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VALUES FOR CONDUCTIVE HEAT TRANSFER IN GEOTHERMAL TECHNOLOGIES

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ABSTRACT

Thermal conductivity and diffusivity of the subsurface are evaluated as critical parameters in the application of certain geothermal technologies. The variability of these parameters as a function of other subsurface properties is investigated. A simple method of estimating thermal conductivity and diffusivity from available information at specific locations is explained, and an interactive computer program that has been developed to assist in this task is described.

INTRODUCTION

Some geothermal technologies rely on conductive transfer of thermal energy in the subsurface either in conjunction with or instead of convective transfer. The use of downhole heat exchangers like those in Klamath Falls (Lund, et al., 1976) involves both conduction and the convection associated with groundwater flow. The lower the hydraulic gradient is, the more important conduction becomes. Increasing attention is being given to the use of heat pumps with downhole heat exchangers where geothermal gradients are normal (Faltermayer, 1982). In these applications conduction is typically the principal means of heat transfer. A third example of the significance of conduction in a geothermal technology is the transfer of heat from hot dry rock to artificially circulating fluids.

When thermal conduction in the subsurface is a significant means of heat transfer in a geothermal system, the thermal conductivity and diffusivity are parameters critical to the development of an efficient design. Because of the wide variability of these thermal properties in the subsurface, a design that is based on a "typical" value is likely to be less efficient than one based on values characteristic of a certain location. Extensive research has led to the correlation of thermal conductivity with other properties, the most important of which are porosity, moisture content, temperature, and mineralogy. From these values, conductivity and diffusivity can be estimated. An interactive computer program has been developed to simplify the task of estimating parameters based on general information about the subsurface at a specific location. By using this approach for improving the precision of these parameters, the efficiency of geothermal applications dependent on thermal conduction should be improved.

THERMAL CONDUCTIVITY AND DIFFUSIVITY

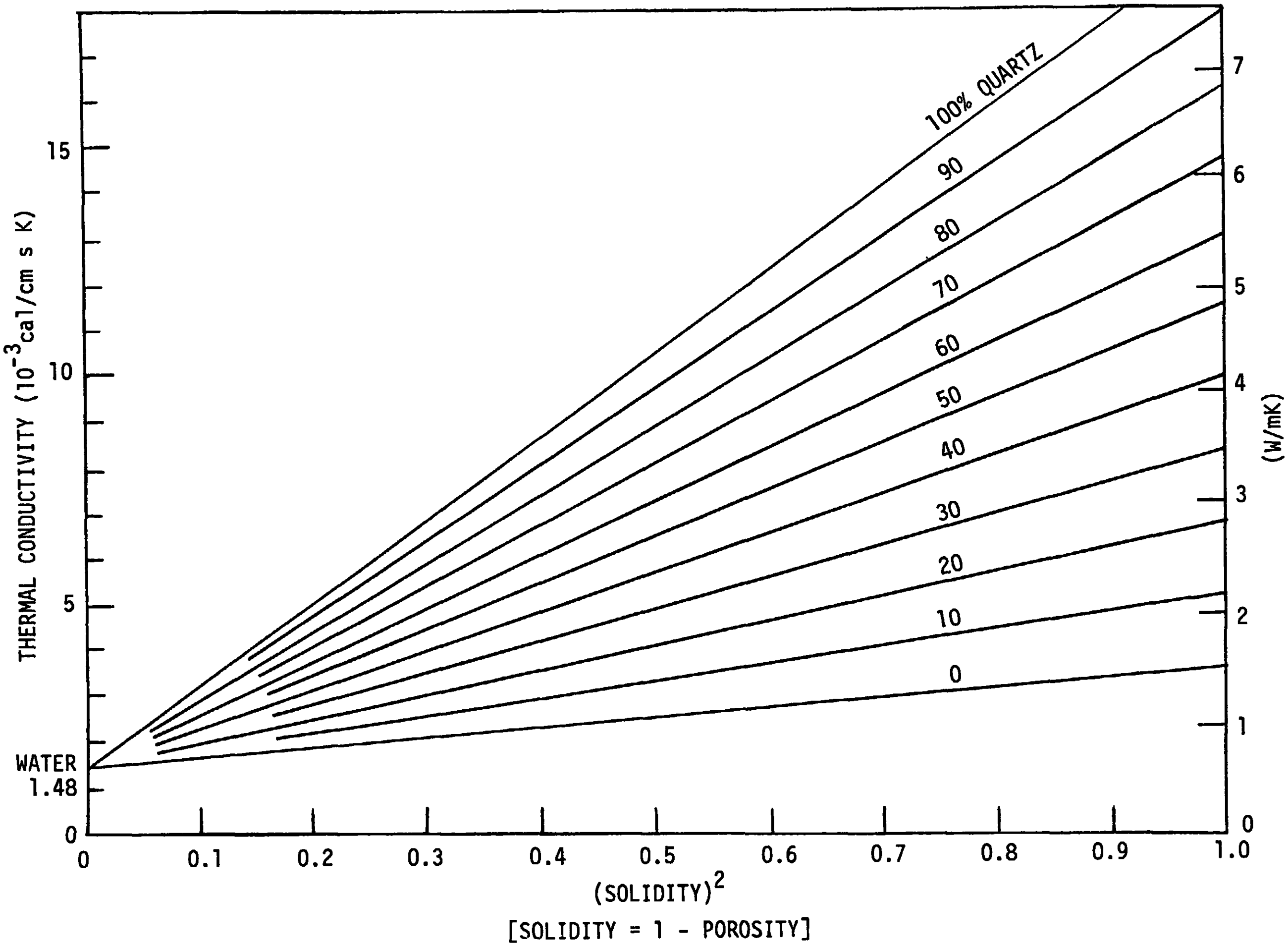
Recognition of the wide variation in the thermal conductivity of different rocks has always been important to understanding the geothermal regime of certain areas. A familiar example is the accumulation of thermal energy below insulating clay or shale strata that are close to the surface. Thermal conductivity in the subsurface has been extensively studied and thousands of measurements have been taken. Diment (1975) provides a comprehensive review of the literature up to 1975. Based on an analysis of nineteen soil types, Kersten's work (1949) is noteworthy for the development of different empirical equations to calculate the bulk thermal conductivities of soils with different textures using bulk density and moisture content as the independent variables. One of the most thorough and recent investigations into the thermal conductivities of rocks has been undertaken by Robertson (1979). His research indicates that, for a standard rock composition, bulk thermal conductivity at a constant temperature is directly proportional to the square of the solidity. Solidity is equal to one minus the porosity.

