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Thermal Properties of a Simulated Lunar Material in Air and in Vacuum

E. C. Bernett,* H. L. Wood,† L. D. Jaffe,‡ and H. E. Martens§

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif.

The thermal diffusivity and thermal conductivity for a crushed olivine basalt were determined from transient state data. Values were obtained over a temperature range of $-100°$ to $200°C$ in vacuums of 5×10^{-3} and 5×10^{-6} mm Hg as well as at atmospheric pressure. A -150 mesh material at a density of 1.14 g/cm³ had a thermal conductivity of 3.9×10^{-6} cal/cm-sec-°C at $100°C$ when measured in a vacuum of 5×10^{-6} mm Hg. This was approximately 100 times lower than the values obtained for the same material measured at atmospheric pressure. Increasing the density to 1.57 g/cm³ increased the thermal conductivity by approximately 60% in both air and vacuum. Over the range studied, the test temperature had very little effect on thermal conductivity in air but showed more of an effect when the material was placed in a vacuum.

I. Introduction

IN preparation for manned landings on the moon, research aimed at determining the physical and mechanical properties of the postulated lunar surface is now in progress. There have been extensive astronomical studies of the moon and its surface; on the basis of these, it is proposed that the moon is composed of igneous rocks similar to certain types that are found on earth. Some measurements,[1-3] however, indicate that the thermal conductivity of the lunar surface is extremely low—much lower than that of any known types of consolidated rock. To account for this, it is postulated that large portions of the lunar surface are covered with a highly porous material, probably powdery and perhaps lightly sintered.

The investigation described here is one part of a program designed to evaluate the properties of a powdered rock simulating the postulated lunar surface material. Its purpose was to measure the effects of vacuum on the thermal diffusivity and conductivity of rock powder.

II. Materials Tested

The material used in the initial runs, which were designed to check equipment operation, was a 70-mesh commercial grade 99% silica foundry sand. The particle size distribution of this material is shown in Fig. 1. The moisture content was less than 0.03%.

The material selected to simulate lunar material for this study was an olivine basalt collected from Pisgah Crater, San Bernardino County, Calif. The large volcanic bombs were crushed to about 3-in. size using a hydraulic press. Any pieces that appeared to be contaminated or that showed signs of weathering were discarded. The remaining material was passed through a Gates jaw crusher and a stainless-steel hammer mill-type pulverizer to reduce it all to -35 mesh material. A detailed mineralogical description of this material and the crushing procedure is given in Ref. 4.

Most of the -35 mesh material was screened into more closely sized fractions: nominally $-35 +48$, $-48 +65$, $-65 +100$, $-100 +150$, and -150 mesh. Actual screen analyses of the fractions used for the thermal conductivity tests are shown in Fig. 1.

The "as-received" density of the rock as measured by water displacement was 2.83 g/cm³ at 24°C. The density of the crushed material was 2.97 g/cm³. All of the screened fractions were stored in closed containers. Measurements made during the program showed that actual moisture content varied from day to day but always was less than 0.1%.
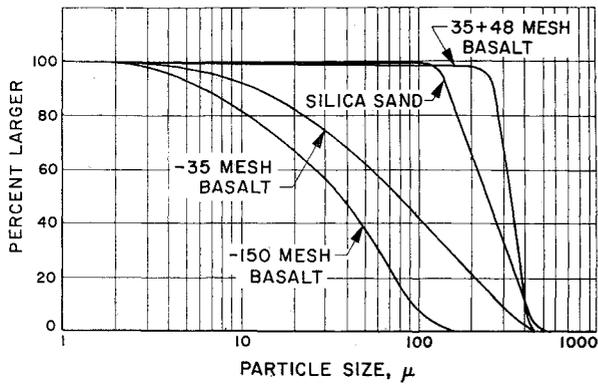
Fig. 1   Particle size distribution of materials tested

III.   Test Apparatus and Experimental Procedure

It was expected that very low thermal conductivity values would be obtained for the loosely packed materials in vacuum; thus, conventional equipment could not be used for these measurements, and a special apparatus was designed and built.

