Instrument for Measuring Terrestrial Heat Flow through the Ocean Floor[1]

Charles Corry, Carl Dubois,[2] and Victor Vacquier

Marine Physical Laboratory of the Scripps Institution of Oceanography University of California, San Diego San Diego, California 92152

ABSTRACT

Terrestrial heat flow through the ocean floor is determined by measuring the temperature gradient and thermal conductivity in the upper few meters of sediment with an instrument lowered on hydrographic wire. The chief novel feature of the device is that the thermal conductivity is measured *in situ* simultaneously with the temperature gradient instead of in a cored specimen of sediment in the laboratory. The instrument is similar to the one developed by Von Herzen and consists of a heavy case containing the recorder, to the lower end of which is fastened a hollow steel probe carrying three thermistors placed one meter apart. Two independent values of the temperature gradients are thus obtained. Thermal conductivity is measured by the Von Herzen-Maxwell needle-probe method, using a needle 23 cm long, mounted on a body that slides upward on the probe during penetration. The needle is electrically connected to the recorder with an extendable telephone-type cord. Water temperature versus depth can be investigated near the bottom by raising the instrument in small steps following the heat-flow measurement.

Introduction. Previously developed instruments for ascertaining terrestrial heat flow through the ocean floor are of two types that are similar in principle. One, which employs the original concept of Bullard et al. (1954, 1956), measures only the temperature gradient; therefore a second lowering is required to secure a core for measuring the conductivity, either on board ship or in a laboratory ashore. The sampling of the sediment may be three hundred meters or more from the spot where the temperature gradient has been measured. Von Herzen et al. (1962) and Uyeda et al. (1961) have described two currently used modifications of the Bullard probe. The other technique for determining the terrestrial heat flow was devised by Maurice Ewing (Gerard et al. 1962). With this method the temperature-sensitive elements are mounted on

1. Contribution from the Scripps Institution of Oceanography, University of California, San Diego. Accepted for publication and submitted to press 10 November 1967.
2. Carl Dubois, Data Science Corporation, 3740 Houston, San Diego, California 92110.

outriggers fastened to the core barrel. Thus, the core in which the thermal conductivity is measured is collected at the place where the gradient is measured, hence only one lowering is needed. The thermal conductivity is measured by one of two methods: (i) by determining the amount of water in the sediment sample, as described by Ratcliffe (1960) and Bullard and Day (1961), or (ii) by employing the needle-probe method of Von Herzen and Maxwell (1959). A review of existing methods for determining terrestrial heat flow has been written by Langseth (1965).

The Ewing method should be more precise than the Bullard method because, when it is used with the piston corer, the temperature gradient is measured at greater depth in the sediment and because the core is collected at the place where the gradient is determined; however, this method is not convenient, since each lowering takes longer to prepare and execute than when the Von Herzen type of probe is used. Also, piston corers are difficult to handle in heavy seas. Fortunately, there are now enough measurements carried out in the same areas by Scripps Institution of Oceanography with the Von Herzen apparatus and by Lamont Geological Observatory with the Ewing *Thermograd* to assure us that in general the two methods give the same results within a useful margin of error (Von Herzen and Langseth 1966).

These considerations made us pattern the new instrument after the Von Herzen modification of the Bullard probe. By measuring the thermal conductivity *in situ* (using the needle-probe method) simultaneously with the temperature gradient, only one lowering is needed to obtain a heat-flow value. An important improvement over previous methods is that the conductivity is measured in sediment undisturbed during the coring procedure, because the coring as well as the drilling into the core to insert the conductivity needle might alter the water content of the sediment.

The water temperature, measured at the top of the recorder housing, can be compared with the temperature recorded in the upper thermistor of the probe; thus unusual short-lived water-temperature transients that might affect the gradient measurement can be detected. Also, the reliability of a thermal gradient measurement can be determined by comparing the temperature differences between the thermistor at the middle of the probe and the ones at the upper and lower ends.

