from the ALSEP central station.

meters. As thermal conductivity is related to porosity, significant conductivity contrasts may be expected at the margins of major topographic features. The effect of such contacts will be to produce a local distortion of the outward flow of heat near the boundary as an edge effect. Surface heat flow near such a boundary deviates significantly (> 20 percent) from the norm for the region only within 20 kilometers or less of the boundary (*17*).

Anticipated Lunar Heat Flow

Estimates of the surface heat flow from the moon, based on measurements of thermal radiation at microwave frequencies ($\lambda = 1$ to 168 centimeters), have been made with radio telescopes from earth. At these wavelengths the radiation in part emanates from the lunar subsurface, and limits may be established for the subsurface temperature gradients by estimating the thermal conductivity, electrical conductivity, and dielectric constant. Baldwin (*2*), using microwave data over a wide range of frequencies, determined the upper limit to the heat flow to be about 1×10^{-6} watt per square centimeter. Krotikov and Troitskii (*18*), using more accurate data at frequencies from 1.6 to 50 centimeters, estimated the flux density as 5.4×10^{-6} watt per square centimeter, which is nearly equal to the earth's heat flow.

Based on the low electrical conductivity required to explain the rapid diffusion times of the interplanetary magnetic field, Ness *et al.* (*19*) inferred that temperatures throughout the moon are below 1000°C. Hollweg (*20*) investigated the possibility that the interaction between the body of the moon and the magnetic field might be explained by an electrically insulating layer surrounding a more conductive interior. Hollweg's results indicate that a layer 100 to 1000 kilometers thick with conductivities in the range 10^{-6} to 10^{-5} per ohm-meter, a range typical of low-temperature silicates (*21*), could shield a hot, more conductive interior. Thus Ness's results do not preclude near-melting temperatures in the deep interior (deeper than 500 kilometers) but do dictate lower temperatures, < 1000°C, at lesser depths.

Temperature below the melting point in the outer 500 kilometers are also suggested by the finite strength exhibited by this upper layer. The departure of the figure of the moon from hydrostatic equilibrium and the instabilities resulting from mascons indicate that the near-surface layers of the moon support considerable stress. Such departures from equilibrium could be supported by dynamic processes; however, the lack of surface evidence for such processes dictates against them.

The evidence for high temperatures at relatively shallow depths comes from surface volcanism, in particular, the flooding of the mare basins and surrounding plains. Van Dorn (*22*) in an analysis of the Eastern Sea impact feature (Mare Orientale) argues that the event may have tapped reservoirs of partially fused material at a depth of 50 kilometers, thus resulting in local flooding of the concentric depressions as well as the central basin. Furthermore, chain craters, sinuous rills, and domes in the mare are apparently of volcanic origin. The principal dangers in inferring the depth of present isotherms from such evidence are that the volcanism may have taken place early in

