MARINE HEAT FLOW MEASUREMENT

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by

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TO MY MOTHER

ABSTRACT

Heat flow out of the Earth and the temperature field at depth are determined by the heat sources in the Earth, thermal history of the Earth and tectonic processes. Heat flow studies also provide a useful tool for understanding crustal and lithospheric structures and the nature of their evolution. Global and regional heat flow studies involve both continental and oceanic experiments. This thesis mainly describes the design, construction and deployment of a microprocessor controlled marine heat flow probe.

Some shortcomings exist in the previous prototypes of sea floor heat flow instruments. They are: inflexibility in their operational parameters; uneconomical use of data storage; vulnerability to stochastic error; lack of communication between instrument and ship; low sensitivity and no real-time information on the records. For heat flow data processing, a software package is desired to allow real-time, interactive reduction using an on-board computer.

The newly designed instrument overcomes these shortcomings by means of the following improvements:

(1) Microprocessor control. The instrument contains a microcomputer which can be used not only to control and re-allocate parameters of the heat flow probe according to ambient conditions but also as a computer for data processing.

(2) Data storage. Only the data which are related to thermal gradient and *in situ* thermal conductivity measurements are stored. Other data, such as those recorded when ship moves to next station, are discarded automatically (but transmitted and kept on the disks of on-ship computer).

(3) Stochastic error. High resolution data acquisition circuits are employed. Any data recorded are the average of eight measurements. This substantially increases the accuracy and stability of the data.

(4) Communication with ship. Digital acoustic linkage of the data and operating messages between the instrument and the ship is achieved by use of a transducer, modem and the microcomputer's standard RS 232C port.

(5) Keeping real time information.

(6) Large working temperature range without hardware adjustment.

The methods of producing reliable geothermal values from the probe data are discussed. A software package is developed to achieve high efficiency. The influences of sedimentation rate, topography, and bottom water temperature transients are considered.

Two sites in offshore Atlantic Canada, namely the inlets of the south coast of Newfoundland and the Labrador Sea and Shelf, were chosen to test the newly designed heat flow probe. An interpretation of the data from these sites in terms of specific geological and geophysical crustal problems has been attempted. The heat flow values in the inlets of the south coast of Newfoundland are consistent with their counterparts on land, whereas the values in the Labrador Sea indicate a thermal regime that is abnormal compared with other geophysical evidence.

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1.1 Terrestrial Heat Flow

The heat that flows from the Earth's interior to its surface is called the "terrestrial heat flow". The study of terrestrial heat flow helps to constrain the distribution of heat sources and temperature within the Earth, a fundamental requirement for a proper understanding of many geophysical, geochemical and geological phenomena. The transfer of heat within the Earth and its eventual passage to the surface by conduction through the crust plays a fundamental role in all modern theories of geodynamics. Heat is the primary energy source for tectonic movements and igneous and metamorphic activity.

The study of temperature within the Earth has a long history. It was thousands of years ago that mankind noticed that heat is transferred from the Earth's interior to the surface by observing volcanoes and hot springs. Later, it was discovered that there existed in mines a general increase of temperature with depth. Temperature gradients in the crust of the Earth were measured as long ago as 1744 (Mairan, 1749, cited by Bullard, 1965), with the first measurements of the thermal conductivity of various Earth materials following about 100 years later (Forbes, 1849; Everett, 1861; Thompson, 1861; Herschel and Lebour, 1873, all cited by Bullard, 1965). The importance of using the same borehole for determining the temperature gradient and thermal conductivity was realized in the 1930's. Benfield (1939) and Bullard (1939) were among the first to make such measurements.

Mathematically, the heat flow q is the product of the thermal gradient ∇T and the thermal conductivity K, written as $q = -K \nabla T$. A determination of terrestrial heat flow requires two separate measurements: the vertical thermal gradient $\frac{\partial T}{\partial z}$ and the thermal conductivity K of the rocks in which the temperatures are measured. Terrestrial heat flow across a unit area is then calculated by the formula $q = -K\frac{\partial T}{\partial z}$, where q is negative when the flow is outward, and the thermal gradient $\frac{\partial T}{\partial z}$ is taken as negative when T increases with depth.

The thermal gradient ordinarily varies between 8 mK/m and 40 mK/m on land and greater in value in deep sea sediments. The value of conductivity K depends on the type of rock and also on temperature, pressure, porosity and water content. The usual values of conductivity lie between 1.5 and 6.5 $Wm^{-1}K^{-1}$ for rocks on land. However, in deep sea sediments of high porosity, the values are lower as the pores are filled with water of low conductivity.

The thermal conductivity of a rock or mineral is the sum of conductivity caused by lattice vibrations and by transfer of heat by radiation. Below about 480^{o} C the thermal conductivity is due almost entirely to lattice vibrations. In general, the lattice thermal conductivity (K_L) of rocks decreases with increasing temperature according the formula

$$K_L = (a + bT)^{-1}$$

where a and b are constants determined by experiment (Schatz and Simmons 1972). The effect of increasing pressure is to cause a slight increase in lattice conductivity with depth (Kieffer, 1976).

The thermal conductivity of most types of non-porous rock measured at room temperature lies between 1.7 and 5.9 $Wm^{-1}K^{-1}$. A realistic bulk estimate of 2.5 $Wm^{-1}K^{-1}$ applies to both continental and oceanic crust with an accuracy of about 10% (Bott, 1982).

Almost everywhere in the world, the temperature of the ground is found to increase downward. This implies a loss of energy from the Earth. The heat felt at the Earth's surface comes mainly from the sun. However, the Earth eventually radiates back into space almost all the heat it receives from the sun and only a very minute fraction is able to penetrate as much as 100 m into the Earth. Thus, its influence on the interior of the Earth is negligibly small in comparison with that of the heat within the Earth.

It is difficult to evaluate how much energy the Earth loses in the processes of volcanic eruptions, the potential energy accumulation in the uplift of a mountain range, rock deformation, water circulation and heat flow by conduction. But calculation shows that the conductive heat flow is the largest item in the thermal budget of the Earth.

To study surface heat flow, the equation of heat conduction has first order importance. Imagine a medium containing uniformly distributed heat sources of intensity ϵ ($Jm^{-3}s^{-1}$). An arbitrary surface S encloses a portion of the medium of volume V. Let q be the heat flow at any point on this surface. The total heat Q escaping through the surface per unit time is

$$Q = \int_S q_n \, ds$$

where q_n is the component of the heat flow vector along the outer normal to the element of surface ds. Conservation of energy requires that Q be equal to the sum of the heat generated per unit time inside the surface, $\int_V \epsilon dV$, and of the heat released by cooling; if $\frac{\partial T}{\partial t}$ is the change in temperature T with time t, the corresponding change in heat content, or heat released, is, by definition of the specific heat c, $\rho c \frac{\partial T}{\partial t}$ per unit volume, where ρ is density. Thus

$$\int_S q_n \, ds = \int_V (\epsilon - \rho c \frac{\partial T}{\partial t}) dV$$

where the sign preceding $\frac{\partial T}{\partial t}$ shows that heat is liberated only if the body cools.

By the divergence theorem, we have

$$\int_S q_n \, ds = \int_V div \ q \ dV$$

Since $q = -K$ grad T, then div $q = -K \nabla^2 T$, (assuming that the thermal conductivity is uniform in the body). Thus,

$$\int_V (K \ \nabla^2 T + \epsilon - \rho c \frac{\partial T}{\partial t}) dV = 0 \ .$$

This relation must hold for any arbitrary surface S and any volume V and, therefore, it must hold at every point. Hence the integrand must be zero everywhere and

$$\rho c \frac{\partial T}{\partial t} = K \nabla^2 T + \epsilon$$

or

$$\frac{\partial T}{\partial t} = k \nabla^2 T + \frac{\epsilon}{\rho c}$$

where $k = \frac{K}{\rho c}$ is called the "thermal diffusivity" which is very low for most rocks, its range being 0.5 to $2 \times 10^{-6} m^2/s$, or, on a geological scale, 15 to 60 km^2/ma. This means that a thermal event originating at a depth of about 100 km will not be perceptible near the surface for somewhere between 10 and 100 million years, if the heat were to be transferred by conduction alone.

Table 1.1 The Earth's Heat Loss

	Average heat flow (mWm^{-2})	Area ($\times 10^6$ Km)	Rate of heat loss ($\times 10^{13}$ W)
Continents and shelves, including lava flows	57	202	1.15
Oceans			
conduction	66		2.03
hydrothermal etc.	33		1.01
total	99	309	3.04
Worldwide	82	510	4.2

Since heat flow is the largest item in the thermal budget of the Earth, an understanding of it is essential to an understanding of how the Earth functions. Over 5400 heat flow measurements are reported in a compilation by Jessop *et al.* (1976). Heat from below reaches the Earth's surface by two main processes: thermal conduction and discharge of hot fluids such as water and lava. Estimates of the global heat loss which take into account the hydro-thermal discharge at ridges have been made by Sclater *et al.* (1980a) and by Davies (1980). The

Earth's heat loss, according to Sclater *et al.*, is summarized in Table 1.1.

One of the central problems of terrestrial heat flow studies is to explain why the average heat flow values of continents and oceans are equal to within a few percent. There are two explanations available. The conventional explanation states that most of the oceanic heat flow is carried through the upper mantle by convection. In the upper mantle beneath the continents, convection is assumed to be absent or to carry a much smaller portion of heat reaching the surface. The convection currents rise near the ocean ridges and discharge heat as they flow towards the continents. This convection hypothesis easily accommodates the modern ideas of continental drift and ocean floor spreading.

Another group of geophysicists argue, however, that the problem of the equality of the average heat flow values of continents and oceans no longer exists (Sclater *et al.*, 1980a; Bott, 1982). When the hydrothermal contribution at the ocean ridges is taken into account, the average continental heat flow is only about 60% of the average oceanic value. The shapes of the continental and oceanic heat flow distributions versus the age of the crust differ significantly. The oceanic values are more scattered than the continental values.

1.2 The Earth's Internal Heat Source

The main source of heat energy within the Earth is believed to be the radioactive decay of long-lived isotopes, but other sources of heat, such as the initial temperature and the heat released by accretion and gravitational energy as well as tidal friction may also contribute substantially to the heat budget.

Before radioactivity was discovered, the flow of heat out of the Earth was believed to be the result of cooling by conduction of an initially hot body. After the discovery of radioactivity, it was recognized that radioactive decay of long-lived isotopes within the Earth may provide a source of heat adequate to explain the observed heat flow without recourse to the cooling hypothesis. The recent idea is that the Earth has actually cooled slightly over its lifespan as a result of vigorous mantle convection (Bott, 1982). A major part of heat now escaping is regarded as coming from the decay of long-lived radioactive isotopes but a significant amount of heat also comes from the slight cooling (Beck, 1969).

Two types of heat sources have contributed to the thermal evolution of the Earth. Once the Earth had formed and the core had separated, the evolution of heat over the Earth's lifespan has mainly been due to the decay of long-lived radioactive isotopes. On the other hand, more short-lived sources of heat might have been present at the time of the Earth's formation to account for the high temperatures established on completion of core formation.

The radioactive isotopes which contribute significantly to the present heat production within the Earth are ^{238}U, ^{235}U, ^{232}Th and ^{40}K. These have half-lives comparable to the age of the Earth and hence they are still sufficiently abundant to be important heat sources. Uranium consists essentially of these two isotopes, the present-day proportion of ^{235}U being 0.71%. ^{40}K forms 0.0118% of present-day potassium. An isotope with decay constant λ was more abundant in the Earth by a factor of $e^{\lambda t}$ at time t before the present. This means that the radioactive heat production from these four isotopes was larger in the past and has progressively decreased since the Earth's formation. The heat-producing isotopes are strongly concentrated into the rocks which form the upper continental crust. In contrast, the granulites believed to form the lower crust appear to be depleted in the radioactive elements relative to the upper crust, so that the main heat sources of the continental crust probably occur within the uppermost 10 to 20 km (Bott, 1982).

1.3 Heat Flow and Geodynamics

The broad features of ocean floor heat flow and topography are generally accepted to be explicable within the framework of plate tectonics. Two models, a simple cooling model and a plate model, have been advanced to account for the variation in depth and heat flow with increasing age of the ocean floor (Parsons and Sclater, 1977). Both are the results of the cooling of hot material after it has accreted to the plate near a midocean ridge and moves away as part of the plate.

In geodynamics, midocean ridges are the surface expressions of the ascending limb of a convection cell in the mantle. Turcotte and Oxburgh (1967) examined this model quantitatively by means of an asymptotic boundary layer treatment of cellular convection. The variation of heat flow calculated from their model was found to show rough agreement with the observations. Mckenzie (1967), however, following a model suggested by Langseth *et al.* (1966), found an alternative explanation in the cooling of a rigid plate moving at constant velocity away from a hot boundary at the ridge crest. The plate was assumed to have a constant thickness in order to reproduce the approximately constant heat flux background observed in the older ocean basins. Sclater and Francheteau (1970) and Sclater *et al.* (1971) showed that there were empirical relationships between heat flow and age, and depth and age, that are similar for all oceans.

To overcome the limitations of the above models, namely an arbitrarily prescribed thickness of the plate and an infinite heat flow at the ridge crest, Sorokhtin (1973) and Parker and Oldenburg (1973) proposed an alternative model. Here the bottom boundary of the lithosphere was taken to be the solid-liquid phase boundary (solidus) of the material. A boundary condition was chosen in which the heat removed by the plate at the ridge crest balances the heat of solidification and cooling in a zone of intrusion at this boundary. This model has a lithosphere the thickness of which is everywhere determined by the physical parameters of the system. The choice of boundary condition removes the singularity in the integrated ridge crest heat flux, a problem that exists in the simple plate and half-space models. The thickness of the lithosphere increases as $t^{0.5}$, where t is the age of the lithosphere in Ma. The heat flow varies asymptotically as $t^{-0.5}$ and the depth increases linearly as t within the age range of 0 to 80 Ma. Heat flow measurement in older ocean floor appears to approach to a constant value.

In a subduction zone, frictional and conductive heating of the plate melts part of it and the melted fraction rises buoyantly to the surface to form the volcanoes and island arcs typically arrayed behind the trenches. Such subduction processes, together with other forms of plate interactions, give rise to thermal metamorphism, the generation of volcanic magma and mountain building on continents. The heat flow patterns are thus more complex above subduction zones, but they nonetheless provide important clues to the subduction process. A pattern generally observed at subduction zones is one of low heat flow near the oceanic trench and very high heat flow to the landward side of the island arc. The pattern suggests that the top part of the cool subducting plate acts as a heat absorber, causing the bend of low heat flow observed adjacent to the trench. Deeper in the subduction zone, the frictional and the conductive heating are sufficient to melt part of the plate, yielding as a product the volcanic island arc itself and the augmented heat flow behind the arc (Pollack and Chapman, 1977a).

Continental heat flow in areas removed from plate boundaries also falls into recognizable patterns (Roy *et al.*, 1968). There is a general decrease in heat flow with the increasing age of a geologic province. This result is similar to that for oceans, but the time scale is obviously quite different. Moreover, there is a clear relation between surface heat flow and the radioactivity of the surface rocks. Evidence which comes from the observed correlation between surface heat flow and heat production of surface rocks shows that lower crust has lower heat sources. About half or even more of the continental heat flow is well accounted for by a layer about 8 km thick with variable heat sources. The heat-producing elements are presumably concentrated upwards by repeated events of metamorphism and partial melting as well as the motion of hydrous fluids. Heat-producing elements (^{238}U, ^{235}U, ^{232}Th and ^{40}K) are more concentrated in granites than in gabbro, basalt and peridotite.

To estimate the contribution of near surface radioactivity to the heat flow, let the volumetric heat productivity of a rock be A (Wm^{-3}). For rocks in the crust where the heat escapes to the surface at the same rate at which it is produced, the surface heat flow above a uniform column b meters long is bA plus whatever heat flowing into the base of the column. If measurements of surface heat flow q and productivity A are made over a region in which different columns extend to the same depth, a linear relation $q = q_o + bA$ is expected, where q_o gives the heat flow beneath the surface layer. In fact, this is true in many continental regions. The parameter b is found to be about 8 km and q_o is about 33.5 mW/m^2, around 40% of the mean surface heat flow measured on continents (Roy *et al.*, 1968).

As the relation $q = q_o + bA$ holds over geological provinces of large horizontal extent, which have suffered differential erosion, the relation must therefore remain unperturbed as material is removed from the upper surface. This leads to the conclusion

$$A_z = A_o \, e^{-\frac{z}{b}}$$

where A_o is the heat productivity of the rock at the uneroded surface, A_z is the value at depth z. The conclusion states that only an exponential decrease of radioactive source concentration with depth leads to the observed fact that the linear relation holds over broad provinces. Starting from this point of view, Pollack and Chapman (1977b) "stripped" the contribution of crustal sources from the surface heat flow for several heat provinces and fitted a spherical harmonic expansion to the residual or mantle heat flow.

A newly developed application of heat flow is to determine the thickness of the lithosphere. The depth at which partial melting takes place in the mantle in a given region depends on the temperature at which the rock of the mantle begins to melt and on the variation of temperature with depth. The depth profile of the actual temperature, called the geotherm, relates strongly with the heat flow. Thus with the aid of considerable extrapolation, surface heat flow data can be used to predict the thickness of the tectonic plates (Chapman and Pollack, 1977b).

Since direct measurement of temperatures in the Earth is limited to the top 10 kilometers of the crust, the extrapolation of temperatures to depths of 100 kilometers or so involves several assumptions. One needs to know how the thermal properties of the rock vary with temperature, how radioactivity is related to depth and, for oceanic regions, how the oceanic plate cools after it is formed at the ridge. Recent laboratory measurements and field observations have provided enough data for the construction of detailed models so that one can calculate characteristic geotherms for both continental and oceanic regions with some confidence (Sclater *et al.*, 1980a). The depths to partial-melting conditions predicted from such calculations agree well with the seismological results from surface wave studies. Both heat flow measurements and seismological data indicate that oceanic plates thicken as they age, from a few kilometers soon after their formation at a ridge to 100 km or more in the oldest ocean basins, where the heat flow is low. The continental portions of the tectonic plates also show a systematic variation in thickness, from 40 km in young geologic provinces where heat flow is high to several hundred kilometers under continental shields where heat flow is characteristically much lower. For some shield areas, the geotherm does not intersect the mantle's melting curve at any depth. In these areas, thick lithosphere would be coupled directly to the deep interior.

1.4 Heat Flow and the Thermal History of the Earth

For a long time it was generally felt that the Earth had a very hot origin, possibly being formed from material expelled from the sun, and that in the process of cooling to its present condition the crust, which had formed early in the Earth's history, had folded as the Earth contracted due to cooling. It was argued that the results of this contraction could be seen in the present day mountain systems. Objections to this theory developed when it became apparent that there were serious astronomical difficulties in the hot origin of the solar system (Beck, 1969).

Today, it is generally accepted that the Earth was formed from a cloud of cold meteoritic particles which during and subsequent to accretion has undergone various stages of heating and cooling.

The modern model of the thermal history of the Earth depends on the escape of heat out of the deep interior by mantle convection controlled by a heavily temperature-dependent viscosity, with the consequent establishment of a thermal equilibrium between internal radiogenic heat production, slight cooling and loss of heat from the surface. The thermal history of the Earth can be subdivided into several stages (Bott, 1982). The beginning stage was the initial heating of the Earth during accretion resulting from release of gravitational energy of the colliding bodies, adiabatic compression and possibly the heat released by the decay of short-lived radioactive isotopes, notably ^{26}Al. This stage was terminated when the temperature at some depth within the outer half became high enough to melt the iron-nickel phase with mixed FeS and FeO. The next stage involved the substantial release of gravitational energy as heat during the process of core formation from an initially homogeneous Earth. Core formation is believed to have been completed over a short period of time. The Earth's internal temperatures were raised to levels significantly above the present day values, possibly causing extensive melting in the upper mantle. The result of this stage was the establishment of a vigorous thermal regime within the Earth, with a molten convection core and a mainly solid convecting mantle. During the following stage, the thermal equilibrium was established between heat production by long-lived radioactive isotopes, steady cooling and heat loss from the Earth's surface. The last stage represents the establishment and maintenance of a stable thermal balance between heat production, slow and steady cooling and heat loss. This stage probably started about 4 b.y. ago and persists to the present day. The Earth has probably cooled by a few hundred degrees over this stage, but the heat flow has fallen off at a decreasing rate by a factor of about three as the radioactive heat sources have progressively decayed.

Following the hypothesis that the Earth was formed by an accretion of chondritic substance at a low temperature about 4.5 billion years ago, it is possible to infer a subsequent history mathematically by devising a number of models with assumptions regarding the initial temperature of the Earth, its initial radioactive content (presumed to be distributed uniformly), its thermal conductivity and other conditions, and to calculate for each model what the present temperature distribution and heat flow would be. Such model calculations have been made (Lubimova, 1958; Macdonald, 1959; Hanks and Anderson, 1969). The calculations indicate that the computed temperature distribution is in reasonable agreement with the current estimates of temperature within the Earth.

1.5 Heat Flow Measurement on Land and on the Sea Floor

The measurement of terrestrial heat flow falls into two categories: on land and on the sea floor (the latter may include lakes). On land, temperature gradients are measured by lowering thermistors down into drill holes or by measuring the temperature of the rocks at different levels in mines. The process of drilling a hole disturbs the thermal equilibrium at the site, hence several weeks or months are allowed to lapse between the drilling and measuring. Even after this disturbance has become negligible, such effects as the daily and annual fluctuations in the surface temperature, unevenness in vegetative cover, the uplift or erosion of the surface, variations in climate and, especially, the underground water circulation must be considered. Thus, reliable data can only be obtained at depths of several tens to hundreds of meters below the surface. Moreover, because borehole drilling is costly, most measurements so far have been made in the holes that were not prepared specifically for the purpose of heat flow measurement. For this reason, the geographic distribution and the geological setting of such measurements are often not satisfactory.

On the ocean floor, where sediments are comparatively soft and the blanket of seawater provides an environment of almost constant temperature, the need of drilling holes is eliminated. Temperature gradients are determined by plunging a long cylindrical probe several meters in length into the soft sediments and measuring the temperature at intervals along the probe with thermistors.

For measuring thermal conductivity, both on land and on the ocean floor, two methods are used. One is to gather rock or sediment samples at the sites where the thermal gradients are measured and determine the thermal conductivity in the laboratory. The other method is *in situ* measurement which needs no samples, speeds up the work and is especially important for heat flow determination when samples are not easily obtained.

To date, over 6000 heat flow measurements have been reported. About 30% of these measurements are from continents and are poorly distributed, leaving large gaps in Antarctica and parts of Africa, South America and Asia. The oceanic observations are more evenly distributed, but show serious gaps in the Arctic and Antarctic regions. The available data are still hardly ideal for statistical investigation.

A general way of studying the global pattern of heat flow is to carry out a spherical harmonic analysis on the observations. The main practical difficulty is that the observations are not evenly distributed over the Earth's surface. This problem has been overcome by predicting the heat flow values in regions without observations, by using the observed correlation between continental heat flow and age of the last tectono-thermal event and between oceanic heat flow and the age of the ocean floor. Several geophysicists have assigned mean heat flow values to each of the 5×5 grid areas on the globe using the observed values where available and the predicted values elsewhere (Chapman and Pollack, 1975; Lister, 1977; Parsons and Sclater, 1977). They then carried out a spherical harmonic analysis of the grid means to degree twelve (Chapman and Pollack, 1975).

1.6 Heat Flow and Petroleum

The application of heat flow measurement to the evaluation of hydrocarbon potential in sedimentary basins formed by extension has been a significant development since the mid 1970's. Petroleum hydrocarbons are formed by the thermal alteration of organic-rich sediments during burial. Although many factors contribute to the metamorphism of organic material, the process is primarily dependent on the integrated time and temperature history of the sediments (Tissot *et al.*, 1974). Some authors have suggested different indices to determine the hydrocarbon maturation. The two most commonly cited are as follows:

(1) Lopatin's (1971) (also see Waples, 1980) time-temperature index of maturity (TTI) values correlate with the thermal regimes corresponding to generation and preservation of hydrocarbons. Lopatin stated that time and temperature are interchangeable: a higher temperature acting for a shorter time can have the same maturation effect as a lower temperature acting over a longer time. He assumed that the dependence of maturation on time is linear while chemical reaction rate theory predicted that the temperature dependence of maturity will be exponential. Lopatin and others have concluded that the reaction rate doubles for each 10 K increase in temperature. Calculated TTI values were compared with measured data from many worldwide samples representing a variety of age and lithologies which are shown in Table 1.2.

(2) Royden *et al.* (1980) suggested a parameter C which reflects the level of thermal alteration:

$$C = \ln \int_0^t 2^{\frac{T(t)}{10}}\, dt$$

Table 1.2 Correlation of TTI with important stages	
Stage	TTI
Onset of oil generation	15
Peak oil generation	75
End of oil generation	160
Upper TTI limit for occurrence of wet gas	~1500
Last known occurrence of dry gas	65,000

where t is time in Ma and

T is the paleotemperature in degrees Celsius in specific sedimentary strata.

Comparison with other indices leads to the conclusion that the oil generation process has barely started at $C \approx 10$ and is essentially completed at $C \approx 16$. The gas generation process is essentially completed at $C \approx 20$.

The application of the above indices involves the thermal history of the basin. McKenzie (1978) studied a model of the development and evolution of sedimentary basins. In the model, the first event consists of a rapid stretching of continental lithosphere, which produces thinning of lithosphere and passive upwelling of hot asthenosphere. This stage is associated with block faulting and subsidence. The lithosphere then cools by heat conduction to the surface and thickens. Further slow subsidence not associated with faulting occurs because of the thermal contraction. The slow subsidence and the heat flow depend only on the stretching factor β.

After the extension, the temperature variation is

$$T = T_1 , \qquad 0 < \frac{z}{a} < \left(1 - \frac{1}{\beta}\right)$$

$$T = T_1 \beta \left(1 - \frac{z}{a}\right) , \qquad \left(1 - \frac{1}{\beta}\right) < \frac{z}{a} < 1 .$$

where z is measured upwards from the base of the lithosphere before extension, a is the original thickness of the lithosphere and T_1 is the temperature of the asthenosphere.

Assuming one dimensional heat flow, McKenzie's (1978) model leads to a solution for the surface heat flow of

$$Q(t) = \frac{KT_1}{a}\left[1 + 2 \sum_{n=1}^{\infty} \left(\frac{\beta}{n\pi} \sin\frac{n\pi}{\beta}\right) \exp\left(\frac{-n^2 t}{\tau}\right)\right] \qquad (1.1)$$

This equation (1.1) expresses the contribution of the determination of present heat flow to the petroleum potential assessment. Substituting $t = 0$, the equation yields the heat flow $Q(0)$ at the time when extension occurs, with the extension factor β as a parameter. By determining the extension factor from seismic data or sedimentary thickness measured in wells, it is then possible to predict the paleoheatflow upon calculating $Q(0)$ using the present observed heat flow $Q(t_o)$ as a constraint. The paleotemperatures thus derived may be used with either of the maturation indices (Lopatin, 1970; Royden *et al.*, 1980) to estimate the thermal maturity of the sediments. It should be pointed out , however, that the above calculations are only suited for the young margins (less than 60 Ma after extension).

1.7 Outline of the Dissertation

This dissertation mainly describes the design, construction and deployment of a microcomputer controlled marine heat flow probe. The outline of the thesis is as follows:

Chapter 2 discusses marine heat flow equipment. A discussion of the advantages and disadvantages of the existing probes is given. The theory of the *in situ* conductivity measurement is also addressed.

Chapter 3 describes the electronic design of the heat flow probe HF1601. The design includes the data acquisition system, the heat pulse generator and its controller, the tilt sensor and the underwater digital acoustic telemetry.

Chapter 4 outlines the computer program (HF1601P) for heat flow measurement. The program is written in assembly language. Flowcharts are given to improve the readability.

Chapter 5 presents the data processing software HF1601D. The software operates in a real-time, interactive environment. The whole data reduction process is displayed on the on-ship computer's screen (or on a printer and plotter). The discussion concentrates on the reduction of the thermal conductivity data.

Chapter 6 gives the field tests and experiments for the newly designed heat probe. Detailed information on five cruises is given.

Chapter 7 discusses the geophysical interpretation of the heat flow data measured in the inlets of the south coast of Newfoundland and in the Labrador Sea and Shelf. The various corrections to the heat flow data measured in the shallow water are discussed.

Chapter 2 Marine Heat Flow Measurement

2.1 Marine Heat Flow Equipment

The equipment for ocean floor heat flow involves a ship, measurement instrumentation on the ship and sea floor, a navigation system and depth sounders.

A major part of the equipment is the heat flow probe itself. Numerous designs have been described in the literature, but they invariably fall into two types. They both use two or more temperature elements which are spaced vertically some known distance apart in or on a probe or probes which can be driven into the ocean floor by the probe's own weight. The temperature difference between the elements is recorded while the heat of penetration dissipates into the sediment. The basic differences between the two types are as follows:

(1) Bullard-type probe, first used in 1950 (Bullard, 1965). These probes have a tube 2-7 m long and about 0.7-2.7 cm O.D. (Outside Diameter). Inside the tube, there are several fixed thermistors at intervals of 0.5-1.0 m. Electronic parts are housed in cylinder(s) at the top of the tube. The whole probe is made pressure tight at 1 atmosphere, therefore the walls of the probe must be thick enough to withstand expected sea bottom hydrostatic pressures up to 1400 atm (142 MPa). The reported accuracy

of the Bullard-type probe is up to ± 1 mK (Haenel 1979). The weight of this type of probe is about 300 kg. The most significant development in this type of probe design, having a violin-bow appearence (Fig. 2.1a) was achieved by Lister (1970, 1979). It permits multiple penetrations on each lowering, high accuracy digital acoustic telemetry to the ship (Von Herzen and Anderson, 1972; a Bullard-type probe) and *in situ* thermal conductivity measurement over the same spatial interval as the temperature gradient measurement. It employs a large diameter strength member and a parallel thin sensor string tube supported at both ends. This instrument was described briefly by Hyndman *et al.* (1979) and Davis *et al.* (1979); the *in situ* thermal conductivity measurement technique is described by Lister (1979) and Hyndman *et al.* (1979).

(2) Ewing-type probe, first used by Gerard *et al.* (1962). The probe has a length of 5-20 m with several small needle probes mounted on the outside and carrying temperature elements (Fig. 2.1b). The probe itself is a piston corer which enables one to obtain sediment sample at the exact locality of the heat flow measurement. With improved Ewing-type probes, temperature and thermal conductivity can be measured successively by the needle probes (Haenel, 1972). Its disadvantages are its heavy weight of 500-1000 kg, and easily damaged small needle probes.

A third type of probe, used in lakes, is not very different from the previous two types except for its shorter length, lighter weight and possibility of using direct electrical and electronic connections to the ship and possibility of bidirectional control (Diment and Werre 1965, Steinhart and Hart 1965, Von Herzen *et*

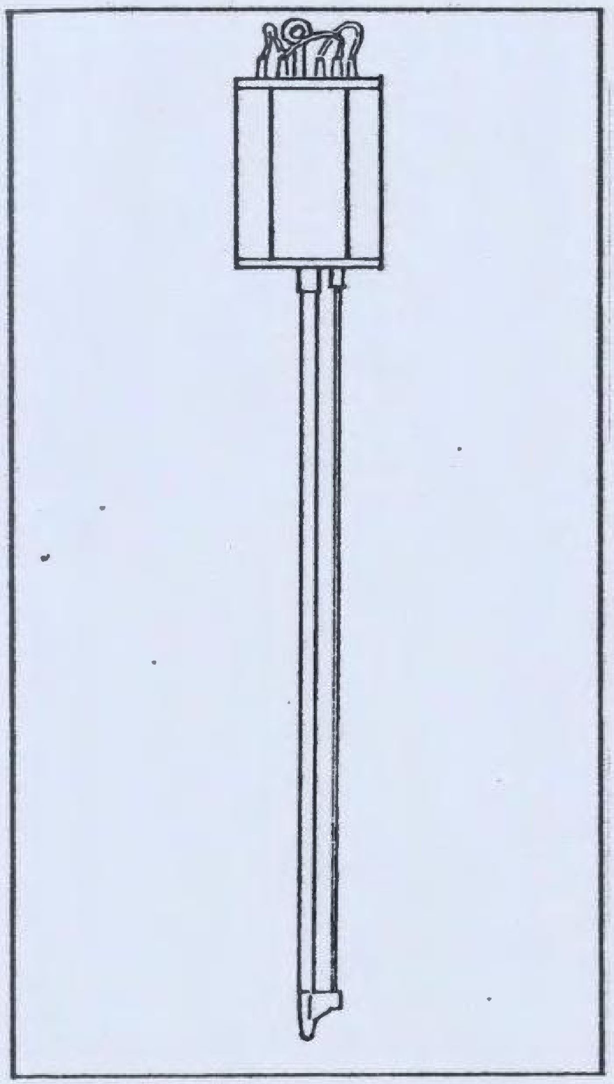


Fig. 2.1a Violin-bow-type probe

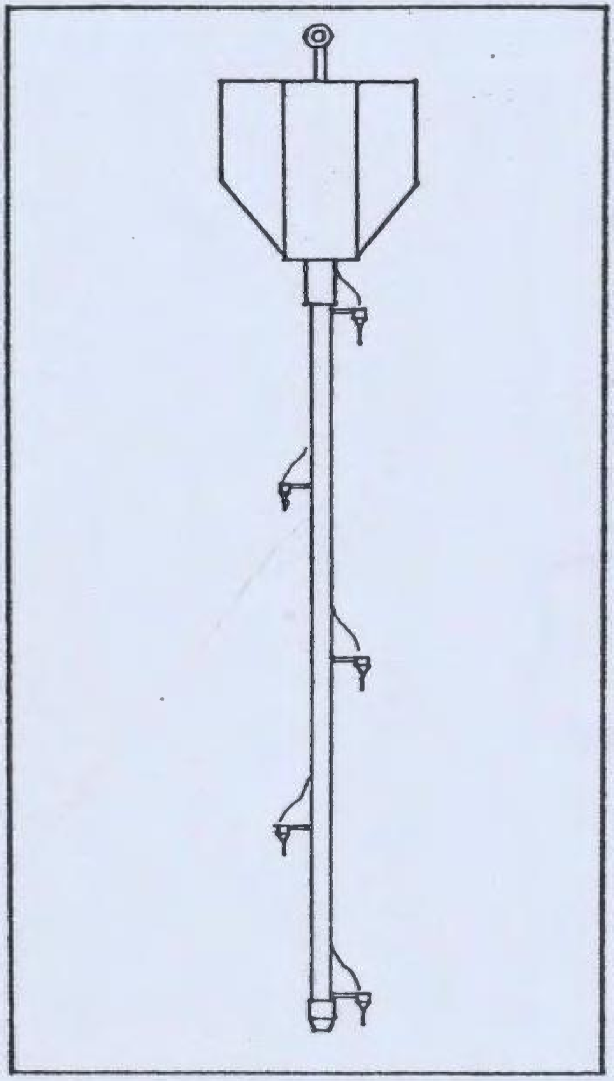


Fig. 2.1b Ewing-type probe

Fig. 2.1a Violin-bow-type probe and Fig. 2.1b Ewing-type probe *al.* 1974, Haenel 1979).

The Bullard and Ewing instruments both use the thermistors as temperature sensing elements. Commonly used thermistors are semi-conductive, highly sensitive resistors which have a spinel crystal structure, the approximate formula being $Ni_{0.6}Mn_{0.4}{}^{+2}Mn_2{}^{+3}O_4$. (Robertson *et al.*, 1966).

The principal advantage of using thermistors in measuring temperatures in the heat probe are that

(1) they have a high temperature coefficient of resistance (5%/C° at 0° C);

(2) they are available in a wide range of resistances, from 10 ohms to 10^7 ohms at 25° C, for optimum matching to the measuring circuit;

(3) their resistance is a function of the absolute temperature;

(4) they are little affected by the chemical and physical conditions of the environment;

(5) they have a small size (for bead-type diameter: 2.4 mm);

(6) they are mechanically rugged and inexpensive.

Thermistors, like other semiconductors, have an electrical conductivity approaching that of a metal at high temperatures and are nearly insulating at low temperatures. The theoretical characteristics of the spinel semiconductors, to which the thermistors belong, are not well understood. However, an empirical adaptation of the equation for electrical resistivity of semiconductors $\sigma = A(T)\exp(-\Delta E/2kT)$ (in which σ is the electric conductivity, $A(T)$ is a slowly varying function of temperature, ΔE is an energy term, and k is the Boltzmann constant) fits the resistance-temperature data for thermistors very well

$$R = A\ e^{\frac{B}{T+C}}$$

where R is resistance, in ohms; T is temperature, in Kelvin; and A , B and C are constants. The relation between temperature and resistance of the thermistors will be further discussed in Chapter 5.

Table 2.1 is the Resistance-temperature relations of the YSI Thermistors (30000 ohms at 25° C).

In heat probes, the individual thermistors should be calibrated carefully, as the characteristics of each element are different. The manufacturer can supply a specially selected group of thermistors that has a small deviation (less than 1%) among the individual thermistor's differential slope of their T-R curves. This deviation should also be verified. Chapter 5 gives a discussion of this matter. Thermistors are also known to change characteristics or to 'drift' with time. However, this drift is usually insignificant and is most commonly a translation of the temperature versus resistance curve rather than a change in slope. Another error source in temperature measurement using thermistors is the 'self-heating'. Thermistors are heated by the current through them during the measurement of resistance. The heating will cause the thermistors to have a higher temperature than the medium they are measuring. This effect can be minimized by using very small currents and by initially calibrating the thermistor with the current to be used in the measuring circuit of the instrument.

The techniques of measuring thermal conductivity of the sediments on the sea floor, as stated above, fall into two kinds: laboratory measurement on samples

Table 2.1 YSI Thermistor Resistance-Temperature Relation

RESISTANCE VERSUS TEMPERATURE -40^{O} TO +100^{O}C

T	R	T	R	T	R	T	R	T	R
-40	884.6K	-10	158.0K	+20	37.30K	+50	10.97K	+80	3843
39	830.9K	9	150.0K	21	35.70K	51	10.57K	81	3720
38	780.8K	8	142.4K	22	34.17K	52	10.18K	82	3602
37	733.9K	7	135.2K	23	32.71K	53	9807	83	3489
36	690.2K	6	128.5K	24	31.32K	54	9450	84	3379
35	649.3K	5	122.1K	25	30.00K	55	9109	85	3273
34	611.0K	4	116.0K	26	28.74K	56	8781	86	3173
33	575.2K	3	110.6K	27	27.54K	57	8467	87	3073
32	541.7K	2	104.9K	28	26.40K	58	8166	88	2979
31	510.4K	- 1	99.80K	29	25.31K	59	7876	89	2887
-30	481.oK	0	94.98K	+30	24.27K	+60	7599	+90	2799
29	453.5K	+ 1	90.41K	31	23.28K	61	7332	91	2714
28	427.7K	2	86.09K	32	22.33K	62	7076	92	2632
27	403.5K	3	81.99K	33	21.43K	63	6830	93	2552
26	427.7K	4	78.11K	34	20.57K	64	6594	94	2476
25	359.6K	5	74.44K	35	19.74K	65	6367	95	2402
24	339.6K	6	70.96K	36	18.96K	66	6149	96	2331
23	320.9K	7	67.66K	37	18.21K	67	5940	97	2262
22	303.3K	8	64.53K	38	17.49K	68	5738	98	2195
21	288.7K	9	61.56K	39	16.80K	69	5545	99	2131
-20	271.2K	+10	58.75K	+40	16.15K	+70	5359	+100	2069
19	256.5K	11	56.07K	41	15.52K	71	5180		
18	242.8K	12	53.54K	42	14.92K	72	5007		
17	229.8K	13	51.13K	43	14.35K	73	4842		
16	217.6K	14	48.84K	44	13.80K	74	4682		
15	206.2K	15	46.67K	45	13.28K	75	4529		
14	195.4K	16	44.60K	46	12.77K	76	4381		
13	185.2K	17	42.64K	47	12.29K	77	4239		
12	175.6K	18	40.77K	48	11.83K	78	4102		
11	166.6K	19	38.99K	49	11.39K	79	3970		

of sediment brought to the surface by coring devices at or near the site of the temperature gradient measurement, and *in situ* measurement. For the former, both steady-state and transient methods of measurement have been used. The steady-state technique is not very suitable for routine measurements on a large number of samples or for shipboard use. The transient method is more convenient and rapid. In this method (Von Herzen and Maxwell, 1959), a very thin needle is heated by an internal heater wire at a known and constant rate. The rate of rise of temperature of the needle is measured by a small thermistor which is inside the needle and midway along its length. The needle is usually 0.5 to 0.9 mm O.D. and 6.4 cm long. This thin needle can be regarded as a line source of heat in the neighbourhood of the thermistor within several seconds after the heater power is turned on. After the heater power has been on for roughly 10 seconds, the temperature T in degree Celsius of the thermistor as a function of time t in seconds is given by

$$T = \frac{Q}{4\pi K} \ln t + C$$

where Q is the heat per unit length per unit time, K is the conductivity and C is a constant. If the temperature is plotted against the logarithm of time, a straight line results and $Q/(4\pi K)$ is the slope of this line. If Q is measured, K can be determined.

The thermal conductivity of deep sea floor sediments can also be estimated if the water content is known. Most deep sea sediments can be considered as very fine solid particles in a water medium. The results of Ratcliffe (1960) and Bullard and Day (1961) have shown that there is a linear relation between the thermal resistivity and the water content of ocean bottom sediment in the range of expected values. This relation is expressed as (Ratcliffe, 1960; in S.I.)

$$R_{in\ situ} = (0.4013 \pm 0.0334) + (0.0162 \pm 0.0007)\ W_c$$

where R is the thermal resistance in mK/W, and W_c is the water content in percent water of the wet weight.

At the present time, the Bullard-type probes without *in situ* conductivity measurement are gradually replaced by the Violin-bow type probes with *in situ* method to determine the thermal conductivity of the sediments. This method will be addressed later in this chapter and other chapters.

From the electronics point of view, the development of marine heat flow probes could be roughly divided into three stages. In the early stage, they were characterized by two or three temperature elements and basic analog electronic circuits such as a Wheatstone bridge, with various analog amplifiers. The recording system was mainly film, paper chart recorder with a self-balancing potentiometer driven by a servomotor. The second stage which started in the early 1970's was characterized by digitization and *in situ* thermal conductivity measurement. Digital electronics enables the probes to fulfill a more sophisticated task: more temperature measuring channels, more accurate timing and direct measurement of the thermistors' resistances (other than Wheatstone bridge). The realization of *in situ* thermal conductivity measurement over the same interval as the gradient measurement and a magnetic tape recording system permits multiple ('pogostick') penetrations on each lowering. High accuracy digital acoustic telemetry to the ship permitted scientists on board to monitor the data. The latest stage can be characterized by the employment of microprocessors and microcomputers in the probe. This phase began in the early 1980's and to date there are few descriptions in the published literature.

2.2 *In situ* Thermal Conductivity Determination on the Sea Floor

For the violin-bow type of marine heat flow probe, the measurement of thermal conductivity *in situ* is accomplished by the application of a transient heat pulse or steady heat supply through the cylindrical probe to the sediment into which the probe is inserted. This method avoids the difficult task of retrieving, storing and measuring a representative sample of the material from the sea floor. Von Herzen and Maxwell (1959) first introduced the method for measuring thermal conductivity in the laboratory, although they used continuous heating in which the temperature rise against the time approaches a logarithmic asymptote whose slope is proportional to the thermal resistivity of the material surrounding the probe. The steady heating method, however, has two drawbacks: it is energy consuming and the sensitivity of the results depends strongly on the stability of the heater power.

The idea has been adapted for *in situ* thermal conductivity measurement on the sea floor by Sclater *et al.* (1969), Christoffel and Calham (1969) and Lister (1970). For a multiple penetration heat flow probe, the time for each measurement must be kept as short as possible and the power required for transient heating must be minimized. Lister (1979) proposed a calibrated heat pulse technique for a maximum thermal conductivity measurement time of ten minutes using a Bullard-type probe and based on theory formulated by Bullard (1954), Jaeger (1956), and Carslaw and Jaeger (1959). After the probe penetrates the sediment and the thermal disturbance caused by the friction dissipates, a heat pulse is supplied to a linear heater along the length of the thermistor string. A heating time of less than 0.2 of a probe thermal time constant appears to be an adequate approximation to a heat pulse for a reasonable measurement period of 1 to 10 time constants. A longer heating can also be treated theoretically.

After the heat pulse, the probe is at temperature T_o above the sediment temperature. Assuming that there is no contact resistance, which is nearly true in the ocean sediments (Hutchison, 1983), the decay of the temperature of the probe can be treated as that of an infinitely long, perfectly conducting cylinder of radius a and heat capacity S (per unit length), initially at temperature T_o and immersed in a half-space of conductivity K, specific heat c and density ρ, initially at temperature zero.

The solution of this problem is given explicitly by Bullard (1954) in terms of a function $F(\alpha,\tau)$ with:

$$\frac{T(\alpha,t)}{T_o} = F(\alpha,\tau)$$

where

$$F(\alpha,\tau) = \frac{4\alpha}{\pi^2}\int_0^\infty \frac{\exp(-\tau u^2)}{u\left\{[uJ_0(u)-\alpha J_1(u)]^2+[uY_0(u)-\alpha Y_1(u)]^2\right\}}\,du \quad , \qquad (2.1)$$

$$\alpha=\frac{2\pi a^2\rho c}{S} \; ,$$

$$\tau=\frac{kt}{a^2}$$

Where k is the sediment diffusivity; a, the probe diameter; and t, the time elapsed after the application of heat pulse. $J_n(u)$ and $Y_n(u)$ are Bessel functions of order n of the first and second kinds. τ defines the thermal time constant of the probe and α is twice the ratio of the heat capacity of sediment to that of probe material.

Unfortunately, it is not possible to evaluate $F(\alpha,\tau)$ analytically and so numerical technique must be employed to calculate sediment thermal conductivity. A method of deriving conductivity by numerical analysis is addressed in Chapter 5 (also see Davis, 1984 and Fang and Wright, 1985).

Besides the direct numerical evaluation of $F(\alpha,\tau)$, two approximate methods of calculating thermal conductivity by *in situ* measurement exist. They are now briefly discussed.

Expand $F(\alpha,\tau)$ into a series valid for large τ ($\tau>1$) (Blackwell, 1954):

$$F(\alpha,\tau) = \frac{1}{2\alpha\tau} - \frac{1}{4\alpha\tau^2} - \frac{(\alpha-2)}{4\alpha^2\tau^2}\left[\ln\frac{4\tau}{1.7811} - 1\right] + O\ \frac{\ln\tau}{\tau^3} \qquad (2.2)$$

On the sea floor and using a steel thermal probe, α has a value close to 2. Thus, for $\tau>10$, the second term of (2.2) is less than 5% of the first term and the third term can be completely omitted. The solution reduces to asymptotic solution

$$F_a \approx \frac{1}{2\alpha\tau}$$

and the asymptotic temperature at large time ($\tau>10$) T_a is

$$T_a = T_o F_a = \frac{T_o}{2\alpha\tau}$$

$$= \frac{T_o}{2[(2\pi a^2\rho c)/S][kt/a^2]} = \frac{ST_o}{4\pi Kt} = \frac{Q}{4\pi Kt}$$

where $Q = ST_o$ is the total heat applied by heat pulse per unit length per unit time. Fig. 2.2 illustrates the difference between T_a and T.

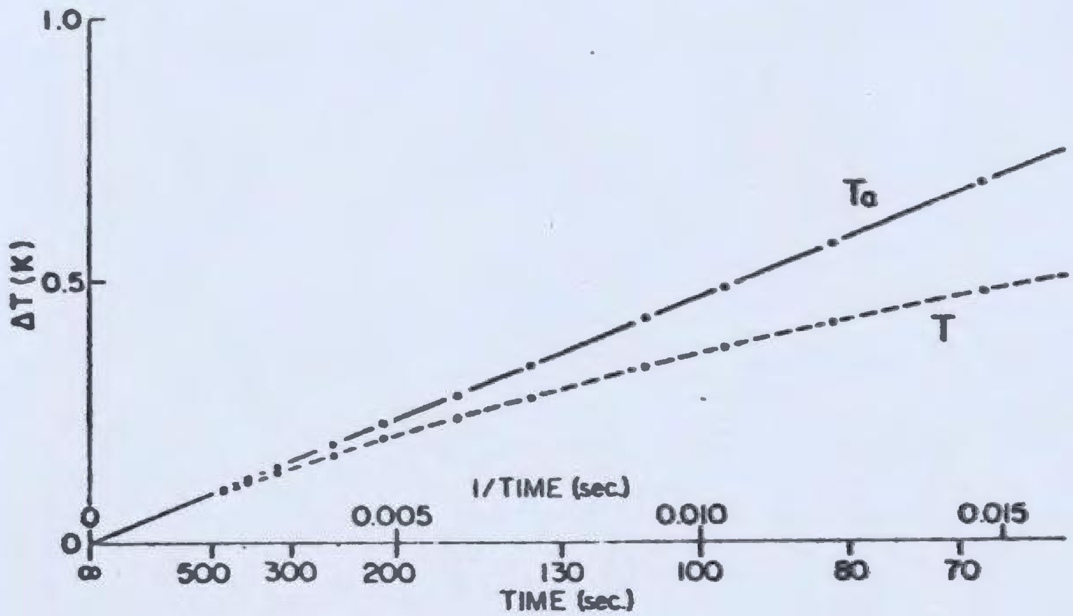


Fig. 2.2 T_a and T (Adapted from Hyndman *et al*., 1979)

Thus the slope of the measured temperature versus the reciprocal time $\frac{1}{t}$ gives the reciprocal conductivity $\frac{1}{K}$ for τ greater than about 10.

In practice, the measured temperature is not taken after $\tau > 10$, but for $\tau = 1$ to 10. In this time range, the probe temperature depends also on the sediment diffusivity and on the probe heat capacity and diameter. To estimate thermal conductivity K in this short time range, it is convenient to multiply the measured temperatures T by a dimensionless correction factor $G(\alpha,\tau)$ to obtain an estimate of the temperatures T_a for the asymptotic solution at the same time range. There are different ways to define the correction factor. The following are the self-consistent τ method and the empirical $k-K$ method.