Robertson illustrates this relationship for different types of rocks with either air or water in the void spaces. Figure 1 is a graph for saturated non-carbonate sediments that demonstrates the variability in thermal conductivity. It also demonstrates the significance of quartz content. Although most common rock and soil forming minerals have a conductivity between 1 and 4 W/mK, quartz has a particularly high conductivity ranging from 7 to 12 W/mK depending on orientation to heat flow. Empirical studies also indicates the significant effect of moisture content and temperature. As moisture content increases, so does conductivity. In contrast, as temperature increases, conductivity typically decreases, although some exceptions have been noted (Robertson, 1979).

Direct measurements of thermal diffusivity are less common than they are for conductivity. Thermal diffusivity (α) is the ratio of thermal

FIGURE 1

THERMAL CONDUCTIVITY OF SATURATED NONCARBONATE SEDIMENTS (from Robertson, 1979)



conductivity (k) to the product of density (ρ) times heat capacity (c) as shown in Equation 1.

$$\alpha = k/\rho c \qquad (1)$$

Therefore, diffusivity can be calculated from the values of these and other properties. Because values of density and heat capacity for each phase in the subsurface fall within a narrow range, use of an average value for these properties should not significantly reduce precision. If average values for these properties are assumed, bulk thermal diffusivity depends on bulk thermal conductivity, either dry bulk density or porosity, either volumetric or gravimetric moisture content, and temperature. Figure 2 shows the theoretical relation between conductivity and diffusivity under saturated conditions at 37°C with varying porosities and varying amounts of quartz. Figures 3 through 6 show the range of conductivity and diffusivity characteristic of different types of rock under saturated conditions at 37°C. The variability of these properties is clearly demonstrated.

COMPUTER ASSISTANCE

Earth-coupled heat pumps are one way of using thermal energy in the subsurface that relies predominantly on thermal conduction. Unlike groundwater heat pumps, earth-coupled heat pumps extract or reject heat to the subsurface through closed loop heat exchangers. To determine the applicability of these systems in different regions of the country, the U.S. Department of Energy has sponsored research on their performance under different conditions. To judge the performance of a design for earth-coupled heat pumps in a certain area, values for thermal conductivity and diffusivity in that area are necessary. The likelihood that use of "typical" values will give misleading results is too great, yet the cost of direct measurement at numerous locations would be prohibitive. Based on the relationships described in the previous section it is possible to estimate reasonably precise values for conductivity and diffusivity from general information about the geology of a certain area.

