WHOI-85-28

Copy 1

**Woods Hole
Oceanographic
Institution**

**In-Situ Measurement of Thermal Conductivity
Using the Continous-Heating Line Source Method
and WHOI Outrigged Probe**

by

J. Jemsek, R. Von Herzen
and P. Andrew

August 1985

Technical Report

*Support was provided by the U. S. National Science Foundation under
grant Nos. OCE-8025181, OCE-8117886, and OCE-8409170.*

Approved for public release; distribution unlimited.

WHOI-85-28

**In-Situ Measurement of Thermal Conductivity
Using the Continuous-Heating Line Source Method
and WHOI Outrigged Probe**

by

J. Jemsek, R. Von Herzen
and P. Andrew

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

August 1985

Technical Report

Support was provided by the U. S. National Science Foundation under grant Nos. OCE-8025181, OCE-8117886, and OCE-8409170.

*Reproduction in whole or in part is permitted for any purpose of the United States government. This report should be cited as:
Woods Hole Oceanog. Inst. Tech. Rept. WHOI-85-28.*

Approved for publication; distribution unlimited.

Approved for Distribution:

A handwritten signature in cursive script, reading "David A. Ross".

David A. Ross, Chairman
Department of Geology & Geophysics

Table of Contents

	<u>Page</u>
ABSTRACT.	2
INTRODUCTION.	2
METHODS OF MEASURING THERMAL CONDUCTIVITY IN-SITU	5
THEORY.	9
INSTRUMENTATION	13
DATA REDUCTION	18
SOURCES OF ERROR.	27
Single-probe Design	30
Double-probe Design	37
FIELD COMPARISON.	49
ACKNOWLEDGEMENTS.	60
REFERENCES.	61
APPENDIX - Construction of the WHOI Thermistor Probe.	63

ABSTRACT

The outriggered thermal probes of a "pogo" marine geothermal probe have been adapted to measure thermal conductivity in-situ by the continuous-heating line source technique. The instrumental uncertainty in applying the analytical theory to a single-probe and double-probe configuration is found to be 3 and 6 percent, respectively. The in-situ outriggered single probe (.32 cm dia.) is essentially a scaled-up version of the needle probe (.08 cm dia.). The main advantage of the outriggered probe over a larger radius probe (e.g., violin-bow probe) is that for short-time temperatures (<2 min.), simple approximations to the exact solution for a perfectly conducting cylindrical probe are achieved. The continuous-heating compares favorably with the pulse-heating technique, the latter being more energy efficient.

The continuous-heating method applied to the thin outriggered probe allows for accurate equilibrium in-situ temperature and thermal conductivity estimates in less than 15 minutes of recording time. The technique has been applied to several hundred marine heat flow stations. Comparison of in-situ measurements to needle probe measurements made on nearby piston cores indicate agreement to within 5%. The conductivity profiles of the in-situ data and core data show that the piston coring process frequently does not retrieve the upper meter of surficial sediment.

INTRODUCTION

Marine geothermal heat flow is determined by measuring the temperature gradient and thermal conductivity within a vertical interval of sediment beneath the ocean floor. The most efficient means of obtaining accurate thermal gradients has been to employ a heat flow probe which permits multiple penetrations upon a single lowering. A WHOI thermal gradient probe design

implemented by Von Herzen and Anderson (1972) was one of the first thermal gradient probes to allow for multi-penetrations ('pogo' stations) by using a cylindrical strength member to facilitate penetration, and acoustic telemetry to monitor instrument operation onboard. The WHOI heat flow system is equipped with small (0.32 cm diam.) outrigger temperature sensor probes designed for rapid thermal response to sediment temperatures while maintaining functional durability. An alternative multi-penetration heat flow instrument that has had much success is the "violin-bow" design of C. Lister. The violin-bow instrument described by Hyndman et al. (1979) has the advantage of measuring in-situ thermal conductivity over the same interval as the thermal gradient measurement. The in-situ conductivities are obtained using a heat-pulse technique (Lister, 1979) which has generally been used in conjunction with the relatively large diameter (0.78 cm) violin-bow temperature sensor and heater tube.

Until recently, the thermal conductivity values corresponding to the WHOI thermal gradient pogo stations were obtained mainly on nearby sediment cores by the needle-probe method (Von Herzen and Maxwell, 1959). The needle-probe measurements of conductivity on cores are accurate to within 3 or 4%, but must be corrected to the temperature and pressure conditions of the ocean-bottom conditions (Ratcliffe, 1960). The needle-probe method has the disadvantage in that the measurements on the core may not correspond with the sediment intervals sampled in the temperature gradient stations. Moreover, the additional time required to retrieve the piston cores cancels to some extent the advantages of the time-efficient 'pogo' stations.

To more efficiently utilize ship time and to facilitate the collection of local thermal conductivity measurements while increasing the accuracy of individual heat flow estimates, the design of the WHOI outrigger heat flow

probe has been modified to include the continuous-heating method of measuring the thermal conductivity of the sediment in-situ at points where temperatures are determined for thermal gradient calculations. There are, however, drawbacks in using a single-thermistor outrigger probe to measure in-situ conductivity. In order to obtain the most accurate heat flow measurement, the mean thermal resistivity of the sediment located within the exact gradient interval must be known. As noted by Lister (1970), the mean resistivity may best be measured with a multipoint averaging temperature sensor located between single point temperature sensors used for the thermal gradient calculation. An averaging sensor, instead of point sensors, would be particularly useful when significant, detailed conductivity stratification exists. Another problem is that in-situ heater probes generally measure horizontal conduction rather than vertical conduction. If anisotropy exists in the sediment conductivity, some systematic errors will exist in the heat flow determination. One of the authors (R.V.H.) has made measurements on some sediments showing that anisotropy is not generally significant, but others have occasionally found conductivities 2-3% higher in the horizontal direction than in the vertical direction (B. Della Vedova, pers. comm., 1984).

The conduction of heat in cylindrical regions is well understood and provides the framework for the use of a transient technique with a cylindrical probe to measure thermal conductivity in-situ. In this paper, we present an experimental study of the in-situ continuous-heating method using the outrigger-type heat flow pogo probe. A brief review of thermal conductivity measurements is made, including the heat-pulse technique used with the violin-bow type heat flow instrument (Lister, 1979; Hyndman et al., 1979). The theory of the continuous-heating line source method and its application with the WHOI digitally-recording heat flow instrument (DHF) and outrigger

heat flow probe are discussed as well as the data reduction process and an analytical study of the instrumental uncertainties. We apply the continuous-heating technique to several probe designs used in field operations. Numerous in-situ data from the Ligurian Basin (NW Mediterranean) and Bermuda Rise are compared to needle-probe measurements made from piston cores obtained nearby. Our study confirms that a significant improvement in local heat flow determinations are made using the in-situ thermal conductivity measurement.

METHODS OF MEASURING THERMAL CONDUCTIVITY IN-SITU

Thermal conductivity of sea floor sediment may be measured in-situ by employing a heat source in a cylindrical thermal probe. Two transient heating techniques have been applied: the continuous-heating method (Sclater et al., 1969) and the pulse-heating method (Lister, 1979). The continuous-heating method for in-situ applications is actually a scaled-up version of the needle-probe method (Von Herzen and Maxwell, 1959) which has proved successful in the accurate determination of thermal conductivity of deep-sea sediments retrieved with piston and gravity corers. The needle-probe method involves the insertion of a thin cylindrical thermal probe into a sediment core sample. The probe is then heated continuously along its length at a constant rate. The rise in temperature against time approaches a logarithmic asymptote whose slope is equal to $(Q/4\pi K)$ where Q is the heat input per unit length per unit time and K is the thermal conductivity. The rate at which the asymptote is approached depends on the radius of the probe. For a needle probe of 0.1 cm diameter the asymptote is reached rather quickly (< 20 seconds) and allows for an accurate conductivity estimate in only a few minutes.

The continuous-heating method has previously been applied to in-situ measurements for a single outrigger attached to a Bullard probe (Sclater et al., 1969) and to the active length of the Bullard probe (Lister, 1970). These in-situ heater probes have a large radius (up to 1 cm) and can require up to 30 minutes of measuring time for a single heat flow station. The analytical expressions for cylindrical heating have been developed by Sass (1965) and Huppert and Sclater (1968) and allow for the earlier part of the heating curve to be used in the calculation. The Bullard probe is not a multipenetration probe so that the above designs have been superseded with the increasing use of 'pogo' probes.

One multipenetration probe has been developed (Hyndman et al., 1979) which uses the pulse-heating method of Lister (1979). The method uses an extension of the theory developed by Bullard (1954) for the decay of thermal transients in cylindrical probes to measure the thermal conductivity of ocean sediment. The impetus behind the pulse-heating was that it might allow for shorter measuring times in addition to using significantly less battery energy than the continuous-heating method. If the conductivity measurement is made in a shorter time period it is also less likely that the measurement will be affected by a mechanical disturbance due to drift of ship position and a subsequent increase in trawl-wire tension. It has been argued (Lister, 1979) that the pulse-heating method is less sensitive than continuous-heating to contact resistance between the probe and sediment, but the method is quite sensitive to factors such as the details of internal probe construction and probe radius. The undesirable presence of a thin water layer surrounding the probe is probably more sensitive to factors such as details of the external mounting of the thermal probe and the radius of the probe itself. For example, Hutchison (1983) found that the design of the violin-bow probe caused

variable contact resistance along its length. During penetration, the uppermost section of the thermal probe pulls through the same sediment disturbance created by the lowermost section, thus sometimes causing a water-filled gap between the uppermost violin string and sediment. The skin resistance of the upper probe will cause curvature in the linearized temperature decay. The effect of the contact resistance can be compensated somewhat by an additional delay of the effective heater pulse origin time (Hutchison, 1983).

Hyndman et al. (1979) have documented in detail the analysis and use of the pulse-heating method with the violin-bow type heat flow probe which can be configured to measure average interval conductivities in-situ. Using this apparatus, Davis et al. (1985) found excellent agreement (<4%) between their in-situ values and needle-probe values obtained on nearby cored sediments as reported by Goldberg (1981). There are some disadvantages of using the pulse-heating method with the above instrument mainly because the violin-bow probe has a relatively large radius (4 mm) compared to the conventional outrigger probe (1.5 mm) (Table 1). The large probe radius increases the probe thermal time constant ten fold (proportional to the square of the radius) and requires accurate determination of the composite thermal properties of the probe to use the early part of the time-temperature curve. Thus, as the probe radius increases, longer times are required to approximate the theory formulated in detail by Jaeger (1956) in which the probe is treated as a perfect conductor. Hyndman et al. (1979) state that the largest uncertainty can be attributed to approximating the heat pulse as a delta function and establishing the effective origin time of the heat pulse. A time delay must be assigned by trial and error during the data reduction because the probe effectively experiences a spread out pulse. Taking into account the

Table 1

Thermal time constants for various thermal probes

	radius, r (cm)	r^2/κ^* (sec)
needle probe	.04	.5
WHOI outrigger probe	.16	8.5
violin-bow probe	.40	53
Bullard probe	1.0	330

*Assuming a sediment diffusivity κ of $.3 \times 10^{-6} \text{ m}^2/\text{s}$

above uncertainties, Hyndman et al. (1979) estimate a maximum random error of $\pm 5\%$ for their in-situ thermal conductivity estimates.

