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THERMAL CONDUCTIVITY OF ORGANIC SEDIMENTS FROM TWO WISCONSIN LAKES

Richard McGaw

November 1974

PREPARED FOR
U.S. ARMY MATERIEL COMMAND
BY
CORPS OF ENGINEERS, U.S. ARMY
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PREFACE

The work reported here was performed by Richard McGaw, Earth Sciences Branch, Research Division, USA CRREL. It is published under DA Project 1T061102B52A, *Mobility and Environmental Research,* Task 02, *Military Aspects of Cold Regions Research,* Work Unit 006, *Physics and Chemistry of Soils and Earth Materials.* The report was technically reviewed by Dr. D. M. Anderson (Chief, Earth Sciences Branch), Dr. J. Brown and Dr. P. Hoekstra.

The author would like to thank Professor Gene E. Likens and Professor Noye M. Johnson of Dartmouth College, Hanover, N.H., for their assistance. Professors Likens and Johnson obtained the samples of sediment and provided data on their physical properties. Professor Likens also reviewed the original draft of the report.

SP 5 Richard E. Kraetsch of CRREL assisted the author in performing the tests for thermal conductivity.

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THERMAL CONDUCTIVITY OF ORGANIC SEDIMENTS FROM TWO WISCONSIN LAKES

by

Richard McGaw

Introduction

The thermal conductivities of four specimens taken from partially gelatinous sediments underlying Stewart's Dark Lake and Tub Lake, northwestern Wisconsin, were measured by the probe method of transient heating. One specimen from each lake represented sediments at the center of the lake; the other represented sediments near the shore. Test temperature was $+5^{\circ}C$, which approximated the average annual temperature of the natural environment. The specimens were obtained by G.E. Likens and N.M. Johnson of Dartmouth College.

The purpose of the tests was to resolve the question of whether the addition of gelatinous or amorphous organic matter to water would raise or lower the conductivity. Previous exploratory tests performed at the University of Illinois indicated that inorganic gels in even small concentrations decreased conductivity to values below that of pure water.* The influence of organic gels is unknown. USA CRREL was approached because of the laboratory's capability of measuring thermal conductivity in materials of high liquid content by means of transient heating.

Probe theory

The probe method of measuring thermal conductivity, in which heat produced along an axial source results in an expanding cylindrical temperature field in the test material, is based on the line heat-source method. Van der Held and Van Drunen (1949) first applied the line-source method, using a heated wire, to measure the conductivity of liquids.

Line-source theory results in the following expression for the temperature rise at a distance r from the source during the heating time t, beginning from an isothermal condition:

$$T = \frac{q}{4\pi K}\left[\ln t + \left(\ln \frac{4a}{r^2} - \gamma\right)\right]. \tag{1}$$

Equation 1 holds when $t \gg r^2/4a$, i.e. when $t > 25r^2/a$, approximately; q is a constant heating rate per unit length of probe, K and a are the conductivity and diffusivity of the test medium, and $\gamma = 0.5772$. With a and r unchanging, the expression in parentheses is a constant, so that the temperature rise between successive large times is

*Personal communication, P. Hoekstra, USA CRREL, 1967.

$$\Delta T = \frac{q}{4\pi K} \ln \frac{t_2}{t_1} \tag{2}$$

the value of the conductivity being given by

$$K = \frac{q}{4\pi \Delta T} \ln \frac{t_2}{t_1} . \tag{3}$$

Thus, after a short initial period of heating the conductivity of the test material can be calculated from the slope of the graph of temperature rise versus the logarithm of time.

The probe, or portable heating element, was introduced by Hooper and Lepper (1950) to measure the thermal conductivity of soils *in situ*. The basic equation for the temperature rise at a probe of outer radius b has been given by Blackwell (1954) and Jaeger (1956). For large times, the temperature rise at a probe is given by

$$T = \frac{q}{4\pi K} \left[\ln t + \left(\ln \frac{4a}{b^2} - \gamma + \frac{2K}{bH} \right) \right] \tag{4}$$

where the symbols are as given before, with the addition that $1/H$ is the contact resistance, per unit area of probe, between the probe and the test material. In an actual test, the quantities in parentheses are again arranged to be constant, so that eq 2 and 3 apply to the probe method as well as to the line-source method.

