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# NATIONAL BUREAU OF STANDARDS REPORT

9665

Thermal Conductance of Soils

First Quarterly Report

Nov, 1967

by

D. R. Flynn and T. W. Watson

Environmental Engineering Section
Building Research Division
Institute for Applied Technology

Report to

U. S. Atomic Energy Commission
Albuquerque, New Mexico

Contract No.: ASB48-6179
Requester: J. B. Boyd, 9312
Buyer: John G. Boyes-2523

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U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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# NATIONAL BUREAU OF STANDARDS REPORT

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December 29, 1967

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U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

Thermal Conductance of Soils

First Quarterly Report

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## Abstract

An apparatus is described which has been designed and built to enable measurement of the thermal conductance of soils at hot face temperatures approaching 1700 °C. The method utilizes radial heat flow through a hollow cylinder of soil contained between a central ceramic core and an outer water-cooled metal shell. The heat flow through the specimen will be determined by measurement of the total power input to a heater in the central ceramic core. The radial temperature drop through the specimen will be inferred from temperatures measured inside the core and outside the shell, thus avoiding entirely the problems of measuring a temperature difference within the specimen material.

## Key Words

Conductance, conductivity, heat transfer, nuclear safety, temperature, thermal conductance, thermal conductivity.

## 1. Introduction

In conjunction with safety evaluation of space nuclear power systems, it is desired to be able to predict the maximum steady-state temperature which will be reached by a given nuclear power supply after reentry impact burial in earth. In order to do this it is necessary to have information regarding the thermal conductance of soils under conditions in which heat flows from a source which may be as hot as 1700 °C to a sink at ambient temperatures.

## 2. Purpose and Scope

Contract No. AGB48-6179 encompasses an experimental study to measure the effective thermal conductance, as a function of temperature, of nine soils (natural and artificial) selected and furnished by Sandia Corporation. Test temperatures shall be from room temperature to just below the molten range for each soil, with a maximum as near 1700 °C as possible wherever the melt range level permits. Duplicate runs shall be made on each type of soil using different samples.

The thermal conductance shall be measured in a manner that simulates a heat source buried in soil. Artificial gas pressure or inert gas shall not be used in these measurements. Application of any compaction load to the soil samples during test is not allowed.

## 3. Soil Samples

Samples of the following nine soils selected by Sandia Corporation have been received at the National Bureau of Standards:

1. Calcareous Soil (natural weathered limestone)
2. Granitic Detrital Soil (weathered decomposed granite soil)
3. Dune Sand (windblown sand)
4. Magnesian Soil (magnesium aluminum silicate)
5. Podzol Soil (leached organic timberland soil)
6. Coastal Plains Clay (coastal flood plain soil)
7. Laterite Soil (tropical rain forest soil)
8. Estancia Playa (Dog Lake) Soil (highly saline playa soil)
9. Ottawa Sand (silica-artificial soil)

All of these soils were screened to a maximum particle diameter of 1/16 inch (0.16 cm) prior to shipment to NBS.

Sandia has provided us with detailed information concerning each soil sample. These data include theoretical estimates of solid-state reaction temperatures and reaction magnitudes and of the melt range for each soil to be tested. Sandia sent us a reconstitution specification (density and moisture) to be used to place each sample in the proper condition for testing. In future quarterly reports we intend to include the information provided by Sandia regarding each soil sample at the time we report data obtained in this laboratory.

## 4. Differential Thermal Analysis

Contract No. ASB48-6179 requires differential thermal analyses (DTA) of each soil sample in order to provide information regarding soil melt ranges, significant reaction temperatures, and rates and magnitudes of reactions at temperatures between room temperature and 1600 °C. These DTA measurements will be carried out shortly by the Analytical Coordination Chemistry Section of the NBS Analytical Chemistry Division. It is planned that all DTA work be completed in time for inclusion in the next quarterly report.

## 5. Method and Apparatus for Thermal Conductance Measurements

### 5.1. Philosophy of Approach

Our prime concern in deciding on the best experimental approach to this problem was to simulate as closely as possible the conditions which a buried heat source would experience. The following considerations apply:

a. The maximum steady-state temperature, $T_m$ (°C), at the surface of a heat source which is surrounded by soil or other material is given by

$$T_m = T_s + \frac{FQ}{\lambda^*} , \tag{1}$$

where $T_s$ (°C) is the temperature of the sink to which heat is lost. The quantity $Q$ (W/m$^2$) is the power output per unit area from the source.