The measurement system described in this paper adapts the transient method of Von Herzen and Maxwell (1959) to the outrigger-type pogo probe and the WHOI DHF instrument. This modification was relatively straightforward as it retained the durable design of the pogo probe. The theory and data analysis of the continuous-heating in-situ probe has been described by Sclater et al. (1969). As they note, the reduction of the in-situ time-temperature record is slightly altered from that of the needle-probe data. An asymptotic solution cannot be readily used because of the longer time constant of the in-situ probe. Also, the frictional heating effect of the heat flow probe penetrating the sediment must be removed from the in-situ heating curve.

THEORY

The theory applicable to the temperature history of a probe after penetration has been presented by Bullard (1954) and Jaeger (1956). The probe is idealized as an infinitely long perfectly conducting cylinder of radius r and heat capacity per unit length m . The surrounding sediment has an equilibrium temperature θ_1 , thermal conductivity K , thermal diffusivity κ , specific heat C and density ρ . At time $t=0$, the probe is at an elevated temperature θ_0 due to the frictional heating along the probe surface during penetration into the sediment. The temperature of the probe at any time, θ , is related to the initial temperature, θ_0 and equilibrium temperature by

$$\theta = \theta_1 + \theta_0 F(\alpha, \tau)$$

(1)

where $F(\alpha, \tau)$ is a decay function of time and probe radius.

$$F(\alpha, \tau) = \frac{4\alpha}{\pi^2} \int_0^{\infty} \frac{\exp(-\tau x^2) dx}{x \Delta(x)} \quad (2)$$

where

$$\Delta(x) = [xJ_0(x) - \alpha J_1(x)]^2 + [xY_0(x) - \alpha Y_1(x)]^2$$

$J_N(X)$ and $Y_N(X)$ are the Bessel functions of order n of the first and second kinds, respectively. The nondimensional quality τ is the probe thermal time constant and is given by

$$\tau = \kappa t / r^2 \quad (3)$$

The non-dimensional probe parameter, α , is given by

$$\alpha = 2\pi a^2 \rho C / m \quad (4)$$

and is equal to twice the ratio of the thermal capacity of the sediment to that of the probe material. The value of α for most steel probes is near 2.0 but varies slightly depending on the sediment thermal properties. The exact solution to the $F(\alpha, \tau)$ decay curve has been tabulated by Bullard (1954), Jaeger (1956), Huppert and Sclater (1968), and Lister (appendix, 1979) for various values of α . For $\tau > 4$, the approximation

$$F(\alpha, \tau) \approx 1/2\alpha\tau - 1/4\alpha\tau^2 - \frac{(\alpha-2)}{4\alpha^2\tau^2} (\ln 2.246\tau - 1) + O\left(\frac{\ln \tau}{\tau^3}\right) \quad (5)$$

(Blackwell, 1954) is within 1% of the exact value. The asymptote is given by

$$F(\alpha, \tau) \approx \frac{1}{2\alpha\tau} = \frac{m}{4\pi K t} \quad (6)$$

and is simply a function of reciprocal time $1/t$. Thus to obtain the equilibrium temperature θ_1 , the observed temperatures θ may be fitted to equation (1). Since F tends to zero as t approaches infinity, θ_1 is simply the intercept of the regression line.

The thermal conductivity is determined by applying a heat input Q at a constant rate along the length of the cylinder. Assuming the cylinder to be

at zero initial temperature, Jaeger (1956) gives the solution

$$\theta = Q/K G(\alpha, \tau) \quad (7)$$

where K is the thermal conductivity. The function $G(\alpha, \tau)$ is given by

$$G(\alpha, \tau) = \frac{2\alpha^2}{\pi^3} \int_0^{\infty} \frac{1 - \exp(-\tau x^2)}{x^3 \Delta(x)} dx \quad (8)$$

where $\Delta(x)$ is as given in equation (2) and τ and α are as in equations (3) and (4). The approximation (Blackwell, 1954)

$$G(\alpha, \tau) \approx \frac{1}{4\pi} \left\{ \ln 2.246\tau + \frac{1}{2\tau} + \frac{(\alpha-2)}{2\alpha\tau} \ln 2.246\tau \right\} \quad (9)$$

is within 1% of the exact solution for $\tau > 3$ and the asymptote

$$G(\alpha, \tau) \approx \frac{1}{4\pi} \ln 2.246\tau \quad (10)$$

is within 1% of the solution for $\tau > 14$ (table 2). As discussed later in the text, the Blackwell approximation (eqn. 9) is applicable to the determination of K for $\tau > 7$ and the asymptote (eqn. 10) for $\tau > 40$. The asymptotic result is used in the needle-probe method. Equation (8) has been evaluated by Jaeger (1956) and Huppert and Sclater (1968), and tabulated for almost all useful values of α by Sass (1965).

In the application of the continuous-heating method with the in-situ probe, the heater is generally turned on at a pre-determined time t_1 after the initial penetration, sufficient to allow determination of the geothermal gradient. This part of the time-temperature curve is used to determine θ_1 in equation (1). After time t_1 , the heating begins but the probe is not at an equilibrium temperature of zero as assumed in equation (7). Both equations (1) and (7) are solutions of linear differential equations and therefore can be combined as

$$\theta = \theta_1 + \theta_0 F(\alpha, \tau_1) + Q/K G(\alpha, \tau) \quad (11)$$

where τ and α are as in equations (3) and (4), but the time variable t in

Table 2

$G(\alpha, \tau)$, $\alpha = 2.0$

τ	$G(\alpha, \tau)^*$	Blackwell Approximation	Asymptote
1	.09768	.10416	.06437
2	.13804	.13942	.11953
3	.16459	.16505	.15179
4	.18445	.18462	.17468
5	.20033	.20039	.19243
6	.21357	.21357	.20694
7	.22491	.22489	.21921
8	.23484	.23480	.22983
9	.24367	.24362	.23920
10	.25161	.25156	.24759
11	.25884	.25879	.25517
12	.26546	.26541	.26209
13	.27158	.27152	.26846
14	.27725	.27720	.27436
15	.28255	.28250	.27985
16	.28752	.28747	.28498
17	.29220	.29215	.28981
18	.29662	.29656	.29435
19	.30080	.30075	.29866
20	.30478	.30473	.30274
24	.31897	.31895	.31729
32	.34144	.34143	.34018
40	.35895	.35894	.35794

* data from Huppert and Sclater (1968) and Sass (1965).

equation (3) is in reference to the time since the instant the heater turns on. τ_1 is given by

$$\tau_1 = \kappa(t+t_1)/a^2 \quad (12)$$

and incorporates time referenced to the frictional heating event.

Since solutions for both θ_1 and θ_0 have been previously obtained, the thermal conductivity K can be determined by fitting the observed temperature to equation (11) by a least-square method. However, to establish τ and α the sediment diffusivity κ must be known. We have used the κ - K empirical relation given by Von Herzen and Maxwell (1959). K is calculated iteratively using a trial value of κ for α and τ , and then recomputing these parameters from the new value of K . The effect of the uncertainty of κ on the computed K is discussed below.

INSTRUMENTATION

The WHOI heat flow system consists of up to 7 outriggered thermistor sensors mounted to a 7.5 cm diameter probe barrel whose end is sealed with a solid nose cone (fig. 1). Several different configurations have been used. A robust version has a 3.5 m long probe barrel with 4 thermal probes attached at .65 m spacing. A probe barrel of 7 m length with as many as 7 outriggered thermistors has also been used. However, this configuration tends to be susceptible to bending when partial or no penetration in hard bottom occurs, during pullouts which apply high bending moments to the barrel, or when other non-ideal conditions prevail. The actual thermal probe is mounted at a radial distance of 7.5 cm from the probe barrel to insure that there is no measurable thermal effect of the probe barrel sensed by the thermal probes. Each thermistor probe is secured by two fins separated by an axial distance of 10 cm (fig. 2), with the actual thermistor being centered between the two fins in

Figure 1. The WHOI outrigger heat flow 'pogo' probe.

Figure 2. Diagram of WHOI fin and probe assembly.

the middle of the tube. The proximity of the fins and barrel to the thermistor may limit the useful measuring time. However, no discernible departure from theory has been noted in the later part of the heating curve (~10 min.) which could be attributed to thermal perturbation by the fins.

Several outriggered thermal probe designs have been used, each with slightly different thermal properties (fig 3). For the thin-walled probe, the heat capacity per unit length, m is found as .053 cal/cm °C from: steel 54%, $\rho C = .926 \text{ cal/cm}^3\text{°C}$; probe internal contents 46%, $\rho C = .370 \text{ cal/cm}^3\text{°C}$. The thick-walled version has $m = .060 \text{ cal/cm}^3\text{°C}$ with the probe being 70% steel. An earlier version of the in-situ probe was of a double-probe design. It consisted of a steel tube housing the thermistor adjacent to the same size tubing containing a heater wire. A procedure on construction of the recent thermal probe ("single-probe design") is presented in the appendix.

The value of Q , the heating power per unit length, determines the relative temperature rise (eqns. 7 and 11). It is calculated as

$$Q = I^2 \left(\frac{R}{L} \right) \quad (13)$$

where I is current and (R/L) is resistance of the wire per unit length. The heater current is maintained at a value near 200 to 250 milliamps D.C. (depending on the instrument used) by a constant current regulator of maximum 15 volt output powered by a battery pack. The resistance of the heating wire used is about 35 ohms/m giving the value of Q as about 2 W/m. After 10 minutes the temperature rise for the in-situ probe in sediment is generally less than 1°C.

The electronic circuitry for the heat flow instrument together with the digital tape recorder, acoustic transponder and battery pack are housed in a single pressure casing located within the weightstand at the top of the probe

Figure 3. Cross section of thermal probes. a) single-probe design (thin-wall). b) single-probe design (thick-wall). c) double-probe design. See appendix for details of construction.

barrel (fig.1). Inputs are sequentially sampled at 2-second intervals and include a pressure transducer, continuous tilt meter, heater current, time counter, and two reference resistors in addition to as many as eight thermistors. Thus, each variable is typically measured each 28 seconds. The thermistors and heater system are connected to the heat flow instrument by a cable, plug, and socket assembly, with the heaters being in a series circuit to assure uniform heating of each probe. The digital data is recorded on a magnetic tape cassette as well as being telemetered to the sea surface for real-time monitoring of the recorded data. The temperature versus time record after the heater current is activated constitutes the in-situ conductivity data set.

