of accuracy desired, and the time available for an individual measurement.

Wide variations are possible in the suitable application of the method. For instance, if it is desirable to have a very small increase of temperature, say 8 to 10 F. rather than the 40 to 50 F. used in the applications above, this may be done with no loss of accuracy provided the sensitivity of the temperature measuring equipment is suitably increased. If very rapid readings are desired, a heater design which gives a rapid approximation to the ideal case can be used. If a value which is representative of a large volume of the sample is desired, a heater which has a low output and which can be operated for a long period without giving excessive temperature increases is used.

The general method, here illustrated by the point source and the line source, can be extended to other types of sources if desired. Because of its flexibility and the rapidity with which results may be obtained, it is being further developed for studies of thermal properties of poor conductors.

## THE THERMAL CONDUCTIVITY PROBE

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Interest in the thermal properties of soils has recently increased because of the introduction of the ground-coil heat pump, and through an awakening to the necessity for an accurate understanding of heat flow in soil freezing and associated problems. However, the determination of thermal conductivity and of thermal diffusivity, the two thermal properties of principal interest, is complicated in the case of natural soils by two factors peculiar to this material. First, soils normally occur in a moist condition and are subject to large seasonal and locational variations in their moisture content. Second, soils have a definite structure which, once disturbed, is difficult to restore. These factors cause test methods adequate for the testing of manufactured bulk materials to be unsatisfactory when applied to soils.

The difficultires associated with obtaining structurally undisturbed soil samples of suitable size and shape for laboratory apparatus are apparent. The difficultires arising from the presence of moisture require some explanation.

When a temperature difference exists between two points in a moist soil, a vapor-pressure difference will also exist. Water will tend to vaporize in the warmer position, flow or diffuse to the cooler position where the vapor pressure is lower, and condense in the cooler position. Thus, a migration of moisture will occur which will not only continuously alter the distribution of the moisture within the soil by drying the warmer position and wetting the cooler position but will also account for a separate mechanism of heat transmission by virtue of the latent heat carried by the vapor. Any apparatus depending upon a steady-state heat-flow principle will not be able to yield a result until a moisture equilibrium has been established, at which time the specimen will not be uniformly wetted and the moisture migration mechanism of heat transmission will not be operative.

To overcome these and other difficulties, the thermal conductivity probe has been developed at Toronto. Because the new instrument is portable, it can be carried to the site and no disturbance of the soil is involved. By utilizing a transient heat-flow principle, the tests are accomplished in a few minutes, before the moisture migration has significantly disturbed the original distribution, while at the same time including this mechanism as a contributing factor in the measured properties.

### The Instrument

The thermal conductivity probe is detailed in Figure 1 and the measuring circuit in Figure 2. The probe itself consists of an aluminum tube approximately 18 in. in length. Inside of the tube is stretched an axial constantan resistance wire which serves as a constant strength heat source. Near the center of the tube length in contact with the inner wall are the hot junctions of several thermocouples arranged in series with external cold junctions. The tube is closed by a steel tip at the lower end and the wiring

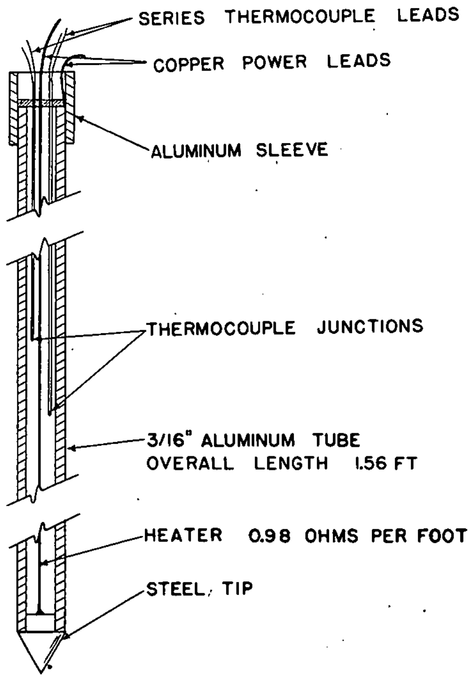


Figure 1. Detail of Probe.

carried out through a seal at the upper end.

The necessary potentiometer, battery and controls are conveniently mounted in a suitcase to make the whole portable.