The geometrical factor, F , depends on the spatial configuration of the heat source and sink. The mean thermal conductivity, $\lambda^*$ ($W\,m^{-1}\,deg^{-1}$), is defined by

$$\lambda^* = \lambda^* (T_s, T_m) = \frac{1}{T_m - T_s} \int_{T_s}^{T_m} \lambda (T)\, d T \quad , \qquad (2)$$

where $\lambda (T)$ is the temperature-dependent thermal conductivity of the soil. From this we see that it is not necessary to measure the actual thermal conductivity, $\lambda (T)$, as a function of temperature if the mean thermal conductivity, $\lambda^* (T_s, T_m)$, can be measured directly as a function of the hot side temperature. This can be done by measuring $T_m$ as a function of Q for some configuration having a known geometrical factor, F, and then computing $\lambda^*$ using eq. (1).

b. If $\lambda^* (T_s, T_m)$, rather than $\lambda (T)$, is measured, the cold surface of the specimen can be kept at room temperature thus considerably simplifying the problem of containment.

c. If $\lambda (T)$ is desired, it can be computed from measured values of $\lambda^* (T_s, T_m)$.

d. Since the quantity of prime interest is the maximum temperature attained by the buried radio-active source, the values of $\lambda^*$ which are appropriate are those obtained after monotonic heating of the hot surface of the specimen.

e. The specimen size should be large enough that the heat flow path is much larger than the average particle size of the soil. For a maximum particle diameter of 1/16 inch, (0.16 cm) it would seem appropriate for the sample to be at least 1 inch (2.5 cm) thick from the hot surface to the cold surface. Similarly, the heat source in contact with the specimen should be large in comparison with the average particle size of the soil. This would preclude the use of "hot-wire" methods.

f. Since the final steady-state temperature at the source surface is of principal concern, it would not be appropriate to attempt to derive thermal conductivity values from measured values of thermal diffusivity and specific heat. This is particularly so for materials such as soils which are subject to decomposition, phase changes, moisture migration, and other phenomena involving heat generation or absorption.

g. However, it must be realized that a buried source may experience transient temperatures which are higher than the final steady-state temperature at the source after equilibrium is attained. This is so because the thermal conductivity may increase, e.g., due to sintering, with time at any given temperature. The best way to determine what would be the maximum transient temperature rise at the surface of a buried heat source of strength per unit area, Q ($W/m^2$), would be by direct measurement of the temperature-time relationship in an experiment which closely simulates the

