MASTER

THE EFFECTS OF A FLUID ANNULUS ON THE PERFORMANCE OF THERMAL TRANSDUCERS IN A BORE HOLE:

SENSITIVITY ANALYSES

Energy Research and Development Administration

Contract E(04-3)-1318

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

H. F. Poppendiek

D. J. Connelly

August 1977

GEOSCIENCE LTD
410 South Cedros Avenue
Solana Beach, California 92075

WDM

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

INTRODUCTION	1
SYSTEM THERMAL PROPERTIES	2
A. The Earth	2
B. Transducer Materials	2
ANALYSES	6
A. Steady State Rod Heat Flux Transducer	6
B. Transient Thermal Conductivity/Thermal Capacity Probe	37
PERFORMANCE CRITERIA AND RESULTS	43
A. Criteria	43
B. Results	43
CONCLUDING COMMENTS	48

INTRODUCTION

The subject down-hole thermal transducer development program for ERDA relates to two different transducer types. One is used to measure the geothermal heat flux under steady state conditions and the other one is used to determine the thermal conductivity and thermal capacity of the earth. In both instances, the measurements are made in place in a bore hole and no core sampling is required. When inserting these transducers into the bore hole, it is clear that a fluid annulus exists between the transducer and the hole. This report describes the effects of the fluid annulus on the transducer performance. On the basis of the analytical work performed, as well as other considerations, the limitations on the annulus thicknesses for these transducers when in a hole are discussed. In addition, the signal outputs for the two measurement methods are considered.

SYSTEM THERMAL PROPERTIES

The thermal properties of various kinds of earth encountered in bore hole measurement work, as well as those for the components of the program transducers, are presented in this section.

A. The Earth

The thermal properties of some sands and soils, sediments and igneous, metamorphic and volcanic rock, as well as other substances are shown in Table I. Note that the thermal conductivity variation for the different materials listed is significantly greater than those for the other properties. Table II shows variations in thermal conductivity alone; note the relatively large ranges in conductivity that can occur for a given earth type (depending upon its complicated composition).

B. Transducer Materials

The thermal properties of the transducer materials used in this program are shown in Table III.

Table I

Thermal Properties of Some Sands and Soils, Sediments and Igneous, Metamorphic
and Volcanic Rock (at room temperature)

	Density gm/cc	Specific Heat cal/gm°C	Density- Specific Heat Product cal/cc°C	Thermal Conductivity cal/sec cm ² °C/cm
<u>Sands and Soils</u>				
dry sand	1.60-1.92			0.00078
wet sand				0.004
coarse soil	2.05	0.44	0.90	0.0012
<u>Sediments</u>				
limestone	2.48	0.22	0.55	0.0012-0.0031
sandstone	2.29	0.22	0.50	0.0045
shale, slate	2.76			0.0036
marble	2.72	0.21	0.57	0.0014
<u>Igneous Meta- morphic and Volcanic Rock</u>				
granite	2.64	0.20	0.53	0.0041-0.0095
mica	2.6-3.2	0.21	0.55-0.67	0.0018
basalt	2.95	0.20	0.59	0.004-0.013
feldspar	2.60			0.0055
<u>Other Substances</u>				
pure water	1.00	1.00	1.00	0.0014
silica	2.3	0.19	0.44	
coal	1.2-1.8	0.3	0.36-0.54	0.0007

Table II

Thermal Conductivities of Various Materials*

* Kappelmeyer and Haenel, Geothermics, 1974, Gebrüder Borntraeger

Table III

Thermal Properties of the Materials that are used in the Thermal Transducers
(at room temperature)

	Density gm/cc	Specific Heat cal/gm°C	Density- Specific Heat Product cal/cc°C	Thermal Conductivity cal/sec cm ² °C/cm
<u>Metals</u>				
copper	8.96	0.091	0.82	0.92
aluminum	2.71	0.214	0.58	0.55
steel	7.80	0.113	0.88	0.11
constantan				0.054
stainless steel	7.82	0.11	0.86	0.039
<u>Plastics</u>				
teflon	2.2			0.0005
silicone				~ 0.0004
<u>Insulators</u>				
glass	2.60	0.16	0.42	0.0021
expanded mica	0.30			0.00028
alumina	3.2	0.18		0.054