The 'pogo' measurement technique usually results in a 1-2 km spacing between penetrations, with the DHF instrument battery power allowing up to 20 to 25 penetrations for a single heat flow station. After penetration of the instrument into the sea bottom, the pressure does not change until the instrument is recovered after measurement. The equilibrium temperature is estimated from the smooth decay of the frictional heating event. The heater current is normally programmed (by a microprocessor) to turn on after 5 minutes of stable pressure readings and is applied for 10 minutes. With rough seas or in a region of large current drift, when the instrument is susceptible to being prematurely pulled by the trawl wire, a preset time delay heater turn-on program can be used as an alternative.

DATA REDUCTION

The data set retrieved from a heat flow station includes a telemetered analog graphical record as well as digital data on cassette tape. The digital data is normally analyzed as it has the highest resolution ($0.5\text{ m}^{\circ}\text{C}$). The

graphical record, normally used for real-time monitoring of instrumentation, can also be used for detailed analysis if the digital tape record is absent or faulty. If the telemetered data is preset for approximately 1°C full scale, the potential resolution is $2\text{--}3\text{ m}^{\circ}\text{C}$. Thus, at a much lower resolution, the graphical data can be digitized and processed in the same way as the cassette tape record.

Figure 4 shows a flow diagram of the basic procedure for reducing the digital data. The tapes are recorded in standard 615 bpi Memodyne tape format and transferred to 5" floppy disks with a customized tape reader and Apple II_e minicomputer. Figure 5 shows the steps used to obtain the temperatures from the binary data stored on disk. The binary data is converted to "counts" and stored in the integer file STN.CON. This file is then edited as STN.WRK and contains only the data pertaining to each of the approximately 20 minute heat flow stations made during each multipenetration lowering of the instrument. Using calibration data the program TEMP processes the STN.WRK (fig. 6) file to give temperatures and tilts. This data is stored in file STN.TMP (fig. 7).

At this point, the data analysis employs the formulae previously outlined in the theory section. A typical temperature record for each heat flow penetration can be divided into four sections (fig. 8): 1) the 2-minute period before initial penetration, 2) 5-minute period for the temperature decay after the initial penetration, 3) the 10-minute period of continuous heating and 4) the 2-minute period after pullout of the instrument. The temperatures before penetration and after pull-out are used to calculate any drift during the penetration and also determine the uniform near-bottom water temperature recorded by each thermistor as a reference temperature. The equilibrium temperatures are determined relative to the water temperatures since

Figure 4. Flow diagram of data acquisition and handling.

Figure 5. Flow diagram of data processing.

FILE NAME B:LIGHF12.WRK

time	press	TO	T1	lo-cal	T2	T3	tilt	T4	T5	htr-cur	hi-cal	T6	T7
119	-8473	-982	1852	189	485	473	183	328	653	1	3462	483	1133 R 2
120	8471	897	426	188	457	447	798	318	651	1	3462	483	1133 R 3
121	8476	897	426	188	457	447	178	319	658	1	3461	482	1143 R 4
122	8474	897	426	187	455	447	858	319	651	1	3461	486	1157 R 5
123	8581	983	431	186	462	453	117	325	657	1	3461	483	1596 R 6
124	8789	898	698	188	817	881	1611	727	1897	1	3461	879	1698 R 7
125	8798	898	555	188	641	663	412	598	974	1	3461	788	1618 R 8
126	8789	898	535	188	611	636	1598	557	943	1	3461	748	1598 R 9
127	8789	898	527	188	599	624	488	544	931	1	3461	731	1582 R 10
128	8791	896	523	188	591	617	1595	534	921	1	3461	722	1593 R 11
129	8791	896	528	189	586	614	487	529	916	1	3461	714	1688 R 12
130	8792	898	516	189	583	611	1595	524	913	1	3461	718	1616 R 13
131	8792	897	515	188	581	689	487	522	989	1	3461	786	1626 R 14
132	8791	897	513	189	579	687	1597	519	987	1	3461	783	1621 R 15
133	8791	896	512	198	577	686	484	519	984	1	3461	781	1647 R 16
134	8791	897	512	198	576	686	1596	517	984	1	-3461	-725	-1682 R 17
135	-8798	-982	-1388	-189	-1283	-1915	-485	-1625	-1778	-23473	-3458	-1392	-1697 R 18
136	-8791	-981	-1678	-198	-1515	-2121	-1682	-1791	-1951	-23472	-3459	-1534	-1782 R 19
137	-8791	-981	-1825	-189	-1631	-2226	-488	-1881	-2858	-23474	-3458	-1618	-1715 R 20
138	-8792	-982	-1888	-198	-1718	-2298	-1682	-1942	-2119	-23474	-3458	-1678	-1721 R 21
139	-8792	-982	-1949	-188	-1769	-2351	-488	-1989	-2171	-23473	-3459	-1724	-1735 R 22
140	-8791	-981	-1999	-187	-1816	-2395	-1682	-2827	-2212	-23474	-3458	-1763	-1763 R 23
141	-8791	-988	-2848	-189	-1855	-2428	-487	-2858	-2258	-23473	-3458	-1795	-1755 R 24
142	-8792	-981	-2874	-198	-1889	-2461	-1683	-2886	-2281	-23472	-3458	-1822	-1754 R 25
143	-8791	-988	-2185	-198	-1919	-2486	-486	-2118	-2386	-23474	-3458	-1847	-1758 R 26
144	-8798	-981	-2131	-191	-1944	-2512	-1686	-2131	-2331	-23473	-3459	-1869	-1767 R 27
145	-8798	-981	-2155	-189	-1968	-2533	-488	-2152	-2353	-23473	-3458	-1889	-1774 R 28
146	-8789	-981	-2177	-191	-1988	-2553	-1685	-2169	-2371	-23473	-3458	-1906	-1781 R 29
147	-8789	-981	-2197	-198	-2889	-2578	-488	-2185	-2398	-23472	-3459	-1923	-1786 R 30
148	-8798	-981	-2215	-198	-2827	-2586	-1688	-2288	-2487	-23472	-3459	-1938	-1796 R 31
149	-8798	-981	-2232	-191	-2842	-2681	-488	-2215	-2421	-23473	-3458	-1953	-1794 R 32
150	-8798	-981	-2248	-198	-2859	-2619	-1686	-2227	-2435	-23472	-3459	-1966	-1882 R 33
151	-8789	-981	-2263	-189	-2873	-2632	-488	-2248	-2458	-23473	-3458	-1978	-1815 R 34
152	-8798	-981	-2277	-198	-2887	-2644	-1688	-2251	-2461	-23471	-3457	-1998	-1818 R 35
153	-8798	-981	-2298	-198	-2188	-2657	-436	-2261	-2473	-23472	-3458	-2881	-1815 R 36
154	-8789	-982	-1983	-187	-1944	-1884	-1149	-1892	-1144	-23473	-3458	-662	-1562 R 37
155	-8697	-984	-1869	-198	-885	-1468	-385	-1877	-1114	-23473	-3458	-674	-1569 R 38
156	-8588	-986	1848	198	486	483	558	325	658	1	3461	487	1526 R 39
157	8485	898	427	187	459	449	322	328	655	1	3461	486	1517 R 40
158	8473	898	427	188	459	449	872	319	652	1	3461	486	1521 R 41
159	8475	898	427	187	459	449	174	328	656	1	3461	486	1515 R 42

Figure 6. Printout of an integer file. The file consists of values of bridge output after conversion from binary to integer values using CONVERT program. Heater ON/OFF status is monitored every cycle, minus sign = ON. Note heater turn-on during time record 134 and turn-off record 156.

FILE NAME LIGHF12.TMP

TIME	PRESS	T-0	T-1	T-2	T-3	TILT	T-4	T-5	T/C	T-6	T-7
119	8473	13.154	13.635	13.148	13.171	1	13.863	13.127	TC OFF	13.131	13.778
120	8471	13.158	13.149	13.128	13.151	3	13.862	13.126	TC OFF	13.132	13.778
121	8476	13.158	13.149	13.128	13.151	2	13.863	13.125	TC OFF	13.131	13.778
122	8474	13.151	13.149	13.119	13.152	3	13.863	13.127	TC OFF	13.135	13.798
123	8581	13.156	13.154	13.125	13.158	1	13.869	13.132	TC OFF	13.134	14.134
124	8789	13.151	13.354	13.398	13.428	4	13.382	13.475	TC OFF	13.585	14.214
125	8798	13.151	13.249	13.262	13.328	2	13.274	13.378	TC OFF	13.427	14.145
126	8789	13.151	13.233	13.238	13.299	4	13.249	13.354	TC OFF	13.482	14.135
127	8789	13.151	13.227	13.229	13.289	2	13.238	13.345	TC OFF	13.389	14.122
128	8791	13.158	13.224	13.223	13.284	4	13.231	13.337	TC OFF	13.382	14.131
129	8791	13.149	13.221	13.218	13.281	2	13.226	13.332	TC OFF	13.375	14.143
130	8792	13.151	13.218	13.216	13.279	4	13.222	13.338	TC OFF	13.372	14.149
131	8792	13.158	13.218	13.215	13.278	2	13.221	13.327	TC OFF	13.369	14.157
132	8791	13.158	13.215	13.213	13.275	4	13.218	13.325	TC OFF	13.366	14.153
133	8791	13.148	13.214	13.211	13.274	2	13.217	13.322	TC OFF	13.364	14.173
134	8791	13.149	13.214	13.218	13.274	4	13.216	13.322	TC OFF	13.383	14.288
135	8798	13.154	13.899	13.768	14.386	2	14.898	14.812	TC ON	13.918	14.214
136	8791	13.153	14.127	13.941	14.469	4	14.221	14.148	TC ON	14.822	14.217
137	8791	13.153	14.228	14.832	14.553	2	14.294	14.229	TC ON	14.889	14.228
138	8792	13.154	14.293	14.894	14.618	4	14.342	14.282	TC ON	14.137	14.232
139	8792	13.155	14.342	14.141	14.653	2	14.388	14.324	TC ON	14.174	14.244
140	8791	13.155	14.382	14.178	14.688	4	14.411	14.357	TC ON	14.286	14.267
141	8791	13.153	14.414	14.288	14.714	2	14.435	14.387	TC ON	14.238	14.259
142	8792	13.153	14.448	14.234	14.748	4	14.457	14.411	TC ON	14.251	14.258
143	8791	13.152	14.465	14.258	14.768	2	14.476	14.431	TC ON	14.271	14.261
144	8798	13.152	14.485	14.277	14.788	4	14.492	14.458	TC ON	14.288	14.268
145	8798	13.153	14.585	14.297	14.798	2	14.518	14.469	TC ON	14.385	14.274
146	8789	13.152	14.522	14.312	14.814	4	14.523	14.483	TC ON	14.318	14.279
147	8789	13.153	14.537	14.328	14.827	2	14.535	14.498	TC ON	14.331	14.283
148	8798	13.153	14.552	14.343	14.848	4	14.547	14.511	TC ON	14.343	14.291
149	8798	13.152	14.565	14.355	14.852	2	14.568	14.523	TC ON	14.355	14.298
150	8798	13.153	14.578	14.368	14.866	4	14.569	14.534	TC ON	14.366	14.296
151	8789	13.153	14.591	14.388	14.878	2	14.588	14.546	TC ON	14.376	14.387
152	8798	13.153	14.682	14.391	14.888	4	14.589	14.556	TC ON	14.386	14.389
153	8798	13.153	14.612	14.421	14.897	2	14.597	14.565	TC ON	14.394	14.386
154	8789	13.155	14.369	14.279	14.218	3	13.678	13.513	TC ON	13.336	14.188
155	8697	13.155	13.649	13.388	13.945	2	13.656	13.488	TC ON	13.343	14.112
156	8588	13.156	13.632	13.141	13.178	2	13.866	13.138	TC OFF	13.134	14.878
157	8485	13.152	13.158	13.122	13.154	2	13.864	13.138	TC OFF	13.135	14.872
158	8473	13.151	13.149	13.121	13.153	3	13.863	13.127	TC OFF	13.135	14.875
159	8475	13.152	13.158	13.122	13.154	2	13.864	13.131	TC OFF	13.135	14.878

Figure 7. Printout of temperature file. Listing is an output of TEMP program using STN.WRK integer file and calibration data as input.