Effective use of the probe method depends on maintaining each of the following quantities constant during the test interval: the thermal properties of the test material, the contact resistance with the probe, and the heat input. These conditions will ordinarily be assured by utilizing a small temperature rise at the probe, putting special attention on the physical contact between the probe and the test material, and by controlling axial heat losses through proper design. When used successfully, the simplicity and accuracy of the probe method duplicate those of the line-source method.

Material and methods

Physical properties of the sediments tested are listed in Table I. The depth given is the depth of water at the location of sampling. Each sample was taken from the surface of the sediment with an Ekman dredge.

Prior to testing, the four samples were stored at +5°C for several weeks. They were then gently stirred to ensure homogeneity, and spooned into an aluminum container (Fig. 1) precooled to the same temperature. The container was fitted snugly into a constant-temperature cooling well (Fig. 2), and the probe inserted along the axis of the container. Spacers at each end held the probe in place.

The probe used is shown schematically in Figure 3. In this probe, a stainless steel sheath encloses a heating coil of constantan wire (73 ohms/cm) within which is mounted a chromel/constantan thermocouple (58.5 $\mu V/°C$) at mid-length. A molded plastic connector supports the thermocouple and power leads. Free length below the connector is 21 cm whereas the outer diameter of the sheath is 0.5 mm. Length/diameter ratio is approximately 420.

Table I. Physical properties of sediments

Data supplied by G. E. Likens and N. M. Johnson.

Source	Water depth (meters)	Fraction of total weight		Water content (%)	Fraction of dry weight	
		Water (%)	Solids (%)		Organic (%)	Ash (%)
Tub Lake						
near shore	1.5	93.0	7.0	1330	47.7	52.3
center	7.0	94.9	5.1	1860	60.4	39.6
Stewart's Dark Lake						
near shore	0.8	93.3	6.7	1400	63.3	36.7
center	8.5	96.0	4.0	2430	63.7	36.3

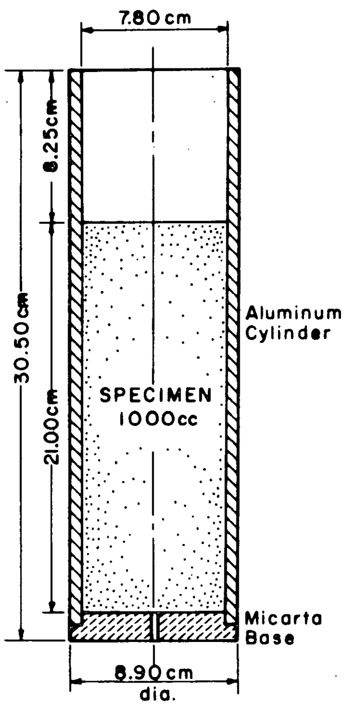

Figure 1. Specimen container.

