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*)

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

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

where l is the mean spacing between particles, α the void ratio, σ Stefan's constant, ε the particle emissivity, and $K(\bar{T})$ 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

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

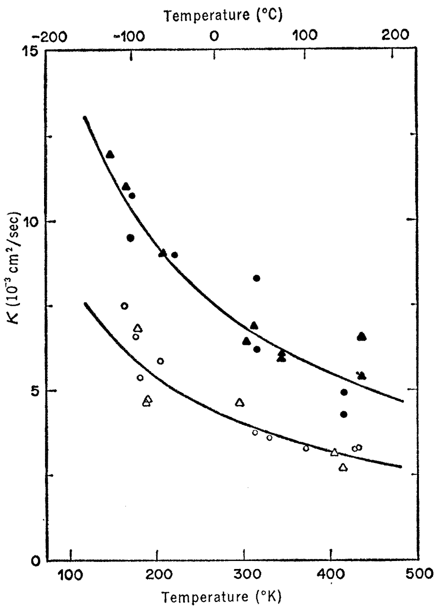

Fig. 1. Thermal diffusivity plotted against temperature for Apollo 11 lunar materials. Closed circles, sample 10020; closed triangles, 10057 (type A). Open circles, 10046; open triangles, 10065 (type C).

siderable porosity (*7*) should exhibit lower thermal diffusivities. An even lower thermal diffusivity is to be expected for the lunar soil, type D material.

The equatorial lunar surface temperature is known to vary about 150°C in amplitude with a period of 2.5×10^6 sec. The measurement of heat flow from the interior of the moon in a shallow borehole, nominally 3 m, expected on Apollo 13 (*8*) depends on a rapid decrease of amplitude of the diurnal wave. For lunar material with thermal diffusivities as high as those found for rocks in air in this investigation, 0.75 and 0.45×10^{-3} cm²/sec, corresponding respectively to the materials of type A and type C, the characteristic depths (*9*) for the diurnal wave are 120 and 155 cm. In Table 1, the depths below the flat lunar surface at which the amplitude of the diurnal variation of temperature, 150°C, becomes 10°C, 1°C, and 0.1°C are shown. Almost surely our values may be taken as upper limits for the diffusivity of lunar surface material, and a reliable thermal gradient for heat-flow determination may be measured in a 3-m hole. However, the presence of boulders scattered through the lunar soil of very low diffusivity may prove to be troublesome.

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7. Porosity of sample 10057, obtained from the point count of cavities on the surfaces of the sample, is 0.174. (see H. Kanamori, A Nur, O. Chung, D. Wones, G. Simmons, *Science*, this issue.)
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9. The characteristic depth given by $2\pi/\sqrt{\omega/2\kappa}$ is the distance at which the amplitude of a periodic temperature variation with frequency ω is reduced by a factor of $\exp(-2\pi) = 0.0019$.

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Compressibilities of Lunar Crystalline Rock, Microbreccia, and Fines to 40 Kilobars

Abstract. *The compressibilities of three lunar samples were studied at room temperature from 0 to 40 kilobars. The samples were a fine-grained vesicular crystalline rock (type A), a microbreccia (type C), and fines (type D). All samples were porous. The microbreccia and fines were quite compressible at all pressures; the compressibility of the crystalline rock was somewhat less, being 8.4 megabar⁻¹ at 1 atmosphere and 1.5 megabar⁻¹ at 35 kilobars. Some porosity appeared to remain in the samples at all pressures. Thus the pressure-volume data derived from these samples may be representative of porous surface and near-surface material in the vicinity of the Apollo 11 landing site but may not be representative of lunar material at depth.*

The pressure-volume properties of three lunar materials were studied to 40 kb at room temperature. These materials were sample 10017,69, a fine-grained vesicular crystalline rock (type A): sample 10048,52, a microbreccia (type C), and sample 10084,78, fines (type D). The method consisted of measuring bulk volume changes under nearly hydrostatic pressure (*1*). If any of the samples can be considered to be representative of lunar material at depth, the pressure-volume data will be useful in calculating lunar density as a function of radius. The data can also be used to perform numerical calculations of meteoritic impact processes. Finally, they provide basic information on the lunar surface material such as compressibility and porosity, and qualita-

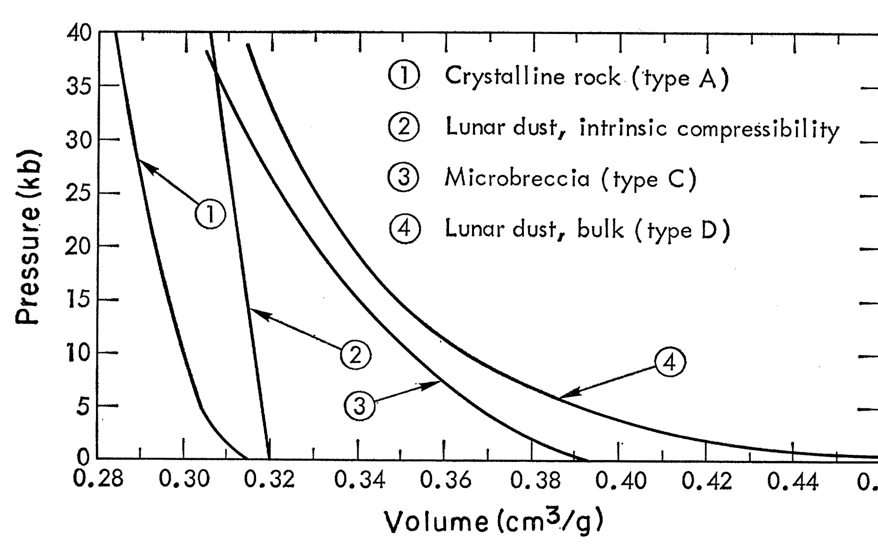

Fig. 1. Pressure versus specific volume for lunar materials.