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HIGH TEMPERATURE THERMAL
CONDUCTIVITY OF SIX ROCKS

Livermore, California

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ABSTRACT

Values of the thermal conductivity of Nevada Test Site granite, basalt, tuff, and dolomite; Indiana limestone; and Gnome salt were measured to 1000°C using a steady-state method. Cylindrical rock samples were heated internally by a resistance-wire-wound porcelain tube and temperatures measured with thermocouples.

The probable error in the data varied from $\pm 5\%$ to $\pm 9\%$. These rather large values are believed due to the heterogeneous nature of the rock.

INTRODUCTION

The diffusion of thermal energy in earth materials is a matter of considerable interest to the Plowshare Program. The success of many projects, such as power production, recovery of oil, of isotopes, or of products from chemical reactions, depends on the rate of dissipation of heat from the nuclear shot zone. The temperature dependence of the thermal conductivity of the medium must be known to calculate thermal losses; thus the thermal conductivities of six earth materials of interest to Plowshare, viz., NTS granite; basalt, tuff and dolomite; Indiana limestone and Gnome salt¹ were measured to 1000°C.

EXPERIMENTAL

A. Method

A steady-state method using cylindrical geometry was chosen. Kingery² has used this method to determine the thermal conductivity for aluminum oxide. Other investigators, such as Birch and Clark,³ have used a flat disk method to obtain data on rocks, but the cylindrical geometry seemed to afford accurate results with simpler experimental technique.

The equation used to calculate the thermal conductivity for a cylindrical sample was

$$k = \frac{Q \ln \frac{r_1}{r_2}}{2\pi L (T_2 - T_1)},$$

where

k = thermal conductivity

Q = steady-state heat flow

r_1, r_2 = radii at measuring points

T_1, T_2 = temperature at r_1 and r_2 , respectively

L = length of test zone.

This equation holds for one-dimensional, cylindrical heat flow only. Therefore, the samples were fabricated with a length-to-diameter ratio of 5 and the power input was measured only for the center 4-in. length of the sample.

B. Samples

The origin of each sample is as follows:

Cores of NTS granite (actually granodiorite), were obtained from the U15b exploratory hole, Area 15, at the 1000-ft level.

Massive samples of basalt were obtained from Shot No. 12, Hole DB-C-4, and Shot No. 13, DB-4, of Project Buckboard.

Two samples of tuff, designated TOS-4, were obtained from location U12b07, at a drill depth of 75-78 feet. The exact location of the sample of TOS-7 tuff was unknown. The TOS-4 samples are fairly representative of most of the coherent NTS tuffs (TOS-1 to 5 and basal part of 7), while the TOS-7 sample is representative of friable material.

Cores of NTS dolomite were obtained from exploratory dolomite hole No. 1, dolomite hill, at the 700-ft level.

The exact origin of the Indiana limestone sample is unknown.

The Gnome salt samples were cored from massive blocks from the Gnome event ground zero room (1200-ft level).

The author is very indebted to Nicholas B. Short, Deane K. Smith, Jr., James S. Kahn, and Frederick B. Smith for analyzing the samples. The analyses are shown in Table I.

Table I. Rock properties

Sample	Appearance	Density (g/cm ³)	Composition	
			Mineral Type	Vol. %
NTS granite	Gray, coarse-grained	2.67	Orthoclase	28
			Plagioclase	34
			Quartz	27
			Biotite	9
			Other	2
NTS basalt	Slate-gray, fine-grained	2.68	Plagioclase	66
			Olivine	8
			Iron minerals	26
			(mainly hematite)	
TOS-4 tuff	Tan, moderately grainy	2.24 (dry)	Feldspar pheno-crysts	6
			Quartz pheno-crysts	8
			Chalcedony segregations	14
			Matrix (clay, chalcedony, zeolite, etc.)	72
TOS-7 tuff	Tan, grainy friable	1.27	Feldspar pheno-crysts	1
			Quartz pheno-crysts	12
			Rock fragments	1
			Glassy matrix	86
NTS dolomite	Slate gray, fine-grained	2.80	Dolomite	99
			Other (primarily quartz and muscovite)	1
Indiana limestone	Tan, fine-grained	2.30	Calcite	98.4
			Quartz	1.0
			Hematite	0.6
Gnome salt	Translucent to red-brown, brown streaks, grainy	2.147	NaCl	95
			Polyhalite	2
			Silt and clay	3

It should be noted that these samples do not necessarily represent the bulk average properties of their formations. This point should be considered when using the data presented in Fig. 1 through 6. The bulk properties of the various rock types have been discussed as follows: NTS granite formation by Houser and Poole⁴; NTS basalt by Anderson⁵; NTS tuff by Diment et al.,^{6, 7} McKeown and Dickey,⁸ and Byers⁹; dolomite by Dickey and McKeown¹⁰; and Gnome salt by Rawson.¹¹ These references should be consulted to obtain the average properties of the medium in an area of interest; these properties should then be compared to those shown in Table I to determine the applicability of the thermal conductivity data presented here.

All of the samples with the exception of NTS dolomite were fabricated into hollow cylinders of 3-1/2-in. outside diameter, 7/8-in. inside diameter and 18-in. length. The dolomite samples had a 2-1/4-in. outside diameter, a 3/8-in. inside diameter and were 12 in. in length. Six 1/16-in. holes were drilled radially into the cylinders to permit emplacement of thermocouples. The hole depths were determined by radiography. The geometry and approximate dimensions of the larger samples are shown in Fig. 7.