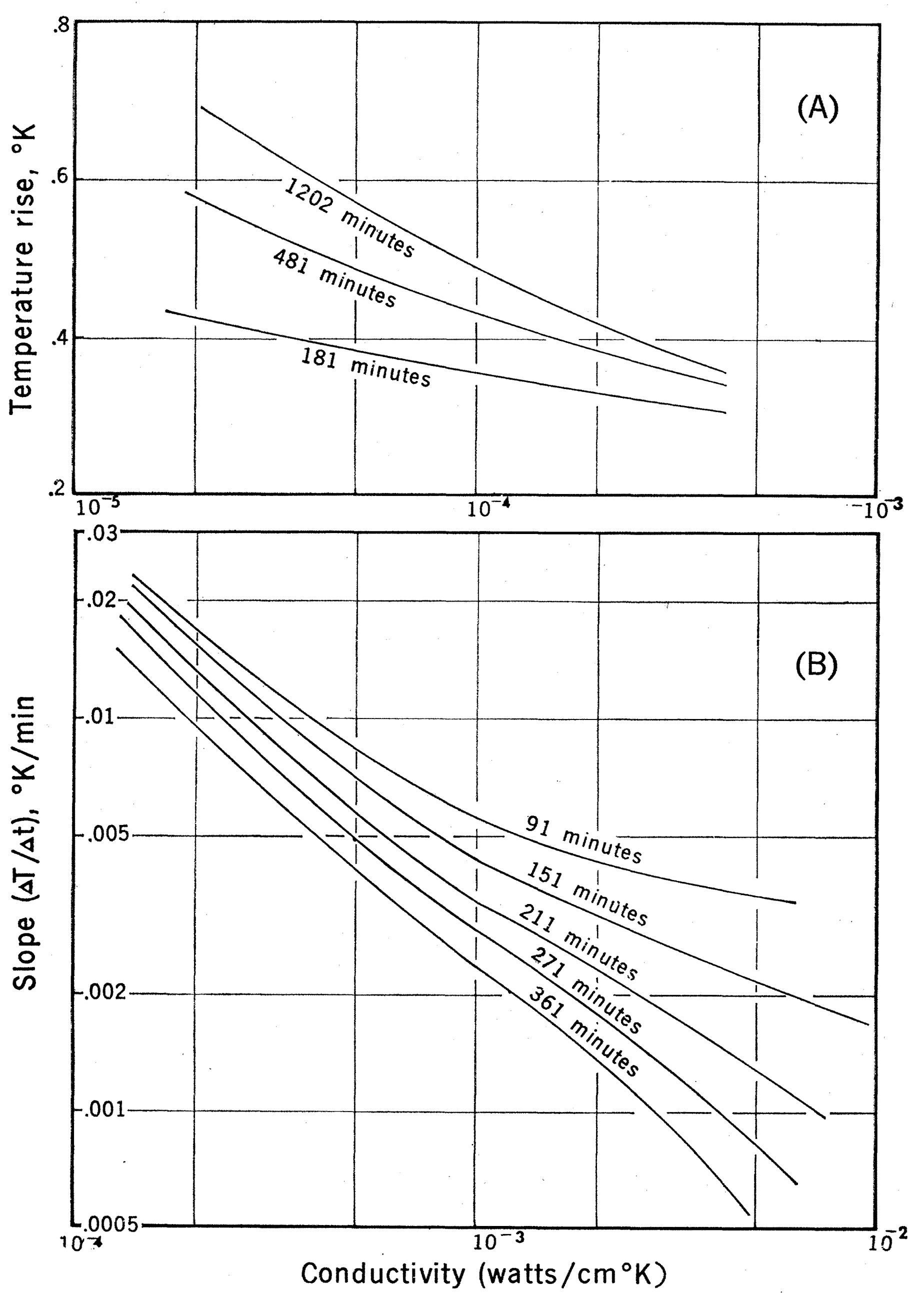

Fig. 6. The response of the gradient and "ring" sensors to energizing the heaters during the thermal conductivity experiments. (A) Temperature rise of the gradient sensor beneath a heater energized at 0.002 watt is graphed as a function of the conductivity of the surrounding material. Results are shown for three times after initiation. Low conductivity (mode 2); ambient temperature, 205°K. (B) Rate of temperature rise at a "ring" sensor 10 centimeters from a heater energized at 0.5 watt is graphed as a function of conductivity. Results are shown at five times after initiation. High conductivity (mode 3); ambient temperature, 225°K. The relations shown here are calculated on the basis of a very detailed finite difference model of the probe assembly in a borehole.

the moon's history and that the extrusives may have come from considerable depth.

The results of calculations of thermal history, that assume radiogenic heat production equivalent to that of chondritic meteorites, lead to temperatures in the range of 1000° to 1300°K at depths of 250 to 500 kilometers (*23*). The present surface heat flow indicated by these calculations is between 1.0 to 2.0×10^{-6} watt per square centimeter for a wide range of interior heat transfer mechanisms and initial temperature distributions.

The abundance of potassium relative to uranium in the Apollo 11 samples is much lower than in chondrites (*24*). In chondrites, potassium-40 contributes about 59 percent of the energy due to the decay of radioisotopes. If this low ratio of potassium to uranium is representative of the bulk composition of the moon, then the moon's surface heat flow may depend principally on the abundance of uranium. If the abundance of uranium is similar to that of chondrites (0.011 parts per million), the lunar heat flow could be substantially less than 1.0×10^{-6} watt per square centimeter. However, if the abundance of uranium is similar to that suggested (*25*) for the earth (0.033 parts per million), surface heat flow will probably be greater than 1.0×10^{-6} watt per square centimeter. If the concentration of uranium were 0.033 parts per million, melting of the interior at depths greater than 250 kilometers would be induced.

Summary

An experiment to make the first direct measurement of the lunar surface heat flow will be emplaced on the moon during the upcoming Apollo 13 mission. The measurement consists of making independent determinations of the vertical temperature gradient in the lunar surface, as a function of time, and of the thermal conductivity of the surrounding lunar soil. These data will provide a yearlong history of the heat flux through the upper 3 meters of the lunar subsurface. The balance of this heat budget will represent the steady-state loss of heat from the interior of the moon at the Apollo 13 site, Fra Mauro. The value of heat flow measured by this experiment will set constraints on the interior temperature and composition of the moon.

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26. The participation of M. G. Langseth, Jr., J. Chute, Jr., and G. Simmons is supported by NASA contract NAS 9-6037, that of S. P. Clark, Jr. is supported by NASA grant NGR-07-004-039. The Aerospace Division of the Bendix Corporation held the prime contract for development of the heat flow experiment. The authors acknowledge the contributions of many individuals at NASA Manned Spacecraft Center. Lamont-Doherty Geological Observatory contribution No. 1502.