Digital Temperature Record

Figure 8. Plot of digital temperature record of a single thermistor (see text).

thermistor calibrations do not take into account lead resistances of the cables and contact resistance at the plug-socket connections and thus do not give accurate absolute temperatures.

The equilibrium temperatures are determined using equation (1) and the asymptotic expression for $F(\alpha, \tau)$ given in equation (6). The observed temperatures versus time are fit to

$$\theta = \theta_1 + b (1/t_1) \quad (14)$$

in a least-squares sense. The coefficient b is the slope of the regression line and the equilibrium temperature θ_1 is simply the intercept (fig 9). Equation (14) is valid only for large t_1 so that the temperatures recorded immediately after the initial penetration must be disregarded in the computation. An ideal data set is generated using the exact solution of the $F(\alpha, \tau)$ decay curve with $b = 1.7^\circ\text{C sec}$ and $\theta_0 = 1^\circ\text{C}$. These data are matched to within $0.5\text{ m}^\circ\text{C}$ of the equilibrium temperature by equation (14) if only temperatures recorded at $\tau > 10$ are used. This translates to ignoring temperatures within 80-90 seconds of the initial penetration for the WHOI instrument. The program that selects the proper portion of STN.TMP and makes a least squares fit to equation (14) is called TIME.BAS.

To determine the thermal conductivity, the Blackwell approximation of $G(\alpha, \tau)$ (eqn. 9) is applied to the temperature data after the heater is turned on. The data are fitted to equation (11) in a least-squares sense, where the slope of the regression line is given by Q/K , with K being the thermal conductivity of the sediment. The program COND.BAS is used to retrieve the desired data from the STN.TMP file and perform the linear regression. The Blackwell approximation is a significant improvement over the asymptotic solution to $G(\alpha, \tau)$. Much earlier times of the heating curve can be used with nearly the accuracy of the exact solution. For the

Heat Flow L4S5.P1

Figure 9. Plot of temperature, θ vs. the reciprocal of time for seven thermal probes during a single penetration. All data are relative to the bottom water temperature.

single-probe design, temperatures are typically retrieved from $\tau=7$ to $\tau=50$ (60 to 450 seconds). For this range in τ and for $\alpha=2$, the Blackwell approximation gives a differential of $G(\alpha, \tau)$ that is within 0.1% of that given by the exact solution and so generates negligible error in the K determination. Also, the Blackwell solution is computationally simple and does not require the retrieval and interpolation of an existing table of the exact solution. If the asymptote is used in a similar τ range, the $G(\alpha, \tau)$ will be underestimated by 1.0% at $\tau=14$ and 0.4% at $\tau=40$. This discrepancy will cause a bias of 2.3% higher conductivity estimate and is readily verified by comparing the Blackwell and asymptotic solutions with the same data set. The observed temperatures are modified to account for the $\theta_0 F(\alpha, \tau)$ term (eqn. 11) by subtracting the residual temperatures extrapolated from the $1/t_1$ fit (eqn. 14) (see fig. 10). The uncertainty in the K calculated from the regression analysis is quoted at the 95% confidence level using the student's t -test.

A basic limitation in the accuracy of the K determination is due to the number and frequency of the digitally recorded temperatures. For example, the seven data sets plotted in figure (10) have an average fit error of $\pm 0.6\%$. If temperatures are selectively sampled from the above data set, we find that, for sample numbers $N \geq 9$, a greater range of time sampled is more important in minimizing the statistical error than the sample frequency (see fig. 11).

SOURCES OF ERROR

The in-situ continuous-heating method is evaluated in light of the analytical approximations and possible instrument uncertainties. The errors incurred in the $G(\alpha, \tau)$ estimate are mainly due to the uncertainty of the sediment thermal diffusivity value in the α and τ parameters. Minor

Heat Flow L4S4.K7

Figure 10. Plot of modified temperature, $\theta - \theta_1 - b(1/t_1)$ vs. $G(\alpha, \tau)$ for seven thermistors. The regression lines of slope Q/K are also shown. The sample number N is 18, sample frequency Δt is 28 s, and the time range $t=(86 \text{ s}, 588 \text{ s})$.

Figure 11. Plots of temperature vs. $G(\alpha, \tau)$ (see fig. 6b for details). a) $N = 9$, $\Delta t = 56$ s, $t = 86$ s, 588 s) and average fit error, $\Delta K = 1.0\%$. b) $N = 9$, $\Delta t = 28$ s, $t = 86$ s, 336 s), and $\Delta K = 1.7\%$. c) $N = 9$, $\Delta t = 28$ s, $t = 338$ s, 588 s), and $\Delta K = 3.4\%$.

random errors are also attributed to the uncertainty of the heater turn-on time as well as the calibration of the heater current itself. As previously mentioned, there are several versions of the in-situ probe used by the WHOI lab: a single-probe design with a thin or thick walled probe housing and a double-probe design (fig. 3). The single-probe design closely approximates the analytical theory because the heater line source and temperature sensor are located near the center of a probe that has a good conducting wall of cylindrical geometry. The double-probe design inherently has a greater uncertainty because the heater and thermistor are separated by several millimeters, each being housed in its own probe. The geometry of the heating is obviously not cylindrical at short times, but becomes increasingly so as the radius of the heating front in the sediment becomes large compared to the probe dimensions. The sources of error of the single-probe design are discussed first. The double-probe design is treated as having an additional random error due to the uncertainty of its "effective radius".

Single-probe design

A small uncertainty is attributed to the heater output Q (eqn. 13). The current is calibrated in the lab to known standards with an accuracy of ± 0.1 ma. The relative value of the current is also known to better than 0.1 ma of a total 200 ma during in-situ measurements, and is monitored every record. An earlier version of the heater-control circuit board provided a relay indicating only the on/off status of the heater. If the heater current falls below its regulated value due to low battery voltage, the temperature versus $G(\alpha, \tau)$ curve shows significant lack of fit and the measurement may be disregarded. The heating wire is of a uniform resistance per unit length. Laboratory measurements indicate a 39.17 ± 0.10 Ω/m resistance for the

constantan heater wire with a temperature coefficient on the order of 10^{-5} $^{\circ}\text{C}^{-1}$. Thus, the uncertainty in K due to the uncertainty of Q is $< 0.5\%$.

The establishment of the heater origin time is important in determining the slope of the heating curve. This time is pre-programmed in the EPROM of the DHF microprocessor. The cycles during which the heater is active are easily seen on the STN.WRK file as the leftmost bit of the binary file is set high and is marked by a negative prefix on the integer file (fig. 6). The cycles in which the heater is ON are marked negative regardless of the heater turn-on mechanism (pressure stability monitor, in which the heater turns on 5 minutes after the instrument has penetrated the sea floor and remains on for 10 minutes; or time interval, e.g., 10 minutes heater ON and 50 minutes OFF). There is a < 1 sec uncertainty in the timing of data written on the tape due to sequential monitoring of the variables. An earlier version of the DHF instrument did not provide for an indication of the particular cycle during which the heater was ON; instead, the heater status was registered only once during the 28-second record. For this case (e.g., in-situ data from 1981 Tyrrhenian and 1982 Ligurian cruises), error in the K determination may occur for an improper origin time. Figure 12 illustrates the effect of a shift in the assigned time since heater ON. For time shifts up to one thermal time constant of the probe (8 sec), there is approximately a linear change in K. Whereas the time shift of a few seconds can affect the K value, it does not produce an appreciable lack of fit in the temperature versus $G(\alpha, \tau)$ plot. A 1-2% error in K can exist when the heater status is not registered for each recorded variable.

Somewhat analogous to the effect of a start time delay is the existence of a thermal contact resistance in the form of disturbed sediment or even water between the steel probe and sediment. Such a boundary zone of different

Figure 12. Variation in calculated K due to uncertainty in 'time since heater on'.

conductivity, if not accounted for, could produce a non-linearity in the predicted heating curve, as discussed by Jaeger (1956). The possibility of a deviation from the predicted curve emphasizes the value of utilizing the entire temperature vs. time record rather than determining its slope only from the end points. However, no systematic evidence for the inclusion of a contact resistance parameter per unit area of probe/sediment interface, $1/H$, exists in the in-situ data. The small probe diameter and the outrigger fins angularly separated around the axis of the probe barrel apparently ensure adequate thermal contact at the sediment/probe interface. It has been assumed that the thermal decay in the pulse-heating is less sensitive to contact resistance than the continuous-heating method (Lister, 1979; Hyndman et al., 1979). However, this is true only in so far as the net change in the probe temperature in presence of a contact resistance would be greater throughout a continuous-heating experiment. The shape of the temperature/time curves would be about equally distorted in both cases (see figs. 2 and 5 of Jaeger (1956)). The internal probe configuration and contents of the in-situ probe may also be closely related to the problem of 'contact' resistance since the heat conduction theory for cylindrical probes assumes the probe to be an infinite conductor.

