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Thermal Conductivity of the Rocks in the Bureau of Mines Standard Rock Suite

M. T. Morgan
G. A. West

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THERMAL CONDUCTIVITY OF THE ROCKS IN THE BUREAU OF MINES STANDARD ROCK SUITE

M. T. Morgan and G. A. West

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
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THERMAL CONDUCTIVITY OF THE ROCKS IN THE BUREAU OF MINES STANDARD ROCK SUITE

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ABSTRACT

Thermal conductivities of eight rocks from the Bureau of Mines Standard Rock Suite were measured in air over the temperature range 373 to 533 K (100 to 260°C). The thermal conductivities of these rocks were measured to furnish standards for future comparisons with host rock from prospective nuclear waste repository sites.

The rocks and their average thermal conductivities at 373 K before thermal cycling were (1) Sioux quartzite, 5.5 W/m·K; (2) St. Cloud gray granodiorite, 2.7 W/m·K; (3) Dresser basalt, 3.0 W/m·K; (4) Barre granite, 2.5 W/m·K; (5) Holston limestone, 2.5 W/m·K; (6) Westerly granite, 2.3 W/m·K; (7) Berea sandstone, 2.2 W/m·K; and (8) Salem limestone, 1.7 W/m·K. The thermal conductivity at a given temperature decreased by as much as 9% after a specimen had been heated to the maximum temperature (533 K), but additional heating cycles had no further effect. This decrease was smallest in the igneous rocks and largest in the sedimentary types. Variations due to orientation were within the precision of measurements (±5%). In most cases the thermal conductivities were linear with the reciprocal of the temperature and were within 14% of published data obtained by other methods.

Measurements were made by a cut-bar comparison method in which the sample was sandwiched between two reference or metering bars made of Pyroceram 9606 glass-ceramic. The apparatus consisted of a Dynatech Model TCFCM-N20 comparative thermal conductivity analyzer controlled by a Hewlett Packard Model 3052A data acquisition system. The four heater controllers in the Dynatech instrument were interfaced to the data acquisition system via a Hewlett Packard Model 6940B multiprogrammer. The computer control increased the instrument efficiency by more than a factor of 3 because overnight and weekend operation could be continued without surveillance and because computations were automatic. A program was written to increment and cycle the temperature in steps between predetermined initial and maximum values. At each step the thermal conductivity was measured after steady-state conditions were established.

The rocks furnished by the Bureau of Mines were quarried in large and fairly homogeneous lots for use by researchers at various laboratories. To investigate any anisotropy, cores were taken from each rock cube perpendicular to each of the cube faces. Samples 2 in. in diameter and ~0.75 in. thick were prepared from the cores and were dried in a vacuum oven for at least one month prior to taking measurements.

1. INTRODUCTION

Thermal conductivities of eight types of rock were determined over the temperature range 373 to 533 K (100 to 260°C) by a comparative technique. The thermal conductivities of these rocks were measured to furnish standards for evaluations of prospective nuclear waste repository sites. Knowledge of thermal characteristics of various rock types will aid in site selection because such data are used to calculate the possibility of thermal damage, such as cracking, in the host rock and to determine the maximum radioactive waste loading (heat source concentration) within the repository. The rocks furnished by the Bureau of Mines were ideal as rock standards because they were quarried in large and fairly homogeneous lots. The eight rock types included Sioux quartzite, St. Cloud gray granodiorite, Dresser basalt, Barre granite, Holston limestone, Westerly granite, Berea sandstone, and Salem limestone. A detailed description of these rocks and their physical properties was reported by Krech, Henderson, and Hjelmstad.[1] The thermal conductivities were determined previously by Hanley et al.[2,3] using a laser flash method and by Navarro and DeWitt[4] using the line heat source method.

2. DESCRIPTION OF SAMPLES AND EXPERIMENTAL METHOD

The samples furnished by the Bureau of Mines were rough-cut 15- to 20-cm cubes. Cores 5.08 cm in diameter were taken perpendicular to each cube face using a diamond core drill. The original orientations of the samples were not furnished; therefore, the core axes were arbitrarily designated x, y, and z. The cores were sliced with a diamond slabbing saw into specimens about 2 cm thick. The specimen faces were ground flat, and grooves 0.25 mm wide by 0.38 mm deep were cut across the center of each face. In all of these operations, water was used as a coolant. Chromel-alumel thermocouples made with 36 B&S gage duplex wire were centered in the grooves and cemented with Saureisen cement as shown in Fig. 1. The final surfaces, which were finished dry on a plastic lap with 800-grit silicon carbide abrasive, were flat to within 0.013 mm and parallel to within 0.13 mm. Thermocouple leads were supported by thin fiberglass tape wrapped around the perimeter of the specimens. All samples were dried in a vacuum oven at 100°C for at least one month before testing.

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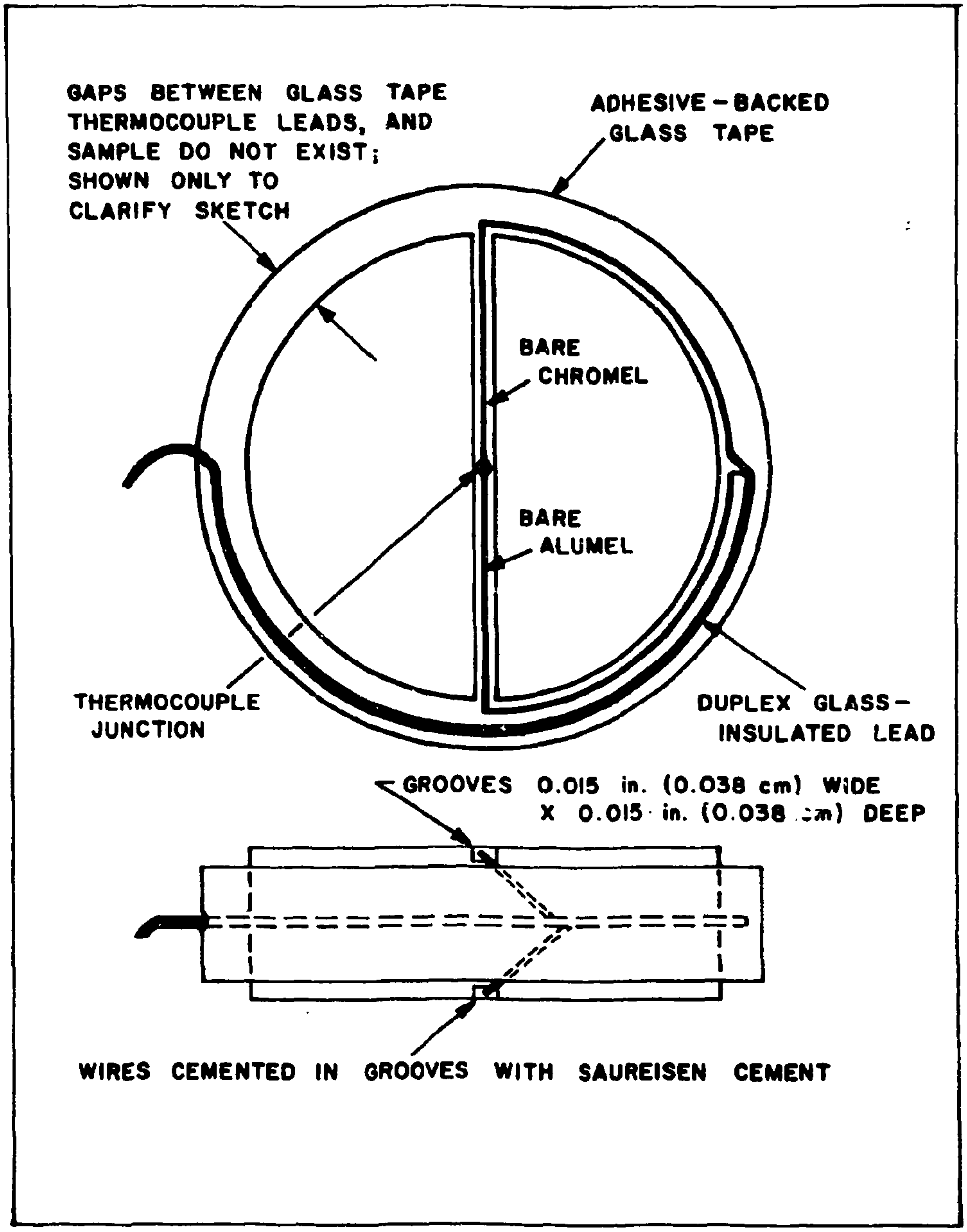

Fig. 1. Installation of thermocouples.

The thermal conductivities were measured using a Dynatech Model TCFCM-N20 comparative thermal conductivity instrument controlled by a Hewlett Packard Model 3052A data acquisition system (Fig. 2). The Dynatech instrument uses a cut-bar method in which the sample is sandwiched between two reference bars of the same diameter as the sample. The reference bars (5.08 cm diam, 1.3 cm thick) were made of Pyroceram 9606 glass-ceramic. Based on repeated measurements in which samples were rewired with thermocouples and on tests of Pyroceram 9606 versus Pyroceram 9606 and Pyroceram 9606 versus Pyrex 7740, the precision of the measurements is believed to be within ±5%. The thermal conductivities of the Pyroceram and Pyrex reference materials are known within ±5% at room temperature and ±10% at other temperatures.[5]

The stack arrangement used in the thermal conductivity analyzer is shown in Fig. 3. The heat flows from the heat source at the top of the stack to the heat sink at the bottom. To control the temperature at the heat sink, a bottom heater is used. The nickel metal spacers between the heaters and the reference bars, which are of the same diameter as the reference bars and the sample, are used to equalize the heat flux over the horizontal cross section of the stack. To prevent radial heat loss, the temperatures in the guard shield surrounding the stack were maintained equal to those existing in the stack at the same axial positions. The thermal conductivities were calculated using the equation

$$k_s = \frac{x_s}{2\Delta T_s}\left(\frac{k_t\ \Delta T_t}{x_t} + \frac{k_b\ \Delta T_b}{x_b}\right), \qquad (1)$$

where

k = thermal conductivity, W/m·K;

x = thickness, cm;

ΔT = temperature differential, K;

s, t, b = subscripts that refer to the sample and top and bottom reference materials in the test stack respectively.

Equation (1) is applicable only when the interface areas are equal and when there is no radial heat flow.

