MASTER

**THE APPLICATION OF DOWNHOLE AND SURFACE
GEOTHERMAL HEAT FLUX AND
THERMAL CONDUCTIVITY TRANSDUCERS IN
GEOTHERMAL RESERVE ASSESSMENTS**

For

**Department of Energy
Division of Geothermal Energy**

Contract EG-77-C-03-1318

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December 1978

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I. INTRODUCTION

This report describes how a downhole rod heat flux transducer¹ can be modified with clamp-on tubular sections so that it can fit into holes of different sizes. In addition, methods are discussed by which a downhole thermal conductivity probe can be modified to be used in holes with different diameters. Also, a short, cylindrical thermal conductivity transducer for use at the bottom of a hole is described and evaluated.

For the sake of completeness, heat flux and thermal conductivity transducers for use at the surface of the earth are also reviewed and discussed.

II. DOWNHOLE GEOTHERMAL HEAT FLUX AND THERMAL CONDUCTIVITY TRANSDUCERS

A. Rod Heat Flux Transducer

In the case of the downhole rod heat flux transducer, there is a simple modification that can be made so that this sensor can be used in holes of different diameters. Specifically, it is proposed that a number of tubes with the same inner diameter but a range of outer diameters are cut into hemi-tubes that can be bolted onto a smaller, thick-wall core tube (whose outer diameter is equal to the inner diameter of the hemi-tubes). A multi-junction thermopile would be located inside the core tube. All the hemi-tubes and the core tube would have the same length, say nine feet. It would, thus, be necessary to build only two core tubes (each containing a thermopile and cablehead); a series of attachable hemi-tubes would yield a versatile transducer system.

The geometrical details of such a transducer are depicted in Figures 1 and 2. Figure 1 shows the cross-section of the core tube containing a multi-junction thermopile. The bottom and top ends of the core-tube are sealed. The top end is provided with the thermopile lead wire adaptor which serves as the terminal point for the cablehead connection. The four threaded holes in the core tube wall (shown at one axial location) are for the purpose of attaching the hemi-tubes shown in Figure 2 with hexagonal bolts. If the downhole diameter is compatible with the core-tube size, the hemi-tubes are not used. In such a case, the threaded holes in the core tube are

Figure 1. Cross-section of core tube.

Scale: 1:1

Figure 2. Cross-section of rod heat flux transducer

safeguarded by plugging them with short allen head screws. The hemi-tube attachment geometry shown in Figures 1 and 2 must be provided in several locations throughout the core-tube length in order to give a rigid transducer assembly. Typical hemi-tube dimensions to be used with the core-tube size of 2-1/2-inch OD are listed in Table I.

TABLE I.
Typical Hemi-shell Sets

Set No.	d_i inches	d_o inches
1	2.5	4.0
2	2.5	5.0
3	2.5	6.0
4	2.5	7.0

The thermal conductivity of the downhole surrounding geological structure may be of high or low value. From the theory involved, two heat flux transducers must be used in making this downhole measurement; one requires being composed of a high thermal conductivity material and the other must have a low thermal conductivity. These materials refer to the core tubes as well as the hemi-tubes. Aluminum is recommended as a practical high thermal conductivity material. Stainless steel, high temperature plastics, impregnated wood, and reinforced concrete are suitable for the construction of the low thermal conductivity rod heat flux transducer.

B. Thermal Conductivity Probe

The evaluation of the data produced by the thermal conductivity probe is made much easier and more accurately if the thermal mass of the transducer itself is as small as possible.¹ Therefore, it is not feasible to attach outer hemi-tubes as in the case of the heat flux transducer. The excess thermal mass would make the data evaluation too difficult.

