(see Fig. 1), from which the travel-time curve of seismic waves can be predicted as shown in Fig. 2. In the Apollo 12 seismogram which recorded the impact of the ascent module, two distinct arrivals were detected (*7*); the first at 20.1 to 24.1 seconds and the second at 37.5 seconds after the origin time. The epicentral distance is 75.9 km. As is shown in Fig. 2, these arrival times agree remarkably well with the predicted P and S arrival times. Although the second arrival has not been confirmed as S, our proposed undifferentiated moon model is at least compatible with the seismic results. This agreement also suggests that the special textures (probably microcracks) of the samples also prevail at depths down to 20 km or so. These microcracks may have important bearings on the physical processes that have taken place on the lunar surface, and therefore deserve more extensive investigation.

If the samples 10020 and 10057 are representative of the lunar material, an efficient wave guide must exist near the lunar surface because of the sharp velocity increase with depth. Calculations of surface-wave dispersion curves made for the structure predicted from the velocity-pressure curve of the sample 10057 show a relatively constant group velocity (velocity, 1.57 km/sec) of Rayleigh waves over a period range 0 to 5 seconds. If future seismic experiments confirm this dispersion character, the evidence for an undifferentiated moon will be strengthened. If, on the other hand, significant deviation from the predicted dispersion curves is found, it will indicate the existence of structural heterogeneity at depths due to temperature, phase change, and compositional change.

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2. The bulk density of any of these rocks is the ratio of its mass to bulk volume. We also estimated the intrinsic density of sample 10057, which contains numerous voids. Assuming that the ratio of the total cross-section area of the voids on the surface to the total surface area of the sample is equal to the porosity, we obtained a porosity of 17.4 percent and intrinsic density of 3.38 g/cm^3. Sample 10020 has few visible voids; the intrinsic density probably does not exceed the bulk density by more than 10 percent.
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4. Full details on synthesis and other physical properties of the simulated Surveyor 5 rocks are to be reported elsewhere by Chung, Horai, Simmons, and Wones. The mineralogical composition of the simulated rocks closely approximates that of the Apollo 11 rocks. The composition (in mole percent) of the Apollo 11 rocks and the simulated rocks are, respectively, for plagioclase, 25 to 40 and 30 to 44; for pyroxene, 46 to 56 and 45 to 60; for olivine, 0.6 to 3 and none; for ilmenite, 10 to 17 and small; and for free silica, 5 to 11 and 6 to 10. The composition of the simulated rocks was based on the recent analysis of Surveyor 5 [see *Science* **165**, 277 (1969)] as well as analyses given for A-22 and B-50 (*5*).
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Infrared and Thermal Properties of Lunar Rock

Abstract. *The infrared absorption properties of lunar rock throughout the range 2 to 2000 micrometers were investigated and, in addition, direct measurements of specific heat and thermal conductivity of rock samples were made. The results suggest that pure radiation is an important, if not dominant, process in heat flow in the lunar surface layer. A new method for determining the mean conductivity of this layer gives somewhat lower values than earlier earth-based measurements. There is also evidence to suggest that, at depths of about 10 meters, the rock is still of a porous and fragmental nature.*

There is a strong connection between the infrared and thermal properties of the lunar surface layer. The infrared emissivity is a controlling factor on the rate at which heat leaves the moon's surface. It is also apparent that, within the regolith, a considerable fraction of heat transfer takes place by radiation rather than by conduction, and measurements of the particle size and infrared absorption in the 2- to 200-μm range now make determination of the relative efficiencies of the two processes possible. Similar measurements at longer wavelengths, together with microwave results from earth-based telescopes, now give the thermal conductivity of the lunar surface regolith. Previously the conductivity could be estimated only from measurements at 8 to 14 μm.

An increase of temperature with depth in the top few meters of the lunar surface is implied by the longer-wavelength ($\gtrsim$ 5 cm) earth-based microwave measurements; now that we have direct measurements of the thermal conductivity of the rock, the infrared and thermal measurements can be used to determine the actual thermal gradient in the layer and to compare this gradient with that predicted from internal radioactive heating.

Thermal sintering as well as mechanical shock may be involved in the formation of the breccia; continuous measurement of the thermal conductivity of a heated sample should be a means of watching the breccia formation process at an enhanced rate.