A general view of the equipment used is presented in Fig. 2; details of the specimen holder configuration are shown in Fig. 3. This apparatus was designed to measure the rate of change of the temperature at points along a diameter of a cylindrical specimen caused by a sudden stepped change in the outer surface temperature. To minimize errors due to heat conduction along the temperature sensors, very thin (0.003-in.-diam) unshielded chromel-alumel thermocouples were strung lengthwise through the specimen holder (Fig. 3). One couple was located on the centerline, two at midradius, and two at the outer surface of the specimen which was also the inner wall of the cylindrical specimen holder. A 1500-w hermetically sealed heating coil and a copper cooling coil
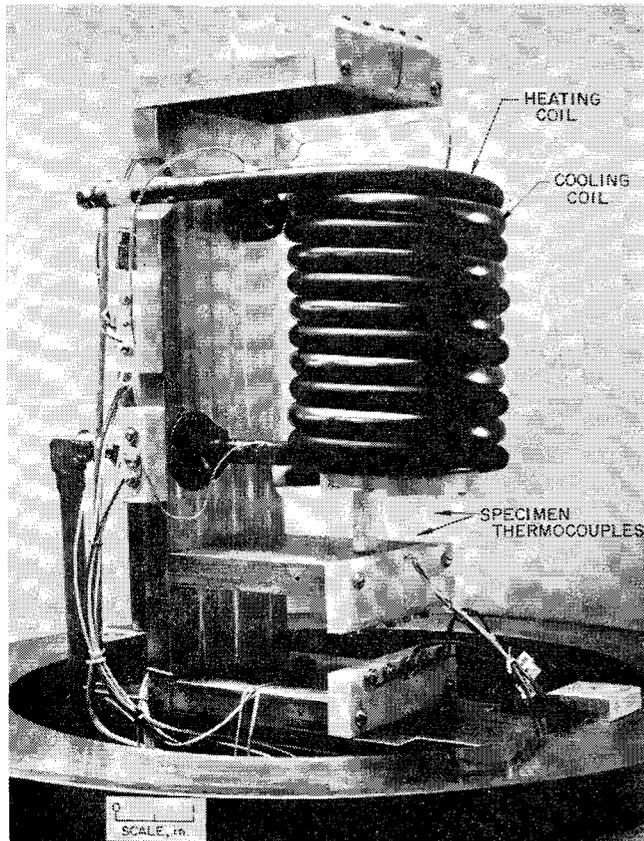
were interwound on the outside of the specimen holder. A two-piece polytetrafluoroethylene closure was provided for the bottom of the holder. To increase thermal resistance between the thermocouples and the copper specimen holder, the bottom closure was designed so that it made only a line contact with the copper holder and also with the thermocouples.

A similar closure was used as a top cover during some of the preliminary runs with the thought that it would reduce radiation losses from the upper surface of the test specimen. However, it was determined that the measured diffusivities were not affected by the presence of such a cover; so, during all subsequent runs, the cover was not used, thus allowing visual observation of the surface of the specimen during the entire test.

The holder assembly and the supporting structure were attached to a double-flanged spacer that contained the vacuum leadthroughs for the thermocouples, heater cables, and liquid-nitrogen supply lines. The vacuum system consisted of a 12-in. glass jar, a liquid-nitrogen-trapped 4-in. oil diffusion pump (210 liters/sec pumping speed at 8×10^{-4} mm Hg), and a 13.3-cfm mechanical pump. Pressures on the order of 5×10^{-6} mm Hg could be reached in about 2 hr and maintained for the duration of the test run.