Another method that has been suggested for generalizing the thermal conductivity probe for use in various sizes of holes deals with an inflatable tube. In other words, if the outer tube of the probe were made of inflatable material, internal air pressure could expand the tube in the hole. There are definite design problems with this concept, however. For instance, the tube would have to be made expandable in the radial direction but restrained in the longitudinal direction so that the thermopile wires and the heater matrix would not be broken by the axial expansion of the tube. It would also be difficult to estimate the flux density produced by the internal heater in the thermal conductivity probe because of the possible variable expansion of the tube due to rough conditions in the hole. It is believed, however, that these difficulties could be overcome in some future development effort.

It would seem to be a more preferable approach, at this time, to work with modular heater thermopile matrices that could be readily installed in a thin wall, low conductivity metal tube, of the required diameter for the hole. These units would consist of thin, long, heater/thermopile assemblies that could be placed side by side and wired together to form a complete assembly corresponding to the inner diameter of the appropriate tube (see Figure 3).

Figure 3. Schematic view of an unfolded modular heater/thermopile matrix.

In this concept, strips of Teflon, perhaps two inches wide and four to six feet long, would be assembled with a number of heater strips and a number of thermopile junctions and then sealed as a unit. When assembled, they would be placed edge-to-edge and electrically and mechanically connected in order to form an assembly that would, in width, approximate the inside diameter of the appropriate tube. The completed heater thermopile assembly could then be pressed into one end of the tube, one end of which had already been welded closed with an end plate and the open end would then be sealed with an O-ring end plate.

A different thermal conductivity probe that could be produced is a short tube transducer for use at the bottom of a drillhole. Specifically, the cylinder would have a length equal to its diameter and would be put into position by means of a low conductivity support tube (see Figure 4). The short cylinder thermal conductivity probe would contain an internal surface heater and a thermopile system similar to the long thermal conductivity probe. In this instance, however, the set of cold junctions would be located external to the short cylinder (at the top of the lowering tube); a mathematical transient temperature solution for a short cylinder would have to be developed; it would be very similar to the classical solution previously described and evaluated by Geoscience for the spherical geometry. It is understood that this short tube transducer would be placed in a hole that contains water or mud.

Figure 4. Schematic view of major elements of the short tube thermal conductivity probe.

III. SURFACE GEOTHERMAL HEAT FLUX AND THERMAL CONDUCTIVITY TRANSDUCERS

Although the downhole transducers developed on this contract can be used in the upper layers of the earth, there are other instruments which have been used to make "surface" measurements which are described below for completeness. One such instrument is the flat disc or plate heat flux transducer (used by Geoscience in shallow holes, in mine tunnels, and at lake bottoms), and the other instrument is a quasi-steady state thermal conductivity probe (used by Geoscience to make soil thermal conductivity measurements).

A. Flat Disc or Plate Heat Flux Transducers

The flat heat flux transducer contains an internal thermopile composed of thousands of thermocouple junction sets connected in series. The thermopile is encased in a stainless steel and Teflon jacket with an O-ring seal that makes the system waterproof. An output cable is connected to a waterproof fitting at the top or side of the transducer. Figure 5 shows a photograph of a flat disc unit that has been used in mine tunnel and lake bottom heat flux measurement programs.

A flat disc or plate heat flux transducer is normally calibrated by the ASTM C-177 method. In this technique, two transducers are separated by flat electric heaters with appropriate end insulation to maintain unidirectional heat flow. By measuring the electrical heat input and the thermopile outputs, the transducer constants can be determined within an accuracy of about ± 5 percent. A typical constant for the 20-inch diameter transducer shown

Figure 5. A photograph of a flat disc geothermal heat flux transducer.

in Figure 5 is 2.3 microcalories per sec cm^2 millivolt. The time constant of such a transducer can be several hours depending on its thickness, thermal conductivity, specific heat and density.