## Principle of Operation

When the probe is immersed in a homogeneous material and a current allowed to flow through the heater, the heat flow approximates that from a line heat source. It can be shown (1) that the temperature rise $\Delta\theta$, in the period between times $t_1$ and $t_2$ after the start of the current, will be given by

$$\Delta\theta = \frac{Q}{4\pi k} \cdot \log_e \frac{t_2}{t_1} \qquad (1)$$

where Q is the heat input per unit length and k is the thermal conductivity.

When a correction factor is applied to compensate for the finite dimensions of the probe, an expression for thermal conductivity

$$k = \frac{i^a C}{\Delta\theta\, t_2\text{-}t_1} \qquad (2)$$

is obtained. Here i is the current in the heater, C is an instrument constant, and $\Delta\theta$ $(t_2\text{-}t_1)$ is the temperature rise in the selected time interval after the start of the test. Times $t_1$ and $t_2$ are preselected in conjunction with the instrument constant.

## The Technique of Measurement

To make a determination, the probe is thrust into the soil for its full length. In sandy or other easily penetrated soils this can be done by hand. In harder soils a steel rod of diameter similar to that of the probe is first driven to make a passage for the probe.

A few minutes are allowed to permit the instrument to come to intitial temperature equilibrium with its surroundings. A constant current is then allowed to pass through the heater, and the current and the temperature at the two times $t_1$ and $t_2$, (typical values are 3 and 7 minutes), is measured.

The thermal conductivity is then determined directly from these observations using equation (2).

## Accuracy and Results

Because the method of use described here is an approximation made for the sake of convenience in measurement, and because the mathematics involve some approximations, the result is not exact. It is probably not more than 5 percent in error and, at least in some materials, much higher accuracy is indicated. The results are highly reproducible among themselves and smooth curves of thermal

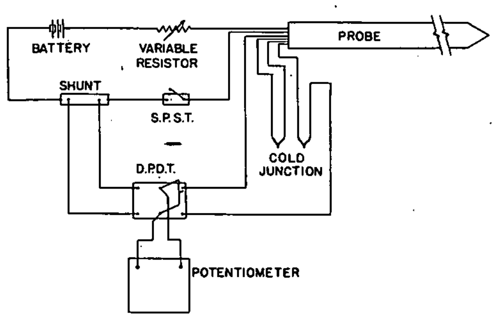


Figure 2. Control Circuit.

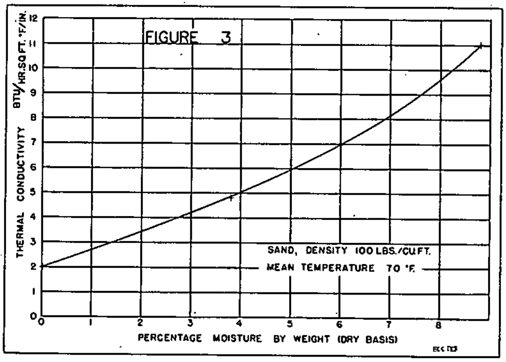


Figure 3. Typical Test Curve.

conductivity plotted against moisture content are obtained. A typical test curve is shown in Figure 3.

While the instrument is especially suited to field work with moist soils, dry soils and similar materials can be tested by the probe.

Some precautions should be observed where possible. The probe should be in an isothermal position in the soil, which strictly speaking is usually a horizontal position, since the temperature tends to vary with depth. In compressible material the probe would be most reliable if a hollow tube were used to cut the path and withdraw the core rather than a solid rod. In a moist material successive readings should not be made without repositioning the probe since local drying would result. In any case, the temperature must be allowed to return to the initial value which requires a lengthy wait between tests.

The probe should be satisfactory in frozen soils if the temperature is not allowed to pass the freezing point during a test. The change in moisture content during the test due to moisture migration has been found to be small. In one 6-minute test with an overall temperature rise of 30 F. the moisture content within a radius of 1/4 in. of the probe changed only from 10. 0 percent to 9. 8 percent on the dry basis.

A method of calculation which permits the derivation of the thermal diffusivity from the same observations has been developed (2). Because of sufficient investigation of its reliability has not so far been possible, it is not presented here. It does, however, show promise of future usefulness.

The probe is not yet commercially available.

## Acknowledgments

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