(1) Self-consistent τ method: (Lister, 1979)

The sediment diffusivity can principally be estimated from the short time temperatures. Jaeger (1959) outlined a technique employing the ratio of the temperatures at τ and 2τ, that is, $\frac{F(\alpha,\tau)}{F(\alpha,2\tau)}$. Lister (1979) has suggested the correction function $L(\alpha,\tau)$:

$$L(\alpha,\tau) = 2\alpha\tau F(\alpha,\tau) = \frac{F(\alpha,\tau)}{F_s(\alpha,\tau)} \quad .$$

The measured temperature T can be written as:

$$T = F(\alpha,\tau) = \frac{F_s(\alpha,\tau)}{F_s(\alpha,\tau)} F(\alpha,\tau)$$

$$= \frac{Q}{4\pi Kt} L(\alpha,\tau) \quad .$$

Thus, if $L(\alpha,\tau)$ is estimated correctly, the thermal conductivity K can be obtained from the slope of the asymptotic temperature curve.

The correction function $L(\alpha,\tau)$ can be estimated only when α and τ are known. α can be taken to be equal to 2 with little error (<2%, Lister, 1979, Hyndman *et al*., 1979). Information relating to the value τ in a measured temperature curve is contained in the way in which the curve deviates from the asymptote; that is, in its curvature. A measure of curvature is expressed by the function:

$$R(\theta,2,\tau) = \frac{\theta F(\alpha,\theta\tau)}{F(\alpha,\tau)} \quad .$$

The R-ratio tends downwards toward unity as τ approaches infinity. θ can be taken as any number, convenient values are 2 and 3. R can be theoretically calculated from $F(\alpha,\tau)$ and $F(\alpha,\theta\tau)$. The essence of the method is to find $L(\alpha,\tau)$, not τ. Thus, a graph comparing R and L has been suggested by Lister (1979, Fig. 2) with τ simply as parameter that varies non-linearly along the curves.

(2) The empirical k–K method: (Hyndman *et al.*, 1979)

Hyndman *et al.* (1979) suggested their correction function $C(\alpha,\tau)$:

$$C(\alpha,\tau) = \frac{T_a}{T} = \frac{1}{2\alpha\tau F(\alpha,\tau)} = \frac{1}{L(\alpha,\tau)} \quad .$$

They favor $C(\alpha,\tau)$ because the short time temperature is very sensitive to the poorly known detailed thermal properties of the probe. It seems preferable to estimate α and k using empirical relations between these parameters and the thermal conductivity K for ocean sediments. The method employs an iterative approach for computing the conductivity K.

For convenience in computation, the correction function $C(\alpha,\tau)$ for a specific probe with known diameter a can be expressed as a series of polynomials for a range of values of thermal conductivity K.

2.3 Shortcomings of the Previous Marine Heat Flow Probes

Although there has been substantial improvement during the last thirty years, there are still some shortcomings in previous probe designs. These shortcomings are:

(1) Most of them are not programmable. Heat flow measurements take place in different environments. A programmable instrument is ideal, for it can easily

change task to meet sophisticated demands without the need of modifying relevant hardware. Moreover, some tasks such as real-time data processing can only be fulfilled by a computer-based programmable instrument.

(2) They are uneconomical in data storage. Most of the instruments have a recording system to store data. All of them work in a way such that up to 80% of the data recorded are temperatures of sea water when the probe is moving between stations, lowering and rising. Most of these recordings have little use. This problem not only hampers the probe's ability to reach its full data capacity, but also slows down the data processing.

(3) They are vulnerable to stochastic error caused by contact resistivity, op-amp (operation amplifier) offset, instability of power supply and mechanical, electrical as well as electronic noise sources.

(4) The communication between the probe and ship is not adequate. Some recent developments use acoustic telemetry to transmit messages but the information is very limited. Bi-directional communication would greatly enhance probe's utility.

(5) The records of the data keep no real time information, thus it is difficult to keep track of data acquisition procedure.

(6) Higher sensitivity is desired especially for thermal conductivity determination.

(7) An efficient data processing software package is required for use on the ship.

The following chapters address these shortcomings.

Chapter 3 Design of Marine Heat Flow Probe HF1601

3.1 Mechanical Design

Since 1982, Memorial University of Newfoundland has been developing a microcomputer-based marine heat flow package capable of real-time measurement (Wright and Fang, 1984, 1985) (Fig. 3.1). The sea floor instrument is a variant of the 'violin-bow' type design (Lister, 1979) with a digital acoustic link to a portable microcomputer on ship. The mechanical design of the probe is a modification of the instrument made by Applied Microsystems Ltd. Fig. 3.2 shows the assembly of the sea floor probe and Fig 3.3 the chassis for the electronic package.

3.2 Electronic Design

The electronics of the HF1601 probe consist of six printed circuit cards; each card has the size of 11.43×19.05 cm. Four of them are commercial CMOS boards from RCA Inc. They are the CDP18S601 microboard computer module, CDP18S652 microboard tape I/O control module, CDP18S629 microboard 32-kilobyte RAM module and CDP18S622 microboard 8-kilobyte battery backup RAM module.

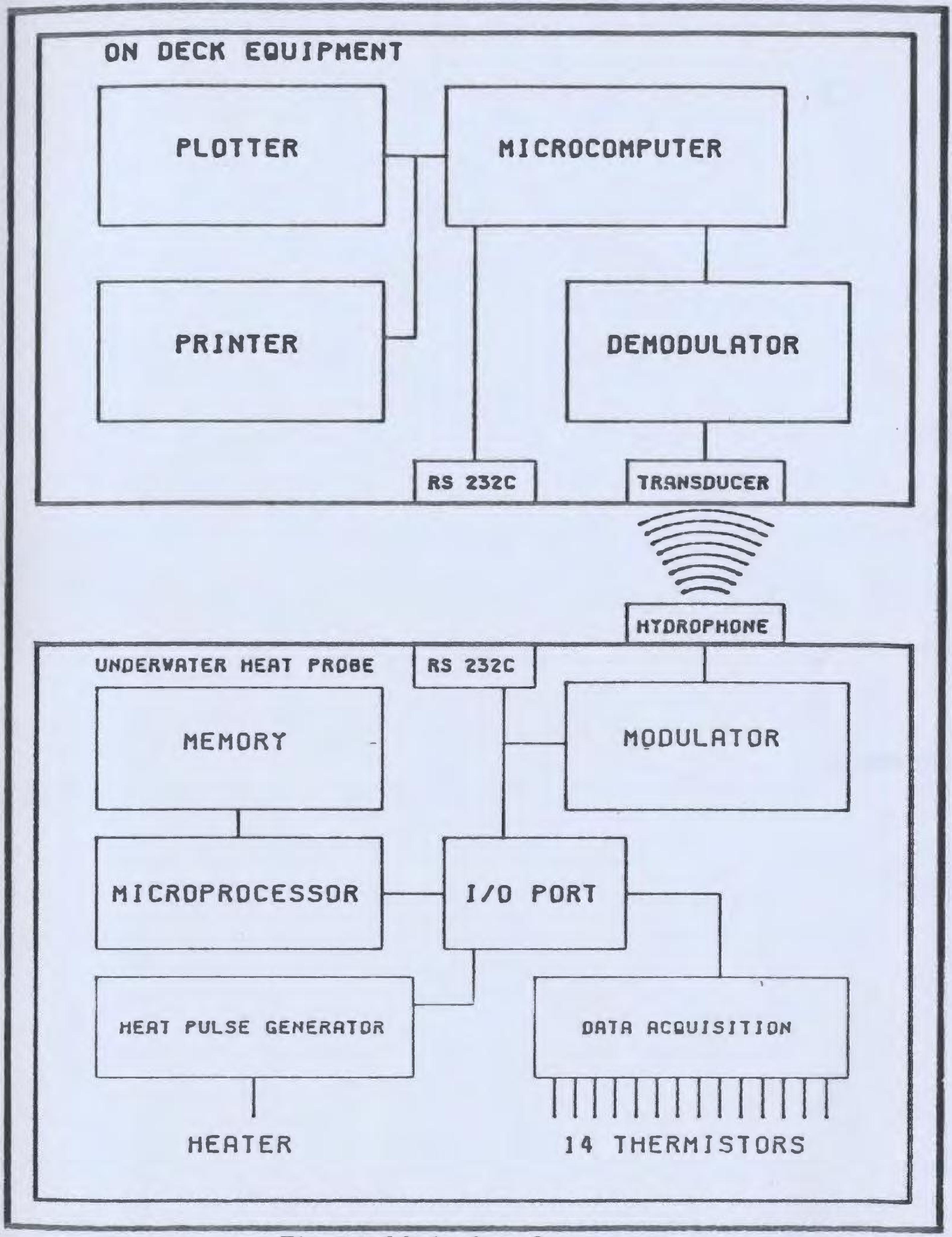


Fig. 3.1 Marine heat flow system

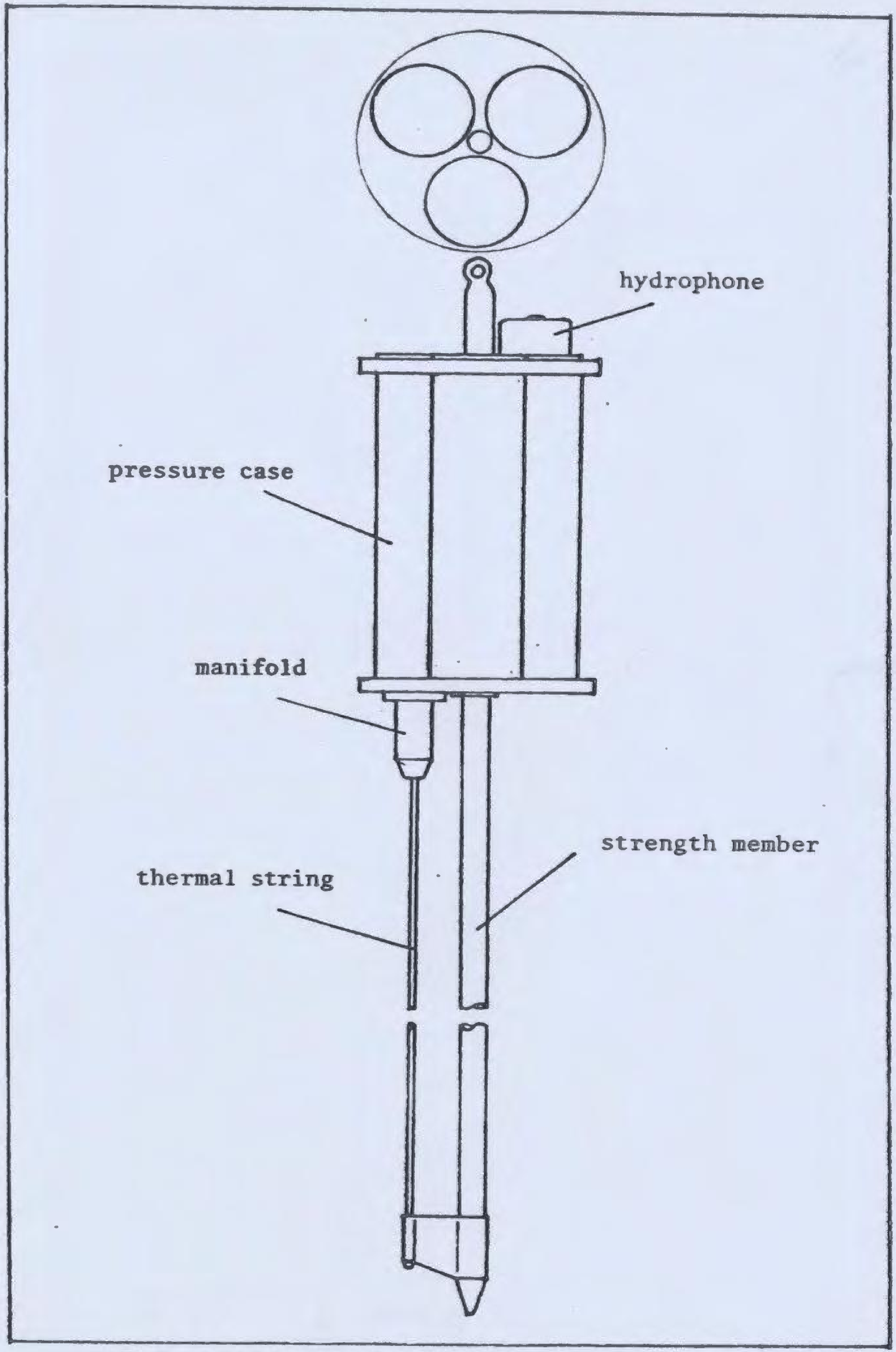


Fig. 3.2 Assembly of the HF1601 heat flow probe

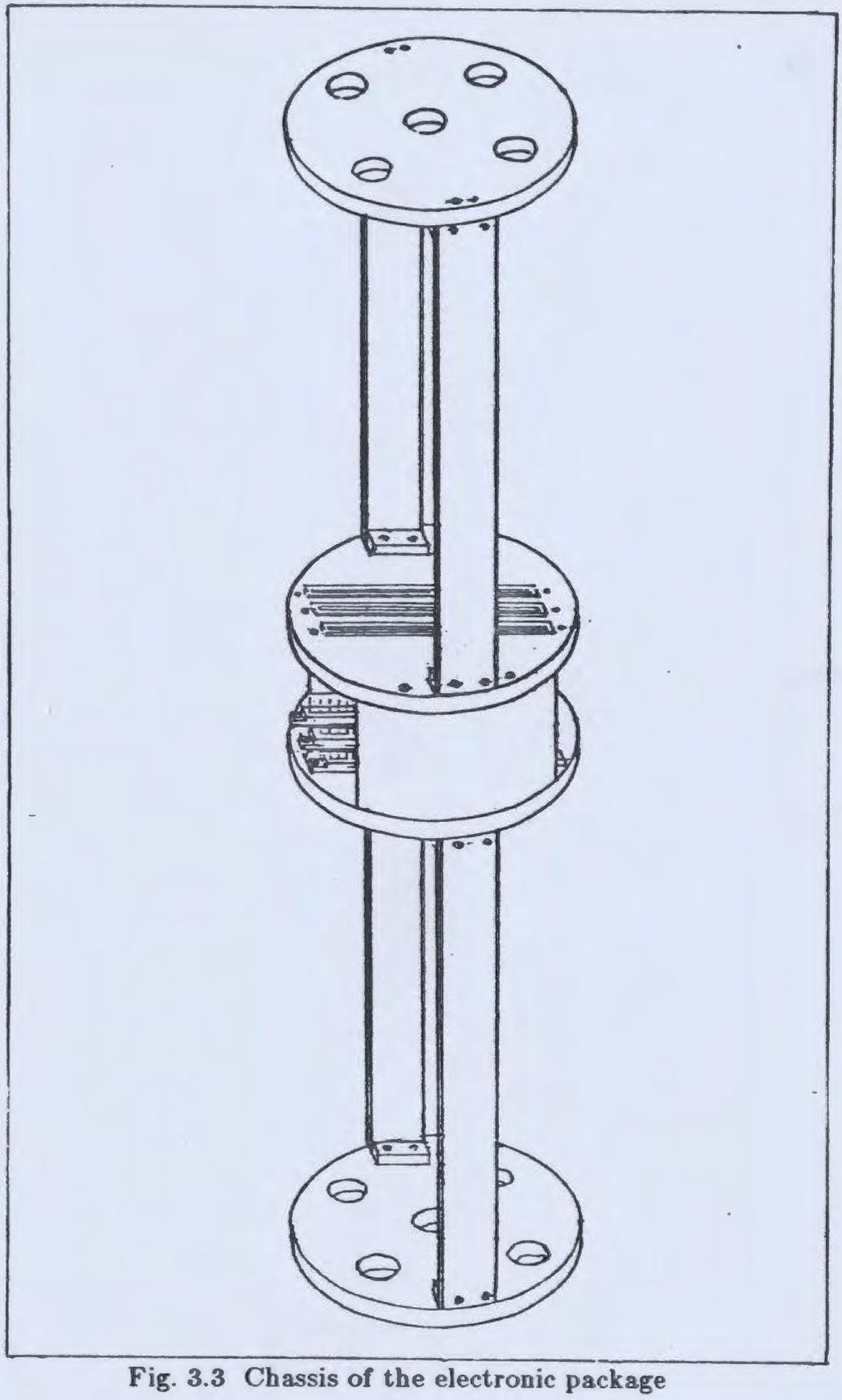


Fig. 3.3 Chassis of the electronic package

3.2.1 CDP18S601 Microboard Computer

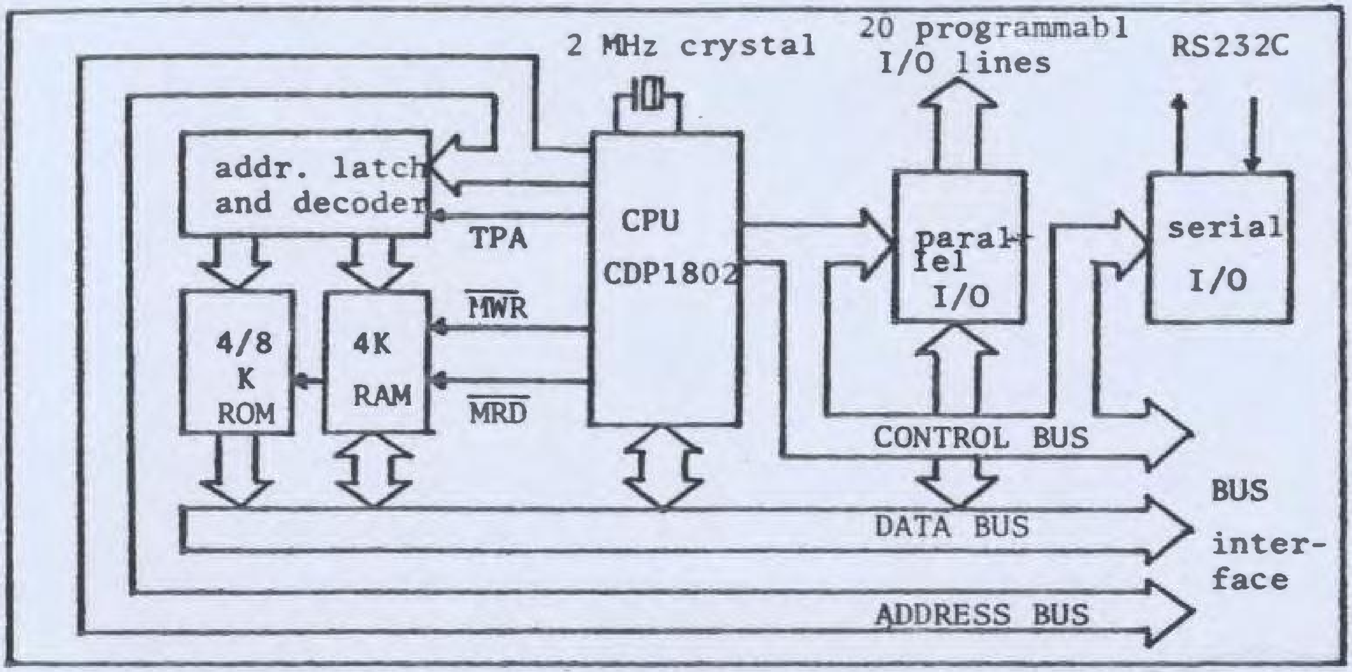


Fig. 3.4 Block diagram of CDP18S601

The main function of the four microboards are:

(1) **Microboard computer (CDP18S601)**

It contains a CDP1802 CPU, a 2 MHz clock, 4 kilobytes of static RAM, parallel I/O ports, a serial communication interface and expansion I/O interface. 4 to 8 kilobytes ROM or EPROM are user expandable. The block diagram is shown in figure 3.4.

(2) **Memory and tape I/O control (CDP18S652)**

It has a total of 44 kilobytes of ROM which can be equipped by user, 4 kilobytes of RAM and a tape I/O controller. The system monitor program UT62 is located on this board.

(3) **32-Kilobyte RAM (CDP18S629)**

It contains 32 kilobytes of static RAM which can be arranged on either high or low half of the 64 kilobytes of the microcomputer space. In the HF1601, it has been modified to accommodate a two kilobyte ROM at address 0000H-07FFH (H for hexadecimal number) for the heat flow measurement program HF1601P (Chapter 4).

(4) **8-Kilobyte RAM (CDP18S622)**

It is a battery backup static RAM. Three 180 mAH (milliampere-hour) nickel-cadium batteries provide backup power for data retention when system power is down.

3.2.2 Data Acquisition System Design

The block diagram of the data acquisition system of HF1601 is illustrated in Fig. 3.5. It contains four major blocks. They are: (1) transducers, multiplexers, amplifier (schematic diagram shown in Fig. 3.5a); (2) analog-to-digital convertor (Fig. 3.5b); (3) logic control (Fig. 3.5c); (4) motion sensor and master clock (Fig. 3.5d).

Note that the analog amplifier is placed after the analog multiplexer to eliminate the difference between the channels caused by different amplifiers (Appendix A).

The transducers of the data acquisition system, RT1 - RT14, are fourteen thermistors (YS1 30000 ohms at 25° C) having temperature-resistance characteristics given in Table 2.1.

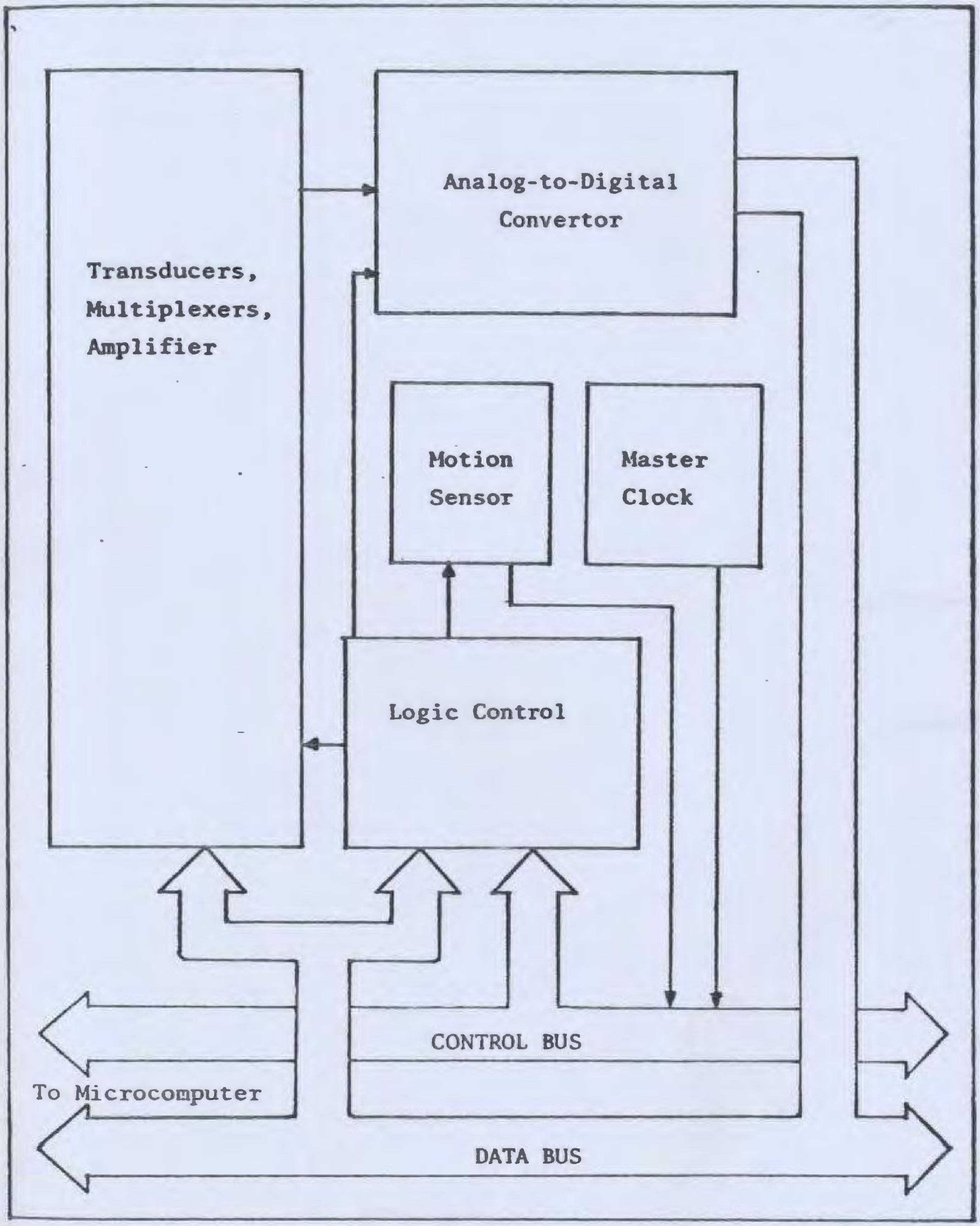


Fig. 3.5 Block diagram of the data acquisition system of HF1601

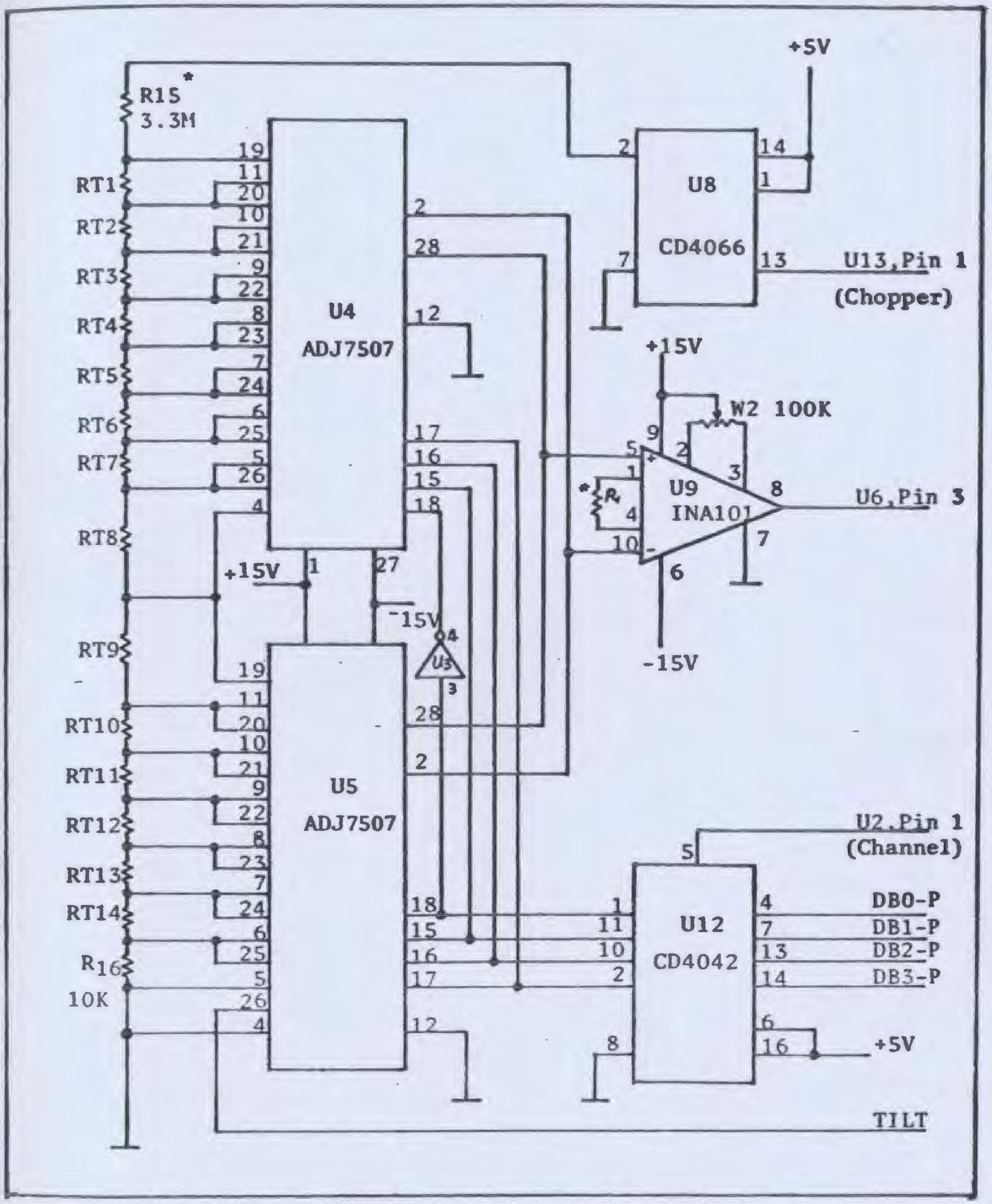


Fig. 3.5a Schematic diagram of the transducers, multiplexers and amplifier

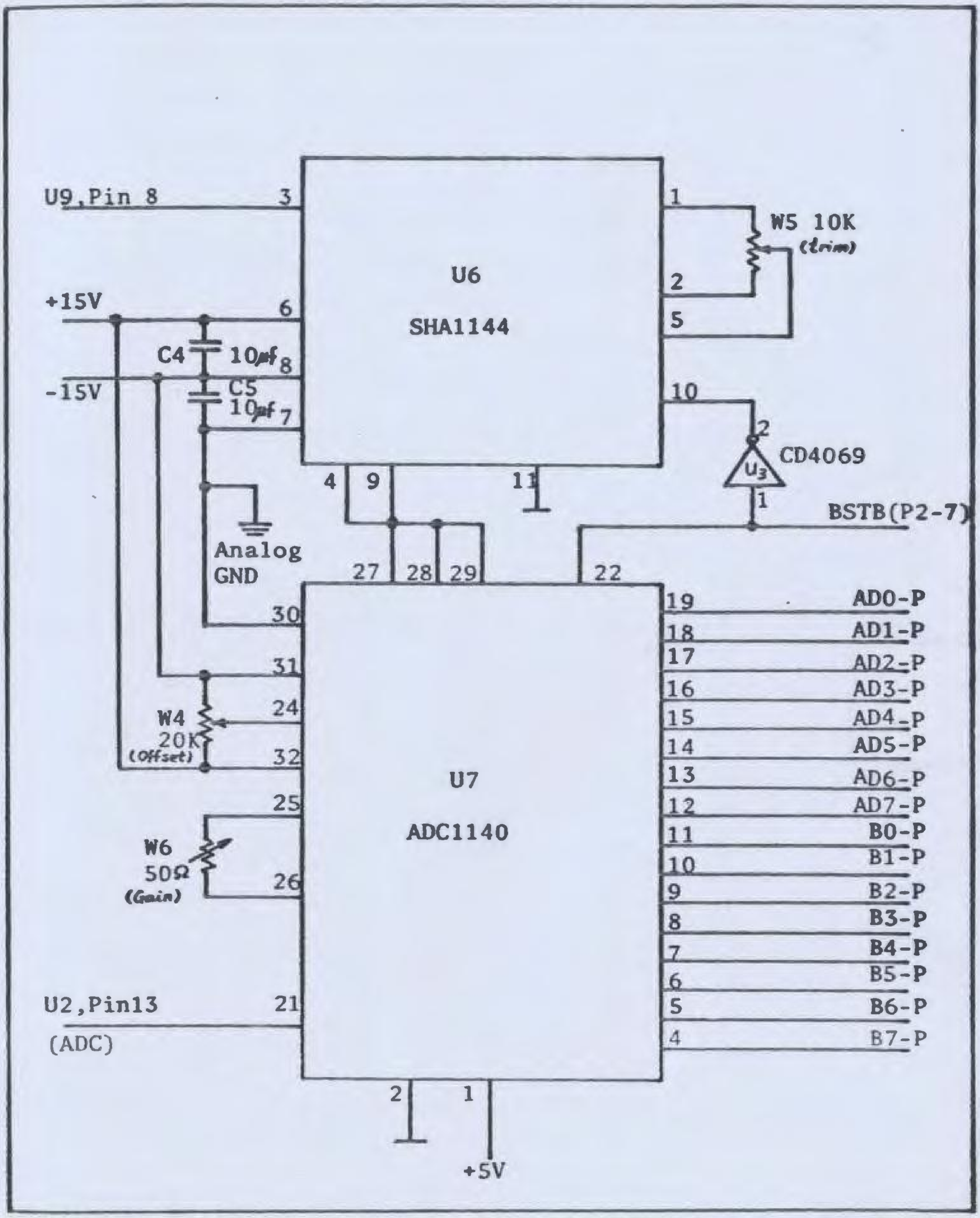


Fig. 3.5b Schematic diagram of the analog-to-digital convertor

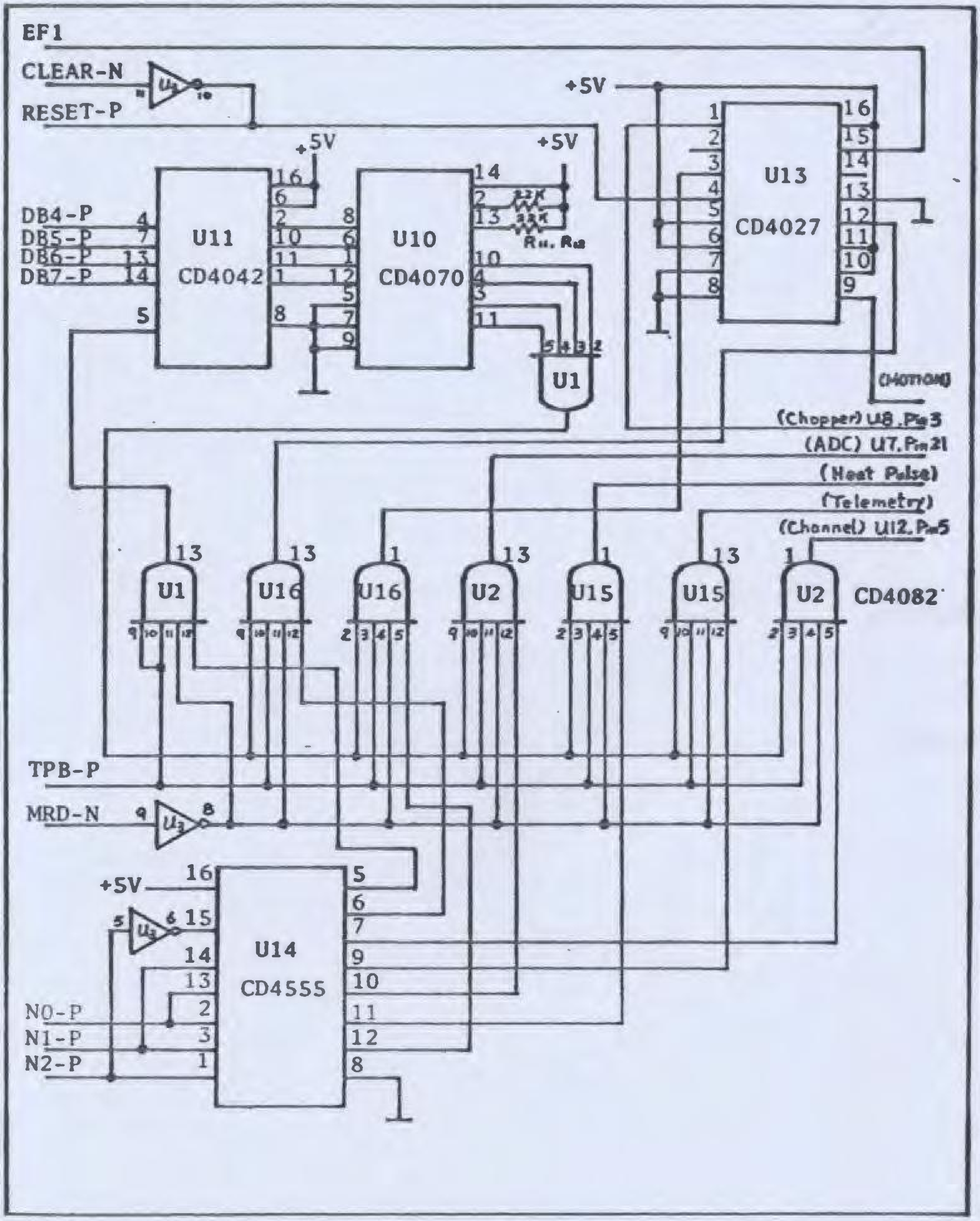


Fig. 3.5c Schematic diagram of the logic control

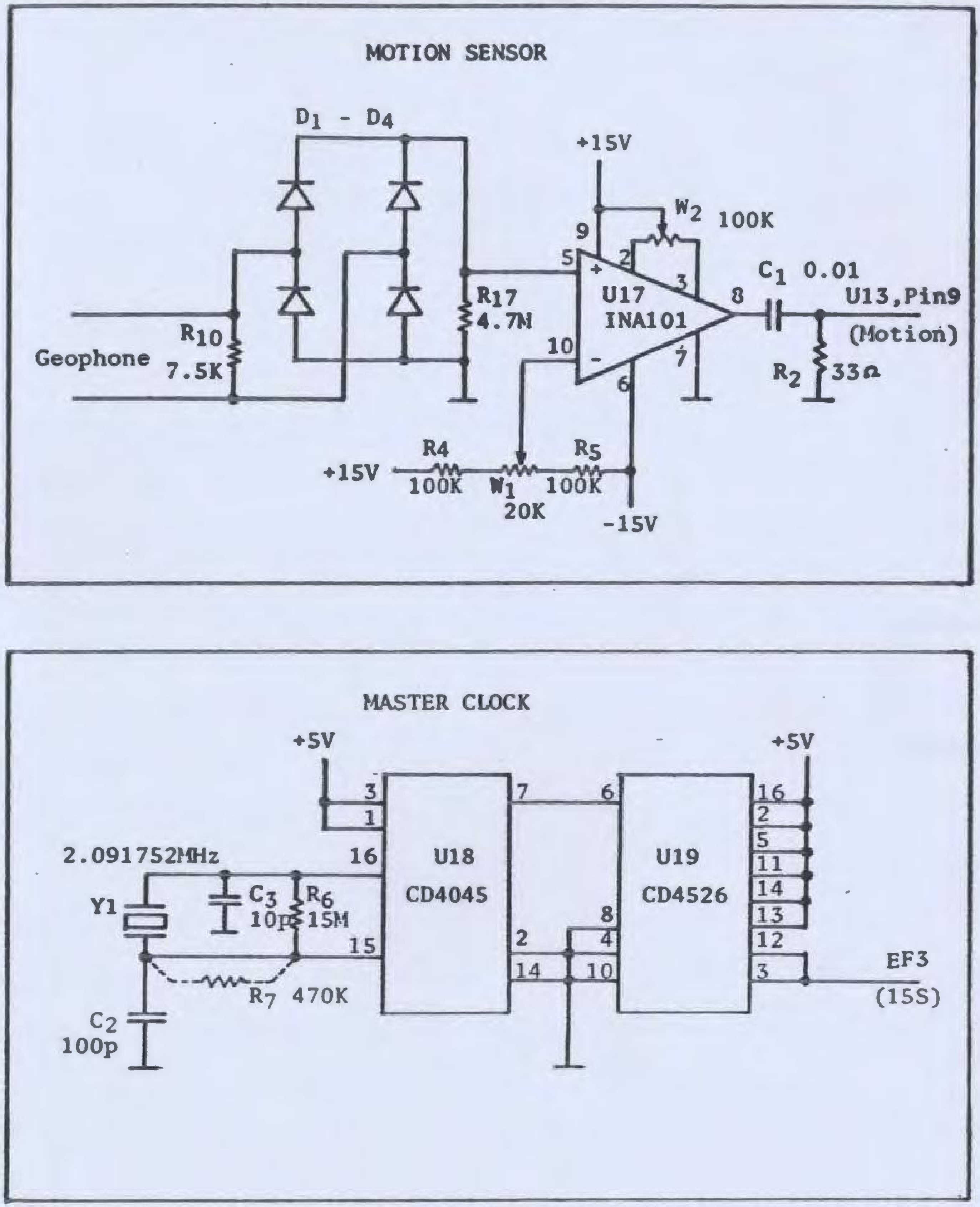


Fig. 3.5d Schematic diagram of the motion sensor and master clock

RT1 - RT14 and a reference resistor R16 are connected in series with a stablized power supply. Temperature variation at any thermistor will cause the corresponding resistance change; meanwhile the current in the series circuit will vary accordingly. To determine these temperature-resistance variations, the voltages across RT1 - RT14 and R16 (reference resistor), V_{RT1} - V_{RT14} and V_{R16}, are measured.

Analog multiplexers U4 and U5 select and switch these voltages one at a time to a high accuracy instrumentation amplifier U9. Since two points are required to measure each voltage drop in a series of resistors, U4 and U5 are CMOS analog multiplexers ADC7507 with two separate outputs to two of 16 inputs selected by three address lines and an "enable" line. Fig. 3.6 is the schematic diagram for ADC7507.

After amplification (U9) with a gain of 10, the output signal level is 2V to 3V within -4 to $+4°$C range. This signal is then routed to the sample and hold circuit U6 (SHA1144). Fig. 3.7 shows the basic structure of the circuit. IC1 is a follower to provide a low-impedance replica of the input. Q1 passes the signal through during "sample" and disconnects it during "hold". The signal presented when Q1 was OFF is held on capacitor C1. IC2 is a high-input-impedance follower, so that the capacitor 'leakage' current during 'hold' is minimized.

U7 is a 16-bit successive-approximation analog-to-digital converter ADC1140 having a 35 μs maximum conversion time. Successive-approximation ADC has good performance in accuracy and speed. The operation of the successive-approximation ADC is to successively determine the values of the various bits of the binary word representing the input voltage V_{in} starting with the MSB (most

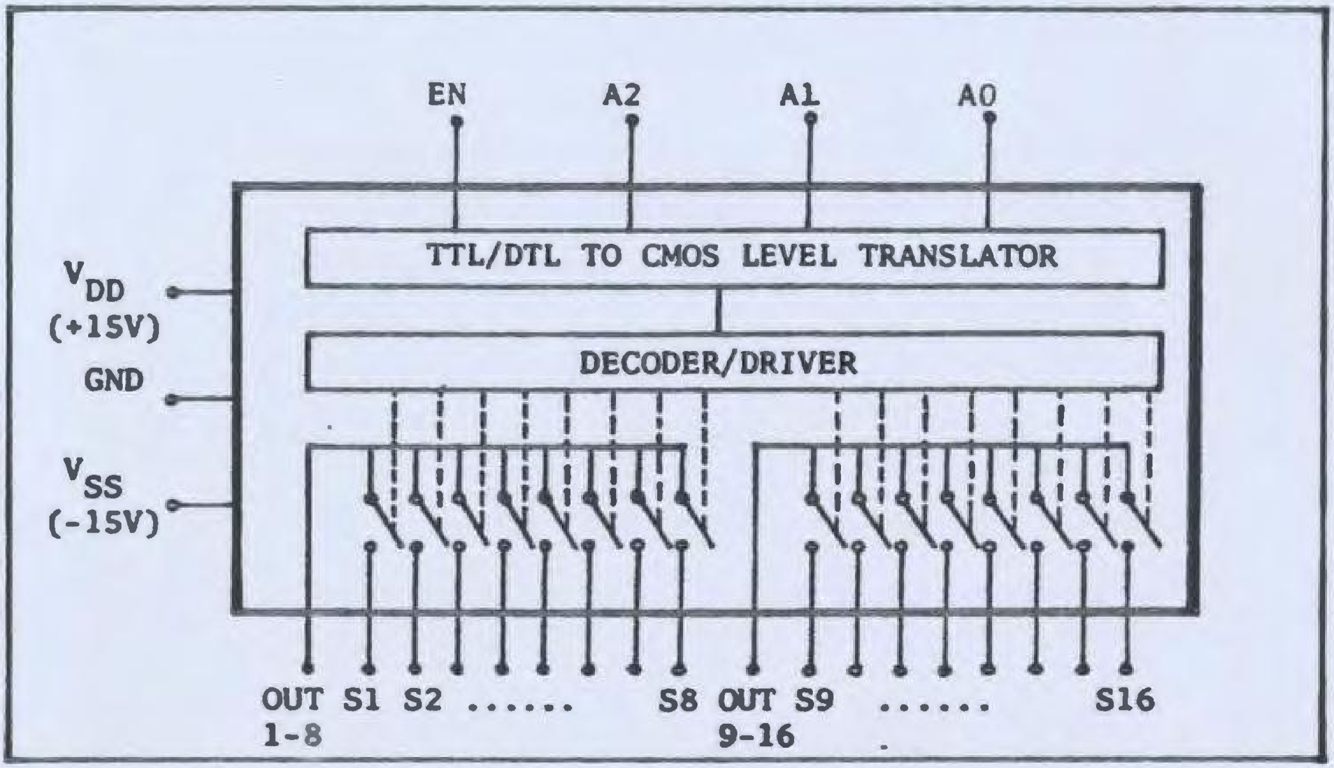


Fig. 3.6 ADC7507 analog multiplexer

significant bit). To this end, the expression for V_{in} can be written as

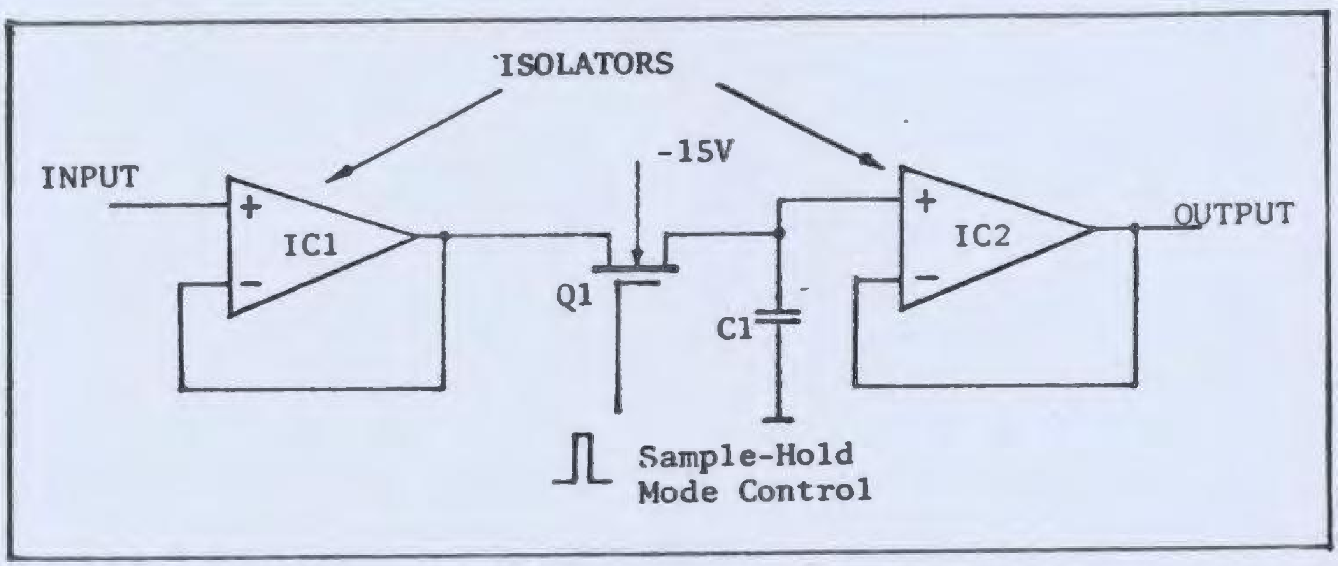


Fig. 3.7 Basic structure of the sample and hold circuit

$$V_{in} = V_{ref}\times(\frac{b_1}{2} + \frac{b_2}{2^2} + \cdots + \frac{b_n}{2^n}).$$

where V_{ref} is a reference voltage. The conversion starts with all the bits b_1 to b_n set to zero. Then, beginning with the MSB, each bit in turn is set provisionally to 1. The ADC has a D/A converter for generating weighted voltage, and a comparator for successively comparing V_{in} with the weighted voltage. If the D/A converter output does not exceed the input voltage, the bit is left as a 1; otherwise it is set back to 0. For an n-bit ADC, only n such steps are required. This process is equal to comparing the V_{in} successively with 1/2 V_{ref}, 1/4 V_{ref}, 1/8 V_{ref} ... $1/2^n$ V_{ref}. After the last comparison, it is valid that

$$V - V_{ref} \times(\frac{b_1}{2} + \frac{b_2}{2^2} + \cdots + \frac{b_n}{2^n}) < \frac{V_{ref}}{2^n}.$$

Thus, the sum of the weighted voltage obtained represents the nearest approximation of V_{in} taking into account the accuracy required.

In the HF1601, the output of this ADC is set in the range 0 to +5V using a straight-binary representation. The relation between analog input and digital output is shown in Table 3.1.

Table 3.1 ADC Input/Output Relationship

Analog Input	Digital Output
+4.999924V	1111111111111111
+2.500000V	1000000000000000
+1.250000V	0100000000000000
+0.625000V	0010000000000000
.	.
.	.
.	.
+0.000076V	0000000000000001
+00000000V	0000000000000000

U1, U2, U10, U11, U12, U13, U14, U15, U16 of Fig. 3.5 play the role of a 'control interface' in the data acquisition system. These various logic circuits are under the supervision of the microprocessor CDP1802. The purpose of the control interface is to provide the strobe pulses for initiating A/D conversion and for "chopping" the power supply to the thermistor string (explained later in this section), as well as for latching data used for selecting RT1 - RT14 and R16 by the multiplexers.

The strobe pulses are generated by the combination of hardware and software to reduce the volume of the instrument. The generation of these pulses takes advantage of the special function of the I/O instructions of CDP1802 microprocessor. The I/O byte transfer instructions of CDP1802 are one-byte instructions whose format is shown in Fig. 3.8. Two 4-bit hex digits contained in each instruction byte are designated as **I** and **N**, and are stored in **I** and **N** registers respectively. **I** specifies the instruction type. When $\mathbf{I} = 6$, the instructions are for input-output operations.