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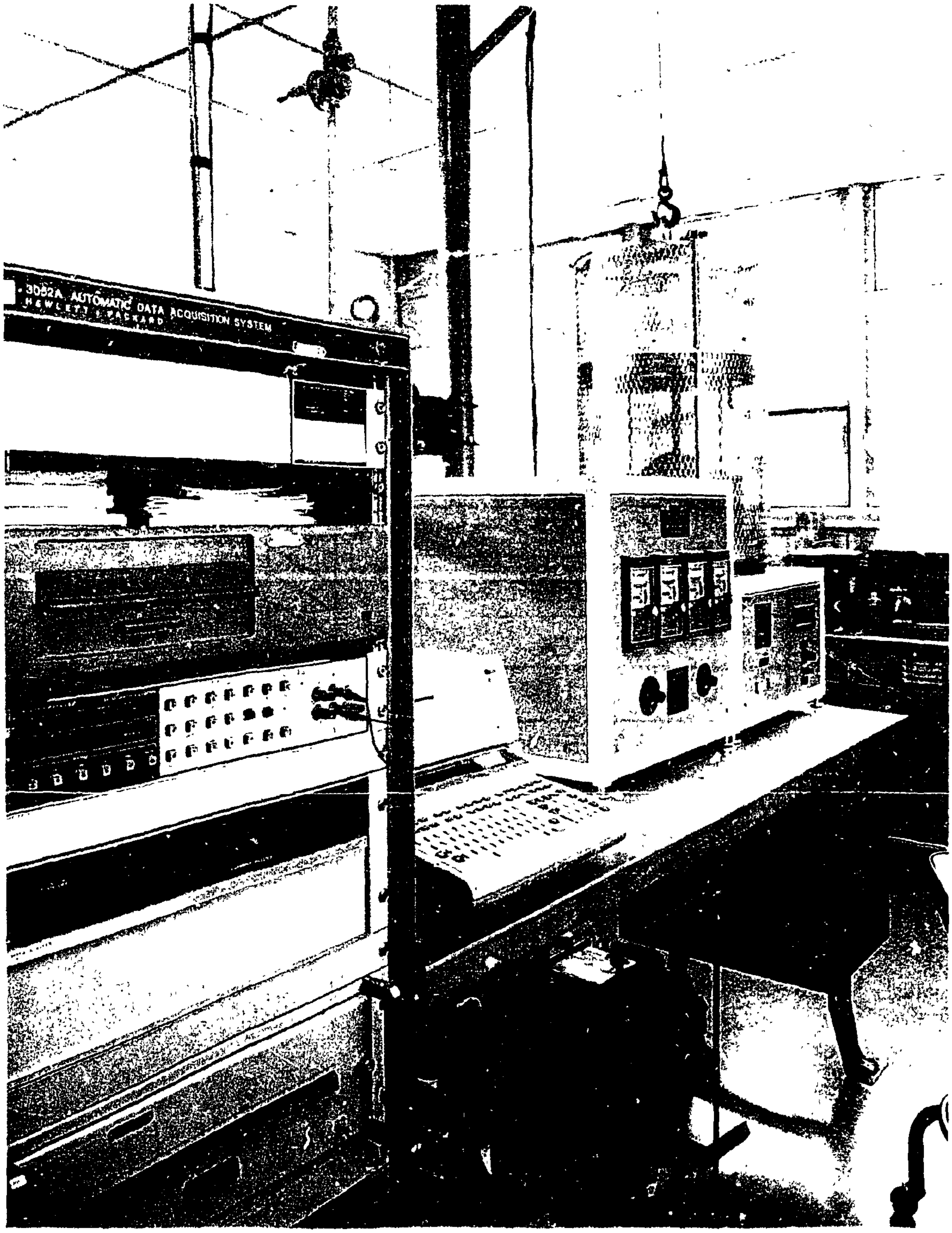

Fig. 2. Thermal conductivity analyzer.

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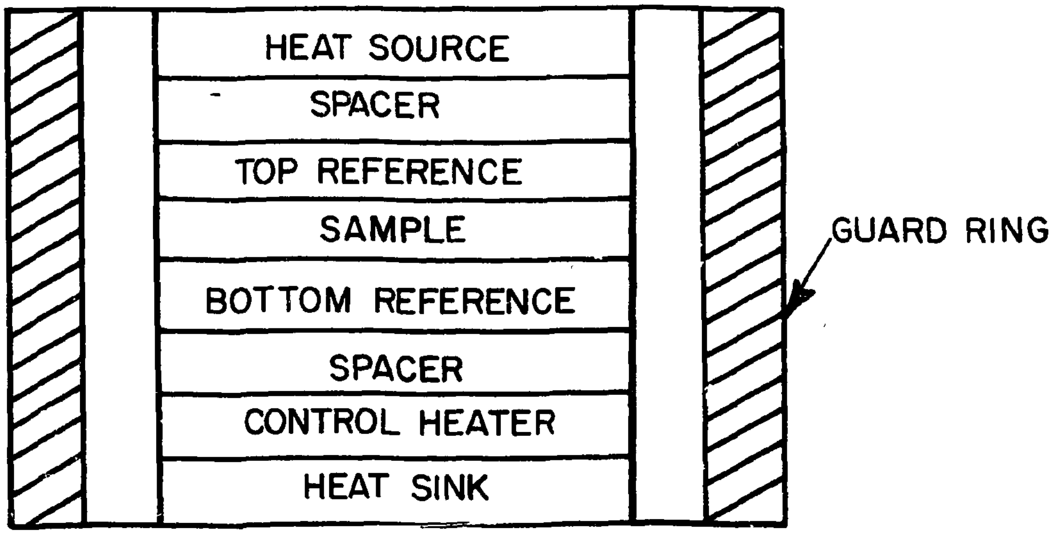

Fig. 3. Stack arrangement in thermal conductivity analyzer.

The maximum fractional change in vertical heat flow (E) due to radial or bypass heat flow has been given[6] as

$$E = k_i(1/k_r - 1/k_s)F , \qquad (2)$$

where

$$F \leq \left[\frac{(b^2/a^2) - 1}{2 \ln(b/a)} - 1\right] ,$$

and where k_i, k_r, and k_s are thermal conductivities of the insulation, reference, and sample materials, respectively; b is the inner diameter of the guard ring; and a is the sample diameter. The maximum estimated error due to the bypass heat flow for these measurements, using Pyroceram 9606 as a reference material and vermiculite as insulation, ranged from 1% at 373 K to 0.3% at 533 K in Sioux quartzite, which had the highest thermal conductivity, and from 5% at 373 K to 8% at 533 K in Salem limestone, which had the lowest thermal conductivity.

The data acquisition system, which was added to automate temperature readings and thermal conductivity calculations and to allow overnight and weekend operation without attendance, included a calculator controller with a 27,000-word memory, a 6-1/2 digit voltmeter, a scanner, and a clock. The 16 thermocouples of the Dynatech instrument were connected to the scanner with individually shielded copper wires (the shields were grounded in the Dynatech instrument). Copper leads connecting the scanner to the voltmeter were connected in series with chromel-alumel wires from an Omega Model TRC ice-point thermocouple reference chamber. All connections of chromel-alumel to copper were made in the Dynatech isothermal thermocouple junction box to properly reference the Dynatech thermocouples.

A Hewlett Packard Model 6940B multiprogrammer with digital to analog voltage output cards was used to control the four Leeds Northrup Electromax III controllers in the Dynatech instrument. Remote/local switches were installed on the face of the Electromax controllers so that computer or manual control was selectable. A printer, a plotter, and a 500,000-word flexible disk memory were also added to increase the system's versatility.

A program was written to increment and cycle the temperature in steps between predetermined initial and maximum values. The Hewlett

Packard system recorded voltages that were 0.015 ± 0.005 mV (0.3 ± 0.1 K) lower than those read on the Dynatech system, but noise pulses from an unknown source produced much greater fluctuations in about one out of every ten computer readings. Consequently, the program was revised to average ten readings and to eliminate those with excessive variation. Average temperatures of each of the four controlling thermocouples were compared with previous averages every 3 min. When temperatures of all four controlling points remained constant within 0.15 K for 6 min, the temperature was considered stable and the thermal conductivity was calculated. The time required to reach equilibrium was usually about 90 min. After the initial heat treatment, repeated measurements at any given temperature between 373 and 533 K agreed within 2%.

3. RESULTS

The thermal conductivities were determined with one set of x, y, and z samples for all of the rock types except St. Cloud gray granodiorite and Westerly granite, for which the measurements were repeated on additional samples. The thermal conductivities versus reciprocal temperatures are plotted in Figs. 4 through 11. The figures show two curves for each core — one from measurements obtained on the initial half cycle to the maximum temperature, and the other from measurements made after reaching the maximum temperature. Additional cycling to the maximum temperature caused no further noticeable change in the thermal conductivities. The variation (anisotropy) among the thermal conductivities of x, y, and z samples of each rock type was within the precision of measurements (±5%). Excellent correlations were obtained for most of the data.

The thermal conductivity is linear with the reciprocal temperature. The probability of correlation for the least squares fit of the data was >99% in all cases and was better than 99.9% for all Sioux quartzite, St. Cloud gray granodiorite, and Holston limestone data, and for at least half of the data from each of the other rocks. Equations for each curve were obtained by the linear least squares method. The coefficient of determination (r^2) was determined by the equation

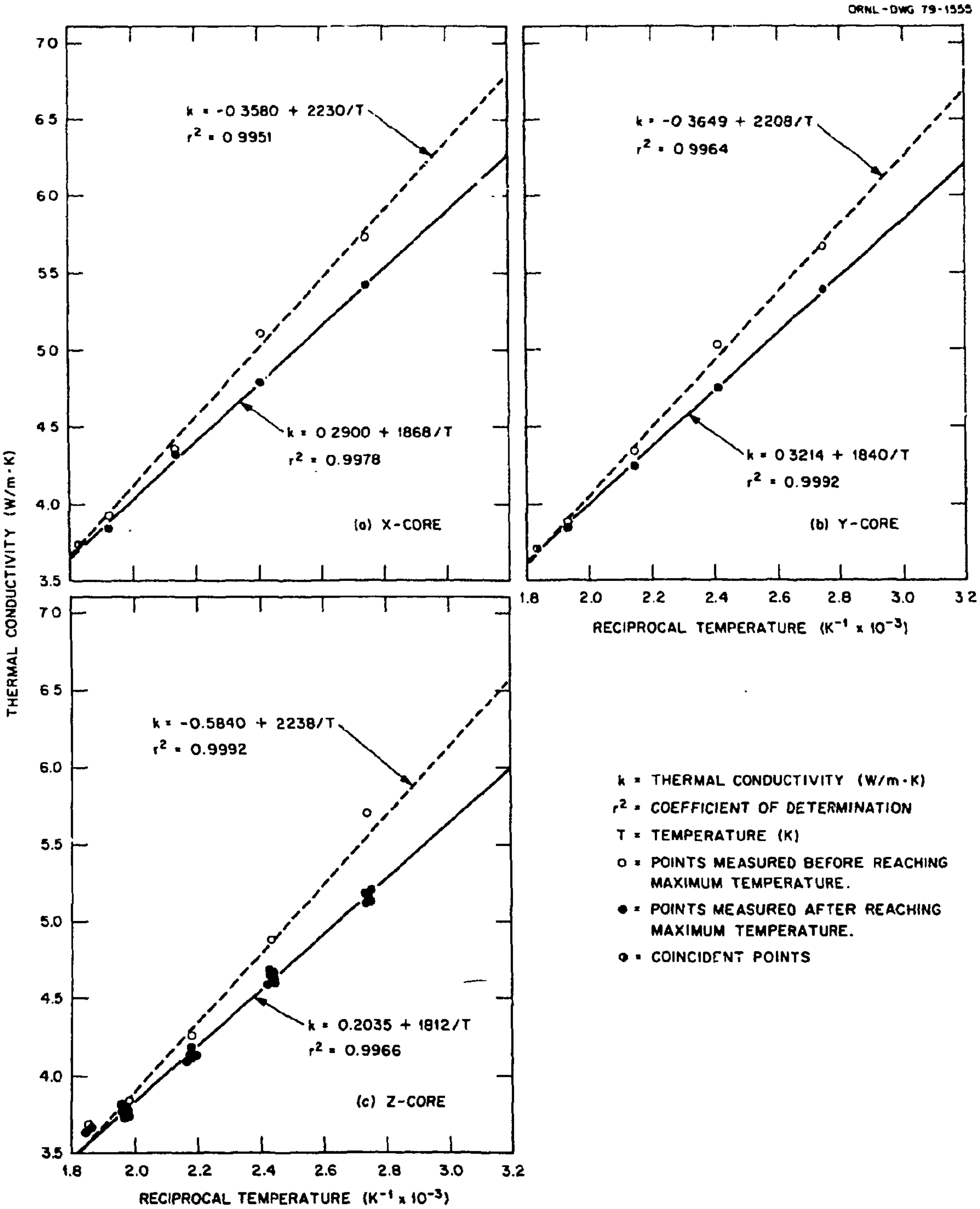

Fig. 4. Thermal conductivity of Sioux quartzite.