Earlier studies of a similar material had indicated that the packing density had a very significant effect upon the properties.[4] Thus, it was necessary to use extreme care in loading test materials into the specimen holder so that packing density could be known and controlled. To accomplish this, a known weight of the test material was loaded into the specimen holder for each run. When it was desired to conduct the experiment with a low packing density, the mate-
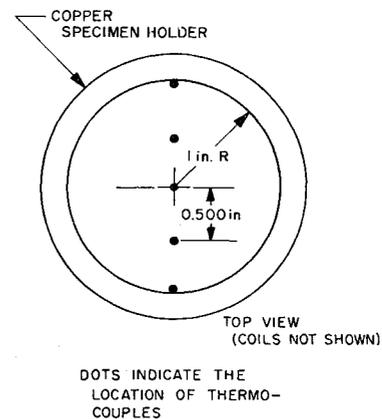
Fig. 2   Thermal diffusivity test equipment
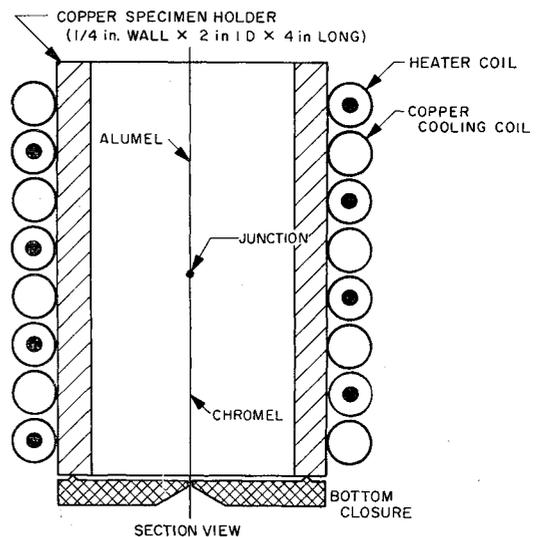
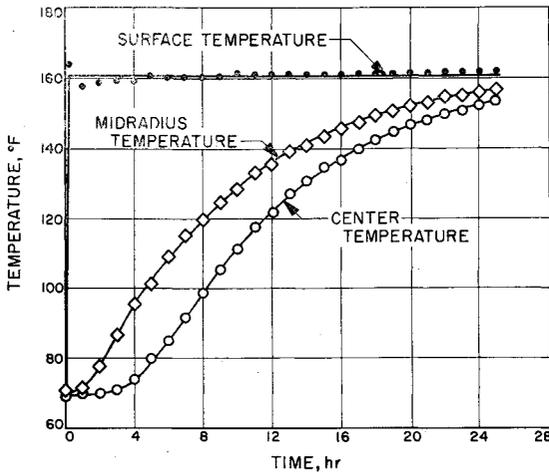

Fig. 3   Details of specimen holder

Fig. 4　Temperature vs time for vacuum test 9-11 (olivine basalt −35 +48 mesh at a density of 97 lb/ft³)

rial was carefully spooned into the holder and every precaution taken to prevent the holder from being bumped or vibrated. The height of the material in the holder was recorded and observed during the entire test to assure that vacuum-pump vibration or other external causes did not produce a significant change in the packing density. When it was desired to conduct the experiment with a high packing density, the material was loaded in the holder, which was then tapped with a soft hammer until no further decrease in height of the material in the holder could be noted. Again this height was recorded and observed during the entire test to assure that degassing during evacuation did not change the surface level of the test material significantly.