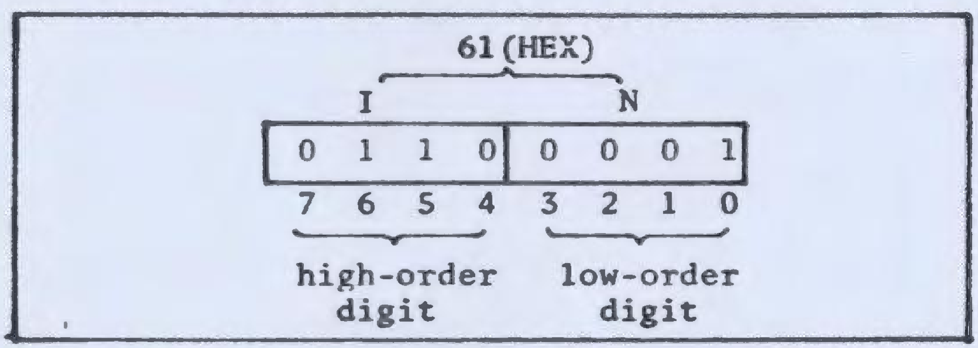


Fig. 3.8 One-byte Instruction Format

When $\mathbf{I} = 6$ and $\mathbf{N} = 1,2,3,4,5,6$ or 7, the memory byte addressed by R(X) is placed on the data bus. The three lower order bits of N are simultaneously sent from the CPU to the I/O system. These three N lines are low at all times except when an I/O instruction is being executed ($I = 6$). If the value of register X is set to the same value as program counter pointer P, then the byte immediately following the output instruction is read out as immediate data and available on the data bus.

In the data acquisition system of the probe, the N lines are decoded with MRD (memory read pulse, a low level on MRD indicates a memory read cycle) to generate strobe pulses as follows.

The data acquisition system is assigned a number '30' which can be altered by rearranging the quad-exclusive OR gate U12. Executing output instruction '61', the states of N0, N1, N2 lines (N=1, so N0=1,N1=0,N2=0) are decoded by U14, that is, a dual binary to 1 of 4 decoder/demultiplexer. Along with MRD and clock pulse TPB, AND gate U1 is activated and the immediate data that all other AND gates U2, U15, U16 are enabled. The instruction set 'E36130' ('E3' for setting main program counter = R3) can thus be regarded as an enable strobe for the whole data acquisition system. After the enable signal, output instruction '63' enables U12 which latches the low-order byte immediate data on the data bus to select one of the 14 thermistors and reference channels for the analog multiplexer. Output instruction '66' generates the pulse required by ADC as its conversion command. This series of instructions completes the process for an A/D conversion on a single channel.

To reduce the stochastic error, the data stored for every cycle of measurement for each channel (thermistor) are average values of eight individual measurements. Moreover, these individual measurements are the reading differences between power 'on' and 'off' to the thermistor string (Fig. 3.9).

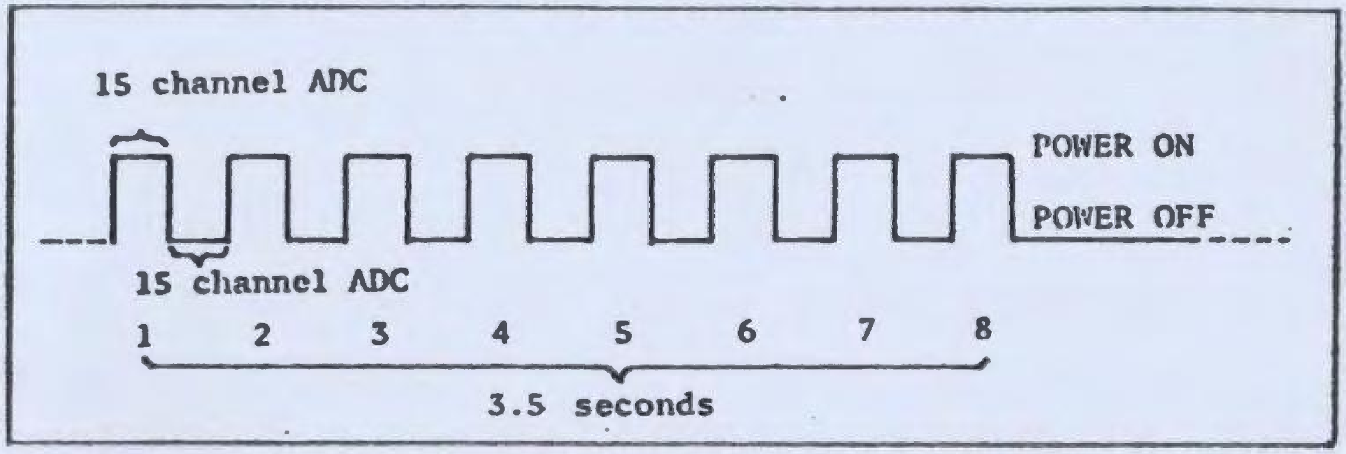


Fig. 3.9 Power supply to the thermistor string

To achieve this average measurement, an electronic switch is placed in series with the thermistors and power supply (Fig. 3.10). This switch, U8, is controlled by a J-K flip flop, U13. Every clock pulse to U13 toggles its output, thus switch U8 is being turned 'on' and 'off' according to U13's output being high or low. The clock pulse of U13 is generated by the same method as A/D conversion using the output instruction '64'.

The total time needed for taking readings for 15 channels with power being switched 'on' and 'off' 8 times is about 3.5 seconds.

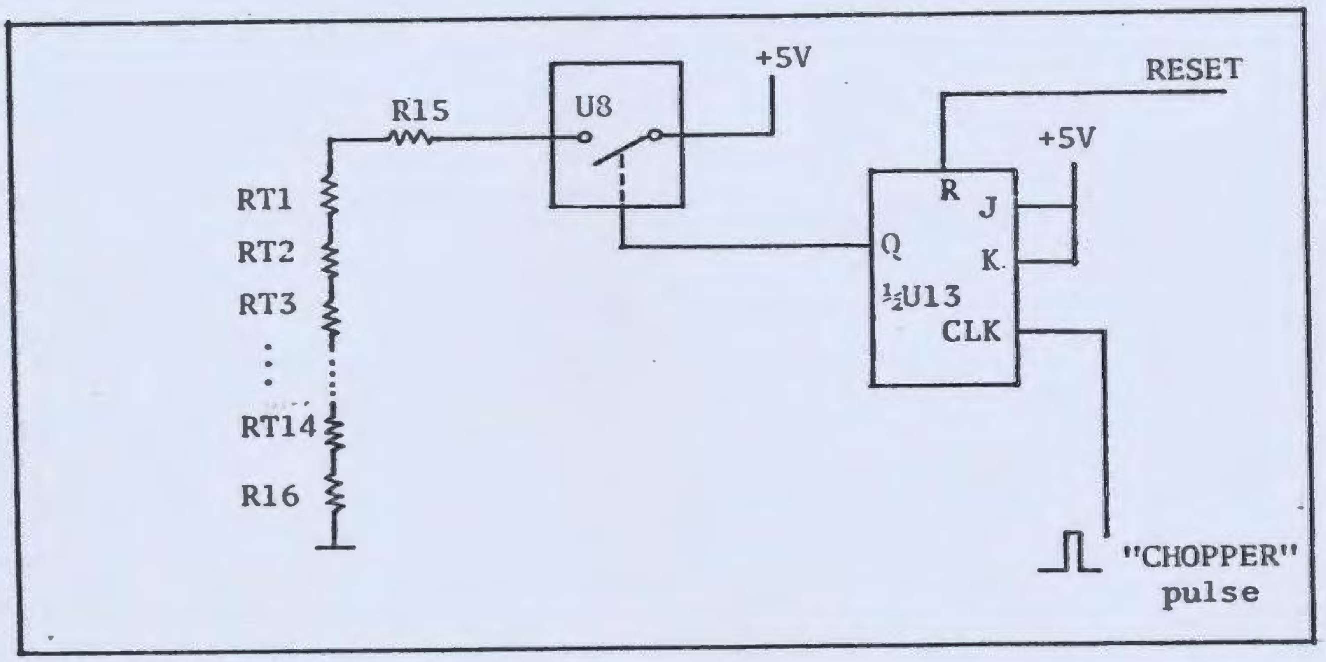


Fig. 3.10 Electronic switch and thermal string

3.2.3 Heat Pulse Generator and its Control

In the practice of heat flow measurement, temperature gradients are determined first after the probe penetrates the sediments. The time lapse for frictional heat to diminish is about 8 - 10 minutes. When the temperature gradient measurement is completed, the thermal conductivity determination proceeds by supplying a heat pulse to the probe and recording the heat pulse decay. It is desired that the heat pulse will not appear at other times. This timing of the heat pulse and the reseting of the probe when it penetrates the sediments is controlled by a 'motion sensor' provided by a geophone (Fig.3.5d). When the probe is suspended in the water before penetration, it jiggles and generates a signal that is rectified by D1 - D4 and amplified by U17. U17's output sets the J-K flip flop Q1 of U13 to which the 'External Flag' (EF1) of the microprocessor is connected. The microcomputer interrogates EF1 regularly so that any motion will be sensed. To reset the 'motion flag' EF1, a software pulse is sent to the 'reset' line of the J-K flip flop. The output instruction for this purpose is '62'. The sensitivity of the motion sensor can be adjusted by W1.

U18 and U19 compose the real time clock. U18 is a CMOS 21-stage counter with its own clock. With a 2.097152 MHz crystal, the frequency of the output pulse is 1 Hz with pulse width of 30 ms. U19 is a CMOS programmable divide-by-n binary counter. In the HF1601 probe, the division factor is 15, so its output is one pulse per 15 seconds. This pulse is linked to EF3 of the microprocessor as a master clock for the instrument.

The heat pulse for conductivity determination is supplied by a high power regulator that is illustrated in Fig. 3.11. S1 is a 15 ampere relay which is controlled by U1,U2 and by 'heat pulse' strobe generated by a software pulse '65'. W1 in Fig. 3.11 is the device for adjusting the voltage to achieve the desired accuracy.

3.3 Underwater Digital Acoustic Data Transmission

In the HF1601 probe, data are output through the serial port of the microcomputer in standard RS 232C protocol, coded by frequency shift keying (FSK) modulation and emitted by a hydrophone. The signal is received by the ship, demodulated and fed to a serial I/O port of a shipboard computer. Conceptually, this is similar to standard computer-to-computer communication using a telephone circuit. There are several practical differences between the standard

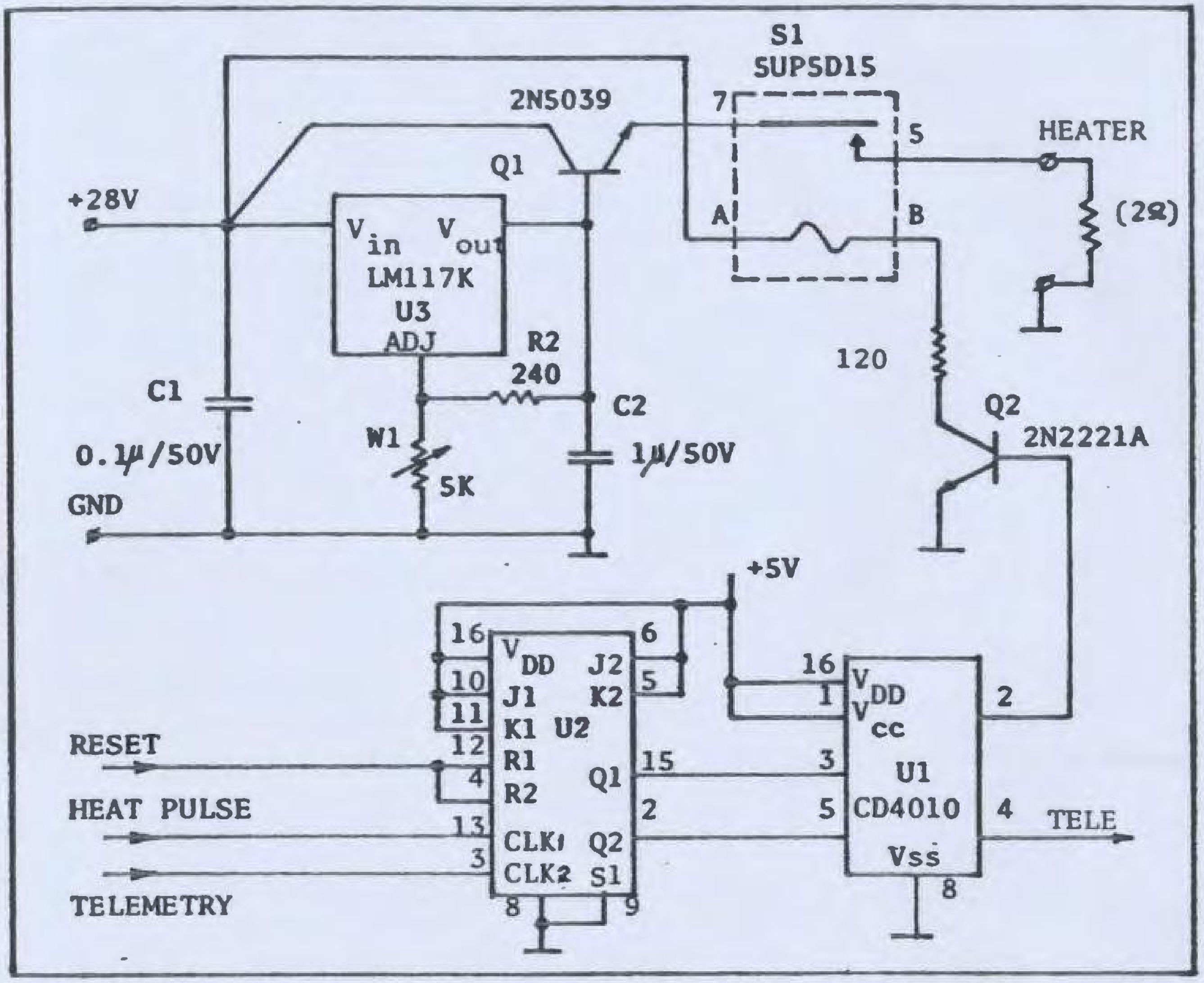


Fig. 3.11 Power supply for the heat pulse

electromagnetic scheme and this acoustic analogue. These may be summarized in the choice of the FSK frequencies and the method of coupling the FSK modulator to the hydrophone.

Transmitter

Every 15 seconds, a new data set is first stored in RAM then coded by FSK modulation and emitted by hydrophone. The frequency of FSK modulation depends upon the specific hydrophone used and its frequency response and the frequency separation from the ship's sounder. The telemetry circuit described here has 8 to 9 KHz FSK modulation (8 KHz for logic 1 and 9 KHz for 0) since the ship's transducer works at 12 KHz and the hydrophone chosen for the probe has a low cut-off frequency of 6 KHz and a relatively flat response to over 40 KHz. The frequency range of the FSK thus can be 6 KHz to less than 12 KHz. Considering the fact that the logarithmic attenuation of the transmission signal increases psuedo-linearly with increasing frequency, frequencies above 12 KHz are not considered and 8 KHz and 9 KHz are chosen.

Fig. 3.12 illustrates the schematic diagram of the transmission circuit which is designed about a 555 timer. IC1 cuts off the negative part of the input RS 232C coded data. The 555's frequency is set by RA, RB, C and by the voltage at pin 5 as well. For 0V at pin 5, the frequency f is

$$f = \frac{1.44}{(R_A + 2R_B)\ C}$$

W2 trims the frequency and W1 adjusts the modulation rate (frequency shifting).

The output of a 555 can be a square wave from pin 3 or a triangle wave from pin 6. This facilitates optimizing the wave form applied to the hydrophone, one of the important facts controlling the efficiency of electric to acoustic energy transfer.

IC3 and IC6 amplify the FSK signal and supply 15 to 20 W to the hydrophone via a transformer, T_1, which raises the output level to 200 - 400 V (peak-to-peak). Transistor Q1 functions as a switch that is controlled by microcomputer generated strobes "Tele" and "Reset", thus allowing telemetry to be turned "off"

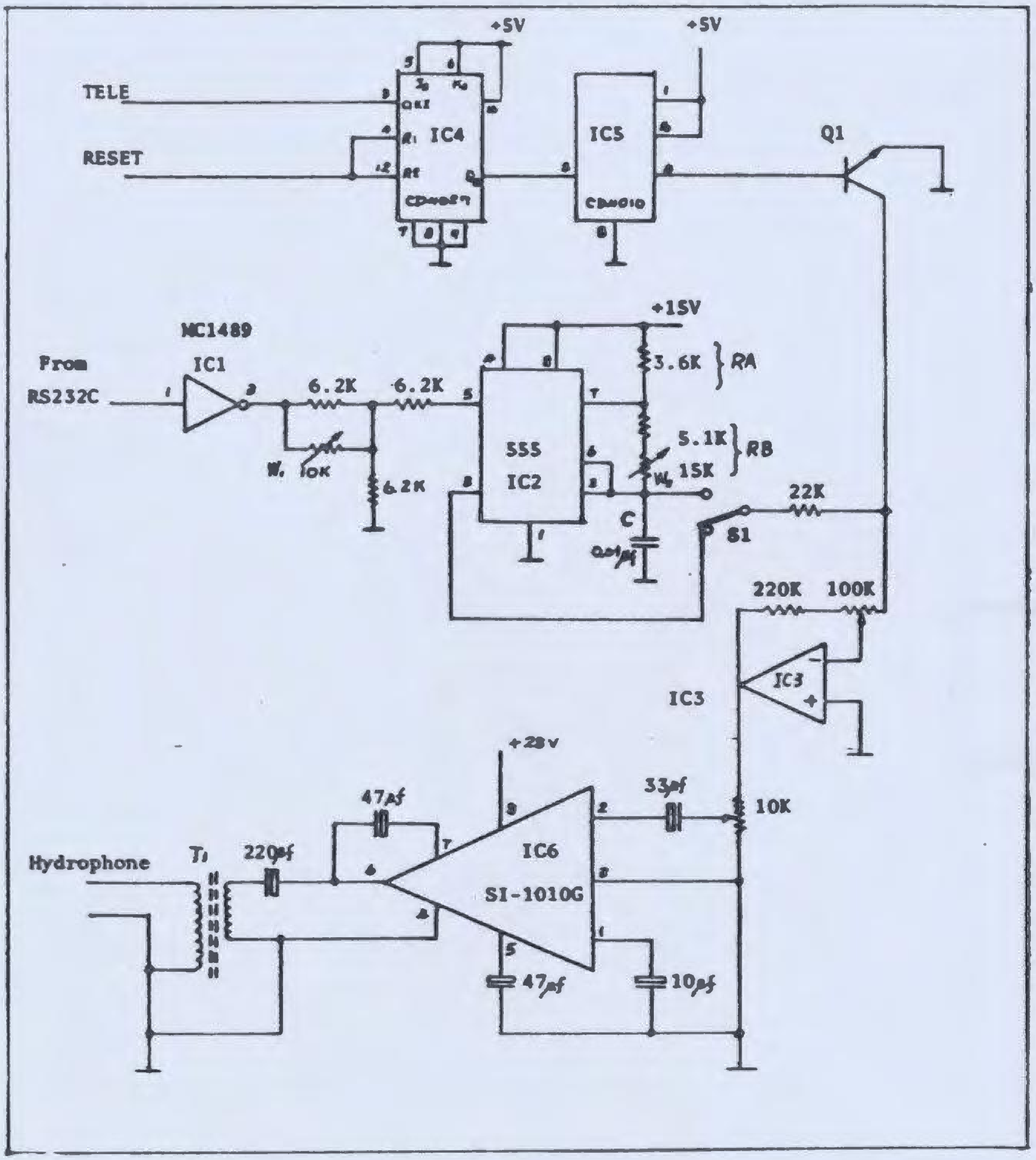


Fig. 3.12 Modulator for underwater digital transmission

and "on" as the program demands.

One point should be emphasized in the design of underwater acoustic telemetry circuit: the efficiency of the power conversion from electric to acoustic in the modulator is the key to long distance acoustic transmission. The power transfer is accomplished by the transformer T_1. It is a ferrite core transformer with the hysteresis characteristics that the signal is distorted when the ferrite core reaches magnetic flux saturation. Therefore, the output of the acoustic wave form could be quite different from the electric signal at the input side of the transformer (the output of IC6 in Fig. 3.12). A pure sine wave input signal may not be output as a sine wave, but may have harmonic distortion. On the contrary, an almost pure sine wave may be created at the output of the transformer even if the input signal has a complex frequency spectrum. In this perspective, a ferrite core transformer performs two functions: a voltage transformer and a filter.

A specially designed ferrite core transformer, therefore, achieves two goals in the modulator circuit:

(1) To create a signal with a peak-to-peak voltage as high as 200V to 400V. Since the hydrophone has a very high impedance, the output acoustic power is mainly determined by the voltage applied to it.

(2) To filter out the high harmonics of the electric signal in order to create as pure as possible a sine wave (8 KHz and 9 KHz)

The mathematics that are involved in the design are complicated and often not helpful, since the characteristics of the ferrite cores are usually not accurately known. In practice, a better result is achieved empirically by trial and error. To

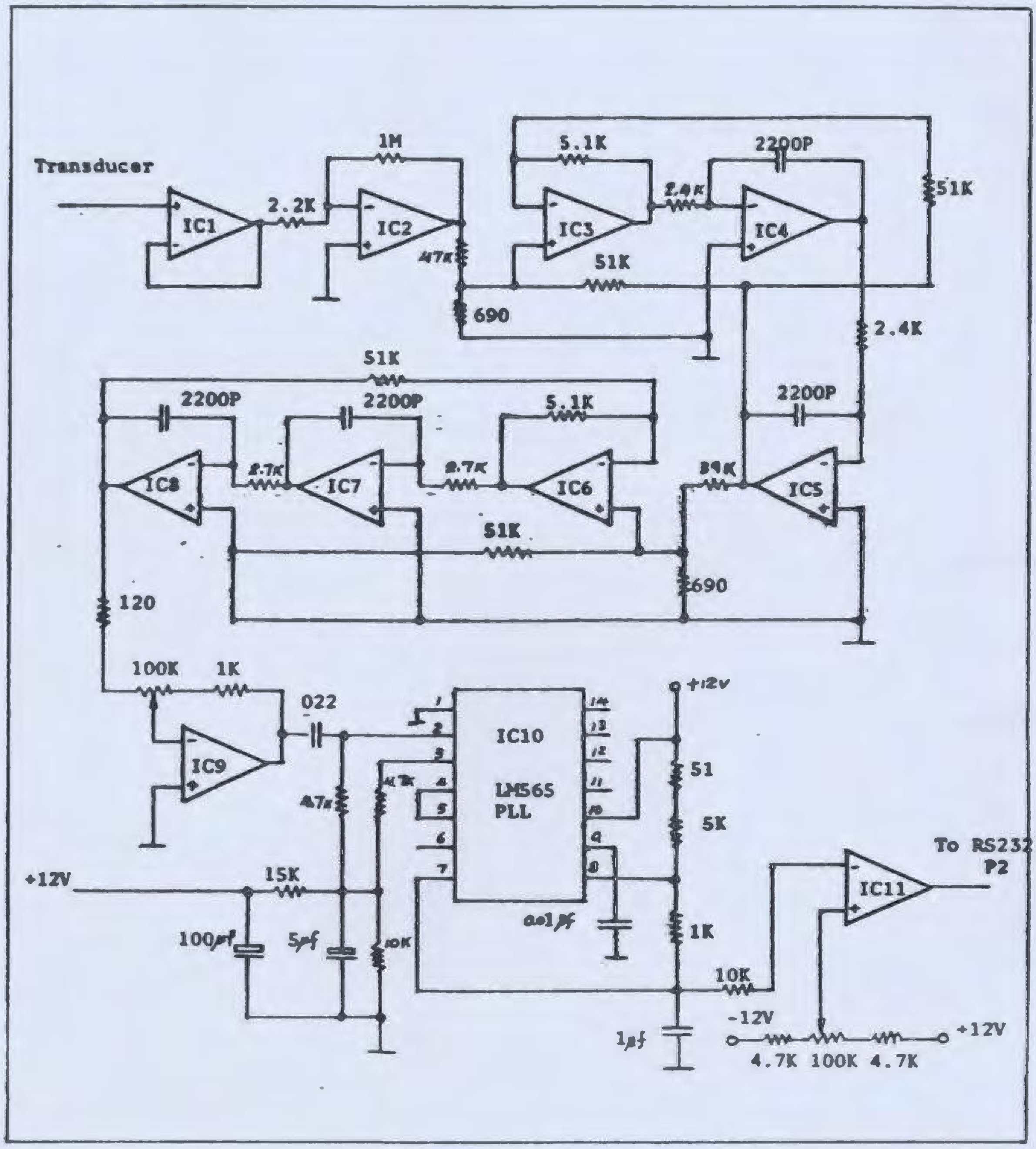


Fig. 3.13 Demodulator for underwater digital transmission

reduce the number of times of trial, a "optimum seeking method" is helpful: estimate the upper and lower limits for the coil turns of the original and secondary windings. As a transformer, these limits are also constrained by the quality factor (by the wire diameter) and the size of the core. If the tests show the result favors the high limit, the low limit is revised as follows:

New low limit = old low limit + 0.382×(high limit - old low limit).

If the result instead favors the low limit, a new high limit is chosen as:

New high limit = low limit + 0.618×(old high limit - low limit).

Three or four times of repetition of this process is adequate to achieve a suitable result.

Receiver

The demodulator is illustrated in Fig. 3.13. The digital signal transmitted from ocean bottom is received by the ship's sounder. IC1 matches the high impedance of the crystal that has a output level of about 10 mV when the transmission is valid. IC2 amplifies the signal to 1V. IC3 through IC8 constitute a 4-pole Butterworth band-pass filter with a quality factor 25 and gain 1. The cutoff frequencies of the filter are 7900 and 9100 Hz (-3db). IC9 creates a gain that suits various water depths and other environment conditions. The demodulation of the FSK signal is accomplished in a phase lock loop IC10. Passing through a comparator IC11, the digital data are recovered.

The technique described here is useful in a variety of applications in marine geophysics, geology, ocean engineering and other fields of science and industry. The advantage of the design is that underwater digital acoustic transmission is achieved with low cost by using the standard RS 232C data transmission protocol. Thus, it facilitates digital communication and data processing using existing digital computer systems without any modifications in an oceanic environment. It is seen that an extension of the method to accommodate bidirectional communication is straightforward.

3.4 Tilt Sensor

The tilt sensing circuit is shown in Fig. 3.14. An angle measurement usually utilizes gravity as a reference, the most convenient tilt sensor is the pendulum. In the HF1601 heat probe, two electrolytic pendulums are used as the gravity reference. Unlike the mechanical pendulum, the electrolytic pendulum has ultra long life, low power consumption and small size. The disadvantage of this pendulum is its slow responding speed.

In Fig. 3.14, two pendulums P_1 and P_2 are mounted horizontally with their sensing axes mutually perpendicular. P_1 and W_1 form a bridge as do P_2 and W_2. The power supply to these bridges is the same as that to the thermal string depicted in Fig. 3.9. Any angle change of the sensor produces a voltage variation of the bridge's output. Instrumentational amplifiers IC1 and IC2 convert these differential signals into voltage signals to the ground across W_3 and W_4. At any moment, only one of the two signals passes electronic switch IC4, this is

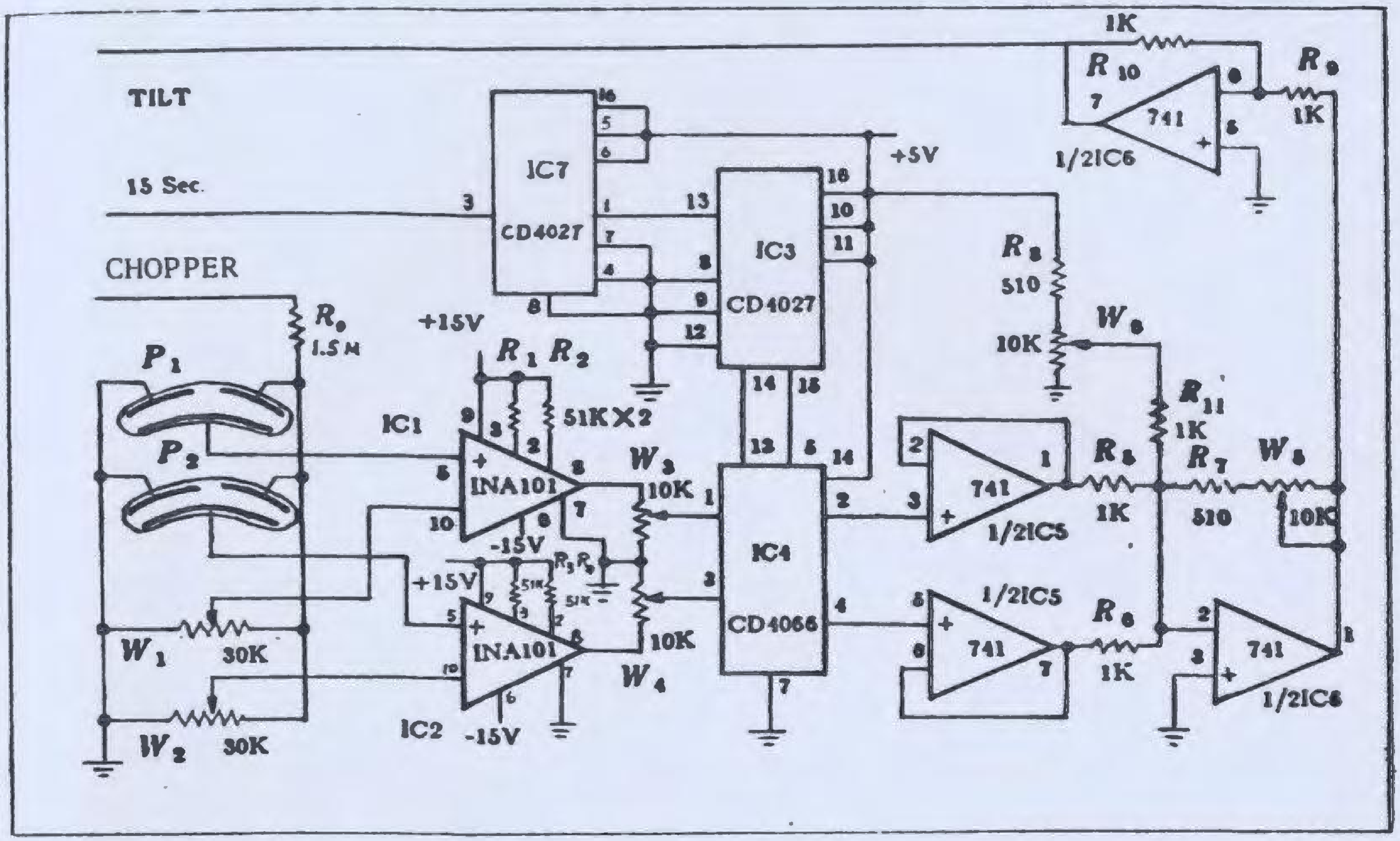


Fig. 3.14 Schematic Diagram of the Tilt Measuring Circuit

accomplished by IC3 and IC7. IC7 produces a 30 second strobe from the master clock and feeds it to IC3, that in turn selects the channel of IC4 one at a time. IC5 isolates the signals from IC4, thus reducing the influence of IC4's finite resistance when the switch is open. The signal is added with a constant voltage from W_6 which facilitates setting the readings of the tilt measurement to anywhere between 0000H-FFFFH. W_5 is for sensitivity adjustment.

This circuit works on a 30 second time base. The tilt measurement and real-time information are stored and telemetered alternately in a single channel, to be discussed in detail in Chapter 4. The data in the "tilt-time" channel appears in a format as follows: time, tilt1, time, tilt2, time, tilt1, time, ... The actual inclination of the probe is calculated from the readings of tilt1 and tilt2.

For summary, the electronic design of the heat probe HF1601 includes the design of the data acquisition system, heat pulse generator, motion sensor, tilt sensor and the underwater acoustic telemetry system. The design also includes the power supply to these circuits and the modification of the microboard computer to suite the special needs of the HF1601 probe electronics. The function of preventing the useless data from being stored in RAM is accomplished mainly by software that will be discussed in Chapter 4.

Chapter 4 Computer Program for Heat Flow Measurement

4.1 Introduction

The program for controlling HF1601 heat flow probe is named HF1601P and is written in assembly language to enhance operating efficiency and memory utilization.

The program is able to fulfill the following tasks:

(1) For the determination of the geothermal gradient, it measures the resistances of 14 thermistors and a reference resistor and stores these data in the microcomputer's internal memory;

(2) Repeats step (1) every specified time interval (e.g. 15 sec.) until the frictional heat diminishes (e.g. 8 min.);

(3) For the determination of the thermal conductivity of sediments *in situ*, it enables a calibrated heat pulse;

(4) After the heat pulse, it measures and stores the data as (1) and (2).

(5) Along with the data, a real time clock value is stored;

(6) The tilt of the probe is measured and stored alternately with the time;

(7) It detects the vertical motion of the probe. Any movement of the probe indicates that the probe is in an unstable situation and the measurement should not be carried out and the process is restarted;

(8) To increase storage capability and to help speed up data processing, it stores only the data related to the thermal gradient and conductivity measurements plus some pre-penetration and post-pullout measurements. All other data are not stored (but are telemetered).

(9) To increase the accuracy and stability of the data, as stated in Chapter 3, the data stored for every single measurement of each channel are average values of eight individual measurements. Moreover, these individual measurements are the reading differences between power on and off.

(10) It establishes digital acoustic linkage of the data and other operating messages between the instrument and the ship. Data (including those which are discarded mentioned in (8)) are transmitted to the ship, displayed on the screen of the on-ship microcomputer and stored on disks. These data comprise real time, tilt, 14 channel thermistor readings and the reference resistor reading. All operating messages such as reset of the measurement caused by movement of the probe, the completion of thermal gradient and conductivity measurement and heat pulse are displayed and stored.

(11) To reduce the influence of the hydrophone signal, the acoustic transmission system is turned off within the working period of data acquisition.

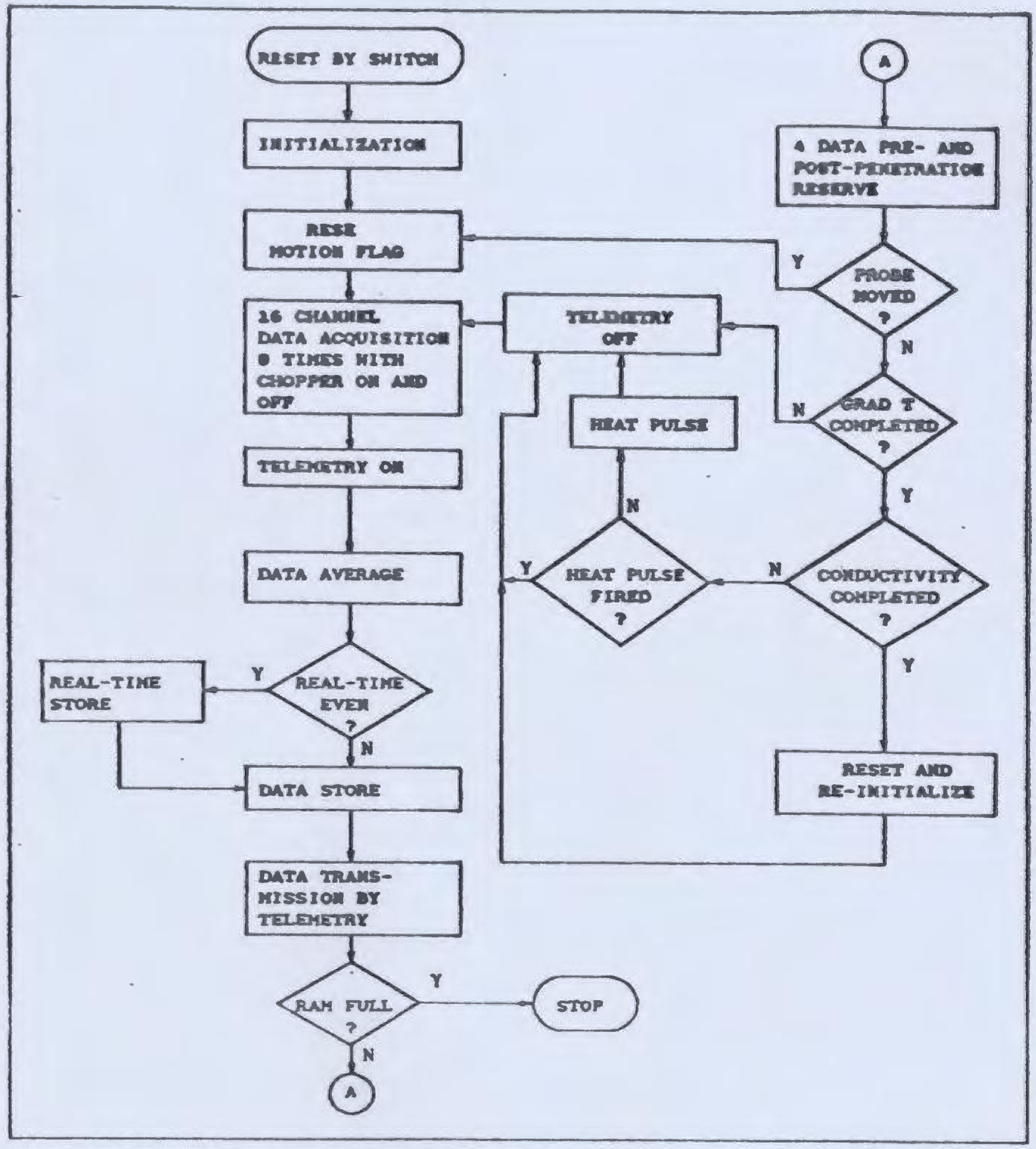


Fig 4.1 Simplified Flowchart of the HF1601P

4.2 The Flowchart of HF1601P Program

A simplified flowchart in Fig. 4.1 outlines the logic of HF1601P program designed to accomplish the tasks stated above.

Following are the explanations of the program.

(1) The instrument is reset by a Reset-Run switch. After resetting, the program starts at address 0000H (H indicates hexadecimal number).

(2) The initialization assigns some scratch-pad registers to certain tasks:

R0: CLOCK, to keep the real time value

R1: RAMPT, RAM pointer for data storage

R2: SP, stack pointer

R3: PC, program counter

R4: CALL, call routine counter

R5: RETN, RETURN routine counter subroutine service

R6: LINK, subroutine data link;

R7: CHANL, CHANL.0 (low byte of R7) for channel counter designated as "N"; CHANL.1 (high byte of R7) for 8 times counter, "M"

R8: MINUTE, MINUTE.0 for minute counter, "T"; MINUTE.1 for phase (grad T or conductivity K) flag, "K"

RC: DELAY, delay routine counter

RE: AUX, AUX.1 holds bit time constant

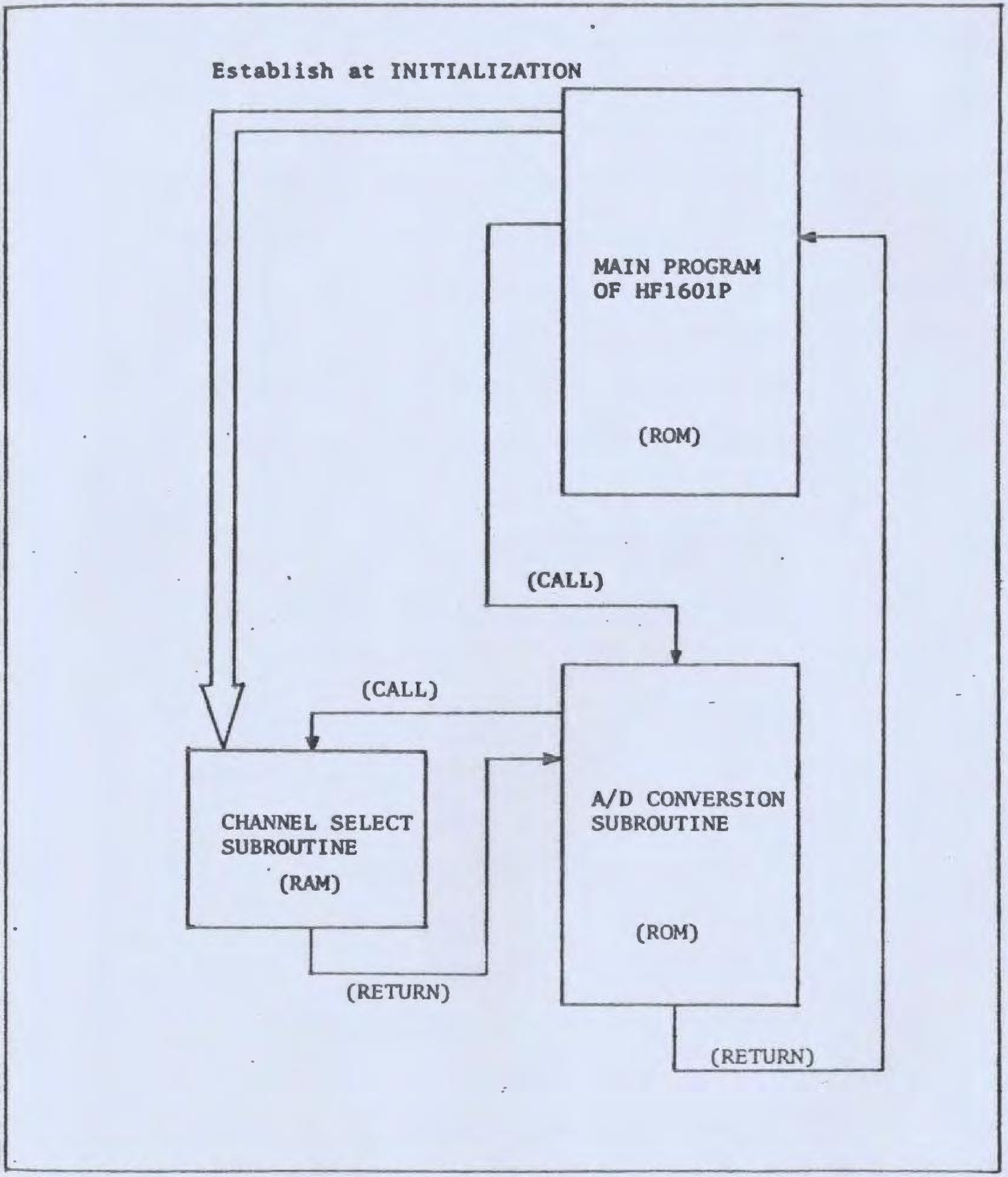


Fig 4.2 Implementation of RAM for channel selection

RD: MOTION, MOTION.0 for motion counter, "J".

Another task in the initialization is to store part of the data acquisition subroutine into RAM address 1300H-1307H as the passage of the parameter of the channel number. The channel number is put on the data bus as an immediate data along with the software pulse "channel selecting" E3613063xx, the last two hexdigits are the channel chosen for analog to digital conversion. This channel number has to be successively changed from 00H to 0FH since 16 channels are to be operated upon (14 thermistor 1 reference resistor and 1 tilt sensor). Thus, ROM cannot be used to store this channel number unless 16 similar subroutines are used (see Fig. 4.2).

(3) Data acquisition includes 16 channel A/D conversion with chopper (thermal-string-power switch) on and off. The flowchart is shown in Fig. 4.3.

(4) The program averages the data as stated in Chapter 3. The CDP1802 is an 8-bit microprocessor. For 16 bit data manipulation, it needs two operations for every datum. For each channel, there are 16 readings from data acquisition operations every 15 seconds. These 16 readings are 8 times chopper ON and 8 times chopper OFF ('chopper' is a symbolic name for the circuit of electronic switch in Fig. 3.10). For 16 channels, 512 bytes locations are needed in the buffer area to store the data temporarily. They are RAM locations 1000H to 1FFFH.

The average operation involves three subfunctions:

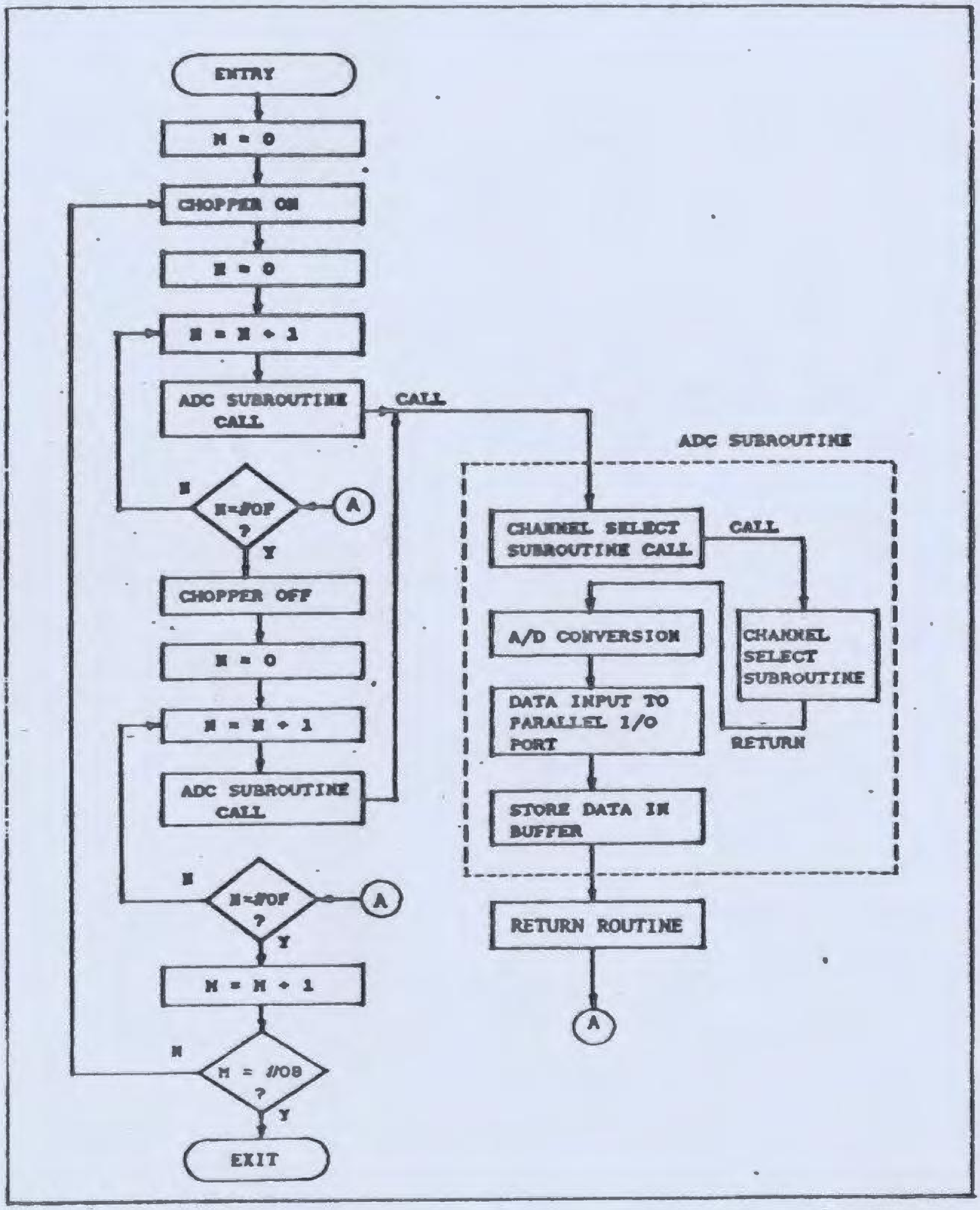


Fig. 4.3 Flowchart of the A/D conversion

(i) Subtract the reading chopper OFF from its corresponding reading of chopper ON; store the resulting difference in the buffer.

(ii) Add all the 8 resulting differences of each channel and store the sum in the buffer.

(iii) Divide the sum by 8 and store the quotient in the buffer.

The average operation takes another 256 bytes buffer locations. They are RAM 1200H to 12FFH.

The 16 channel readings with 8 times of chopper ON and chopper OFF are shown in Fig. 4.4.

In the figure, the first line is the data after averaging and it is stored in RAM as well as transmitted by telemetry. In this line, the first two digits are sequence number. The following 16 two-byte data are real-time (or tilt), reference, 14 thermistors, respectively. Starting from the second line, it shows the data buffer 1000H to 12FFH. The leftmost column is the RAM address location.

Note that, for the convenience of data processing, the order of the data are stored in reverse in the buffer. For example, the reading 9C6F is written as 6F9C for the datum in address 1000H and 1001H.

The data in 1000H to 101FH are 16 channel readings with chopper ON and 1020H to 103FH with chopper OFF. This process repeats 8 times up to 11FFH.