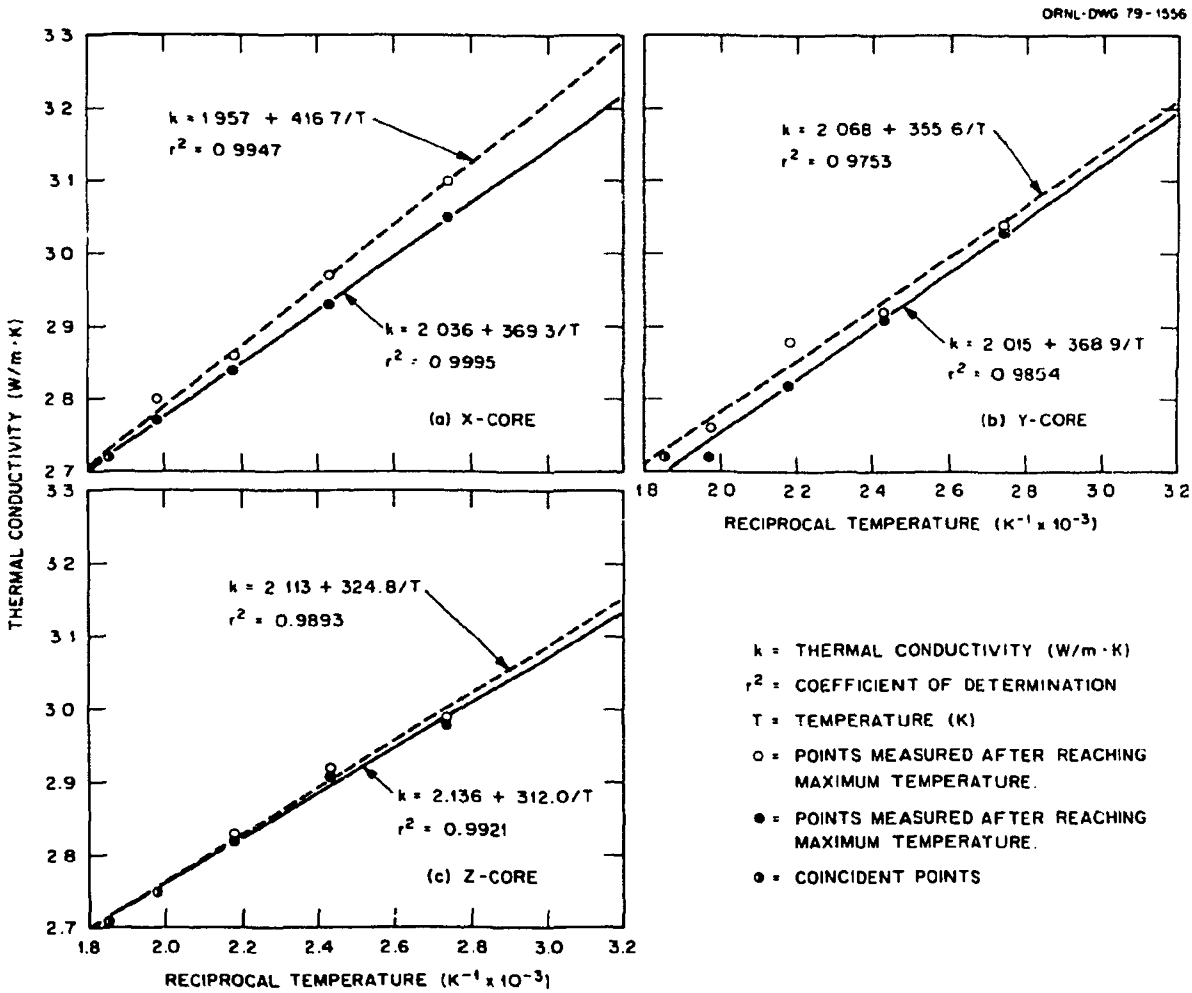

Fig. 5. Thermal conductivity of Dresser basalt.

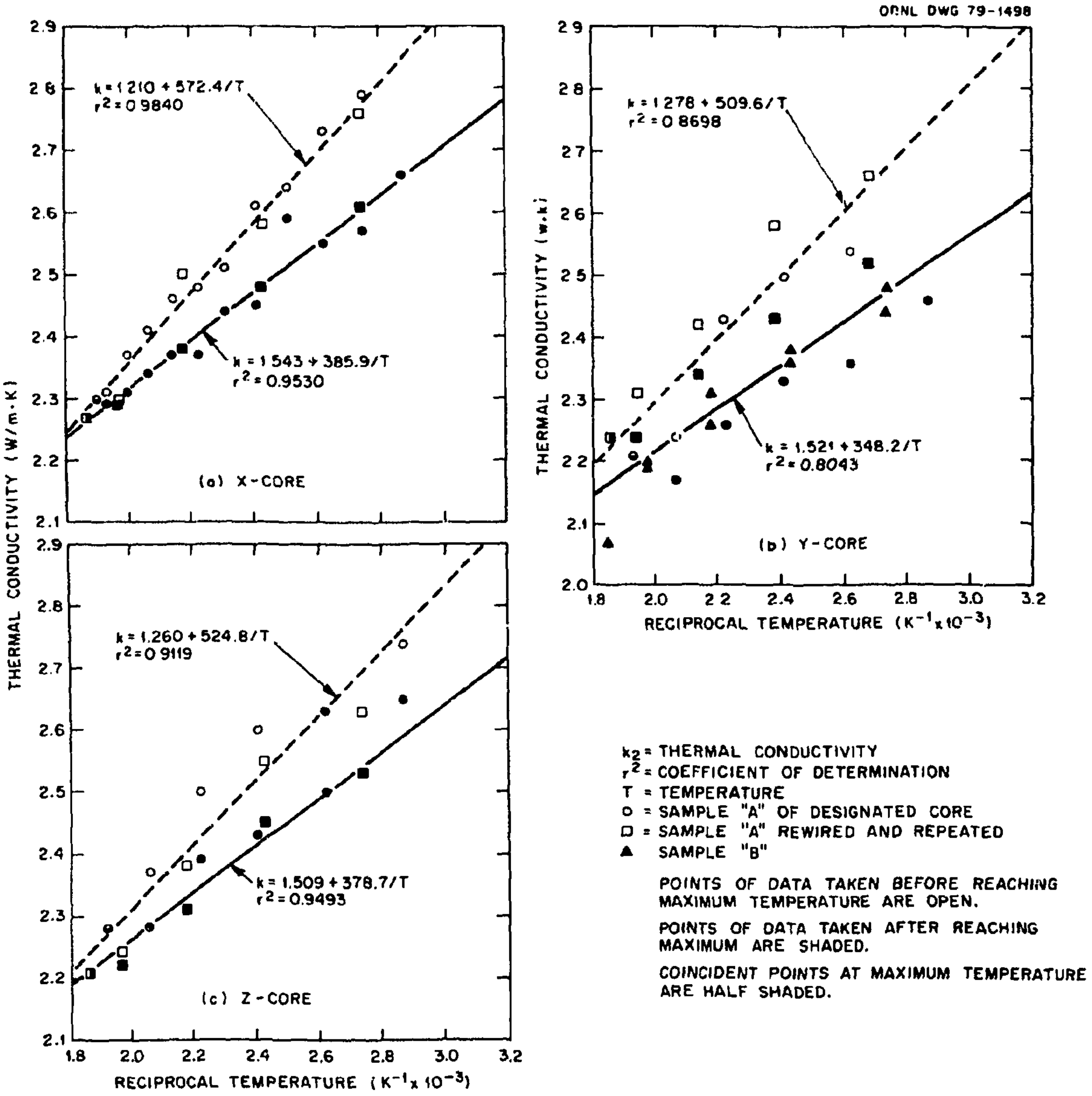

Fig. 6. Thermal conductivity of St. Cloud gray granodiorite.

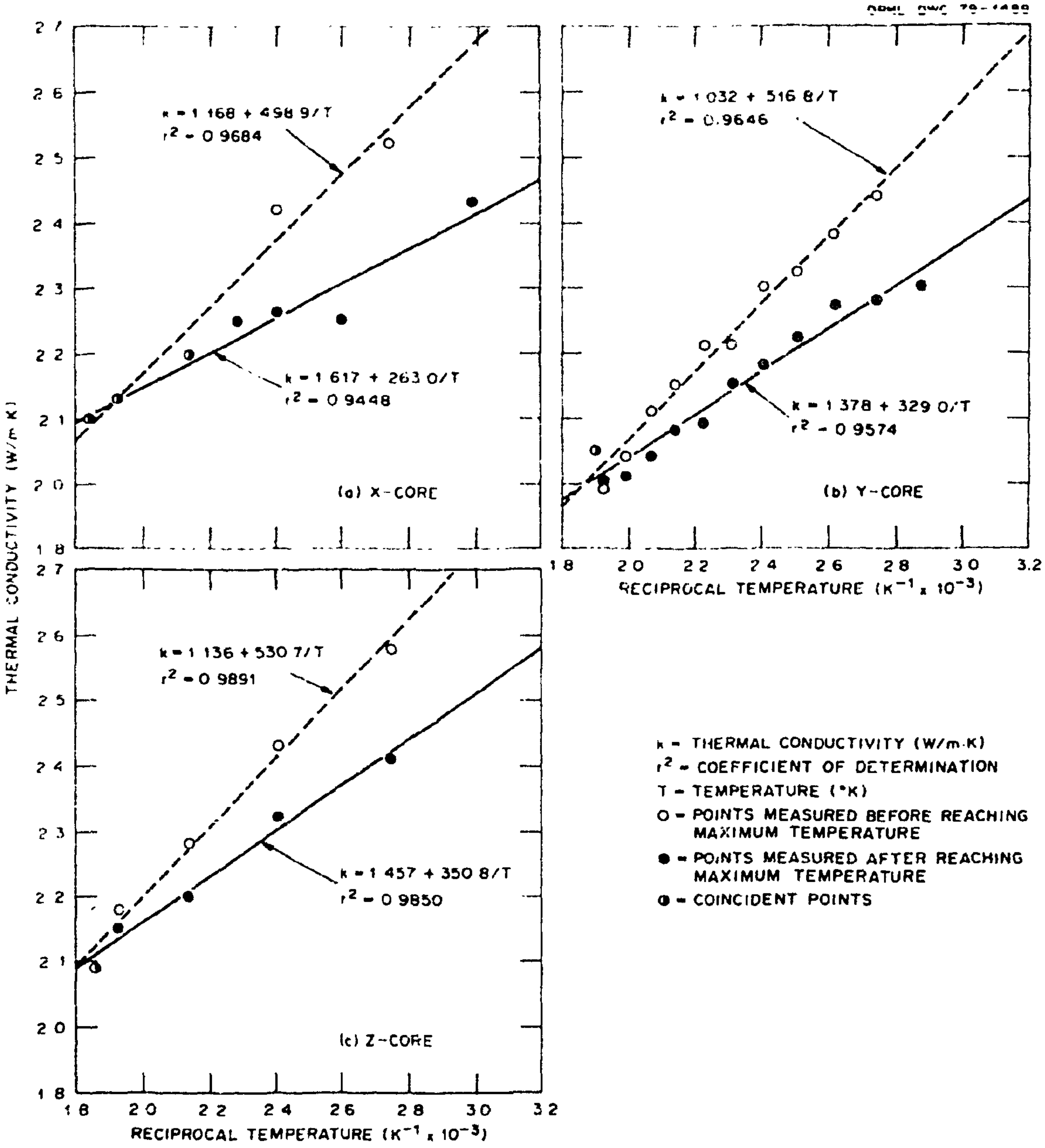

Fig. 7. Thermal conductivity of Barre granite.

