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Thermal Conductivity Measurements of Pacific Illite Sediment[1]

C. E. Hickox,[2] D. F. McVey,[2] J. B. Miller,[3] L. O. Olson,[3] and A. J. Silva[4]

Results are reported for effective thermal conductivity measurements performed *in situ* and in core samples of illite marine sediment. The measurements were obtained during a recent oceanographic expedition to a study site in the north central region of the Pacific Ocean. This study was undertaken in support of the U.S. Subseabed Disposal Project, the purpose of which is to investigate the scientific feasibility of using the fine-grained sediments of the sea floor as a repository for high-level nuclear waste. *In situ* measurements were made and 1.5-m-long hydrostatic piston cores were taken, under remote control, from a platform that was lowered to the sea floor, 5844 m below sea level. The *in situ* measurement of thermal conductivity was made at a nominal depth of 80 cm below the sediment surface using a specially developed, line-source, needle probe. Thermal conductivity measurements in three piston cores and one box core (obtained several kilometers from the study site) were made on shipboard using a miniature needle probe. The *in situ* thermal conductivity was approximately 0.91 $W \cdot m^{-1} \cdot K^{-1}$. Values determined from the cores were within the range 0.81 to 0.89 $W \cdot m^{-1} \cdot K^{-1}$.

KEY WORDS: illite; line-source probe; sediment; thermal conductivity.

1. INTRODUCTION

Results are reported for effective thermal conductivity measurements perform *in situ* and in core samples of illite marine sediment. This study was undertaken in support of the U.S. Subseabed Disposal Project, the purpose

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[2] Sandia National Laboratories, Albuquerque, New Mexico 87185, U.S.A.

[3] Applied Physics Laboratory, University of Washington, Seattle, Washington 98105, U.S.A.

[4] University of Rhode Island, Narragansett, Rhode Island 02882, U.S.A.

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of which is to investigate the scientific feasibility of using the fine-grained sediments of the sea floor as a repository for high-level nuclear waste. As part of this program, experiments are being conducted to determine the thermal, geotechnical, and geochemical response of the sediment that results from an implanted heat source. In addition, appropriate physical properties of the sediment are being measured. The thermal conductivity measurements reported herein were obtained during a recent oceanographic expedition to a study site in the north central region of the Pacific Ocean (30°21′N, 157°51′W) which is approximately 1100 km north of the island of Oahu. The study was undertaken during September 1984 aboard the *R/V Melville*, an oceanographic research vessel operated by the Scripps Institution of Oceanography.

In situ measurements were made and 1.5-m-long piston core samples were taken, under remote control, from a platform that was lowered to the sea floor, 5844 m below sea level. The platform is being developed in support of the *In Situ* Heat Transfer Experiment (ISHTE) [1, 2]. This experiment is designed for the long-term, *in situ*, monitoring of the effects of elevated temperature on thermal, geotechnical, and geochemical processes in marine sediments. The ISHTE is a cooperative effort among engineers and scientists from Sandia National Laboratories, University of Washington Applied Physics Laboratory, University of Rhode Island, Woods Hole Oceanographic Institute, and the Naval Ocean Research and Development Activity.

The *in situ* measurement of thermal conductivity was made at a nominal depth of 80 cm below the sediment surface using a specially developed, line-source, needle probe that incorporated three termistors for redundancy in temperature sensing. Thermal conductivity measurements in the piston cores were made on shipboard using a miniature needle probe. Measurements in these cores were made at depths ranging from 8.5 to 100.5 cm below the sediment surface. In addition, one measurement of thermal conductivity was made in a box core sample (at a depth of 18.5 cm below the sediment surface) that was taken several kilometers from the study site.

2. EXPERIMENTAL PROCEDURE

2.1. *In Situ* Measurement

As mentioned previously, the *in situ* measurement of sediment thermal conductivity was made, under remote control, from a platform that was lowered to the sea floor. The thermal conductivity was determined from the transient response of a specially designed, line-source, needle probe that was hydrostatically implanted so that the temperature-sensing elements were nominally 80 cm below the sediment surface.