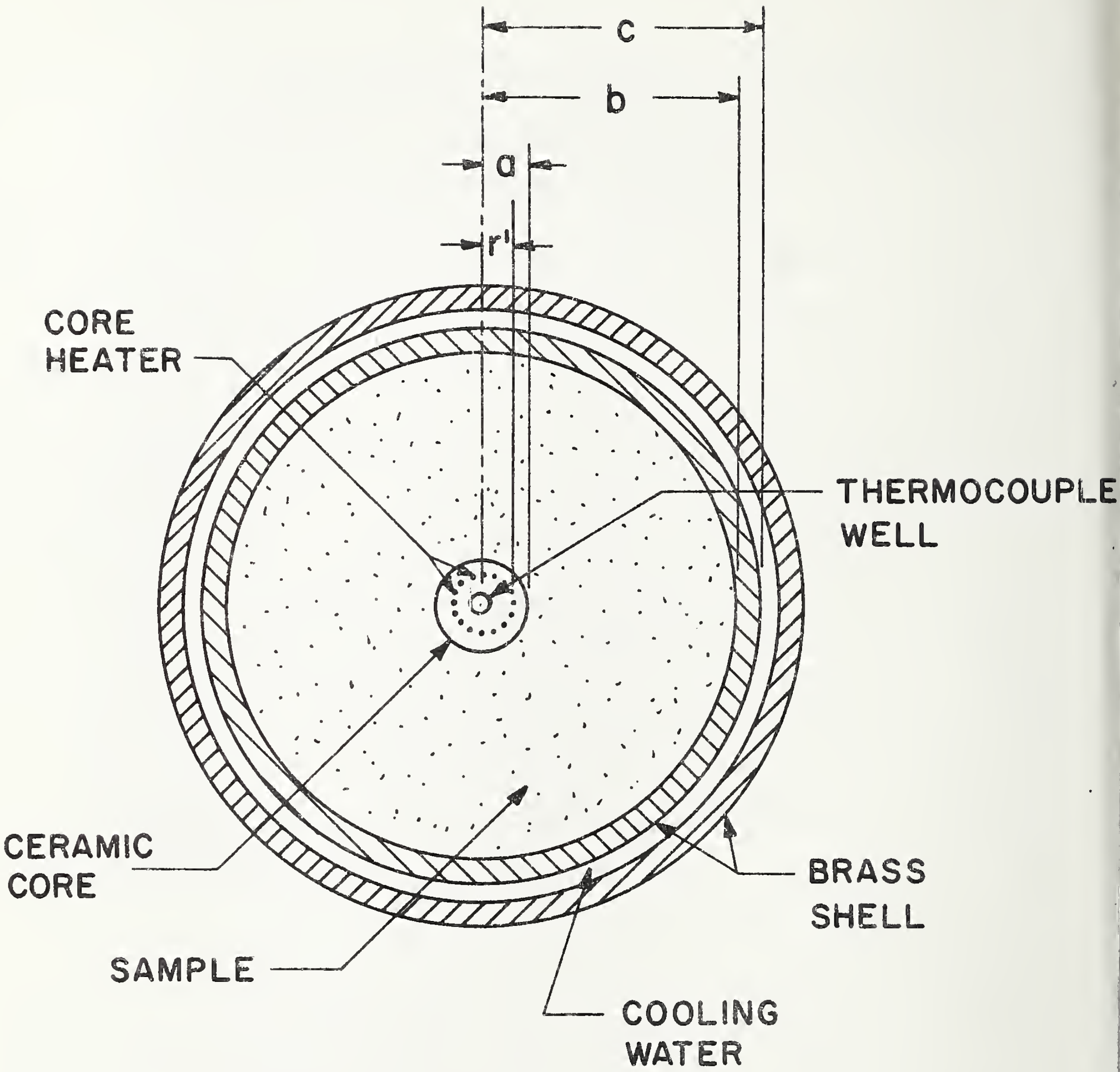


Figure 1. Horizontal cross section of the apparatus for measuring the thermal conductance of soils.

conditions which a heat source buried in soil would encounter.

## 5.2. Method

It was decided to measure the thermal conductance of the soil samples using the method of radial heat flow in a right circular cylinder. A cross section of the apparatus is shown in figure 1. The specimen is contained within the annular space between the outer radius, a, of a ceramic core and the inner radius, b, of a brass shell. A measured quantity of heat per unit time generated electrically in the ceramic core flows radially through the specimen to the inner concentric water-cooled brass shell. The ceramic core has a concentric ring of equally spaced holes at a radius, r', parallel to the axis, each containing a heater wire. Temperatures are measured by an axial thermocouple in the ceramic core and by thermocouples attached to the outer surface of the inner brass shell at radius c.

In figure 1, if the cylindrical surfaces $r = a$ and $r = b$ are each isothermal, the heat flow between these surfaces will be radial except near the ends of the apparatus. In general, the thermal conductivity of the specimen material will vary with temperature, and the heat flow rate per unit area through a cylindrical element of the sample is

$$-\lambda(T)\frac{dT}{dr} = \frac{Qa}{r} \quad , \qquad (3)$$

where temperature is denoted by the symbol T and the temperature-dependent thermal conductivity by $\lambda(T)$. If eq. (3) is rearranged and integrated, we obtain

$$\int_{T_b}^{T_a} \lambda(T)\, dT = Qa\, \ell n\, b/a \quad , \tag{4}$$

where $T_a$ and $T_b$ are the temperatures at $r = a$ and $r = b$ respectively. Let us define a mean thermal conductivity $\lambda^* (T_b, T_a)$ over the temperature range $T_b$ to $T_a$:

$$\lambda^* (T_b,T_a) = \frac{1}{T_a - T_b} \int_{T_b}^{T_a} \lambda(T)\, dT \quad . \tag{5}$$

Combining eqs. (4) and (5), we obtain

$$\lambda^* (T_b,T_a) = \frac{Qa\ \ell n\ b/a}{T_a - T_b} \tag{6}$$

as the expression which can be used to compute $\lambda^*$ from measurable quantities.

As an example of the use of (6) let us consider the case where the thermal conductivity of the sample can be assumed to vary linearly with temperature:

$$\lambda (T) = \lambda_o [1 + \alpha_o (T - T_o)] \quad , \tag{7}$$

where $\lambda_o$ is the thermal conductivity at an arbitrary reference temperature, $T_o$ , and $\alpha_o$ is the corresponding temperature coefficient of thermal conductivity. Substitution of (7) into (5) yields, after integration,

$$\lambda^* (T_b,T_a) = \lambda_o \left[ 1 + \alpha_o \left( \frac{T_a + T_b}{2} - T_o \right) \right] = \lambda \left( \frac{T_a + T_b}{2} \right) \quad . \tag{8}$$

Thus, for a material for which the thermal conductivity varies linearly with temperature, eq. (6) yields a thermal conductivity corresponding to the average of the temperatures at the hot and cold surfaces of the sample.