ANALYSES

A. Steady State Rod Heat Flux Transducer

Because the closed form rod heat flux transducer solution has been shown to be in satisfactory conformance with the numerical, two-dimensional heat flow solutions described previously,* the former solution was used to perform the annulus analyses for the rod transducer. Specifically, the thermal resistance of the fluid annulus was added to the cylindrical earth resistance to obtain an increased value for R_{∞} for values of $k_{\infty} > k_a$. Similarly, the effect of fluid at the ends of the transducer was also included resulting in an increased R_e for values of $k_{\infty} > k_a$. Equations (10) and (12) in GLR-188 were evaluated for the following typical conditions:

$$\begin{aligned}
 2l &= 6 \text{ feet (1.83 meters)} \\
 d &= 4 \text{ inches (0.102 meters)} \\
 r_0 &= 9 \text{ feet (2.75 meters)} \\
 q/A &= 10^{-6} \text{ cal/sec cm}^2 = 1 \text{ HFU} \\
 k_{\infty} &: 0.7, 2.0, 3.0 \text{ Btu/hr ft}^2(\text{°F/ft}) \\
 k_{\text{rod}} &: 10, 27, 132 \text{ Btu/hr ft}^2(\text{°F/ft}) \\
 \frac{r_{\text{hole}}}{r_{\text{transducer}}} &: 1, 1.1, 1.2 \\
 \text{annular fluids:} & \text{ water, air}^{**}
 \end{aligned}$$

Figures 1 to 30 show the results of the parameter evaluation.

* "Development of Improved Geothermal Well Logging Components: The Heat Flux Transducer and Thermal Conductivity Probe," GLR-188, April 1977.

** The thermal resistance used for the air annulus is based on the worst-case presumption that the transducer surface emissivity is very small (negligible radiant transfer compared to the conduction term).

Figure 1

Figure 2.

Figure 3.

Figure 4.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Figure 11.

Figure 12.

Figure 13.

Figure 14.

Figure 15.

Figure 16.

Figure 17.

Figure 18.

Figure 23.

Figure 24.

Figure 25.

Figure 26.

Figure 27.

Figure 28.

Figure 29.

Figure 30.

Calculations for an 8 inch diameter rod transducer were also made for most of the conditions for the 4 inch transducer noted above. The results for the 8 inch transducer (not shown here) are similar to those for the 4 inch unit except that the temperature profiles are lowered somewhat because of more lateral conduction, as expected.

B. Transient Thermal Conductivity/Thermal Capacity Probe

The addition of a fluid annulus between the thermal conductivity/thermal capacity probe and the bore hole changes the transient conduction system into a two region problem. One region is a thin annulus and the other is a semi-infinite solid. Consider first the case of a thin slab located adjacent to a semi-infinite slab (the thin slab representing the fluid annulus and the semi-infinite slab representing the surrounding earth). The transient boundary value problem for this system is:

For $0 < x < a$:

$$\frac{\partial t}{\partial \theta} = D_1 \frac{\partial^2 t}{\partial x^2} \quad (1)$$

$$t(x, 0) = 0 \quad (2)$$

$$\left(\frac{q}{A}\right)_0 = -k_1 \frac{\partial t}{\partial x} (0, \theta) \quad (3)$$

For $x > a$:

$$\frac{\partial t}{\partial \theta} = D_2 \frac{\partial^2 t}{\partial x^2} \quad (4)$$

$$t(x, 0) = 0 \quad (5)$$

$$\lim_{x \rightarrow \infty} t(x, \theta) = 0 \quad (6)$$

where,

- t , temperature
- θ , time
- x , distance into the semi-infinite solid measured from the outer surface of the thin slab
- D_1 , thermal diffusivity of the thin slab
- D_2 , thermal diffusivity of the semi-infinite solid
- $\left(\frac{q}{A}\right)_0$, constant heat flux addition at $x = 0$
- k_1 , thermal conductivity of the thin slab
- a , thickness of the thin slab

The interface conditions for this boundary value problem are:

$$t(a-0, \theta) = t(a+0, \theta) \quad (7)$$

$$k_1 \frac{\partial t}{\partial x}(a-0, \theta) = k_2 \frac{\partial t}{\partial x}(a+0, \theta) \quad (8)$$

where, k_2 , is the thermal conductivity of the semi-infinite solid.