A sketch of the line-source thermal conductivity probe, with nominal values for the design parameters, is shown in Fig. 1. The active portion of the probe consists of a 12.01-cm-long line-source heater that is composed of 382 bifiler turns of manganin wire uniformly wound about a stainless-steel tube. The measured resistance of the heater is 135.46 Ω. Three thermistors are located within the heater coil support tube at axial distances of 5, 6, and 7 cm from the tip of the tube. Although one thermistor is sufficient for monitoring the thermal response, the additional thermistors are included for redundancy. The thermistors are 0.028 cm in diameter, thermobead assemblies, with nominal resistances of 8 kΩ at 25°C [3]. The heater–thermistor assembly is contained within a 17-cm-long stainless-steel tube that is filled with transformer oil. The heater assembly is inserted into a 75-cm-long support tube which provides the stiffness required for the hydrostatic implant of the probe.

The probe was designed so that, for a sufficiently long time, the transient temperature response is given by [4]

$$T = A + B\ln(t) \tag{1}$$

where T is the temperature, t is the time, $B = q/4\pi k$, and A is a constant that can be expressed in terms of the initial temperature and the physical properties of the probe and surrounding medium. In the definition of B, q

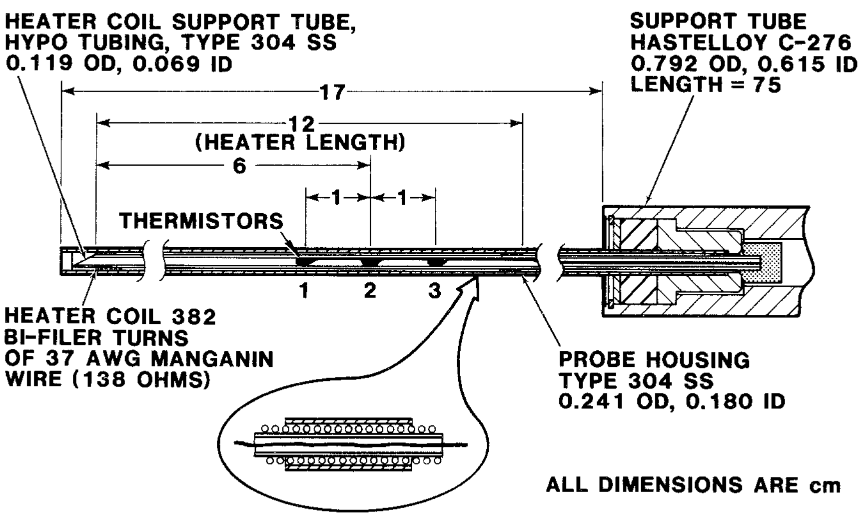

Fig. 1. Sketch of *in situ*, line-source, thermal conductivity probe.

is the power dissipation per unit length of the heater and k is the thermal conductivity of the surrounding medium. Hence, the thermal conductivity can be inferred, in the usual way, from the slope of the temperature versus $\ln(t)$ response, i.e.,

$$k = q/4\pi B \tag{2}$$

In application, the power dissipation per unit length was $0.05848\ \mathrm{W \cdot cm^{-1}}$, which yielded an overall temperature increase of approximately 2°C over the course of the measurement.

Information from the *in situ* measurement was transmitted to the surface via acoustic data telemetry. A backup record was retained on board the platform on magnetic tape that was retrieved when the platform was returned to the ship. Temperature data, as determined from the measured resistances of the thermistors, were recorded at 30-s intervals for a total time of 1200 s. All measurements were performed automatically under the control of a specially designed electronics package. A plot of the response exhibited by thermistor 1 is given in Fig. 2. The response is seen to be linear, thus allowing the thermal conductivity to be inferred from Eq. (2). Responses of the remaining two thermistors were essentially identical to that shown in the figure.

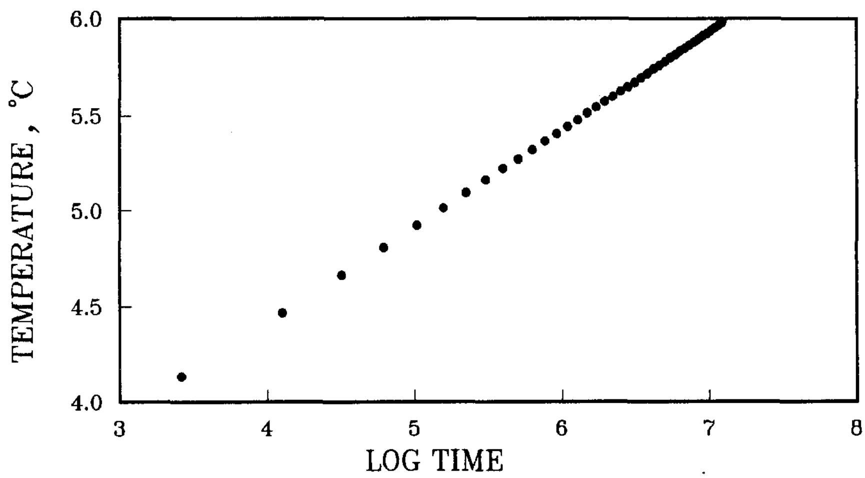

Fig. 2. Transient response (time in seconds) of *in situ*, line-source, thermal conductivity probe. Response of thermistor 1 is plotted.