The largest uncertainty in determining K lies in the estimation of the thermal diffusivity κ . Since κ is incorporated into the α and τ parameters, its value can significantly alter the $G(\alpha, \tau)$ variable determined for the specified times during the continuous-heating period. In practice, κ for ocean sediments is found using an empirical relation with K

such as

$$\kappa = (3.66K - .70) \times 10^{-7} \quad (K \text{ in } \text{Wm}^{-1}\text{°C}^{-1}, \kappa \text{ in } \text{m}^2\text{s}^{-1}) \quad (15)$$

given by Von Herzen and Maxwell (1959). A similar relation

$$\kappa = \frac{K}{10^6(5.79 - 3.67K + 1.016 K^2)} \quad (16)$$

has been established by Hyndman et al. (1979). Both relations (eqns. 15 and 16) are derived by using measurements of K and water content W , and by assuming thermal capacities and densities for the liquid and solid components of the sediment. The theoretical relationship used to determine κ is

$$\kappa = \frac{K}{\rho_w C_w} \left(\frac{1 + \frac{1-W}{W} \frac{\rho_w}{\rho_s}}{1 + \frac{1-W}{W} \frac{C_s}{C_w}} \right) \quad (17)$$

where W is the water fraction by weight, ρ_w and ρ_s are the density of the water and solid components, and C_w and C_s are the heat capacities of the water and solid, respectively (Von Herzen and Maxwell, 1959). Equation (16) (curve b, fig. 13) gives values of κ that are 1% higher for $K=0.7$, 8% higher for $K=1.0$, and 20% higher for $K=1.4 \text{ Wm}^{-1}\text{°C}^{-1}$ than the equation (15) (curve d, fig. 13). Equation (16) was obtained for a greater range of conductivities, as equation (15) only sampled conductivities in the range of .7 to $1.1 \text{ Wm}^{-1}\text{°C}^{-1}$.

W can be either measured directly, as was done above, or obtained using the relation of Ratcliffe (1960) and Bullard and Day (1961). They give the empirical relation

$$K = (aW + b)^{-1} \quad (18)$$

where a and b are constants. K vs. W plots for deep-sea sediments generally have high scatter. As noted by Davis et al. (1985), the thermal conductivity of the constituent mineral grains accounts for some variability. Sediment

Figure 13. Plot of thermal diffusivity vs. conductivity curves derived from empirical relations. Curve (b) uses equation (16), curve (d) equation (15), and curves a and c use equations (17) and (18) (see text).

grain shape, inter-grain contacts and anisotropic properties also play a role in the conductivity values and in their subsequent relationship to water content. Therefore, it is the variability of W with respect to K that essentially produces the uncertainty in the thermal diffusivity estimate.

To investigate the maximum and minimum bounds for the κ vs. K curves, we have substituted the variable W (eqn. 17) into equation (18) and tested a range of values for the parameters a , b , and ρ_s assuming the values of $\rho_w = 1.03 \text{ g cm}^{-3}$, $C_w = .94 \text{ cal gm}^{-1} \text{ }^\circ\text{C}^{-1}$ and $C_s = .184 \text{ cal gm}^{-1} \text{ }^\circ\text{C}^{-1}$ (from Bullard, 1954). The upper bound (curve a, fig. 13) uses values of $\rho_s = 2.5 \text{ g cm}^{-3}$ of $a = 709$ and $b = 182$ from Bullard and Day (1961). The lower bound (curve c, fig. 13) consists of a $\rho_s = 2.6 \text{ g cm}^{-3}$ and $a = 741$ and $b = 95$ from Lachenbruch and Marshall (1966). We note that a decrease in the assumed density of the solid component from 2.6 g cm^{-3} to 2.5 g cm^{-3} will increase the κ values by 3%. Thus, it seems incorrect for Hyndman et al. (1979) to state that their estimated κ (eqn. 16) is higher than relation (15) because they use a higher solid density ($\rho_s=2.6$ rather than $\rho_s=2.5$). Instead, it seems that they have based their study on sediments that have a solid component with a low conductivity.

Since equation (15) is used to estimate κ in our data processing, it appears from figure (13) that the diffusivity might be systematically under-estimated. The studies made thus far with the WHOI probe include regions which have a moderate amount of terrigenous input. As a result, the overall grain thermal conductivity and density is higher than typical deep-sea sediment (Langseth and Von Herzen, 1971). In fact, analysis of physical property data of sediments from the Ligurian Basin indicate some similarity to Arctic sediments (M. Langseth, 1983). Thus, curve c (fig. 13), which is determined for Arctic sediments, is probably our best estimate of K - W relation

(18) for the field comparisons considered in this paper. The region studied west of Bermuda (Davis et al., 1985) also seems to have a K-W relationship more similar to curve c (fig. 13). The higher curve (a, fig. 13) is mainly derived from Pacific and Atlantic pelagic sediment and is more applicable to clay-rich sediment.

Values of α (eqn. 4) for a range of diffusivities are shown in figure (14a). The uncertainty of α is on the order of 10% as shown by the pair of curves dependent on the κ -K relation chosen. Figure (14b) indicates that assuming an arbitrary value of $\alpha = 2.0$ would give rise to a small $\pm 0.5\%$ error in the computed value of K. The uncertainty of K due to τ (eqn. 3) is isolated by choosing a constant value of α and examining G between $t=100$ and $t=400$ seconds. From figure (13), it is apparent that κ uncertainty increases from about 10% for small κ ($K=.7$ W/m°C) to 20% for larger κ ($K=1.4$ W/m°C). Thus, we have constructed two curves suitable for a low (.7 W/m°C) and high (1.4 W/m°C) conductivity to investigate the error in K due to τ (fig. 15). The K determination is more sensitive to uncertainties in τ at low conductivities, but our knowledge of κ is also more accurate for small K. If the total error in α and τ that arises from the probable inaccuracy in the sediment diffusivity is considered (fig. 16), then the error in computed K is less than 2% which is comparable with that found by Hyndman et al. (1979) for the pulse-heating method. Thus, the total uncertainty in the computed K for the continuous-heating method when all instrumental errors are taken into account is 3 to 4%.

Double-probe design

The double-probe design was a consequence of a simple conversion of the already existing temperature probe into assemblies capable of measuring

Figure 14. a) α vs. K curves for probe with heat capacity of $m = 0.06 \text{ cal cm}^{-1} \text{ } ^\circ\text{C}^{-1}$. Curve (A) uses equation 16 and Curve (B) uses equation 15. b) Error in α vs. percent change in K. $G(\alpha, \tau)$ is determined at $\tau = 10$ and 40 for all cases of α . For reference, $\alpha = 2.0$ is assumed as the true value in equation (7).

Figure 15. Error in τ vs. percent change in K . Equation (15) used for κ - K relation. Curve A assumes $K = 0.7$ W/M°C and $\alpha = 2.7$. Curve B assumes $K = 1.4$ W/M°C and $\alpha = 2.3$.

Figure 16. Error in κ vs. percent change in K . $G(\alpha, \tau)$ is determined at $t = 100 \text{ s}$ and 400 s after heater turns on. Equation (15) used for κ - K relation. Curves assume $K = 0.7$ and $1.4 \text{ W/M}^\circ\text{C}$ and are extended to realistic uncertainty in κ according to figure (13).

in-situ K . An externally mounted heater wire circuit was positioned adjacent to the thermistor probe in its own steel tube (fig. 3c). The more complicated geometry of the double-probe design does not lend itself easily to analytical theory. The two probes will sometimes separate slightly during field use and consequently have a variable thermal contact between their lengths. However, at sufficiently long times, the double probe must approach the behavior of an equivalent single probe since temperatures will only be a function of the asymptote $\ln(t)$.

Since we are interested in using times as short as possible to recover the conductivity data, the finite heat capacity of the double-probe system is taken into account (see eqn. 9). The thermal capacity of the bi-axial probe has approximately doubled, as has the volume of sediment displaced by the probe. Thus, α is similar to that of the single probe.

The uncertainty of thermal diffusivity on τ was investigated above for the single probe. In the case of the double-probe design, the radius r of the double probe is indefinite so that the relationship of r to $G(\alpha, \tau)$ must be studied. The double probe is approximated by assuming an "effective" radius which lies between the radius of the single probe ($r = .16$ cm) and the distance between the axes of the heater and thermistor probes ($r = .32$ cm). Thus, with a larger uncertainty than the single-probe design, the actual conductivity can be bracketed between high and low estimates. An analytical test of the double-probe design is to determine at what times equation (9) is valid.

The Blackwell approximation (eqn. 9) for the probe model is compared to an off-axis model described by Jaeger (1958) in which temperature θ is recorded a distance d from an infinite line heat source in an infinite medium of κ diffusivity and K conductivity. The medium is initially at $\theta=0$ and at time

$t > 0$ heat is supplied at a rate Q per unit length per unit time. For $t > 0$, θ is given by

$$\theta = -\frac{Q}{4\pi K} E_1\left(\frac{-d^2}{4\kappa t}\right) \quad (19)$$

where $-E_1(-x)$ is the exponential integral whose series expansion is

$$-E_1\left(\frac{-d^2}{4\kappa t}\right) = \ln\left(\frac{4\kappa t}{Cd^2}\right) - \sum_{n=1}^{\infty} \frac{(-1)^n}{nn!} \left(\frac{d^2}{4\kappa t}\right)^n \quad (20)$$

and $C=1.7811$ (Abramowitz and Stegun, 1965). For the double-probe design, d is analogous to the distance between the heater wire and thermistor located in the adjacent cylindrical probes. The main inaccuracy in the off-axis model is that the high conductivity and possibly different heat capacity of the steel probes is not taken into account; instead, the model assumes that the material between heater and thermistor sensor is relatively low-conducting sediment, which is the extreme case for two probes in contact. By equating the probe radius r with d , we compare $K\theta/Q$ of the Blackwell approximation for the single probe (eqn. 9) to the off-axis model (eqn. 19) in figure (17). At $\tau=7$ and $\alpha=2.0$, calculated K for the single probe is about 1% higher than the off-axis model with the solutions converging for large τ . Accepting $\tau=7$ as the minimum τ for equation (9) to become valid for the double-probe design, we estimate the minimum time by examining values of τ for different radii (fig. 18). The minimum time is 60 to 235 seconds for sediment of $\kappa=.3 \times 10^{-6} \text{ m}^2/\text{s}$ depending on the value of the "effective" radius being .16 or .32 cm, respectively. Accordingly, if temperature data recorded later than 200 seconds are successively dropped, we find little change in the computed K , regardless of the radius used. On the other hand, if temperatures recorded <100 seconds after the heater turns on are considered, the computed K will be underestimated by a few percent and will have a larger curve fit error.

Probe Model vs. Off-Axis Model

Figure 17. Percent difference in $K\theta/Q$ value for probe model to the off-axis model for various kt/r^2 . Curves drawn for cases of $\alpha = 2.5$, 2.0, and 1.5. Distance between heater and thermistor in off-axis model is equated to radius of probe model.

Figure 18. Curves of $\tau = 7$ plotted in time vs. κ for radii of $r = .16$ and $.32 \text{ cm}$. A doubling of r quadruples the equivalent time.

When using high and low estimates of the probe radius in the K determination, the small radius case always produces the higher K value. In figure (19), the increase in K computed with $r=.16$ cm instead of $r=.32$ cm is plotted against the K value using $r=.32$ cm. The theoretical curves are dependent on the minimum time value utilized. When short times are considered, there is a larger discrepancy between the computed K for the small and large radius cases. For a delay time of 150 seconds, a change of about $.04 - .05$ W/m°C in K can be expected.