After loading, the temperature of each thermocouple was read to insure that the entire unit was thermally stabilized.
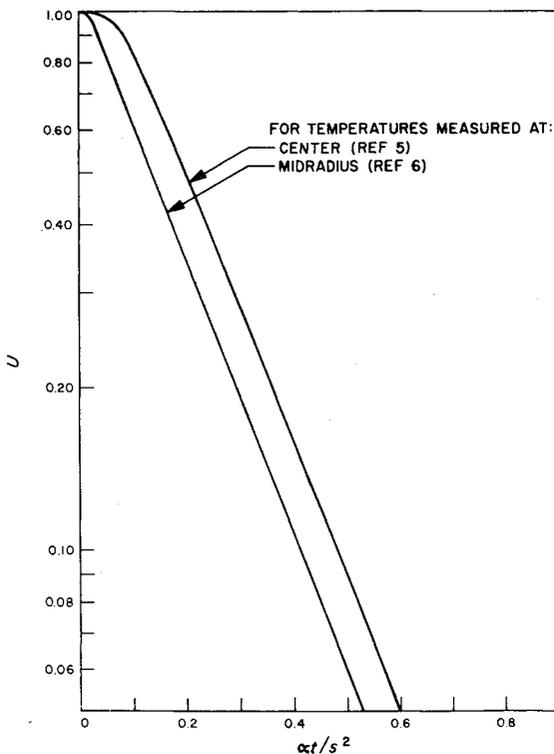

Fig. 5　Change in temperature of infinite cylinder caused by sudden change of surface temperature. Note: U = ratio of temperature excesses, i.e., $(T_2 - T)/(T_2 - T_1)$, where T = center or midradius temperature at time t, and T_1 = temperature of specimen before thermal pulse. Also, T_2 = specimen surface temperature after thermal pulse, s = specimen radius, and α = thermal diffusivity

When the test was to be run in vacuum, the assembly first was evacuated to the desired pressure range. The temperature of the specimen holder then was changed suddenly by energizing the heater or flowing liquid nitrogen through the cooling coil as required for a change of approximately 75°F. This sudden temperature change was performed manually to assure maximum rate of change. An automatic controller then was used to maintain the outside wall of the specimen at the new temperature level. The outputs of the thermocouples in the test specimen (Fig. 3) were recorded on a multipoint recorder.

Each test was continued until the temperature at the center of the specimen was within about 10°F of the wall temperature, at which time the temperature of the holder again could be changed suddenly to extend the run to a new temperature range. In air, less than 1 hr was required for the center temperature to reach the desired point, whereas in vacuum the time required was on the order of 36 hr. Specimen temperature vs time plots were prepared for each test. A typical example of a plot for a test in vacuum is shown in Fig. 4. In this test the initial and final temperature excesses ($T_2 - T_1$ and $T_2 - T$, Fig. 5) measured for the center thermocouple were 92° and 9°F, respectively. For the midradius thermocouple, the values measured were 91° and 5°F, respectively.

IV.　Data Reduction

Methods for calculating the thermal diffusivity of a material from such transient state data are described in several texts. Jakob[5] presents a graphical method for determining the
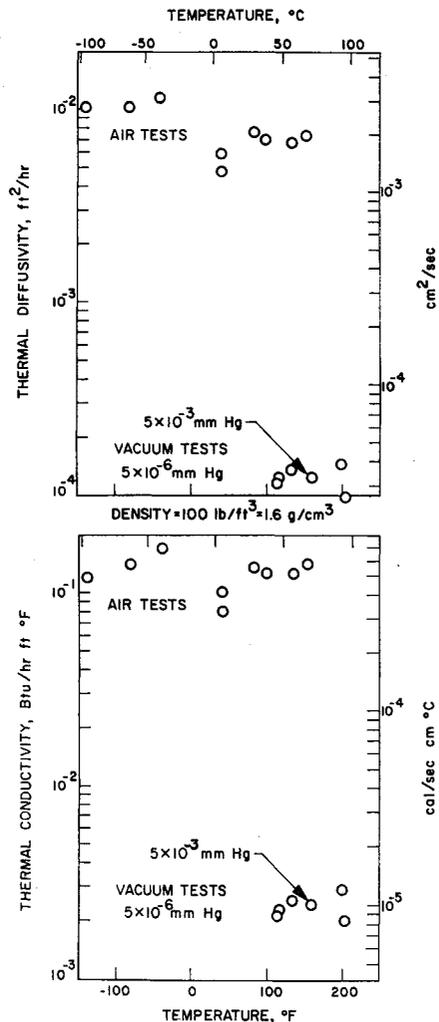