It was difficult to fabricate the Gnome salt cylinders. Only two samples were obtained, and one of these broke cleanly in two upon handling. This cylinder was cemented together with a grout of 75% Gnome salt, 25% plaster of Paris ($\text{CaSO}_4 \cdot 1/2 \text{H}_2\text{O}$). The data obtained with this sample agreed within experimental error with those obtained from the unbroken cylinder.

C. Heater

The heater for all samples except NTS dolomite was a 3/4-in. outside diameter hollow porcelain tube wrapped with 0.010-in. Pt resistance wire. The ends were "overwound" to compensate for end losses. One inch at both ends of the tube was wound 18 turns to the inch and the remainder 10 turns per inch. However, the power input was measured only for the center 4-in. portion. To effect this, voltage leads were spot-welded to the resistance wire and taken out by holes drilled into the hollow portion of the tube. After winding, the tube was coated with alundum cement and fired to 1300 °C to hold the winding in place.

The heater for the dolomite samples was 3/8 in. in diameter and had a test section of 1 in. instead of 4 in. for the larger heater. Otherwise it was very similar to that described above.

Fig. 1. Thermal conductivity of NTS granite vs temperature.

Fig. 2. Thermal conductivity of NTS basalt vs temperature.

Fig. 3. Thermal conductivity of NTS tuff vs temperature.

Fig. 4. Thermal conductivity of NTS dolomite vs temperature.

Fig. 5. Thermal conductivity of Indiana limestone vs temperature.

Fig. 6. Thermal conductivity of Gnome salt vs temperature.

Fig. 7. Cross section of sample assembly.

D. Thermocouples

The thermocouples used were 0.010 in. Pt-Pt-10% Rh. They were sheathed in two-hole 1/16-in. -outside-diameter alundum tubes; the junctions remained bare. They were standardized to 1000°C against standard thermometers and thermocouples.

E. Procedure

The samples were emplaced in a 16 kW pot furnace to provide control over the mean sample temperature. Figure 8 shows the assembly before emplacement in the furnace. The sample was hung by steel tie rods from the furnace lid, as shown.

A Weston No. 310 wattmeter was used to measure power input to the heater and a Leeds and Northrup K3 potentiometer and null detector used to determine temperatures. Twenty-four hours was allowed for each data point to insure that the sample had reached equilibrium.

RESULTS AND DISCUSSIONS

Thermal conductivities for the six rocks are shown in Figs. 1 through 6. The measured thermal conductivity for these rocks is in general smaller than literature values for similar rocks³; to check the values obtained for granite and for tuff, A. H. Mulvey measured the thermal conductivity for these two rocks at 65°C by a different technique. These points are shown in Figs. 1 and 3; the probable error is rather large, approximately $\pm 20\%$, but it can be seen that the values are in qualitative agreement with our higher temperature data.

The probable error in our data is $\pm 5\%$ for NTS granite, basalt and dolomite; $\pm 6\%$ for Indiana limestone; $\pm 7\%$ for Gnome salt; and $\pm 9\%$ for NTS tuff. The magnitude of these errors seem rather large at first examination. The heat input was measured to an accuracy of $\pm 0.5\%$, the length of the test zone to $\pm 0.2\%$, the temperature differences to $\pm 0.2\%$, and $\ln(r_2/r_1)$, to about $\pm 0.5\%$. The temperature gradient may have been disturbed due to the presence of the thermocouples, as heat could be conducted radially along them. However, this error was not believed to be over $\pm 1.0\%$, due to the small size of the wire. The main source of error is believed due to the heterogeneous nature of the rocks. Different samples were used for each run, and, within

Fig. 8. Sample assembly before insertion in furnace.

a given sample, different thermocouples could be placed in entirely dissimilar environments and thus could record quite different temperature gradients. It may be noted that the most heterogeneous rock, tuff, had the highest probable error.

The thermal conductivities of NTS granite and basalt were similar; the temperature dependence of k was quite low.

It may be seen from Fig. 3 that the k for TOS-7 tuff is less than half of that for TOS-4. This is undoubtedly due to the much higher porosity of the TOS-7. The k of the TOS-7 sample also shows a rapid increase with temperature above 900°C. Upon examination after the run it was apparent that the sample had partially sintered. Initially the sample crumbled easily, but after heating over 1000°C, it was quite coherent. The increase in k was probably due to this high temperature sintering.

The temperature dependence of k for the dolomite and limestone were similar; other types of carbonate rocks show conductivities higher by a factor of two.³ The dotted portion of the curves in Figs. 4 and 5 indicate the region of decomposition of the carbonates; the values in this region are of qualitative value only, due to the formation of microcracks and some large fissures in the samples.

Data on Gnome salt were obtained only to 325°C, as the samples shattered at this temperature. This was probably due to the decomposition of the polyhalite impurity in the salt. The temperature dependence of k for this salt is qualitatively similar to that of literature values.³

It is interesting to note that the temperature dependence of k for all the rocks except Gnome salt is quite small. It would be sufficient for many calculations to use an average k assumed independent of temperature over a wide temperature range.

Data were not obtained to a temperature sufficiently high to show the effect of radiation. The radiation contribution to k increases as the third power of temperature; thus at very high temperatures k should increase rapidly. This effect was observed in massive rock salt.¹

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