The flowchart of the average operation is shown in Fig. 4.5. The 8 data of reading difference of each channel are summed and stored at the location where the first data used to be, for example, 1200H to 1201H for

```
TEMP.
00 0000 0E4E 9A1D 9B6C 9BCF 9BD0 9A1D 9D71 9D39 9CCC 9A47 9C87 9902 9201
        969A 9BA5

1000   6F9C 7F96 F391 FB98 8A9C 4B9A CB9C 3B9D;
1010   739D 329A E79B D39B 639B C399 4F0E 0000;  > chopper on
                                                                > #1 reading
1020   CF00 0000 0000 0000 0000 0000 0000 0000;
1030   0000 0000 0000 0000 0000 0000 0000 0000;  > chopper off
1040   3B9C 9B96 0B92 DB98 779C 3F9A CB9C 339D;
1050   5F9D FF99 B39B B79B 879B BB9B 870E 0000;  > chopper on
                                                                > #2 reading
1060   1B00 0000 0000 0000 0000 0000 0000 0000;
1070   0000 0000 0000 0000 0000 0000 0000 0000;  > chopper off
1080   339C 8A96 C391 E398 779C 439A CB9C 3B9D;
1090   7B9D 2B9A EE9B E39B 539B B799 4B0E 0000;  > chopper on
                                                                > #3 reading
10A0   D300 0000 0000 0000 0000 0000 0000 0000;
10B0   0200 0000 0000 0000 0000 0000 0000 0000;  > chopper off
10C0   2B9C AA96 1A92 2B99 839C 439A CB9C 339D;
10D0   729D 0B9A AB9B BF9B 839B 239A 470E 0000;  > chopper on
                                                                > #4 reading
10E0   A300 0000 0000 0000 0000 0000 0000 0000;
10F0   0000 0000 0000 0000 0000 0000 0000 0000;  > chopper off
1100   939C 8B96 F291 EF98 839C 4A9A CB9C 3A9D;
1110   729D 239A EF9B E39B 639B C399 370E 0000;  > chopper on
                                                                > #5 reading
1120   C300 0000 0000 0000 0000 0000 0000 0000;
1130   0200 0000 0000 0000 0000 0000 0000 0000;  > chopper off
1140   279C A296 2392 1F99 9B9C 4F9A CA9C 439D;
1150   729D 139A B39B BF9B 739B 0B9A 470E 0000;  > chopper on
                                                                > #6 reading
1160   B700 0000 0000 0000 0000 0000 0000 0000;
1170   0000 0000 0000 0000 0000 0000 0000 0000;  > chopper off
1180   AB9C AA96 0392 0B99 879C 4B9A D39C 3B9D;
1190   729D 339A EB9B EF9B 6B9B B699 3F0E 0000;  > chopper on
                                                                > #7 reading
11A0   CF00 0000 0000 0000 0000 0000 0000 0000;
11B0   0300 0000 0000 0000 0000 0000 0000 0000;  > chopper off
11C0   1F9C 8B96 1B92 1A99 9B9C 4B9A CF9C 3B9D;
11D0   7F9D 1B9A C39B BB9B 639B 139A 4F0E 0000;  > chopper on
                                                                > #8 reading
11E0   B700 0000 0000 0000 0000 0000 0000 0000;
11F0   0000 0000 0000 0000 0000 0000 0000 0000;  > chopper off
1200   A59B 9A96 0192 0299 879C 479A CC9C 399D;
1210   719D 1D9A D09B CF9B 6C9B 1D9A 4E0E 0000;  > AVERAGE DATA
1220   209C 9B96 0B92 DB98 779C 3F9A CB9C 339D;
1230   5F9D FF99 B39B B79B 879B BB9B 870E 0000;  > #2 "on" - "off"
1240   609B AA96 C391 E398 779C 439A CB9C 3B9D;
1250   799D 2B9A EE9B E39B 539B B799 4B0E 0000;  > #3 "on" - "off"
1260   889B AA96 1A92 2B99 839C 439A CB9C 339D;
1270   739D 0B9A AB9B BF9B 839B 239A 470E 0000;  > #4 "on" - "off"
1280   D09B 8B96 F291 EF98 839C 4A9A CB9C 3A9D;
1290   709D 239A EF9B E39B 639B C399 370E 0000;  > #5 "on" - "off"
12A0   709B A296 2392 1F99 9B9C 4F9A CA9C 439D;
12B0   729D 139A B39B BF9B 739B 0B9A 470E 0000;  > #6 "on" - "off"
12C0   BC9B AA96 0392 0B99 879C 4B9A D39C 3B9D;
12D0   6F9D 639A ED9B EF9B 6B9B B699 3F0E 0000;  > #7 "on" - "off"
12E0   689B 8B96 1B92 1A99 9B9C 4B9A CF9C 3B9D;
12F0   7F9D 1D9A 839B BD9B 639B 139A 4F0E 0000   > #8 "on" - "off"
```

Fig. 4.4 Data buffer in RAM 1000H-12FFH

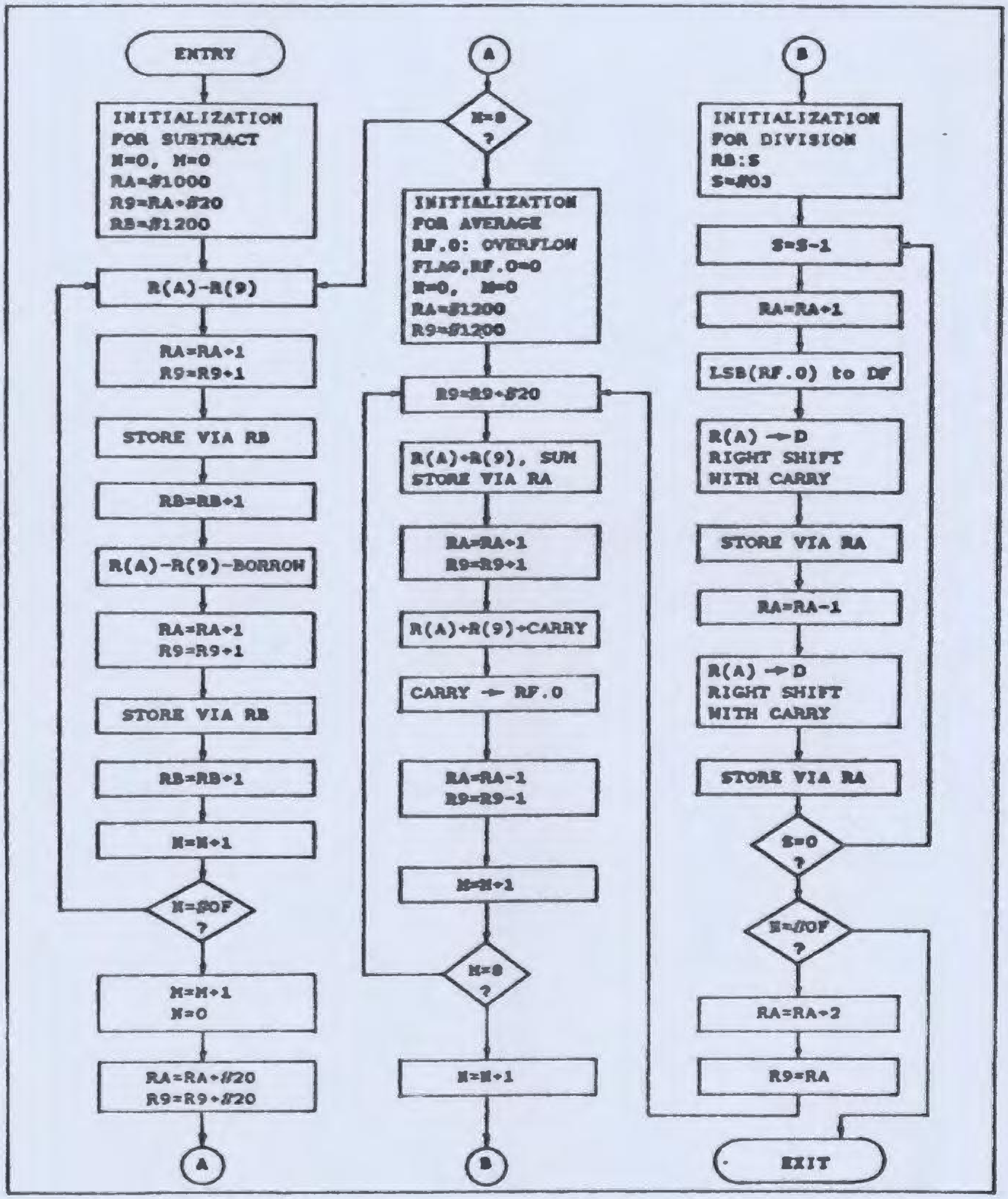


Fig. 4.5 Flowchart for data averaging

channel 16. The carry (overflow) is stored in a temporary overflow flag RF.0. The summation is then to be right shifted with carry three times, which is an operation for dividing by 8 in binary arithmetic.

(5) The program stores the real-time value and tilt value. The REAL-TIME and TILT data share one channel, because both of them are less important than temperature readings and vary more systematically. The microprocessor interrogates the real-time clock regularly and stores the value in R0. When the real-time reading is an even number, the program puts it into channel 1 to replace the tilt reading. When it is an odd number, the tilt reading is left untouched.

(6) Data Store in RAM. Data in buffer location 1200H to 121FH are then the average readings of the respective 16 channels. They are stored in RAM via RAM pointer R1. The memory map of the HF1601 probe is shown in Fig. 4.6.

The memory locations for data storage are 1400H to 7FFFH and D000H to FFFFH. With heat flow measurement going on, these memory locations are successively filled. The program stops when memory location FFFFH is filled with data.

(7) Four Pre-penetration Data and Post-pullout Data Reserve. To save the RAM storage spaces, the data that are irrelevant to the determination of thermal gradient and thermal conductivity are prevented from being stored in RAM. However, the four data that are taken just before penetration and the data measured when the probe is suspended in water before penetration for temperature stablizing are saved, thus some infor-

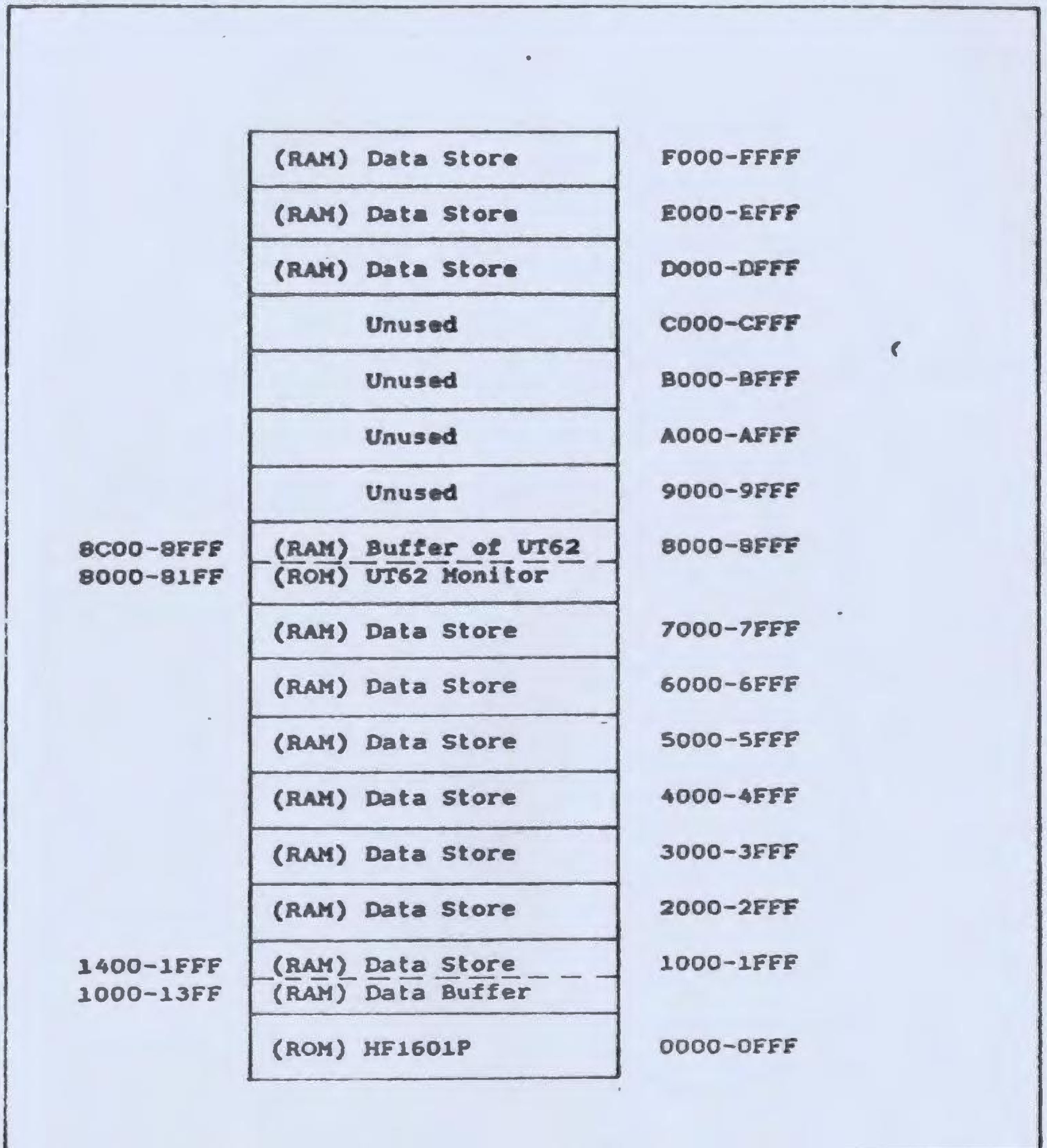


Fig. 4.6 Memory map of the HF1601 heat flow probe

mation such as bottom water temperature as well as the temperature in the "zero gradient zone" (discussed in Chapter 5) are stored. By the same token, the four data that are taken just after the probe is pulled from sediments when a measurement cycle has completed are also saved. This is shown in Fig. 4.7.

The program determines whether the probe is steady in the sediments or is hanging in the water by checking the motion flag. If the motion flag is set, the program not only resets its processing, but also stores the number to which the motion flag has been set. This number is stored in the motion counter "J" (RD). If the number is eight, the fourth last datum in the RAM (note: every datum has 16 channels' readings, i.e., 20H bytes) is discarded (overwritten by the last three data, i.e., the sixth datum is now number 5, the seventh is number 6, and so on). If the probe keeps jiggling, this process will go on such that only the last four data just before penetration are kept. If the probe stops jiggling for 15 seconds, the data will also be kept. The flowchart of four data pre-penetration and four data post-pullout is shown in Fig. 4.8.

(8) Underwater Digital Data Telemetry Digital data transmission by telemetry takes place when the 16 channels' readings are completed. The HF1601P uses subroutine TYPE2, TYPE6 and OSTRNG of UT62 monitor program for RS232C serial data communication. (The User Manual for CDP18S694 system: RCA MPM-293).

(9) Phase Detection. The program distinguishes the thermal gradient measurement and the conductivity measurement phases by checking the phase

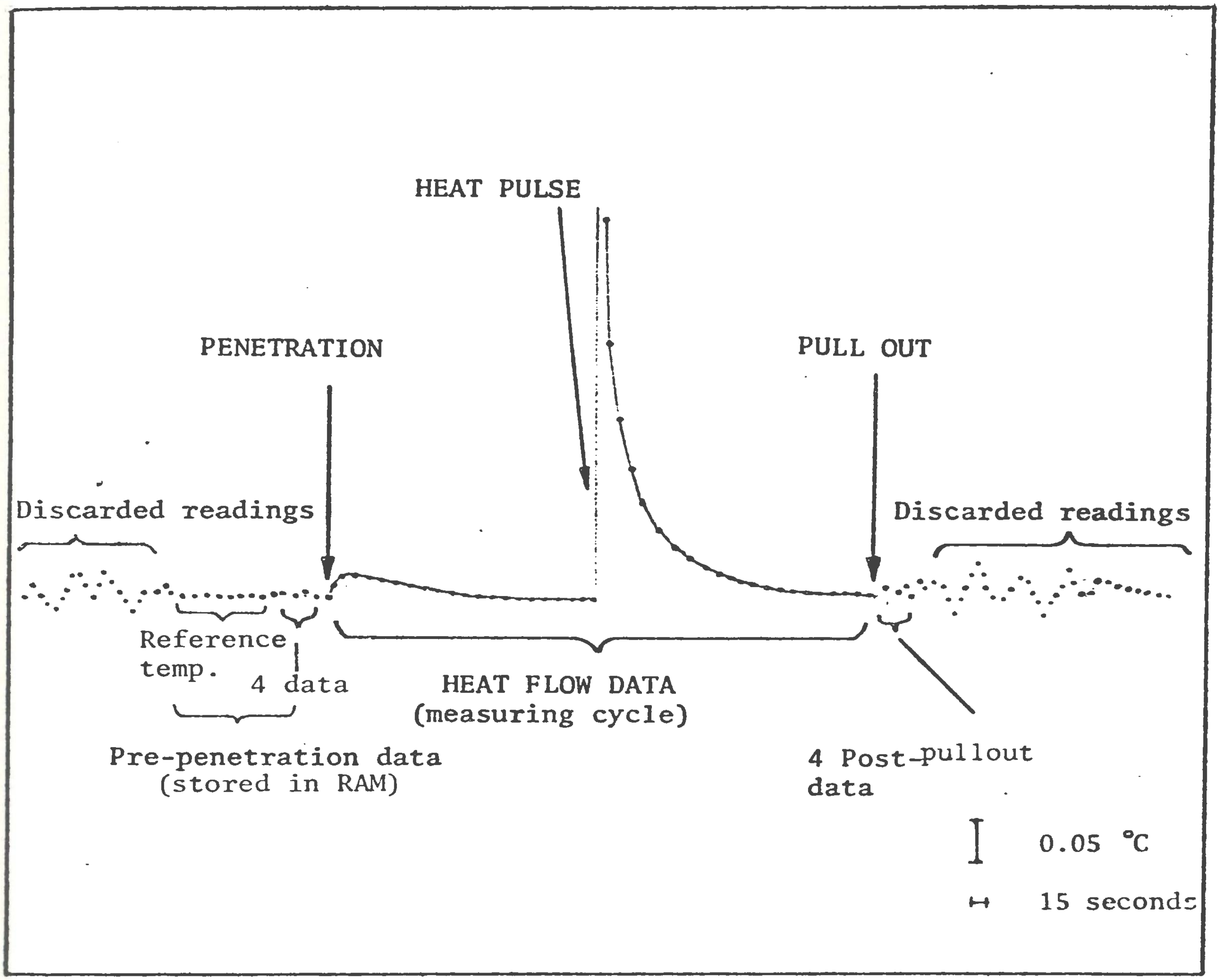


Fig. 4.7 Pre-penetration and Post-pullout data

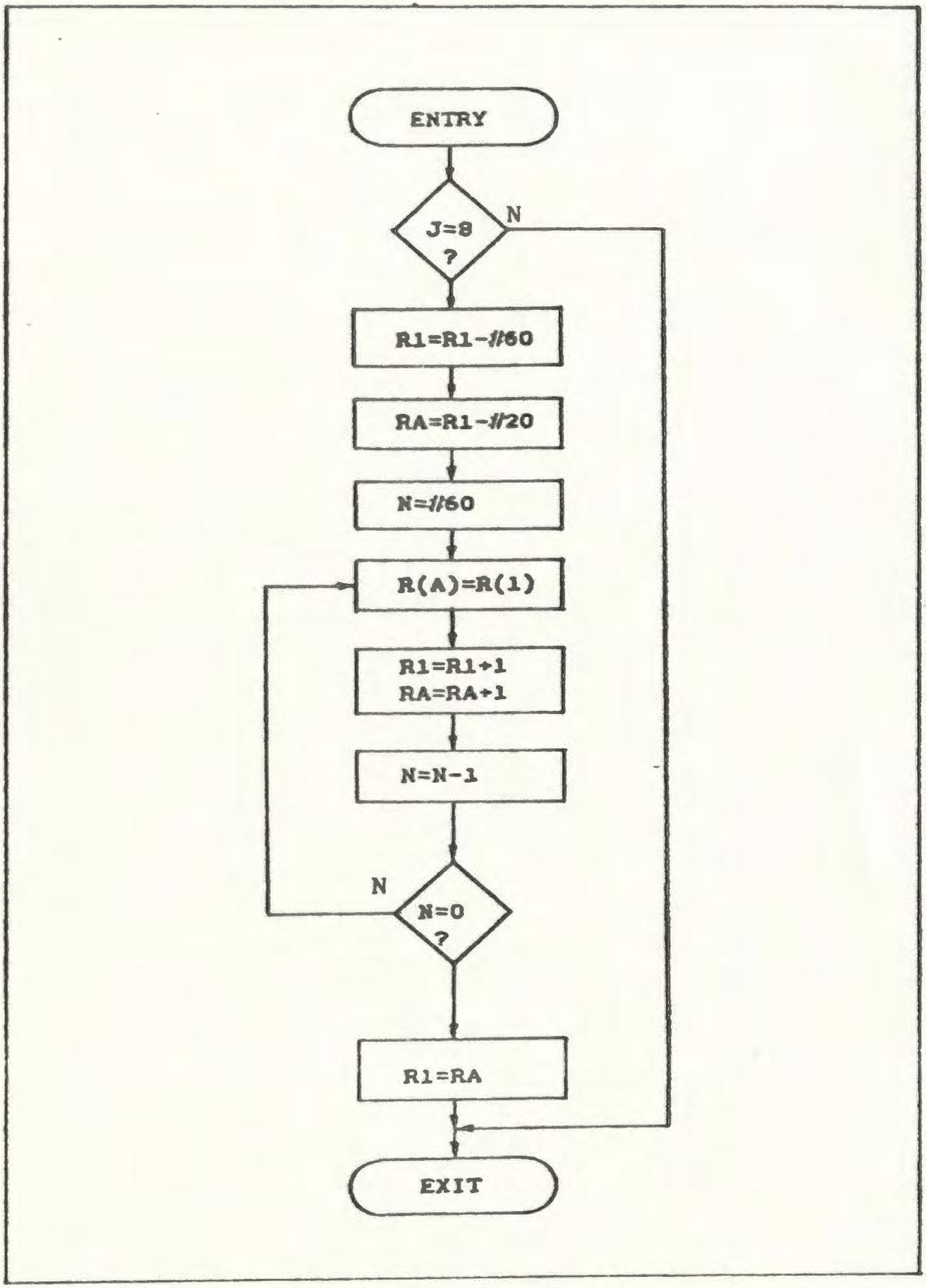


Fig 4.8 Flowchart of pre-penetration and post-pollout data storage

```
line number
   | time/tilt                    temperature
   ↓   ↓ reference
   00 00B4 0F18 778F 7689 7489 786D 7919 7558 7686 7C4E 7E3D 80C0 84C3 8C63 9C55 DCA4
   TEMP.
   00 0000 0F18 7792 7689 7485 786D 7918 7556 7684 7C4E 7E43 80C9 84C6 8C62 9C55 DCA0
   TEMP.
   00 00B6 0F1C 7791 7686 7484 786B 7917 7557 7683 7C4F 7E46 80C8 84C6 8C68 9C56 DC9F
   01 0000 0F1C 7792 7689 7483 7868 7915 7557 7684 7C50 7E42 80C9 84C5 8C62 9C5D DC9E
   02 00B8 0F1C 7795 7681 7483 7864 7916 7558 7685 7C51 7E43 80C9 84C6 8C62 9C54 DC9D
   03 0000 0F1E 7793 7682 7480 7865 7918 755A 7687 7C51 7E43 80C9 84C4 8C62 9C56 DC97
   04 00BA 0F1A 7796 7688 7481 7864 7917 755A 7685 7C54 7E44 80C9 84C7 8C61 9C5C DC97
   05 0000 0F1B 7794 7686 7485 7869 7913 7559 7687 7C53 7E45 80C4 84C9 8C61 9C5E DC9E
   06 00BC 0F1A 7792 7687 7482 7867 7913 7558 7684 7C54 7E45 80C7 84C6 8C62 9C55 DC9E
   07 0000 0F1C 7798 7689 7483 786A 7914 7558 7686 7C55 7E46 80C8 84C6 8C61 9C5F DC97
   08 00BE 0F1A 7795 7686 7485 7865 7915 7559 7685 7C56 7E47 80C2 84C6 8C65 9C5D DC95
   09 0000 0F1C 779A 7684 7486 7869 7914 7558 7683 7C56 7E49 80C6 84C7 8C64 9C5D DC94
   0A 00C0 0F1A 779E 768F 7487 7861 7912 7558 7687 7C56 7E4A 80C8 84C7 8C6F 9C5D DC8D
   0B 0000 0F1C 7798 7689 7482 7867 7912 7559 7689 7C59 7E4A 80C9 84C3 8C68 9C58 DC82
   0C 00C2 0F1B 7799 7683 7485 7869 7915 755A 768B 7C5B 7E4A 80CD 84C7 8C62 9C5D DC89
   0D 0000 0F1E 779C 7691 7487 786B 7915 755A 7687 7C59 7E4B 80CA 84C8 8C67 9C5D DC8B
   0E 00C4 0F1A 77A1 7694 74C0 786A 7917 7559 76BE 7C5A 7E4B 80D1 84C9 8C69 9C5B DC84
   0F 0000 0F1B 77A0 7697 74C2 7870 7919 7559 768B 7C5A 7E49 80D1 84C8 8C63 9C5A DC88
   10 00C6 0F1B 77A2 7691 74C2 7871 791B 7559 76BA 7C5A 7E49 80D5 84C0 8C67 9C5B DC81
   11 0000 0F1B 77A2 7694 74C1 7873 791C 755C 768C 7C5B 7E4D 80D4 84C1 8C65 9C59 DC8A
   12 00C8 0F1A 77A6 769C 74C2 7872 7922 755B 76C0 7C5F 7E4E 80D5 84CC 8C61 9C5A DC81
   13 0000 0F1C 77A1 7695 74C1 7872 7926 755C 76B4 7C62 7E50 80D7 84C2 8C66 9C5A DC83
   14 00CA 0F1F 77A2 769A 74C2 7874 7926 755C 76C0 7C62 7E51 80D8 84C8 8C62 9C5E DC82
   15 0000 0F1A 77A6 7698 74C1 7873 7927 755C 768D 7C62 7E54 80DD 84C7 8C66 9C58 DC85
   16 00CC 0F1A 77A2 7698 74C2 7872 7927 755B 76BE 7C63 7E53 80DE 84C1 8C69 9C59 DC84
   17 0000 0F1F 77A3 7697 74C3 7875 7929 755C 76BF 7C63 7E58 80E1 84C3 8C67 9C5A DC8F
   18 00CE 0F1C 77A1 7696 74C4 7876 7925 755D 76BE 7C64 7E54 80E1 84CE 8C6A 9C55 DC8C
   19 0000 0F1A 77A2 7698 74C2 7876 7927 755C 76C1 7C66 7E58 80E2 84C0 8C67 9C58 DC83
   1A 00D0 0F1A 77A3 7694 74C7 7873 7929 755D 76BE 7C66 7E53 80E6 84CA 8C69 9C56 DC85
   1B 0000 0F1E 77A3 7696 74C5 7875 7929 755D 76BF 7C67 7E55 80E4 84CA 8C65 9C58 DC83
   1C 00D2 0F1F 77A5 7697 74C3 7876 7928 755C 76C1 7C68 7E57 80E8 84CB 8C64 9C5A DC80
   1D 0000 0F1C 77A2 7692 74C1 7876 792A 755E 76BE 7C68 7E5A 80E3 84C3 8C65 9C5A DC82
   1E 00D4 0F1D 77A5 769A 74C3 7875 7928 7558 768B 7C68 7E58 80E8 84C8 8C62 9C59 DC83
   1F 0000 0F1C 77A3 7690 74C2 7873 7929 755E 76C1 7C69 7E58 80E7 84CC 8C6C 9C5C DC89
   TEMP.END
   20 00D6 0F1D 77A1 7692 74C3 7876 792A 755E 76C1 7C69 7E53 80E9 84C8 8C68 9C59 DC83
   21 0000 0F1A 77A0 7698 74C0 7875 792A 755E 76C2 7C66 7E59 80E3 84C8 8C66 9C5F DC80
   22 00D8 0F19 77A4 7695 74C2 7879 792A 7560 76C1 7C69 7E58 80E8 84C8 8C66 9C5F DC8E
   23 0000 0F1C 77A8 7696 74C1 7878 792A 755F 76C2 7C66 7E52 80E7 84C4 8C60 9C5E DC8C
   CONDUCTIVITY
   00 0000 0FED 6B6C 669F 5AC4 602D 662A 630A 691E 7A22 77A3 7D2D 7FCA 889E 964C C512
   01 00DC 0F68 6DD3 6E92 6713 6F35 6FE2 6A8D 700A 785E 7CCF 7F00 810C 8A6F 9954 C84A
```

Fig. 4.9 Displaying format on the ship's monitor

```
02 0000 0F51 7254 72A0 6DBE 7404 7440 7005 731D 7BB9 7D98 7FE9 82FF 8B8B 9B2D D156
03 00DE 0F3A 7478 7428 70C4 75C0 7610 7230 7469 7BCD 70A5 801F 83DA 8BFB 9BC6 D634
04 0000 0F2D 758E 74E9 7245 769C 7716 7349 7512 7BE5 7DD0 804B 843A 8C2D 9C0F DBB3
05 00E0 0F2A 7622 7555 730E 770A 7799 738B 7572 7BF5 7DE2 8060 8481 8C4B 9C2F DA15
06 0000 0F24 766D 758B 7370 773F 77D7 7430 75AA 7C14 7DF2 8072 847B 8C4B 9C27 DAA6
07 00E2 0F25 76A7 75A0 7385 7775 7819 7465 75D7 7C13 7E07 8088 8495 8C54 9C48 DB40
08 0000 0F27 76CA 75C9 73DC 778F 7839 74A2 75F8 7C0D 7DFE 8089 849A 8C55 9C50 DBA0
09 00E4 0F23 76DD 75D8 740D 779F 7850 749C 7604 7C19 7E05 808A 84A3 8C55 9C52 DBCD
0A 0000 0F1F 76F2 75F0 73F1 77C3 7847 7481 7614 791A 7E0A 8091 84A5 8C58 9C52 DBE8
0B 00E6 0F1E 7703 75F4 7419 77C5 7872 74BD 7621 7C1D 7E17 8093 84AC 8C5A 9C54 DC08
0C 0000 0F1F 7709 7604 742F 77DC 7882 74CF 762D 7C1E 7E16 8099 84AF 8C5B 9C56 DC1B
0D 00E8 0F1E 7710 760F 7436 77E6 7886 74DB 762D 7C20 7E0D 809B 84B3 8C5A 9C58 DC2D
0E 0000 0F1F 771E 7617 743C 77FE 7894 74DA 7639 7C20 7E1F 80A5 84B4 8C5C 9C59 DC3D
0F 00EA 0F1D 771F 761B 743D 77E7 7895 74DD 7642 7C2C 7E25 80A8 84B8 8C57 9C5B DC42
10 0000 0F1E 772F 7623 7446 77EA 789E 74E8 7648 7C2E 7E29 80AE 84B7 8C58 9C5E DC45
11 00EC 0F1A 772B 762E 7460 77EE 78AA 74EE 764F 7C35 7E29 80AD 84B3 8C5C 9C5F DC48
12 0000 0F1B 7740 7635 7461 7809 78B9 7508 765E 7C3B 7E44 80B7 84B5 8C65 9C5F DC53
13 00EE 0F1B 7749 7639 7463 780C 78B9 750F 7660 7C47 7E3A 80BB 84B5 8C6A 9C5E DC5E
14 0000 0F1B 7747 763E 7461 7804 78B4 7512 7665 7C48 7E36 80BE 84B4 8C68 9C60 DC62
15 00F0 0F1C 7750 7641 746A 7810 78BF 7515 766C 7C4A 7E37 80BB 84BA 8C65 9C63 DC66
16 0000 0F1A 7753 7645 7470 7818 78C3 7518 766F 7C4B 7E59 80BE 84BC 8C6D 9C65 DC63
17 00F2 0F19 7754 7649 7478 781D 78CC 751B 766F 7C4A 7E31 80BD 848E 8C62 9C66 DC65
18 0000 0F19 7756 764B 7476 781E 78C2 7523 7670 7C49 7E39 80BC 84BD 8C67 9C66 DC68
19 00F4 0F17 7757 764C 7475 781E 78C5 7525 7671 7C4C 7E5B 808F 84C0 8C63 9C67 DC66
1A 0000 0F16 7759 764C 7473 781F 78C5 7526 7672 7C4E 7E33 80C1 84C2 8C66 9C69 DC6A
1B 00F6 0F15 775A 764E 7478 781D 78C9 7527 7674 7C50 7E35 80B9 84C3 8C66 9C6A DC6E
1C 0000 0F15 775E 764F 7476 781F 78C6 7528 7676 7C52 7E34 80B9 84C2 8C68 9C68 DC6F
1D 00F8 0F15 7760 7652 7479 781E 78CC 7528 7676 7C50 7E3A 80BD 84C9 8C66 9C66 DC70
1E 0000 0F15 7762 7655 7479 781F 78CD 7529 7676 7C54 7E3A 80BE 84CD 8C67 9C6F DC72
1F 00FA 0F14 7766 7659 7478 7820 78CC 7527 7679 7C50 7E38 80BD 84CE 8C66 9C64 DC73
CONDUCTIVITY END
20 0000 0F15 7763 765A 747C 7821 78CB 752E 767A 7C58 7E39 80BE 84CA 8C65 9C65 DC76
21 00FC 0F14 7766 765D 747E 7822 78D3 7531 767B 7C53 7E31 80BB 84C4 8C63 9C68 DC79
22 0000 0F15 7768 765D 747F 7821 78CB 7532 767D 7C5B 7E36 80C2 84C6 8C69 9C68 DC7A
23 00FE 0F17 7763 765E 7480 7824 78CE 753F 767E 7C56 7E29 80C3 84CB 8C6A 9C6E DC7D
TEMP.
00 0000 0F16 7765 765E 7480 7826 78D4 7535 767E 7C5F 7E36 80C5 84C8 8C67 9C6F DC7D
01 0100 0F16 7762 765F 7482 7809 78DB 753F 7683 7C64 7E35 80C5 84C9 8C67 9C63 DC7F
02 0000 0F14 776A 765E 748C 7834 78DD 753F 768A 7C65 7E47 80C6 84CF 8C67 9C65 DC79
03 0102 0F19 776E 765F 748D 7822 78CE 7542 768B 7C65 7E26 80C9 84C6 8C6B 9C6D DC7C
04 0000 0F18 776A 765F 748D 7841 7912 7547 768F 7C5C 7E51 80CE 84CE 8C67 9C65 DC78
TEMP.
00 0104 0EED 7778 765F 7498 7840 78F4 754E 76A0 7C7D 7E5A 80CF 84CB 8C68 9C6A DB7A
TEMP.
```

Fig. 4.9 Displaying format on the ship's monitor (continued) flag K which is the least significant bit of the high byte of R8.

(10) It is not necessary to measure thermal conductivity for each station, if the conductivity of the sediments in the research area is relatively uniform. The program gives a signal "TEMP. END" after 8 minutes of thermal gradient measurement to alert the operator to decide whether the procedure should continue. By similar reasoning, a signal "CONDUCTIVITY END" 'tells' the operator to pull out the probe. Fig. 4.9 shows the typing format of the on-ship printer.

Fig. 4.10 is a detailed flowchart of the HF1601P program. Appendix B gives the HF1601P listing. In addition, the program includes a routine HF1601T for printing data in RAM on a printer or copying data from RAM to a disk. To run HF1601T, reset the probe and type *P0600. For copying data to disk, the microcomputer on ship should be set to terminal and data collection mode. Appendix C gives the instruction repertoire of the CDP1802 microprocessor.

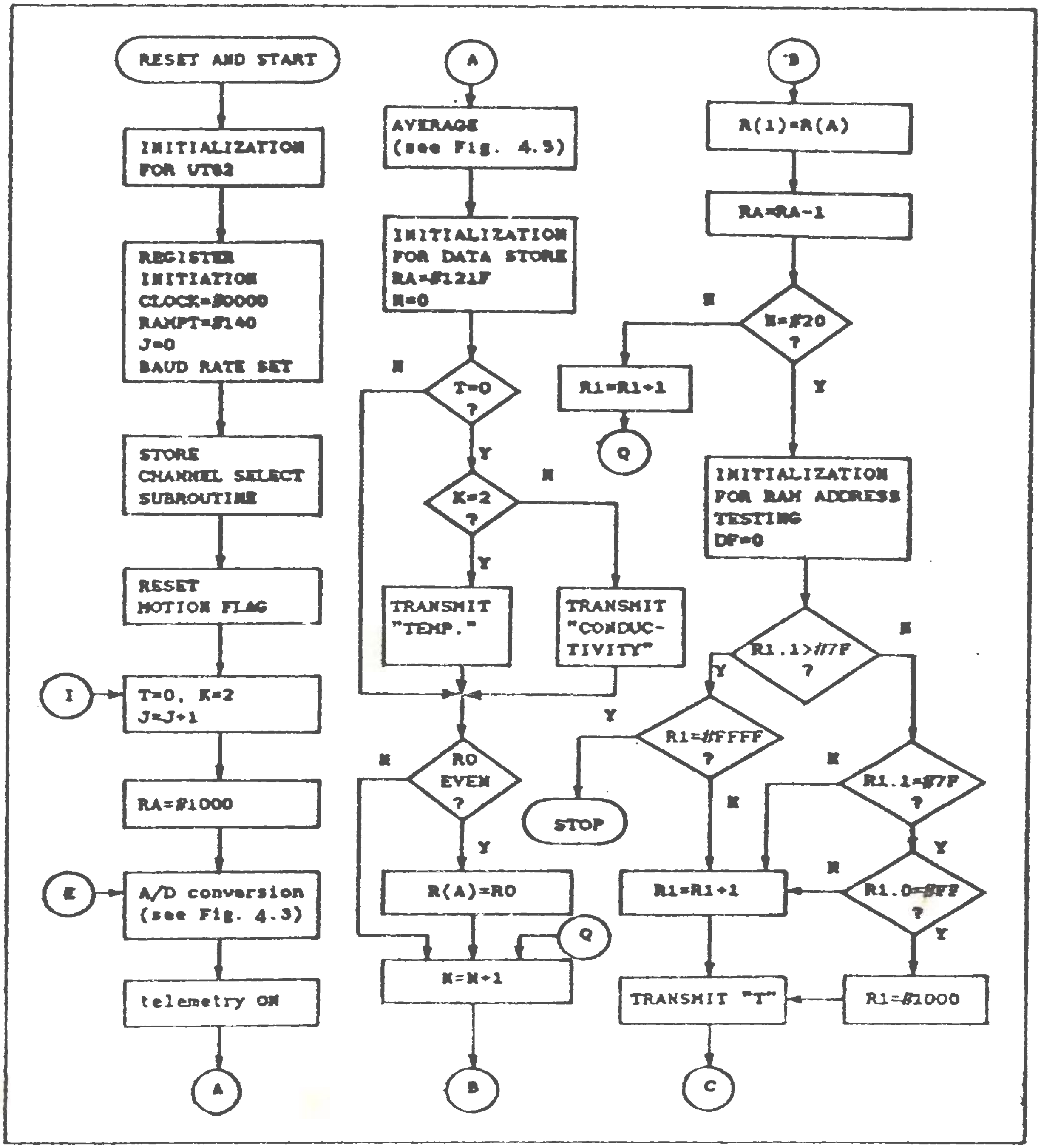


Fig. 4.10 Flowchart of the HF1601P

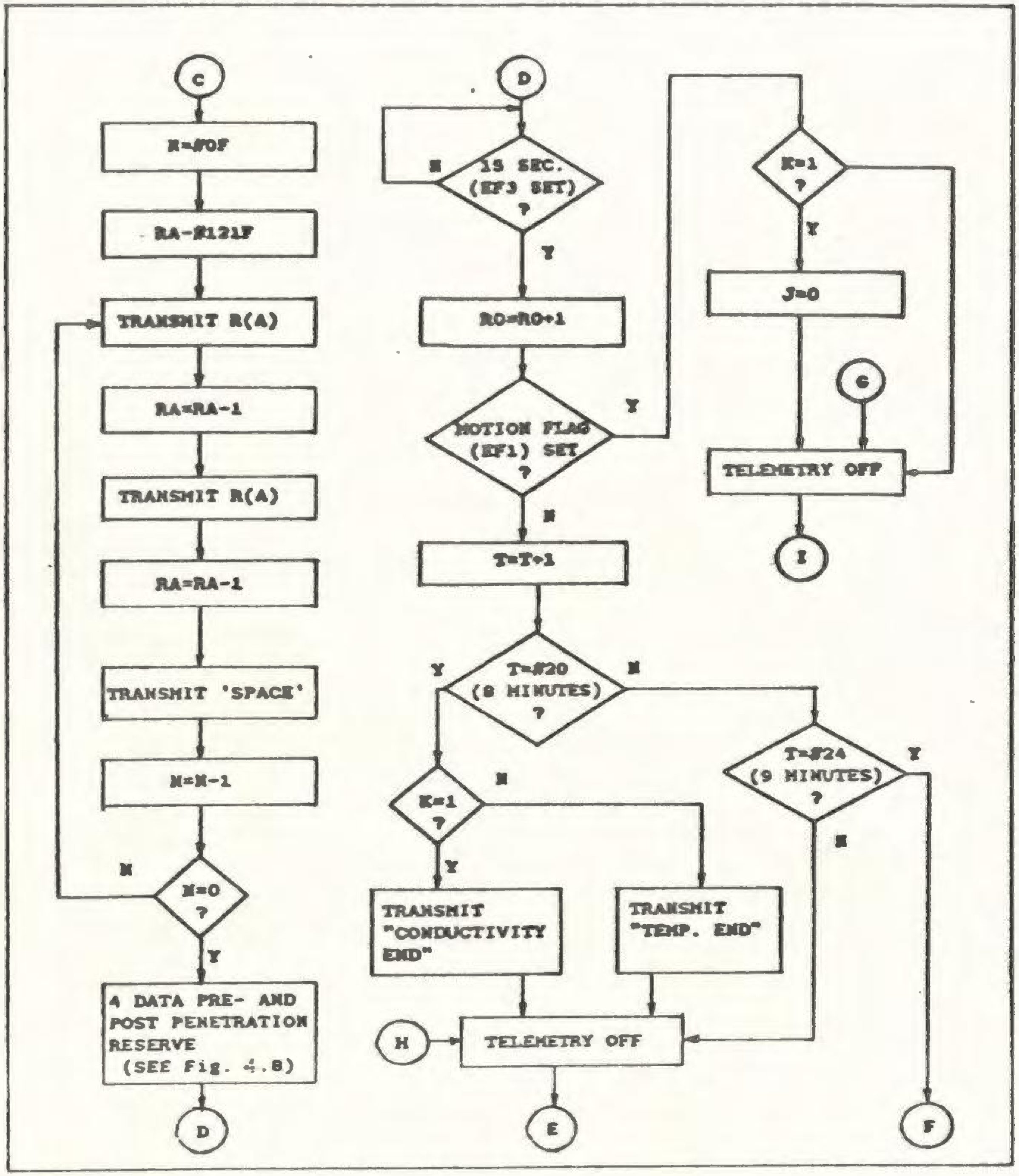


Fig. 4.10 (Continued)

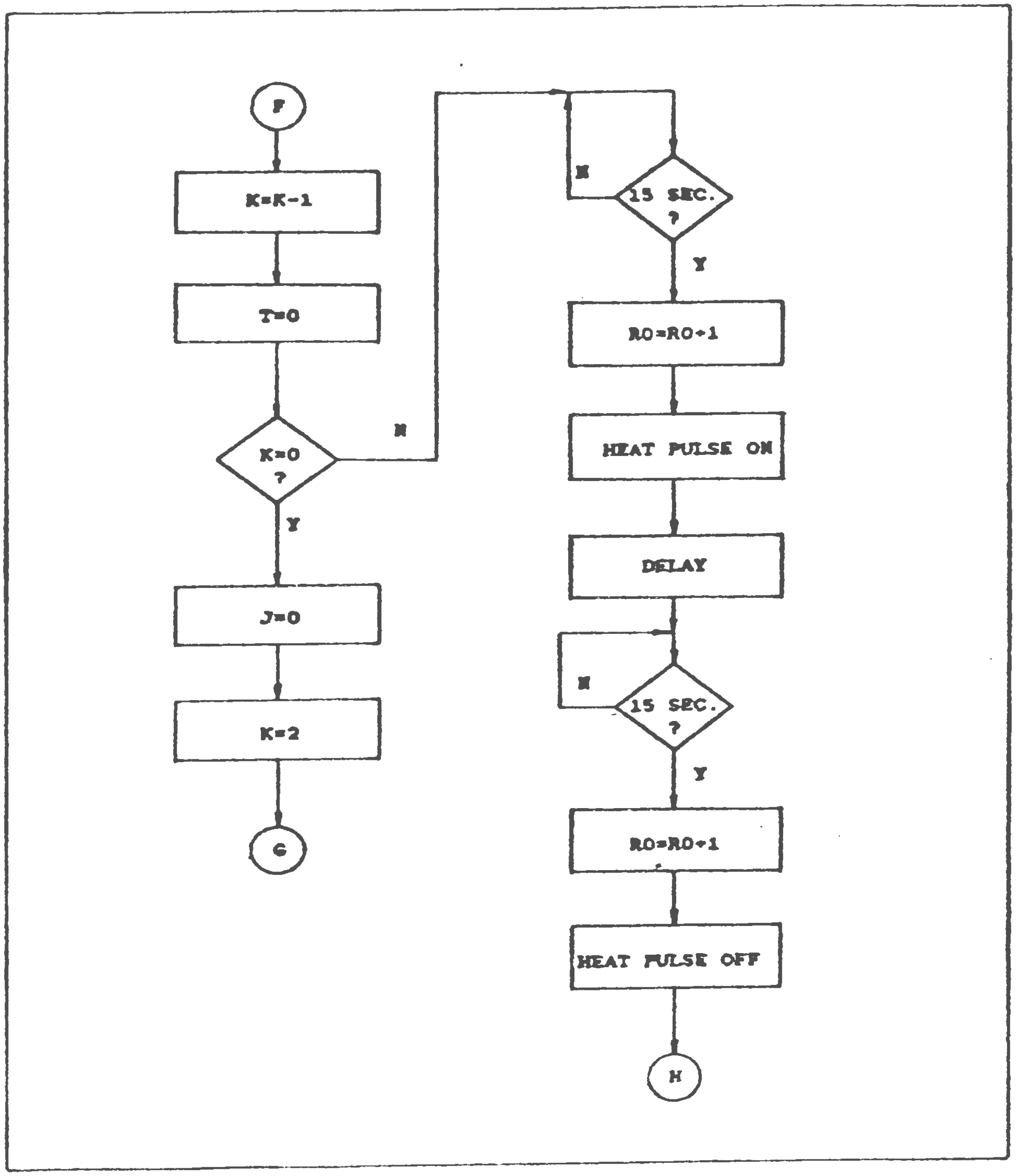


Fig. 4.10 (Continued)

Chapter 5 Data Processing

In connection with the microcomputer-based marine heat flow probe HF1601, a software package for data processing has been developed and named HF1601D (Appendix D). The routines perform the following tasks:

(1) Process the raw data received by telemetry and translate them to resistance values in decimal form;

(2) Display and plot the temperature-time relationship for each of the thermistors in the string;

(3) Calculate the thermal conductivity and gradient for the stations where *in situ* thermal conductivity measurements are taken;

(4) Compute infinite-time temperatures for stations where no *in situ* thermal conductivity measurements are taken;

(5) Interactively fit the thermal gradient using data obtained in (4);

(6) Estimate the thermal gradient rapidly without resorting to infinite-time temperatures.

5.1 Routine for reducing raw data into resistance

The raw (hexadecimal) data as telemetered from the sea floor are displayed line-by-line by the computer and stored on floppy disks. In a typical case, a scan of all the thermistors in the string is completed every 15 seconds. A complete data set for a penetration includes one minute of pre-penetration data, eighteen minutes of penetration data (nine for gradient determination and nine for thermal conductivity measurement) and one minute of post-pullout data. The set of data is stored in matrix form as resistance values for further processing.

The fourteen thermistors and the reference resistor are connected in series, hence the resistance of each resistor is:

$$\mathbf{R}_{thermistor} = \frac{\mathbf{V}_{thermistor}}{\mathbf{V}_{reference}} \times \mathbf{R}_{reference}$$

where **R** is resistance and **V** is voltage. The voltages are the averaged voltage differences as determined in Chapter 4.

5.2 Temperature-time calculations

The temperature-time relationship is important in that it gives a visual representation of the nature of the heat flow measurement, especially of the quality of the data. This stage in data reduction changes the resistance readings into temperature according to the characteristics of the specific thermistors and then displays the temperature-time relations of the fourteen thermistors on the computer screen. It also generates a serial data file of the temperature-time values to facilitate plotting.

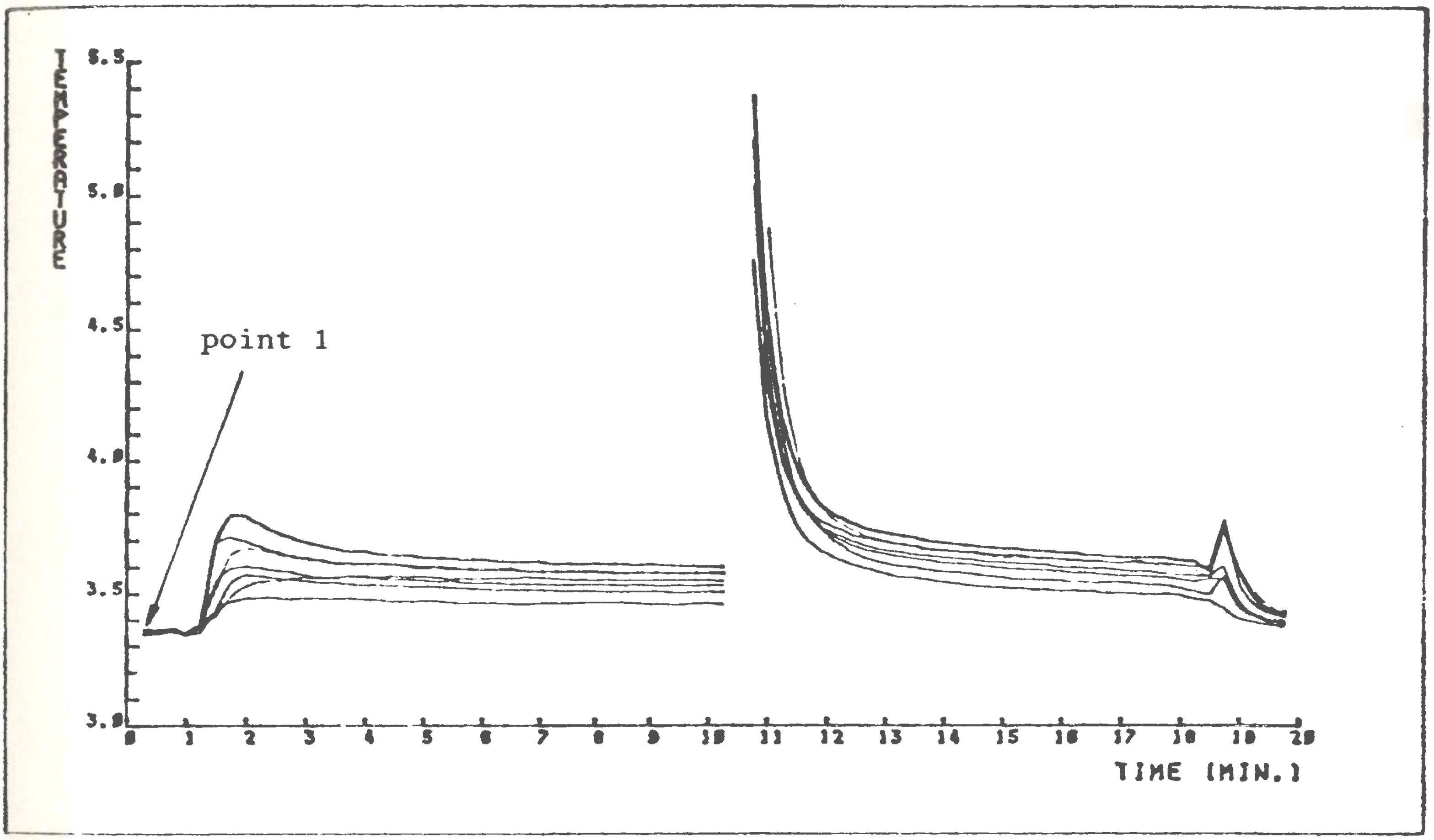


Fig. 5.1 Temperature-time graph

In this routine, a relative calibration is implied. All of the thermistors meet, to within a specified tolerance, the temperature-resistance function supplied by manufacturer. This specification is verified by calibration in the laboratory in a temperature controlled bath. Hence, the resistance-temperature transformation for the 14 thermistors in the string uses a single formula whose parameters are determined by resistance-temperature relations listed on the specification sheets. for example, the temperature-resistance function for thermistors YSI (Yellow Springs Instruments) 44032 (30 KΩ at 25° C) is

$$T = \frac{5811.403}{\ln R + 5.493939} - 342.7457$$

A discussion of the above parameters in this relation is given in section 5.6 of this chapter. The temperature differences of the 14 thermistors after the probe penetrates the sediment are based on the fact that no differences exist before penetration. It is assumed that before penetration the probe is located in water where the temperature gradient is negligible. In most of the cases, this assumption is realistic; otherwise corrections must be applied. Figure 5.1 is a plot of the temperature-time relationship for data taken on the Labrador Shelf. In this routine, any of the eighty time points may be taken as the reference point for temperature readings. The point when the probe is in water one minute before penetration is the usual reference point (point 1 on Fig. 5.1).