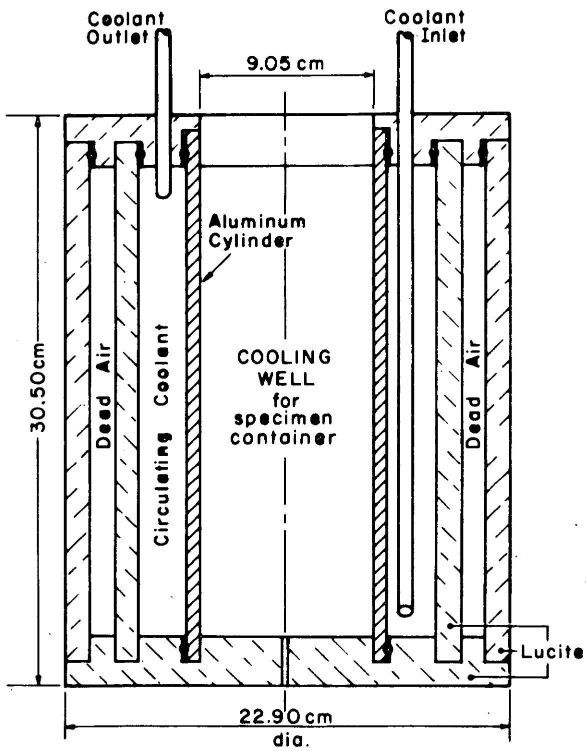

Figure 2. Cooling chamber.

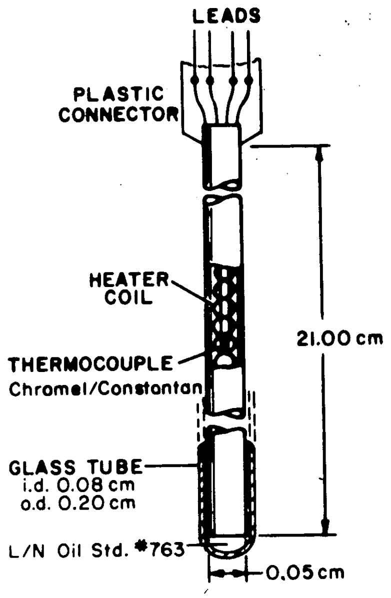

Figure 3. Thermal probe.

To reduce convective disturbances, the probe was encased in a glass tube having an outer diameter of 2 mm and an inner diameter of 0.75 mm; this arrangement had previously been found effective in measuring the thermal conductivity of water using the same apparatus. The probe was placed in the tube after being coated with a small quantity of recorder oil. The presence of the glass decreases the initial temperature rise in the sediment adjacent to the tube, thereby resulting in more uniform heating for a given input. Heating time to the linear portion of the temperature curve was less than 1 minute.

Circuitry consisted of the probe heater circuit, the probe thermocouple circuit, and a monitoring circuit (Fig. 4). For each test, a bias voltage in microvolts was selected to maintain the trace on the scale from about 6 seconds of heating. The probe temperature was the sum of the bias voltage and scale voltage.