In-situ K measurements made during the 1982 Ligurian Sea cruise utilized the double-probe design. The curve fit errors of these data are examined for $r=.32$ cm (fig. 20). We find that the data are very linear with $G(\alpha, \tau)$ and most of the errors are between 1 and 3% regardless of the magnitude of K. We investigated whether or not a minimum in fit error for the radius variable is indicative of the "proper" probe radius. From figure (21) the change in the fit error for the two radii is random when all measurements are considered. Some systematic variations do occur such that some probes tend to consistently have smaller errors for the smaller radius. Each individual biaxial probe probably has a different degree of thermal contact and spatial separation between the heater probe and thermistor probe. However, a minimization routine to find the "proper" radius does not seem warranted since the effect only amounts to a few tenths of a percent of the fit error and is also complicated by other instrumental uncertainties. Large curve fit errors likely indicate either disturbance in the $F(\alpha, \tau)$ decay or significant separation of the heater and thermistor probe.

In practice, the final K value is obtained either by averaging solutions to the low estimate ($r = .16$ cm) and high estimate ($r = .32$ cm) or by using an intermediate value for the radius ($r = .23$ cm). A $\pm .03$ W/m°C uncertainty is

Figure 19. K obtained using $r = .32$ cm is plotted with the increase in K found using $r = .16$ cm. Curves show the relation that the initial time considered in the temperature record (50, 100, 200, 400 s) has on the difference in the computed K for the two radii.

Figure 20. Plot of curve fit error in K determination vs. K found using $r = .32$ cm. Data set is comprised of in-situ K using double-probe design. Lines of 1 and 3% error are shown. Errors determined using student's t-test at 95% confidence level.

Figure 21. Plot of change in the curve fit error from K using $r = .16$ cm and K using $.32$ cm. Data set same as figure (16). Note the change in error is $< 0.5\%$ for all cases of K

generally attributed to uncertainty in r , making the total instrumental error for the double-probe design $< 6\%$. It is not clear that a "proper" value of radius can be found using minimization techniques or using a numerical approach due to the variable thermal contact of the double-probe construction. The single-probe design is a physical system easily quantified by analytical theory for heat conduction in cylindrical probes, and therefore inherently has greater accuracy.

FIELD COMPARISON

The in-situ conductivities are calibrated by comparison to needle-probe values obtained from piston cores located adjacent to 'pogo' stations. The double-probe design has been compared to the pulse-heating method on a violin-bow instrument in a Tyrrhenian Basin site (Hutchison et al., 1985). The continuous-heating method gave values that were within 1-2% of the pulse-probe values obtained in a region of rather uniform conductivity both laterally and vertically. However, for the Tyrrhenian Basin both in-situ methods had a few percent higher conductivity than the piston core values which were corrected for ambient pressure and temperature on the seafloor (Ratcliffe, 1960). The introduction of excess water into the sediment during the coring process or exsolution of gas after recovery could cause the needle-probe values to be low. Additional comparisons of the in-situ continuous-heating technique have been made to needle-probe measurements made on nearby cores at sites in the Ligurian Basin and Bermuda Rise (table 3). For each site, all in-situ stations made within 3 km of the piston core were considered, and only needle-probe values from the upper 7 m of the piston core were selected. The mean of the needle-probe values have been plotted against the mean of all in-situ measurements in each site (fig. 22). The deviation

Table 3

Selected Piston Core and In-Situ 'Pogo' Stations

<u>Site</u> ¹	<u>Station</u> ²	<u>Latitude</u>	<u>Longitude</u>	<u>NK</u> ³	<u>Mean K(W/m°C)</u>	<u>ΔK</u> ⁴
S1	B83PC04	30°12.5N	69°47.8W	15	.898	.008
	B83S6B.4	30°12.3N	69°48.3W	5	.918	.036
	B83S6B.5	30°12.2N	69°47.4W	5	.918	.036
S2	B83PC05	31°08.0N	68°08.1W	19	.946	.022
	B83S10.8	31°08.3N	68°06.5W	7	.909	.031
	B83S10.11	31°09.8N	68°07.3W	7	.935	.028
S3	B83PC06	31°12.1N	68°03.8W	19	.937	.028
	B83S9.5	31°12.6N	68°04.8W	5	.923	.087
	B83S9.6	31°12.5N	68°03.3W	5	.905	.053
	B83S9.7	31°12.2N	68°01.8W	5	.893	.022
S4	B83PC07	31°01.5N	66°29.7W	18	.890	.009
	B83S11.4	31°02.1N	66°27.8W	7	.961	.072
	B83S12.1	31°02.3N	66°31.6W	6	.959	.033
S5	L84PC03	43°38.3N	7°28.4E	27	1.098	.035
	L84S5.6	43°38.2N	7°28.6E	7	1.120	.088
S6	L84PC04	43°41.6N	7°28.4E	27	1.200	.031
	L84S5.9	43°41.6N	7°28.2E	7	1.251	.108
D1	L82PC01	42°49.9N	8°40.8E	18	1.090	.038
	L82S9.1	42°49.9N	8°40.8E	4	1.085	.039
D2	L82PC05	43°31.8N	7°48.2E	12	1.331	.124
	L82S16.9	43°32.7N	7°46.8E	4	1.413	.300
	L82S16.10	43°31.8N	7°48.2E	4	1.178	.144
D3	B83PC09	31°32.8N	65°42.1W	18	1.045	.036
	B83S14.2	31°32.6N	65°41.9W	6	1.069	.104
	B83S14.4	31°33.3N	65°41.7W	6	1.150	.052
D4	B83PC13	33°44.0N	67°27.7W	21	.900	.019
	B83S21.1	33°43.0N	67°29.6W	7	.864	.023
	B83S21.2	33°43.1N	67°29.0W	7	.911	.034
	B83S21.3	33°42.7N	67°28.0W	7	.955	.031

¹ S = in-situ data using single probe, D = using double probe

² piston core stations (nnnPCnn), pogo stations (nnnSnn.nn)

³ number of measurements

⁴ error derived from 95% confidence level using student t-test based on NK measurements

Figure 22. Plot of mean K from all needle-probe and in-situ data at selected sites S1 - S6 (single-probe design, closed circle) and D1 - D4 (double-probe design, open circle) (see Table 3). Error bars are for 95% confidence level using t-test.

between the core and in-situ values appears to be $< 5\%$ which is within the experimental error of the measurement techniques. Moreover, there is no apparent systematic difference between the in-situ and needle-probe values.

An estimate of the variability of the conductivity is made by comparing individual conductivity-depth profiles of the core stations (corrected to in-situ conditions) and 'pogo' stations. Where sediment conductivity is uniform with depth the comparison is most clear (fig. 23). When significant conductivity stratification occurs, the match-up of the profiles can be less convincing. However, we find that a best fit of the needle-probe and in-situ profiles are found when the piston core depths (as determined as distance from top of core) are consistently increased by up to 1 meter. The upper portion of the piston core may be lost frequently because of the uncertainty of the triggering process (McCoy and Von Herzen, 1971). Normally a small "pilot" gravity corer is used to retrieve the surface sediment. Heat flow measurements allow for an estimation of actual in-situ depths by extrapolation of the geothermal gradient to the sediment surface. Consequently, the core conductivity profiles have been shifted to greater depths to best align with the conductivity stratigraphy indicated by the in-situ conductivities and depths (figs. 24-28). These comparisons show remarkably good correlation and include in-situ values obtained by the single-probe and double-probe designs, in sediments of different mean conductivity.

The variability of the field comparison results is probably due to local (< 200 m), lateral changes in sediment conductivity. Regions of more uniform conductivity are located in areas of pelagic clays where normal ($.75$ to $.95$ $W/m^{\circ}C$) and below normal ($< .75$ $W/m^{\circ}C$) conductivity is found (Langseth and Von Herzen, 1971). Regions of higher than normal conductivity ($> .95$ $W/m^{\circ}C$) are associated with greater variability both laterally and vertically. Our field

Figure 23. Comparison of conductivity-depth profiles of piston core B83PC04 and 'pogo' station B83S6B.4. Needle-probe values of core are shown as diamonds with error bars of $\pm 5\%$ uncertainty. In-situ data is given by circles. Error bar at center of circle is curve fit error. Core data depths are relative to top of core and in-situ data depths are determined by extrapolation of geothermal gradient to the bottom water temperature. Position of stations given in table (3).

Figure 24. Comparison of conductivity-depth profiles of B83PC05 and B83S10.11. To improve the fit-by-eye of the core data profile to the in-situ data profile, the plot on right has piston core depths increased by $\Delta = 0.9\text{m}$. See figure (23) for further explanation.

Figure 25. Comparison of conductivity-depth profiles of B83PC06 and B83S9.6, $\Delta = 0.7\text{m}$.
See figures (23) and (24) for further explanation.

Figure 26. Comparison of conductivity-depth profiles of B83PC13 and B83S21.2, $\Delta = 1.0\text{m}$.
See figures (23) and (24) for further explanation.

Figure 27. Comparison of conductivity-depth profiles of B83PC09 and B83S14.2, $\Delta = 1.0\text{m}$.
See figures (23) and (24) for further explanation.

Figure 28. Comparison of conductivity-depth profiles of L82PC05 and L82S16.9, $\Delta = 0.8m$.
See figures (23) and (24) for further explanation.

study tends to sample higher than normal conductivities since Bermuda and the Ligurian Basin are proximate to continental margin environments. Variability in the conductivity values is to be expected. Figure 28 illustrates the problem of constructing accurate conductivity profiles from discrete in-situ measurements (1 meter spacing) in sediment with a significant increase in conductivity with depth. In such instances, an averaging thermistor chain such as that which has been employed in the violin-bow instrument would be most useful. Since conductivity variability is a geographically dependent problem, the uncertainty in the conductivity due to the sampling technique has been reserved for the interpretation of the specific data sets.

An interesting field experiment to compare the piston core data to in-situ data could involve the assembly of the outriggered thermal probes to a piston corer. Since the factor of lateral change in conductivity would essentially be removed, one could study the significance of effects such as anisotropy and vertical variability. Specific needle-probe data could be compared to the in-situ data to examine uncertainties the piston coring technique may have on the sediment core sample. For samples with high interval conductivity contrasts, gamma-ray attenuation logs could be used to study what effect fine-scale layering of bulk densities may have on the mean conductivity value for the core. In such an investigation, the cause of any measured non-linear temperature gradients may be better understood.

In summary, the in-situ measurement of thermal conductivity and temperature gradient gives the most reliable estimate of the surface heat flux. There are distinct advantages in using thermal probes of small radial dimension. Simple analytical approximations are attained for predicting probe temperatures at relatively short times. The short measurement times also reduce the risks of temperature perturbations due to probe disturbances. The

WHOI heat flow outrigger probes considered in this study will soon be modified to include an averaging thermistor chain which will increase the number of in-situ K values per penetration and will consequently allow for more accurate heat flow measurements.

ACKNOWLEDGEMENTS

We thank M. Dougherty, M. Van Gool, G. Pelletier, P. Schweitzer and S. Tavares for providing assistance in various phases of this study. This project was stimulated particularly by geothermal measurements made in the Western Mediterranean and on the Bermuda Rise with the support of grants from the U. S. National Science Foundation (OCE-8025181, -8117886, and -8409170).