Equation (6) requires a knowledge of the temperatures $T_a$ and $T_b$ at the inner and outer surfaces of the sample. Experimental difficulties (e.g., finite size of temperature sensors and contamination of sensors by the sample) preclude direct measurement of $T_a$ and $T_b$. Reference to figure 1 shows that there are four temperature drops which must be considered in deriving $T_a$ and $T_b$ from the measured temperatures:

1. The temperature drop between the thermocouple well in the center of the ceramic core and the surface, r = a, of the ceramic core.
2. The temperature drop due to the thermal contact resistance between the surface of the ceramic core and the inner surface of the sample, both surfaces being nominally at r = a.
3. The temperature drop due to the thermal contact resistance between the outer surface of the sample and the inner surface of the brass shell, both surfaces being nominally at r = b.
4. The temperature drop between the inner surface, r = b, of the brass shell, and the outer surface, r = c, where the temperature is measured.

If the circle of heater wires at $r = r'$ were a continuous cylindrical heat source, the entire region $r < r'$ inside the heater circle would be isothermal. For the case of a finite number of line heat sources at $r = r'$, the temperature measured at the axis is equal to the average temperature, $T_h$, at the radius of the heater circle [1,2][1]. Therefore the temperature drop between the thermocouple well in the center of the core and the surface of the core is given by

$$T_h - T_a' = \frac{Qa \ \ell n \ a/r'}{k_c} , \tag{9}$$

where $k_c$ is the thermal conductivity of the ceramic core material and $T_a'$ is the temperature at the outer surface, $r = a$, of the ceramic core (as opposed to $T_a$, which is the temperature at the inner surface, also $r = a$, of the sample).

If we designate $R_a$ as the thermal contact resistance per unit area (deg $m^2$ $W^{-1}$) at the core-specimen interface ($r = a$), then the temperature drop across this interface is given by

$$T_a' - T_a = R_a Q . \tag{10}$$

Similarly, the temperature drop at the specimen-shell interface ($r = b$) is given by

$$T_b - T_b' = \frac{a}{b} R_b Q , \tag{11}$$

[1] Figures in brackets indicate the literature references at the end of this report.

where $T_b'$ is the temperature at the inner surface, $r = b$, of the brass shell (as opposed to $T_b$, which is the temperature at the outer surface, also $r = b$, of the sample) and $R_b$ is the thermal contact resistance per unit area at the specimen-shell interface.

The temperature drop across the brass shell is

$$T_b' - T_c = \frac{Qa \, \ell n \, c/b}{k_s} , \tag{12}$$

where $T_c$ is the temperature at the outer surface of the shell, $r = c$, and $k_s$ is the thermal conductivity of the shell material.

In the apparatus configuration shown in figure 1, the temperatures measured correspond to $T_h$ and $T_c$ as defined above. Combining equations (6), and (9) through (12), we can eliminate all of the temperatures involved except $T_h$ and $T_c$ and thus obtain, instead of (6),

$$\lambda^*(T_b,T_a) = \frac{Qa \ell n b/a}{T_h - T_c} \left[1 - \frac{Qa}{T_h - T_c}\left(\frac{\ell n a/r'}{k_c} + \frac{\ell n c/b}{k_s} + \frac{R_a}{a} + \frac{R_b}{b}\right)\right]^{-1} . \tag{13}$$

The magnitude of the correction terms in eq. (13) is more readily seen if we define

$$\lambda^*_{app} = \frac{Qa \, \ell n \, b/a}{T_h - T_c} \tag{14}$$

as the apparent value of thermal conductivity obtained by neglecting the correction terms; combining (13) and (14) we obtain

$$\lambda^* (T_b,T_a) = \lambda^*_{app} \left[ 1 - \frac{\lambda^*_{app}}{\ell n b/a} \left( \frac{\ell n \, a/r'}{k_c} + \frac{\ell n \, c/b}{k_s} + \frac{R_a}{a} + \frac{R_b}{b} \right)\right]^{-1} . \tag{15}$$

Equation (15) is the basic equation to be used for calculating mean thermal conductivity values using the apparatus shown in figure 1. The quantities a, l, Q, $T_h$, and $T_c$ involved in the definition of $\lambda^*_{app}$ (eq. (14)) are all directly measurable. The quantities $k_c$, $k_s$, $R_a$, and $R_b$ (required for the correction terms in (15)) must either be known or the corresponding correction terms shown to be negligible. Since eq. (15) is based on the assumption of purely radial heat flow, it must also be demonstrated that longitudinal heat flows are negligible; alternatively, corrections would have to be made for the effects of non-radial heat flows.

