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Thermal Conductivity of Rocks from
LASL Geothermal Test Holes GT-1 and GT-2**

by

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PRELIMINARY MEASUREMENTS OF THE THERMAL CONDUCTIVITY OF ROCKS

FROM LASL GEOTHERMAL TEST HOLES GT-1 and GT-2

by

Wilmer L. Sibbitt

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ABSTRACT

The conductivities on a number of dry rocks have been measured in an air environment. These experimental values are probably about 10% lower than the in situ values.

Initial attempts to prepare "wet" rock samples (rocks saturated with water) have so far resulted in only "damp" rocks. Considerable effort will be required to characterize the crack system in "solid" rocks and to predict the probable conductivity values for in situ conditions.

INTRODUCTION

In order to determine the heat flux in a potential geothermal energy source in the region adjacent to the Valles Caldera, it is necessary to measure the thermal conductivity of the rock. The relation for the flow of heat by conduction originates from the French physicists Biot and Fourier and can be expressed by

$$\frac{q_z}{A} = -\lambda \frac{\partial T}{\partial z} \quad (1)$$

The factor of proportionality λ is called "heat conductivity" or "thermal conductivity." The temperature gradient $\frac{\partial T}{\partial z}$ and the thermal conductivity of the rocks in that area must be measured in order to determine the terrestrial heat flux.

Temperatures measured in the topmost 100 m of deep drill holes tend to depart considerably from the usual approximately linear variation observed at greater depths; the data obtained from shallow holes have inherent large uncertainties in both the gradient and the conductivity.

The greatest uncertainty in the determination of the heat flow is the selection of a good mean value of the conductivity of the rocks. An apparently uniform section of rock core may have markedly different conductivities. Two plots (temperature vs depth and temperature gradient vs depth) are of use

in selecting the specimens for conductivity measurements.

If it is assumed that the heat flux is constant (with respect to depth) for deep holes, then changes in temperature gradient must be concomitant with changes in thermal conductivity. (Of course, such effects as weathering, oxidation, radioactivity, moving water vapor or groundwater, etc., are considered to be negligible.) Yet it has frequently been observed that significant changes of temperature gradient occur which do not correlate with visual inspection of the core with respect to rock type. On the other hand significant changes in lithology are not always accompanied by significant changes in temperature gradient.

Thermal conductivities are conventionally determined by measuring the rate of heat flow through a specimen and the corresponding temperature drop across it; the temperature distribution is nearly linear. If this is used for diathermanous* materials, the results depend on the thickness of the specimen as well as the material. It has been called an "apparent conductivity," since it is not a physical property of the material. The apparent conductivity

*All rocks transmit infrared radiation. Even black rocks are not opaque; therefore, there are always two parallel flow paths for the heat.

is the sum of the true conductivity (a physical property) and this radiation conductivity. The radiation contribution is usually negligible for temperatures below 800°K. The experimental specimens should be of such a size that the average values found will be characteristic of large masses. The intercrystalline resistance to heat flow in relatively fresh, wet igneous rocks is low at moderate temperatures, however, the thickness of the specimen should be of an order of magnitude greater than the grain size.

At the end of FY 1972, an exploratory hole 785-m (2575-ft) deep was completed (Geothermal Test Hole No. 1, GT-1). The bottom 50 m (165 ft) of the hole were cored continuously. During FY 1973, selected samples from this core were submitted to two outside laboratories (US Geological Survey (USGS) Menlo Park and New Mexico Institute of Mining and Technology) for thermal conductivity measurements. Results from these laboratories initially seriously disagreed; these differences have now been resolved. However, these discrepancies emphasized the need for developing a reliable in-house capability at LASL for this type of measurement.

DESCRIPTION OF THERMAL-CONDUCTIVITY APPARATUS

The LASL thermal-conductivity measurements were made on a guarded, steady-state, divided-bar apparatus (cut-bar thermal-conductivity comparator). A disc specimen of unknown conductivity is placed in series with copper discs containing thermocouple wells and between two standard discs of known conductivity. The heat source (at the top of the vertical stack of discs) is a condenser. The heat sink is a massive copper block which is maintained at a constant temperature by coolant circulated from a constant temperature bath.