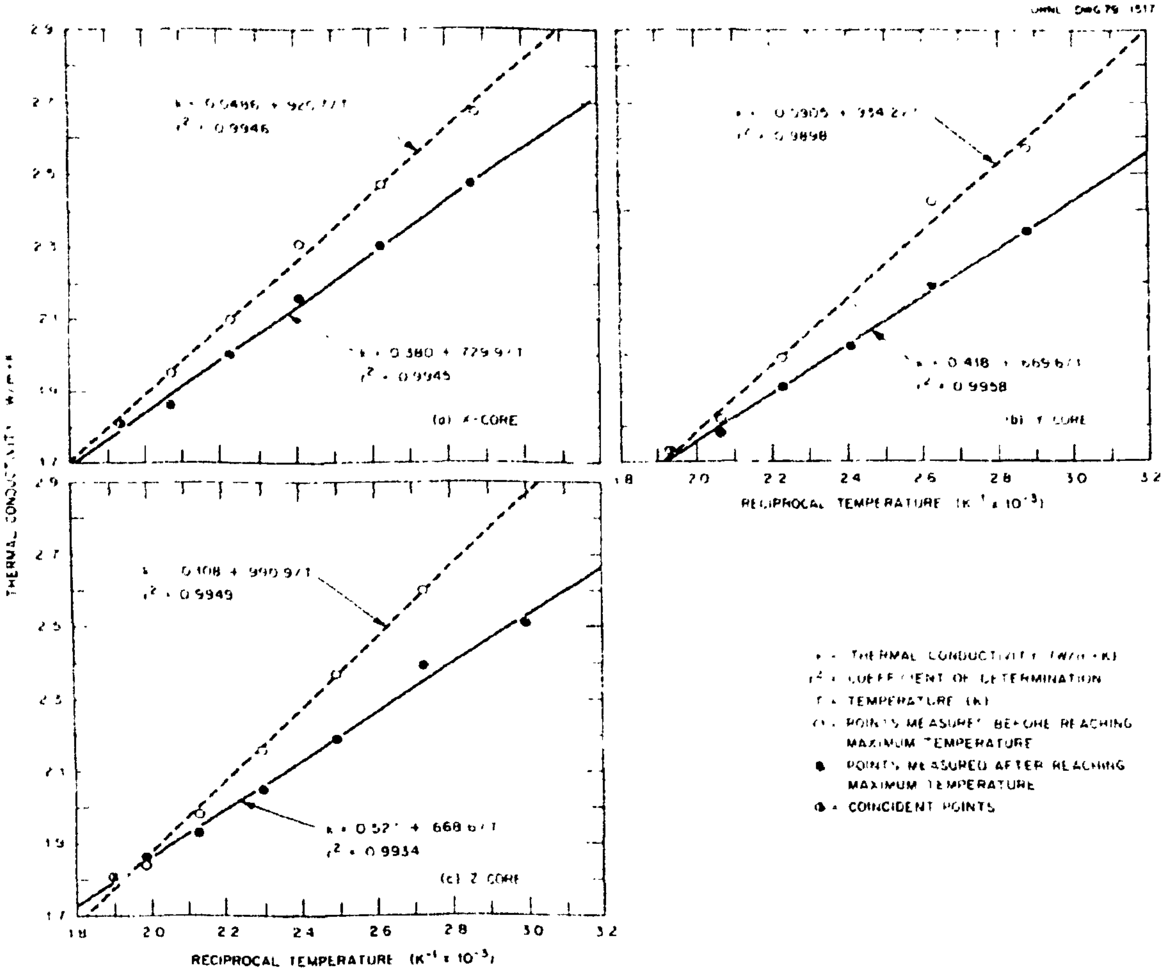

Fig. 8. Thermal conductivity of Holston limestone.

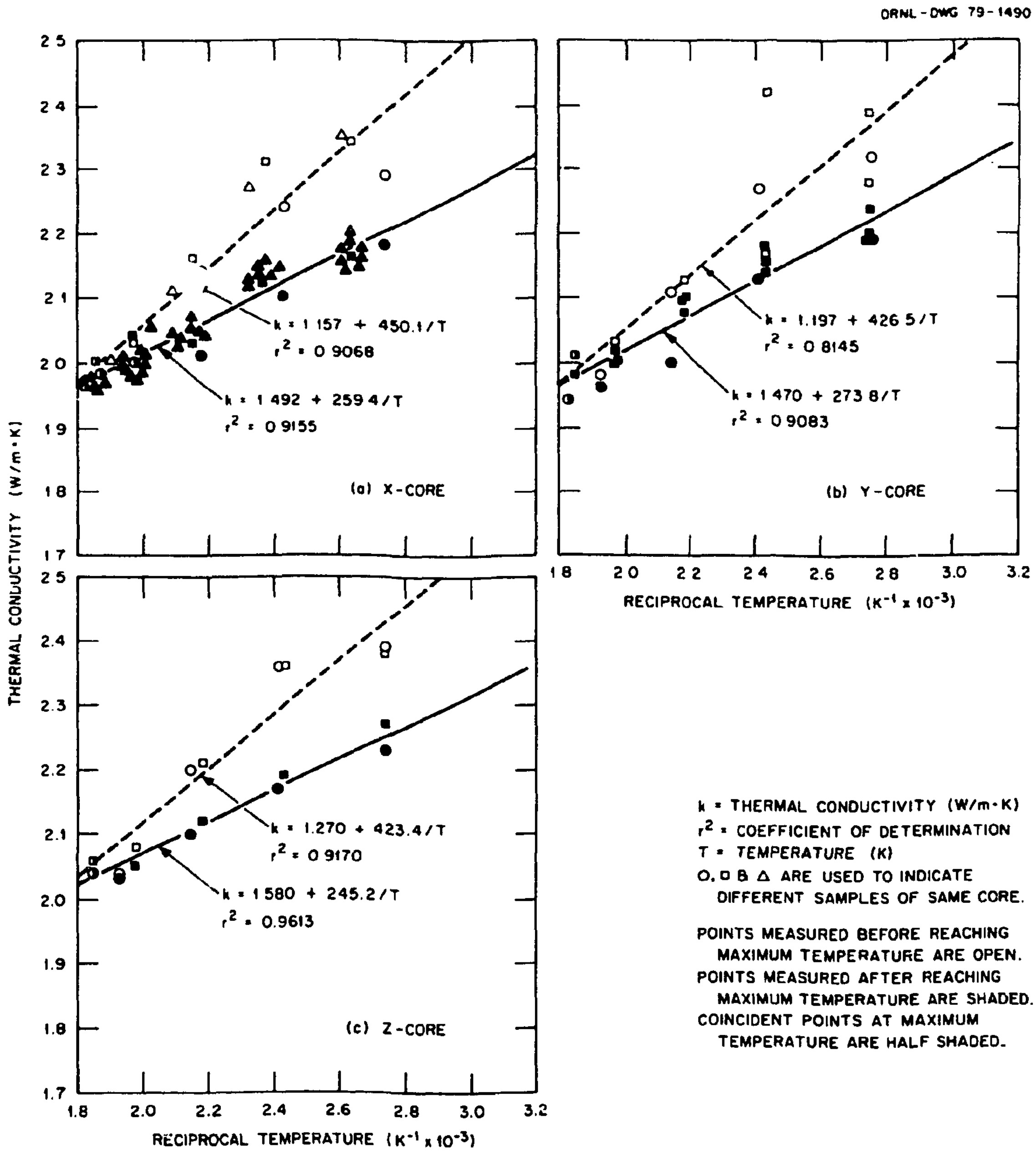

Fig. 9. Thermal conductivity of Westerly granite.

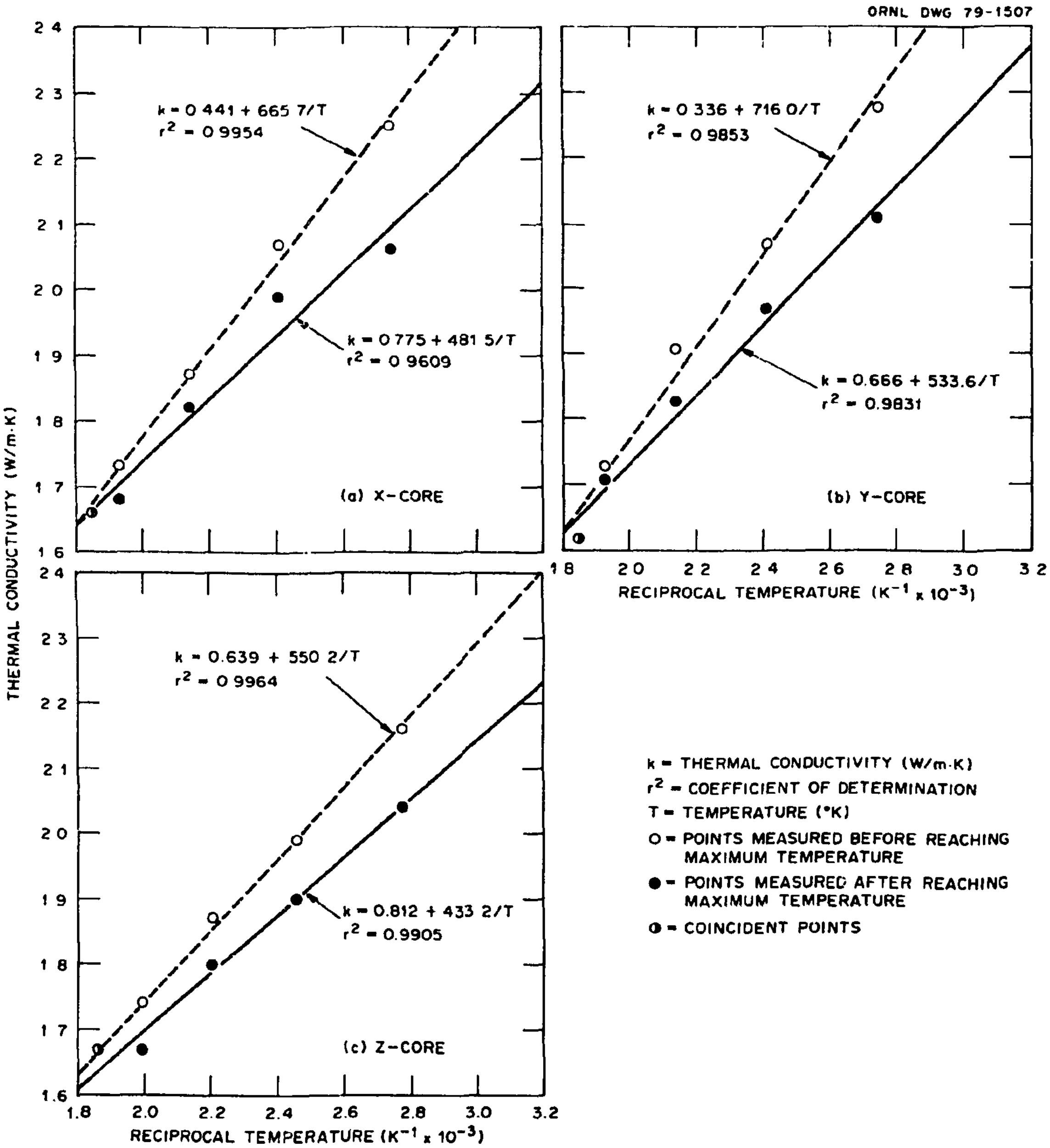

Fig. 10. Thermal conductivity of Berea sandstone.