General Description and Launching. Fig. 1 shows a general diagram of the instrument. The probe is a hardened stainless-steel tube 2 cm O. D. and 230 cm long. The thermistors (Tu, Tm, and Tl) in the upper, middle, and lower part of the probe are mounted in an aluminum retainer that is spring-loaded against the inner wall of the probe. The one-way slider carries the small corer (1.2 cm I. D. × 10 cm long) as well as the thermal conductivity probe with its thermistor, Tc. The recorder housing consists of a pressure case that has an inside diameter of 13.5 cm and an inside length of 73 cm. The outside over-all length

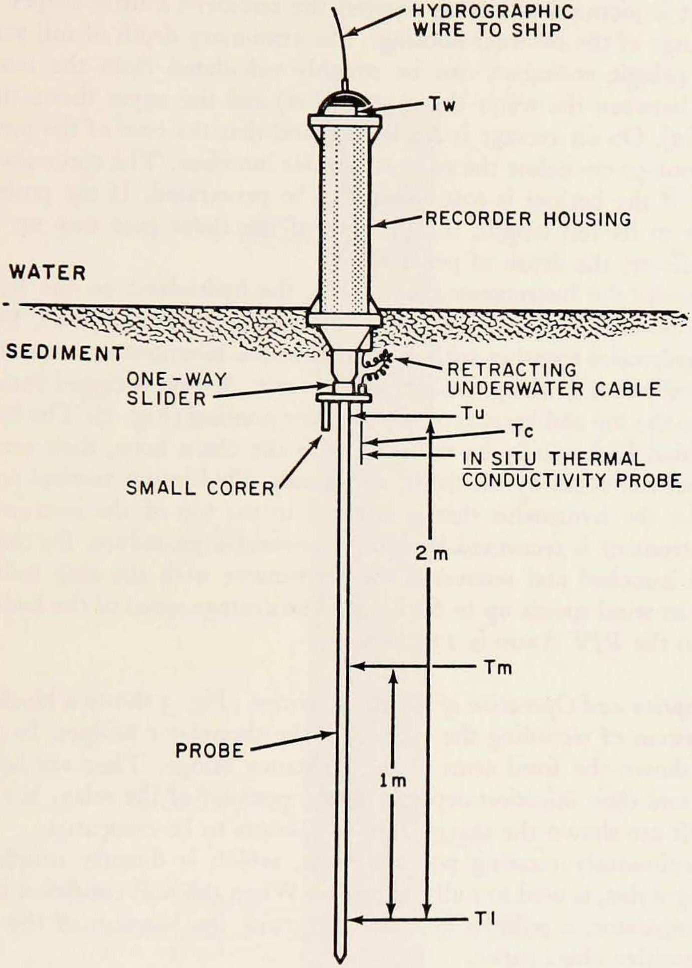

Figure 1. Simplified drawing of the instrument as it would appear in the sediment (see text).

of the case is 92 cm. The wall is 1.27 cm thick and is made of 17–4 P. H. stainless steel. The housing has been pressure tested to 1400 kg/cm^2 for use at the greatest ocean depths. The total air weight of the instrument is 93.3 kg. The description and operation of the recorder system follows. In the final section the thermal conductivity probe is described in detail.

During the instrument's descent, the slider is held at the end of the large probe (Fig. 2) by means of the ball detents. As the probe reaches the water-sediment interface, the slider stops a short distance below the surface and the large probe passes through its center down into the sediment. The general aspect of the instrument as it is imbedded in the ocean floor is also shown in

Fig. 1. It is pictured as having entered the sediment a little deeper than the lower flange of the recorder housing. The customary depth of full penetration in most pelogic sediments can be roughly calculated from the temperature gradient between the water thermistor (Tw) and the upper thermistor in the probe (Tu). On an average it has been found that the base of the probe penetrates about 40 cm below the sediment-water interface. The corer always takes a sample if the bottom is soft enough to be penetrated. If the probe fails to penetrate to its full length, the position of the slider part way up the large probe indicates the depth of penetration.

To handle the instrument aboard ship, the hydrodavit on the R/V Argo has been modified so that it is hydraulically rotatable through 180°. The sheave for the hydrowire together with a chain hoist are mounted on a traveler that is hydraulically moved along the arm of the davit. A sling is rigged between eyes welded to the top and bottom of the recorder housing (Fig. 2). The instrument is first lifted horizontally by the sling with the chain hoist, then rotated over the side of the vessel by the davit, and finally tilted into a vertical position by reeling in the hydrowire that is fastened to the top of the instrument case. The instrument is recovered by using the reverse procedure. By this method we have launched and recovered the instrument with the ship rolling up to 35° and in wind speeds up to 60 knots. The average speed of the hydrographic winch on the R/V Argo is 135 m/min.