REFERENCES

- Abramowitz, M., and Stegun, I.A. (Eds.), Handbook of Mathematical Functions, p. 248, Dover, New York, 1965.
- Blackwell, J.H., 1954, A transient-flow method for determination of thermal constants of insulating materials in bulk, *J. Appl. Phys.*, 25, 137-144.
- Bullard, E.C., 1954, The flow of heat through the floor of the Atlantic Ocean *Proc. Roy. Soc. London Ser. A*, 222, 408-429.
- Bullard, E.C. and Day, A., 1961, The flow of heat through the floor of the Atlantic Ocean, *Geophys. J.*, 4, 284-292.
- Davis, E.E., Lister, C.R.B. and Sclater, J.G., 1985, Toward determining the thermal state of old ocean lithosphere, *Geophys. J.*, in press.
- Goldberg, D.S., 1981, The physical properties of deep ocean sediments from the northern Atlantic: a comparison of in-situ and laboratory methods, M.S. thesis, M.I.T.
- Huppert, H.E., and Sclater, J.G., 1968, On the in-situ measurement of the thermal conductivity of deep sea sediments, *Marine Phys. Lab. Tech. Memo.* 191, Scripps Inst. Ocean., Univ. of Calif., San Diego.
- Hutchison, I., 1983, Heat flow studies in the Gulf of Oman and western Mediterranean, Ph.D. thesis, Univ. of Cambridge, Cambridge.
- Hutchison, I., Von Herzen, R.P., Loudon, K.E., Sclater, J.G., and Jemsek, J., 1985, Heat flow in the Balearic and Tyrrhenian Basins, western Mediterranean, *J. Geophys. Res.*, 90, 685-701.
- Hyndman, R.D., Davis, E.E., and Wright, J.A., 1979, The measurement of marine geothermal heat flow by a multipenetrating probe with digital acoustic telemetry and in-situ thermal conductivity, *Mar. Geophys. Res.*, 4, 181-205.
- Jaeger, J.C., 1956, Conduction of heat in an infinite region bounded internally by a circular cylinder of a perfect conductor, *Australian J. Physics*, 9, 167-179.
- Jaeger, J.C., 1958, The measurement of thermal conductivity and diffusivity with cylindrical probes, *Trans. Amer. Geophys. Union.*, 36, 708-710.
- Lachenbruch, A.H., and Marshall, B.V., 1966, Heat flow through the Arctic Ocean floor: The Canada Basin-Alpha Rise Boundary, *J. Geophys. Res.*, 71, 1223-1248.
- Langseth, M.G. Jr., 1983, Developing better methods for estimating the thermal conductivity of deep-sea sediments, unpublished report.

- Langseth, M.G. Jr., and Von Herzen. R.P., 1971, Heat flow through the world oceans, in: A.E. Maxwell (Ed.), The Sea, Vol. 4, Pt. 1, Interscience, New York, 299-352.
- Lister, C.R.B., 1970, Measurement of in-situ conductivity by means of a Bullard-type probe, Geophys. J., 19, 521-533.
- Lister, C.R.B., 1979, The pulse-probe method of conductivity measurement, Geophys. J., 57, 451-461.
- McCoy, F.W., and Von Herzen R.P., 1971, Deep-sea corehead camera photography and piston coring, Deep-Sea Research, 18, 361-373.
- Ratcliffe, E.H., 1960, The thermal conductivities of ocean sediments, J. Geophys. Res., 65, 1535-1541.
- Sass, J.H., 1965, Theoretical temperature-time curves for the cylindrical thermal conductivity probe, in: W.H.K. Lee (Ed.), Terrestrial Heat Flow, Geophys. Mono. 8, Amer. Geophys. Union, Washington, D.C., 50-57.
- Sclater, J.G., Corry, C.E., and Vacquier, V., 1969, In-situ measurement of the thermal conductivity of ocean-floor sediments, J. Geophys. Res., 74, 1070-1081.
- Von Herzen, R.P., and Maxwell A.E., 1959, The measurement of thermal conductivity of deep-sea sediments by a needle probe method, J. Geophys. Res., 64, 1557-1563.
- Von Herzen, R.P., and Anderson, R.N., 1972, Implications of heat flow and bottom water temperature in the Eastern Equatorial Pacific, Geophys. J., 26, 427-458.

APPENDIX

CONSTRUCTION OF THE WHOI THERMISTOR PROBE

This appendix illustrates the assembly procedure of the "single-probe" design.

- A. Preparation of thermistor: Before calibration and final assembly in tubing, the bare thermistor must be connected properly to heavier insulated leads.

The materials list is:

- a. Thermistors (2000 Ω @25°C, Fenwal Electronics, GB32L2 $\pm$ 5% & GB32L1 $\pm$ 20%)
 - b. M.L. Tubing with I.D. closely matching the diameters of (i) thermistor leads (0.01 cm, 0.004 in.), and (ii) teflon wires (spaghetti tubing may, in this case, replace the more expensive ML tubing).
 - c. 24 AWG spaghetti tubing (for use explained above) (thin wall; Chemplast, Inc.).
 - d. Teflon wire (insulation type-ET, 32 AWG, 7/40 strand).
 - e. Thermal wire stripper (model #TW-1, Teledyne).
1. Strip back both ends of each teflon wire ~ 0.3 cm with electric wire strippers and tin (apply thin coat of solder to) the bare leads.
 2. Cut the spaghetti tubing into ~ 1.5 cm sections and place them onto the teflon wires. These small "splints" will be used later to stabilize, protect and insulate the connections between the thermistor & teflon wire leads (figs. A1 and A3).
 3. Remove one thermistor from its protective case and CAREFULLY straighten the leads with a pair of tweezers.
 4. Cut two lengths of ML tubing to match each of the leads of the thermistor, leaving about 0.2 cm of the lead available for the solder connection (fig. A2). Thread the tubing onto each thermistor lead before soldering.
 5. Solder each connection making sure that it is clean, smooth and sufficiently strong, yet thin enough for the splint to slide over it (fig. A3). Once the connections are made and both splints are in place, test the connections by tugging gently on the teflon wires. Note that a well-soldered connection is stronger than the thermistor itself and too much tension will result in its ruin.

Figure A1. Schematic of a tinned teflon wire lead showing the "splint" arrangement.

Figure A2. Schematic of thermistor leads with ML-tubing insulation.

Figure A3. Schematic of thermistor with attached teflon lead and insulating "splint". Note the thin, smooth solder connection.

- B. Measuring Thermistor Resistance at 0°C. Thermistors resistances must be measured at a uniform temperature so that they may be selected as groups with uniform resistance ($\leq 50 \Omega$ range). This is usually done in an ice bath.

Materials and Instrument List:

- a. Stainless steel tubing (0.3175 cm (1/8") OD, 0.051 cm (0.020") wall, 304 seamless)
- b. Decade Resistance Box, Resist-o-Stat II (RDS 53B)
- c. Cooling container
- d. Crushed ice and water
- e. Oil (10-W-30)
- f. Thermistor sorting program (on Apple computer, WHOI heat flow lab)
- g. Stirring utensil ie., electric stirring rod

1. Fill the cooling container to the brim with a 1:1 ratio of crushed ice and water.

2. Place the thermistors in stainless steel tubes filled with oil and assemble tubes into a single support system that is suitable for submergence into the ice bath.

3. Lower the support system into the bath. The bath should be stirred constantly throughout the calibration to ensure uniform temperatures. For reference, record the resistance of the 1st thermistor. After about 15 minutes, check to see if the system has equilibrated by monitoring any change in the resistance of this thermistor. Note that the resistance should be near 5000Ω @ 0°C .

4. Record the resistances of the remaining thermistors, periodically checking the first reading to see if there is any change in the ice bath temperature. If drift occurs then the bath has not yet stabilized.

C. Final thermistor probe assembly.

I. Grease Test.

This was an experimental stage in the development of the thermistor probe assembly in which a dielectric compound was sought to satisfy the following requirements: 1) ensure adequate thermal contact between the thermistor, heater and probe housing, 2) have a quality of viscosity which would allow it to be drawn into the probe yet not flow out after emplacement, 3) have low thermal expansion so that the compound would not flow out when, for example, the probe heats up on the hot deck of a ship, 4) retain a gel-like or pliable consistency. If the compound hardens, it would create a brittle environment for the thermistors. This hardening characteristic would also make it impossible to repair thermistors at sea because the thermistor and heater wires would no longer be removable from the stainless steel support tubes. This latter fact became very apparent on the KNORR 102 cruise to the Bermuda Rise.

From the results of experimentation, a mixture of silicon (in a volumetric ratio of 5 parts grease to 6 parts liquid proved satisfactory.

The materials needed are:

- a) Dielectric compounds (DC-4 silicon grease and DC-200 Silicone liquid)).
- b) Vacuum Pump (precision 20 l/m (0.7CFM) 5 μ . Model #DD20).
- c) Extension hoses (for vacuum pump; includes tight fitting adapter for S.S. tubes).

The silicon "mixture" met all the necessary criteria mentioned in the beginning of this section. Namely, it fills the voids between the tube walls and the thermistor, thus providing good thermal contact between the sample sediment, S.S. tube and the thermistor. Note that in the mixing of the grease with the oil, many small air bubbles may become trapped in this silicone medium. These bubbles can be removed by a short spin in a high speed centrifuge (~3 minutes @2000 RPM). But this only dissolves the gas and when a vacuum is applied to the mixture some of the bubbles reform. However, the amount of trapped gas is reduced by centrifuging. Note: the "dummy" end (the end of the S.S. tube from which no leads protrude, fig. A4) should be plugged soon after the tube has been filled so that the silicone mixture will not flow out of the tube.

II. Assembly of thermistor and heater arrays in the stainless steel tubes.

Materials required:

- a) S.S. tubing (0.3175 cm (1/8") O.D., 0.051 cm (0.020") wall, 304 seamless; see "thin-wall" probe (fig. 3a).
- b) Support Tabs for S.S. tubes (fig. A4).
- c) Heater wire (constantan/Tef./Fe 0.013 cm (005"), Omega Eng. Inc.).
- d) Teflon wire (insulation type - ET, 32 Awg, 7/40 strand).
- e) #24 AWG spaghetti tubing (thin wall; CHEMPLAST, Inc.).
- f) Plug for "dummy" end of S.S. tube (~1 cm long, matching the I.D. of S.S. tubes, see fig. A4).
- g) Pipe cleaners.
- h) Silver solder.
- i) Silver flux.
- j) HCL solder flux

1. Cut (using MOTO-tool) the S.S. tubing stock into 45 cm (18") lengths and remove any metal shavings from within the tubes using the electric grinder and drill press. The support tabs should then be silver soldered to the tube as indicated on figure (A4).