The apparatus is allowed to reach a steady-state condition after the guard heaters have been adjusted to a temperature distribution somewhat above the temperature distribution in the stack of discs. The space between the thermal-guard heater and the stack of discs is filled with an insulating powder such as silica aerogel.

The temperature drops across the sample and the two standards are measured, and then the conductivity of the sample is computed.

The experimental techniques are given in more detail in the Appendix.

TABLE I

THERMAL CONDUCTIVITY OF ROCKS FROM GT-1

Sample No.	LASL		Sample No.	Wet at ~25°C	
	Wet at 25°C (W/m-K)	Dry at 100°C (W/m-K)		N. M. (W/m-K)	USGS (W/m-K)
2444-3	3.287	2.945	2444	3.102	3.354
2488	2.865	2.627	2488	2.939	3.056
2513	2.872	2.630	2513-6	3.081	3.424
2524	2.423	2.303	2528	2.470	2.721
2554	2.213	2.108	2556-6	2.282	2.378
2569	2.354	2.238	2568-6	2.378	2.537

LASL samples: 56-mm-diam
10- to 20-mm-thick

USGS samples: 38.1-mm-diam
11-mm-thick

DATA FOR SAMPLES FROM GT-1 DRILL CORE

The petrography of some rock types of this drill core have been reported.¹ The samples are designated by the true depth below the surface. The LASL samples shown in Table I were from the same section of core as those samples used by New Mexico Tech and the USGS, but they were probably not adjacent samples; therefore any comparison is ambiguous. A sample was obtained from the USGS for a direct comparison of the conductivity values. The results are given in Table II. Since the LASL measurements were made in the temperature interval from 47 to 120°C, it was necessary to interpolate for the value at 100°C and to extrapolate to 25°C.

Since the thermal conductivity of "wet" rock should approach that of the rock in situ, it was necessary to measure the conductivity of "wet" rock. These measurements are difficult at temperatures

TABLE II

COMPARISON OF CONDUCTIVITY VALUES FOR SAMPLE GT-1, 2425 FT

(Density, wet, 2.66 g/cm³)

USGS, wet at ~25°C	3.78 W/m-K
LASL, wet, 1st run at 25°C	3.797 ± 0.040 W/m-K
LASL, wet, 2nd run at 25°C	3.789 ± 0.035 W/m-K

Note. Between Runs 1 and 2, the stack was disassembled; the sample was cleaned, dried, and resaturated with water; and then the stack was reassembled.

TABLE III

THERMAL CONDUCTIVITY^a OF WET AND DRY ROCKS FROM GT-1

Sample No.	λ Wet ^b (W/m-K)	λ Dry ^b (W/m-K)	$\frac{\lambda \text{ Wet}}{\lambda \text{ Dry}}$ ^b (W/m-K)
2444-3	3.287	3.248	1.0120
2488	2.865	2.858	1.0224
2513	2.872	2.765	1.0387
2524	2.423	2.382	1.0172
2569	2.354	2.337	1.0073

^aOptimum saturation of the pores and cracks was not approximated since the maximum hydrostatic pressure was only 1 atm.
^b25°C.

above 100°C, but the measurements on dry rocks are still relatively simple. Preliminary measurements were made on wet and dry rocks and the results are given in Table III. The rocks were dried in a hard vacuum at 70°C, then water vapor was introduced, then the rock was covered with liquid water, and the pressure increased to atmospheric.

DATA FOR SAMPLES FROM GT-2 DRILL CORE

Geothermal Test Hole No. 2 (GT-2) is a deep 2932-m (9619-ft) exploratory hole drilled into Precambrian-age basement granitic rocks of the Jemez Mountains in north-central New Mexico. The purpose of the hole is to confirm the suitability of the site for development of the dry-hot-rock geothermal-energy experiment. A number of reports have been issued covering the drilling, testing, and various diagnostic logging operations in this hole. A report on the petrography of the GT-2 drill core is in preparation.