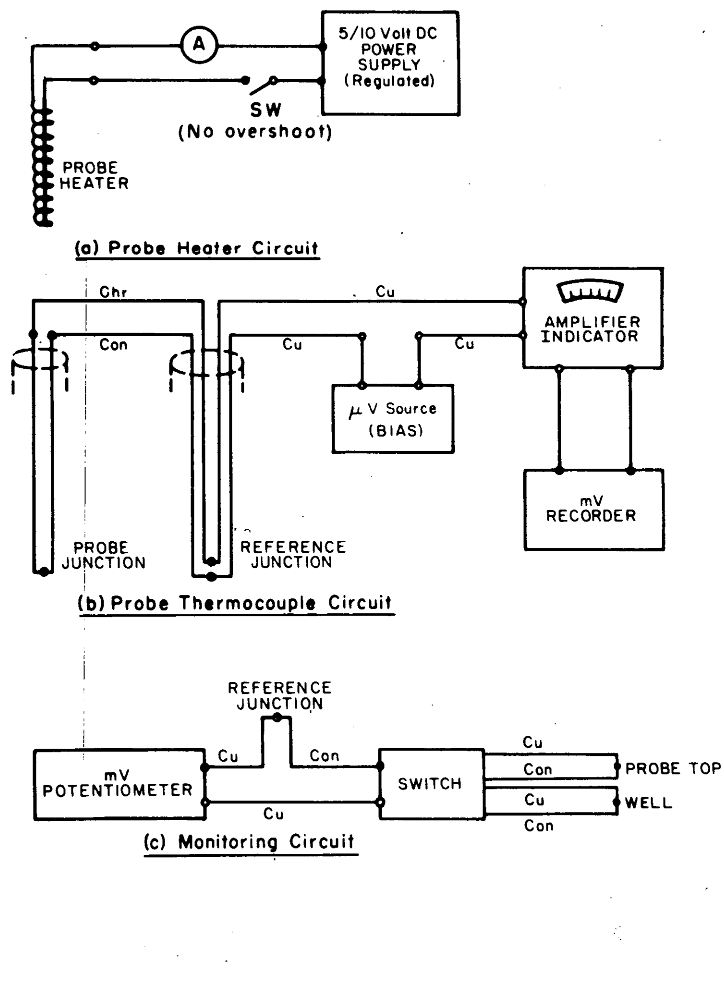

Figure 4. Circuits.

Thermal conductivities in mcal/°C cm sec were calculated from the expression

$$K = \frac{0.186\, I^2}{\Delta T_1} \qquad (5)$$

which was derived from the heating coil resistance and eq 3. The value of the heating current I was measured in milliamps for each test to 1 part in 1000; ΔT_1, the slope of the temperature curve expressed in microvolts over a single decade of time, was obtained from the semilog plot of the temperature rise. An example of the test data is given in Figure 5. Several tests were made at each of three levels of heat input for each specimen.

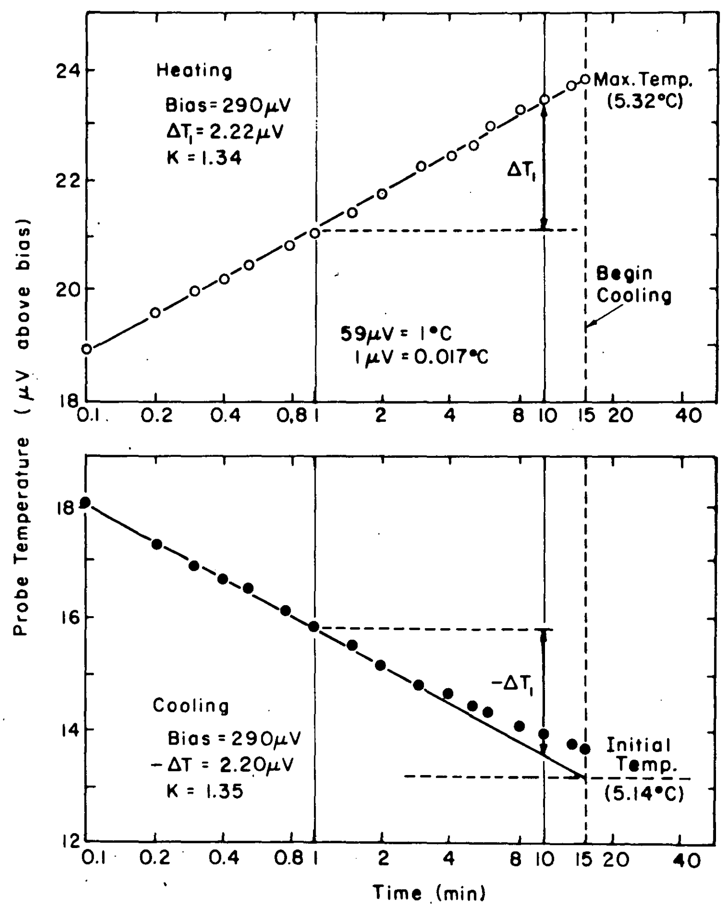

Figure 5. Heating and cooling data, Stewart's Dark Lake, center (3.0 mw/in.).

Results and discussion

Test results are given in Table II, and are plotted against heat input in Figures 6-9. Conductivity values obtained on heating and on cooling are treated separately, inasmuch as there was a tendency for the latter to be approximately 1% higher. For comparison with the test values, the thermal conductivity of water at 5.0°C is shown by a dashed line at 1.34 mcal/°C cm sec. This value was taken from Table 130 (data BN) given by Dorsey (1940); a graph of the full tabular data for water is given in Figure 10.