We describe here infrared and conductivity measurements now in progress. The infrared transmission throughout the range 2 to 2000 μm has been measured for the type D material with (i) double-beam spectrometers with Nernst sources and Golay detectors (range, 2 to 50 μm); (ii) Fourier transform spectrometer with a mercury source and Golay detector (range, 50 to 1000 μm); and (iii) grating spectrometer of the type described by Bloor *et al.* (*1*) with a mercury lamp source and Golay detector (range, 200 to 2000 μm).

In addition, a check at 1300 μm has been made with a 1.5-m Cassegrain telescope with the sun as source and an InSb photoconducting detector. A similar spot measurement at 338 μm is being made with a cyanogen laser with a Golay cell as a detector. The fines were compressed to a density of 1.8 g/cm^3. In each case we measured the attenuation or extinction coefficient μ defined by the equation

$$\frac{I_x}{I_0} = e^{-\mu\rho x} \qquad (1)$$

where I_x is the intensity after passage through a thickness (x) of material, I_0 is the incident intensity, and ρ is the sample density. Below 50 μm, measurements were also made with crushed fines in a transparent substrate, and, in this way, the coefficient of pure absorption K_λ was determined. Because of the tendency for the dust to shake down and form macroscopic cracks, the far infrared measurements were made with the powder spread evenly over a horizontal Mylar (melinex) window. These measurements will be described elsewhere (*2*).

Measurements of the thermal conductivity of types A (fine grained crystalline), C (breccia), and D (fines) materials are being made with a method in which a thermal step function is supplied to the sample by a straight electrically heated wire. In the case of the rock types A and C, comparison is being made with materials of known conductivity. From the diffusion equation for heat flow

$$\frac{\delta T}{\delta t} = \frac{k}{\rho c}\Delta^2 T \qquad (2)$$

which relates the temperature T to the specific heat c, thermal conductivity k, and density ρ, it is seen that, for systems of the same boundary conditions, the temperature at any point will only depend on $kt/\rho c$. These measurements will be described elsewhere (*3*).

We have also made measurements of specific heat and are, at present, measuring the Hall effect and electrical conductivity of samples. Since both the electrical and thermal conductivities are dependent on interparticle contacts, we have made a number of measurements of the shapes and distribution of sizes of particles of the type D material, and have examined its microcrystalline morphology using electron-microscope techniques.

The infrared absorption and scattering coefficients of the type D sample are shown in Fig. 1. In the middle infrared (5 to 50 μm), these measurements show features associated with the Si–O bond. At the longer submillimeter wavelengths the absorption coefficient of the fines varies very much more rapidly with wavelength than would be expected from an extrapolation of the microwave data obtained from earth-based telescopes in the millimeter wavelength region. At the long wavelength limit of our measurements there is an octave of overlap (1000 to 2000 μm) with the microwave measurements. The microwave results essentially give the parameter

$$\delta = \frac{1}{K_\lambda}\left(\frac{\omega c}{2\rho k}\right)^{1/2}$$

where K_λ is the absorption coefficient at wavelength λ, ω the angular frequency corresponding to the lunar diurnal period, c the specific heat, ρ the density of "average" lunar material, and k its thermal conductivity. Our measurement of K_λ of the fines at 1400 μm, together with previously obtained values of the microwave parameter (*4*), give a value of the conductivity $k = 2.5 \times 10^{-6}$ cal cm^{-1} °K^{-1} sec^{-1} for the lunar surface layer.

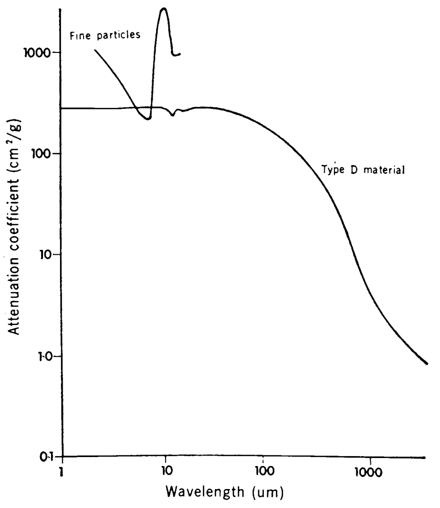

Fig. 1 (above). Absorption properties of type D material in the infrared range.