The temperature solution of this boundary value problem can be found in the literature; ^{*} for the thin slab (annulus) region,

^{*}

Poppendiek, H.F., "Two-Dimensional Transport Models for the Lower Layers of the Atmosphere", International Journal of Heat and Mass Transfer, Vol. II No. 1, pp. 67-79, 1968.

$$\begin{aligned}
t = & \frac{\left(\frac{q}{A_0}\right) \sqrt{D_1 D_2}}{\sqrt{D_1 k_2 + \sqrt{D_2 k_1}}} \sum_0^n \lambda^n \left[2 \sqrt{\frac{\theta}{\pi}} e^{-\frac{(2an+x)^2}{4D_1 \theta}} - \frac{(2an+x)}{\sqrt{D_1}} \operatorname{erfc}\left(\frac{2an+x}{2\sqrt{D_1 \theta}}\right) \right. \\
& \left. + 2 \sqrt{\frac{\theta}{\pi}} e^{-\frac{(2an+2a-x)^2}{4D_1 \theta}} - \frac{(2an+2a-x)}{\sqrt{D_1}} \operatorname{erfc}\left(\frac{2an+2a-x}{2\sqrt{D_1 \theta}}\right) \right] \\
& + \frac{\left(\frac{q}{A_0}\right) k_2}{\sqrt{D_1 k_2 + \sqrt{D_2 k_1}}} \left(\frac{D_1}{k_1}\right) \sum_0^n \lambda^n \left[2 \sqrt{\frac{\theta}{\pi}} e^{-\frac{(2an+x)^2}{4D_1 \theta}} - \frac{(2an+x)}{\sqrt{D_1}} \operatorname{erfc}\left(\frac{2an+x}{2\sqrt{D_1 \theta}}\right) \right. \\
& \left. - 2 \sqrt{\frac{\theta}{\pi}} e^{-\frac{(2an+2a-x)^2}{4D_1 \theta}} + \frac{(2an+2a-x)}{\sqrt{D_1}} \operatorname{erfc}\left(\frac{2an+2a-x}{2\sqrt{D_1 \theta}}\right) \right]
\end{aligned}
\tag{9}$$

$$\text{where } \lambda = \frac{\sqrt{D_2 k_1} - \sqrt{D_1 k_2}}{\sqrt{D_2 k_1} + \sqrt{D_1 k_2}}
\tag{10}$$

and $n = 0, 1, 2 \dots$

Typical calculations were made for a water annulus using Equations (9) and (10). The results are shown in Figures 31 and 32; also shown are the curves for a system where no water annulus exists. The parameters used in the calculations are shown in the legends.

From the results of this work it can be shown that the time constant for establishing the small temperature difference across the annulus is about 0.06 hours (based on the $1/e$ fractional definition). This value is in good agreement with a 0.05 hour time constant for a simple, lumped R-C annulus (also based on the $1/e$ fractional definition). Further, the temperature difference across the annulus is small in comparison to the transducer surface temperature rise above at the initial temperature datum for times greater than the annulus time constants. Therefore, it is Geoscience's position that in a cylindrical coordinate system consisting of a fluid annulus contiguous to the surrounding semi-infinite earth, the annulus time constants and temperature drops will be the same as those for the corresponding linear, two-component slab system. In other words, the annulus solution given by Equation (10) can be used to define the temperature field of the annulus in the cylindrical system; its combination with the temperature field of the one-component cylindrical system yields the total solution.

Figure 31. Time-temperature history of a thermal conductivity/thermal capacity slab system with and without a water annulus (for $0 < \theta < 0.1$ hours).