Fig. 6　Thermal diffusivity and conductivity vs temperature of 99% silica sand

diffusivity when the $(T_2 - T)/(T_2 - T_1)$ ratio U at the center of a specimen of given geometry is known at any particular time. Russell[6] describes this solution for the midradius position. These graphical methods for an infinitely long cylindrical sample are illustrated in Fig. 5. It was found from error analysis that the most accurate values of diffusivity are obtained if calculated from the segment of the time-temperature curves (Fig. 4) where U is in the range 0.2 to 0.5. Four diffusivity values were calculated for each test run, that is, two values from the center temperature curve at the points where U was near 0.2 and 0.5, and two from the midradius temperature curve at the same U values. The four diffusivities so obtained were averaged, and these average values are plotted in Figs. 6–10.

Thermal conductivity can be calculated from diffusivity values if the density and specific heat are known. The packing density was measured for each test as indicated previously. Consistent specific-heat values for pure silica over a wide temperature range are available in the literature.[7,8] These data are shown in Fig. 11 and were used to make the calibration calculations.

Specific-heat data for olivine basalt (or similar materials) are limited, extend over a narrow temperature range, and may be sensitive to the composition. Because of this lack of reliable data, determinations of the specific heat of the olivine basalt used were made between room temperature and 100°, 200°, and 300°F. These determinations were made using a calorimetric method in accordance with American Society for Testing and Materials Standard Procedure C351-61. These measured specific heat values are plotted in Fig. 11.
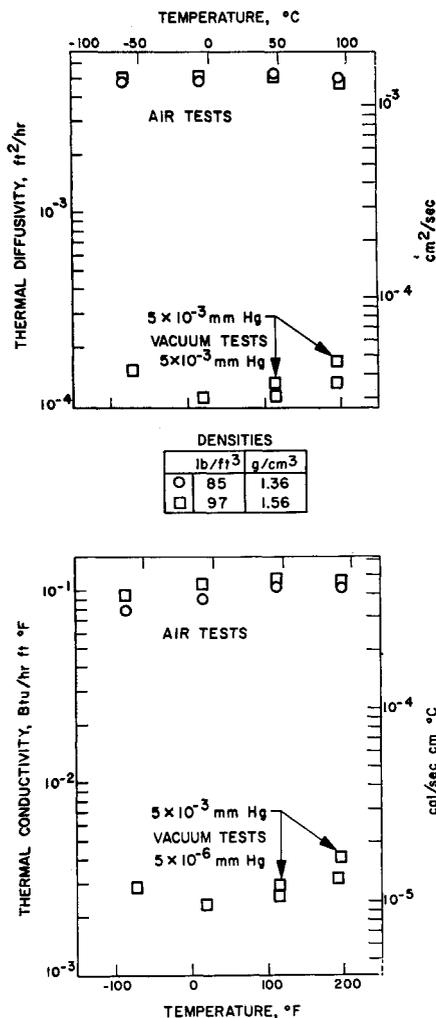

DENSITIES

	lb/ft³	g/cm³
O	85	1.36
□	97	1.56

Fig. 7   Thermal diffusivity and conductivity vs temperature of −35 +48 mesh olivine basalt