Description and Operation of Recorder System. Fig. 3 shows a block diagram of the system of recording the outputs of the thermistor bridges. In the upper left are shown the fixed arms of the resistance bridge. They are labeled Rb_1 or Rb_2, and their selection depends on the position of the relay, K 11. In the lower left are shown the thermistors or resistors to be compared.

A continuously rotating potentiometer, which is directly coupled to the recording stylus, is used to null the bridge. When the null condition is detected by a comparator, a pulse is generated to mark the location of the stylus on electrosensitive chart paper.

The potentiometer completes one revolution per second, during which time the stylus traverses the full chart width, and for each sweep of the stylus a null point is sensed. This produces a record composed of spots on the chart, each spot nominally displaced in time from its neighbors by one second, unless the segment being sampled is on the second scale, as explained below. The potentiometer is adjusted so that the winding terminates as the stylus reaches the edge of the paper. The open-circut portion of the potentiometer pulses a binary counter, causing digitally controlled relays to advance the recording sequence.

The revolutions are first divided by 2 in order to allow two sweeps of the stylus across the width of the chart for each input. The remainder of the count is then decoded to select and drive the required relays to make each measurement. As an aid in checking the operation, a lamp indicates each step in the

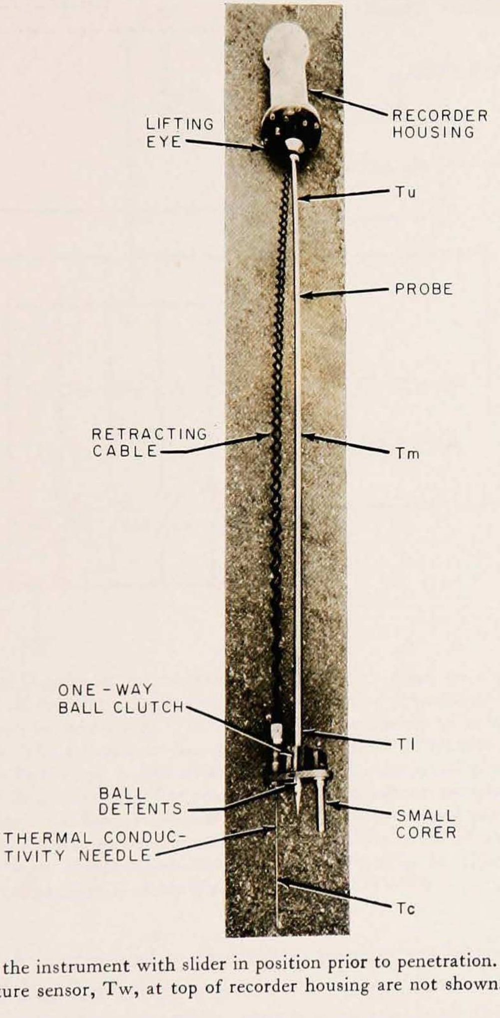

Figure 2. View of the instrument with slider in position prior to penetration. Lifting eye and water-temperature sensor, Tw, at top of recorder housing are not shown.