FIGURE 2

THEORETICAL RELATION BETWEEN THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY BELOW THE WATER TABLE

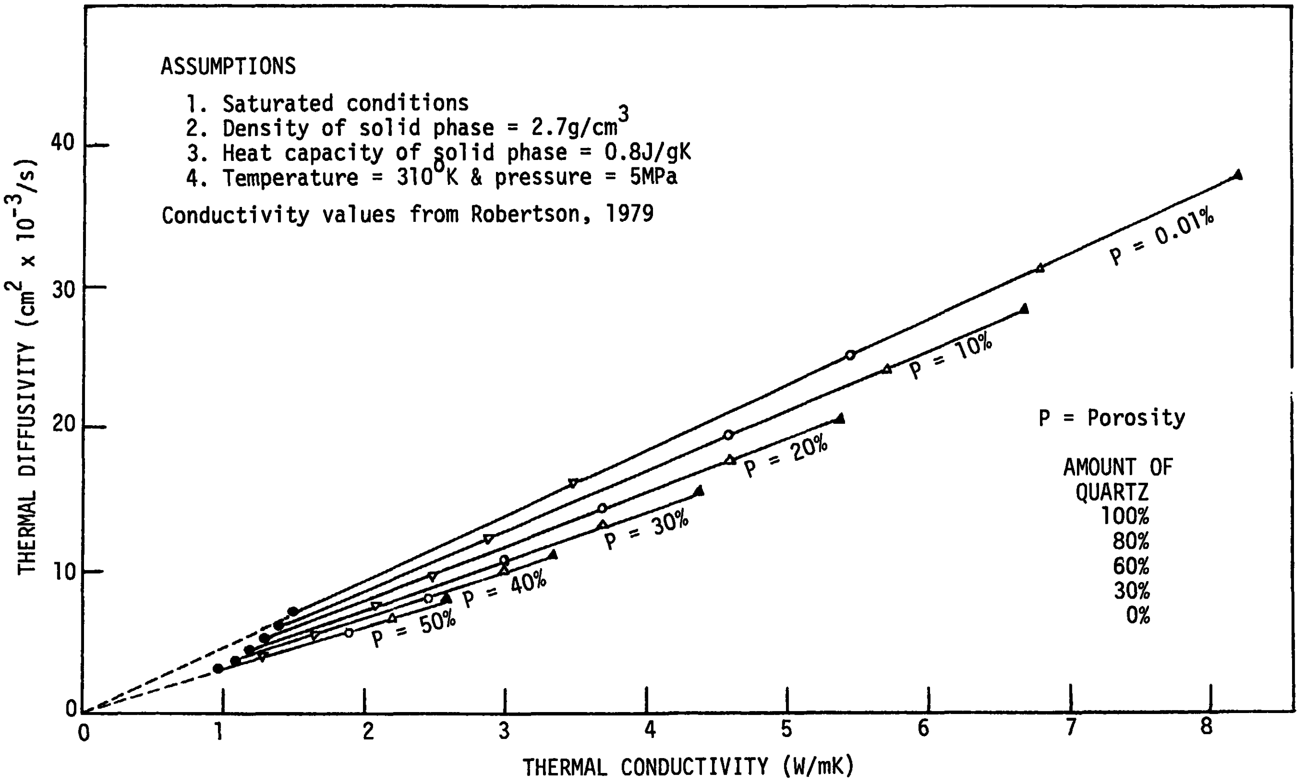


FIGURE 3

THERMAL DIFFUSIVITY AND CONDUCTIVITY OF SANDS AND SANDSTONES

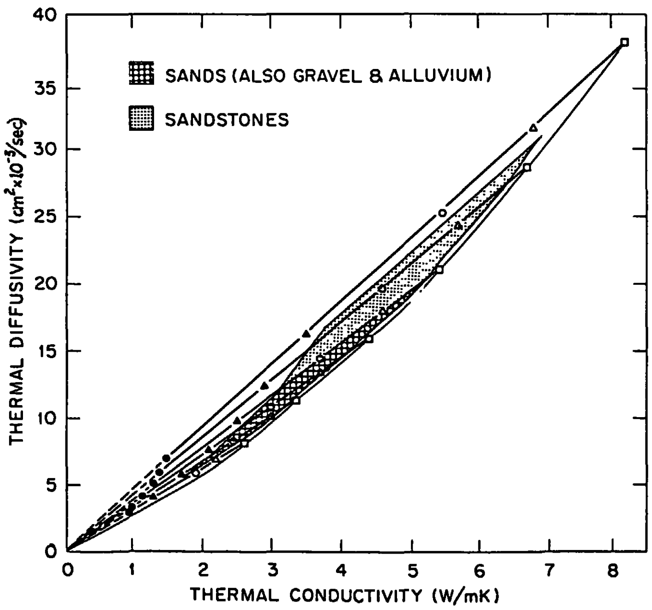