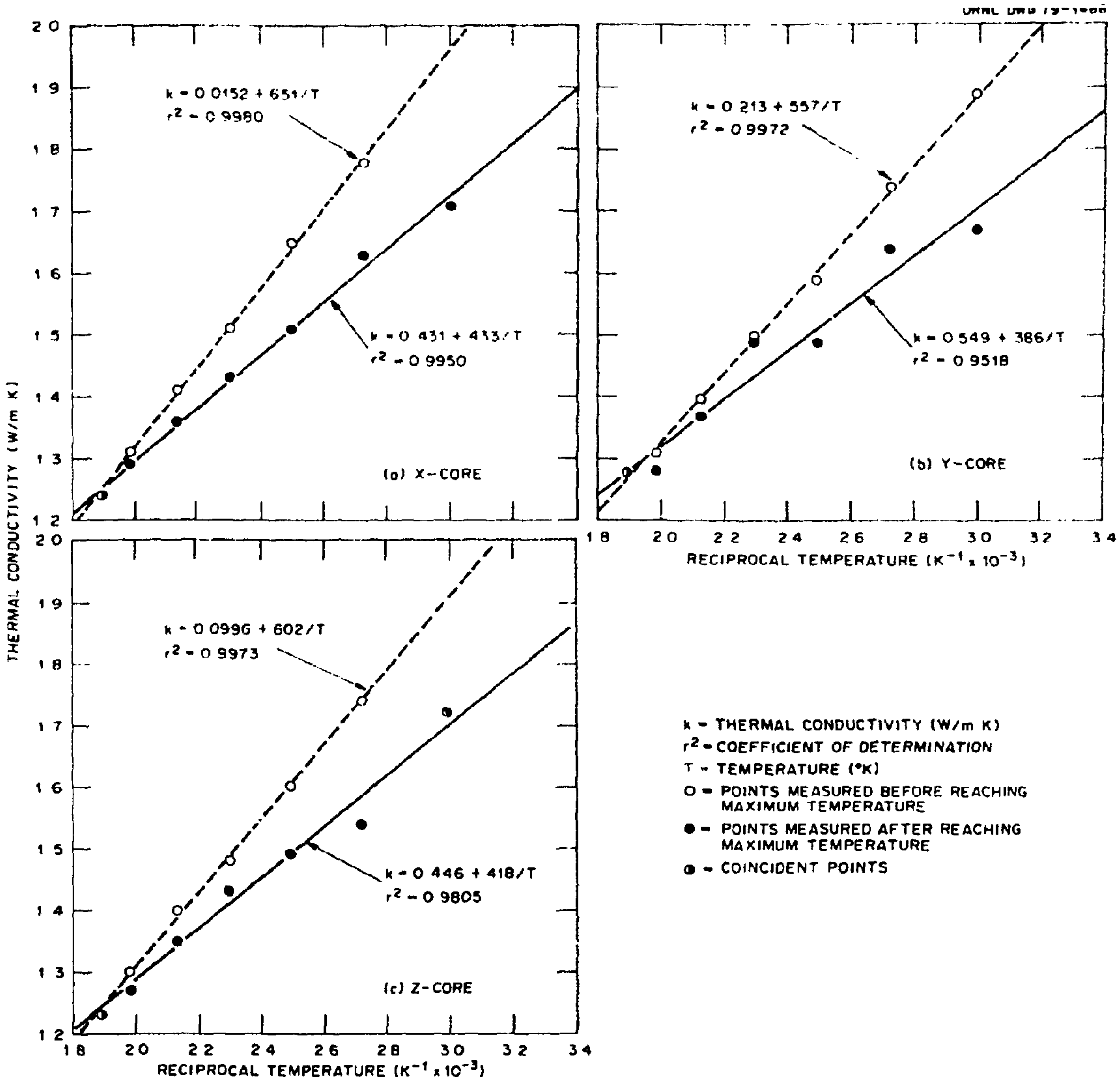

Fig. 11. Thermal conductivity of Salem limestone.

$$r^2 = \frac{\left[\Sigma X_1 Y_1 - \frac{\Sigma X_i \; \Sigma Y_i}{n}\right]^2}{\left[\Sigma X_i^2 - \frac{(\Sigma X_i)^2}{n}\right]\left[\Sigma Y_i^2 - \frac{(\Sigma Y_i)^2}{n}\right]} \; , \qquad (3)$$

where Y = thermal conductivity (k),

X = reciprocal temperature ($1/T$),

n = number of determinations.

The thermal conductivity determined for sample A of the Westerly granite x-core was considerably less than that of the other orientations. This result was verified by rewiring the sample and repeating the measurement. Three additional samples from the x-core were measured along with one additional sample for each of the y and z orientations. The results for these additional samples (Fig. 9) agreed with those for the previous y and z orientations; therefore, sample A of the x-core was considered defective, and the anomalous values were omitted from the determination of average thermal conductivity. In Fig. 12 the thermal conductivity of the defective rock is compared with the average thermal conductivities in the three orientations. Although no reason for the anomalous value is apparent from the external appearance of sample A, the difference indicates a possible change in the rock composition, internal cracking, or porosity of the sample.

Sample A of the y-core of St. Cloud gray granodiorite was also rewired and remeasured. An additional set of samples was run for all three orientations. All of these results were in reasonable agreement and were included in the determinations and in the values plotted in Fig. 6.

The averages of the thermal conductivities of the standard rocks are presented in Table 1. These values are averages of values over three orientations for each rock type and were calculated using the average preheat coefficients listed in Table 2 and the equation

$$k = a + b/T \; ,$$

where T is the absolute temperature (K). The thermal conductivities are

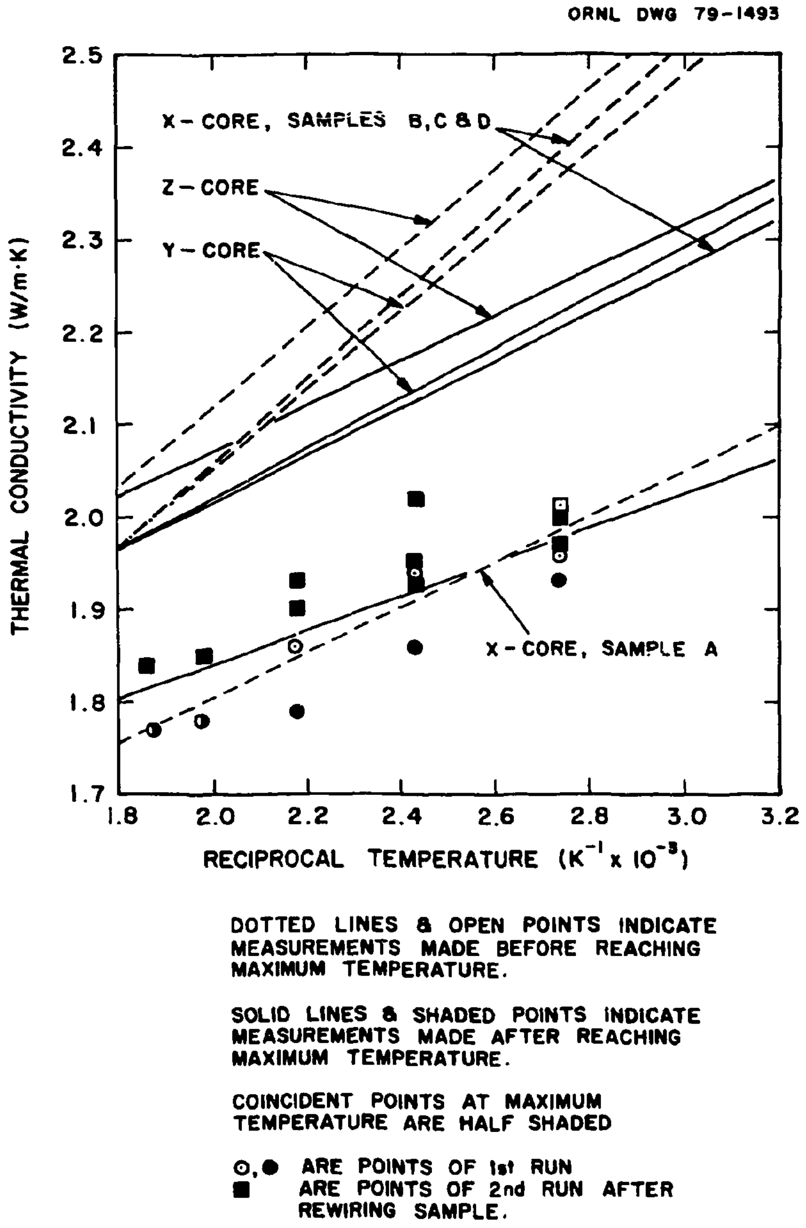

Fig. 12. Variations in the thermal conductivity of Westerly granite.

Table 1. Thermal conductivity of standard rocks

	Thermal conductivity (W/m·K)					Density[d] (g/cm^3)
	This experiment[a]			Hanley[b]	Navarro[c]	
	at 373 K	at 533 K	at 300 K	at 300 K	at 300 K	
Sioux quartzite	5.53	3.74	6.98	5.38	7.04	2.64
Dresser basalt	3.03	2.73	3.26	2.84	2.72	3.02
St. Cloud gray granodiorite	2.68	2.25	3.04	2.62	2.54	2.74
Barre granite	2.49	2.08	2.83	2.79	2.50	2.65
Holston limestone	2.49	1.73	3.11	2.80	3.08	2.70
Westerly granite	2.36	2.00	2.66	2.68	2.70	2.64
Berea sandstone	2.20	1.68	2.62	2.90	2.65	2.13
Salem limestone	1.73	1.24	2.12	2.15	2.25	2.34

[a]All of these values were calculated using coefficients from Table 2 for data measured before reaching maximum temperature of 533 K. Average values for samples in the three orientations.

[b]See ref. 2.

[c]See ref. 4.

[d]Density measured after drying in vacuum oven at 100°C for >1 month.

Table 2. Coefficients for the calculation of thermal conductivities of standard rocks before and after heating to 533 K

	Coefficients*			
	Preheat†		Postheat‡	
	a (W/m·K)	*b* (W/m)	*a* (W/m·K)	*b* (W/m)
Sioux quartzite	-0.436	2225	0.272	1840
Dresser basalt	2.046	365.7	2.062	350.1
St. Cloud gray granodiorite	1.250	534.9	1.525	374.4
Barre granite	1.112	515.5	1.334	314.3
Holston limestone	-0.050	948.6	0.442	689.4
Westerly granite	1.157	450.1	1.492	259.4
Berea sandstone	0.476	641.7	0.753	484.7
Salem limestone	0.109	603.6	0.475	412.3

*For equation $k = a + b/T$, where k = thermal conductivity (W/m·K) and T = temperature (K), the coefficients were calculated from averages of individual values for x, y, and z samples.

†From data measured before heating to maximum temperature of 533 K.

‡From data measured after heating to maximum temperature.

given for the temperatures 300, 373, and 533 K. The 300 K values are beyond the actual range of measurement but were needed for the comparison with conductivities obtained by Hanley, Dewitt, and Taylor,[2] who used a pulsed laser, and Navarro and DeWitt,[4] who used a line heat source method. Although Hanley measured diffusivity over the range 0 to 1000 K, it was difficult to obtain the necessary precision using the graphs, and tabulated values were reported only at 300 K. Navarro's report[4] was not available; the values used were from Hanley and were also at 300 K.

The lower value for quartzite reported by Hanley may be due to the high degree of transparency that this rock has to the laser pulse used in his method. Other values agreed within 17% at 300 K. Densities measured after drying the rocks in a vacuum oven at 373 K for over one month (Table 1) agree with those reported by Krech et al. within 0.9%.

The mathematical coefficients a and b for each rock type obtained by linear least squares fit for data measured in different orientations were averaged and are presented in Table 2. These values include those from measurements made both before and after heating to 533 K. The thermal conductivity at any temperature can be calculated from these coefficients.

The decrease in thermal conductivity due to the heat treatment ranges from 1% in Dresser basalt to 9% in Salem limestone. Repeated cyclic heating to 533 K had no further effect. This effect of heat treatment has been reported previously [3,7] and has been attributed to differential thermal expansion of the mineral grains, producing an irreversible structural change. The average thermal conductivities are plotted versus temperature in Fig. 13 for all of the rock types. (A tabular summary of the experimental data is given in the Appendix.)

To maximize precision in the measurements, the temperature differential across the samples and reference bars was normally maintained $\geq$7 K. Because it was impossible to maintain this differential at temperatures below 363 K, the thermal conductivities measured in this range were more variable. At temperatures above 600 K in air some of the reference bars had previously been observed to change slightly, and supporting insulation for thermocouple lead wires deteriorated. Therefore, the series of measurements for this study were limited to the range 363 to 533 K. Accurate measurements above and below this range can only be obtained by extensive changes in equipment and procedures.