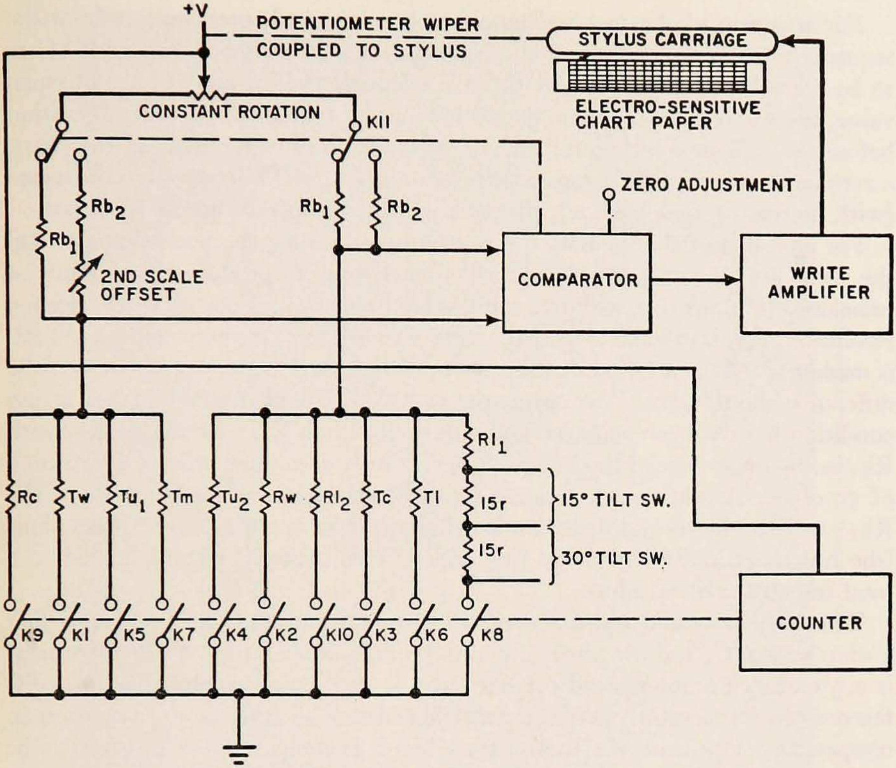

Figure 3. Functional diagram of the recorder. Rb_1 and Rb_2 are fixed arms of resistance bridge for first and second scales, respectively. The comparator actuates switch K 11 when bridge fails to null on first sweep. The resistors and thermistors to be compared appear in the lower left. The resistors are located in the recorder. The location of the thermistors are shown on Figs. 1 and 2. The switching sequence is established by the counter from pulses generated by the recorder. The counter actuates the selector switches K 1 to K 10 in order to measure the following differences: Rc–Rw and Rc–Rl_1 calibrate the sensitivity of the first scale; Rc–Rl_1 and Rc–Rl_2 calibrate the sensitivity of the second scale. Tw–Rw measures the water temperature. The thermal conductivity is derived from Tw–Tc. The temperature gradient is obtained from Tm–Tl and Tu–Tl.

sequence. A switch is provided so that the sequence can be stopped on any step position to check that individual input.

The advantage of this instrument over a conventional paper-chart recorder is that the time to record any input is small, hence a relatively large number of inputs that vary with time can be recorded. A reference trace is recorded, and the individual traces are separated by the predetermined sequence in which the traces are generated. This allows the full chart width to be used for each trace in order to achieve the best recording precision. In comparison with conventional servo loops, another advantage is reduced system complexity. The instrument uses a printed chart 4.5 inches wide for easy readability in data reduction.

For selection of the two resistances to be compared, each output from the sequencer drives two relays. For example, when thermistors Tu_1 and Tl are to be compared, relays K 5 and K 6 are selected. If Tu_1 and Tl are of equal value, the servo potentiometer would have to be rotated to its central position before the bridge would be nulled. To offset the null to the edge of the chart, a zero adjustment in the comparator is used. Then, as Tl decreases in resistance (with increasing temperature), the spot will move upward across the chart.

For any given value of Rw, the resistance values for the potentiometer and the fixed bridge arms, Rb, can be calculated so as to produce the amount of imbalance in ohms that will give a full-scale indication. To achieve the desired resolution, Rb_1 is calculated so that a difference of 20 ohms between Rc and Rl_1 is made to produce a full-scale indication. To prevent loss of information if the difference should exceed 20 ohms, the comparator will detect whether a null condition has not been achieved and will then switch K 11 to replace Rb_1 with Rb_2 in the upper legs of the bridge. Rb_2 is calculated to give a full-scale reading of 50 ohms. In addition, a variable resistor is placed in series with one of the Rb_2's so that the second scale can be offset to start at a difference of 20 ohms (the full chart indication of the first scale). This makes it possible to record a total imbalance of 70 ohms.

The sensitivity and resistance values of the thermistors used are such that 1 ohm $\approx$ 0.01°C, and the total differential temperature range of the instrument is 0.7°C. Since differences of 0.1 ohm can be easily read on the chart, the differences in temperature between two thermistors as well as the variation in temperature with time of a thermistor when it is compared to a resistor can be read with a sensitivity of 0.001°C. The calibration of the water thermistor permits determination of the absolute water temperature to better than 0.02°C.

To detect whether a second-scale reading has occurred, two successive readings on each input are made. The two readings produce two spots on the record. If the input is off the first scale, the comparator senses the missing spot and switches relay K 11 to the second scale. Traces with single spots therefore indicate a second-scale reading (Fig. 4).

Tilt is indicated by two mercury switches. When the tilt exceeds 15°, one of them shorts 15 ohms of the chart-calibrating resistor, Rl_1. The other shorts out an additional 15 ohms for tilt exceeding 30° (Fig. 5).