Figure 32. Time-temperature history of a thermal conductivity/thermal

PERFORMANCE CRITERIA AND RESULTS

A. Criteria

If the thermal properties and the dimensions of fluid annuli between the thermal conductivity transducer and the bore hole wall are known, the effect of the annulus can be accounted for in the two region transient heat transfer solutions. In the case of the thin rod transducer, it is also possible to account for the presence of the annulus using the corresponding analytical representations. However, it is desirable at this point in the transducer development program, to have the annulus effect on the temperature field be relatively small. Then there will be less concern about possible uncertainties in the thicknesses of the annuli and the thermal properties of the fluid contained therein. Therefore, the criterion that will be used to limit the annulus dimension is simply that the hole to transducer radius ratio can range from 1.1 to 1.2, (these ratios are also in general agreement with practical information available on well tool spacing). A second criterion is that the fluids in the annular space will be limited to water or mud.

B. Results

1. Rod Heat Flux Transducer

Table IV summarizes typical thermopile millivolt output signals for the rod heat flux transducer for the case of $q/A = 10^{-6}$ cal/sec cm² (1 HFU), transducer length = 6 ft, transducer diameter = 4 inches, thermopile junctions: copper-constantan.

Table IV

Junction sets	Btu/hr ft ² (°F/ft) k _∞	Output voltage millivolts
50	0.7	0.103
100	0.7	0.206
50	2.0	0.029
100	2.0	0.058

These output signals are large enough to be measured with available laboratory potentiometric instruments. If it is desired to further increase the output, however, it can readily be done by increasing the number of junction sets or using an amplifier at the surface prior to making the potentiometric measurement. It is also pointed out that the millivolt values given in Table IV are for a low HFU value (less than the mean earth value).

Analyses have also been made of the earth thermal conductivity-output voltage sensitivity. For example, if the thermal conductivity of the earth were to change from 1 Btu/hr ft²°F/ft to 2 Btu/hr ft²°F/ft, (for an invariant vertical earth temperature gradient representing the 1 HFU range) the thermopile output voltage would change by 13 percent. This percentage corresponds to a voltage change of 0.0075 to 0.015 millivolts for these severe conditions.

Because 0.001 MV is estimated to be the least reading or limiting noise level, the worst-case sensitivity is believed to be 0.001/0.0075 or 13 percent. Clearly, the sensitivity for more typical conditions would be far better.

2. Thermal Conductivity/Thermal Capacity Probe

Figure 33 shows perturbation calculations where the thermal conductivity, k , and thermal capacity per unit volume, γc_p , for the earth are varied about fixed values by 10 percent. On the basis of such evaluations, it is believed that these two properties can be deduced from such time temperature traces yielding sensitivities that are approximately within 10 percent of true values.

Because of the relatively large temperature differences sensed by the thermal conductivity probe thermopile in comparison to the rod transducer thermopile, the system sensitivity of the thermal conductivity probe will be one to two orders of magnitude greater than that for the rod system.

In addition, the end fringing effects have been investigated. From thermal boundary layer concepts, it is possible to evaluate the length of time that one can operate such a transient probe before the effect of end fringing significantly distorts the temperature profiles. Consider the following illustrative conditions:

Probe diameter : 4 inches

Surface heating : $100 \frac{\text{BTU}}{\text{hr ft}}$

Figure 33

From the time-temperature solution, it can be shown that (for a 36" heater length) the ratio of the thickness of the thermal boundary layer (to the 10% point) to the heated length is $1/9$ after 1.8 hours. The temperature field at the heater center is not influenced significantly by the end fringing for this ratio. If the heater length is 54 inches, it would take 3.5 hours for the thermal boundary layer thickness heater length ratio to reach $1/9$. For a 72 inch heater length, the operating time would be 8 hours.

CONCLUDING COMMENTS

On the basis of the analytical results described in this report and for the conservative criteria that annulus effects on the thermal structure of the sensor systems remain relatively small, the following hole specifications are desired:

1. Open holes with diameter variabilities less than 20 percent.
2. Cased holes containing liners that are plastic with the proviso that the cement annuli are thin (of the order of 10 percent of the liner diameter).
3. All holes are filled with water or mud at those depths where measurements are to be made.

There are several additional application limitations that appear obvious but should be noted here. These transducers are presumed to be used only in homogeneous and isotropic zones. In addition, the transducer should not be used in holes where there is a net flow rate of geothermal fluids as then conductive heat flow is not the only mechanism in operation. Finally, these transducers should be used in holes that are essentially at steady state; the transducers themselves must also be allowed to come to thermal equilibrium before being used.