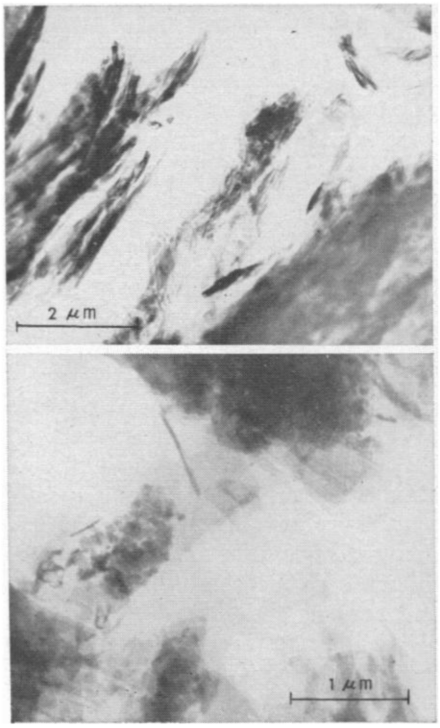

Fig. 2 (right). Electron micrographs of type D material.

Thermal measurements indicate a specific heat of 0.20 ± 0.02 cal g^{-1} °K^{-1} for the breccia (sample 10065). The thermal conductivity of the fines seems to be somewhat higher than that found by the indirect method just described. The conductivity is dependent on the degree of packing, and we are at present studying this effect. For the crystalline (type A) rock and the breccia, the conductivities have provisionally been found to be in the range 0.5 to 2.0 × 10^{-3} cal cm^{-1} °K^{-1} sec^{-1}, the conductivity of the breccia being lower than that of the type A material.

The electron micrographs, which were made to investigate interparticle contacts, suggest a predominance of lamellar crystals up to 500 Å thick (Fig. 2).

The mean conductivity of the lunar surface layer 2.5 × 10^{-6} cal cm^{-1} °K^{-1} sec^{-1} determined here is somewhat lower than that deduced from earth-based lunation measurements at 8 to 14 μm. The difference is most likely to be explained by the fact that the mean measured midnight temperatures are weighted strongly in favor of those areas with high thermal conductivity. This explanation is reinforced by the fact that the values of conductivity obtained from eclipse observations at 8 to 14 μm are in good agreement with our determination.

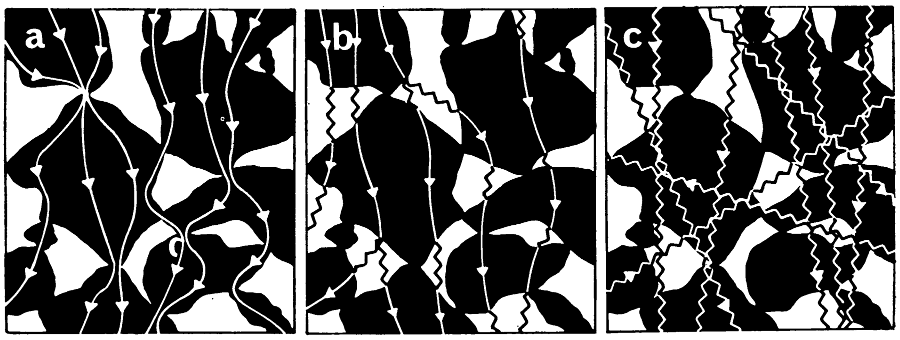

Fig. 3. Possible modes of heat transfer in type D material. (a) Pure conduction, (b) conduction-radiation, and (c) pure radiation. The curved line denotes the photon path. The solid line denotes the line of heat flow (normal to isothermal). ■ Solid material; □ void (vacuum).

In considering the heat flux coming from the lunar interior, our direct measurements of the thermal conductivity of the rock types A and C can be compared with the variation of mean disk temperature with wavelength (*5*, *6*). If we assume that the region from 1 to 20 m below the surface is composed of these rocks (A and C), then a heat flux of about 3 × 10^{-5} cal cm^{-2} sec^{-1} is implied—a result two orders of magnitude greater than that predicted by Jaeger (*7*) and MacDonald (*8*) from radioactive heating of chondritic material. This suggests that, even at depths of about 10 m, the lunar material has a mean thermal conductivity considerably lower than that of the solid samples we have investigated, and this in turn implies that, at these depths, the crust is still likely to be fragmental and porous.