2.2. Measurements in Cores

Three 10.2-cm-diameter, 1.5-m-long, hydrostatic, piston core were obtained from two separate lowerings of the platform. These cores were processed on board ship by inverting the core and hydraulically extruding the sediment vertically out the end of the core barrel. Hence, the deepest sediment was processed first. Thermal conductivity measurements were made at three vertical locations in each core using a commercially available miniature line-source thermal conductivity probe. The number of thermal conductivity measurements was, of necessity, limited due to the large number of geotechnical measurements that were performed on the cores. One thermal conductivity measurement was made in a box core that was obtained several kilometers from the study site. The measurement was performed on the axis of a 5.08-cm-diameter, 22-cm-long subsample of the core.

The miniature probe was manufactured by Thermometrics, Inc. In general, the geometry of the line source heater is similar to that adopted for the large probe illustrated in Fig. 1, although different materials are used in the construction of the miniature probe. A thermistor, identical to those used in the *in situ* probe, is located within, and at the midpoint of, a helically wound heater coil 6.99 cm long. The heater coil is confined between two concentric plastic sleeves and the entire heater coil–thermistor assembly is encased in an epoxy encapsulant. The assembly is housed in a stainless-steel tube (20 gauge, 0.091-cm outside diameter) which is, in turn, attached to a 1.59-cm-diameter, 3.02-cm-long Delrin plastic hub through which electrical connections are made via a standard five-pin connector. The measured resistance of the heater is 372.27 Ω.

For measurements, the probe was inserted vertically into the end of the piston core midway between the center and the wall of the core barrel. A steady voltage of approximately 10 V was maintained across the heater during measurements with a regulated power supply. An overall temperature increase of approximately 5°C resulted. Thermistor resistance and probe voltage were recorded at 2-s intervals for a total period of 400 s. These data were monitored with digital multimeters which were interfaced to a computer. The data were recorded on magnetic tape for subsequent reduction.

The miniature probe response was not as linear over the entire range of data as that shown in Fig. 2 for the *in situ* probe and exhibited a nonlinear decrease in slope for late times. This nonlinearity can be attributed to the finite sample size. However, a linear region could easily be identified which allowed consistent determination of the slope. Hence, thermal conductivity could be inferred from Eq. (2).

2.3. Calibration of Probes

The thermistors in both the *in situ* and the miniature probes were calibrated in constant-temperature baths to an accuracy of $\pm 0.01\,^\circ$C over the range of temperatures encountered in the thermal conductivity measurements. It should be noted that the absolute accuracy of the temperature masurement is not as important as the precision of the measurement since we require only the slope of the semilogarithmic temperature response curve. Temperatures could easily be resolved with a precision of $\pm 0.001\,^\circ$C.

Both the *in situ* and the miniature probes were calibrated prior to their use by comparing their response with those of previously calibrated probes [5]. The comparisons were performed in a specially designed, water-saturated, packed bed of 150-mesh glass beads. The packed bed was contained in a Plexiglas cylinder 30.48 cm deep and 11.43 cm in diameter. To establish the bed, the cylinder was first filled with deionized water. Both ends were sealed and a vacuum was applied with a roughing pump in order to remove dissolved gases. The upper end was then opened and the beads were poured into the water in one continuous stream so that a uniform packed bed was established. A 2.54-cm-thick brass plate, with a diameter slightly smaller than the inside diameter of the cylinder, was placed on the beads in order to control the packing near the upper surface of the bed. A 2.54-cm-diameter hole in the center of the plate allowed for the insertion of thermal conductivity probes into the bed.