The comparator includes a differential dc amplifier and a Schmitt trigger. These circuits detect when the potentiometer sweeps the bridge through null. The bridge null detector is referenced by two mercury cells, which, because of low current drain, are permanently wired into the circuit. With this arrangement, the gain of the dc amplifier is not critical, since the only important parameter is the stability of the input stage. By using selected components, the required stability over the expected temperature range can be achieved. The Schmitt trigger generates a sufficiently fast transition to trigger the write amplifier and produce a spot on the chart.

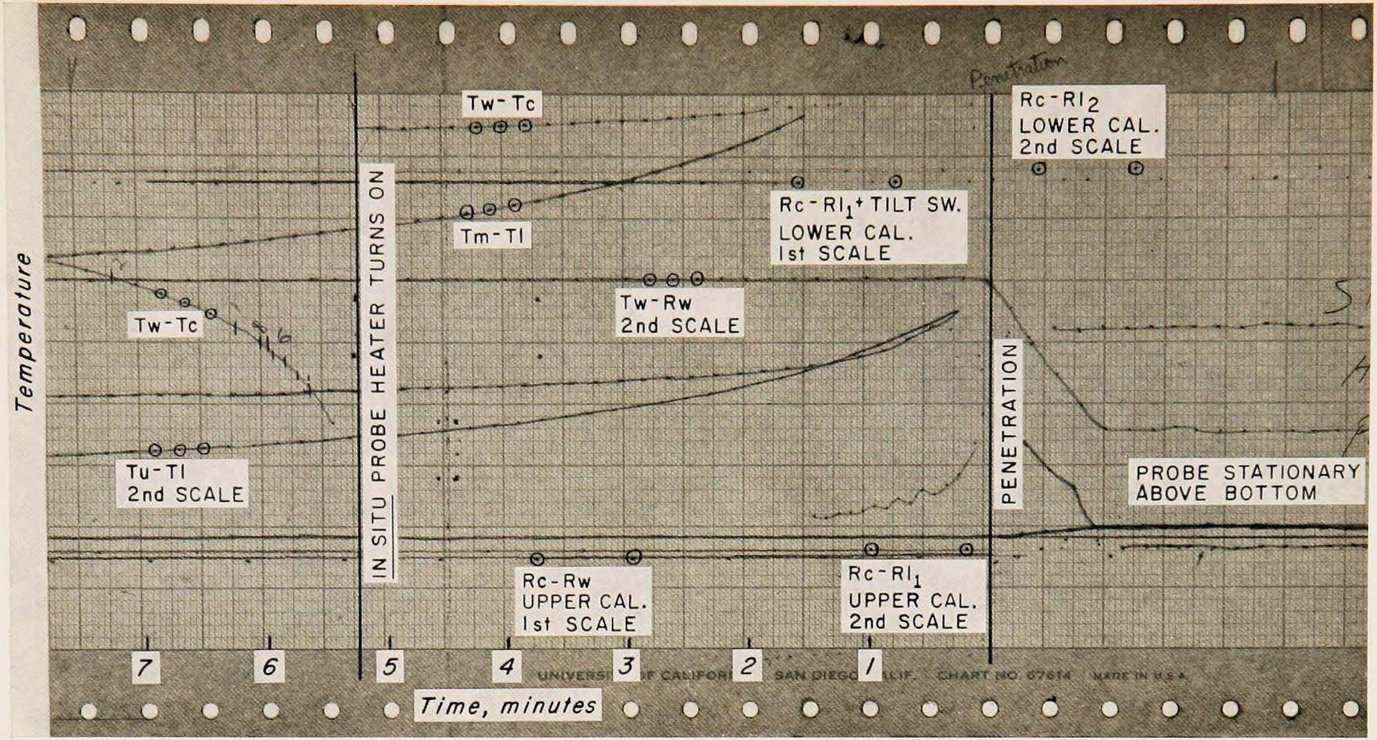

Figure 4. Typical record of (i) the instrument at a stationary position 100 m above the bottom, (ii) the penetration, and (iii) the heater turned on in the *in situ* conductivity probe.