The possible mechanisms for heat flow in the uppermost layer of the lunar surface fines are shown in Fig. 3. An analytic expression for the pure conduction process is possible only if the nature of the particle contacts is known, but expressions for the conduction-radiation (k_{rc}) and pure radiation (k_r) processes have been given by Troitski (*9*) and Clegg *et al.* (*10*)

$$k_{rc} = 4\,\sigma\alpha T^3 l\left(\frac{\varepsilon}{2-\varepsilon}\right) \qquad (4)$$

$$k_r = \frac{16}{3}\,\sigma\,\frac{T^3}{K(\overline{T})} \qquad (5)$$

where l is the mean spacing between particles, α the void ratio, σ Stefan's constant, ε the particle emissivity, and $K(\overline{T})$ the Rosseland mean absorption coefficient. From our measurements of absorption coefficients throughout the infrared wavelength region we can determine this mean absorption coefficient and the calculation shows that the pure radiation process is in general more effective than the conduction-radiation process. The spectroscopic results given in Fig. 1 demonstrate that the effects of scattering and reflection of the infrared radiation must also be considered in a model for heat transfer in the type D material. Since the breccia has a higher conductivity than the fines, it is clear that we cannot ignore the pure conduction process especially where the fines are well packed.

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Thermal Diffusivity and Conductivity of Lunar Material

Abstract. *The thermal diffusivity and conductivity of type C lunar samples returned by Apollo 11 are lower and less dependent on temperature than those of type A samples. The thermal properties of both types are lower than the corresponding properties of normal terrestrial rocks.*

The thermal diffusivity of four Apollo 11 lunar specimens, 10020, 10046, 10057, and 10065, with bulk densities 2.99, 2.21, 2.88, and 2.36 g/cm^3 respectively, was measured over the temperature range –130°C to +150°C by the modified Ångstrom method (*1*, *2*). All of these samples were rectangular prisms, 1 by 1 by 2 cm. The thermal diffusivity κ may be determined from either the phase lag or the amplitude decay with distance of a periodic temperature wave. Geometry B of Kanamori *et al.* (*2*), in which the temperature wave propagates through the specimen in the direction perpendicular to the long axis of the prism, was used. The d-c component of the temperature wave heated the samples about 100°C above the ambient temperature, which was controlled by either liquid nitrogen or solid carbon dioxide in order to obtain the desired sample temperature.

Results of the investigation are summarized in Fig. 1. The temperature variation of thermal diffusivity is almost identical for samples 10020 and 10057 and for samples 10046 and 10065, but is quite distinctive for each of the two groups. The difference is attributed to the differences in texture and the composition of the specimens. Samples 10020 and 10057 are fine-grained vesicular crystalline igneous rocks, type A according to the classification of the Preliminary Examination Team (*3*). Samples 10046 and 10065 are breccias (type C). The presence of microcracks, larger cracks, and glass in the type C samples is probably the cause of the lower thermal diffusivity and smaller temperature dependency.

In many solids, the reciprocal of thermal diffusivity varies almost linearly with temperature t. Coefficients of a linear relationship were determined by least-squares from our data. For type A

$$\kappa^{-1} = (0.314 \pm 0.159) \times 10^2 + (0.378 \pm 0.051)t$$

and for type C

$$\kappa^{-1} = (0.545 \pm 0.207) \times 10^2 + (0.648 \pm 0.068)t$$

where κ is in cm^2/sec and t in degrees K. These relationships are illustrated in Fig. 1.

In order to obtain the thermal conductivity, $K = \kappa\rho c_p$, and the thermal inertia $\gamma^{-1} = \sqrt{K\rho c_p}$ from the diffusivity, we calculated the heat capacity at 273°K, c_p, for samples 10020 and 10046 from the mineral composition (*4*) and the thermodynamical data on minerals (*5*). Taking the values of c_p as 0.174 cal/g °C for both samples 10020 and 10046, we find, for type A, $K = 3.87 \times 10^{-3}$ cal/cm sec °C and $\gamma = 22$ cm^2 $sec^{1/2}$ °C/cal and for type C, $K = 1.66 \times 10^{-3}$ cal/cm sec °C and $\gamma = 40$ cm^2 $sec^{1/2}$ °C/cal. These estimates of γ are substantially smaller than those obtained from infrared and passive microwave data on the lunar surface (*6*). It must be mentioned that the thermal diffusivity measurements reported here were made in air at atmospheric pressure. Under lunar surface conditions the materials with con-

Table 1. Attenuation of diurnal temperature variation of the moon with depth.

Amplitude °C	Depth (cm)	
	Type A*	Type C†
150	0	0
10	67	52
1	124	96
0.1	180	140

* $\kappa = 0.75 \times 10^{-3}$ cm^2/sec. † $\kappa = 0.45 \times 10^{-3}$ cm^2/sec.