The thermal conductivity of the packed bed was measured with two separate, previously calibrated probes. Reproducibility of measurements was $\pm 1\,\%$ for each probe, and agreement between the two probes was $\pm 0.3\,\%$. The measured value was $0.84\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$. Based on prior comparisons [6] with a material (alumina microspheres) that has been well characterized by measurements performed at several scientific laboratories, it was concluded that the uncertainty in the measured value is $\pm 10\,\%$.

The thermal conductivity of the packed bed, as determined with the *in situ* probe, ranged from 0.824 to $0.845\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$, which is within 2% of the value measured with the calibrated probes. A value of $0.93\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ was indicated by the miniature proble, with a reproducibility of $\pm 2\,\%$. Hence, we elected to apply a correction factor of 0.90 to the value of thermal conductivity determined from Eq. (2), in order to obtain agreement between the miniature and the calibrated probes. This correction, in effect, accounts for the fact that there is some power dissipation external to the line-source heater but within the main body of the probe. Care was taken to eliminate this effect in the design of the *in situ* probe, hence no correction was required.

3. RESULTS

Two separate lowerings of the experimental platform were made. On the first lowering, one hydrostatic piston core was obtained, but no *in situ* measurement of thermal conductivity was made. The core obtained is designated HLC1. During the second lowering, two cores, HLC2 and HLC3, were obtained and, in addition, an *in situ* measurement of thermal conductivity was obtained from each of the three thermistors in the *in situ* probe. The measurements are denoted by APL1–APL3, corresponding to thermistors 1–3. The box core, that was obtained several kilometers from the study site, was given the identifier H-374. A summary of all measurements is given in Table I. Water content was determined from samples acquired during the geotechnical processing of the piston and box cores. Thus, water contents are not available for the *in situ* measurements.

From Table I, it is clear that the *in situ* thermal conductivity is larger than any of the values determined from core samples. Furthermore, taken as a whole, the data exhibit no clear dependence on depth below the sediment surface. The cores HLC2 and HLC3 were acquired during the same (second) lowering of the platform that resulted in the *in situ* measurements, APL1–APL3. Aside from the one measurement in the HLC3 core at a depth of 100.5 cm, the data obtained during the second lowering are reasonably consistent in exhibiting a slight increase in thermal

Table I. Summary of Thermal Conductivity Measurements[a]

Sample No.	D (cm)	T (°C)	P (atm)	w (%)	k ($W \cdot m^{-1} \cdot K^{-1}$)	Sample type
HLC1	28.5	24.5	1	112	0.823	Piston core
HLC1	63.5	24.1	1	115	0.821	Piston core
HLC1	98.5	23.8	1	115	0.828	Piston core
HLC2	13.5	24.0	1	117	0.858	Piston core
HLC2	47.5	24.9	1	121	0.864	Piston core
HLC2	97.5	27.7	1	116	0.888	Piston core
HLC3	8.5	26.4	1	112	0.844	Piston core
HLC3	45.5	26.0	1	114	0.875	Piston core
HLC3	100.5	25.0	1	120	0.810	Piston core
H-374	18.5	19.8	1	112	0.832	Box core
APL1	79.5	4.2	600	—	0.911	*In situ*
APL2	80.5	3.9	600	—	0.914	*In situ*
APL3	81.5	4.1	600	—	0.920	*In situ*

[a] D, T, P, w, and k are, respectively, the depth below the sediment surface, initial temperature prior to measurement, ambient pressure, water content, and thermal conductivity. Water contents were corrected for a salinity of 35 ppt.

conductivity with depth. However, this trend is not evident in the measurements obtained from the HLC1 core.

We now consider the effect of the water content on the thermal conductivity. The water content w is defined as the ratio of the weight of water to the weight of solids in a sediment sample and is related to the porosity ϕ by $w = \rho_w \phi / \rho_s (1 - \phi)$, where ρ_w and ρ_s are the densities of water and solids, respectively. All water contents were corrected for an assumed salinity of 35 ppt. The data exhibit no clear trend with water content, although there is an apparent modest increase in thermal conductivity with decreasing water content.

In a prior study, Hadley et al. [7] concluded that the effective conductivity of laboratory reconsolidated illite marine sediment was very nearly 1.00 $W \cdot m^{-1} \cdot K^{-1}$ at a temperature of 20°C and a pressure of 600 atm. It was also suggested that a parallel mixture model, using the properties of slate for the solid, would accurately predict the effective thermal conductivity. This was verified by a comparison of predicted and measured values for a single porosity and temperatures in the range 20 to 400°C.