DENSITIES

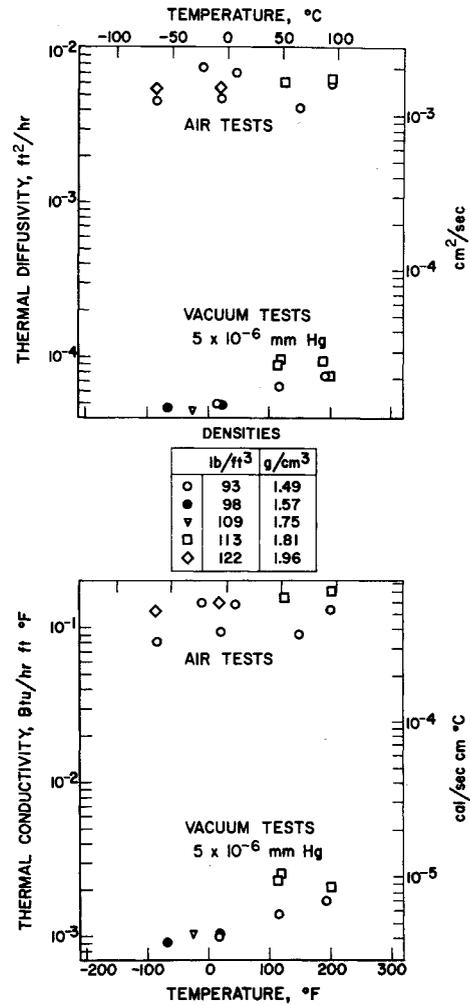|	lb/ft³	g/cm³
O	93	1.49
●	98	1.57
▼	109	1.75
□	113	1.81
◇	122	1.96

Fig. 8   Thermal diffusivity and conductivity vs temperature of −35 mesh olivine basalt

It has been reported[9] that, within limits, the variation of specific heat with temperature is similar for various types of crushed rock. With this in mind, the curve through the measured points for the olivine basalt (Fig. 11) was extrapolated to give specific-heat values over the temperature range used in this investigation. Thermal conductivity values listed in Figs. 6–10 were calculated from the average thermal diffusivity values determined graphically (Fig. 5) and the measured densities and specific heat values (Fig. 11).

For a few of the tests, thermal conductivity also was calculated from the experimental data using a digital computer. The computer solution avoids the assumption made in the graphical method that conductivity and specific heat are constant over the temperature range of a single test. Values obtained with the computer were in agreement with those obtained graphically.

In order to facilitate analysis of the test data, the diffusivity and conductivity values are shown graphically in Fig. 6–10. The last plot (Fig. 10) shows the thermal diffusivity and conductivity for the three lots of basalt measured at approximately the same packing density. The effect of particle size may be evaluated readily.

An error analysis of the measuring and calculation procedure also was made; details of it are presented in Ref. 10. The chief sources of error were found to be heat flow through the ends of the test specimen, lack of complete temperature uniformity at the start of a test, and uncertainties in the specific heat. Less important sources were temperature, time, and position measurements, heat flow along thermocouples and bottom closure, and variation of thermal proper-
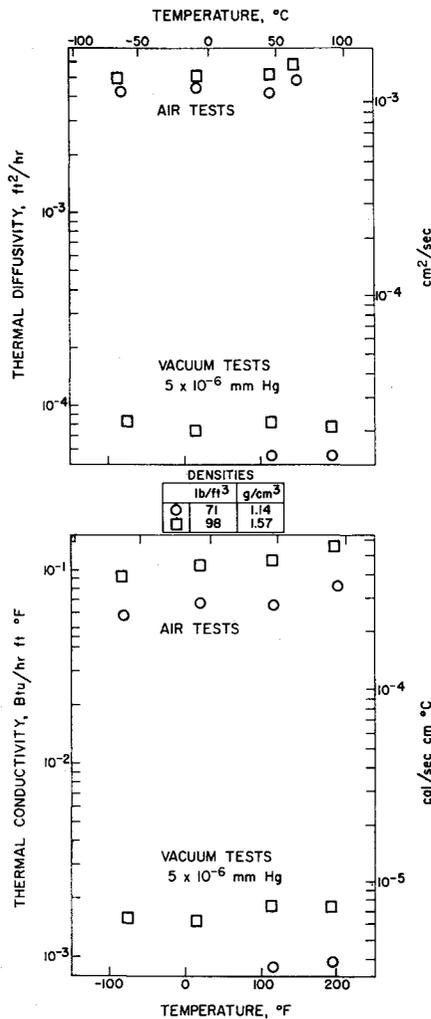
Fig. 9 Thermal diffusivity and conductivity vs temperature of −150 mesh olivine basalt

ties with temperature during the course of a test. The estimated error from all of these sources in each value of diffusivity is about 10%, and in each value of conductivity about 15%.