Table II. Test data

Specimen	Heat input (mw/in.*)	Wall temp (°C)	Probe temp Initial (°C)	Probe temp Max (°C)	Avg temp (°C)	Period of linearity (min)	Thermal conductivity Heating (mcal/°C sec cm)	Thermal conductivity Cooling (mcal/°C sec cm)
Tub Lake								
Near shore	1.5	5.0	5.1	5.2	5.10	0.1-15	1.39	(1.25)
	3.0	5.0	5.1	5.3	5.15	0.5-15	1.35	1.35
	6.0	5.0	5.1	5.4	5.20	1.0-15	1.35	1.40
Center	1.5	5.0	5.2	5.3	5.15	0.2-15	1.33	1.39
	"	"	"	"	"	"	1.37	1.39
	"	"	"	"	"	"	1.35	1.36
	3.0	5.0	5.2	5.4	5.20	0.5-15	1.30	1.30
	"	"	"	"	"	"	1.43	1.43
	"	"	"	"	"	"	1.37	1.32
	6.0	5.0	5.2	5.6	5.30	1.0-15	1.35	(1.30)
	"	"	"	"	"	"	1.35	1.37
Stewart's Dark Lake								
Near shore	1.5	5.0	5.0	5.1	5.05	0.1-10	1.37	1.36
	"	"	"	5.3	5.15	0.1-6	1.38	1.36
	"	"	5.1	5.2	5.10	0.1-15	1.46	1.46
	"	"	"	"	"	0.5-15	1.47	1.47
	"	"	"	"	"	0.1-15	1.47	1.46
	3.0	5.0	5.1	5.3	5.15	0.1-15	1.33	1.42
	"	"	"	"	"	"	1.45	1.40
	6.0	5.0	5.1	5.4	5.20	0.1-15	1.40	1.42
Center (I)	1.5	5.1	5.1	5.2	5.15	0.5-15	1.24	1.26
	"	"	5.2	5.3	5.20	"	1.25	1.30
	"	"	"	"	"	"	1.30	1.28
	"	"	"	"	"	"	1.28	1.32
	3.0	5.1	5.2	5.3	5.25	0.2-15	1.34	1.35
	6.0	5.1	5.2	5.5	5.30	1.0-15	1.31	1.34
	"	"	"	"	"	0.5-15	1.32	1.34
Center (II)	1.5	5.0	5.0	5.1	5.10	0.2-15	1.20	1.22
	3.0	5.0	5.0	5.2	"	0.2-15	1.32	1.32
	"	"	"	"	"	"	1.29	1.34

* 1 mw/in. = 0.0941 mcal/sec cm = 0.0393 mw/cm = 3.93 mw/m = 3.93 x 10^{-3} w/m.

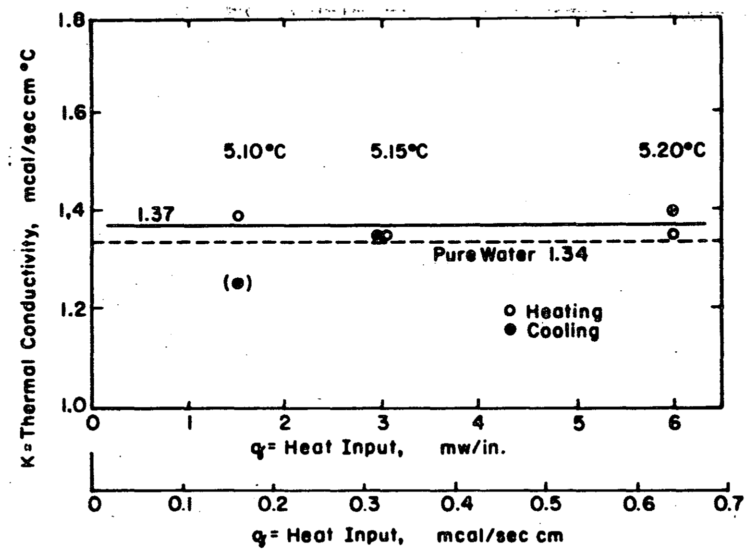

Figure 6. Thermal conductivity, Tub Lake, nearshore.