It may be recalled that the parallel mixture model for effective thermal conductivity k is expressed by $k = \phi k_w + (1 - \phi) k_s$, where k_w and k_s are the water and solid conductivities. It can be shown that the parallel model provides an upper limit for the effective conductivity of a mixture. In contrast, the lower limit is given by the series model $k = k_w k_s / [(1 - \phi) k_w + \phi k_s]$. Using the properties of slate, as given by Birch and Clark [8], the properties of seawater tabulated by Riley and Skirrow [9], and the measured water content, predictions of the parallel and series models were determined for an assumed temperature of 22°C. All data were found to be bounded, from above, by the parallel model prediction and, from below, by the average of the two models.

4. DISCUSSION

Results were reported for thermal conductivity measurements of illite marine sediment performed *in situ*, in piston core samples, and in a sample obtained from a box core. The core samples were processed on shipboard shortly after obtaining the samples from the sea floor. Measurements were made at depths ranging from 8.5 to 100.5 cm below the sediment surface. The nine thermal conductivity measurement performed in the core samples yielded values in the range 0.810–0.888 $W \cdot m^{-1} \cdot K^{-1}$, while the *in situ* values were in the range 0.911–0.920 $W \cdot m^{-1} \cdot K^{-1}$. The *in situ* thermal conductivity was thus larger than any of those determined from the core samples.

Water content for the core samples ranged from 112 to 121 %. These data were compared with theoretical predictions based on parallel and series models for the effective thermal conductivity in which the properties of slate were assumed for the solid following an approach that had been used successfully in a prior study [7]. The data were bounded from above by the prediction based on the parallel model and from below by the average of the two models. However, the dependency on water content was not sufficiently well defined to allow a specific model to be proposed.

The larger value of thermal conductivity inferred from the *in situ* measurement is, most likely, the result of the combined effects of pressure, temperature, and porosity or, equivalently, water content. *In situ* pressure and temperature were 600 atm and 4°C, while typical values for shipboard measurements with the cores were 1 atm and 25°C. Based on the parallel model and a mean water content of 115%, an increase in pressure from 1 to 600 atm results in an increase of 3% in the effective thermal conductivity. Similarly, a decrease in temperature from 25 to 4°C results in a decrease of 5% in the effective thermal conductivity. Hence, the effects of pressure and temperature tend to cancel. Based on the parallel model, a decrease of 17% in the water content is required to effect a 5% increase in the effective thermal conductivity. Thus, although the data seem to suggest a lower *in situ* water content, no solid evidence is available to support an *in situ* value low enough to account for the difference observed between *in situ* and core measurements. We thus conjecture that the *in situ* water content is probably somewhat less than that measured in the core samples, with the additional difference in thermal conductivity attributable to measurement errors. During the processing of the cores, incompetent regions of sediment were encountered that appeared to be the result of artifacts of the sampling procedure, further tending to support our suggestion of lower *in situ* water content.

Prior studies performed by Hadley *et al.* [7] suggested that the thermal conductivity should be approximately $1.00\ W \cdot m^{-1} \cdot K^{-1}$. This measurement was made at a pressure of 600 atm and a temperature of 20°C. The initial water content was 97% but decreased during the test to a value in the range 80–88%. Comparing the core measurements with those of the reference quoted above, we note that, since our cores were processed at 1 atm, we would expect the thermal conductivity to be lower due to the effect of pressure. Also, the higher water content in our cores can account for a further reduction in thermal conductivity. We thus conclude that the differences in thermal conductivity between our core samples and the results in Ref. 7 can, most plausibly, be attributed to differences in pressure and water content.

Finally, we note that our measurements compare favorably with those reported by VonHerzen and Maxwell [10] for sediment core samples obtained in the southeastern Pacific Ocean. For water contents in the range 87–125%, they reported thermal conductivities in the range 0.98–0.87 $W \cdot m^{-1} \cdot K^{-1}$, in essential agreement with our results.

Based on our, admittedly limited, *in situ* data and their comparison with core measurements and prior laboratory experiments, we suggest that the effective *in situ* thermal conductivity of illite marine sediments in the geographical area of our study is 0.91 $W \cdot m^{-1} \cdot K^{-1}$. Considering the subseabed disposal of nuclear wate, it is noted that the temperature of a heat-generating waste canister depends in an approximately linear fashion on the thermal conductivity of the surrounding mdium, with a lower thermal conductivity resulting in a higher canister temperature.

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