V. Discussion of Results

The thermal properties of silica sand determined in air (Fig. 6) are in good agreement with literature values.[11] At reduced pressures (10^{-3} and 10^{-6} mm Hg range), the measured diffusivities and conductivities were roughly 100 times lower. There were no comparable thermal property data at these vacuum levels found in the literature. Tests in poorer vacuum environments are reported,[12] and it is interesting to note that the thermal conductivity of sand at 10^{-1} and 10^{-2} mm Hg is not greatly different from the values obtained in the present investigation at 10^{-3} and 10^{-6} mm Hg. The major change in thermal properties occurs when the interstitial air pressure drops from atmospheric down to about 10^{-2} mm Hg; beyond this, the thermal diffusivity and conductivity are relatively constant.

The results of the tests on the olivine basalt are shown in Figs. 7–10. Again the thermal diffusivity and conductivity as measured in vacuum were approximately 100 times lower than the values measured in air. These data also show that the effects of vacuum are very much greater than the effects of temperature, packing density, or particle size of the test material.

It is interesting to note that the values of thermal conductivity obtained for the olivine basalt in vacuum are in good agreement with the value (3 to 10 × 10^{-6} cal/cm-sec-

°C) of thermal conductivity calculated for the lunar surface from the measurements made during a lunar eclipse.[1, 2]

The effects of the vacuum may be explained by considering the thermal conduction process. For the tests in air, the conduction is through the particles of basalt and through the air that fills the voids. For the tests in vacuum, there is conduction through the basalt particles but very little through the evacuated voids. Thus, a major portion of the thermal energy must be transferred through the voids by radiation, which is very low at the temperature used in this study. Therefore, the thermal conductivity as measured in vacuum would be lower than the value measured in air.

The degree of vacuum in which the measurement was made would affect the amount of energy transferred by conduction through the voids, but this would be small except for very poor vacuums. Although the equipment used was not particularly suited to running tests at various levels of vacuum, it was possible to run some tests at two levels. The results of these (Figs. 6 and 7) show that increasing the pressure from 10^{-6} to 10^{-3} mm Hg increased the conductivity by a small amount. It therefore would seem reasonable to assume that, at pressures below 10^{-6} mm Hg, the thermal conductivity will not be affected markedly by the pressure.

The effect of test temperature on the values obtained during the tests in air is small (Figs. 7–10). This is what would be expected, as the thermal conductivity of the basalt particles and of the air in the voids between the particles would not change markedly over the range of temperatures studied. Since the test temperature would affect the radiation through the evacuated voids, it should affect the thermal conductivity as measured in vacuum. The lower the test temperature,
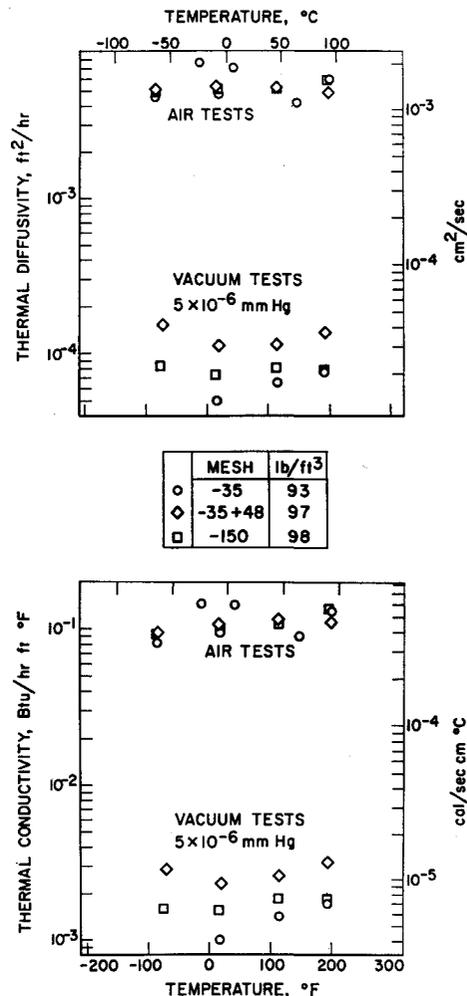