The thermal conductivity value $\lambda^* (T_b, T_a)$ is a mean value corresponding to a case where the hot-side and cold-side temperatures differ greatly. If the actual thermal conductivity value at the hot-side temperature is desired, this can be obtained using the relation,

$$\lambda(T_a) = \lambda^* (T_b, T_a) + (T_a - T_b) \frac{\partial \lambda^* (T_b, T_a)}{\partial T_a} , \qquad (16)$$

which is obtained by differentiation of eq. (5).

## 5.3 Apparatus

A vertical cross section of the apparatus designed and built for the thermal conductance measurements is shown in figure 2. The specimen is contained in the annular space between the central ceramic core, which is supported at both ends, and the inner brass shell. Cooling water flows in the 3-mm annulus between this inner brass shell and a coaxial outer brass shell.

The central core is an extruded alumina rod, 46 cm long and 1.25 cm in diameter. A horizontal cross-section of this core is shown in figure 3. Sixteen equally-spaced holes, 0.09 cm in diameter, extend the entire length of the rod. The centers of these holes form a circle of 0.44 cm radius. The core heater, which provides the heat flowing radially through the specimen, consists of a continuous length of platinum - 40 percent rhodium (0.06 cm diameter) wire threaded back and forth through the sixteen holes. The core is held from beneath by a ceramic insulating support designed to permit free expansion of the heater wire. The upper end of the core passes through a hole in the removable flange at the top of the apparatus; this hole is a sufficiently loose fit to permit free expansion of the core. Current leads and voltage taps are attached to the heater winding at the upper end of the core.