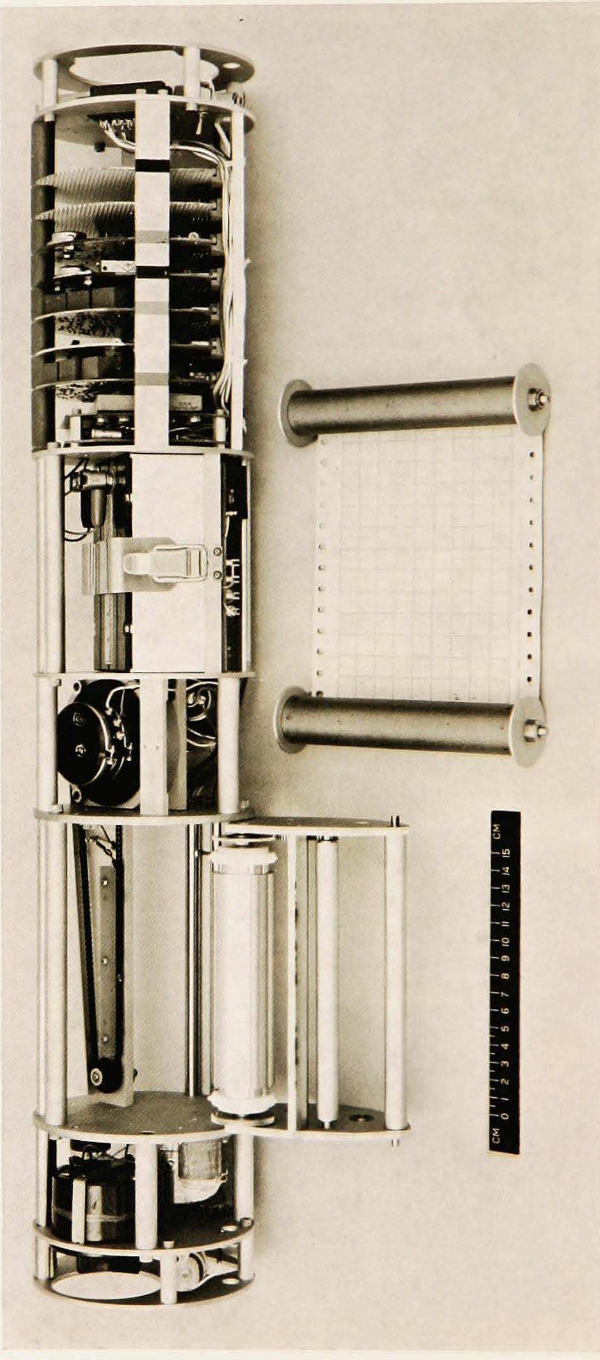

Figure 5. View of recorder with magazine opened for loading.

The write amplifier forms the spot on the chart by discharging a capacitor through the electrosensitive chart paper. This capacitor is charged to 400 volts by an oscillator driving a flyback transformer. The high voltage is sufficient to break down the paper and any surface film that has formed on the paper.

The recorder is powered by a single rechargeable 25-volt, 1.2-ampere hour Nicad battery. Recorder current is 450 ma. Voltage is regulated for all critical circuits. A delay timer turns on the recorder after a delay adjusted to allow for launching and lowering.

The traces for nine channels are labeled on a sample record in Fig. 4 whereas the resistors and the thermistors that are being switched into the bridge are labeled in Fig. 3. Five of the traces in Fig. 4 are data channels, all of which are sampled once every 12 seconds for two seconds. They are: Tw–Rw, Tw–Tc, Tw–Tu_2, Tu_1–Tl, Tm–Tl. These groups of five are separated by one of the four calibration comparisons: Rc–Rw, Rc–Rl for the first scale and Rc–Rl_1, Rc–Rl_2 for the second scale. Each of these calibration points on the chart is sampled once every 48 seconds. For the sake of convenience in the wiring of the switching, the top of the probe has two thermistors: Tu_1 and Tu_2, one in each arm of the bridge; one measures the gradient across the water-sediment interface (Tw–Tu_2), the other the gradient between the top and bottom of the probe (Tu_1 and Tl).

The linearity of the recording system between the calibration points is probably an order of magnitude greater than the smallest readable division (approximately 0.01 inches). A test for checking the linearity to greater than reading accuracy has not been devised. The instrument is continously self-calibrating and the temperature coefficient of the calibration resistors is less than 2 ppm/°C; since this gives a worst-case calibration error of Δ0.2 ohms, the temperature effect is ignored. The linearity of the thermistors used is irrelevant to the recording since only resistance differences are measured. A careful calibration of the thermistors is performed, and the correction is applied in the final calculation. All thermistors used are closely matched.