5.3 Thermal conductivity reduction

As stated in Chapter 2, the theory of *in situ* conductivity determination in marine heat flow measurement using heat pulse method has been well established (Bullard, 1954; Lister, 1979; Hyndman *et al.*, 1979; Davis *et al.*, 1984). For the convenience of discussion, some formulas are repeated herewith. The thermal decay curves after frictional heating and pulse heating follow an $F(\alpha,\tau)$ function (Bullard, 1954; Jaeger, 1956)

$$F(\alpha,\tau) = \frac{4\alpha}{\pi^2} \int_0^\infty \frac{\exp(-\tau u^2)\, du}{u\left\{[uJ_0(u) - \alpha J_1(u)]^2 + [uY_0(u) - \alpha Y_1(u)]^2\right\}} \tag{5.1}$$

$$\tau = 0, \quad F(\alpha,\tau) = 1; \qquad \tau = \infty, \quad F(\alpha,\tau) = 0$$

where $J_n(u)$ and $Y_n(u)$ are bessel functions of order n of the first and second kinds. Series expressions for these are given as

$$J_0(u) = \sum_{m=0}^{\infty} \frac{(-1)^m \; u^{2m}}{2^{2m} \; (m!)^2}$$

$$J_1(u) = u \sum_{m=0}^{\infty} \frac{(-1)^m \; u^{2m}}{2^{2m+1} \; (m+1)! \; m!}$$

$$Y_0(u) = \frac{2}{\pi} \left[J_0(u)(\ln\frac{u}{2} + \gamma) + \sum_{m=1}^{\infty} \frac{(-1)^{m-1} \; h_m \; u^{2m}}{2^{2m+1} \; (m!)^2} \right]$$

$$Y_1(u) = \frac{2}{\pi} \left[J_1(u)(\ln\frac{u}{2} + \gamma) - \frac{u}{4} \right] + \frac{u}{\pi} \sum_{m=0}^{\infty} \frac{(-1)^{m-1}(h_m + h_{m+1}) u^{2m}}{2^{2m+1} m! \; (m+1)!}$$

where $h_0 = 0$, $h_m = 1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{m}$, and $\gamma = 0.57721566490$

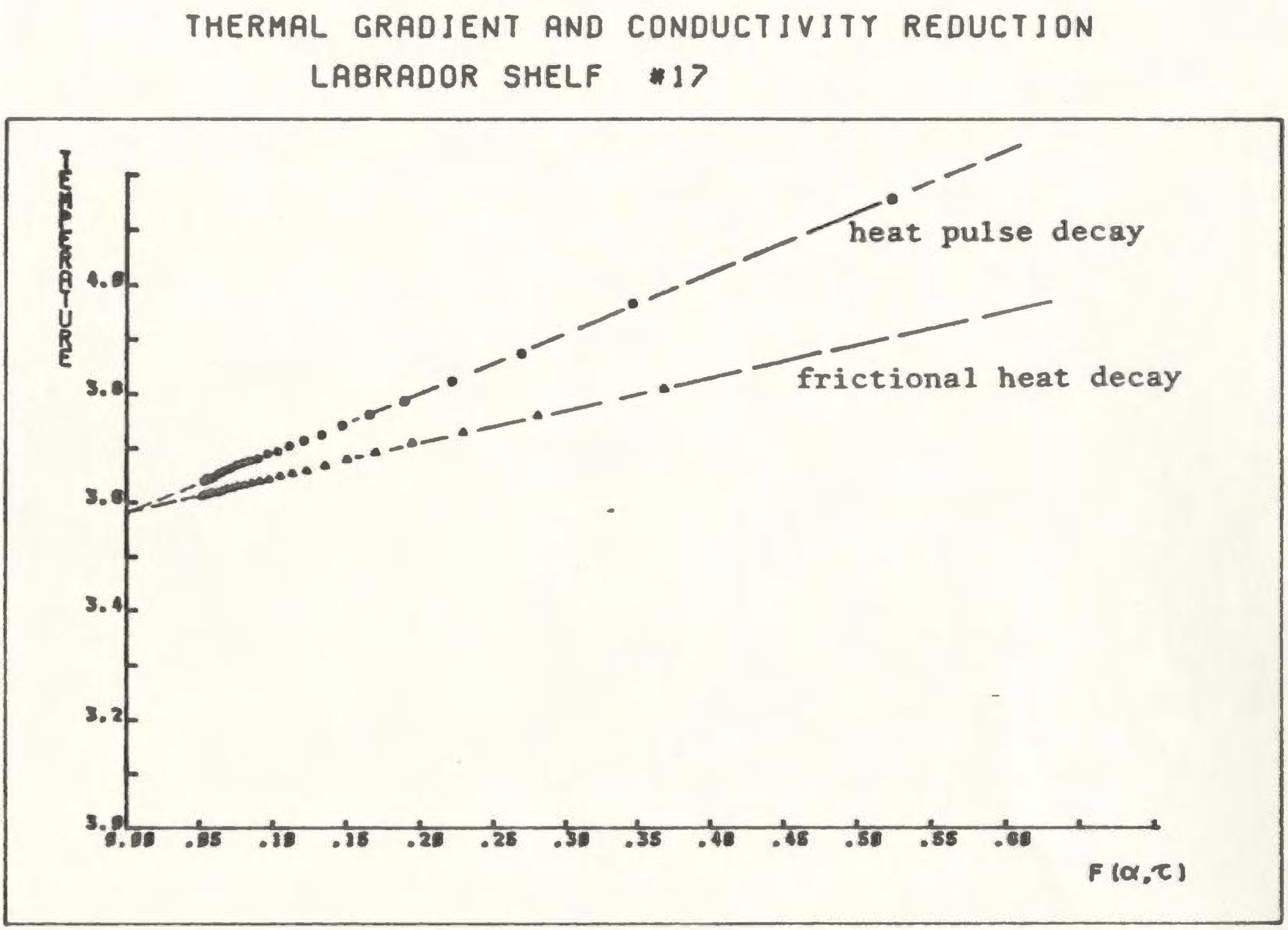


Fig. 5.2 T - $F(\alpha,\tau)$ graph

Applying a transformation of coordinates from $T-t$ (temperature-time) to $T-F(\alpha,\tau)$, the temperature decay curve becomes linear, (Fig. 5.2).

Since $F(\alpha,\tau) = 0$ when $\tau = \infty$, the intercept on the temperature coordinate expresses the infinite-time temperature.

$J_0(u)$, $J_1(u)$, $Y_0(u)$ and $Y_1(u)$ must be determined in advance in order to obtain a numerical solution of $F(\alpha,\tau)$. For an instrument with a resolution of 0.5 mK, it is sufficient to compute $J_n(u)$ and $Y_n(u)$ using u = 0, 0.1, 0.2,...,15 and m = 0, 1, 2,...,15.

In the $F(\alpha,\tau)$ function, $\tau = \dfrac{kt}{a^2}$ describes the thermal time constant of a probe of radius a in sediment of diffusivity k. $\alpha = \dfrac{2\pi a^2 \rho c}{S}$ is twice the ratio of the heat capacity of the sediments to that of the probe material (S is the probe's heat capacity). Both α and τ can be estimated by empirical relations between these parameters and the conductivity K for ocean sediments (Hyndman *et al.*, 1979) as follows

$$k = \frac{K}{5.79 - 3.67K + 1.016K^2} \qquad (\text{in } 10^{-6}\text{m}^2\text{s}^{-1},\ K \text{ in } \text{Wm}^{-1}\text{K}^{-1})$$

That is

$$\tau = \frac{Kt}{(5.79 - 3.67K + 1.016K^2)\, a^2} \tag{5.2}$$

$$\alpha = \frac{2(5.79 - 3.67K + 1.016K^2)}{\rho c} \tag{5.3}$$

In (5.3), ρc of the probe is estimated using the table in Lister (1979).

To evaluate $F(\alpha,\tau)$ numerically, rewrite (5.1) into a summation form as

$$F(\alpha,\tau) = \frac{4\alpha}{\pi^2} \sum_{u=0}^{\infty} \frac{\exp(-\tau u^2)\Delta u}{u\left\{[uJ_0(u) - \alpha J_1(u)]^2 + [uY_0(u) - \alpha Y_1(u)]^2\right\}} \tag{5.4}$$

$F(\alpha,\tau)$ and conductivity K have a direct relation. Blackwell (1954) gives an approximation of $F(\alpha,\tau)$ for large τ as

$$F(\alpha,\tau) = \frac{1}{2\alpha\tau} - \frac{1}{4\alpha\tau^2} - \frac{(\alpha-2)}{4\alpha^2\tau^2}\left(\ln\frac{4\tau}{1.7811} - 1\right) + O\,\frac{\ln\tau}{\tau^3} \tag{5.5}$$

When α is about 2 and at large τ ($\tau > 10$), the solution of $F(\alpha,\tau)$ reduces to asymptotic $F_a(\alpha,\tau)$ and T_a (Hyndman *et al.*, 1979)

$$\frac{T_a}{T_o} = F_a(\alpha,\tau) = \frac{1}{2\alpha\tau}$$

$$= \frac{1}{2[(2\pi a^2\rho c)/S](kt/a^2)}$$

$$= \frac{S}{4\pi Kt} = \frac{Q/T_o}{4\pi Kt}$$

where T_o is the constant temperature above the ambient after a heat pulse or frictional heating, and the heat capacity of the probe S equals the total heat of the pulse Q divided by temperature rise T_o. Multiplying both sides by T_o,

$$T_a = \frac{Q}{4\pi Kt} \tag{5.6}$$

Let T be the temperature above the ambient at any moment after frictional heating or pulse heating. It has been stated that

$$\frac{T}{T_o} = F(\alpha,\tau) \qquad or, \qquad \frac{T}{T_0 \times F(\alpha,\tau)} = 1 .$$

Hence,

$$\frac{T_a}{T_0} = \frac{1}{2\alpha\tau} = \frac{1}{2\alpha\tau} \times \frac{T}{T_0 F(\alpha,\tau)} = \frac{T}{T_0[2\alpha\tau F(\alpha,\tau)]}$$

and

$$T_a = \frac{T}{2\alpha\tau F(\alpha,\tau)} \tag{5.7}$$

Renaming T as ΔT and comparing (5.6) and (5.7),

$$\frac{\Delta T}{2\alpha\tau F(\alpha,\tau)} = \frac{Q}{4\pi K t}$$

or

$$K = \frac{Q\,\alpha\tau F(\alpha,\tau)}{2\pi \Delta T t} \tag{5.8}$$

where Q is the heat supplied to the probe per unit time per unit length and t is the time elapsed at ΔT. The initial time $t = 0$ is usually 15 to 45 seconds following the middle of the heat pulse (Hyndman *et al.*, 1979).

A study of equation (5.8) shows that two quantities have to be known for reduction of thermal conductivity; namely,

(i) the infinite-time temperature (ambient temperature) for determining ΔT at all the points after the heat pulse and

(ii) an estimation of conductivity K for determining α and τ using the empirical relations in equations (5.2) and (5.3).

The second requirement suggests that the reduction of thermal conductivity for *in situ* measurement is an iterative process. Specifically, the procedure involves the following steps:

(i) Make an estimate of the thermal conductivity of the sediment and compute α, τ and $F(\alpha,\tau)$ using relations shown in equations (5.2), (5.3) and (5.4).

(ii) Plot the temperature decay curve after frictional heating using $T-F(\alpha,\tau)$ coordinates. Estimate a "delay" time (determined by the probe's thermal resistance) for the initial time $t = 0$ of the frictional heating. The decay is a straight line if all estimates are close enough to their real values. The infinite-time temperature is the intercept of a least square fitted line of the decay on the temperature coordinate. Along this straight line, extrapolate the residual temperatures at times during heat pulse decay. Remove these residuals from heat pulse decay curve.

(iii) Plot the heat pulse decay curve in $T-F(\alpha,\tau)$ coordinates. Estimate a delay time to establish the initial time $t = 0$ of the heat pulse. Calculate the thermal conductivity K for each point on the decay curve using equation (5.8). Take their average as the tentative result of the thermal conductivity.

(iv) Compare the tentative conductivity and the initial estimate. If the difference exceeds a predetermined value, use the tentative conductivity as an initial estimate and repeat steps (i) to (iv).

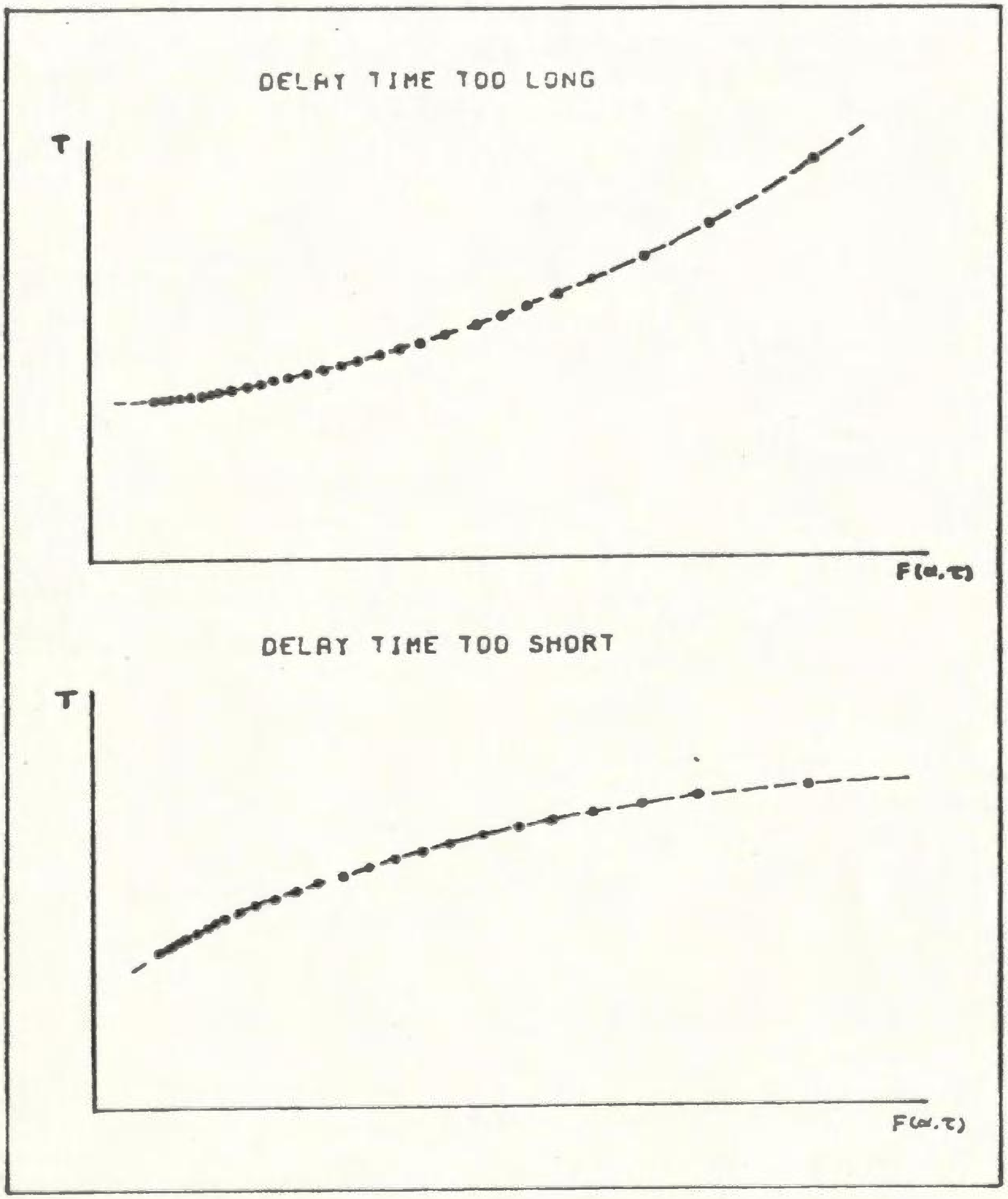


Fig. 5.3 Incorrect delay time

The routine uses two criteria to decide if the iteration has to continue. Besides the difference between the estimated and the calculated values, it checks the difference between the two infinite-time temperatures reduced from the thermal decay curve after frictional heating and after heat pulse heating. The routine is able to automatically adjust the two delay times in iterations to minimize this difference. The delay time implies the initial time $t = 0$. Incorrect values for the delay times, along with $F(\alpha,\tau)$, make the plot of the decay curve in $T-F(\alpha,\tau)$ coordinates deviate from a straight line convexly or concavely (Fig. 5.3) (see also Hyndman *et al.*, 1979, Fig. 10).

5.4 Infinite-time temperature estimation and interactive fitting of the thermal gradient

In an area where the variation of thermal conductivity is not great, it is not necessary to take *in situ* conductivity measurements at every station. The usual practice is to allow heat pulses for 20 to 30 percent of the total stations. To facilitate discussion, these stations are called type A stations. The remaining stations, without heat pulses, are called type B.

To reduce the heat flow for type B stations, an immediate difficulty is estimation of the infinite-time temperature for each thermistor, since there no longer exists the mechanism of iteration and delay time adjustment. This difficulty is resolved using the following steps.

(i) Deduce a representative thermal conductivity for this area from type A stations or estimate the conductivity by other means such as the water content-conductivity relationship (Ratcliffe, 1960).

(ii) Choose a group of readings along the $T-t$ curve for the thermistor in question.

(iii) Determine empirically the delay time or the 'initial' time of frictional heating.

(iv) Compute $F(\alpha,\tau)$ values as described in the previous section. Plot the $T-F(\alpha,\tau)$ relationship. If it is a well-approximated straight line, the intercept of the least square fitting line on the T-axis is the infinite-time temperature desired. Otherwise another delay time or conductivity estimate is chosen.

The routine to interactively determine the geothermal gradient plots the depth-temperature relationship and computes the least squares fitting line whose slope is the geothermal gradient. In the case that the temperature distribution in the sediments is disturbed, the routine is able to redisplay and calculate the thermal gradient using only those thermistors that the operator deems are not influenced by the temperature variation. This allows an interactive means of comparing the geothermal gradients during a multipenetration profile.

5.5 Fast estimation of the geothermal gradient

In many cases, it is adequate to have an estimate of the geothermal gradient using only the temperature readings at a relatively long time after penetration

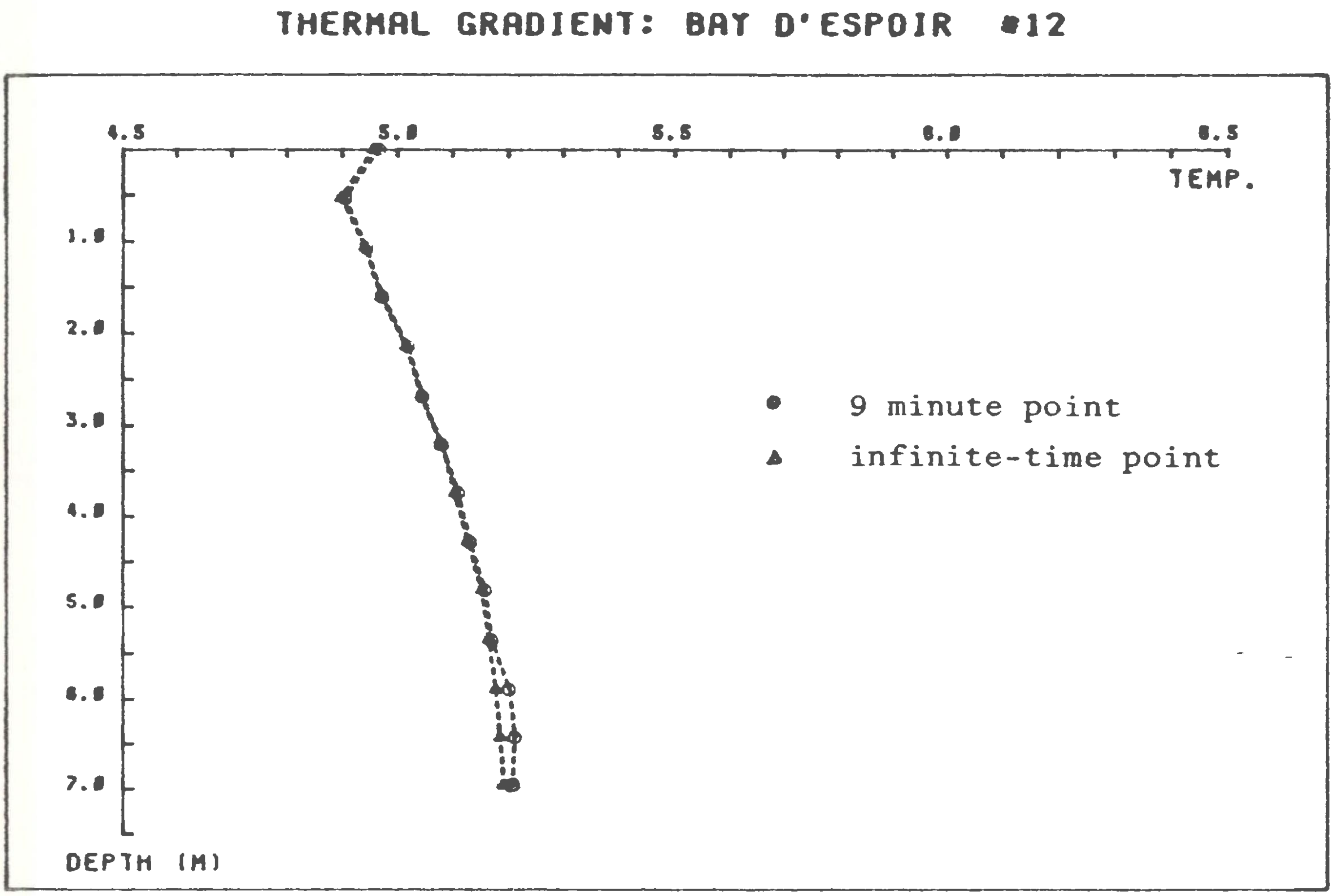


Fig. 5.4 A comparison of the gradient derived from infinite-time and 9 minute temp.

(e.g. 9 min.). This temperature may differ from its infinite-time value. However, the gradients reduced from the two types of temperatures may not differ significantly, since the gradient is measured by temperature differences among adjacent thermistors (Fig. 5.4).

The routine gives a fast estimation of the geothermal gradient using the temperatures of a group of thermistors at a specific time after penetration. It displays the $T-t$ graph and the point picked for gradient calculation. If the time point is not satisfactory, it can be changed and re-displayed. The program then displays the new depth-temperature curve. If there is a disturbance in the temperatures, the routine allows the operator to include only the deeper thermistors with negligible perturbation in the geothermal gradient calculation.

The procedures stated above are all structured to run as sequential jobs on a portable microcomputer. This, combined with the digital acoustic link from the sea floor package HF1601, makes real-time, interactive processing of marine heat flow data possible. Of special significance is the fact that at each stage the data are displayed in graphical form on the screen (or plotted for hard copy) so that the quality of the data can be monitored. The iterative procedure for reducing the heat pulse/frictional heating decay curves to a common infinite-time temperature allows control over the empirical parameters that are commonly used in the process. All routines are written in BASIC under MS-DOS and will run on any computer using this operating system.

5.6 Thermistor calibration

The calibration of thermistors has been discussed in a few publications (Robertson *et al.*, 1966; Raspet *et al.*, 1966; Steinhart and Hart, 1968; Bennett, 1972). The absolute calibration of thermistors involves the establishment of a stable temperature environment. The vast ocean body with its tremendous heat capacity is a tempting environment to carry out the calibrations. Considering that only the temperature difference is vital in heat flow measurement, a "relative calibration" has been used for some marine heat flow probes (Davis *et al.*, 1984). It assumes that all thermistors in a probe are located in a "zero gradient zone" before penetrating into sediments.

However, even the "relative calibration" requires the relationship of resistance to temperature of the thermistors. An assembly has been set up for determining this relationship (Fig. 5.5). The purpose of this assembly is to verify the differential slope of the temperature-resistance function supplied in the specification sheets which declares that the discrepancy in this slope among the thermistors of a selected group is less than one percent.

In order to simulate a situation as close to the actual probe as possible, the calibration takes place after the thermistor string has been made, and the fourteen thermistors are calibrated simultaneously. The temperature-resistance readings are taken by the same electronic package used in heat probe so that no extra noise sources are involved. In a sense, this also acts as a complete system calibration.

The thermistor string is made into a coil of about 200 cubic centimeters ($6 \times 6 \times 6$ cm). To minimize the inductance, the string is folded in the middle and then coiled. The string is dipped in mineral oil in a metal oil container that is immersed in a mixture of ice and water in a glass bath of about 0.1 cubic meters in volume. The bath is surrounded by styrofoam five centimeters thick. A platinum resistance thermometer is placed at the geometric center of the thermal string coil. Near room temperature, the temperature of the string coil rises non-linearly with an average rate of approximately 1.5 mK per minute (10 days to rise from 0.01° C to 21° C). The four wire ohm-meter that reads the resistance of the platinum thermometer has a resolution of 0.001 ohm in the 100 to 200 ohm range. This implies a resolution of 2.5 mK.

At certain temperatures, the microcomputer records and stores twenty minutes of resistance readings for 14 thermistors as in the heat flow measurement. The average temperature within the time span and the average resistance for each of the 14 thermistors are used to establish the temperature-resistance relationship. The measurement repeats at different temperatures at an interval of approximately 1 K. About 15 temperature points (from 0° C to 15° C) are adequate to allow fitting the temperature-resistance curve. A least-squares fitting of the $T-R$ relationship of the thermistors is discussed below.

An empirical equation (5.10) modeled after the relation

$$\sigma = A(T)e^{-\frac{E}{2kT}} \tag{5.9}$$

fits the real thermistor behaviour well (Rorbertson *et al.*, 1966):

$$R = A \exp[B(T+C)^{-1}]$$

or

$$\ln R = \ln A + B(T+C)^{-1} \tag{5.10}$$

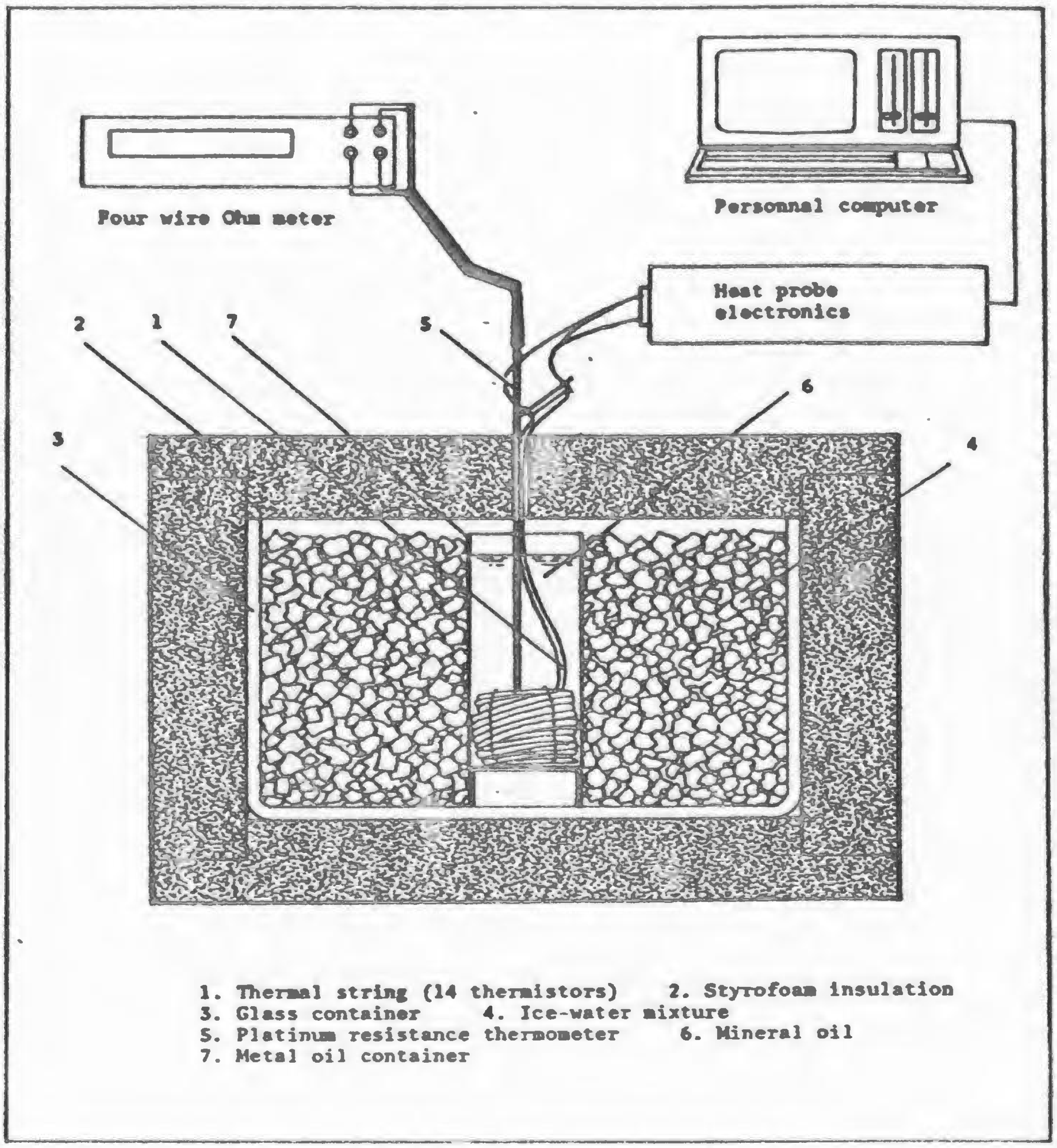


Fig. 5.5 Thermistor calibration apparatus

For simplicity in deriving the computer programs, rename R for $\ln R$ and A for $\ln A$, that is

$$R = A + B(T+C)^{-1} \tag{5.11}$$

To determine a least-square fitting of the measured data R_i at T_i in the process of calibration, let

$$D = \sum_{i=1}^{n} (R-R_i)^2 \tag{5.12}$$

where n is the number of measuring points; R_i is the value of R.

To find A, B, C such that D is minimized, set

$$\frac{\partial D}{\partial A} = 0; \qquad \frac{\partial D}{\partial B} = 0; \qquad \frac{\partial D}{\partial C} = 0$$

That is

$$\begin{cases} \sum(R-R)_i = 0 \\ \sum(R-R_i)(T_i+C)^{-1} = 0 \\ \sum(R-R_i)(T_i+C)^{-2} = 0 \end{cases} \tag{5.13}$$

Rename T for T_i. From (5.13),

$$\sum(R-R_i) = 0 \quad \rightarrow \quad \sum[A+B(T+C)^{-1}] = \sum R_i \tag{5.14}$$

Note that $\sum_{i=1}^{n} A = nA$. (5.13) and (5.14) can be written as:

$$nA + B\sum(T+C)^{-1} = \sum R_i \tag{5.15}$$

$$A\sum(T+C)^{-1} + B\sum(T+C)^{-2} = \sum[R_i(T+C)^{-1}] \tag{5.16}$$

$$A\sum(T+C)^{-2} + B\sum(T+C)^{-3} = \sum[R_i(T+C)^{-2}] \tag{5.17}$$

Let $\bar{R} = (\sum_{i=1}^{n} R_i)/n$. From (5.15),

$$A = \bar{R} - \frac{B}{n}\sum(T+C)^{-1} \tag{5.18}$$

substitute (5.18) into (5.16) and (5.17), and let

$$L = \sum(T+C)^{-1}$$
$$M = \sum(T+C)^{-2}$$
$$K = \sum(T+C)^{-3}$$
$$P = \sum[R_i(T+C)^{-1}]$$
$$Q = \sum[R_i(T+C)^{-2}] ,$$

then:

$$A = \bar{R} - \frac{BL}{n} \tag{5.19}$$

$$B = \frac{Q - \bar{R}M}{K - LM/n} \quad or \quad B = \frac{P - \bar{R}L}{M - LL/n} \tag{5.20}$$

where K, L, M, P, Q are all functions of C.

A program for seeking A, B, C is listed in Appendix E. It requires the input of trial values of C, C_{max} and C_{min}, which are the estimates of the maximum and minimum of C. The program narrows this C range by calculating A and B accordingly and minimizing the least-squares errors in (5.12) to establish new C_{max} or C_{min} using the "optimum seeking method". If C_{max} should be changed, the new C_{max} is

$$C_{min} + 0.618(C_{max} - C_{min})$$

If C_{min} should be changed, the new C_{min} is:

$$C_{min} + 0.382(C_{max} - C_{min})$$

The above method of seeking temperature-resistance relationship of thermistors has been tested with two thermal strings. It verifies that selected thermistors have a discrepancy less than one percent for the differential slope of their temperature-resistance curve, although they may have different offsets at specific temperatures. Therefore it is justified to convert the resistances to temperatures for the fourteen thermistors using a single formula. To compensate the offsets of 14 thermistors, take one of the fourteen thermistors as reference and calculate the offsets when the probe is suspended in the "zero gradient zone" (about 50 - 100 meters above the sea floor) for about 5 to 10 minutes. Using the temperature-resistance data supplied by the specification sheets, the parameters for the thermistor YSI 44032 (30 KΩ at 25° C) are:

$A =$ -5.493939; $B =$ 5811.403; $C =$ 342.7457

Rewrite equation (5.10) and notice that A stands for $\ln A$,

$$T = \frac{B}{\ln R - A} - C ,$$

that is:

$$T = \frac{5811.403}{\ln R + 5.493939} - 342.7457 \qquad (5\ 21)$$

In summary, the heat flow data processing software HF1601D accomplishes the data analysis by converting the raw data then calculating the thermal gradient and conductivity in a real-time base. The advantage of this software is that the process of the data analysis is visible on the on-ship microcomputer's screen or on the printer and plotter. The calculation of the thermal gradient as well as thermal conductivity is based on a relative calibration of the thermistor and employs the temperature at the "zero gradient zone" as the reference. To this end, a system calibration method is discussed.

Chapter 6 Field Tests and Experiments

6.1 Cruise Summaries

Since the HF1601 heat probe was constructed in September 1983, four sea tests and experiments have been conducted.

(1) Date: September 23 to October 5, 1983

Location: Saguenay Fjord (St. Lawrence River)

Ship: Navimar Un

Objectives: Test of heat flow equipment

Nineteen deployments of the heat flow equipment were attempted. The mechanical equipment functioned well. Data were recorded at all sites. However, the -15V power supply reduced to -6V making the A/D converted values unreliable. A visual check of the digital values showed operation for data in the water column. There was no reception on the telemetry. The stability was about 2 mK, the noise mainly arising from the oscillator in the telemetry circuit.

Conclusion: The test led to three revisions. (i) Re-design the circuit of the negative power supply. (ii) Revise the operating program HF1601P such

that the telemetry is turned off during data acquisition in order to reduce electric noise. (This is a good example to show the flexibility of a programmable heat probe: to change the function without hardware revision).
(iii) Improve the Telemetry receiving circuit.

(2) Date: December 7 to 23, 1983

Location: Fortune Bay

Ship: C.S.S. Hudson

Objective: Test of marine heat flow equipment and geothermal flux measurement

Five penetrations were attempted. No data were collected due to an electric connection failure. The cruise was curtailed because of adverse weather conditions.

Conclusion: Design and construct a chassis for electronics package to improve the electrical and mechanical stability.

(3) Date: June 23 to July 7,1984

Location: Belle Bay, Bay d'Espoir, St. George's Bay

Ship: C.S.S. Dawson

Objective: Test of marine heat flow equipment and geothermal flux measurement

Twenty nine stations were completed. The equipment functioned as designed, with the exception of the acoustics. The acoustics were clearly audible at all depths but no decoding occurred. The data play back showed that the probe's stability was approximately 0.5 mK as designed. Due to the high internal resistance of the batteries used (approximately two ohms), the probe was not able to supply an adequate heat pulse for *in situ* conductivity measurement.

Conclusion: Redesign the circuitry for underwater acoustic telemetry. Replace the batteries (sealed lead-acid) with a type with lower internal resistance (Ni Cd).

(4) Date: July 24 to August 26, 1984

Location: Labrador Sea and Labrador Shelf (Hopedale Saddle)

Ship: C.S.S. Hudson

Objective: Measurement of geothermal flux (joint program with Dalhousie University) and test of newly designed underwater acoustic telemetry circuits

Sixteen stations of heat flow measurement in five lowerings were completed. The underwater digital acoustic telemetry functioned as designed. The receiving circuit employed the ship's sounder as its transducer. The telemetry's frequencies (8.0 KHz and 9.0 KHz) and the frequency of ship's sounder (12.0 KHz) are separated on both the on-ship monitor of the heat flow equipment and the recorder of ship's depth sounder; therefore a pinger was able to be attached about 10 meters above the probe for locating the sea floor.

Conclusion: The digital telemetry using standard digital transmission protocol in deep sea environment improved the productivity of heat flow measurement. The operator on ship was fully aware of the probe's condition and working process while the instrument was on the sea floor. The real-time data displayed on the monitor along with messages of all events gave an opportunity to record a complete work procedure. Some mechanical problems were found. More weight will improve the probe's performance in the deep sea. The data showed instability in the readings for some stations; it is mainly caused by contact resistance at the connectors.

The data processing software, which was partly created within this cruise, along with the real-time data recorded by telemetry helped to evaluate the quality of the data and reduce the heat flux results promptly.

6.2 Heat flow measurements in the inlets of the south coast of Newfoundland

Fig. 6.1 is the geographic positions of the heat flow stations taken in the inlets of the south coast Newfoundland (Fig. 6.1a: Belle Bay 1 and 2, Bay d'Espoir; Fig. 6.1b: St. George's Bay). The detailed location and water depth is listed in Table 6.1.

Fig. 6.2 is a collection of the results of some representative stations. Shown are the temperature-time graphs and temperature-depth graphs. On the latter, the top thermistor is assumed at the zero depth (sea floor), although this may not be true for some stations. The depth of the penetration for individual station will be discussed in Chapter 7 where the geophysical interpretations are given.

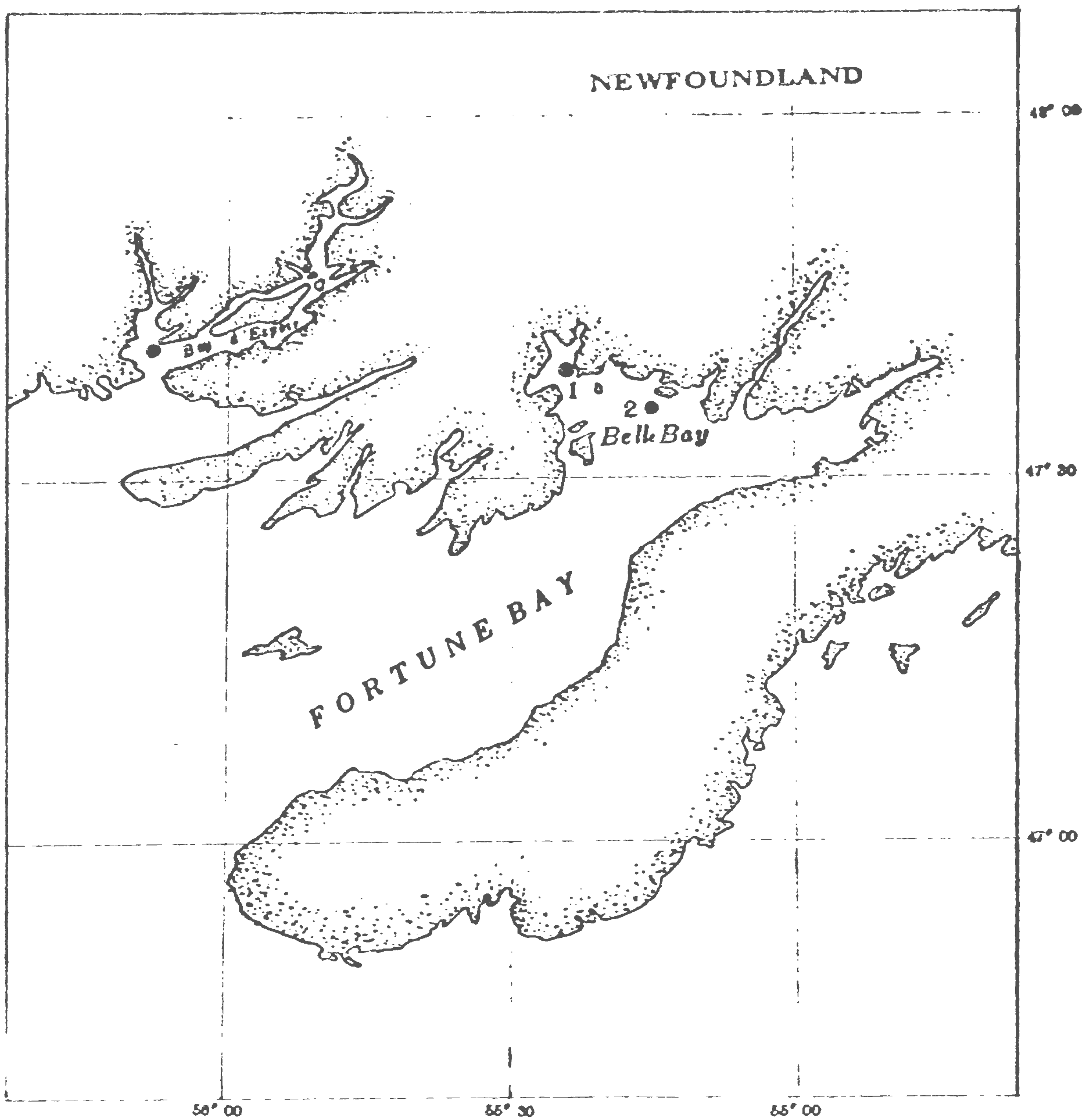


Fig. 6.1a The geographic position of heat flow stations in Belle Bay and Bay d'Espoir

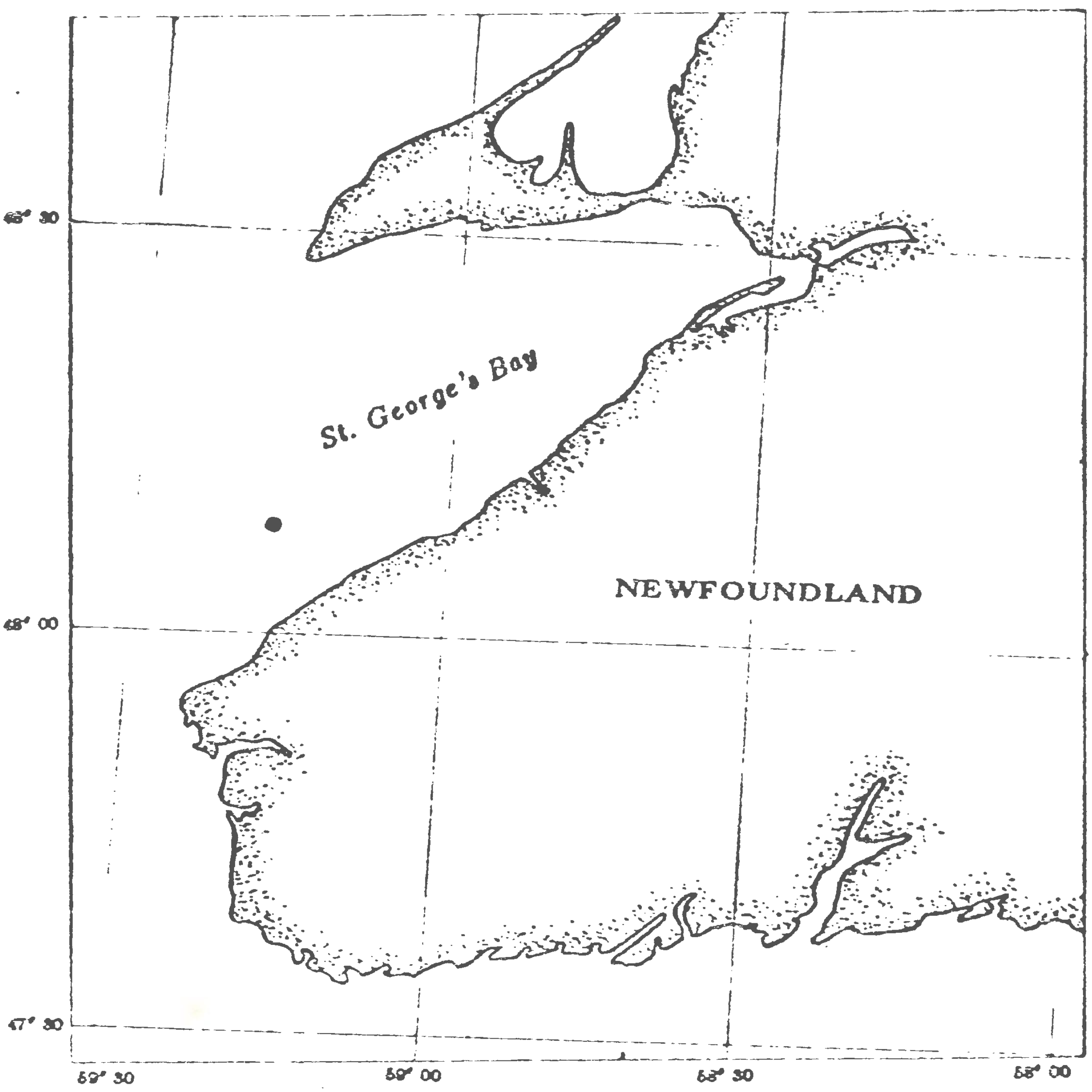


Fig. 6.1b The geographic position of heat flow stations in St. George's Bay

Table 6.1 Heat Flow Stations in Southern Newfoundland Inlets

location	Station	Date	Latitude	Longitude	Water Depth
Belle Bay 2	HF#1	179,1984	47° 36.72	55° 15.15	490m
	HF#2		47° 36.65	55° 14.92	505m
	HF#3		47° 36.51	55° 14.62	516m
	HF#4		47° 36.38	55° 14.35	487m
	HF#5		47° 36.75	55° 15.12	475m
	HF#6		47° 36.68	55° 14.78	513m
	HF#7		47° 36.54	55° 14.50	530m
	HF#8		47° 36.49	55° 14.30	530m
Belle Bay 1	HF#20	181,1984	47° 39.63	55° 23.38	515m
	HF#21		47° 39.49	55° 24.45	518m
	HF#22		47° 39.24	55° 24.29	516m
	HF#23		47° 39.06	55° 24.16	526m
	HF#24		47° 38.59	55° 24.01	526m
Bay d'Espoir	HF#10	180,1984	47° 41.48	56° 08.28	760m
	HF#11		47° 41.28	56° 08.10	762m
	HF#12		47° 41.09	56° 07.90	762m
	HF#13		47° 40.90	56° 07.77	760m
	HF#14		47° 40.72	56° 06.20	762m
	HF#15		47° 40.42	56° 07.22	765m
	HF#16		47° 40.35	56° 07.25	765m
Bay St. George	HF#30	183,1984	48° 07.65	59° 17.50	155m
	HF#31		48° 07.73	59° 17.35	155m
	HF#32		48° 07.92	59° 17.20	156m
	HF#33		48° 08.08	59° 17.02	156m
	HF#34		48° 08.22	59° 16.84	156m
	HF#35		48° 08.37	59° 16.64	151m
	HF#36		48° 08.51	59° 16.40	151m
	HF#37		48° 08.62	59° 16.19	151m
	HF#38		48° 08.77	59° 15.93	151m