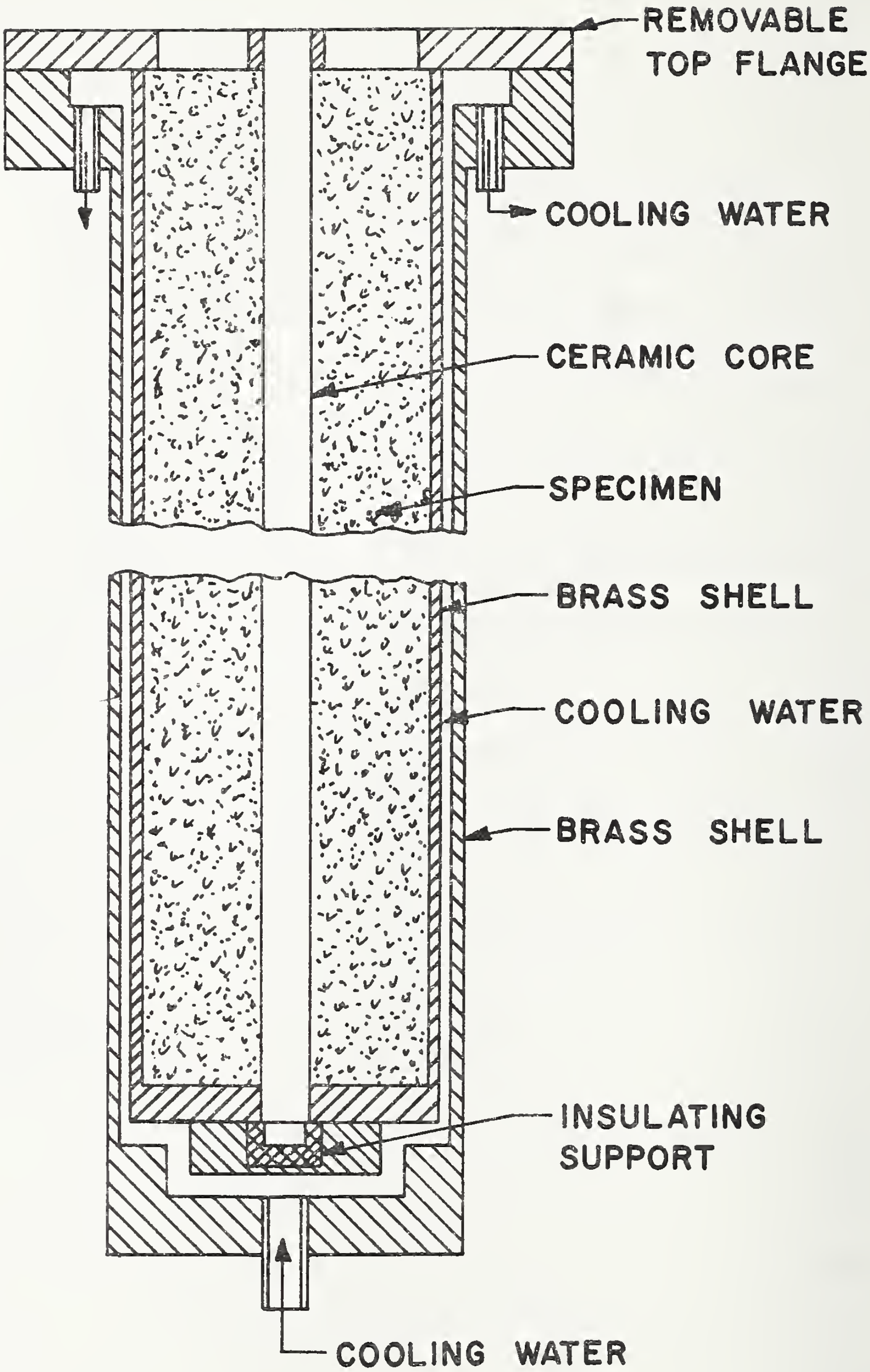


Figure 2. Vertical cross section of the apparatus for measuring the thermal conductance of soils.

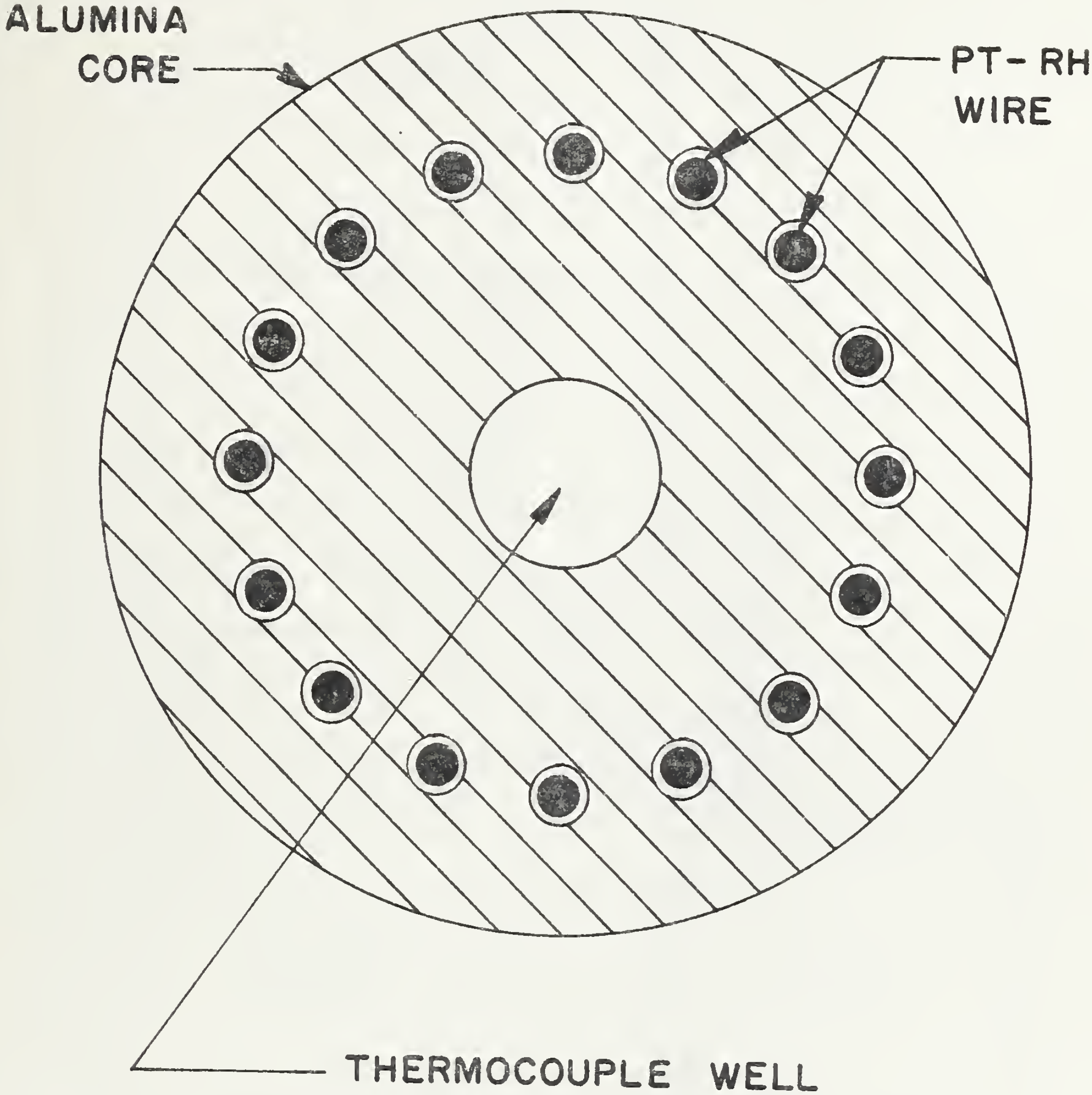


Figure 3. Horizontal cross section of the ceramic core.