Thermal Conductivity Measurement. Thermal conductivity is measured by the method of Jaeger (1958) and Von Herzen and Maxwell (1959) by means of a small probe or needle mounted on the slider (Fig. 2). This small probe consists of a stainless-steel tube (4 mm O. D. and 23 cm long) containing uniform resistance wire along its entire length as well as a thermistor (Tc) near its middle. A magnet on the slider keeps open a reed relay in the tip of the large probe, but when the slider is forced upward off the end of the large probe during penetration, the reed relay closes, activating a timed sequence. After a time delay of about 5 minutes, which allows the probe to reach near-thermal equilibrium with the sediment, the needle heater voltage is turned on. Since the heater is turned on only when channel Tw–Tc is being sampled by the recorder, the instant of time when heating is initiated is accurately known. After an on-time of 8 minutes, the heater voltage is turned off to save battery power. The heater circuit will not recycle until the whole instrument has been turned off and turned on.

The conductivity measurement with the small probe is made approximately 65 cm below the water-sediment interface. This is approximately the same depth as the average depth of the measurement ($\approx$60 cm) made in gravity cores. Since most of the variation in conductivity with depth should be near the water-sediment interface, the measurement should be in the region of uniform sediments, well below the biogenic zone. Deeper variations in conductivity will appear as variations in the thermal gradients between the middle and ends of the large probe. Measurements of thermal gradients at more than 200 stations have shown no systematic variation between the two gradients.

The small probe is electrically connected by means of an underwater cable that coils and retracts like an extended spring as the probe moves down through the slider (Figs. 1 and 2). Occasionally the hydrowire and cable become entangled so that, on an average, the cable lasts for about 15 stations.

The small probe has proved to be remarkably durable in use. Only once has it been broken on the sea floor—when the probe struck a rock. The greatest danger is on deck where it may be bent or broken. Barring accidental breakage, a small probe will last through approximately 50 stations.

Acknowledgments. Robert Warren made important contributions in the early stages of designing. We also thank Don Pretot of the Mektron Division of California General Company for developing small high-precision resistors for this recorder. This work was supported by the National Science Foundation under grant NSF GP 3791.

REFERENCES

Bullard, E. C.

1954. The flow of heat through the floor of the Atlantic Ocean. Proc. roy. Soc., London, (A) *222*: 408–429.

Bullard, E. C., A. E. Maxwell, and Roger Revelle

1956. Heat flow through the deep sea floor. Advan. Geophys., *3*: 153–181.

Bullard, E. C., and A. Day

1961. The flow of heat through the floor of the Atlantic Ocean. Geophys. J., *4*: 282–292.

Gerard, Robert, M. G. Langseth, Jr., and Maurice Ewing

1962. Thermal gradient measurements in the water and bottom sediment of the western Atlantic. J. geophys. Res., *67*: 785–803.

Jaeger, J. C.

1958. The measurement of thermal conductivity and diffusivity with cylindrical probes. Trans. Amer. geophys. Un., *39* (4): 708–710.

Langseth, M. G.
1965. Measuring heat flow through the ocean floor, *In* Terrestrial heat flow. Ed., W. H. K. Lee. Geophys. Monograph Series No. 8: Amer. geophys. Un., NAS-NRC, Publ. 1288: 58–76.

Ratcliffe, E. H.
1960. The thermal conductivities of ocean sediments. J. geophys. Res., *65*: 1535–1541.

Uyeda, Seiya, Y. Tomoda, K. Horai, H. Kanamori, and H. Futt
1961. A seabottom thermogradmeter. Bull Earthquake Res. Inst., Tokyo Univ., *39*: 115–131.

Von Herzen, R. P., and A. E. Maxwell
1959. The measurement of thermal conductivity of deep sea sediments by a needle probe method. J. geophys. Res., *64* (10): 1557–1563.

Von Herzen, R. P., A. E. Maxwell, and J. M. Snodgrass
1962. Temperature, its measurement and control in science and industry. Reinhold Publishing Corporation, New York, *3* (1): 769–777.

Von Herzen, R. P., and M. G. Langseth
1966. Present status of ocean heat flow measurements, *In* Physics and chemistry of the earth. Ed., L. H. Ahrens et al. Pergamon Press, London, *6*: 367–407.