When a flat heat flux transducer is positioned in a medium such as soil in the upper layers of the earth or in the silt at the bottom of a lake, there is some two-dimensional heat flow or flux fringing in the system. If the sensor is designed properly so that (1) its width-to-thickness ratio is relatively large, (2) the transducer thermopile is surrounded by a guard ring, and (3) the thermal conductivity of the transducer is not greatly different from the range of values found for earth, then the transducer flux measurement is representative of the actual flux. In the case of a mine tunnel heat flux measurement,* however, the tunnel width-to-height aspect ratio is not large and thus flux fringing effects are of importance. There are classical two-dimensional transport equations for the case of an infinite cylinder located in a second infinite medium that possesses a uniform potential gradient (normal to the cylinder). From the solution to this two-dimensional steady state boundary value problem, calculations can be made for the change in heat flux at the cylinder bottom (or top) in comparison with the undisturbed flux at some distance from the cylinder. These results can be applied to tunnel heat flux measurement efforts. The solution requires knowing the equivalent or effective thermal conductivity of the tunnel. This value is obtained by making a heat exchange analysis of a mine tunnel including radiative and natural convective transport mechanisms within the tunnel.

* In choosing a mine tunnel in which geothermal heat fluxes are to be measured, the depth must be great enough so that annual heat flow variations are small and it must have a dead end so that forced convection air flow does not exist in the flux measurement region.

In 1974, the flat disc transducer shown in Figure 5 was used to measure the geothermal heat fluxes in four mine tunnels whose depths below the earth's surface were estimated to be greater than 35 feet. In addition, each tunnel had a dead end region so that forced flow convection did not play a role. Figures 6 and 7 show photographs of the recording apparatus and a typical sensor installation, respectively.

The results of steady state (or nearly steady state) geothermal heat flux measurements determined in the mine tunnels are noted in Figure 8, together with D. D. Blackwell's measurements, extrapolated from his iso-heat flow contours.² These contours were established from the drill-hole temperature gradient measurements and strata thermal conductivities. It appears that the direct, heat flux measurements made are in reasonable agreement with Blackwell's data.

B. The Quasi-Steady State Thermal Conductivity Probe

The quasi-steady state thermal conductivity probe is used for measuring the thermal conductivity of soil. The thermal conductivity probe is based on the principle that the temperature gradient around a rod heater inserted into the soil approaches a constant value within a reasonable time. The transient temperature field in the ground around such a rod heater is shown in Figure 9.

At this quasi-steady state, the thermal conductivity of the soil is defined in terms of the heat output per unit length of the rod heater, the temperature difference between the surface of the heater and the measuring station, and the logarithm of the radius ratio between the surface of the heater and the point at which the measurements are made in the soil.

Figure 6. View of the recorder used with the geothermal heat flux transducer.

Figure 7. View of the geothermal heat flux transducer buried at the end of a tunnel.

Figure 8 . Iso-heat flux contours in the Marysville area.

Figure 9.

A quasi-steady state thermal conductivity probe has previously been built by Geoscience and used successfully. It consisted of a long, thin-walled metal tube which was heated by an electrical current which flows through it. The heater tube was surrounded by four radially-placed temperature probes spaced a short distance from the tube. The temperature difference between the surface heater and the four temperature probes spaced around the heater was measured by an internal thermopile system. The aspect ratio of the heater tube was large so nearly one-dimensional radial heat transfer existed. This thermal conductivity probe has been tested in the laboratory with wet and dry sand and the results were found to be in agreement with the values obtained in a laboratory ASTM C-518 thermal conductivity system. The conductivity probe has been successfully used in the field; Figure 10 shows the complete field test system (including a soil electrical conductivity probe).

Figure 10. Geoscience developed field system for thermal and electrical soil conductivity measurement.

IV. REFERENCES

1. Poppendiek, H. F.; D. J. Connelly; A. J. Sellers; C. M. Sabin; J. D. Dunbar; "Development of Downhole Geothermal Heat Flux and Thermal Conductivity Transducers," GLR-201, Sep 1978.
2. Blackwell, D. D.; Czang-Go Baag; "Heat Flow in a "Blind" Geothermal Area Near Marysville, Montana," GEOPHYSICS, Vol 38, No. 5, p 941-956, Oct 1973.