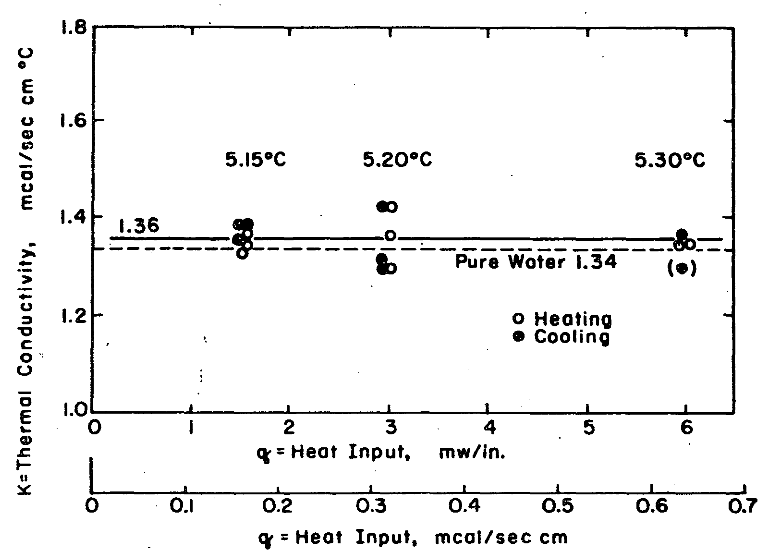

Figure 7. Thermal conductivity, Tub Lake, center.

The two Tub Lake specimens (Fig. 6, 7) were similar in appearance and in thermal conductivity. Although partially gelatinous in appearance, they were nearly fluid with a good percentage of the organic matter being fibrous in nature and tending to settle somewhat after stirring. Their conductivities were 1.37 and 1.36 mcal/°C cm sec, or approximately 2% higher than the tabular value for water. Within the experimental error, there was no noticeable variation with the level of heat input.

The nearshore specimen of Stewart's Dark Lake (Fig. 8) was fibrous and similar in appearance to the Tub Lake specimens; its conductivity was 1.41 mcal/°C cm sec, or 5% higher than that of pure water. Again, there was no change with heat input. In contrast, the thermal conductivity of the specimen taken from the center of Stewart's Dark Lake was less than that of water and showed a distinct variation with heat input (Fig. 9).

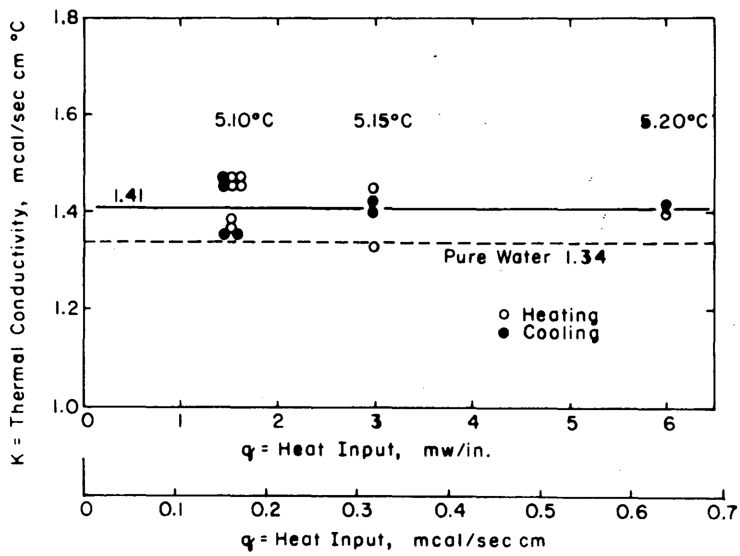

Figure 8. Thermal conductivity, Stewart's Dark Lake, nearshore.