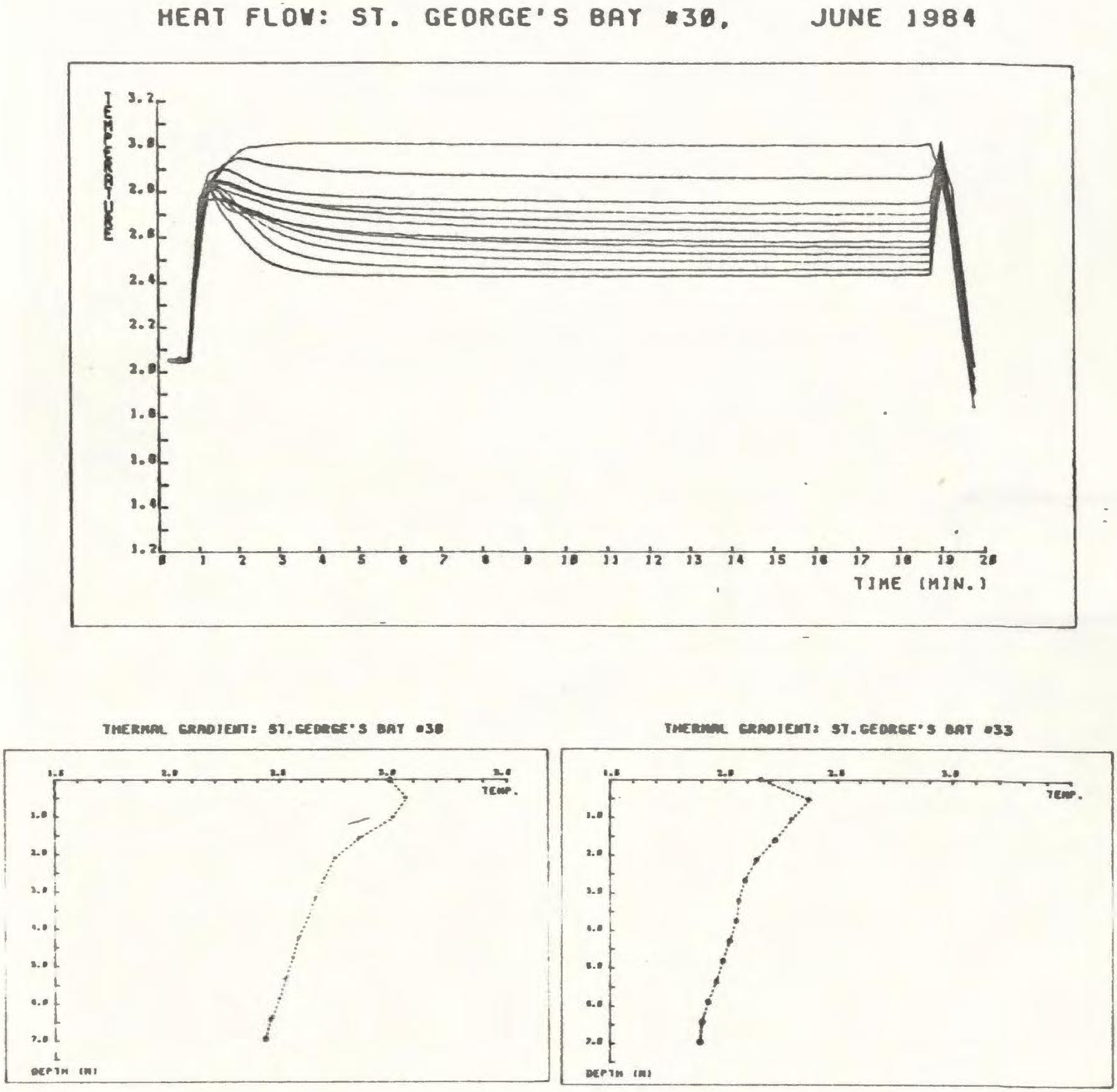
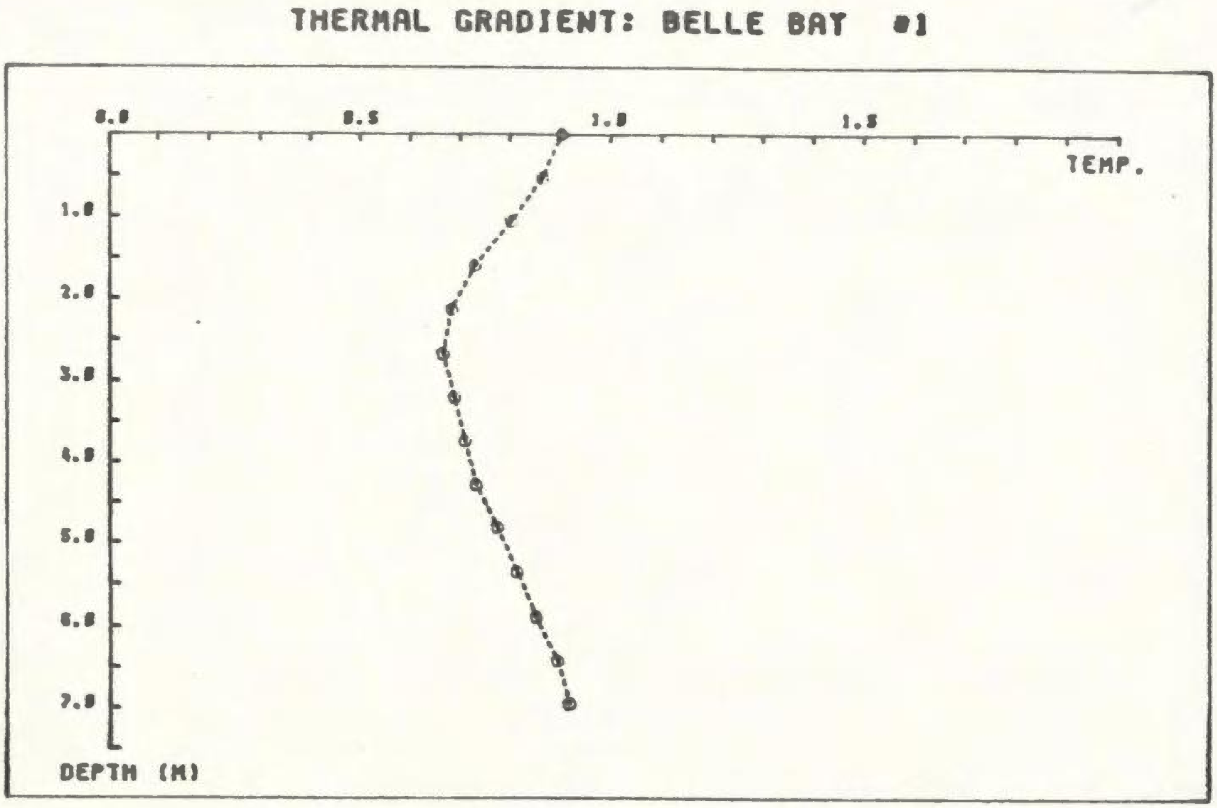


Fig. 6.2 Temp.–time and Temp.-depth graphs for Newfoundland Inlets



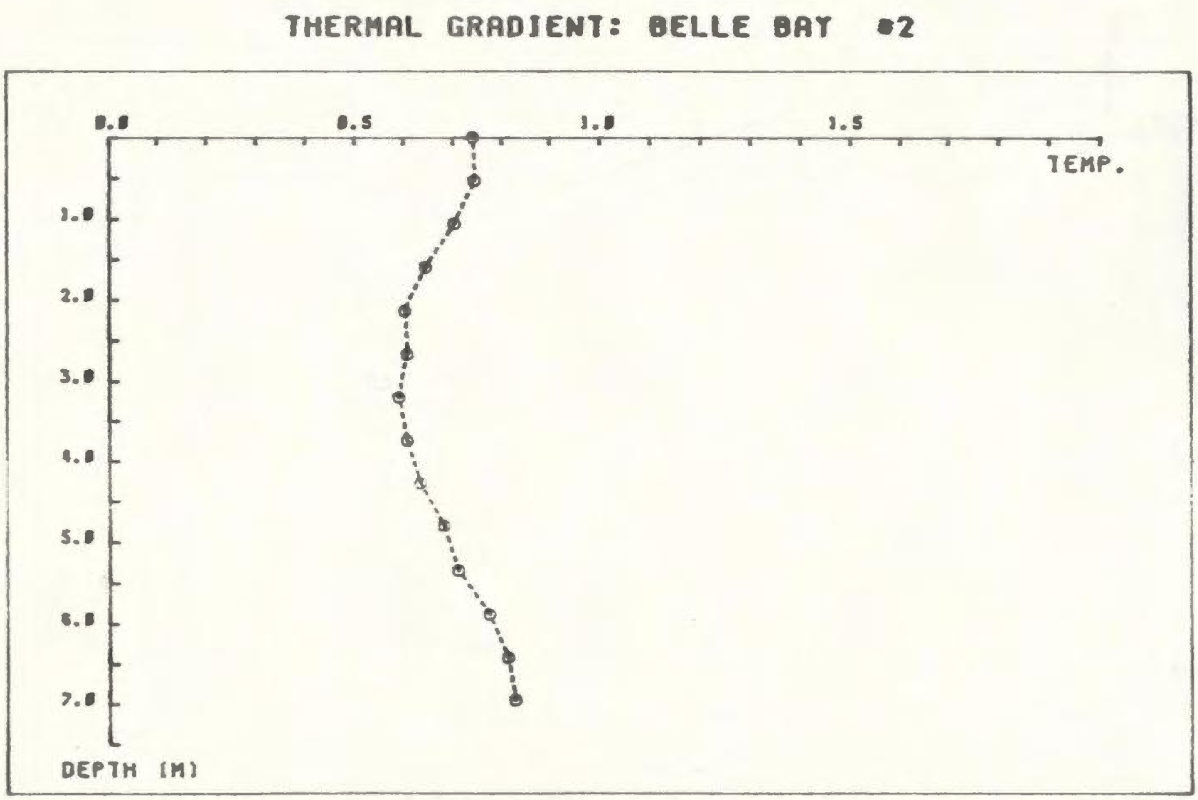
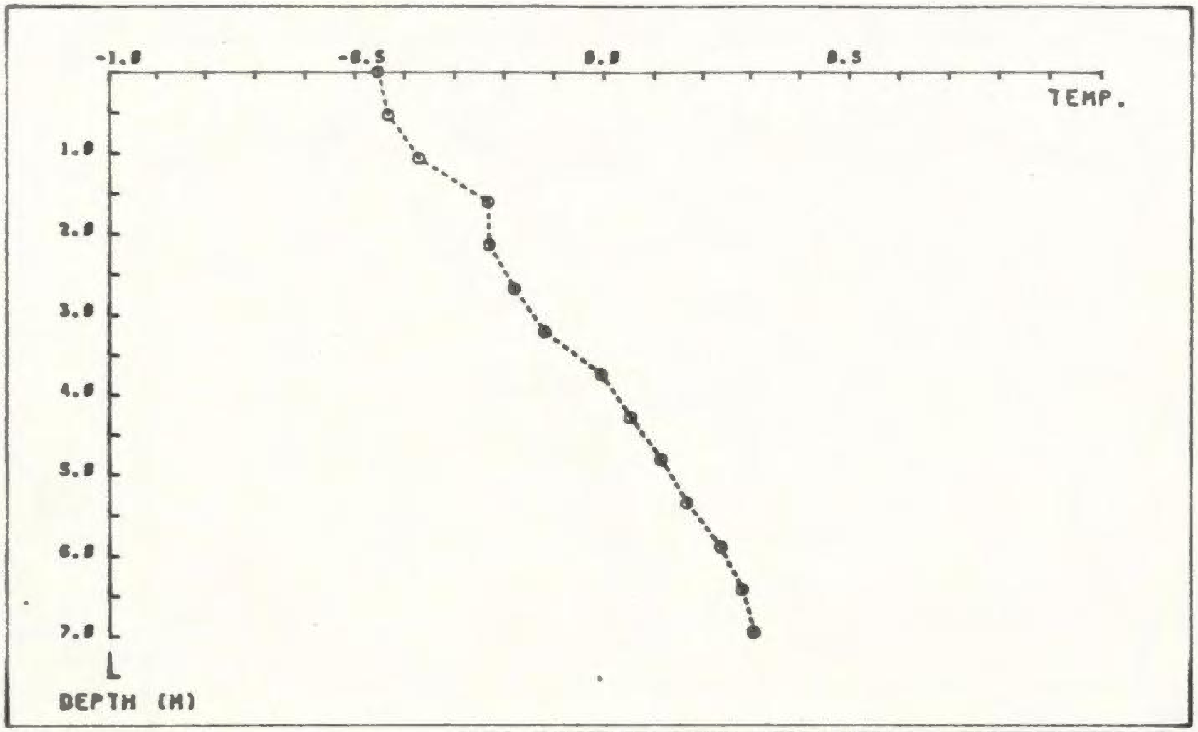


Fig. 6.2 Temp.-time and Temp.-depth graphs (continued)

THERMAL GRADIENT: BELLE BAY #20



THERMAL GRADIENT: BELLE BAY #21

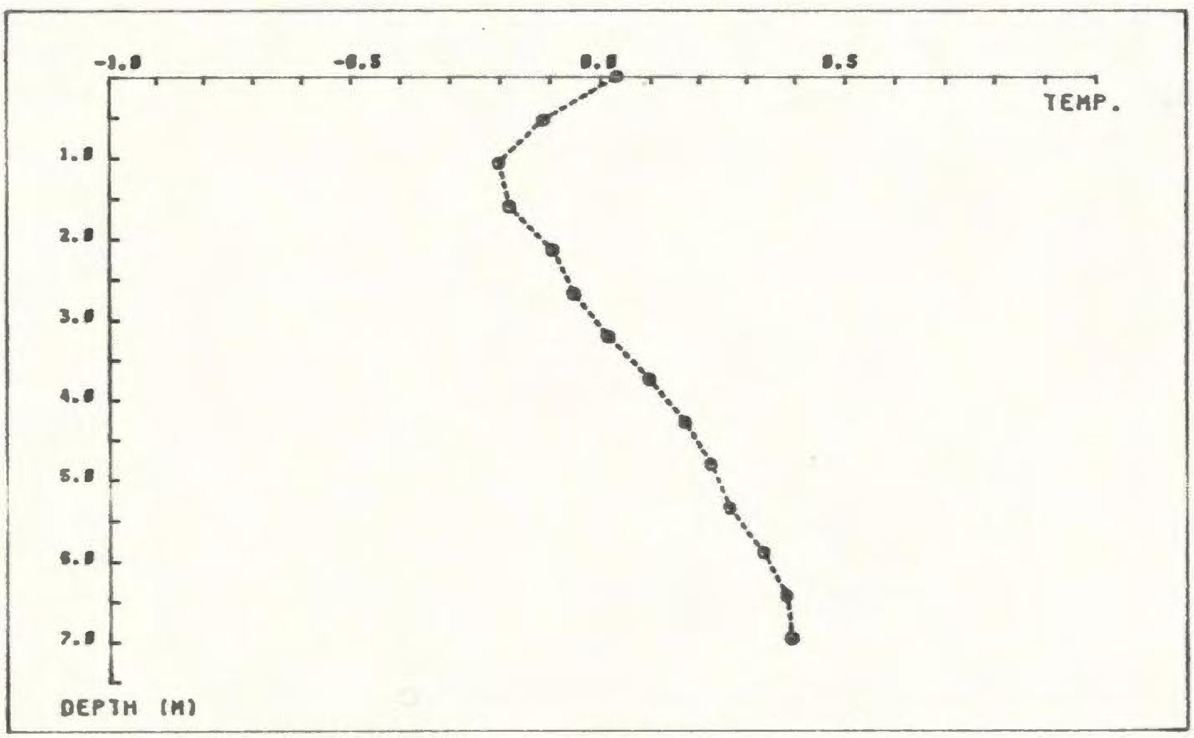
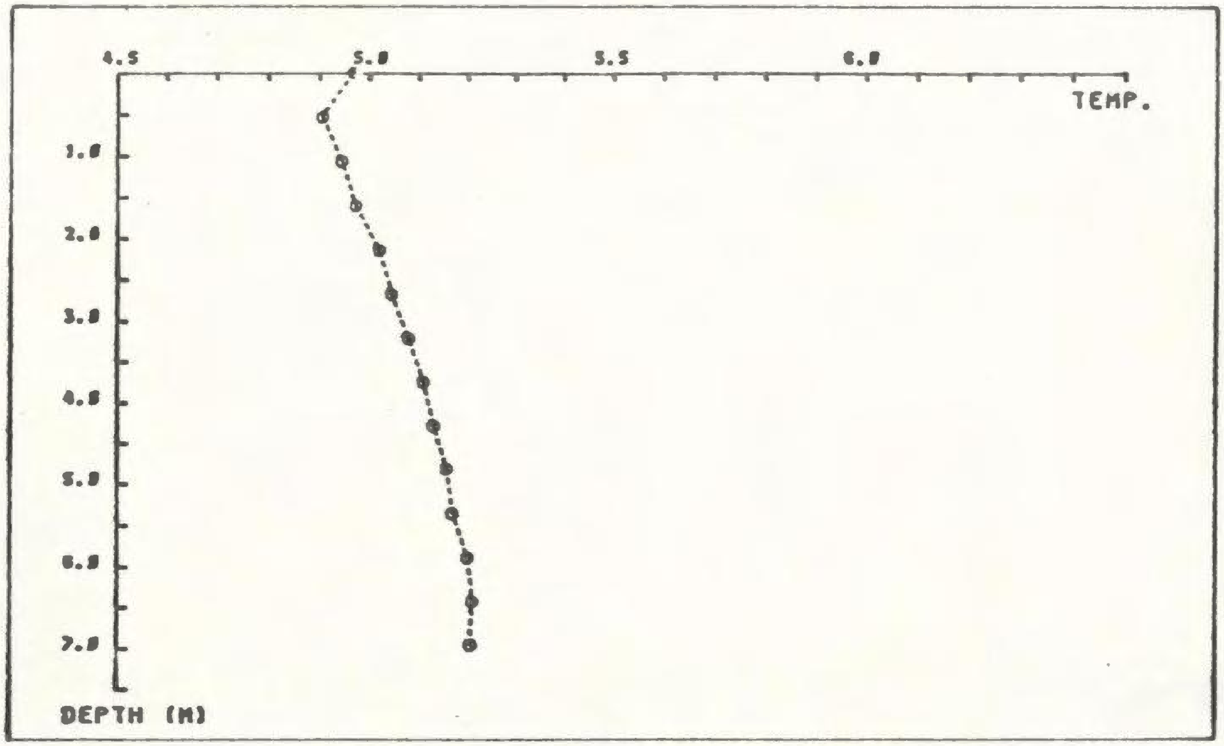


Fig. 6.2 Temp.-time and Temp.-depth graphs (continued)

THERMAL GRADIENT: BAY D'ESPOIR #12



THERMAL GRADIENT: BAY D'ESPOIR #13

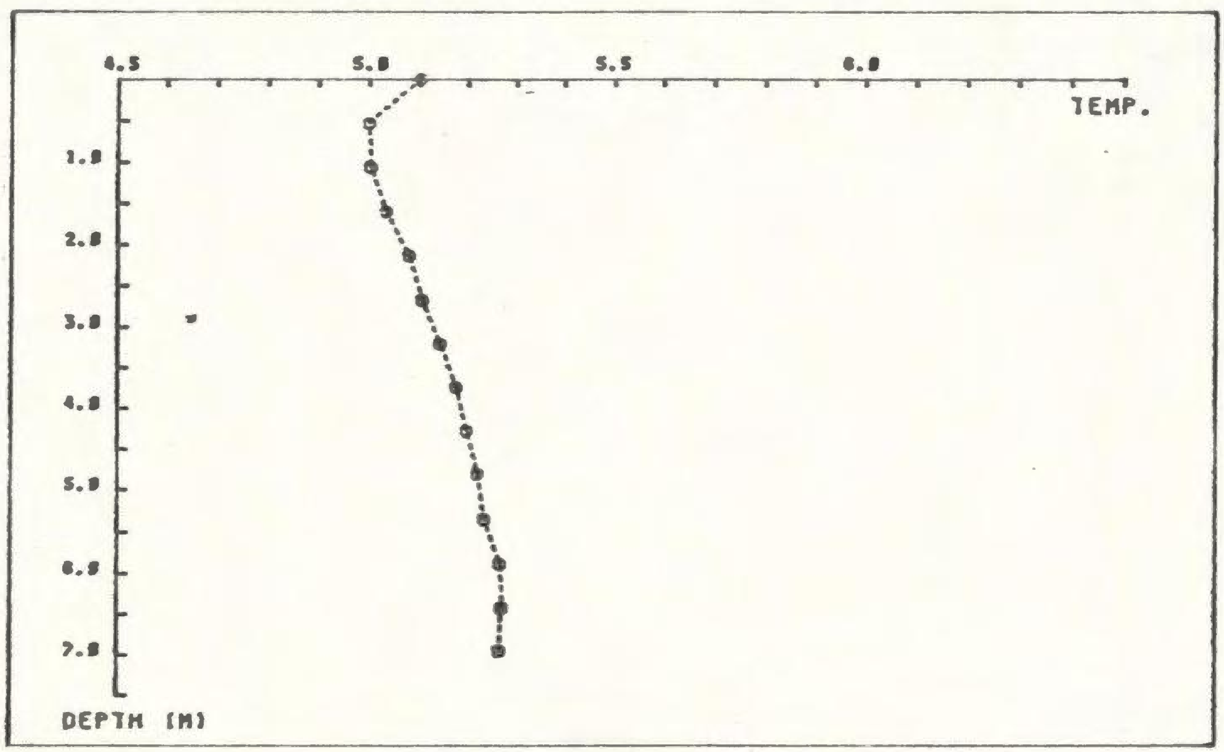


Fig. 6.2 Temp.-time and Temp.-depth graphs (continue)

6.3 Heat flow measurement in the Labrador Sea and Labrador Shelf

Fig. 6.3 is the geographic locations of the heat flow stations on the Labrador Sea and on the Labrador Shelf (Hopedale Saddle).

Table 6.2 lists the detailed information of the heat flow stations at the above localities.

The objectives of the Labrador Sea cruise were to carry out geological and geophysical surveys including heat flow of three sites in the Labrador Sea and one site on the Labrador Shelf as a part of the Ocean Drilling Program. A total of 52 heat flow measurements were made during the cruise by Dalhousie and Memorial Universities using their respective equipment. Table 6.2 lists only the Memorial stations. Fig. 6.4 illustrates the measurement on Labrador Shelf. The detailed results will discussed in Chapter 7.

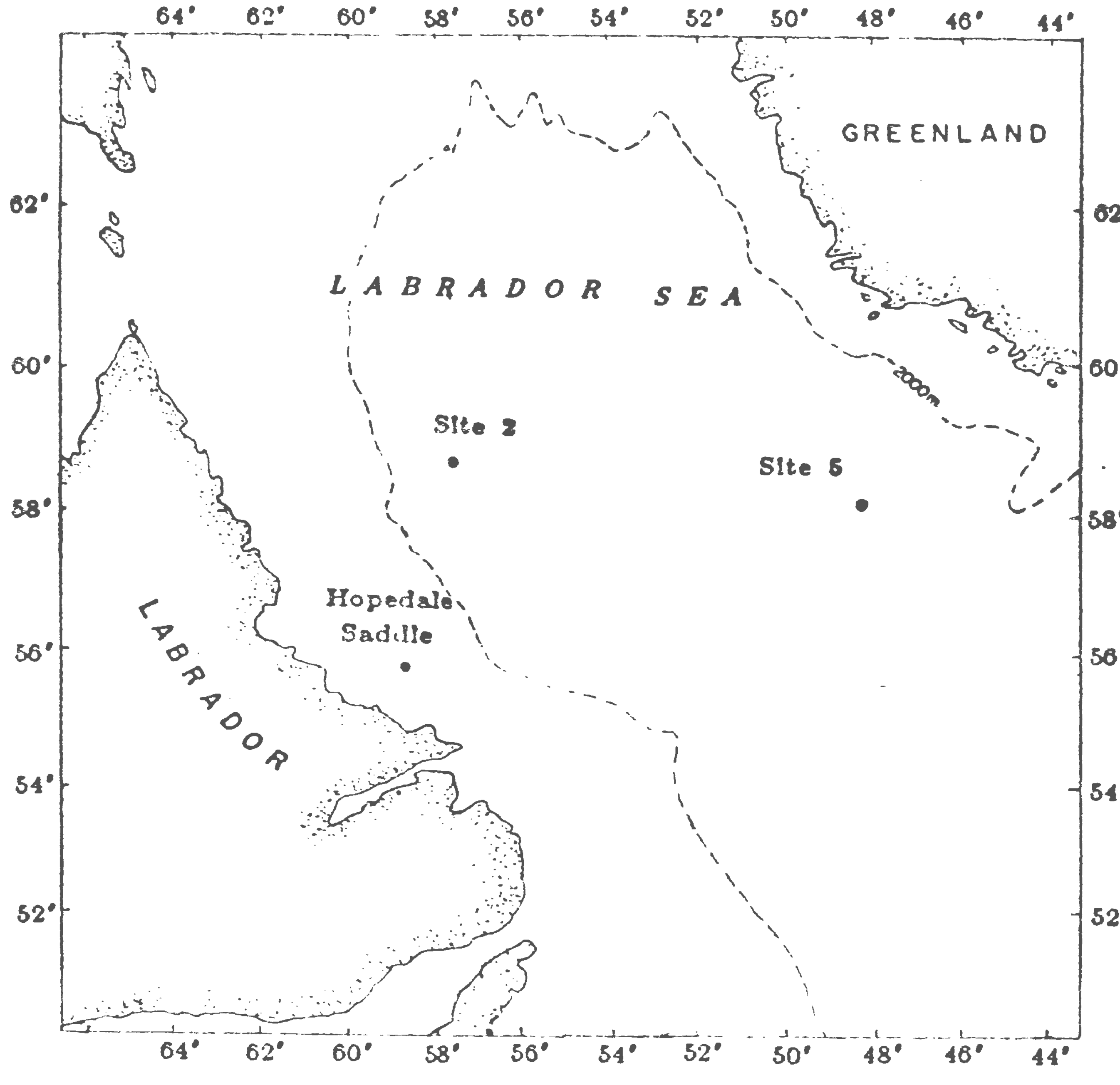
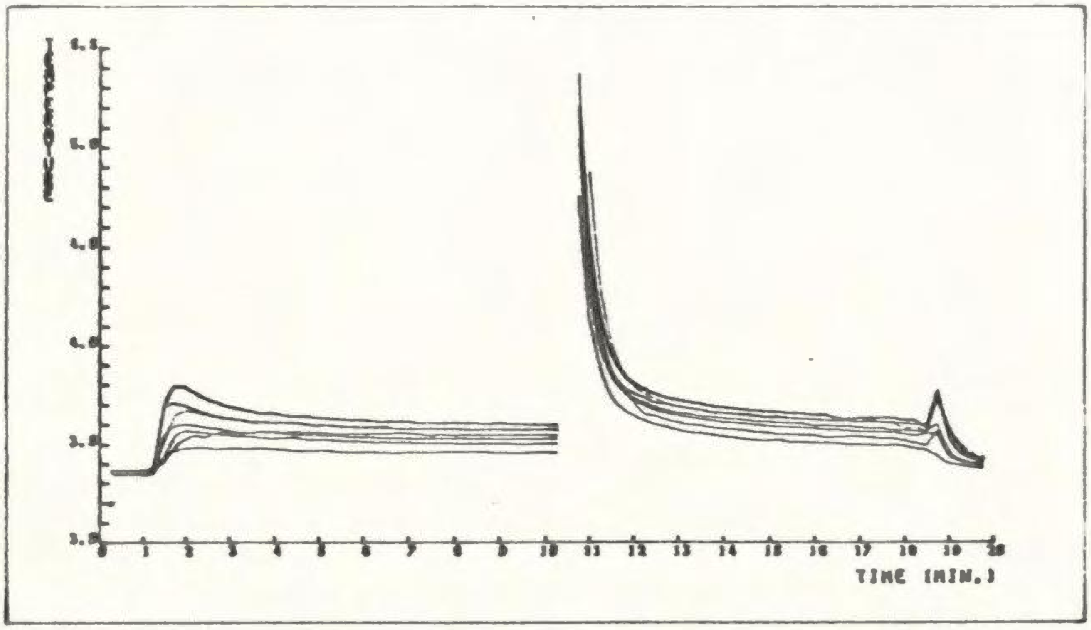


Fig. 6.3 Locations of heat flow stations on the Labrador Sea and Shelf

Table 6.2 Heat Flow Stations in the Labrador Sea and Shelf					
Location	**Station**	**Date**	**Lat. (° N)**	**Long. (° W)**	**Depth (m)**
Site 5	5-1	223,1984	58° 00.84	48° 23.36	3435
	5-2		58° 03.73	48° 21.92	3435
Site 2	2-1	231,1984	58° 30.82	57° 56.17	2614
	2-2		58° 30.71	57° 54.57	2623
	2-3		58° 30.43	57° 53.47	2623
	2-4		58° 30.10	57° 52.42	2655
	2-5		58° 29.65	57° 51.16	2646
	2-6		58° 29.04	57° 49.79	1472
Hopedale Saddle	HS-1	235,1984	55° 49.90	58° 40.52	573
	HS-2		55° 48.49	58° 40.47	594
	HS-3		55° 47.55	58° 41.37	594
	HS-4		55° 46.55	58° 42.02	607
	HS-17	236,1984	55° 38.39	58° 44.47	657
	HS-18		55° 38.19	58° 43.24	641
	HS-19		55° 38.19	58° 41.31	641

HEAT FLOW: LABRADOR SHELF #17, AUG. 1984



THERMAL GRADIENT: LABRADOR SHELF #17

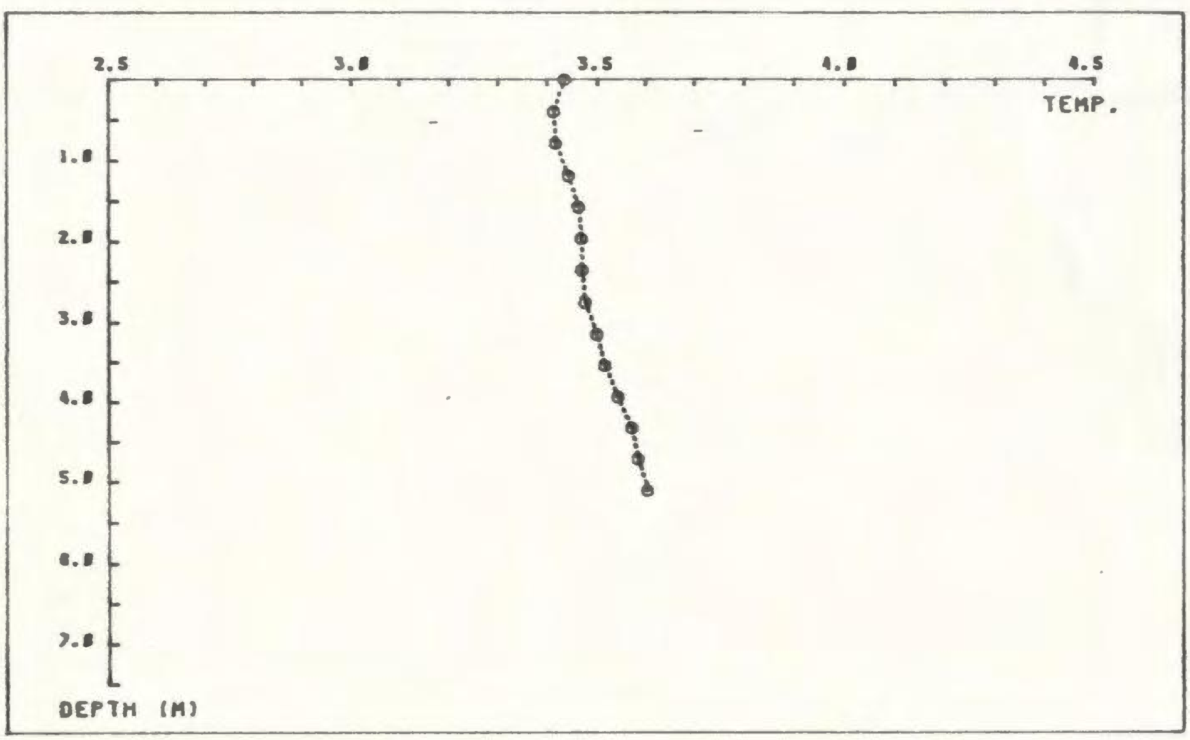


Fig. 6.4 The heat flow measurement on the Labrador Shelf

Chapter 7 Geophysical Interpretation

The geophysical interpretation of the data from the above geological sites, namely the inlets of the south coast of Newfoundland and the Labrador Sea and Hopedale Saddle, is discussed in this Chapter. Some corrections are necessary to obtain a reliable heat flow value, especially in the inlets where the temperature gradient in the sea floor sediments is often disturbed by various geological and geographical factors.

7.1 Heat flow in the inlets of the south coast of Newfoundland

A visual inspection of the temperature-depth graphs of heat flow measurements in the inlets of the south coast of Newfoundland (Fig. 6.2 in Chapter 6) shows that the thermal gradients in these inlets are perturbed to one degree or another by the variation of bottom water temperatures. This is most obviously seen from stations in St. George's Bay #30 and #33, where the geothermal gradients are negative. Without a correction, any attempt to use the calculations for geophysical studies would be suspect.

It will be difficult to carry out the bottom water temperature corrections if the information needed for the correction is not adequate. Usually this entails the use of a long term record of the bottom water temperature at the same locality.

For discussion of the temperature perturbation in the sediments due to the bottom water temperature variation, a mathematical formulation of the problem is discussed below.

The variation of bottom water temperature induces a downward propagation of thermal waves. Consider a semi-infinite solid under the following boundary and initial conditions:

$T = 0$ when $t = 0$

$T = T_o(t)$ at $z = 0$ (z: depth, $z = 0$ is the water-sediment interface)

The temperature distribution in the solid is expressed as

$$\frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} \tag{7.1}$$

where k is diffusivity of the solid. For the perturbing influence, take $T_o(t)$ to be a periodic function with frequency ω. A standard solution is of the form

$$T = U e^{i(\omega t - \phi)} \tag{7.2}$$

where U is a function of z only. In this solution, T will have period $\frac{2\pi}{\omega}$ and a phase ϕ.

Substituting (7.2) into (7.1)

$$\frac{\partial^2 U}{\partial z^2} = \frac{i\omega}{k} U \quad . \tag{7.3}$$

The solution of (7.3) that is finite as $z \to \infty$ is:

$$U = A\ e^{-z\sqrt{\frac{i\omega}{k}}} = A\ e^{-z(i+1)\sqrt{\frac{\omega}{2k}}} ,$$

thus from (7.2)

$$T = A\ e^{-Kz} \begin{Bmatrix} \cos \\ \sin \end{Bmatrix} (\omega t - \phi - Kz) ,$$

where $K = \sqrt{\frac{\omega}{2k}}$,

and the solution that has the value $A\ \cos(\omega t - \phi)$ at $z = 0$ is

$$T = A\ e^{-Kz} \cos(\omega t - Kz - \phi) \tag{7.4}$$

Equation (7.4) represents a temperature wave with wave number K and wave length S given by

$$S = \frac{2\pi}{K} = \sqrt{\frac{4\pi k}{f}} ,$$ where f is frequency.

The properties of this solution are:

(1) The temperature at water-sediment interface $z = 0$ propagates downwards with a wave length determined by diffusivity k and bottom water temperature variation frequency f. For a numerical example, take the average of diffusivity of sediments $k \approx 0.23 \times 10^{-6} m^2 s^{-1}$ for the daily temperature variation $S = 0.5$ m, for an annual variation $S = 9.5$ m.

(2) The amplitude of the temperature oscillation diminishes exponentially:

$$e^{-Kz} = e^{-z\sqrt{\frac{\omega}{2K}}} = e^{-\frac{2\pi z}{S}}$$

At a depth of one wave length, the amplitude is attenuated by a factor of $\exp(-2\pi) = 0.0019$. If the bottom water temperature is given by a Fourier series, the higher harmonics disappear more rapidly as depth increases.

(3) The temperature variations propagate into the sediments with a velocity $\sqrt{2k\,\omega}$. There is a progressive lag

$$Kz = z\sqrt{\frac{\omega}{2k}}$$

in the phase of the thermal wave. The lag increases with ω. This phase difference between bottom water and deep sediment variations is an important fact and that should be considered when a correction is applied to the measured data.

A sudden change of the bottom water temperature can be treated as a step function. Finding the power spectrum of the step function by Fourier transformation, the temperature propagating in the sediments is obtained by a summation of (7.4) with different periods of individual amplitude and phase lag. For a unit step function of bottom water temperature $B(t)$:

$$B(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases}$$

its Fourier transform is $\frac{1}{i\,\omega}$. A numerical solution of the change with a step function is discussed in Appendix F (also see Von Herzen *et al.*, 1974).

The above analysis shows that a sufficiently long probe overcomes the seasonal influence in the sediments of the sea floor. However, if a temperature perturbation at the depth the probe penetrates is still detectable, a correction must be applied. The analysis also shows that in order to make the correction for bottom water temperature perturbations, it is necessary to have information on the relation between bottom water temperature and time both for the long term and the short term changes. Clearly, for most applications the long term information is more important. In the case of heat flow measurements in Bay St. George, the reversed heat flow may be caused by a sudden and great increase of the bottom water temperature a few years previous to the measurement. Due to the lack of detailed information, the correction is not able to be carried out and the data are thus not interpretable.

Fig. 7.1 illustrates the temperature variations of the bottom water in Belle Bay and Bay d'Espoir during the period of June, 1983 to December, 1984 (Alex Hay, 1985, personal communication). With these bottom water temperature-time records, the correction of temperature perturbation is attempted for the stations at Belle Bay 1 and 2 and Bay d'Espoir. From Fig. 7.1a, a sine wave is a good approximation to the variation of bottom water temperature at Belle Bay 2. The amplitude of the variation is within a range of 1.2 to 1.7 $^\circ$C and the period is about one year. The data processing program HF1601D associated with gradient estimation includes a routine for an annual bottom water temperature perturbation. After the correction of bottom water perturbation, the temperature-depth relations of stations Belle Bay 6-1 to 6-6 are shown in Fig. 7.2. Table 7.1 is a list of the thermal gradient values of these stations before and after the correction.

The thermal conductivity values for all the four locations are not available. An estimation is made by comparing with the heat flow measurements in other

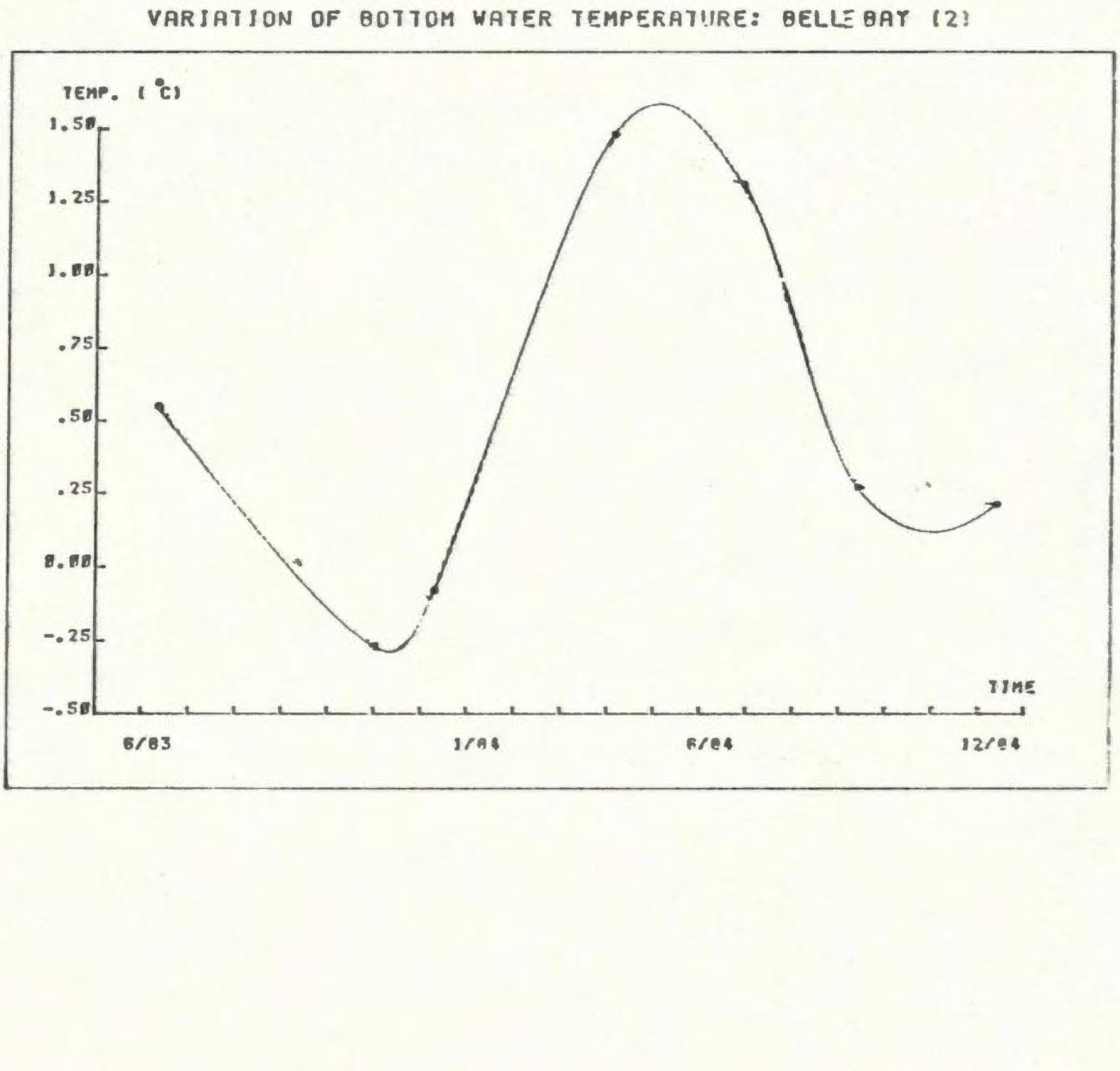
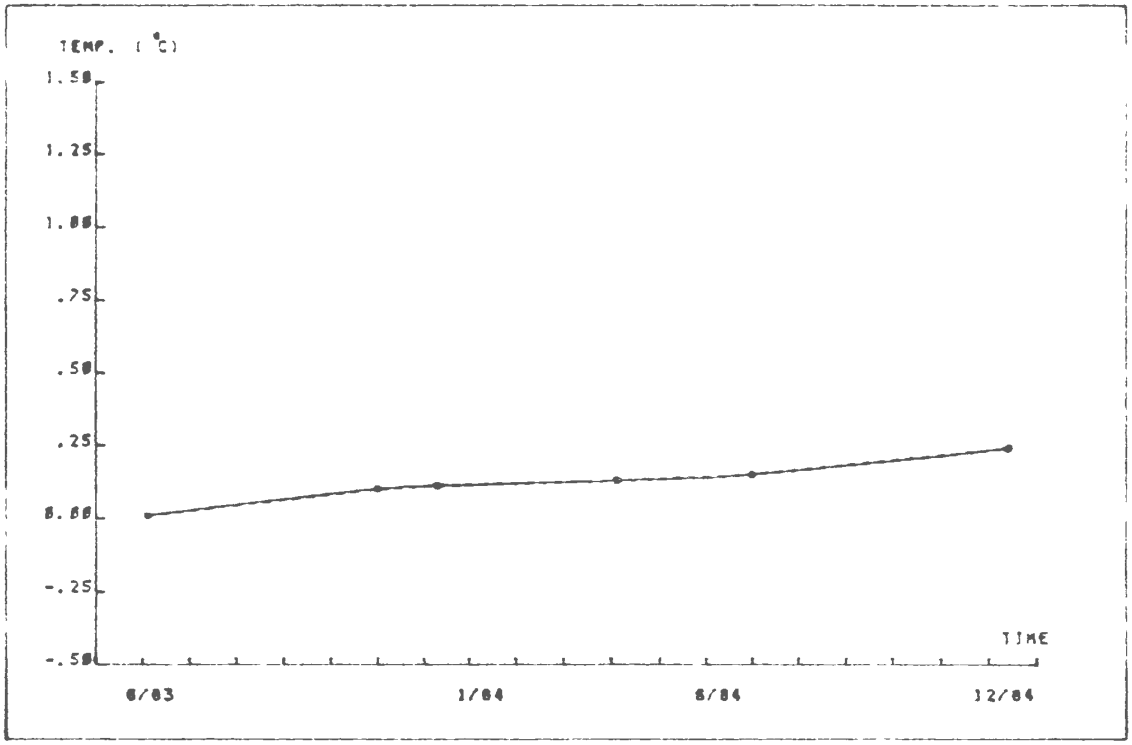


Fig. 7.1a Bottom water temperature record of Belle Bay 2

VARIATION OF BOTTOM WATER TEMPERATURE: BELLE BAY (1)



VARIATION OF BOTTOM WATER TEMPERATURE: BAY D'ESPOIR

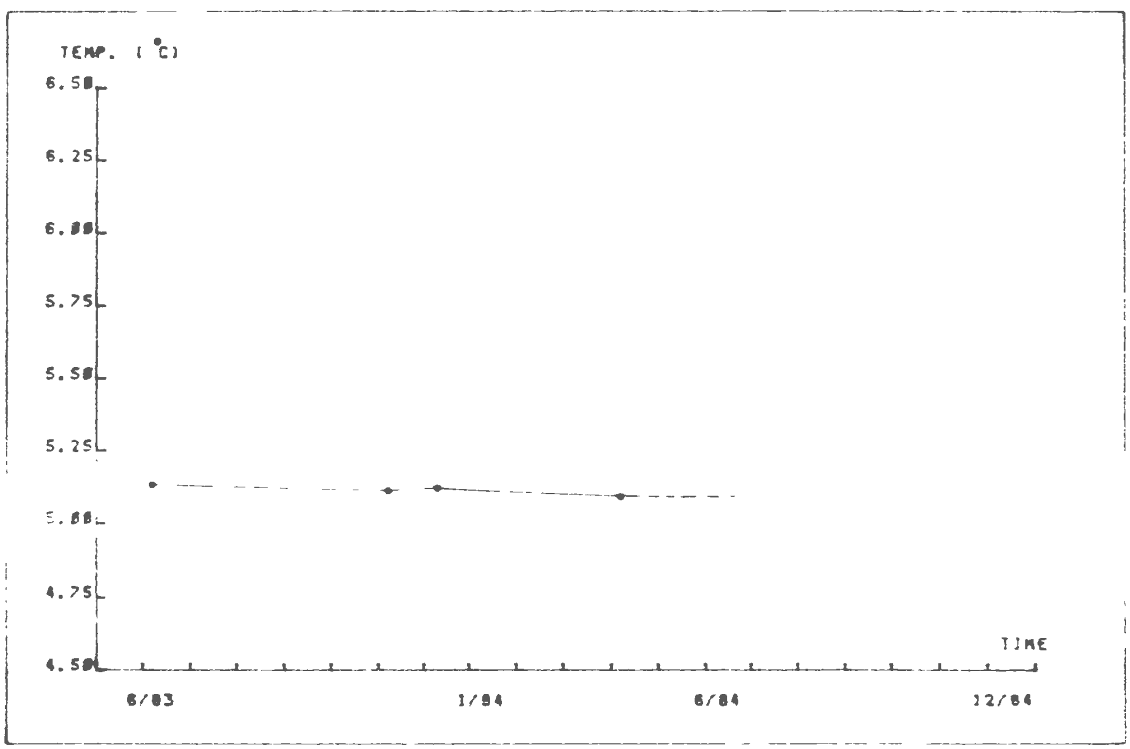


Fig. 7.1b Bottom water temperature record of Belle Bay 1 and Bay d'Espoir

Table 7.1 Thermal gradient at Belle Bay 2				
Station	Gradient (no correction)	Gradient (corrected*)	Correction (mKm^{-1})	Correction (%)
B2-1	63.5	69.4	+5.9	8%
B2-2	70.1	73.1	+3	4%
B2-3	67	69.8	+2.8	4%
B2-4	67.7	65.6	-2	3%
B2-5	63.6	65.1	+1.5	2.5%
B2-6	65	65.5	+0.5	<1%
			average	3.5%
*: for bottom temperature corrections only				

localities in the Newfoundland inlets other than Belle Bay but in the same geological environment. Wright *et al.* (1984) list 14 thermal conductivity values determined by the method of conductivity-water content using core samples from the inlets of northeast Newfoundland. The mean value of these measurements is 0.71 ± 0.16 $Wm^{-1}K^{-1}$. It is consistent with the world mean value for the sea floor sediments (Bott, 1982). Accordingly, the world mean value of thermal conductivity of sea floor sediments 0.8 $Wm^{-1}K^{-1}$ is used for the inlets of Newfoundland with an estimated error of about 15%.

For the heat flow measurements in the inlets, the topographic and sedimentation rate correction may both be important (Wright *et al.*, 1984). A high sedimentation rate reduces the heat flux measured as part of the heat from below is used to warm the sediments as they are buried. The sedimentation rate correction can be as high as +6% in some inlets of northeast Newfoundland (Wright *et al.*, 1984). Mathematically, if the material is added by sedimentation with a rate V, the material below can be regarded as moving away from the surface with the same velocity. Following the analysis of Jaeger (1965), the thermal gradient at

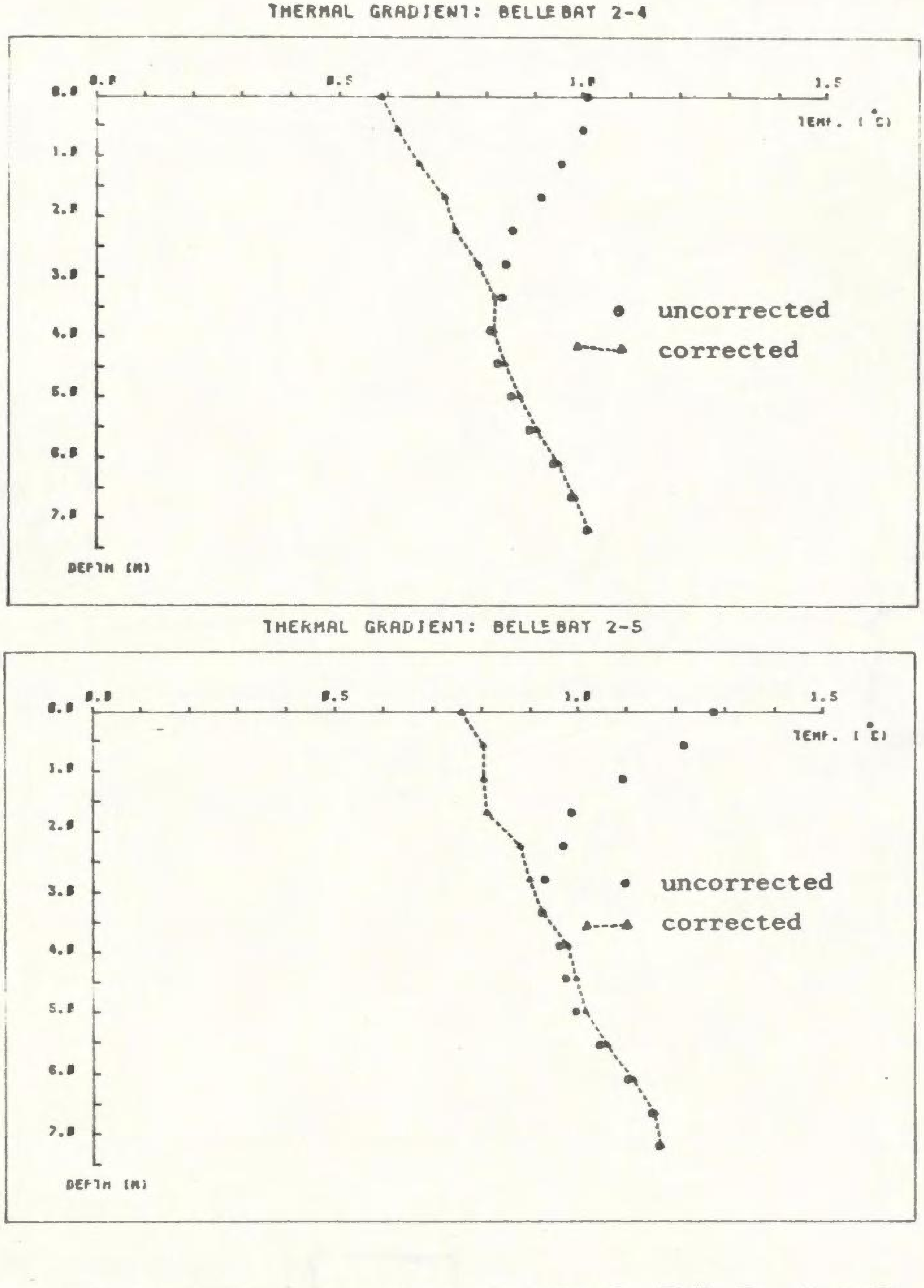


Fig. 7.2 Bottom water temperature correction for Belle Bay 2 stations

the surface of sediment is

$$\frac{\partial T}{\partial z} = q_u \left[1+Q(p)\right]$$

where q_u is the undisturbed thermal gradient at great depth and

$$Q(p) = \frac{1}{2}p^2 - (1+\frac{p^2}{2})\, erf\,(\frac{p}{2}) - (\frac{1}{\sqrt{\pi}}p)e^{-\frac{p^2}{4}}$$

and

$$p = \frac{Vt}{\sqrt{kt}} .$$

Table 7.2 shows the correction values for sedimentation rates of 0.01 to 5 mm per year.