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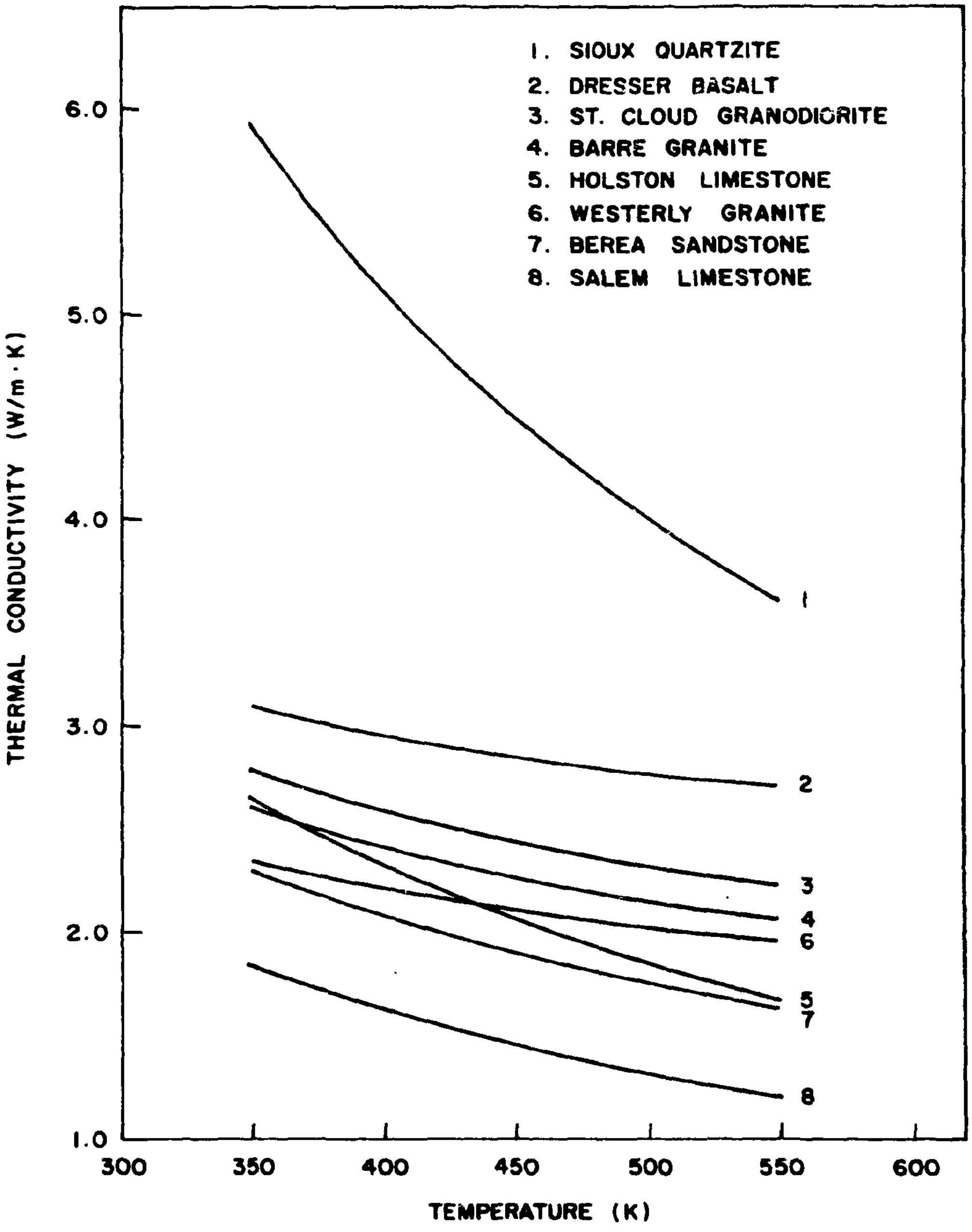

Fig. 13. Thermal conductivity of standard rocks versus temperature (measured before reaching maximum temperature).

4. CONCLUSIONS

Thermal conductivity measurements of the eight standard rocks in the Bureau of Mines Standard Rock Suite indicate no significant anistropy although the variation in one sample of Westerly granite indicates inhomogeneity in this rock type. The data compare well with those obtained by other workers using different methods. This comparison can be used to determine the expected extent of variation from use of these different methods, and to establish the range of uncertainty of these particular standards.

5. ACKNOWLEDGMENTS

We are grateful to Kenneth E. Hjelmstad of the Bureau of Mines, Twin Cities Mining Research Center, Twin Cities, Minnesota, for supplying the rock samples and the report[1] on them.

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APPENDIX

APPENDIX

The Appendix is a summary of all sample temperatures, temperature differentials across sample and reference, measured thermal conductivities, and differences between the measured thermal conductivities and those calculated from the least squares fit of k versus $1/T$. The temperature difference across the reference is an average of that for the top and bottom references. Although data below 363 K (90°C) were not used in calculations because of excessive variations in this range, some data in this range were collected and are included in these tables. The tables are arranged by rock types and by x, y, z orientations. The data in each table are arranged in the order in which the measurements were made. Measurements at maximum temperatures are duplicated as coincident end points in tables of data taken before reaching maximum temperature and data taken after reaching maximum temperature.

The numbers of data and sample temperatures vary for different samples because temperature steps were increased after the program started to speed up the program and because the system was allowed to cycle continuously on some samples during weekends and holidays.

Table A.1. Sioux quartzite, *x*-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
314	4.3	4.1	6.66	1.22
365	8.4	9.4	5.73	0.62
415	14.6	14.9	5.11	-1.84
467	22.2	19.2	4.36	1.42
519	29.5	23.9	3.93	0.29
547	20.1	15.6	3.74	-0.47
Measured after reaching maximum temperature				
547	20.1	15.6	3.74	0.90
518	29.0	23.2	3.84	5.58
467	22.2	19.4	4.32	-7.61
415	15.6	14.5	4.79	0.08
365	8.8	9.2	5.42	0.01
314	3.6	4.1	6.65	-6.48

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.2. Sioux quartzite, *y*-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
314	3.6	4.0	6.65	0.27
365	9.4	9.1	5.67	0.48
415	16.0	14.4	5.03	-1.34
466	24.0	19.0	4.34	0.75
518	31.5	23.0	3.86	0.98
546	22.0	15.6	3.71	-0.83
Measured after reaching maximum temperature				
546	22.0	15.6	3.71	-0.53
518	31.8	23.9	3.88	-0.04
467	24.3	19.2	4.24	0.64
415	16.7	14.1	4.75	0.18
364	9.5	9.0	5.39	-0.27
314	3.8	4.0	6.29	-1.68

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.3. Sioux quartzite, z-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
319	4.2	4.3	6.35	1.3
365	9.4	9.4	5.56	-0.2
365	9.5	9.5	5.65	-1.8
365	9.7	8.9	5.41	2.6
365	9.3	9.1	5.59	-0.7
411	15.6	14.0	4.88	-0.4
459	22.9	18.6	4.26	0.8
506	30.7	22.8	3.83	0.3
539	27.5	18.9	3.59	-0.7
Measured after reaching maximum temperature				
539	27.5	18.9	3.59	-0.71
506	30.6	22.2	3.84	-1.41
459	23.9	18.8	4.14	0.35
411	16.2	14.0	4.64	-0.66
365	9.7	8.9	5.15	0.31
320	4.8	4.4	5.77	1.77
365	9.8	9.1	5.17	-0.03
411	16.5	14.1	4.66	-1.11
459	24.1	18.0	4.11	1.09
506	31.3	22.5	3.78	0.21
540	27.5	18.8	3.57	-0.21
506	30.9	22.2	3.75	1.00
459	23.7	18.4	4.11	1.09
411	16.4	13.8	4.61	-0.03
365	10.0	9.1	5.12	0.95
319	4.4	4.4	5.86	0.34
365	9.9	9.5	5.19	-0.40
412	16.3	13.9	4.68	-1.60
459	23.0	18.4	4.19	-0.88
506	30.1	22.4	3.74	1.14
539	27.1	19.0	3.56	0.09
506	30.6	22.4	3.78	0.17
459	23.3	18.4	4.11	1.07
412	16.8	14.0	4.61	-0.10
365	10.0	9.1	5.12	0.89
319	4.5	4.4	5.89	-0.12
365	9.6	9.1	5.19	-0.38
412	16.4	14.1	4.62	-0.27

[a]Temperature difference across sample or reference.
[b]Percent deviation of thermal conductivity from calculated line value.

Table A.4. Dresser basalt, x-core

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
	Measured before reaching maximum temperature			
319	6.4	3.4	3.14	3.77
365	13.0	7.7	3.10	-0.02
411	20.4	11.2	2.97	0.04
458	28.0	15.5	2.86	0.23
505	35.2	19.7	2.80	-0.61
540	29.5	16.7	2.72	0.37
	Measured after reaching maximum temperature			
540	29.5	16.7	2.72	0.04
506	35.3	19.4	2.77	-0.12
459	27.7	15.4	2.84	0.04
411	20.9	11.4	2.93	0.12
365	13.7	7.4	3.05	-0.03
319	6.2	3.4	3.21	-0.54

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.5. Dresser basalt, y-core

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
	Measured before reaching maximum temperature			
319	6.3	3.6	3.11	2.31
365	13.4	7.6	3.04	0.13
411	20.6	11.3	2.92	0.49
459	28.3	16.1	2.88	-1.24
506	35.3	20.0	2.76	0.45
539	30.4	17.5	2.72	0.34
	Measured after reaching maximum temperature			
539	30.4	17.5	2.72	-0.76
506	35.5	19.7	2.72	0.88
459	28.3	15.5	2.82	-0.05
411	20.5	11.5	2.91	0.08
365	13.1	7.5	3.03	-0.14
319	6.4	3.6	3.11	1.95
293	0.9	0.5	3.05	6.88

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.6. Dresser basalt, *z*-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
319	6.8	3.5	3.08	1.60
365	14.1	7.4	2.99	0.41
411	21.8	11.5	2.92	-0.60
458	29.8	15.6	2.83	-0.28
505	37.2	19.3	2.75	0.23
540	32.2	16.8	2.71	0.23
Measured after reaching maximum temperature				
540	32.2	16.8	2.71	0.23
505	37.2	19.3	2.75	0.14
458	29.9	15.6	2.82	-0.10
411	21.9	11.5	2.91	-0.53
365	14.1	7.3	2.98	0.35
319	6.8	3.5	3.07	1.40

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.7. St. Cloud gray granodiorite, x-core, sample A

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
314	6.2	3.0	2.88	5.04
330	8.7	4.2	2.78	5.54
347	11.6	5.4	2.72	4.88
364	13.9	6.8	2.79	-0.24
381	17.1	8.6	2.73	-0.59
397	20.0	9.5	2.64	0.40
414	22.5	11.1	2.61	-0.72
432	26.3	12.9	2.51	1.03
449	29.6	13.6	2.48	0.23
466	32.1	14.6	2.46	-0.87
483	35.9	16.7	2.41	-0.63
501	38.3	17.6	2.37	-0.69
517	41.5	18.5	2.31	0.29
526	34.4	15.5	2.30	-0.05
Measured after reaching maximum temperature				
526	34.4	15.5	2.30	-1.01
517	41.4	18.6	2.29	-0.04
501	39.1	17.5	2.31	0.15
483	35.3	15.7	2.34	0.07
466	33.1	15.3	2.37	0.05
449	29.3	13.1	2.37	1.36
432	26.2	11.7	2.44	-0.16
415	23.1	10.4	2.45	0.94
398	20.4	9.4	2.59	-3.07
381	17.4	8.1	2.55	0.23
364	14.6	6.7	2.57	1.24
348	11.9	5.6	2.66	-0.26
331	9.1	4.3	2.71	-0.01
314	5.8	2.8	2.73	1.47
297	3.5	1.6	2.78	2.18

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.8. St. Cloud gray granodiorite, x-core, sample B

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
		Measured before reaching maximum temperature		
319	6.7	3.6	2.86	4.80
365	14.2	7.4	2.76	0.69
411	22.9	11.9	2.58	0.89
459	31.3	15.6	2.50	-1.75
506	40.3	18.8	2.30	1.72
533	28.4	13.6	2.27	0.57
		Measured after reaching maximum temperature		
533	28.4	13.6	2.27	-0.16
506	40.2	18.7	2.29	0.70
459	31.0	14.7	2.38	0.17
411	22.6	11.1	2.48	0.04
365	14.8	7.2	2.61	-0.35
319	6.8	3.6	2.74	0.48

[a]Temperature difference across sample or reference.
[b]Percent deviation of thermal conductivity from calculated line value.