FIGURE 4

THERMAL DIFFUSIVITY AND CONDUCTIVITY OF CLAYS AND SHALES

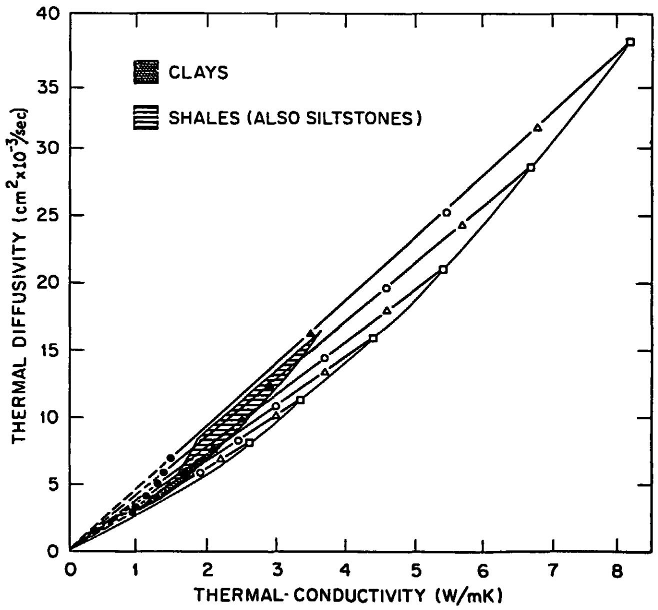


FIGURE 5

THERMAL DIFFUSIVITY AND CONDUCTIVITY OF LIMESTONES AND DOLOMITES

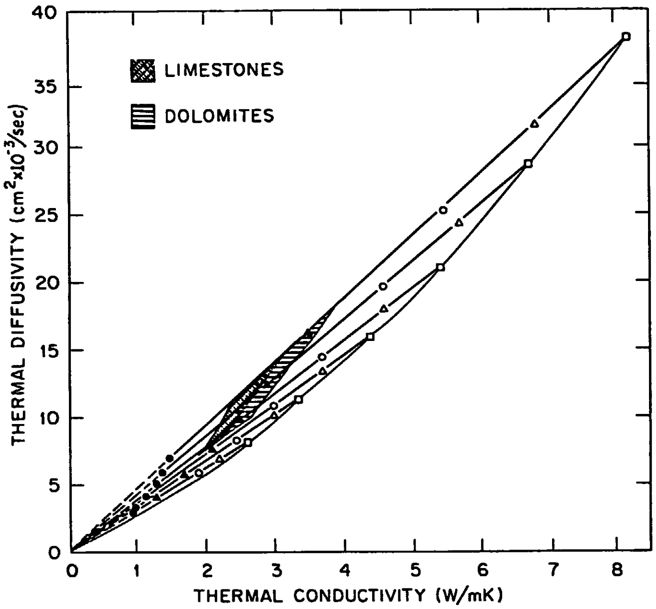
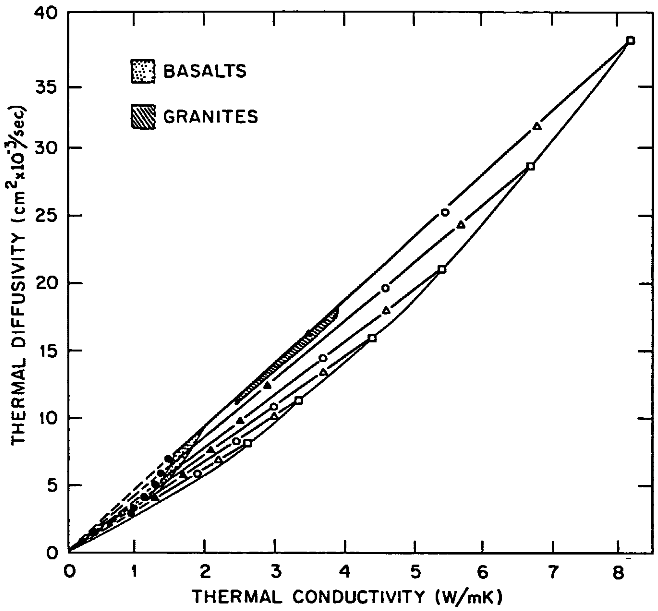