Fig. 10 Thermal diffusivity and conductivity vs temperature of olivine basalt
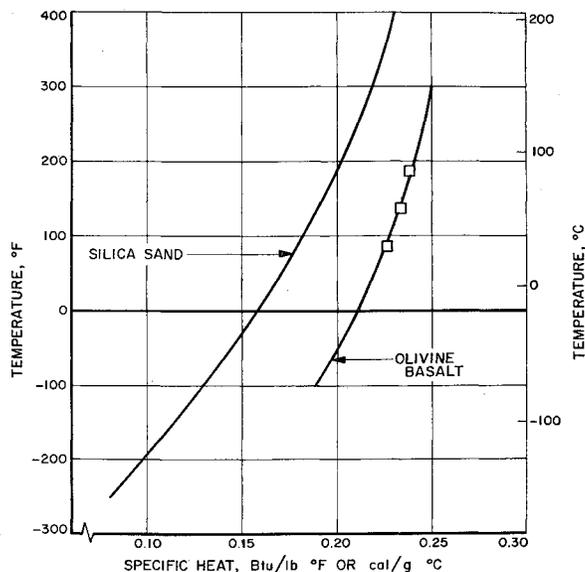
Fig. 11   Specific heat vs temperature (silica sand data from Refs. 7 and 8)

the lower the conductivity would be. Although the test data are limited, they do seem to show some effect of temperature (Figs. 7–10).

For a given particle size distribution, the higher the packing density, the lower the percentage of voids and the more continuous the conduction path. Thus, it would be expected that the thermal conductivity in both air and vacuum should increase with an increase in packing density. Again, the available data are limited; however, they do indicate this behavior.

The effects of the particle size distribution are not as clearly understood. The data available from the tests run during this investigation are shown in Fig. 10. From these, it would appear that the particle size distribution has very little effect upon the thermal conductivity as measured in air but does have an effect on the value measured in vacuum: material with a sharp and coarse distribution (-35 $+48$ mesh) has a higher conductivity than the material with a broader distribution of particle sizes. Because of other factors that also could be affecting these data, they should not be considered as conclusive.

VI.   Conclusions

From the results obtained during this investigation, the following conclusions may be stated:

1) The thermal conductivity of the crushed olivine basalt used was approximately 100 times lower when measured in

vacuum than when measured in air at atmospheric pressure. The value measured in vacuum is in good agreement with the value for the lunar surface calculated from astronomical data.

2) Increasing the pressure from 5×10^{-6} to 5×10^{-3} mm Hg had no marked effect on the thermal conductivity of the crushed basalt.

3) For the -150 mesh material, the thermal conductivity in air and in vacuum was increased approximately 60% at all test temperatures when the packing density was increased from 1.14 to 1.57 g/cm³.

4) Decreasing the average temperature of the crushed basalt specimen from 100° to $-70°$C caused a decrease in the thermal conductivity.

5) For the particular distributions used, the particle size had a greater effect on the values of thermal conductivity measured in vacuum than on the values measured in air.

6) The thermal conductivities of the olivine basalt and the silica sand are not markedly different. From this, it is concluded that composition of the crushed material has only a minor effect on its thermal conductivity.

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