Table A.9. St. Cloud gray granodiorite, y-core, sample A

Sample Temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
		Measured before reaching maximum temperature		
314	5.5	2.8	2.68	7.40
348	10.7	5.4	2.55	6.87
381	16.0	8.0	2.54	2.67
415	21.8	11.3	2.50	0.05
450	26.9	13.4	2.43	-0.98
484	33.8	15.7	2.24	3.73
518	38.4	18.6	2.21	2.09
		Measured after reaching maximum temperature		
518	38.4	18.6	2.21	-0.75
484	33.5	15.0	2.17	3.15
450	26.9	13.5	2.26	1.54
415	21.9	10.5	2.33	1.26
381	16.5	7.9	2.36	3.07
348	10.8	5.1	2.46	2.46
314	5.8	2.9	2.64	-0.42

[a]Temperature difference across sample or reference.
[b]Percent deviation of thermal conductivity from calculated line value.

Table A.10. St. Cloud gray granodiorite, y-core, sample A rewired and rerun

Sample temperature (K)	ΔT^a (K)		Thermal conductivity (W/m·K)	Deviation[b] (%)
	Sample	Reference		
Measured after reaching maximum temperatures				
319	6.6	3.3	2.65	-1.47
365	14.4	7.1	2.48	-0.22
412	22.6	11.2	2.38	-0.55
459	31.0	14.9	2.31	-1.32
506	39.0	18.4	2.20	0.41
540	34.3	15.4	2.07	4.42
506	38.6	18.6	2.19	0.84
459	31.3	14.8	2.26	0.86
412	23.3	10.9	2.36	0.27
366	14.6	7.0	2.44	1.36
319	7.1	3.1	2.44	6.56

[a]Temperature difference across sample or reference.
[b]Percent deviation of thermal conductivity from calculated line value.

Table A.11. St. Cloud gray granodiorite, y-core, sample B

Sample temperature (K)	ΔT^a (K)		Thermal conductivity (W/m·K)	Deviation[b] (%)
	Sample	Reference		
Measured before reaching maximum temperature				
319	6.8	3.4	2.79	2.95
319	6.8	3.3	2.84	1.19
319	7.0	3.1	2.73	5.05
373	16.2	7.7	2.66	-0.59
419	24.1	11.6	2.58	-3.50
467	33.2	15.2	2.42	-2.11
514	40.9	18.5	2.31	-1.79
537	25.6	11.6	2.24	-0.56
Measured after reaching maximum temperature				
537	25.6	11.6	2.24	-3.22
514	41.7	18.2	2.24	-1.89
467	33.5	14.9	2.34	-3.20
420	25.3	11.5	2.43	-3.37
373	16.7	7.4	2.52	-2.66
327	8.8	3.9	2.61	-0.98

[a]Temperature difference across sample or reference.
[b]Percent deviation of thermal conductivity from calculated line value.

Table A.12. St. Cloud gray granodiorite, *z*-core, sample A

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
		Measured before reaching maximum temperature		
314	6.6	3.2	2.83	3.42
348	12.5	5.5	2.74	1.08
381	18.3	7.9	2.63	0.28
415	24.6	11.1	2.60	-2.96
449	31.0	13.3	2.50	-2.94
484	37.4	16.0	2.37	-1.06
518	43.2	18.1	2.28	-0.31
		Measured after reaching maximum temperature		
518	43.2	18.1	2.28	-1.77
484	37.7	15.3	2.28	0.54
449	31.6	13.2	2.39	-1.59
415	25.3	10.3	2.43	-0.30
381	19.0	8.0	2.50	0.12
348	12.6	5.3	2.65	-1.98
314	6.7	2.9	2.77	-2.05
291	1.1	0.4	2.65	5.68

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.13. St. Cloud gray granodiorite, *z*-core, sample B

Sample temperature (K)	ΔT^{a} (K) Sample	ΔT^{a} (K) Reference	Thermal conductivity (W/m.K)	Deviation[b] (%)
Measured before reaching maximum temperature				
319	7.5	3.2	2.73	6.01
365	15.7	6.3	2.63	2.53
411	25.0	10.6	2.55	-0.52
459	33.9	13.8	2.38	0.97
506	43.6	16.9	2.24	2.50
533	31.0	12.6	2.21	1.53
Measured after reaching maximum temperature				
533	31.0	12.6	2.21	0.44
506	43.4	16.7	2.22	1.68
459	34.8	13.6	2.31	1.09
411	24.9	10.0	2.45	-0.83
293	1.3	0.5	2.48	11.53
319	8.0	3.1	2.62	2.84
319	7.8	3.1	2.57	4.68
365	15.6	6.4	2.53	0.66
393	25.7	9.9	2.39	3.39
459	34.2	13.4	2.28	2.35
411	25.3	10.0	2.40	1.24
365	16.2	6.6	2.49	2.24

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.14. Barre granite, x-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
314	6.6	2.9	2.60	5.64
365	15.0	6.6	2.52	0.64
415	24.6	11.0	2.42	-2.14
467	34.8	14.7	2.20	1.66
518	43.6	18.1	2.13	0.05
540	23.3	9.4	2.10	-0.40
Measured after reaching maximum temperature				
540	23.3	9.4	2.10	0.18
518	43.7	18.0	2.13	-0.26
467	34.9	14.4	2.20	-0.90
415	25.2	10.5	2.26	-0.43
334	10.0	4.1	2.43	-1.06
384	20.2	7.7	2.25	2.23
436	28.8	12.2	2.25	-1.31

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.15. Barre granite, *y*-core

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
		Measured before reaching maximum temperature		
310	10.4	4.5	2.49	7.73
331	9.1	3.9	2.48	4.37
348	12.3	5.2	2.39	5.02
365	14.6	6.4	2.44	0.39
381	17.7	7.8	2.38	0.31
398	21.2	9.0	2.32	0.44
415	23.7	10.4	2.30	-0.98
432	27.3	11.5	2.21	0.80
449	30.5	12.6	2.21	-1.27
467	34.2	14.1	2.15	-0.48
484	37.2	15.2	2.11	-0.45
501	40.9	16.6	2.04	1.13
518	44.7	17.1	1.99	1.98
526	37.3	15.4	2.05	-1.75
		Measured after reaching maximum temperature		
526	37.3	15.4	2.05	-2.32
518	43.9	17.4	2.00	0.68
501	40.4	16.0	2.01	1.24
484	37.3	14.7	2.04	0.89
467	34.6	14.1	2.08	0.17
449	30.8	12.2	2.09	0.97
432	27.8	11.3	2.15	-0.50
415	25.1	9.9	2.18	-0.43
398	21.2	8.7	2.22	-0.73
381	18.4	7.4	2.27	-1.29
365	15.0	6.2	2.28	-0.02
348	12.5	5.1	2.30	1.03
331	9.5	3.8	2.29	3.47
310	6.5	2.7	2.33	3.91
297	3.7	1.5	2.39	3.84

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.16. Barre granite, *z*-core

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
	Measured before reaching maximum temperature			
314	60.0	3.0	2.71	4.05
365	14.5	6.8	2.58	0.45
415	23.7	10.5	2.43	-0.64
467	33.7	15.1	2.28	-0.32
518	42.2	17.8	2.18	-0.94
540	22.8	9.6	2.09	1.35
	Measured after reaching maximum temperature			
540	22.8	9.6	2.09	0.78
518	42.2	18.4	2.15	-0.76
467	33.9	14.2	2.20	0.38
415	24.4	10.5	2.32	-0.80
365	14.9	6.8	2.41	0.37
314	6.7	3.0	2.49	3.23

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.17. Holston limestone, x-core

Sample temperature (K)	ΔT^{a} (K) Sample	ΔT^{a} (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
314	6.2	2.9	2.82	5.35
348	11.9	5.3	2.67	1.03
381	17.9	7.9	2.47	-0.16
415	25.0	10.4	2.31	-1.82
449	32.3	13.0	2.10	-0.04
484	40.0	14.7	1.95	0.13
517	46.1	16.6	1.81	1.05
Measured after reaching maximum temperature				
517	46.1	16.6	1.81	-1.05
484	39.9	13.5	1.86	1.62
449	33.4	11.8	2.00	0.28
415	25.7	10.2	2.16	-0.97
381	18.9	7.5	2.30	-0.21
348	12.5	5.6	2.47	0.37
314	6.3	3.0	2.68	0.80

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.18. Holston limestone, y-core

Sample temperature (K)	ΔT^{a} (K) Sample	ΔT^{a} (K) Reference	Thermal conductivity (W/m·K)	Deviation (%)
Measured before reaching maximum temperature				
314	5.8	3.1	2.83	1.82
348	11.2	5.7	2.57	1.00
381	17.0	8.3	2.42	-2.51
415	23.4	10.9	2.13	1.44
450	30.4	12.6	1.99	-0.15
484	37.0	14.5	1.82	1.10
518	44.0	16.8	1.73	-1.03
Measured after reaching maximum temperature				
518	44.0	16.8	1.73	-1.17
484	38.2	14.7	1.78	1.19
450	31.5	12.8	1.91	-0.16
415	24.4	9.9	2.02	0.57
381	18.0	7.8	2.19	-0.77
348	11.8	5.6	2.34	0.11
314	6.2	2.9	2.42	5.02
291	0.9	0.5	2.58	5.17

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.19. Holston Limestone, z-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
	Measured before reaching maximum temperature			
334	9.3	4.4	2.73	4.56
367	14.9	7.4	2.60	-0.37
401	21.7	9.9	2.37	-0.32
435	28.7	11.9	2.16	0.43
470	36.5	14.2	1.98	1.06
504	43.8	15.9	1.84	1.03
527	38.2	14.4	1.81	-2.17
	Measured after reaching maximum temperature			
527	38.2	14.4	1.81	-0.82
504	43.7	16.6	1.86	-0.33
470	37.1	13.7	1.93	1.03
435	29.7	11.7	2.05	0.64
401	22.3	9.2	2.19	0.22
367	15.8	6.9	2.39	-1.75
334	9.8	4.5	2.51	0.79
300	4.1	1.9	2.74	0.54

[a] Temperature difference across sample or reference.

[b] Percent deviation of thermal conductivity from calculated line value.

Table A.20. Westerly granite, x-core, sample A

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
320	8.3	2.9	2.02	2.81
366	17.1	5.7	1.96	1.16
412	26.9	9.1	1.94	-1.68
460	35.6	12.1	1.86	-0.70
507	45.9	14.9	1.78	1.01
534	34.0	11.2	1.77	0.21
Measured after reaching maximum temperature				
534	34.0	11.2	1.77	2.57
507	45.3	15.1	1.78	3.00
460	36.6	11.7	1.79	4.42
412	27.1	8.8	1.86	11.53
366	17.3	5.7	1.93	2.31
320	8.3	2.6	2.01	1.87
293	1.4	0.4	2.00	4.76

[a]Temperature difference across sample or reference.
[b]Percent deviation of thermal conductivity from calculated line value.

Table A.21. Westerly granite, x-core, sample A rewired and rerun

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
319	8.5	2.8	2.04	0.43
365	17.4	6.0	2.01	-1.70
411	26.9	9.6	2.02	-5.24
459	36.4	13.0	1.93	-3.04
506	45.5	16.0	1.85	-0.77
539	39.9	13.7	1.84	-1.48
Measured after reaching maximum temperature				
539	39.9	13.7	1.84	-1.48
506	45.9	15.8	1.85	-0.78
459	36.4	12.6	1.90	-1.42
411	27.5	9.3	1.95	-1.60
365	17.6	5.9	2.00	-1.19
319	8.2	2.8	2.00	2.39
365	17.6	5.9	1.97	0.32
412	27.5	9.2	1.93	-0.56

[a]Temperature difference across sample or reference.
[b]Percent deviation of thermal conductivity from calculated line value.