Table 7.2 Sedimentation Correction ($t = 10{,}000$ years, $k = 3\times10^{-7} m^2/s$)

Sedimentation rate (mm/year)	q_0/q_u	Correction (%)
0.01	0.9998	+0.02
0.1	0.998	+0.2
0.5	0.982	+1.8
1.0	0.963	+3.7
2.0	0.927	+7.3
5.0	0.825	+17.5

q_o : Measured thermal gradient on the sea floor

Heat flow is also distorted in an area of steep topography. The observed heat flow at the surface in a valley is greater than normal, whereas that on peaks is below normal, because the isotherms in the rock and sediment are distorted to match the nearly isothermal irregular boundary of the sea floor.

Another correction that should be carried out accounts for refraction of heat at the interface between the unconsolidated sediments and the bedrock. It causes the heat to flow preferentially through areas where the sediment is thinner or the conductivity is higher. Wright *et al.* (1984) give a topographic and conductivity contrast correction up to ±7% to the measured heat flow values in northeastern inlets of Newfoundland.

It should be pointed out that the topography and sedimentation rate as well as conductivity contrast corrections may negate each other under certain conditions making the net correction negligible.

None of the above corrections can be carried out accurately, however, owing to the lack of information needed. Nevertheless, an estimate of heat flux at Belle Bay 2 is attempted. The estimate is based on the heat flow data interpretation for the northeast fiords of Newfoundland (Wright *et al.,* 1984). The major effect on heat flow in that area was rapid deposition of sediments during the glacial maximum about 20 000 years ago. Older sediments were deposited sufficiently long ago that their contribution is negligible. For 25-80 m of sediments, it results in correction of +3% to +12%. A bulk correction of +10% thus assigned to Belle Bay 2. The resultant mean heat flux is 59 mW/m^2 (mean thermal gradient 67.6, conductivity 0.8), with an uncertainty about 20%. This value is comparable with the heat flow measured on land in Newfoundland in the same geological zone. The estimates of heat flux value 50 mW/m^2 and 45 mW/m^2 (Wright *et al.*, 1984) have been assigned to the Avalon zone and the Dunnage zone (Williams, 1979), respectively. Geologically, Belle Bay 2 is located in the Avalon zone.

The record of the bottom water temperature in Belle Bay 1 during June, 1983 to December, 1984 shows a linear increase of temperature with time, the rate is about 0.013 K/month (4.9×10^{-9} K/s). The temperature-depth graphs also imply a sinusoidal temperature variation of the bottom water, with a period that may be longer than one year. Another possible feature of the temperature variation is that the temperature increases linearly for a few years then a sudden drop occurs due to a flood of cold water, causing the temperature-time curve to have a "saw-tooth" shape.

A mathematical model of linear increase at the surface of a semi-infinite solid with zero initial temperature has been established by Carslaw and Jaeger (1959). Solving the following equation

$$\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2}$$

$$T = 0, \quad \text{for } t = 0$$

$$T = T_0 + bt \quad \text{at } z = 0$$

where b is the rate of increase of the surface temperature, yields a solution

$$T = \int_0^t (bu)\frac{\partial}{\partial t}F(z,t-u)\,du$$

where

$$F(z,t-u) = \frac{2}{\sqrt{\pi}}\int_{\frac{z}{2\sqrt{k(t-u)}}}^{\infty} e^{-\xi^2}\,d\xi \quad .$$

The temperature disturbance in the solid due to a linear increase of temperature at the surface is then:

$$T = 4bt \; i^2 erfc \; \frac{z}{2\sqrt{kt}} \tag{7.5}$$

where

$$i^2erfc\ (y) = \frac{1}{4}[erfc(y) - 2y\ ierfc(y)]$$

and

$$ierfc(y) = \frac{1}{\sqrt{\pi}}e^{-y^2} - y^2\ erfc(y)\ .$$

A numerical solution of (7.5) for the 7.5 m heat probe is listed in Table 7.3, given the parameters for the Belle Bay 1 measurement.

Table 7.3 Temperature perturbation by a linear function

Thermistor	Depth (m)	Temperature perturbation (K)
14	0	0.15
13	0.55	0.0548
12	1.10	0.0383
11	1.66	0.0261
10	2.22	0.0169
9	2.77	0.0107
8	3.32	0.0067
7	3.87	0.0043
6	4.43	0.0052
5	4.98	0.0014
4	5.54	0.0008
3	6.09	0.0004
2	6.65	0.0002
1	7.2	0.00006

Table 7.3 shows that the temperature perturbation in the sediment is negligible at a depth greater than three meters in the case of the bottom water temperature variation rate about 0.013 K/month. The correction for the linear surface temperature variation is then unnecessary. Applying a sine wave correction for the bottom water temperature variation with a period of 5 to 10 years, which represents the basic harmonic of the "saw-tooth" wave, and an amplitude of 0.3 K, the resultant thermal gradient calculations are listed in Table 7.4.

Table 7.4 Thermal gradient at Belle Bay 1			
Station	Gradient (mK/m)	Mean gradient (mK/m)	Heat flux* (mW/m^2)
B1-20	93		
B1-21	86		
B1-22	91.3	86±5.9	74±13
B1-23	79.3		
B1-24	83.7		
*: conductivity 0.8 W/Km, +10% correction			

Table 7.4 also gives an estimation of heat flow value of 74 mW/m^2, with a bulk correction of +10% as commented for Belle Bay 2. The high heat flux compared to the mean heat flux of the Avalon zone has two possible explanations: the conductivity estimation of 0.8 Wm^{-1}K^{-1} is higher than reality or there exits a heat source such as granite intrusion with high heat production in the vicinity of Belle Bay.

Compared with Belle Bay, the bottom water temperature in Bay d'Espoir is less influenced by the cold ocean current that flows into some of the inlets on the southeast coast (Alex Hay, 1985, personal communication). The bottom water temperature is about 5 K higher than that of Belle Bay 1 and 2. The temperature recording of the bottom water within the same period shows no detectable variations, although the temperature-depth graphs of the heat flow measurements indicate a long term influence that may have a "saw-tooth" shape. Like the station at Belle Bay, only an estimate for topography and sedimentation rate corrections can be done. The tentative calculations of the thermal gradient and heat flux are shown in Table 7.5. The heat flow stations in Bay d'Espoir are located in the Dunnage zone. The resultant heat flux is consistent with the Dunnage zone value measured on land (45 mW/m^2).

Table 7.5 Thermal gradient at Bay d'Espoir

Station	gradient (mK/m)	Mean gradient (mK/m)	Heat flux * (mW/m^2)
E10	39.7		
E11	58.2		
E12	51.5		
E13	53.4	52±5.7	45.6
E14	55.3		
E15	56.9		
E16	50.8		

*: conductivity 0.8 W/Km, +10% correction

7.2 Heat flow in Labrador Sea and Labrador Shelf

7.2.1 Labrador Sea spreading models

Heat flow measurements have been successfully achieved at two sites in the Labrador Sea, namely ODP sites 2 and 5. The geophysical interpretation is centered on an estimate of the age of the sea floor at the localities and their relevant tectonic features.

The Labrador Sea was formed by sea floor spreading. According to Srivastava (1978), there are two phases of opening for the Labrador Sea, occurring 75-60 Ma and 60-40 Ma ago, respectively. The evidence for sea floor spreading is clearly shown by the magnetic anomaly patterns. Other geophysical evidence substantiates the model. A pronounced gravity low in the middle of the sea coin-

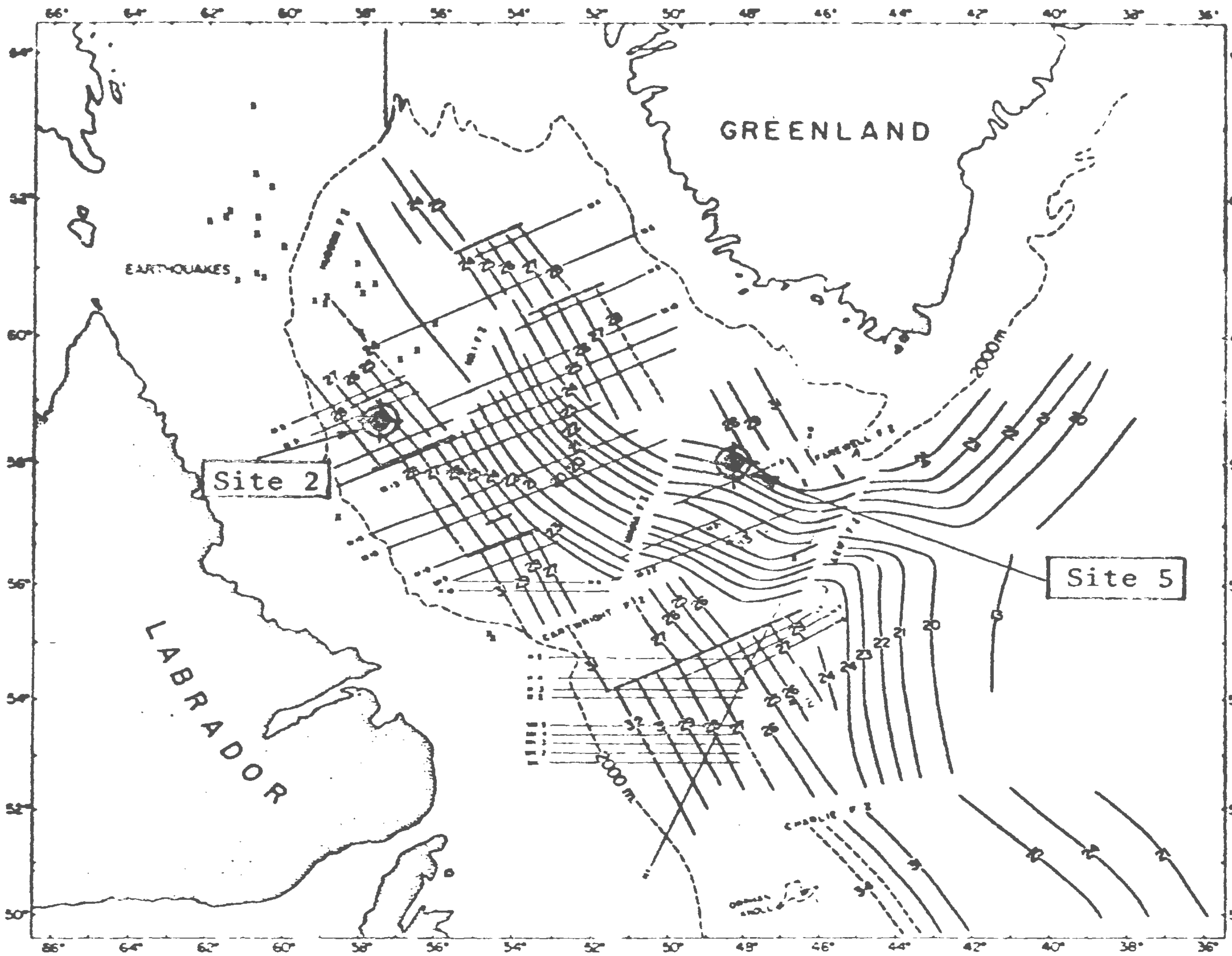


Fig. 7.3 Heat flow stations and magnetic anomaly pattern, Labrador Sea (after Srivastava, 1978)

cides with the axis of symmetry of the magnetic anomalies, marking the position of the mid-Labrador Sea Ridge.

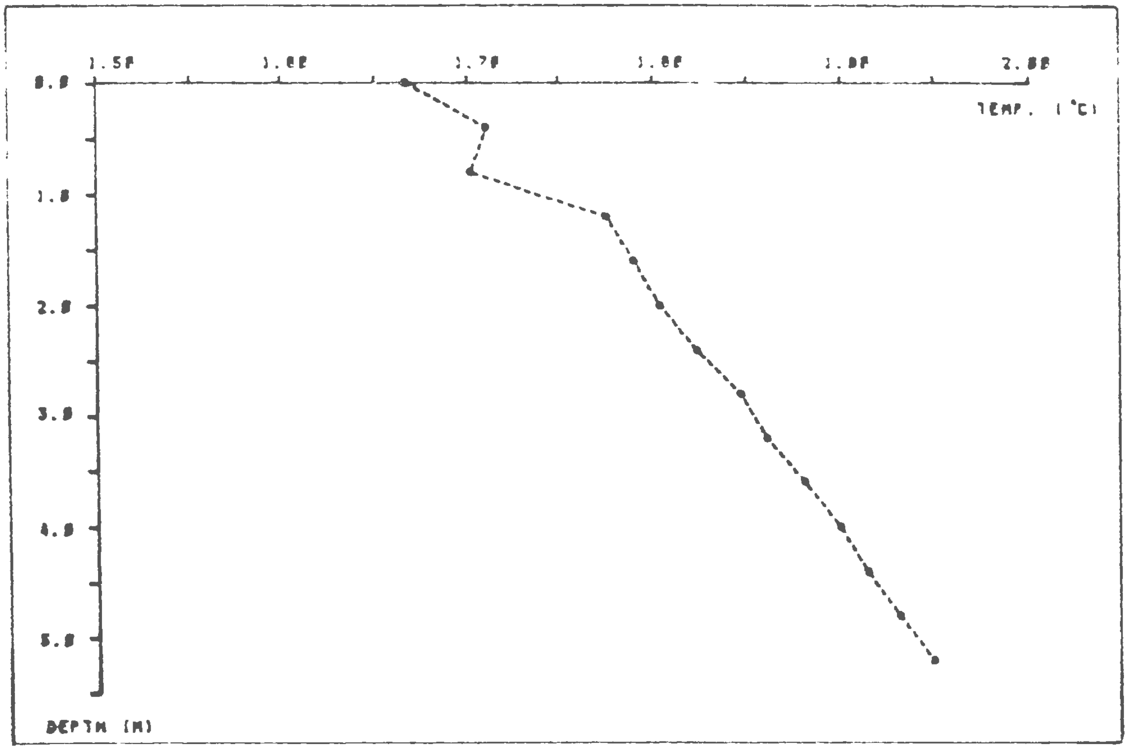
The development of the Labrador Sea and North Atlantic ocean north of Flemish Cap is described by a sequence of events. The sea floor spreading between Newfoundland and British Isles and in the Rockall Trough started around 90 Ma ago. The Labrador Sea started to spread about 75 Ma ago (anomaly 32 time, Fig. 7.3), initiating rifting between Greenland and North America. The time of active sea floor spreading started earlier in the south and later in the north. The absence of anomalies older than magnetic anomaly 28 and the presence of thinned continental crust in the northern Labrador Sea result from stretching of the crust rather than true sea floor spreading during the time when sea floor had already started to spread in the southern Labrador Sea (75 Ma). True sea floor spreading in the northern Labrador Sea started at anomaly 28 time (55 Ma). Sea floor spreading in the Labrador Sea ceased about 40 Ma ago.

7.2.2 Heat flow in the Labrador Sea

The two sites of heat flow stations and the magnetic anomalies are shown in Fig. 7.3. Site 5 is located in the southern part of the Labrador Sea between anomalies 23 and 24, whereas Site 2 is located in the northern Labrador Sea close to anomalies 26 and 27.

Fig. 7.4 shows the temperature-depth graphs of two stations at Site 2 and Fig. 7.5 shows those of two stations at Site 5. About 4 meters penetration at Site 2 (probe length 7.5 m) and 5 meters at Site 5 (probe length 5.5 m) are observed.

THERMAL GRADIENT: LABRADOR SEA, SITE 2-3



THERMAL GRADIENT: LABRADOR SEA, SITE 2-6

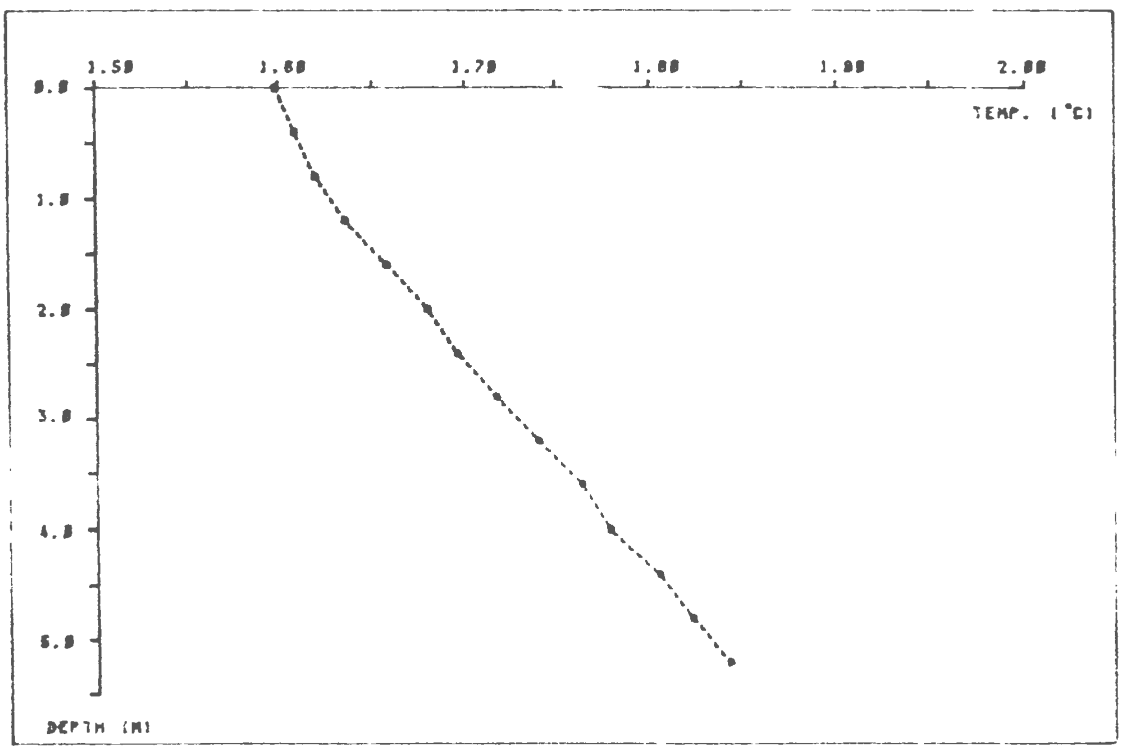
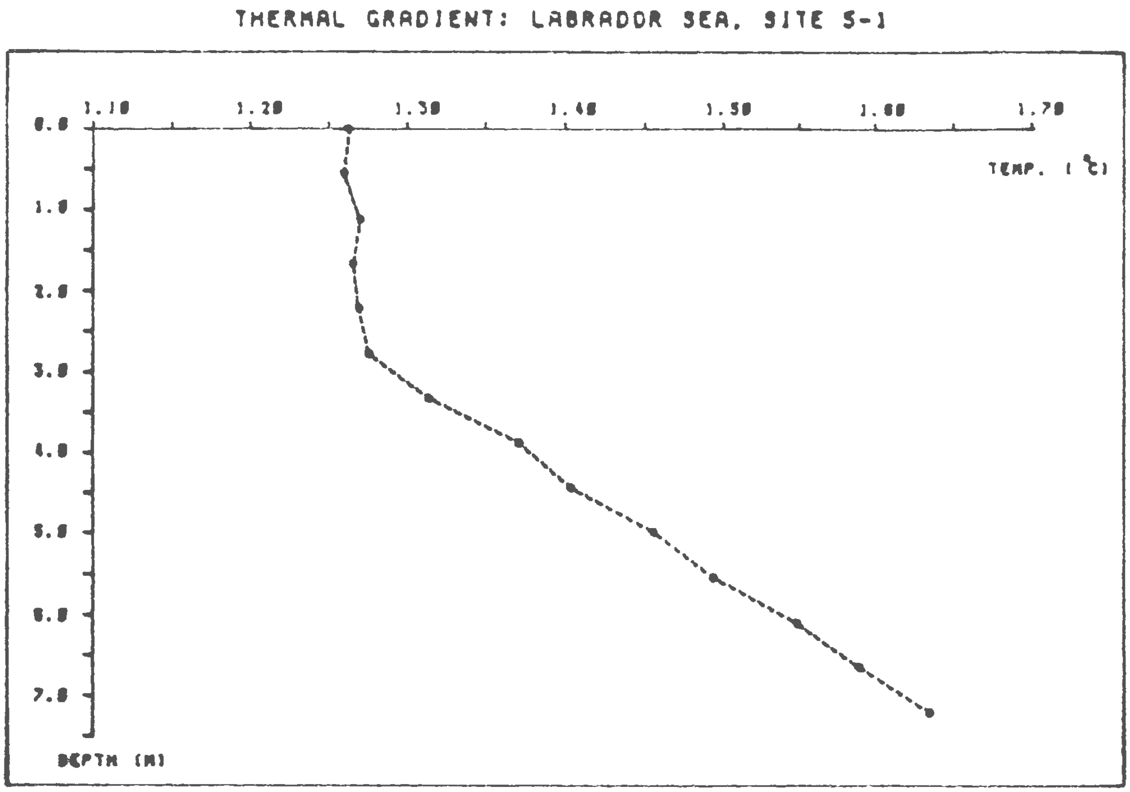


Fig. 7.4 Heat flow measurements at Site 2



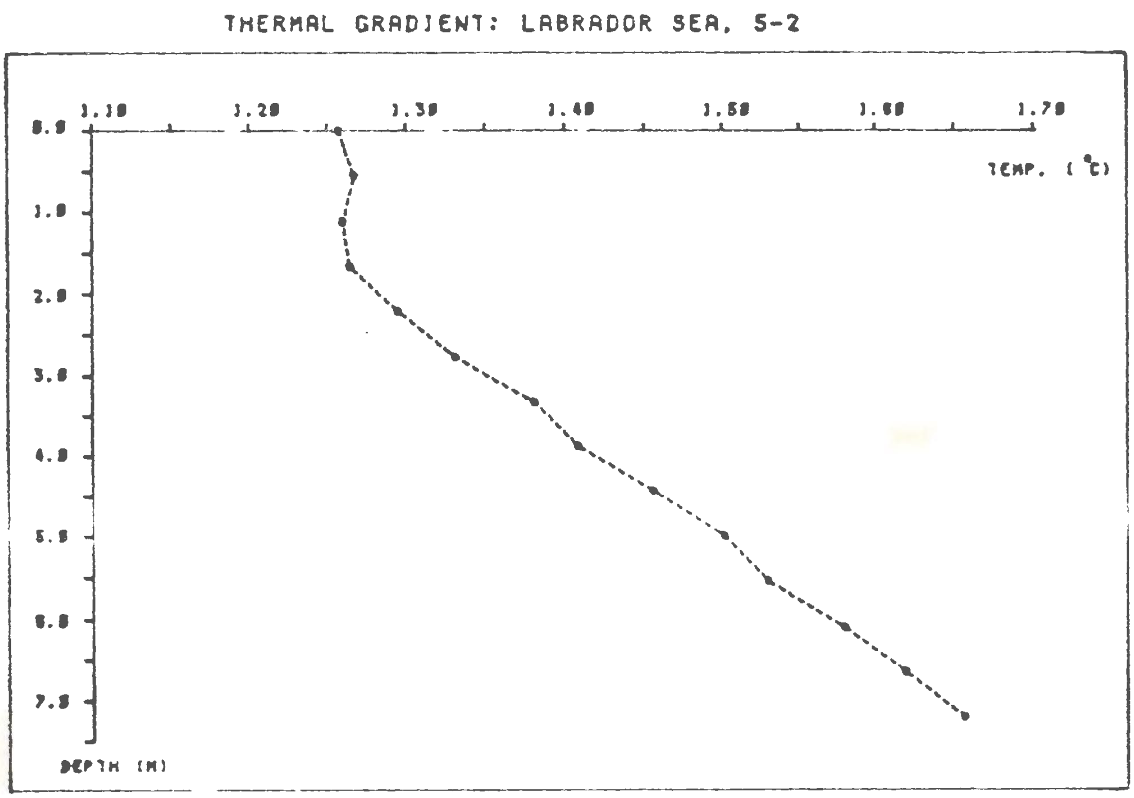


Fig. 7.5 Heat flow measurements at Site 5

Little bottom water temperature perturbation is recorded due to the great water depth (2600-3800 m).

A least-squares fitting line including all the thermistors that penetrated is used to derive the thermal gradient for all the stations. The thermal conductivity values of the sediments are reduced from the *in situ* conductivity measurements, with the values measured by needle probe method from the core samples (Keith Louden, personal communication) as a quality control. For station 2-4 and 2-6 where no *in situ* measurement was conducted, a mean value of the site is assigned.

Table 7.6 lists the thermal gradient, conductivity and heat flow results for the stations at both sites.

Table 7.6 Heat flow measurement on the Labrador Sea

Station	Gradient (mK/m)	Conductivity ($Wm^{-1}K^{-1}$)	Heat flow (mW/m^2)	Mean heat flow (mW/m^2)
2-1	48.3	1.48	71.5	
2-2	54.2	1.27	68.8	
2-3	43.9	1.49	65.4	69±5
2-4	44.4	1.43*	63.5	
2-5	53.8	1.33	71.6	
2-6	50.7	1.43*	72.5	
5-1	83.3	0.89	74.7	73±3
5-2	74.4	0.95	71.1	

*: mean value of thermal conductivity of Site 2.

According to the plate model and the boundary layer model discussed in Chapter 1, The heat flow and the sea floor depth can be predicted knowing the age of the sea floor. Parsons and Sclater (1977) and Sclater *et al.* (1980a) give a group of simplified formulas for estimating the depth, heat flow and age of the sea floor, which are listed in Table 7.7. These relations give the prediction of heat flow and depth of the sea floor at Site 2 and Site 5

Site 2 $\quad Q(t) = 63 \pm 2$ mW/m^2, $\quad D(t) = 5140 \pm 70$ m;

Site 5: $\quad Q(t) = 66 \pm 2$ mW/m^2, $\quad D(t) = 5025 \pm 60$ m.

Table 7.7 Simple relations between depth, heat flow and age of the sea floor (after Parsons and Sclater, 1977)

Age	Relation
	Depth
0-70	$D(t) = 2500 + 350\ t^{0.5}$
>20	$D(t) = 6400 - 3200\ e^{-\frac{t}{62.8}}$
	Heat Flow
0-120	$Q(t) = \dfrac{473}{t^{0.5}}$
>60	$Q(t) = 37.5 + 67\ e^{-\frac{t}{62.8}}$

t is in millions of years, $D(t)$ is in meters, $Q(t)$ is in mWm^{-2}. The decay of the radioactive elements contributes 4mWm^{-2} to the heat flow

Table 7.8 summarizes the values of heat flow and the sea floor age at the two sites determined by magnetic anomaly and by observation.

Table 7.8 Heat flow and age of the Labrador Sea floor

Location	Magnetic anomaly number	age of magnetic anomaly	Heat flow measured (mW/m^2)	Heat flow predicted by age (mW/m^2)
Site 2	26 - 27	55 - 60	69±5	63±2
Site 5	23 - 24	50 - 55	73±3	66±2

The comparison in Table 7.8 shows that the heat flow values derived from magnetic ages are comparable with those observed, although the observed values are slightly greater. However, the depths of sea floor (basement depth, with sediments removed) determined from the magnetic age or the heat flow at both sites are much greater than the observed values (Table 7.9).

Table 7.9 Age of sea floor and water depth in the Labrador Sea

Location	Water depth (measured)	basement depth *	basement depth (magnetic)	basement depth (heat flow)
Site 2	2630 m	3585 m	5140±70 m	4900±260 m
Site 5	3230 m	4270 m	5025±60 m	4770±420 m

*: personal communication with Louden, K., 1985

If the age of the Labrador Sea has been correctly interpreted from magnetic anomalies, then both the heat flow and bathymetry point to lithospheric temperatures in excess of what is predicted from standard plate tectonic models. The fact that bathymetry is even shallower than is consistent with observed heat flow suggests that the Labrador Sea may have formed by a variation on the basic extensional process postulated by McKenzie (1978). Consideration of such possibilities requires more data and is beyond the scope of this thesis.

7.2.3 Heat flow on the Labrador Shelf

Heat flow measurement on the Labrador Shelf (Hopedale Saddle) is summarized in Table 7.10.

The average water depth of the heat flow stations on the Hopedale Saddle is 610 m. The bottom water temperature variation is detectable (Fig. 6.5). As information on the bottom water temperatures is lacking, no corrections have been applied. The heat flow is derived from individual thermistors by calculating

Table 7.10 Heat flow on Hopedale Saddle				
Station	Gradient (mK/m)	Conductivity ($Wm^{-1}K^{-1}$)	Heat flow (mW/m^2)	Mean Heat flow (mW/m^2)
HS-1	31.3	0.96	30	
HS-2	24.1	0.92	22.3	
HS-3	31.5	1.06	33.3	
HS-4	-	-	-	28.3±4
HS-17	24.9	1.02	25.4	
HS-18	33.4	0.85	28.5	
HS-19	33.6	0.90	30.2	

the gradient between adjacent thermistors and multiplying it by the conductivity values determined for each thermistor. The resultant heat flow is the harmonic mean of all individual interval heat flows.

The relatively low heat flow value determined for the Hopedale Saddle is unexpected. Rifting between Labrador and Greenland may have commenced as recently as 55 Ma ago and if so the heat associated with that rifting would not yet have dissipated. Therefore, the heat flow value is expected to be higher than 35 mW/m^2 (a typical deep sea floor heat flow value). Long term past bottom water temperature changes or relatively high sedimentation rate may be responsible for the abnormal low value. However, no correction can be carried out at the present time due to the lack of necessary information.

7.3 Summary of Results

The interpretation shows that more data are required to complete the study of the thermal regimes of these sites. In the inlets, long-term bottom water temperature recording should be carried out. Repeating measurements in different seasons and with longer time intervals (e.g. several years) will give more accurate correction for the bottom water temperature disturbance.

More heat flow measurements in the Labrador Sea are needed to see if the apparent discrepancy between the heat flow predicted by the heat flow - depth - age models and the observed heat flow values is real. If so, its explanation must probably be sought in the mechanism of margin formation.

It is possible to assess the thermal maturity of the sediments in the Hopedale basin with more heat flow measurements.

Chapter 8 Summary

The dissertation describes the development of a new heat probe and its application to geophysical study. The design of the heat probe is based on the fact that a computer-based, programmable heat probe can meet the demand of modifying and revising the probe's function as the programme develops. This instrument incorporates several novel features that improve the operation of marine heat flow measurement.

8.1 Instrument and Processing Accomplishments

The new heat probe achieves the following features:

(1) The quality of the determination of geothermal gradient and *in situ* conductivity value is improved by a high resolution data acquisition system, auto-zero adjustment and raw data processing with a time averaging facility.

(2) An underwater acoustic digital data telemetry system using standard data transmission protocol is achieved. This provides the opportunity for monitoring the total operation of the heat flow measurement by observing data acquisition, tilt and the heat pulse on a real-time base. This technique has more applications in geophysics and other oceanic sciences beyond marine

heat flow.

(3) The arrangement of data storage permits rapid data reduction and enhances the storage efficiency.

(4) A software package that complements the probe's operation speeds up the data processing. It embraces the functions of raw data reduction, temperature-time graphing, thermal gradient and conductivity determination. It also allows the data processing to proceed interactively between computer and operator when necessary, and therefore reduces the possibility for error while enhancing the efficiency.

(5) The wide temperature range, the simplicity of operation (starting the instrument, retrieving data and charging batteries on deck without disassembling the pressure case, etc) greatly enhances the reliability of the instrument and improves the efficiency.

8.2 Summaries of Experiments and Data

A series of sea trials and scientific cruises proved that the design and construction of the microcomputer-based heat probe and its data processing software have achieved the desired goal.

Data have been obtained for two specific geological sites. The heat flow values in the inlets of south coast of Newfoundland are consistent with the values measured on land in the same geological zones. When the necessary geological and oceanographic information are available, in which the long term record of the bottom water temperature variation usually has the primarily importance the heat flow measurement in the inlets is interpretable.

The results of heat flow measurements on the Labrador Sea raise a question related to the thermal regime. It seems that the crust under the Labrador Sea floor is hotter and/or thinner than is predicted by the various sea floor spreading models. This might be the result of the extensional mode of the Labrador margin. Further studies are required to improve the knowledge of the history of the Labrador Sea and the development of its adjacent plates.

8.3 Future Developments

The further development of the heat probe may start with investigating the possibility of a bidirectional acoustic link between the probe and the ship. Developments in software should include functions to correct for sedimentation rate, topography, conductivity contrast and sediment thickness.

More data are required to complete the study of the thermal regime of the Labrador Sea and shelf. Measurements on sites of different magnetic anomalies will render a better understanding of the history of the Labrador Sea and may resolve the discrepancy between the predicted and observed heat flow. With more measurements on the shelf, an attempt at assessing the thermal maturity in the Hopedale basin will be possible.

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Appendix A: Microprocessor and Microcomputer

The design of the HF1601 marine heat flow probe addressed in this thesis involves a microprocessor controlled instrument which contains a fully featured microcomputer. All the information in this appendix is relevant to the design of the probe electronics.

Microprocessor

A microprocessor is a large-scale-integrated (LSI) circuit assembly that contains much of the computing capability of a microcomputer. A digital computer is shown in Fig. A.1. The elements of a microprocessor contain all the functions a CPU (central processing unit) has; namely, ALU (Arithmetic Logic Unit), registers, part of the memory, control section and part of the input and output units.

The operation of a microprocessor is specified by sequences of instruction codes stored in a memory (external to the microprocessor). Sequences of instructions, that is, programs, determine the specific function of a microcomputer-based system. System functions can be easily changed by modifying the program stored in memory. This ability to change function without extensive hardware modifications is the basic advantage of a stored-program computer.

Every instruction execution has three basic subfunctions. They are instruc-

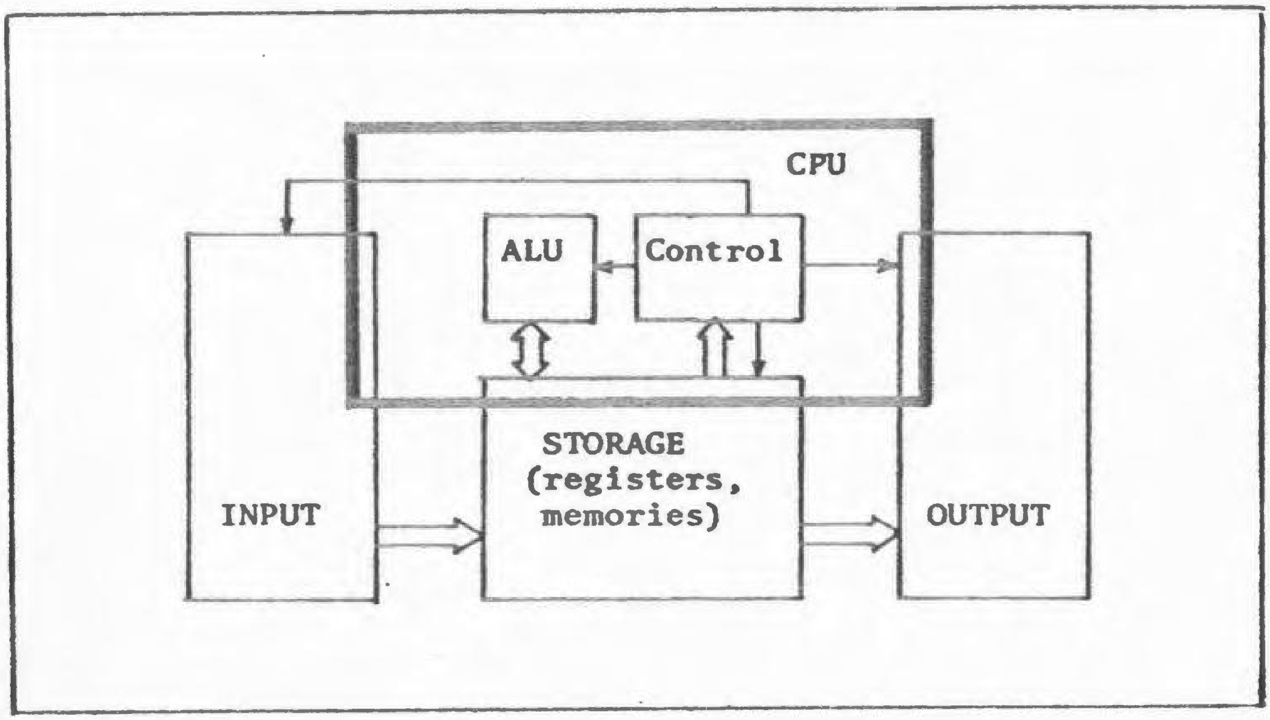

Fig. A.1 Functional Diagram of a Digital Computer

tion fetch, instruction interpretation and instruction execution. All these functions have to progress in a systematic manner organized by 'timing'. Most of the present microprocessors contain the basic timing capability within the chip, requiring only an external frequency determining element (usually a piezoelectric crystal).

A microprocessor contains some supervisory logic called the control section. This section usually consists of the program counter, instruction register, instruction decoder and control generator. The control section links all registers in the microprocessor to perform the requirements of a particular instruction.

The storage section internal to a microprocessor includes mainly a register stack and some of the microprocessors also include ROM and even RAM. The register stack is a collection of individual temporary storage registers. There are some special registers such as stack pointer (SP), condition code register (CCR), etc. and a group of general purpose registers. The general purpose registers are used principally for manipulation and temporary storage of data. They are often called 'scratch-pad' registers.

The Arithmetic Logic Unit of the microprocessor performs the data modifications required to accomplish both logical and arithmetic operations. Several dedicated registers are required to store operands during ALU operations. The most important of these registers is an accumulator which is the principal working register in the microprocessor and frequently it is the I/O port to the CPU. A single-bit register is used to store any overflow information so that it may be included in subsequent calculations. The ALU also contains a status or flag register which indicates certain specific conditions that could arise during certain manipulations. Some typical conditions indicated by flags are overflow, zero, negative sign and carry. In the CPU, flags are used to perform conditional jumps or branches.

The capability of input/output section of a microprocessor is usually determined by software which will be discussed in detail for a particular microprocessor the RCA CDP1802.

Microcomputer

A microcomputer is a digital computer using a microprocessor as its CPU. Fig. A 2 illustrates a microprocessor supported by Input/Output ports and system memory devices making a microcomputer.

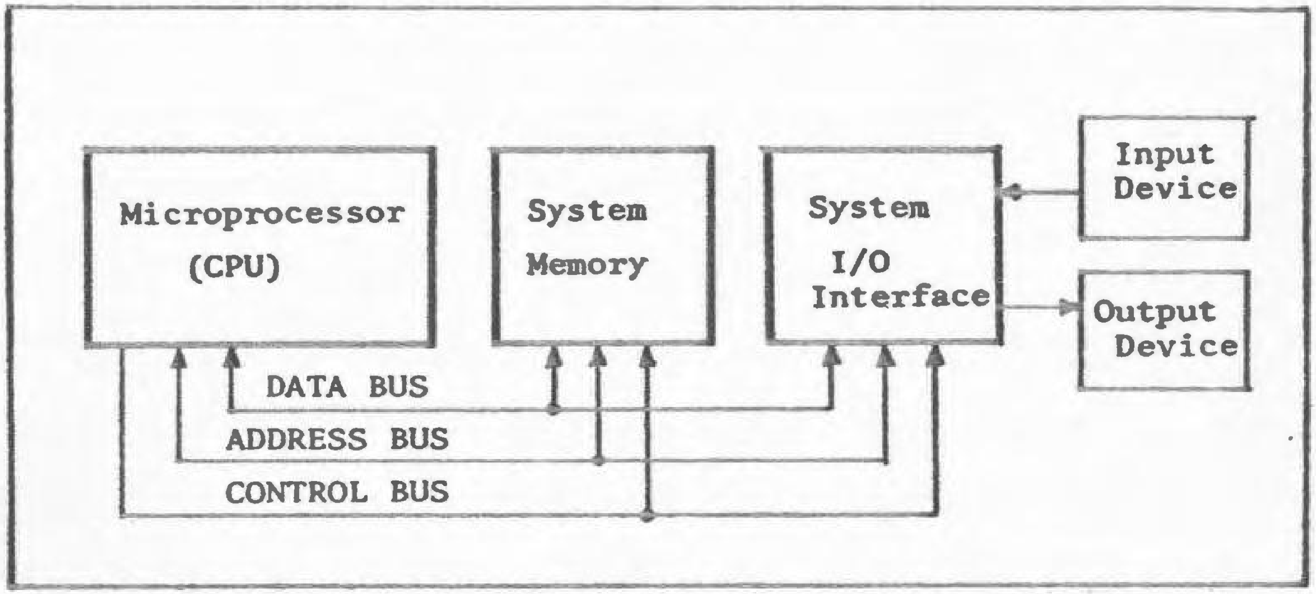

Fig. A.2 Microcomputer

The information exchange between the microcomputer and the peripherals (input/output) has two forms: parallel and serial. A microprocessor is basically a device that accepts information in parallel form. Yet, it must also accommodate input and output devices that furnish and accept information appearing in serial form. The communication between devices and microcomputers separated by any appreciable distance uses serial transmission to reduce the number of lines necessary to carry information. The underwater digital data telemetry must also use serial form.

The computer and peripherals - CRT displays, input keyboards, floppy disk memories, A/D converters, etc. - usually operate at different speeds. Furthermore, the data formats of the peripherals may be different from the format used by the CPU. One or more interface networks are required to provide data and signal compatibility between the CPU and various peripherals. In a microcomputer these interface networks are provided on one or more chips called I/O ports that are separated from the microprocessor chip(s).

For serial I/O ports, problems are created by timing differences between the CPU and the external serial devices. Problems also occur in recognizing and framing the data words in serial bit streams. The serial I/O interface is a programmable unit that performs serial-to-parallel and parallel-to-serial conversion of data. They can operate either in the half-duplex mode (i.e. alternate reception and transmission of data) or in full-duplex (i.e. simultaneous reception and transmission of data).

Serial input may also be accomplished using software (often subroutines). Usually the serial input is supplied to one of the parallel input lines or special external flag lines, and is converted from serial to parallel form by means of software. The same principle can be also used for serial output.

The serial data can be in the form of binary bits or in a predetermined code. One of the most commonly used serial data coding system is ASCII (American Standard Code for Information Interchange).

A microcomputer usually has a chip memory system which is compatible with the low cost, light weight and small sized microprocessor. The most frequently used chip memories are as follows:

ROM (Read Only Memory). The information can only be read out of the addressed location during normal operation of the computer system. Information is written into ROMs either during the manufacturing process or written in by the user by means of special equipment prior to inserting the chip in the computer system. ROMs are non-volatile (Power-off has no influence to the contents), non-destructive readout (NDRO, the process of reading out does not destroy the original information), random access memories (any word or byte can be randomly accessed without going through the prior addresses). In the HF1601 probe, a ROM contains the UT62 monitor program.

EPROM Erasable Programmable ROM. It allows the user to erase the previous bit pattern on chip by exposing to high intensity ultraviolet light for 15 to 20 min, and to rewrite a different pattern. In the HF1601, the heat flow program is written in an EPROM.

RAM Random Access Memory. NDRO, volatile. RAM chips can be further subdivided into two categories: static and dynamic RAMs. Static RAM's storage cells store data in one of the two stable states while dynamic cells store data using absence or presence of an electric charge in a capacitor which should be refreshed periodically since the charge tends to deteriorate with time.

A typical organization in a microcomputer memory system with total capability of 64K 8-bit words memory is as follows: Address bits A0 through A11 are applied to all memory chips for selection of one of 4096 storage locations. Address bits A12 to A15 are used for chip ENABLE (CE) on an appropriate 4K chip(s) through a one-of-sixteen decoder. This arrangement allows the user to assign ROMs and RAMs to any 4K memory blocks. The HF1601 heat flow probe uses this strategy.

The above memory chips constitute the primary memory of the microcomputer. If large storage capacities are needed, external mass memories (also called auxiliary or secondary memories) can be used. Mass memories reside at the lowest levels of memory hierarchies and are capable of storing a vast amount of data in a permanent, non-volatile form at a very low cost. The most commonly used mass storages in a microcomputer are made of magnetic media such as magnetic cassette tape and floppy disk.

Data Acquisition System

Data acquisition is the process of taking analog signals from the real world, processing and converting them to digital data which are to be stored in the computer's memory. A data acquisition system is illustrated in Fig. A.3.

In a heat flow probe, temperature of the sediments or sea water is converted by the transducer to voltage or current. An isolator separates the transducer from the other parts of the system in order to reduce the feedback influence. An amplifier amplifies the signal, if it is necessary, to improve the signal strength for later processing. A filter removes high and/or low frequency noise. These processes aim at increasing the S/N (signal/noise) ratio, a crucial parameter for any electronic instrument. If more than one analog sensing channels is involved in the system, the signal may be switched by an analog multiplexer and sent to a

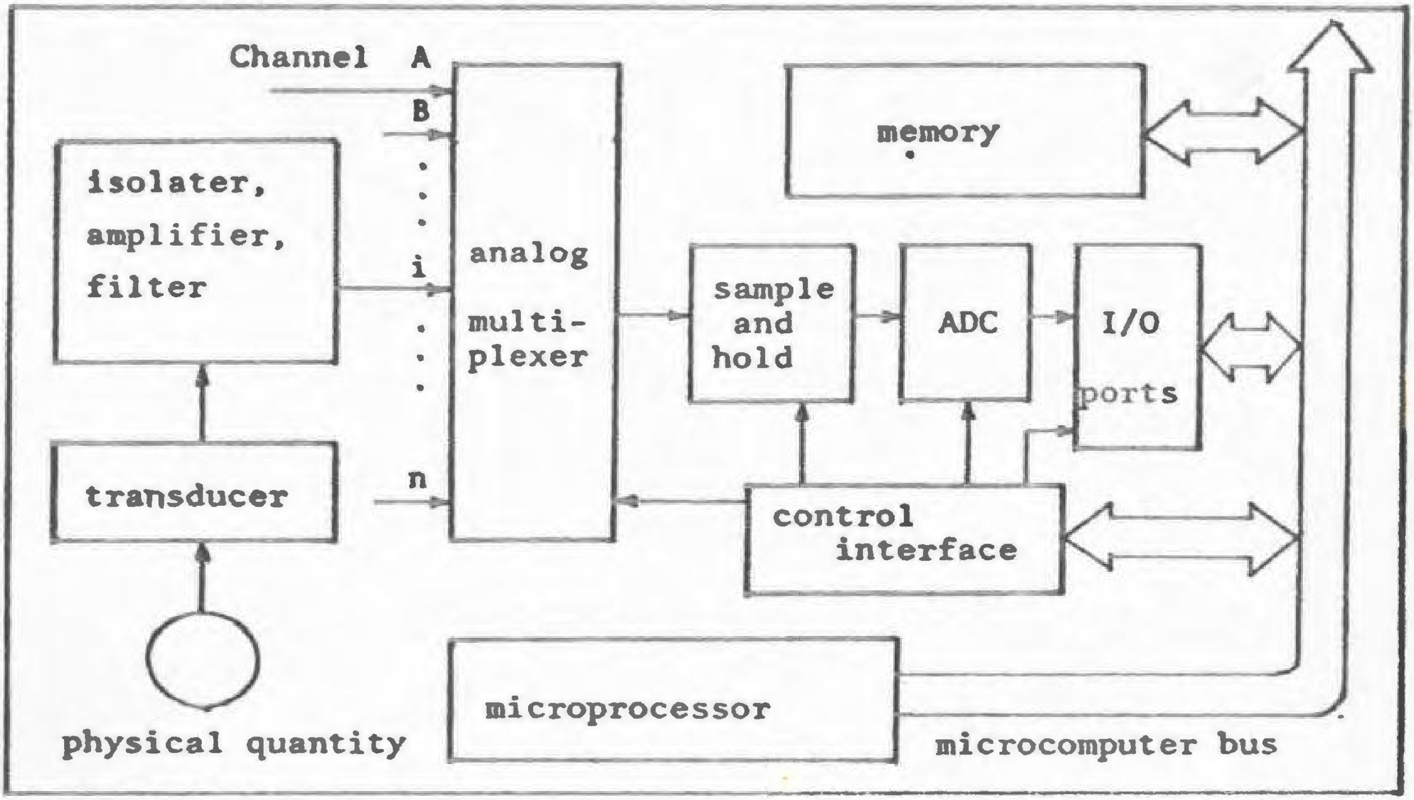

Fig. A.3 Data Acquisition System

sample-hold unit which samples the voltage level of the input at a specific instant of time and holds it constantly at its output so that the following analog-to-digital converter (ADC) can work on a steady voltage level. The ADC converts the stable voltage level to a digital value corresponding to the input voltage. These data are taken in the I/O port(s) and sent to the microprocessor and finally stored in the memory.

The microprocessor must control the system to insure that the proper analog inputs are selected, that data are sampled at the proper time and that the A/D conversion has enough time to be completed.

CMOS Circuit and Microprocessor

In the application of a microcomputer for marine heat flow, low power dissipation is of overriding importance, since the probe has to accommodate all the batteries for power supplies and it is expected to work for several hours for each lowering of the probe.

Two types of transistors can be used to form microprocessor chips and the support logic families: the bipolar transistor and the metal oxide semiconductor transistor (MOS). The latter has relatively slow operation speed but lower power dissipation. There are three subcategories of MOS based on electronic and physical characteristics. They are PMOS, NMOS and CMOS. PMOS and NMOS are essentially the same except for polarity, P stands for positive and N negative. CMOS stands for complementary MOS, its circuit includes both P and N MOS transistors. CMOS circuits are faster than that of either P or NMOS and consume even less power.