FIGURE 6

THERMAL DIFFUSIVITY AND CONDUCTIVITY OF BASALTS AND GRANITES



A simple interactive computer program named CREATE.THERM has been developed to assist in this task. The computer requests certain data which the analyst provides as shown in Figure 7. From available information about the subsurface at some location, bulk density, moisture content, rock type, quartz content, and heat capacity of the solid phase are estimated for different depth intervals to account for variability with depth. From this information, a value for bulk thermal conductivity is taken from the graphs in Robertson (1979). However, the program can readily be modified to calculate conductivity. Finally, diffusivity is calculated from the above properties. The results are displayed in a tabular form and the weighted averages of the properties over the entire depth are provided. Figure 8 is an example of the results for a well in the Phoenix area. In addition to the aforementioned parameters, information about subsurface temperatures and depth to water table can be input.

CONCLUSION

The program CREATE.THERM has been developed to provide information about the subsurface in order to estimate the performance of designs for earth-coupled heat pumps at a particular location. For this application, which involves moderate temperatures, the effect of temperature on conductivity and diffusivity is considered insignificant and is disregarded. With some simple modification to account for the effects of high temperatures, the program should also be useful to the design of other applications using geothermal technologies that are at least partially dependent on thermal conduction.

FIGURE 7

INPUT FOR CREATE.THERM: AN INTERACTIVE PROGRAM

```
ENTER THE BASE AND THICKNESS FOR INTERVAL # 8
305 129
THE ENTERED BASE AND THICKNESS=  305.0  129.0
IS THE ENTRY CORRECT (Y OR N)?

ENTER THE BULK DENSITY (G/CC)
2.25
THE ENTERED BKD =  2.25
IS THE ENTRY CORRECT (Y OR N)?

ENTER THE MOISTURE CONTENT (PERCENT)
15
THE ENTERED MC = 15.000
IS THE ENTRY CORRECT (Y OR N)?

ENTER THE BULK THERMAL COND. (W/M DEG K)
4.7
THE ENTERED TCB =  4.70
IS THE ENTRY CORRECT (Y OR N)?

IS THE SOLID CAPACITY 0.8 (J/CC DEG K)?

THE CALCULATED TDB = 19.34
```

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Faltermayer, Edmund, 1982, Solar Energy Goes Underground, Fortune, December 27, pp. 91-95.

FIGURE 8

SUBSURFACE PROPERTIES FOR A WELL IN ARIZONA

Well AZ-MURI MARICOPA (PHOENIX) AZ

	BASE	THICK	BKD	MC	TCB	HCS	TDB
1	4.0	4.0	1.50	0.20	1.30	0.80	6.37
2	70.0	66.0	1.90	0.32	1.70	0.80	5.94
3	73.0	3.0	2.00	0.25	3.00	0.80	11.32
4	78.0	5.0	2.10	0.20	2.50	0.90	9.16
5	115.0	37.0	2.00	0.25	3.50	0.80	13.21
6	142.0	27.0	1.60	0.40	1.50	0.80	5.07
7	176.0	34.0	2.10	0.20	5.20	0.80	20.63
8	305.0	129.0	2.25	0.15	4.70	0.80	19.34
9	322.0	17.0	2.10	0.25	2.10	0.80	7.69
Weighted Average			2.06	0.23	3.50	0.80	13.82
Standard Dev.			0.09	0.02	0.49	0.01	2.04

BASE - Base of interval (ft)
THICK - Thickness of interval (ft)
BKD - Bulk density (g/cm^3)
MC - Volumetric moisture content
TCB - Bulk thermal conductivity (W/mK)
HCS - Solid volumetric heat capacity (J/cm^{3}K)
TDB - Bulk thermal conductivity (cm^2 x 10^{-3}/s)

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