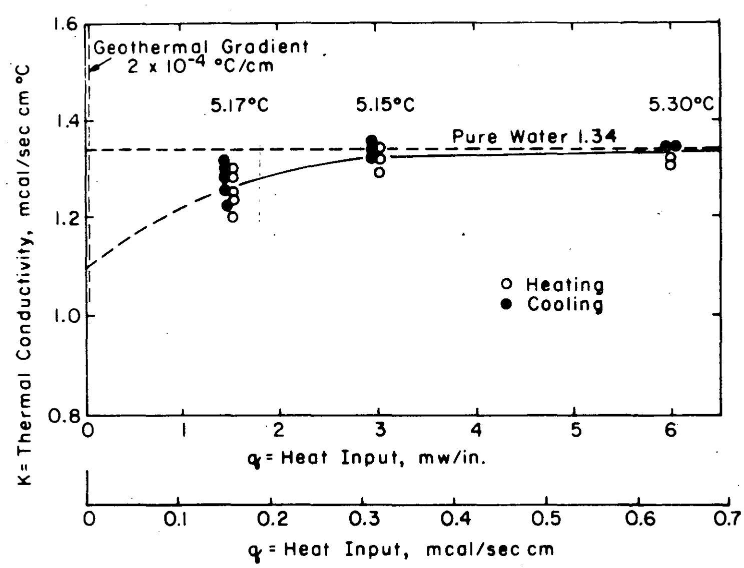

Figure 9. Thermal conductivity, Stewart's Dark Lake, center.

The latter specimen differed in appearance from the other three. Although somewhat higher in water content, it was viscous, and very little of the organic matter appeared to be fibrous. The environment of this sample is known to differ in several respects from that of the other three. Although complete vertical circulation or turnover occurs yearly in Tub Lake and in the upper layers of Stewart's Dark Lake, the center of Stewart's Lake is stratified the year-round. The sediments in the center of this lake are known to be oxygen-depleted and rich in hydrogen sulfide; bacteria in this location are anaerobic (Likens 1962). As shown in Figure 9, the thermal conductivity of this latter specimen was considerably less than that of water at low heat inputs, but appeared to approach the value for water as an asymptote with heat inputs approaching 3 mw/in. To ensure that reliable values were being obtained, several tests were run on a second specimen taken from the original sample. As shown in Table II, thermal conductivities of both specimens were similar. A comparison with Figure 10 indicates that the magnitude of the variation with heat input is at least two orders of magnitude greater than the increase in the thermal conductivity of water that would occur between the minimum and maximum temperatures for each test.

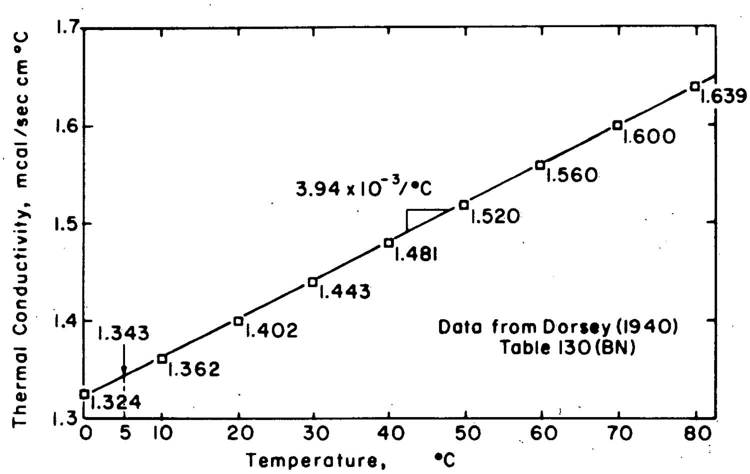

Figure 10. Tabular data; thermal conductivity of water.