The measured conductivity values are given in Table IV. Samples 6153-3A and -3B were adjacent discs from the drill core.

DISCUSSION

The apparent or effective conductivity of a composite rock is determined by the relative abundances and orientations of the anisotropic solid phases and of the voids as well as the fluid in the voids. Most samples of igneous and metamorphic rocks can usually be saturated with water for laboratory measurements and thus approach the conductivity of the rock *in situ*. The effect of pressure on a wet (saturated) rock is small. The conductivity of a

TABLE IV

THERMAL CONDUCTIVITY OF ROCKS FROM GT-2

Sample No.	λ Dry at 25°C (W/m-K)	λ Dry at 100°C (W/m-K)
3-2580-43	3.615	3.206
12-4918	3.622	3.209
5964-2A biotite gneiss	2.796	2.565
6153-3A granite gneiss	3.343	2.992
6153-3B granite gneiss	3.264	2.921
16-6156-1	2.866	2.625

Samples: ~60-mm-diam
13-mm-thick

dry rock increases rapidly with pressure up to about 1 kbar where the conductivity approaches that of the same wet rock at low pressure. Apparently 1-kbar pressure is adequate to close most of the microcracks and thus reduce the internal contact resistance in the dry rock. The actual value of the pressure coefficient is a function of the void fraction and of the shapes and orientations of the voids as well as the fluid in the voids.

These generalizations are based on the data reported by Bridgman, Birch, Clark, and Starr et al. as collated by Clark.² The data reported by Walsh and Decker,³ and shown in Tables V and VI, are of particular interest. (There is an obvious mix-up in the caption for Fig. 3 in this publication.)

"Solid rock" is not solid at all but contains many small voids, presumably created upon removal of the high temperature and high pressure which were present during the formation of the rock. Some of the voids may be nearly spherical, but other are fissures (oblate ellipsoids or platelets with very large axial ratios). These fissures or cracks may

TABLE V

THERMAL CONDUCTIVITY OF GRANITE FROM CASCO, MAINE

Pressure (bars)	λ Dry (W/m-K)	λ Wet (W/m-K)	$\frac{\lambda \text{ Wet}}{\lambda \text{ Dry}}$ (W/m-K)
0	2.977	3.224	1.083
50	3.061	3.245	1.060
100	3.111	3.257	1.047
250	3.190	3.270	1.025
500	3.236	3.282	1.014
1000	3.270	3.303	1.010

TABLE VI

CHARACTERIZATION OF GRANITE FROM CASCO, MAINE

Density, 2.626 g/cm ³
Grain diameter, 5.0 ± 1.0 mm
Total porosity, 0.007 ± 0.001
Crack porosity, ^a 0.004 ± 0.0005
Pore porosity, 0.003 (by difference)
Modal analysis: 45 or
28 qu
22 an ₁₅
5 mica

^aThe crack porosity was derived from the pressure-volumetric strain data.

be of the order of a few millimeters long in a granite rock with a total porosity of 0.01.

Unoriented platelets (cracks) of lower conductivity (cracks filled with air or water) will reduce the effective conductivity of the rock.

The effect of orientation is somewhat startling! Consider a fixed but small volume fraction of a second phase initially in the form of spheres. A lowering of the apparent conductivity is effected when the spheres are flattened in the direction of the heat flux for all cases; however, the lowering is at a very rapid rate if the spheres are of low conductivity. Conversely, the apparent conductivity is raised when elongation is in the direction of the heat flux, whether the elongated phase is of higher or of lower conductivity than the matrix.

Anisotropy in a rock is usually caused by anisotropic crack distribution, since the material between cracks in most cases is nearly isotropic and elastic. Cracks nearly normal to the direction of axial compression (also normal to the heat flux) have the greatest effect upon thermal conductivity measurements and are the first cracks to close. Cracks nearly parallel to the axial stress remain open; however, they have only a small effect in reducing the heat flux.