In the center of the alumina core there is an axial hole 0.25 cm in diameter. This hole accommodates a thermocouple which can be moved vertically by exterior manipulation. This thermocouple is fabricated from 0.04 cm diameter platinum and platinum - 10 percent rhodium wire and is contained in double-bore alumina tubing which is a snug slip fit in the thermocouple well. The temperature measured at the midlength of the apparatus is designated $T_h$. This thermocouple can also be utilized to obtain the longitudinal temperature distribution along the core - this information is needed to make corrections for longitudinal heat losses.

With the exception of the ceramic core, all surfaces in contact with the specimen are water-cooled to maintain them at room temperature. As shown in figure 2, the cooling water enters the center of the bottom of the apparatus, passes upward in the annulus between the inner and outer brass shells, and exits at the top of the apparatus. A circulating system, shown in figure 4, is used to maintain a constant temperature in the apparatus. The water leaving the apparatus is pumped through a heat exchanger which cools the water to a temperature lower than that desired at the inlet to the apparatus. From the heat exchanger, the water enters a small commercial hot water heater where it is reheated to the desired temperature for circulation to the apparatus. A resistance thermometer at the exit from the tank is used to control the power to the heater in the tank and thus maintain the desired water temperature.

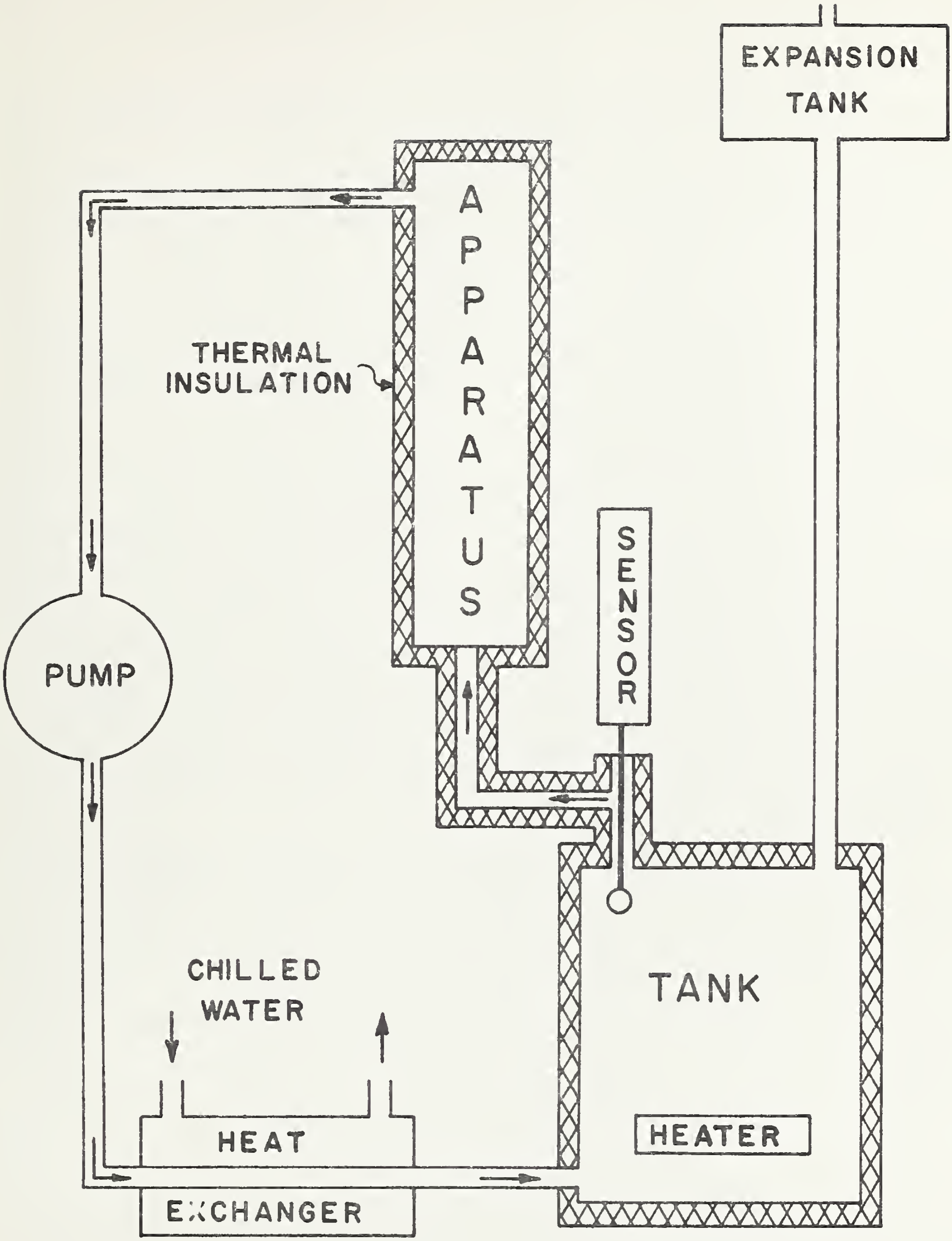


Figure 4. The circulating system used to cool the apparatus.

Two copper versus constantan thermocouples (0.025 cm diameter) are attached to the outer surface of the inner brass shell at the midplane of the apparatus. The junctions of these thermocouples are thermally insulated from the cooling water by plastic electrical tape. The average of these two temperatures is designated $T_c$. Additional copper-constantan thermocouples are used to monitor temperatures at different locations in the circulating system.

Individual ice junctions are used with the platinum versus platinum-10 percent rhodium thermocouple used to measure $T_h$. The constantan leads of the copper versus constantan thermoccuples are brought to an isothermal zone box at room temperature. A thermocouple with one junction in the zone box and one in an ice bath is placed in series with a double-pole selector switch, so that each measuring thermocouple is automatically referenced against the ice bath [3].

The ceramic core heater, which provides the heat flowing radially through the specimen, is fed a-c power from a saturable core reactor which is controlled by a current-adjusting-type proportional controller incorporating automatic rate and reset action. This controller is being modified to operate in either of two modes. It can adjust the power to the core heater so as to maintain the temperature, $T_h$, at the center of the core at a constant value. Alternatively, it can control the saturable core reactor so as to provide constant current to the core heater. The power dissipated in the core heater is determined by measuring the current through the heater and the voltage drop across the heater utilizing a one-quarter-percent-accuracy electrodynamic voltmeter and ammeter.