The physical basis for the observed thermal effect can only be speculated on at this time. It seems likely, however, that an aqueous structure contributed by the gelatinous constituent of the anaerobic Stewart's Lake sediment is a factor. As previously mentioned, inorganic gels added to water have also been reported to result in a decrease in thermal conductivity, although the apparent change with the level of heat flow was not observed.

The variation in the conductivity of the specimen from the center of Stewart's Lake raises a question as to the value that should be assigned to the *in situ* sediment. The logical value would seem to be that conductivity which corresponds to a mean laboratory temperature gradient similar to the natural gradient. Since it is known that the temperature at the bottom of Stewart's Dark Lake is nearly constant the year-round, the natural gradient may be assumed to approximate the average geothermal gradient in the United States (Johnson and Likens 1967, Likens and Johnson 1969). Van Orstrand (1939) gives this figure as being about 1°C in 50 m, or 0.0002°C/cm. The temperature gradients in the laboratory test are not constant for a given heat input, but vary with time and radial distance from the probe. Nevertheless, if we take the mean test gradient to be the difference between the mean probe temperature and the wall temperature, divided by the specimen radius (3.9 cm), we will have a reasonable value for comparison. For the three heat inputs used in the laboratory tests, the mean gradients calculated in this way are 0.015, 0.030 and 0.060°C/cm. The geothermal gradient is thus some 75 times smaller than the smallest mean gradient developed in the tests. The corresponding *in situ* thermal conductivity would be approximately 1.10 mcal/°C cm sec, as indicated by the extrapolated portion of the curve in Figure 9, or about 20% lower than the thermal conductivity of pure water.

Conclusions

Thermal conductivity tests have been performed on four samples of organic lake sediments. The tests tentatively indicate that fibrous organic material increases thermal conductivity to above that of pure water, while gelatinous organic material decreases conductivity to below that of water.

The thermal conductivity of a fibrous sediment appears to be independent of the imposed heat flow. The conductivity of a gelled sediment approaches the conductivity of water as heat flow is increased.

Literature cited

Blackwell, J. H. (1954) A transient-flow method for determination of thermal constants of insulating materials in bulk; Part I-Theory. *Journal of Applied Physics*, vol. 25, no. 2, p. 137-144.

Dorsey, N. E. (1940) *Properties of ordinary water substance.* New York: Reinhold.

Hooper, F. C. and F. R. Lepper (1950) Transient heat-flow apparatus for the determination of thermal conductivities. *Heating, Piping, and Air Conditioning*, vol. 22, no. 8, p. 129-134.

Jaeger, J. C. (1956) Conduction of heat in an infinite region bounded internally by a circular cylinder of a perfect conductor. *Australian Journal of Physics*, vol. 9, p. 167-179.

Johnson, N. M. and G. E. Likens (1967) Steady-state thermal gradient in the sediments of a meromictic lake. *Journal of Geophysical Research*, vol. 72, no. 12, p. 3049-3052.

Likens, G. E. (1962) Transport of radioisotopes in lakes. Ph. D. Thesis, University of Wisconsin, 152 pp.

Likens, G. E. and N. M. Johnson (1969) Measurement and analysis of the annual heat budget for the sediments in two Wisconsin lakes. *Limnology and Oceanography*, vol. 14, p. 115.

Van Orstrand, C. E. (1939) *Internal constitution of the earth* (Gutenberg, Ed.). New York: McGraw-Hill, p. 125-151.

Van der Held, E. F. M. and F. G. Van Drunen (1949) A method of measuring the thermal conductivity of liquids. *Physica*, vol. 15, no. 10, p. 865-881.

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13. ABSTRACT

The thermal conductivity of four organic sediments was measured using transient heating. It was found that a gelatinous constituent reduces conductivity to below that of water. The magnitude of the reduction diminishes with increasing heat flow. A fibrous constituent apparently increases conductivity, and shows no variation with heat input.

14. Key words

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