The data shown in Table V are in general agreement with theory. Increasing the axial compression causes cracks to decrease in volume and results in an increase in the conductivity of both dry rock and wet rock. At high stress some porosity still remains; more than 200 kbar would be required to close spherical cavities, but only 3 kbar would be required to close nearly all of the cracks normal to the axis.

Similar data could have been obtained as a result of changes in contact resistance with stress in the divided-bar apparatus itself. Walsh and Decker found this effect to be negligible in previous tests in their apparatus. This could be true if the contact resistances in the apparatus were negligible compared to the thermal resistance of the sample, or if data were acquired in such an arrangement that the film contact resistances in the apparatus cancelled each other in the data analysis.

The thermal-conductivity hysteresis loop as reported by Walsh and Decker is of considerable interest. Cracks with suitable orientations may be closed under uniaxial compression yet some sliding motion of opposed crack faces is possible, although this motion is resisted by friction. While rock grains are nearly perfectly elastic, this sliding motion may also produce a pseudo-plastic deformation. If the dry-rock data in Table V are cast in the form

$$\lambda = \lambda_{P=0} [1 + aP^m], \quad (2)$$

then m is ~ 0.51 for this granite rock. Idealized contact models have shown that values of $m = 0.33$ for elastic deformation and $m = 0.5$ for plastic deformation appear reasonable. The hysteresis loop should not occur for hydrostatic compression. Thermal-conductivity hysteresis loops were not reported for the wet samples.

A similar thermal-conductivity hysteresis loop could have been a result of changes in contact resistances in the divided-bar apparatus itself. The general conclusions from a comprehensive study of contact thermal-conductance activities has been that actual conductance for surfaces in contact under stress is not only difficult to predict but it is usually not reproducible between successive loadings. The data have shown that conductances between coarse finished surfaces are more reproducible in experiments than are highly polished surfaces such as optical flats where the conductance is proportional to the load stress.

Complete saturation of low-porosity rocks such as granite with water is very difficult; in fact, it may be impossible. Hirschwald⁴ recommended the following procedure to obtain optimum saturation of the pores: clean the rock sample; remove air by warming in a hard vacuum environment; let the sample imbibe water vapor for at least 3 h in partial vacuum equal to the vapor pressure of water at room temperature;

cover with liquid water and then apply a pressure of 50 to 150 bars. This technique probably saturates most of the open pore-volume pores which intercommunicate and are connected to the surface including the "dead-ends" pores. Hirschwald showed that imbibition of water under atmospheric pressure resulted in an erroneous large deficiency of apparent porosity. Of course, there is no method of proving that the rock is ever completely saturated.

Since the LASL wet rocks were allowed to imbibe water at atmospheric pressure, they were never saturated with water; consequently, the effect of wetting as reported in Table III is much lower than that shown in Table V.

If the LASL cut-bar comparator has adequate precision then measurements made in vacuo, then in nitrogen environment, then in a helium environment would provide the data for computing the conductivity of a rock with an apparent porosity of zero or with the open pores filled with water.

CONCLUSIONS

1. The effects of cracks in low-porosity rocks must be studied in detail (data from dry vs "wet" rocks).

The characterization of the rocks should include measurements of total porosity as well as apparent porosity.

Apparatus and a technique must be developed for obtaining optimum saturation of the rocks with water.

Conductivity measurements should be made in vacuo as well as in a helium environment in order to completely determine the conductance characteristics of the crack system.

2. Conductivity measurements should be made in the temperature range from 300°K to at least 450°K.

3. The characterization of the rocks should be collated with the conductivity values of the rocks.

4. Assume that conductivity values reported in the literature are accurate (free of systematic and random errors) then these values are all low--below the "true" or in situ values at all temperatures below 300°C.

Even Birch and Clark⁵ assumed that the apparent conductivity of the rock was independent of the helium or nitrogen environment! Their values are probably of the order of 7% low.

If Walsh and Decker suspended the sample over a beaker of water in a vacuum chamber, as they have indicated, then over 3% of the air remained in the sample. Therefore their values for wet compressed rock must still be somewhat low!