## 5.4 Longitudinal Heat Flow

The equations in section 5.2 were derived on the assumption of no longitudinal heat flow. In the apparatus being used for these measurements, the ends are at the same temperature as the outer convex surface of the specimen. Thus there will be longitudinal heat flow in the specimen and in the ceramic core. The effect of this heat flow must either be calculated or shown to be negligible. Peavy [2] has considered this problem for a geometry very similar to that of the apparatus described in section 5.3. Reference to Peavy's figure 4 and the accompanying text indicates that if the thermal conductivity of the ceramic core is not more than about 100 times that of the specimen, the correction for longitudinal heat flow will not exceed 5 percent. The worst case to be encountered in the present measurements would be near room temperature where the thermal conductivity of the alumina core might be as much as 500 times that of the soil sample. This is outside the range of Peavy's calculations. For this large a ratio of thermal conductivities, longitudinal heat flow in the specimen will be small compared with that in the core and the simplified analysis of Flynn [1] may be used. Neglecting the effect of the temperature coefficient of resistance of the heater wire, Flynn's analysis yields a correction of about five percent for a thermal conductivity ratio of 100 (in agreement with the results of Peavy's analysis) and a correction factor of thirty to forty percent for a conductivity ratio of 500.

Peavy's analysis [2] includes the effects of longitudinal heat flow in both the core and the specimen but is limited by the assumptions of constant thermal conductivities for the core and the specimen and constant electrical resistivity for the heater wire. Flynn's analysis [1] allows for a linear variation in the electrical resistivity of the heater wire, assumes constant thermal conductivities, and considers longitudinal heat flow in the core but not in the specimen. For the large range of temperatures to be covered in the present investigation, the thermal conductivity of the core, the thermal conductivity of the specimens, and the electrical resistivity of the heater wire vary considerably. In the next quarter we intend to carry out an analysis of longitudinal heat flow in the apparatus taking the temperature-dependence of these properties into account.

## 6. Summary of Work

During this reporting period, the apparatus described in this report was essentially completely fabricated. The cooling system described was also built.

The noble metal heater wire and thermocouple wire to be used were ordered and received. Orders were placed, but have not yet been filled, for the alumina heater forms, an electrodynamic voltmeter, an electrodynamic ammeter, and a device to permit using an existing proportional controller to control an existing saturable core reactor in a constant current mode to provide power to the core heater. Once these items are received, apparatus fabrication can be completed and measurements begun.

## 7. References

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