Table A.22. Westerly granite, x-core, sample B

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
	Measured before reaching maximum temperature			
319	7.3	3.0	2.30	10.37
365	16.0	6.3	2.29	4.18
412	24.4	10.1	2.24	0.47
459	34.1	13.6	2.14	-0.09
506	42.9	16.5	2.00	2.26
534	31.4	12.4	1.98	1.01
	Measured after reaching maximum temperature			
534	31.4	12.4	1.98	-0.08
506	42.3	16.6	2.00	0.27
459	34.6	13.1	2.01	2.32
412	25.7	9.8	2.10	1.06
365	16.2	6.3	2.18	1.03
319	7.7	3.0	2.24	2.82

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.23. Westerly granite, x-core, sample C

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
	Measured before reaching maximum temperature			
338	12.2	5.0	2.36	5.24
379	20.1	8.3	2.34	0.14
422	27.2	11.9	2.31	-3.84
465	36.7	15.2	2.16	-1.64
508	44.5	17.4	2.03	0.66
538	38.6	15.2	2.00	-0.31
	Measured after reaching maximum temperautre			
538	38.6	15.2	2.00	-1.28
507	44.8	17.8	2.04	-1.82
465	37.7	14.7	2.03	1.00
422	28.6	11.4	2.13	-1.06
379	20.5	7.9	2.16	0.75
338	12.2	4.7	2.22	1.80
297	3.0	1.2	2.34	1.06

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.24. Westerly granite, x-core, sample D

Sample temperature (K)	ΔT^{a} (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
	Measured before reaching maximum temperature			
338	12.0	4.9	2.42	2.81
384	20.6	8.7	2.35	-0.88
431	29.7	12.3	2.27	-3.08
478	38.9	15.9	2.11	-0.54
525	48.1	18.8	2.00	0.69
546	28.8	11.5	1.96	1.04
	Measured after reaching maximum temperature			
546	28.8	11.5	1.96	0.36
525	47.7	18.5	1.99	-0.18
478	39.9	15.5	2.04	-0.22
431	30.5	12.0	2.13	-1.70
384	21.1	8.2	2.18	-0.55
338	12.7	4.9	2.25	0.47
338	12.5	5.1	2.27	-0.42
380	20.4	8.2	2.16	0.72
422	28.3	11.3	2.14	-1.58
465	37.7	14.7	2.07	0.98
508	44.6	17.0	2.00	0.16
538	39.0	15.3	1.97	0.24
508	44.8	17.6	1.98	1.16
465	37.1	14.6	2.03	0.99
422	29.1	11.3	2.13	-1.09
380	20.6	8.1	2.16	0.72
338	12.7	4.8	2.20	2.66
380	20.4	7.9	2.20	-1.12
422	28.9	11.2	2.14	-1.56
465	37.0	14.7	2.05	0.02
507	44.9	17.7	2.00	0.19
538	39.5	15.5	1.96	0.75
508	44.9	17.4	1.99	0.65
492	37.4	14.5	2.05	-1.50
422	28.9	11.0	2.14	-1.56
380	20.4	8.1	2.16	0.73
338	12.3	4.7	2.19	3.12
380	20.2	8.0	2.15	1.19
422	28.6	11.3	2.14	-1.55
465	37.9	14.5	2.04	0.49
508	44.8	17.5	2.00	0.16
538	39.1	15.1	1.98	-0.27
508	45.1	17.1	1.97	1.67
465	37.9	14.4	2.03	1.00
422	29.3	11.4	2.13	-1.10
379	20.2	7.9	2.15	1.20
338	12.5	4.8	2.24	0.92
380	20.1	7.6	2.16	0.72
422	29.1	11.4	2.15	-2.04
465	37.4	14.7	2.04	0.49
508	45.1	17.1	1.99	0.66
538	38.7	15.1	1.97	0.25
508	27.6	11.0	2.02	-0.86
508	22.3	8.9	1.98	1.17

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.25. Westerly granite, y-core, sample A

Sample temperature (K)	ΔT^{a} (K) Sample	ΔT^{a} (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
	Measured before reaching maximum temperature			
314	6.5	2.6	2.44	4.45
365	15.2	6.2	2.32	1.98
415	24.9	10.3	2.27	-2.05
467	35.4	14.0	2.11	0.04
518	44.8	17.4	1.98	2.01
547	30.0	11.6	1.94	1.98
	Measured after reaching maximum temperature			
547	30.0	11.6	1.94	1.54
518	45.1	17.2	1.96	1.87
467	36.6	13.4	2.00	2.72
415	25.6	10.0	2.13	-0.07
365	15.6	6.0	2.19	1.35
314	6.9	2.7	2.21	5.58

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.26. Westerly granite, *y*-core, sample B

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
319	6.5	2.8	2.41	2.75
365	14.9	6.6	2.39	2.75
411	23.3	10.4	2.42	2.75
319	7.1	2.9	2.30	9.18
293	1.0	0.4	2.34	11.75
319	7.2	2.9	2.29	9.59
293	1.1	0.4	2.32	12.51
319	7.2	2.8	2.31	8.79
365	15.2	6.4	2.28	3.57
411	24.2	10.0	2.17	2.86
458	33.4	14.2	2.13	-0.12
506	41.4	17.1	2.03	0.50
540	36.3	14.8	2.01	-1.13
Measured after reaching maximum temperature				
540	36.3	14.8	2.01	-1.67
506	41.7	17.1	2.00	0.53
459	33.1	13.9	2.10	-2.62
412	24.0	10.0	2.14	-0.26
365	15.2	6.5	2.24	-0.94
319	7.2	2.9	2.25	3.30
365	15.5	6.5	2.20	0.87
412	24.4	10.2	2.18	-2.12
459	33.5	13.7	2.10	-1.62
506	42.0	17.0	2.02	-0.45
540	36.2	14.6	1.98	-0.16
506	42.5	17.4	2.00	0.53
459	33.2	13.6	2.08	-0.66
411	23.9	9.9	2.16	-1.16
365	15.5	6.3	2.19	1.32
319	7.9	3.0	2.24	3.76

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.27. Westerly granite, z-core, sample A

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
315	6.3	2.6	2.52	3.63
365	14.9	6.2	2.39	1.66
416	24.0	10.2	2.36	-3.11
467	35.3	14.2	2.20	-1.07
518	44.8	17.0	2.04	2.25
540	24.1	9.3	2.04	0.67
Measured after reaching maximum temperature				
540	24.1	9.3	2.04	-0.27
518	45.0	17.1	2.03	1.16
467	35.6	13.5	2.10	0.27
415	25.1	9.9	2.17	0.05
365	15.1	5.9	2.23	0.99
315	6.8	2.6	2.34	0.85

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.28. Westerly granite, z-core, sample B

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
319	7.5	3.1	2.47	4.90
365	16.4	6.5	2.38	2.06
411	25.2	10.8	2.36	-2.65
459	34.3	13.6	2.21	-0.77
506	43.4	16.6	2.08	1.28
540	37.4	14.6	2.06	-0.28
Measured after reaching maximum temperature				
540	37.4	14.6	2.06	-1.24
506	44.3	16.8	2.05	0.73
459	36.1	13.3	2.12	-0.24
412	25.9	10.0	2.19	-0.64
365	16.6	6.3	2.27	-0.79
319	8.0	3.0	2.33	0.80

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.29. Berea sandstone, x-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
314	6.3	2.7	2.37	7.39
365	15.1	6.3	2.25	0.74
415	24.3	9.8	2.07	-1.24
466	35.5	14.0	1.87	-0.08
518	45.9	16.4	1.73	-0.19
540	24.5	8.6	1.66	0.78
Measured after reaching maximum temperature				
540	24.5	8.6	1.66	0.38
518	45.8	16.0	1.68	1.44
466	35.5	13.4	1.82	-0.72
415	26.0	10.2	1.99	-2.81
365	15.9	6.1	2.06	1.72
314	6.7	2.7	2.24	2.93

[a]Temperature difference across sample or reference.
[b]Percent deviation of thermal conductivity from calculated line value.

Table A.30. Berea sandstone, y-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
315	5.8	2.9	2.42	7.37
365	14.1	6.5	2.28	0.89
415	23.7	10.4	2.07	-0.44
467	34.9	14.0	1.91	-2.18
518	44.7	16.7	1.73	-0.70
540	24.5	9.3	1.62	2.54
Measured after reaching maximum temperature				
540	24.5	9.3	1.62	2.10
518	44.8	17.1	1.71	-0.84
467	34.8	13.9	1.83	-1.17
415	24.5	9.9	1.97	-0.99
365	14.6	6.2	2.11	0.94
315	6.5	2.7	2.28	3.52

[a]Temperature difference across sample or reference.
[b]Percent deviation of thermal conductivity from calculated line value.

Table A.31. Berea sandstone, *z*-core

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
314	6.0	2.5	2.37	0.81
360	13.6	5.4	2.16	0.28
407	22.3	8.5	1.99	0.08
454	32.2	12.0	1.87	-1.02
501	42.0	14.8	1.74	-0.15
537	39.9	13.5	1.65	0.81
Measured after reaching maximum temperature				
537	39.9	13.5	1.65	-2.00
501	42.3	14.5	1.67	0.33
454	33.0	11.6	1.80	-1.96
407	22.7	8.3	1.90	-1.33
360	13.8	5.3	2.04	-1.32
314	6.3	2.4	2.13	2.69

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.32. Salem limestone, *x*-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
		Measured before reaching maximum temperature		
334	11.1	3.6	1.80	8.45
367	17.9	6.2	1.78	0.48
401	25.3	7.6	1.65	-0.69
435	33.4	9.8	1.51	0.12
470	42.0	11.4	1.41	-0.59
504	50.2	13.2	1.31	-0.20
527	44.2	10.8	1.24	0.82
		Measured after reaching maximum temperature		
527	44.2	10.8	1.24	0.97
504	49.7	12.9	1.29	0.01
470	42.6	11.4	1.36	-0.56
435	34.0	9.1	1.43	-0.35
401	27.0	7.6	1.51	-0.05
367	18.9	5.5	1.63	-1.18
334	11.6	3.5	1.71	1.04

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.33. Salem limestone, *y*-core

Sample temperature (K)	ΔT^a (K) Sample	ΔT^a (K) Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
		Measured before reaching maximum temperature		
334	11.3	3.7	1.89	-0.42
367	17.8	5.6	1.74	-0.51
401	25.3	7.6	1.59	0.80
435	33.5	9.4	1.50	-0.47
470	41.7	11.2	1.40	-0.09
504	49.2	12.4	1.31	0.63
527	42.7	11.0	1.28	-0.80
		Measured after reaching maximum temperature		
527	42.7	11.0	1.28	0.10
504	49.0	12.6	1.28	2.64
470	42.7	11.3	1.37	0.05
435	34.1	9.8	1.49	-3.76
401	26.3	7.4	1.49	1.44
367	18.2	5.4	1.64	-2.45
334	11.3	3.3	1.67	2.09

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.

Table A.34. Salem limestone, *z*-core

Sample temperature (K)	ΔT^a (K) Sample	Reference	Thermal conductivity (W/m·K)	Deviation[b] (%)
Measured before reaching maximum temperature				
334	11.5	3.5	1.80	5.52
367	18.5	5.5	1.74	0.03
401	25.8	7.4	1.60	0.16
436	34.8	9.4	1.48	0.22
470	43.3	10.9	1.40	-1.24
504	51.3	12.3	1.30	-0.37
528	45.3	10.5	1.23	0.93
Measured after reaching maximum temperature				
528	45.3	10.5	1.23	0.66
504	51.4	12.1	1.27	0.46
470	43.8	10.7	1.35	-1.07
436	36.5	9.7	1.43	-1.74
401	27.5	7.1	1.49	-0.13
367	19.5	5.2	1.57	0.91
334	12.0	3.3	1.72	-1.28

[a]Temperature difference across sample or reference.

[b]Percent deviation of thermal conductivity from calculated line value.