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APPENDIX

CHARACTERISTICS OF THE LASL CUT-BAR THERMAL COMPARATOR

Igneous rocks are not readily machined; the fabrication of the sample may change the thermal characteristics of the rock! The formation of complicated shapes and holes of very large aspect ratios may introduce a myriad of very small cracks.

Consequently a simple form of a conductivity comparator was arbitrarily selected.

The LASL comparator was originally developed to measure the conductivities of carbide composites with void fractions as large as 0.93; hence, the requirement for operation in a vacuum environment. The

comparator will accept disc samples up to 63.5 mm in diameter. Some samples as small as 100 mm² in cross section were submitted; therefore, the coaxial guard heaters were added in order to maintain a high degree of precision in the measurements. Another heater which supplied the heat flowing longitudinally through the insulation was used on a few experiments; however, it augmented the problems encountered during evacuation of the system. The use of this heater was discontinued.

Two types of practical problems continuously plague the cut-bar comparator: radial heat losses and contact conductance.

RADIAL HEAT LOSSES

The comparator operates with quasilinear heat flow under certain conditions. Near room temperature, in vacuo, with insulation but unguarded, the radial heat losses are negligible when the diameter-to-thickness ratio of the sample is $\geq \frac{16}{3}$. The guard heaters are necessary to control the radial heat flow under all other conditions. The insulation thickness was optimized (diameter ratio of 1.78) for a nominal rock sample 57 mm in diameter. The guard cylinder approximated a thermal match for anorthosite but is low for granite samples; consequently, two or three guard heaters (function of the stack) are used.

There is always an axial flow of heat in the insulation (shunting effect) since the source and sink temperatures are set in order to establish the temperature gradient in the stack. The guard is slightly mismatched in order to supply the axial heat flow through the insulation. The approximate magnitude of the required mismatch can be established by a numerical analysis for the appropriate useful ranges of thermal and geometrical parameters or by a series of experiments with different degrees of mismatch.

Flat disc samples were selected on the basis of convenience of production and the maintenance of the integrity of the sample. A suitable thickness of sample is used in relation to that of the reference material; however, the sample thickness should decrease as the conductivity decreases. The practical working range of this comparator is of the order of 0.1 to 10 W/m-K; consequently, the optimum thickness of the sample also varies over a wide range.

A linear temperature gradient in both the stack of discs and the guard is the ideal situation. The copper discs in the stack negate this condition to some degree; however, the standards should be selected to match the sample. This is a major problem since the choice of standard materials is very limited--see Table A-I. Probably the only materials with any justifiable claim to being standards are ARMCO iron, Inconel 702 (these are out of the range of this comparator), and Pyroceram and fused silica. The latter two standards do match a few rocks at isolated temperature points. The discs (containing wells for temperature sensors) are made of oxygen-free high-conductivity copper; consequently, they present a negligible constrictive resistance to heat-flow distribution. Therefore, the cross-sectional areas of the standards may be varied and thus match the temperature gradients in a rock sample at any specified temperature.

CONTACT CONDUCTANCE

In this modified divided-bar apparatus, two adjacent temperature transducers measure the temperature drop across the sample disc plus two interfaces (copper and rock) plus two copper discs of one-half thickness. Therefore, the measured temperature drops must be corrected in order to obtain the true values. These corrections should be as small as possible. The correction for the copper discs is very small.

The faces of all rock discs are made as nearly parallel and as nearly flat as is practical. A practical limit to the useful degree of flatness is imposed by the warping of the surfaces due to the imposed temperature gradient as well as the action of an aggregate of noncubic crystals with temperature. Many rock samples are not suitable for precise lapping; there are always slight differences in the perfection of the surfaces. The effective film thickness between two small fused quartz disc standards was about 2×10^{-3} mm but this increased to about 6×10^{-3} mm for the large discs. The conductance is high and it increases rapidly with pressure, but it is not reproducible with successive loadings. This type of variation is intolerable!