2. Assemble the heater wires by connecting the teflon leads to a 12.7 cm (5") length of constantan heater wire. The soldering techniques are essentially the same as is done in thermistor preparation (see Part A), except that one should etch the leads of the constantan wire with HCL soldering flux in order to aid solder adhesion.

3. Mark the center point between the tabs on the S.S. tube. This should

a.

b.

NOTE: TUBE FILLED WITH DIELECTRIC GREASE

Figure A4. a) Diagram of the thermistor probe showing the position of the tabs on the stainless steel tube. b) Diagram showing the placement of the thermistor and heater wires within the probe housing.

be the final position of the thermistor bead (± 1 cm) (see fig. A4).

4. Measure the necessary lengths of the thermistor and heater wire leads that are needed for correct placement of these arrays within the S.S. tubes. One of the two leads of each wire (thermistor and heater) should be bent at a point one or two inches beyond the solder connections. Place each wire loop parallel to the tube and position the thermistor and heater wire so that they symmetrically overlies the centerpoint between the tabs. Sharply bend the wires at the end of the tube and use this "marking" bend for reference to the final position of the wires (fig. A4).

5. Insert the heater wire in the S.S. tube first. Once the heater wire itself is about half the way in, insert the thermistor. Push by the strongest leads which are the ones without any soldered connections along their lengths. When all the protective splints are within the tube, even-up the leads of the thermistor and heater. Then push both arrays in until you reach the "marking bends". The finished product should look like figure (A4), with the thermistor bead in the middle of the tabs and the heater wire symmetrical about the thermistor.

III. Application of "silicone mixture" within S.S. tubes.

Using the materials listed in Sections I and II of Part C, start by:

1. Stir together a "silicone mixture" of 5 parts DC-4 silicone grease to 6 parts DC-200 silicone liquid.

2. Spin this mixture for ~3 minutes @2000 rpm in a centrifuge. This will dissolve all the air bubbles that are formed during the mixing process.

3. Set up a vacuum system that will draw the grease through the S.S. tubing and place the "dummy" end of the finished probe to the vacuum hose fitting.

4. Place the end of the thermistor with the protruding leads, into the silicone mixture and turn on the vacuum pump. Wait until the silicone mixture begins to flow out of the top and then separate the thermistor from the vacuum hose.

5. Clean the "dummy" end of the S.S. tube with a pipe cleaner, dip it into the silver flux and immediately insert the plug and butt it up to the end of the tube.

6. Solder an even bead of silver around the "dummy" end. Watch for signs of escaping gas and smoke, this is proof that there is a leak in the connection which MUST be water tight. Grind off any excess silver solder which might exist along the sides of the S.S. tubing, but do not grind the end.

7. This newly completed thermistor should now be checked for electrical shorts or leakage. The resistance of the heater wire should be $\sim 8\Omega$ while the thermistor should read $\sim 2000\Omega$. There should be no shorts between the two arrays and the S.S. tubing or between the arrays themselves.

IV. Calibration of Thermistors.

Precise calibration for a range of selected temperatures (normally between 0 and 20 °C) is usually accomplished in a special calibration facility and therefore will not be described in this paper. The thermistors are most easily calibrated when they are in the finished tubes (Part III, step 7) but may also be calibrated when they are in the temporary housings used for the initial 0° calibration.

V. Attaching Calibrated Thermistor Assemblies to Cables, Barrels, Pressure Fittings and Outrigger Fins.

Required materials:

- a) Variable length probe cable, (Crouse-Hinds Electric Co.).
- b) Probe barrels.
- c) 0.3175 cm (1/8") male, pressure tube fittings (Lindco, Inc., #100-2-59).
- d) Teflon Tape ("thread seal", 1.27 cm (1/2") wide, Dupont Co.).
- e) Heat shrink tubing (0.3 cm O.D.)
- f) DC-4 silicone grease (for O-rings)
- g) "loctite" 242 thread sealant (Loctite Corp.).
- h) Outrigger fin assembly including outrigger fins and clips (fig. A5).
- i) S.S. panhead bolts (6/32" x 3/8").
- j) S.S. washers (locking and flat washers)
- k) S.S. hex nuts.

1. Attach the pressure fittings. This involves: a) Wrapping a length of teflon tape around the threads of the pressure fitting ~1 1/4 times around the threads in a clockwise direction, when viewed from the end of the threads which first make contact; and b) Placing the probe barrel in the vice and screwing in the pressure fitting.

2. Once all the pressure fittings are attached, connect the thermistors to the probe barrels and cables as described below (see fig. A5):

- a) Engraving the probe barrels with an I.D. number.
- b) Grease the O-ring that goes between the probe barrel and cable fitting. For this use DC-4 silicone grease.
- c) Trim the cable, thermistor and heater wire leads to 2 cm and then strip these newly shorted leads ~0.3 cm.
- d) Tin the cable, thermistor and heater wire leads.
- e) Thread the pressure fitting and probe barrel onto the S.S. tube of the thermistor.
- f) Determine (using OHM-meter) which two cable leads are "sisters". That is, which two leads go to the SAME plug at the other end of the cable.
- g) Cut the required number of 0.3 cm O.D. heat shrink tubing into ~1 cm long sections and place one over each of the cable leads.
- h) Connect (solder) the thermistor leads to one of the set of associated cable leads (sisters) and then solder the heater wire leads to the remaining "sisters". Note: It is usually desirable that the longest cables be linked to thermistors which have the highest calibrated resistance. This is done because the longest cables correspond to the most deeply penetrated thermistors which will inevitably encounter the

Figure A5. Schematic of the outrigger fin, thermistor (with heater) probe, and cable assembly. An exploded version of the pressure fitting and cable arrangement is shown.

greatest temperatures. Since increases in temperature causes a decrease in resistance, it is best to have the higher calibrated thermistor resistances at the bottom in order to offset this problem.

i) Once the connections are all made and checked, slide the heat shrink tubing over the newly soldered connections and shrink them with the heat gun.

j) Slide the probe barrel gently over the connections and screw it onto the threads of the probe cable. Note: It is very important not to twist or pull the thermistor and heater wire leads during this stage as their placement within the S.S. tube is critical.

k) Now carefully slide down the cap of the pressure fitting and screw it on finger tight, PLUS 1/4 turn. Remember that until the cap of the pressure fitting is tight, the S.S. tube can be easily moved and could perhaps disrupt the positioning of the thermistor and heater wire.

l) Again, test for closed circuits, shorts and thermistor bead placement. Note: the heater wire should register $\sim 8\Omega$ and the thermistor $\sim 2000\Omega$ at room temperature.

3. Finally, connect the thermistors with their newly attached cables to the outrigger fins.

REPORT DOCUMENTATION PAGE	1. REPORT NO. WHOI-85-28	2.	3. Recipient's Accession No.
4. Title and Subtitle In-Situ Measurement of Thermal Conductivity Using the Continuous-Heating Line Source Method and WHOI Outrigged Probe		5. Report Date August 1985	
7. Author(s) J. Jemsek, R. Von Herzen and P. Andrew		8. Performing Organization Rept. No. WHOI-85-28	
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, Massachusetts 02543		10. Project/Task/Work Unit No.	
		11. Contract(C) or Grant(G) No. (C) (G) OCE-8025181, -8117886, and -8409170	
12. Sponsoring Organization Name and Address U. S. National Science Foundation		13. Type of Report & Period Covered Technical	
		14.	
15. Supplementary Notes This report should be cited as: Woods Hole Oceanog. Inst. Tech. Rept., WHOI-85-28.			
16. Abstract (Limit: 200 words) The outrigged thermal probes of a "pogo" marine geothermal probe have been adapted to measure thermal conductivity in-situ by the continuous-heating line source technique. The instrumental uncertainty in applying the analytical theory to a single-probe and double-probe configuration is found to be 3 and 6 percent, respectively. The in-situ outrigged single probe (.32 cm dia.) is essentially a scaled-up version of the needle probe (.08 cm dia.). The main advantage of the outrigged probe over a larger radius probe (e.g., violin-bow probe) is that for short-time temperatures (<2 min.), simple approximations to the exact solution for a perfectly conducting cylindrical probe are achieved. The continuous-heating compares favorably with the pulse-heating technique, the latter being more energy efficient. The continuous-heating method applied to the thin outrigged probe allows for accurate equilibrium in-situ temperature and thermal conductivity estimates in less than 15 minutes of recording time. The technique has been applied to several hundred marine heat flow stations. Comparison of in-situ measurements to needle probe measurements made on nearby piston cores indicate agreement to within 5%. The conductivity profiles of the in-situ data and core data show that the piston coring process frequently does not retrieve the upper meter of surficial sediment.			
17. Document Analysis a. Descriptors 1. thermal conductivity 2. marine instrumentation 3. heat flow b. Identifiers/Open-Ended Terms c. COSATI Field/Group			
18. Availability Statement: Approved for publication; distribution unlimited.		19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 73
		20. Security Class (This Page)	22. Price

DOCUMENT LIBRARY

April 9, 1985

DISTRIBUTION LIST FOR TECHNICAL REPORT EXCHANGE

Institute of Marine Sciences Library
University of Alaska
O'Neill Building
905 Koyukuk Ave., North
Fairbanks, AK

Attn: Stella Sanchez-Wade
Documents Section
Scripps Institution of Oceanography
Library, Mail Code C-075C
La Jolla, CA 92093

Hancock Library of Biology & Oceanography
Alan Hancock Laboratory
University of Southern California
University Park
Los Angeles, CA 90089-0371

Gifts & Exchanges
Library
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, NS, B2Y 4A2, CANADA

Office of the International
Ice Patrol
c/o Coast Guard R & D Center
Avery Point
Groton, CT 06340

Library
Physical Oceanographic Laboratory
Nova University
8000 N. Ocean Drive
Dania, FL 33304

NOAA EDIS Miami Library Center
4301 Rickenbacker Causeway
Miami, FL 33149

Library
Skidaway Institute of Oceanography
P.O. Box 13687
Savannah, GA 31416

Institute of Geophysics
University of Hawaii
Library Room 252
2525 Correa Road
Honolulu, HI 96822

Library
Chesapeake Bay Institute
4800 Arwell Road
Shady Side, MD 20876

MIT Libraries
Serial Journal Room 14E-210
Cambridge, MA 02139

Director, Ralph M. Parsons Laboratory
Room 48-311
MIT
Cambridge, MA 02139

Marine Resources Information Center
Bldg. E38-320
MIT
Cambridge, MA 02139

Library
Lamont-Doherty Geological Observatory
Columbia University
Palisades, NY 10964

Library
Serials Department
Oregon State University
Corvallis, OR 97331

Pell Marine Science Library
University of Rhode Island
Narragansett Bay Campus
Narragansett, RI 02882

Working Collection
Texas A&M University
Dept. of Oceanography
College Station, TX 77843

Library
Virginia Institute of Marine Science
Gloucester Point, VA 23062

Fisheries-Oceanography Library
151 Oceanography Teaching Bldg.
University of Washington
Seattle, WA 98195

Library
R.S.M.A.S.
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149