Large contact resistances can be reduced at the contacting surfaces by the application of pressure and heat-transfer media such as fluids, cements, thin

TABLE A-I

THERMAL CONDUCTIVITIES OF STANDARD MATERIALS

Temp. (°K)	Fused Quartz		Birch & Clark (W/m-K)
	T.P.R.C. (W/m-K)	Ratcliffe (W/m-K)	
250	1.28	1.275	--
273	1.33	1.323	1.36
300	1.38	1.374	1.40
350	1.45	1.431 ^a	1.46
400	1.51	--	1.51
Error	+4%	+2%	+1%
Pyroceram			
9606			
(W/m-K)			
273	4.13		
300	3.99		
350	3.79		
400	3.65		
500	3.45		
600	3.31		
Error	+5%		

^aExtrapolated.

metal foils or screens--see Table A-II. The liquid mercury-indium-thallium alloys are very good. Teflon can even be wetted by these alloys if sonic agitation is used; light brushing or rubbing is adequate for other materials. The use of these alloys is temperature limited since mercury and thallium are highly toxic. These alloys can be used as a "tinning agent" by dropping molten high-melting solder onto the alloy-wetted surface.

Many suitable low-melting solders, semiliquid and liquid contact materials, silver pigment coating and loaded cements are commercially available. However, in some cases the minimum quantity of material available is one drum (198 liters). Many of the cements have strengths in the range from 6.8×10^6 to 20.7×10^6 Pa, hence the disassembly is a problem.

Most of the liquids listed in Table A-II can be loaded with silver by using a thickening agent (thixotropic) such as methyl cellulose and/or silicon dioxide (CAB-O-SIL).

Excellent results have been obtained with a mixture of Acryloid A-10 (Rohm and Hass) and silver

TABLE A-II

APPROXIMATE THERMAL CONDUCTIVITIES OF MATERIALS

	W/m-K
Silica aerogel (in air)	0.02
Nitrogen gas (atmospheric)	0.026
Helium gas	0.15
Light oil	0.15
Siloxane	0.16
Vaseline	0.18
Ethylene glycol	0.26
Glycerol	0.29
Silicone rubber (96-069)	0.50
Water (liquid)	0.62
Epoxy cements (loaded)	1-10
Mercury (liquid)	8.4
Graphite	141
Aluminum	235
Copper OFHC	398
Silver	427

pigment (Silflake 131, Handy and Harmon). The cement provides a strong bond with uniform high conductance, it can be used in ultrahigh vacuum, it is bakeable to 450°C, yet it can easily be removed. The efficiency of the silver flake varies with the amount of stearic acid on the flakes. The stearic acid should be removed before the flakes are added to the mixture.

A cement mixture of graphite, sodium silicate and clay has been used to bond rocks for the temperature range to above 600°C.

The effective cement film thickness between a copper disc and a large rock sample may be as great as 5×10^{-2} mm--just about the same as for a good silver solder joint. The effective film thickness is measured and the corresponding temperature drop correction is computed. The correction is very small.

The apparent conductivities of various cement films were measured in a stack of 20 copper discs and in a stack of fused quartz discs. The true conductivities of the cements were measured on discs of cast cements. Since in general $\lambda_{\text{copper}} \gg \lambda_{\text{cement}} > \lambda_{\text{rock}}$, the experimental values based upon the measured effective cement film thickness are as follows:

- $\lambda_{\text{film}} > \lambda_{\text{true}}$ for the copper discs,
- $\lambda_{\text{true}} > \lambda_{\text{film}}$ for the quartz discs.

ASSEMBLY

The stack is a sandwich structure with the rock sample placed between two heat meters. A heat meter is a permanent integral unit composed of a comparison standard glued between two copper sensor discs. A loaded epoxy cement is used in the heat meters.

A loaded acryloid cement is used to glue a dry rock sample between the two heat meters. A loaded paste (water and glycerol base) is used to glue a wet rock sample. All gluing operations are carried out in a jig fixture with an axial load maintained on the stack until the glue has set.