The HF1601 heat flow probe employs an RCA COSMOS microprocessor CDP1802 and RCA COSMAC microboard computer system as the main body of its control circuits. The CDP1802 microprocessor was the only 8-bit CMOS microprocessor for industrial applications at the time when the HF1601 was designed.

The architecture of the CDP1802 is relatively simple compared to other microprocessors. It is well suited to battery-powered instrument applications. Fig. A.4 illustrates the internal structure of the CDP1802 microprocessor. It is based on a register array comprised of 16 general-purpose 16-bit scratch-pad registers, each of which is designated by a 4-bit binary code (using hexadecimal notation).

Each register can be designated as a data pointer, program counter, I/O register or general-purpose register. Three 4-bit registers labeled N,P and X are used to select individual scratch-pad registers. The P register is the program counter pointer. It specifies which one of the registers is the program counter. The X register works as data counter pointer and the N register contains the lower 4-bits of the instruction code and may be used to select registers for data transfers to and from the accumulator for some of the register operations.

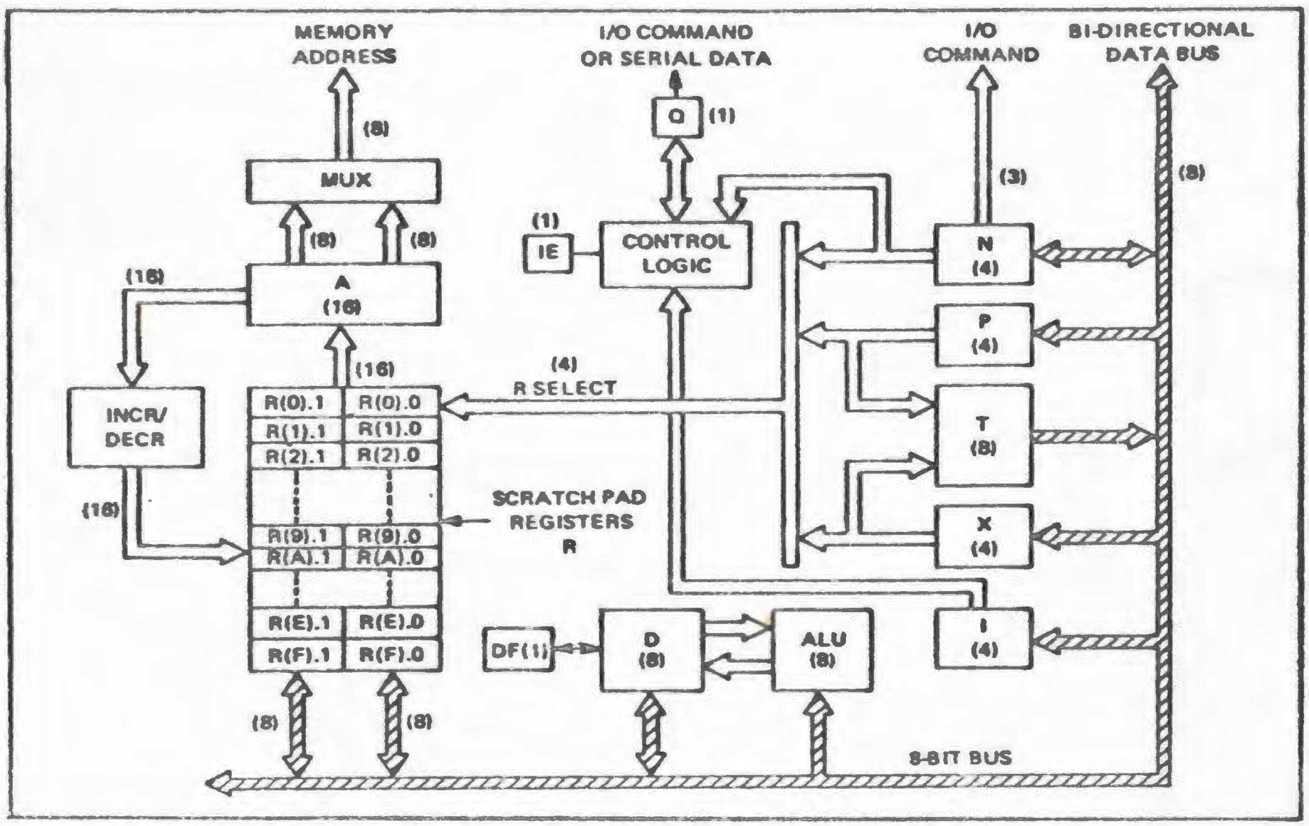

Fig. A.4 The structure of the CDP1802 microprocessor

Arithmetic and logic operations are carried out in the 8-bit accumulator or D register which also handles all data transfers between registers, memory and input-output. An 8-bit register T is used to store the contents of the P and X registers during interrupt servicing and for subroutine operations. Memory addresses are normally latched in a 16-bit A register.

An on-chip clock generator is provided with the maximum clock frequency 2.5 MHz for a 5V power supply.

For I/O operations, three output lines N0, N1 and N2 may be used to identify a particular peripheral device. The four external flags EF1 to EF4 may be used by peripherals to indicate the status and may be tested to control branch operations in the program.

The instruction set of CDP1802 microprocessor is given in Appendix C.

Appendix B: HE1601P HEAT FLOW PROBE PROGRAM LISTING

```
0000  ;   ..****************************************
0000  ;   ..NAME: HE1601P
0000  ;   ..DESC: HEAT FLOW MEASUREMENT
0000  ;   ..DATE: 16/05/1984
0000  ;
0000  ;   ..     HF1601 IS DESIGNED FOR MEASURING
0000  ;   ..     MARINE HEAT FLOW. 16 CHANNELS.
0000  ;   ..     SAMPLING RATE 15 SEC.DATA STORE IN
0000  ;   ..     RAM. UNDERWATER TELEMETRY.
0000  ;   ..     4 DATA STORE FOR PREPENETRATION.
0000  ;   ..     18 MINUTES FOR THERMAL GRADIENT
0000  ;   ..     AND CONDUCTIVITY MEASUREMENTS.
0000  ;   ..     THIS PROGRAM IS LINKED TO UT62 FOR
0000  ;   ..     DELAY, SUBROUTINE CALL AND
0000  ;   ..     RETURN. TYPE DATA VIA RS 232C.
0000  ;
0000  ;   ..****************************************
0000  ;   ..          SYSTEM EQUATES
0000  ;   ..****************************************
0000  ;
0000  ;   ..      REGISTER ASSIGNMENTS
0000  ;
0000  ;   CLOCK==#00 ..CLOCK COUNTER
0000  ;   RAMPT==#01 ..RAM POINTER FOR DATA
0000  ;   SP==#02    ..STACK POINTER
0000  ;   PC==#03    ..PROGRAM COUNTER
0000  ;   CALL==#04  ..CALL ROUTINE COUNTER
0000  ;   RETN==#05  ..RETURN ROUTINE COUNTER
0000  ;   LINK==#06  ..SUBROUTINE DATA LINK
0000  ;   CHANL==#07 ..CHANL.0, CHANNEL COUNTER
0000  ;          ..CHANNEL.1, FOR 8 TIMES COUNTER
0000  ;   MINUTE==#08..MINUTE.0, MINUTE COUNTER
0000  ;          ..MINUTE 1, Grad T OR K FLAG
0000  ;   DELAY==#0C ..DELAY ROUTINE COUNTER
0000  ;   AUX==#0E   ..AUX.1 HOLDS TIME CONSTANT
0000  ;   MOTION==#0D..MOTION.0 MOTION FLAG
0000  ;
0000  ;
0000  ;   ..       RAM/ROM ALLOCATIONS
```

```
0000    ;           
0000    ;           HF1601P=#0000
0000    ;           HF1601W=#0300
0000    ;           HF1601R=#0500
0000    ;           HF1601T=#0600
0000    ;           UT62=#8000
0000    ;           TOPSTK=#8CFF
0000    ;           RDBUFF=#1000
0000    ;           DATST1=#1400
0000    ;           DATST2=#D000
0000    ;           
0000    ;           ..****************************************
0000    ;                        ORG HF1601
0000    7100;             DIS;,0  ..DISABLE INTERRIPTS
0002    ;           
0002    ;           ..****************************************
0002    ;           ..        INITIALIZE UT 62 MONITOR
0002    ;           
0002    CO83F3;           LBR INIT1
0005    ;                 INIT1=#83F3
0005    ;           
0005    ;           ..****************************************
0005    ;           ..        STORE A/D SUBROUTINE
0005    ;           .. (PART OF A/D ROUTINE INTO #1300-#1307)
0005    ;           ..****************************************
0005    ;           
0005    F800B0A0;         LOD #00; PHI CLOCK; PLO CLOCK ..R0=0
0009    F813B9;           LDI #13; PHI R9  ..R9 STORES
000C    F800A9;           LDI #00; PLO R9  ..ROUTINE TO RAM
000F    F8E359;           LDI #E3; STR R9  ..1300 SEX R3
0012    19;               INC R9           ..1301 OUT 1, #30
0013    F86159;           LDI #61; STR R9  ..1303 OUT 3,CHANL.0
0016    19;               INC R9        ..1305 LBR A(RETURN).
0017    F8305919;         LDI #30; STR R9; INC R9
001B    F86359;           LDI #63; STR R9
001E    1919;             INC R9; INC R9
0020    F8C05919;         LDI #C0; STR R9; INC R9
0024    F8025919;         LDI A.1(RETURN); STR R9; INC R9
0028    F89B59;           LDI A.0(RETURN); STR R9
002B    ;           
002B    ;           ..****************************************
002B    ;           ..      REGISTER INITIALIZATION
002B    ;           ..****************************************
002B    ;           
002B    F800A1;     RESTAT
002E    F814B1;           LDI $14; PHI RAMPT   ..R1=#1400.
0031    F828BE;           LDI #28; PHI AUX.1 ..BAUD RATE 300.
0034    F800AD;           LDI #00; PLO MOTION  ..MOTION FLAG
0037    C4;               NOP                ..“J”, J=0.
```

```
0038    ;              
0038    ;              ..****************************************
0038    ;              ..  16 CHANNEL A/D CONVERSION, 8 TIMES
0038    ;              ..****************************************
0038    ;              
0038    E3;            RESET: SEX PC
0039    6130;                 OUT 1, #30    ..PULSE #613062
003B    6200;                 OUT 2, #00          ..RESET J.
003D    F800A8;               LDI #00; PLO MINUTE.0..T=0.
0040    F802B8;               LDI #02; PHI MINUTE.1..K=2.
0043    1D;                   INC MOTION          ..J=J+1.
0044    F800AAB7;      PHASE1:LDI #00; PLO RA;PHI CHANL ..M=0.
0048    F810BA;               LDI #10; PHI RA       ..RA=#1000.
004B    C4C4;                 N0P; N0P
004D    E36130;        REPEAT:SEX PC; OUT 1, #30
0050    6400;                 OUT CHOPPR, #00
0052    ;                     CHOPPR=4            ..CHOPPR ON.
0052    F800A7;               LDI #00; PLO CHANL   ..N=0.
0055    D40290;        HIGH:  SEP CALL; A(A/D)
0058    17;                   INC CHANL           ..N=N+1.
0059    ;                     A(A/D)=#0290
0059    87FD10;               GLO CHANL; SDI #10   ..N=16?
005C    3A55;                 BNZ HIGH
005E    E36130;               SEX PC; OUT 1, #30
0061    6400;                 OUT CHOPPR, #00      ..CHOPPR OFF.
0063    F800A7;               LDI #00; PLO CHANL   ..N=0.
0066    D40290;        LOW:   SEP CALL; A(A/D)
0069    17;                   INC CHANL           ..N=N+1.
006A    87FD10;               GLO CHANL; SDI #10
006D    3A66;                 BNZ LOW
006F    97FC01B7;             GHI CHANL;ADI #01;PHI CHANL..M+1.
0073    FD083A4D;             SDI #08; BNZ REPEAT  ..M=8?
0077    E36130;               SEX PC; OUT 1, #30
007A    6700C4;               OUT TELE, #00; NOP
007D    ;                     TELE=7              ..TELE ON.
007D    ;              
007D    ;              ..****************************************
007D    ;              ..           SUBTRACTION
007D    ;              ..    (CHOPPER ON) - (CHOPPER OFF)
007D    ;              ..****************************************
007D    ;              
007D    F800B7;               LDI #00; PHI CHANL   ..M=0.
0080    A7ABAA;               PLO CHANL:PLO RB;PLO RA ..N=0.
0083    F810B9BA;             LDI #10;PHI R9;PHI RA ..RA=#1000
0087    F820A9;               LDI #20; PLO R9       ..R9=#1020
008A    F812BB;               LDI #12; PHI RB       ..RB=#1200.
008D    E9;                   SEX R9
008E    4AF7605B;      DOSUB: LDA RA;SM;IRX;STR RB  ..L BYTE SUB.
0092    1B4A7760;             INC RB;LDA RA;SMB;IRX ..H BYTE SUB.
```

```
0096   5B1B;          STR RB; INC RB
0098   17;            INC CHANL          ..N=N+1.
0099   87FD10;        GLO CHANL; SDI #10   ..N=16?
009C   3A8E;          BNZ DOSUB
009E   97FC01B7;      GHI CHANL;ADI #01;PHI CHANL ..M+1.
00A2   F800A7F6;      LDI #00;PLO CHANL;SHR ..N=0, DF=0.
00A6   8AFC20AA;      GLO RA;ADI #20;PLO RA ..RA=RA+#20.
00AA   9A7C00BA;      GHI RA;ADCI #00;PHI RA
00AE   F800F6;        LDI #00; SHR    ..DF=0.
00B1   89FC20A9;      GLO R9;ADI #20;PLO R9 ..R9=R9+#20.
00B5   997C00B9;      GHI R9; ADCI #00; GHI R9
00B9   97FD08;        GHI CHANL; SDI #08       ..M=8?
00BC   3A8E;          BNZ DOSUB
00BE   ;
00BE   ;         ..****************************************
00BE   ;         ..             AVERAGE
00BE   ;         ..   DO SUM FOR 8 TIMES, DIVIDED BY 8
00BE   ;         ..****************************************
00BE   ;
00BE   ;         ..             DO SUMS
00BE   ;
00BE   B7A7;          PHI CHANL; PLO CHANL ..N=0,M=0.
00C0   AAA9;          PLO RA; PLO R9  ..RA=R9=#1200.
00C2   F812BAB9;      LDI #12; PHI RA; PHI R9
00C6   F800AF;   AGAIN: LDI #00; PLO RF   ..RF.0=0.
00C9   89FC20A9; AVERAG:GLO R9;ADI #20;PLO R9  ..R9+#20.
00CD   E9;            SEX R9
00CE   0AF460;        LDN RA; ADD; IRX   ..L BYTE ADD.
00D1   5A1A;          STR RA; INC RA
00D3   0A74;          LDN RA; ADC   ..H BYTE ADD WITH
00D5   5AC4;          STR RA; NOP      ..CARRY.
00D7   3BDA;          BNF GO          ..OVERFLOW?
00D9   1F;            INC RF          ..YES.
00DA   292A;     GO:   DEC R9; DEC RA  ..R9-1,RA-1.
00DC   97FC01;        GHI CHANL; ADI #01   ..M=M+1.
00DF   B7FD07;        PHI CHANL; SDI #07    ..M=8?
00E2   3AC9;          BNZ AVERAG            ..NO.
00E4   17;            INC CHANL         ..YES. N=N+1.
00E5   DCFFDCFF;      DELAY, #FF; DELAY, #FF
00E9   DCFFDC80;      DELAY, #FF; DELAY, #80
00ED   C4C4C4;        NOP; NOP; NOP
00F0   ;
00F0   ;         ..            DIVIDED BY 8
00F0   ;
00F0   F803AB;        LDI #03; PLO RB      ..RB AS "S".
00F3   2B;       DIVIDE:DEC RB               ..S=S-1.
00F4   1A;            INC RA  ..RA POINTS TO LOW BYTE.
00F5   8FF6AF;        GLO RF; SHR; PLO RF ..OVERFLOW OUT
00F8   0A765A;        LDN RA; SHRC; STR RA  ..HIGH BYTE
```

```
00FB  ;                         ..RIGHT SHIT WITH CARRY.
00FB  2A;                  DEC RA  ..RA POINTS TO LOW BYTE.
00FC  OA765A;              LDN RA; SHRC; STR RA  ..LOW BYTE
00FF  ;                         ..RIGHT SHIT WITH CARRY.
00FF  8BCA00F3;            GLO RB; LBNZ DIVIDE  ..S=0? NO.
0102  87FD10;              GLO CHANL; SDI #10   ..YES, N=16?
0106  3214;                BZ ENDAVE      ..YES, DATA STROE.
0108  1A1A;                INC RA; INC RA   ..NO, RA=RA+2.
010A  8AA99AB9;            GLO RA;PLO R9;GHI RA;PHI R9 ..RA=R9.
010E  F800B7;              LDI #00; PHI CHANL       ..N=0.
0111  C000C6;              LBR AGAIN    ..NEXT CHANNEL.
0114  ;
0114  ;               ..****************************************
0114  ;               ..          DATA STORE IN RAM
0114  ;               ..****************************************
0114  ;
0114  F800A7;         ENDAVE:LDI #00; PLO CHANL     ..N=0.
0117  F812BA;              LDI #12; PHI RA
011A  F81FAA;              LDI #1F; PLO RA      ..RA=#121F.
011D  88;                  GLO MINUTE       ..TEST T.
011E  3A45C4;              BNZ EVEN; NOP          ..T NOT 0.
0121  98F6;                GHI MINUTE; SHR      ..T=0, TEST K.
0123  3333C4;              BDF TITLE2; NOP ..K=1,TO CONDUCT.
0126  D483F0;         TITLE1:SEP CALL; A(OSTRNG) ..K=0,TELE
0129  ;                    OSTRNG=#83F0        .."TEMP".
0129  54454D50;            ,T'TEMP'
012D  2E;                  ,
012E  0D0A;                ,T'0D0A'
0130  00;                  ,#00
0131  3045;                BR EVEN
0133  D483F0;         TITLE2:SEP CALL, A(OSTRNG) ..K=1,
0136  434F4E44;            ,T'CONDUCTIVITY'   ..TELE
013A  55435449;            ,      .."CONDUCTIVITY".
013E  56495459;            ,
0142  0D0A;                ,T'0D0A'
0144  00;                  .#00
0145  80F6;           EVEN:  GLO CLOCK; SHR ..IF CLOCK EVEN.
0147  334F;                BDF STORE   .STORE CLOCK, IF ODD.
0149  905A2A;              GHI CLOCK;STR RA;DEC RA..STR TILT.
014C  805A1A;              GLO CLOCK; STR RA; INC RA
014F  ;
014F  ;               ..     DATA STORE INTO RAM
014F  ;
014F  17;             STORE: INC CHANL              ..N=N+1.
0150  0A2A51;              LDN RA;DEC RA;STR RAMPT..DATA STR.
0153  87FD20;              GLO CHANL; SDI #20       ..N=32?
0156  325B;                BZ ADTEST  ..YES, RAM < #7FFF?
0158  11;                  INC RAMPT
0159  304F;                BR STORE
```

```
015B  ;
015B  ;          ..****************************************
015B  ;          ..        RAM ADDRESS TEST
015B  ;          ..****************************************
015B  ;
015B  F800F6;    ADTEST:LDI #00; SHR
015E  91FD7F;          GHI RAMPT; SDI #7D   ..IF RAMPT >
0161  3B75;            BNF HIADRS  ..#7FFF GO TO #D000.
0163  3A72;            BNZ INCR1
0165  81FDFF;          GLO RAMPT; SDI #FF
0168  3A72;            BNZ INCR1
016A  F8D0B1;          LDI #D0; PHI RAMPT
016D  F800A1;          LDI #00; PLO RAMPT
0170  3095;            BR TRANSM
0172  11;        INCR1: INC RAMPT
0173  3095;            BR TRANSM
0175  ;
0175  ;          ..****************************************
0175  ;          ..        RAM FULL DETECTION
0175  ;          ..****************************************
0175  ;
0175  91FDFF;    HIADRS:GHI RAMPT; SDI #FF  ..#FFFF?
0178  3A7F;            BNZ INCR2  ..NO, GO ON.
017A  81FDFF;          GLO RAMPT; SDI #FF
017D  3282;            BZ END  ..YES, END.
017F  11;        INCR2: INC RAMPT
0180  3095;            BR TRANSM
0182  D483F0;    END:  SEP CALL, A(OSTRNG)  ..TELE
0185  52414D20;        ,T'RAM FULL'  .."RAM FULL"
0189  46554C4C;        ,
018D  0D0A;            ,T'0D0A'
018F  00;              ,#00
0190  C4C4;            NOP; NOP
0192  3092C4;    STOP:  BR STOP; NOP ..PROGRAM HALTS.
0195  ;
0195  ;          ..****************************************
0195  ;          ..     DATA TRANSMISSION VIA TELEMETRY
0195  ;          ..****************************************
0195  ;
0195  88BF;      TRANSM:GLO MINUTE; PHI RF ..TELE "T".
0197  D481AE;          SEP CALL, A(TYPE2)
019A  ;                TYPE2=#81AE
019A  D481A2;          SEP CALL, A(TYPE6)
019D  ;                TYPE6=#81A2
019D  20;              ,T' '     ..TELE ONE SPACE.
019E  F810A7;          LDI #10; PLO CHANL      ..N=16.
01A1  F812BA;          LDI #12; PHI RA  ..RA=#121F.
01A4  F81FAA;          LDI #1F; PLO RA
01A7  0ABF;      TELEOU:LDN RA; PHI RF
```

```
01A9   D481AE;      SEP CALL, A(TYPE2)
01AC   2A0ABF;      DEC RA; LDN RA; PHI RF
01AF   D481AE;      SEP CALL, A(TYPE2)
01B2   2A;          DEC RA
01B3   D481A2;      SEP CALL, A(TYPE6)
01B6   20;          ,T' '       ..TYPE ONE SPACE.
01B7   27873AA7;    DEC CHANL;GLO CHANL;BNZ TELEOU
01BB   D483F0;      SEP CALL, A(OSTRNG)
01BE   0D0A;        ,'0D0A'
01C0   00;          ,#00
01C1   ;
01C1   ;          ..***************************************
01C1   ;          ..     4 DATA PREPENETRATION
01C1   ;          ..***************************************
01C1   ;
01C1   8DFD08;      GLO MOTION; SDI 08   ..J==8?
01C4   3AEF;        BNZ WAIT1             ..NO.
01C6   2DC4C4;      DEC MOTION; NOP; NOP  ..J==J-1.
01C9   F860A7;      LDI #60; PLO CHANL     ..N==#60.
01CC   2127;      DEC:  DEC RAMPT; DEC CHANL
01CE   873ACC;      GLO CHANL; BNZ DEC ..RAMPT-#60.
01D1   81AA;        GLO RAMPT; PLO RA
01D3   91BA;        GHI RAMPT; PHI RA  ..RA==RAMPT
01D5   F820A7;      LDI #20; PLO CHANL     ..N==#20.
01D8   2A27;      DEC1:  DEC RA; DEC CHANL
01DA   873AD8;      GLO CHANL;BNZ DEC1..RA==RAMPT-#20.
01DD   F860A7;      LDI #60; PLO CHANL     ..N==#60.
01E0   415A1A;    COPY:  LDA RAMPT;STR RA;INC RA ..R(1)==R(A).
01E3   2787;        DEC CHANL; GLO CHANL    ..N==0?
01E5   3AE0;        BNZ COPY   ..COPY #60 BYTES.
01E7   8AA1;        GLO RA; PLO RAMPT  ..RAMPT==RA.
01E9   9AB1;        GHI RA; PHI RAMPT
01EB   30EF;        BR WAIT1
01ED   C4C4;        NOP; NOP
01EF   36EF;      WAIT1: B3 WAIT1     ..15 SECONDS?
01F1   10;          INC CLOCK
01F2   ;
01F2   ;          ..***************************************
01F2   ;          ..        MOTION DETECTION
01F2   ;          ..***************************************
01F2   ;
01F2   34FF;        B1 ALERT   ..EF1 AS MOTION FLAG.
01F4   ;
01F4   ;          ..***************************************
01F4   ;          ..      MEASUREMENT COMPLETION
01F4   ;          ..***************************************
01F4   ;
01F4   98F6;        GHI MINUTE; SHR   ..K==1?
01F6   CB021B;      LBNF OFF1 ..NO, CONDUCTIVITY.
```

```
01F9   F800AD;      0334        LDI #00;PLO MOTION ..YES,J=0,TEMP.
01FC   C0021B;      0335        LBR OFF1
01FF   18;          0336   ALERT: INC MINUTE      ..T=T+1.
0200   88FD20;      0337        GLO MINUTE; SDI #20  ..8 MINUTES?
0203   3A4EC4;      0338        BNZ NINE; NOP  ..NO, GO ON.
0206   98F6;        0339        GHI MINUTE; SHR
0208   3328C4;      0340        BDF CONDUC; NOP
020B   D483F0;      0341        SEP CAL, A(OSTRNG)
020E   54454D50;    0342        ,T'TEMP.END'
0212   2E454E44;    0343        ,
0216   0D0A;        0344        ,T'0D0A'
0228   00;          0345        ,#00
0219   3044;        0346        BR OFF2
021B   E36130;      0347   OFF1:  OUT 1,#30   ..TELE OFF.
021E   6700;        0448        OUT TELE
0220   C00038;      0349        LBR RESET   ..RETURN TO RESET.
0223   C4C4C4;      0350        NOP; NOP; NOP
0226   C4C4;        0351        NOP; NOP
0228   D483F0;      0352   CONDUC:SEP CALL, A(OSTRNG)
022B   434F4E44;    0353        ,T'CONDUCTIVITY END'
022F   55435449;    0354        ,
0233   56495459;    0355        ,
0237   20454E44;    0356        ,
023B   0D0A;        0357        ,T'0D0A'
023D   00;          0358        ,#00
023E   C4C4C4C4;    0359        N0P; N0P; N0P; N0P;
0242   C4C4;        0360        N0P; NOP
0244   E36130;      0361   OFF2:  OUT 1,#30  ..TELE OFF.
0248   6700C4C4;    0362        OUT TELE; NOP; NOP;
024B   C00044;      0363        LBR PHASE1  ..CONTINUE.
024E   ;            0364
024E   ;            0365   ..****************************************
024E   ;            0366   ..            HEAT PULSE
024E   ;            0367   ..****************************************
024E   ;            0368
024E   ;            0369   ..          PHASE DETECTION
024E   ;            0370
024E   88FD24;      0371   NINE:  GLO MINUTE;SDI #24 ..9 MINUTES?
0251   3A44C4;      0372        BNZ OFF2; NOP
0254   98FF01;      0373        GHI MINUTE; SDI #01  ..K=K-1.
0257   B8;          0374        PHI MINUTE
0258   F800A8;      0375        LDI #00; PLO MINUTE  ..T=0.
025B   98FF00;      0376        GHI MINUTE; SMI #00
025E   3A6C;        0377        BNZ PULSE
0260   F800AD;      0378   DONE:  LDI #00; PLO MOTION  ..J=0.
0263   F802B8;      0379        LDI #02; PHI MINUTE  ..K=2.
0266   C4C4;        0380        NOP; NOP
0268   C4;          0381        NOP
0269   301BC4;      0382        BR OFF1; NOP
```

```
026C  ;
026C  ;          ..          HEAT PULSE
026C  ;
026C  366C;      PULSE: B3 PULSE             ..15 SECONDS?
026E  10;             INC CLOCK
026F  E36130;         SEX PC; OUT 1, #30
0272  6500;           OUT 5, #00
0274  DCFFDCFF;       DELAY, #FF; DELAY, #FF
0278  DCFFDCFF;       DELAY, #FF; DELAY, #FF
027C  C4C4C4C4;       NOP; NOP; NOP; NOP
0280  C4C4C4C4;       NOP; NOP; NOP; NOP
0284  3684;      WAIT3: B3 WAIT3   ..HEAT PULSE 15 SEC.
0286  C4;             NOP
0287  E36130;         SEX PC; OUT, #30
028A  6500;           OUT 5, #00 ..HEAT PULSE OFF.
028C  3044;           BR OFF2
028E  C4C4;           NOP; NOP
0290  ;
0290  ;
0290  ;
0290  ;          ..****************************************
0290  ;          ..    SUBROUTINE FOR A/D CONVERSION
0290  ;          ..****************************************
0290  ;
0290  F810B9;    A/D:  LDI #13; PHI R9  ..#1304 FOR STR N.
0293  F804A9;         LDI #04; PLO R9
0296  8759;           GLO CHANL; STR R9
0298  CO1300;         LBR RAM
029B  ;               RAM==#1300
029B  DC10;      RETURN:DELAY, #10
029D  E36130;         SEX PC;OUT 1, #30 ..CONVER PULSE
02A0  6600;           OUT 6, #00   ..#613066
02A2  DC15;           DELAY, #15
02A4  E36108;         OUT 1, #08   ..I/O INTERFACE.
02A7  C4C4;           NOP; NOP
02A9  EA;             SEX RA
02AA  6C;             INP PORT(A)   ..INPUT LOW BYTE.
02AB  ;               PORT(A)==C
02AB  60;             IRX
02AC  6E;             INP PORT(B)   ..INPUT HIGH BYTE.
02AD  ;               PORT(B)==E
02AD  60;             IRX
02AE  D5;             SEP RETN    ..RETURN TO MAIN PROG.
0600  ;
0600  ;
0600  ;
0600  ;
0600  ;          ..****************************************
0600  ;          ..NAME: HF1601T
```

```
0600    ;               ..DESC: TYPE DATA
0600    ;               ..DATE: 23/10/1983
0600    ;
0600    ;               ..     TYPE DATA IN RAM #1400-#7FFF AND
0600    ;               ..     #D000-#FFFF. FORMAT:1, DATA No.:
0600    ;               ..     2, TILT(ODD No.),TIME(EVEN No.);
0600    ;               ..     3, REFERENCE;4, 14 CHANNEL DATA.
0600    ;               ..     RUN THIS PROGRAM TYPE *P0600.
0600    ;               ..****************************************
0600    ;
0600    7100;                  DIS; ,0   ..DISABLE INTERRUPTS.
0602    F806B3;                LDI A.1(START3); PHI R3
0602    ;                      A.1(START3)==#06
0605    F80BA3;                LDI A.0(START3); PLO R3
0608    ;                      A.0(START3)==#0B
0608    C083F6;                LBR INIT2
060B    D483F0;                SEP CALL, A(OSTRNG)
060E    0D0A;                  ,'0D0A'
0610    00;                    ,#00
0611    DCFF;                  DELAY, #FF
0613    C4C4C4C4;              NOP; NOP; NOP; NOP
0617    C4C4C4C4;              NOP; NOP; NOP; NOP
061B    F814B1;         START3:LDI #14; PHI R1 ..R1 RAM POINTER.
061E    F800A1;                LDI #00; PLO R1    ..R1=#1400.
0621    F803B7;                LDI #03; PHI R7..R7 LINE COUNTER.
0624    F860A7;                LDI #60; PLO R7   ..R7==#0360.
0627    F802AD;                LDI #02; PLO RD ..RD TWICE COUNTER.
062A    F800A0;                LDI #00; PLO R0 ..R0 No. COUNTER.
062D    F800B0;                LDI #00; PHI R0..R0 STARTS #0000.
0630    F810A8;         NEXT:  LDI #10
0633    90BF;                  GHI R0; PHI RF   ..TYPE No.
0635    D481AE;                SEP CALL, A(TYPE2)
0638    80BF;                  GLO R0; PHI RF
063A    D481AE;                SEP CALL, A(TYPE2)
063D    10;                    INC R0           ..R0=R0+1.
063E    D481A2;         DATA:  SEP CALL, A(TYPE6)
0641    20;                    ,T' '     ..TYPE ONE SPACE.
0642    01BF;                  LDN R1; PHI RF  ..TYPE DATA.
0644    D481AE;                SEP CALL, A(TYPE2)
0647    11;                    INC R1
0648    01BF;                  LDN R1; PHI RF
064A    D481AE;                SEP CALL, A(TYPE2)
064D    11;                    INC R1
064E    2888;                  DEC R8; GLO R8  ..16 CHANNELS?
0650    3A3E;                  BNZ DATA
0652    D483F0;                SEP CALL, A(OSTRNG)
0655    0D0A;                  ,T'0D0A'
0657    00;                    ,#00
0658    2797;                  DEC R7; GLO R7 ..#0360 LINES?
```

```
065A    3A30;          BNZ NEXT
065C    873A30;        GLO R7; BNZ NEXT
065F    2D8D;          DEC RD; GLO RD    ..TWICE?
0661    3271;          BZ FINISH      ..YES, STOP.
0663    F801B7;        LDI #01; PHI R7  ..NO, R7=#0180.
0666    F880A7;        LDI #80; PLO R7
0669    F8D0B1;        LDI #D0; PHI R1 ..R1=#D000.
066C    F800A1;        LDI #00; PLO R1
066F    3030;          BR NEXT ..TYPE DATA #D000-#FFFF.
0671    C087F0;     FINISH:LBR UT62 ..RETURN TO UT62.
```

Appendix C: Instruction Summary for CDP 1802 Microprocessor

The instruction summary is given below. Hexadecimal notation is used to refer to the 4-bit binary codes.

In all registers bits are numbered from the least significant bit to the most significant bit starting with 0.

R(W): Register designated by W, where W=N or X, or P

R(W).0: Lower order byte of R(W)

R(W).1: Higher order byte of R(W)

N0= Least significant bit of N Register

Operation Notation

$M(R(N)) \rightarrow D$; $R(N)+1$

This notation means: The memory byte pointed to by R(N) is loaded into D, and R(N) is incremented by 1.

INSTRUCTION	MNEMONIC	OP CODE	OPERATION
MEMORY REFERENCE			
LOAD VIA N	LDN	0N	$M(R(N)) \rightarrow D$; FOR NOT 0
LOAD ADVANCE	LDA	4N	$M(R(N)) \rightarrow D; R(N)+1 \rightarrow R(N)$
LOAD VIA X	LDX	F0	$M(R(X)) \rightarrow D$
LOAD VIA X AND ADVANCE	LDXA	72	$M(R(X)) \rightarrow D; R(X)+1 \rightarrow R(X)$
LOAD IMMEDIATE	LDI	F8	$M(R(P)) \rightarrow D; R(P)+1 \rightarrow R(P)$
STORE VIA N	STR	5N	$D \rightarrow M(R(N))$
STORE VIA X AND DECREMENT	STXD	73	$D \rightarrow M(R(X)); R(X)-1 \rightarrow R(X)$
REGISTER OPERATION			
INCREMENT REG N	INC	1N	$R(N)+1 \rightarrow R(N)$
DECREMENT REG N	DEC	2N	$R(N)-1 \rightarrow R(N)$
INCREMENT REG X	IRX	60	$R(X)+1 \rightarrow 3R(X)$
GET LOW REG N	GLO	8N	$R(N).0 \rightarrow D$
PUT LOW REG N	PLO	AN	$D \rightarrow R(N).0$

INSTRUCTION	MNEMONIC	OP CODE	OPERATION
GET HIGH REG N	GHI	9N	R(N).1→D
PUT HIGH REG N	PHI	BN	D→R(N).1
LOGIC OPERATIONS			
OR	OR	F1	M(R(X)) OR D→D
OR IMMEDIATE	ORI	F9	M(R(P)) OR D→D R(P)+1→R(P)
EXCLUSIVE OR	XOR	F3	M(R(X)) XOR D→D
EXCLUSIVE OR IMMEDIATE	XRI	FB	M(R(P)) XOR D→D R(P)+1→R(P)
AND	AND	F2	M(R(X)) AND D→D
AND IMMEDIATE	ANI	FA	M(R(P)) AND D→D R(P)+1→R(P)
SHIFT RIGHT	SHR	F6	SHIFT D RIGHT, LSB(D)→ DF,0→MSB(D)
SHIFT RIGHT WITH CARRY	SHRC	76	SHIFT D RIGHT,LSB(D)→ DF,DF→MSB(D)
SHIF LEFT	SHL	FE	SHIFT D LEFT, MSB(D)→ DF,0→LSB(D) 0→LSB(D)
SHIFT LEFT WITH CARRY	SHLC	7E	SHIFT D LEFT,MSB(D)→ DF,DF→LSB(D)
ARITHMATIC OPERATIONS			
ADD	ADD	F4	M9R(X))+D→DF,D
ADD IMMEDIATE	ADI	FC	M(R(P))+DS→ DF, D; R(P)+1→R(P)
ADD WITH CARRY	ADC	74	M(R(X))+D+DF→ DF,D
ADD WITH CARRY, IMMEDI-ATE	ADC1	7C	M(R(P))+D+DF→ DF, D; R(P)+1→R(P)
SUBTRACT D	SD	F5	M(R(X))-D→DF,D
SUBTRACT D IMMEDIATE	SDI	FD	M(R(P))-D→ DF, D; R(P)+1→R(P)
SUBTRACT D WITH BOR-ROW	SDB	75	M(R(X))-D-$\overline{DF}$→DF,D
SUBTRACT D VITH BOR-ROW, IMMEDIATE	SDBI	7D	M(R(P))-D-$\overline{DF}$→ DF, D; R(P)+1→R(P)
SUBTRACT MEMORY	SW	F7	D-M(R(X))→DF,D
SUBTRACT MEMORY IMMEDIATE	SMI	FF	D-M(R(P))→ DF, D; R(P)+→R(P)

INSTRUCTION	MNEMONIC	OP CODE	OPERATION
SUBTRACT MEMORY WITH BORROW	SMB	77	D-M(R(X))-$\overline{DF}$ →DF,D
SUBTRACT MEMORY WITH BORROW, IMMEDIATE	SMBI	7F	D-M(R(P))-$\overline{DF}$ →DF, D; R(P)+1→R(P)
BRANCH INSTRUCTIONS - SHORT BRANCH			
SHORT BRANCH	BR	30	M(R(P))→R(P).0
SHORT BRANCH IF D=0	BZ	32	IF D=0, M(R(P))→R(P).0 ELSE R(P)+1→R(P)
SHORT BRANCH IF D NOT 0	BNZ	3A	IF D NOT 0, M(R(P))→ R(P).0 ELSE R(P)+1→R(P)
SHORT BRANCH IF DF=1	BDF	33	IF DF=1, M(R(P))→ R(P).0 ELSE R(P)+1→R(P)
SHORT BRANCH IF DF=0	BNF	3B	IF DF=0, M(R(P))→ R(P).0 ELSE R(P)+1→R(P)
SHORT BRANCH IF Q=1	BQ	31	IF Q=1, M(R(P))→R(P).0 ELSE R(P)+1→R(P)
SHORT BRANCH IF Q=0	BNQ	39	IF Q=0, M(R(P))→R(P).0 ELSE R(P)+1 →R(P)
SHORT BR IF EF1=1	B1	34	IF EF=1, M(R(P))→ R(P).0 ELSE R(P)+1→R(P)
SHORT BR IF EF1=0	BN1	3C	IF EF1=0, AS ABOVE
SHORT BR IF EF2=1	B2	35	IF EF2=1, AS ABOVE
SHORT BR IF EF2=0	BN2	3D	IF EF2=0, AS ABOVE
SHORT BR IF EF3=1	B3	36	IF EF3=1, AS ABOVE
SHORT BR IF EF3=0	BN3	3E	IF EF3=0, AS ABOVE
SHORT BR IF EF4=1	B4	37	IF EF4=1, AS ABOVE
SHORT BR IF EF4=0	BN4	3F	IF EF4=0, AS ABOVE
BRANCH INSTRUCTIONS - LONG BRANCH			
LONG BRANCH	LBR	C0	M(RP))→R(P).1, M(R(P))→R(P).0
LONG BR IF D=0	LBZ	C2	IF D=0, M(R(P))→R(P).1 M(R(P)+1)→R(P).0 ELSE R(P)+2→R(P)

INSTRUCTION	MNEMONIC	OP CODE	OPERATION
LONG BR IF D NOT 0	LBNZ	CA	IF D NOT 0,AS ABOVE
LONG BR IF DF=1	LBDF	C3	IF DF=1, AS ABOVE
LONG BR IF DF=0	LBNF	CB	IF DF=0, AS ABOVE
LONG BR IF Q=1	LBQ	C1	IF Q=1, AS ABOVE
LONG BR IF Q=0	LBNQ	C9	IF Q=0, AS ABOVE
CONTROL INSTRUCTIONS			
NO OPERATION	NOP	C4	CONTINUE
SET P	SEP	DN	$N \rightarrow P$
SET X	SEX	EN	$N \rightarrow X$
SET Q	SEQ	7B	$1 \rightarrow Q$
RESET Q	REQ	7A	$0 \rightarrow Q$
PUSH X,P TO STACK	MARK	79	$(X,P) \rightarrow T$; $(X,P) \rightarrow M(R(2))$ THEN $P \rightarrow X$; $R(2)-1 \rightarrow R(2)$
INTERRUPT CONTROL			
EXTERNAL INTERRUPT ENABLE	XIE	680A	$1 \rightarrow XIE$
EXTERNAL INTERRUPT DISABLE	XID	680B	$0 \rightarrow XIE$
COUNTER INTERRUPT ENABLE	CIE	680C	$1 \rightarrow CIE$
COUNTER INTERRUPT DISABLE	CID	680D	$0 \rightarrow CIE$
RETURN	RET	70	$M(R(X)) \rightarrow X,P$; $R(X)+1 \rightarrow R(X)$; $1 \rightarrow IE$
DISABLE	DIS	71	$M(R(X)) \rightarrow X,P$; $R(X)+1 \rightarrow R(X)$; $0 \rightarrow IE$
SAVE	SAV	78	$T \rightarrow M(R(X))$
INPUT-OUTPUT BYTE TRANSFER			
OUTPUT 1	OUT 1	61	$M(R(X)) \rightarrow BUS$; $R(X)+1 \rightarrow R(X)$; N LINES=1
OUTPUT 2	OUT 2	62	AS ABOVE;N LINES=2
OUTPUT 3	OUT 3	63	AS ABOVE;N LINES=3
OUTPUT 4	OUT 4	64	AS ABOVE;N LINES=4
OUTPUT 5	OUT 5	65	AS ABOVE;N LINES=5
OUTPUT 6	OUT 6	66	AS ABOVE;N LINES=6
OUTPUT 7	OUT 7	67	AS ABOVE;N LINES=7

INSTRUCTION	MNEMONIC	OP CODE	OPERATION
INPUT 1	INP 1	69	BUS→M(R(X)); BUS→; N LINES=1
INPUT 2	INP 2	6A	AS ABOVE;N LINES=2
INPUT 3	INP 3	6B	AS ABOVE;N LINES=3
INPUT 4	INP 4	6C	AS ABOVE;N LINES=4
INPUT 5	INP 5	6D	AS ABOVE;N LINES=5
INPUT 6	INP 6	6E	AS ABOVE;N LINES=6
INPUT 7	INP 7	6F	AS ABOVE;N LINES=7

Appendix D: HF1601D Software Listing

```
10    REM PROGRAM FOR HEAT FLOW DATA PROCESSING (DEC. 24,1984)
20    CLEAR:CLS:PRINT SPC(18);"Heat Flow Data Processing":GOSUB 9020
21    PRINT:PRINT SPC(25); "MAIN MENU"
30    PRINT:PRINT:PRINT "1). Reducing raw data into resistance": PRINT; PRINT
      "2). Display temperature-time relation": PRINT: PRINT "3). Gradient estima-
      tion": PRINT: PRINT "4). Conductivity and gradient estimation":PRINT
31    PRINT "5). Infinite-time temperature reduction": PRINT: PRINT "6). Interac-
      tive fitting of geothermal gradient": PRINT: PRINT "7). Exit": PRINT:
      PRINT"Press corresponding key"
40    HH$=INKEY$:IF HH$="" GOTO 40
50    IF HH$="1" GOTO 6000
51    IF HH$="2" GOTO 8000
52    IF HH$="3" GOTO 3000
53    IF HH$="4" GOTO 200
54    IF HH$="5" GOTO 9500
55    IF HH$="6" GOTO 15000
56    IF HH$="7" GOTO 90
57    IF HH$="8" GOTO 70
58    IF HH$<>"7" GOTO 40
70    GOSUB 9020:CLS:CLEAR:CLOSE:SYSTEM
90    GOSUB 9010:PRINT:PRINT:PRINT "BYE!":PRINT:END
200   REM ROUTINE OF CALCULATING CONDUCTIVITY
210   CLEAR:CLOSE:DIM J1(200),J0(200),Y0(200),Y1(200),F(100), X(40), Y(40),
      HEAT(1666), H1(120), H(120), HH(120), GG(120), J(120), S1(120), HC(120),
      FT1(100,2), FT2(100,2), FT3(100,2)
215   DIM FT4(100,2), FT5(100,2), FT6(100,2)
220   KEY OFF:CLS:PRINT:PRINT:SPC(12); "THERMAL CONDUCTIVITY AND
      GRADIENT CALCULATION": PRINT: PRINT SPC(12); "!! Start with
265   PRINT:PRINT:PRINT:PRINT SPC(20); "Loading F function tables...": PRINT:
      GOSUB 9000
270   CLOSE:OPEN"R",#1,"F-T1.DAT":FIELD #1,8 AS T$,8 AS F$
271   FOR J=1 TO 100:GET #1,J:FT1(J,1)=CVS(T$):FT1(J,2)=CVS(F$):NEXT
272   CLOSE:OPEN"R",#1,"F-T2.DAT":FIELD #1,8 AS T$,8 AS F$
273   FOR J=1 TO 100:GET #1,J:FT2(J,1)=CVS(T$):FT2(J,2)=CVS(F$):NEXT
274   CLOSE:OPEN"R",#1,"F-T3.DAT":FIELD #1,8 AS T$,8 AS F$
275   FOR J=1 TO 100:GET #1,J:FT3(J,1)=CVS(T$):FT3(J,2)=CVS(F$):NEXT
276   CLOSE:OPEN"R",#1,"F-T4.DAT":FIELD #1,8 AS T$,8 AS F$
277   FOR J=1 TO 100:GET #1,J:FT4(J,1)=CVS(T$):FT4(J,2)=CVS(F$):NEXT
278   CLOSE:OPEN"R",#1,"F-T5.DAT":FIELD #1,8 AS T$,8 AS F$
279   FOR J=1 TO 100:GET #1,J:FT5(J,1)=CVS(T$):FT5(J,2)=CVS(F$):NEXT
```

```
280   CLOSE:OPEN"R",#1,"F-T6.DAT":FIELD #1,8 AS T$,8 AS F$
281   FOR J=1 TO 100:GET #1,J:FT6(J,1)=CVS(T$):FT6(J,2)=CVS(F$):NEXT
300   LOOP=0:LOOP1=0:LOOP2=0:LP1=0:CLOSE
301   DL=0:DL1=0:DDLY=0:DDLY1=0:DDY=0:DDY1=0
305   PRINT:PRINT "Loading F function for K=0.8...":PRINT:GOSUB 9000
310   OPEN "I", #1,"A;F0.8"
315   FOR I=1 TO 120:INPUT #1,F(I):F1(I)=F(I):NEXT I:CLOSE:K=0.8
320   PI=3.141593:E=2.718282:A2=.004725^2
325   DU=.1:PI2=PI^2:CMP=0:TUN=0
330   BEEP:BEEP:CLS:FOR I=1 TO 6:PRINT:NEXT I:PRINT SPC(20); "Mount disk
      on drive B": PRINT SPC(20); "Press any key to continue"
340   MM$=INKEY$:IF MM$="" GOTO 340
350   CLS:FILES "B:"
355   PRINT:PRINT "!! May use random or serial data file !!"
360   PRINT:BEEP:PRINT:LINE INPUT "Which data file? ";DA$
365   PRINT:DA$="B:"+DA$
370   BEEP:INPUT "Thermistor # (bottom is #1)";TN
381   PRINT:PRINT "Is ";DA$;" a random file or a serial file ? (type R or S)"
382   RS$=INKEY$:IF RS$="" GOTO 382
383   IF RS$="R" OR RS$="r" GOTO 387
384   IF RS$="S" OR RS$="s" GOTO 389
385   IF RS$<>"S" GOTO 382
387   GOSUB 5200:GOTO 531
389   PRINT:PRINT "Loading from serial data file ";DA$:GOSUB 9000
430   CLOSE:OPEN "I",#1,DA$:FIRST=0
440   IF TN=14 THEN FITT=1665 ELSE FITT=TN*119
450   FOR I=1 TO FITT:INPUT #1,HEAT(I) 'Input data from 1 to this channel
480   NEXT I
490   IF TN<>14 GOTO 530
510   FOR I=1 TO 118:KK=(TN-1)*119+I
515   H1(I)=HEAT(KK):NEXT:GOTO 531   'Channel 14
530   FOR I=1 TO 119:KK=(TN-1)*119+I:H1(I)=HEAT(KK):NEXT I  'This channel
531   PRINT:BEEP:INPUTC"Heat quantity Q (Jole/M) = ";QQ
532   FOSUB 4900
533   BEEP:INPUT "Temp. reference point ";TRR:IF TRR=0 THEN TRR=1
534   XX1=25+(TRR-1)*5:YY1=234+Q*24-120*H1(TRR): CIRCLE (XX1,YY1), 3:
      CIRCLE (XX1,YY1),5
535   PRINT "Is it acceptable ? (y/n)"; BEEP
536   DD$=INKEY$:IF DD$="" GOTO 536
537   IF DD$="Y" OR DD$="y" GOTO 543
538   IF DD$="N" OR DD$="n" GOTO 532
539   IF DD$<>"N" GOTO 536
543   CLOSE:OPEN "R",#1,DA$
544   FIELD #1,4 AS L$,8 AS T$,4 AS R$,8 AS D1$,8 AS D2$,8 AS D3$,8 AS D4$,8
      AS D5$,8 AS D6$,8 AS D7$,8 AS D8$,8 AS D9$,8 ASA D10$,8 AS D11$,8 AS
      D12$,8 AS D13$,8 AS D14$
547   FOR S=1 TO TRR:GET #1,S:S1(S)=CVS(D1$):NEXT S: RRF =
      (5811.403/(LOG (S1(TRR)) + 5.493939))-342.7457
548   RRF=RRF-H1(TRR):FOR I=1 TO 119:H1(I)=H1(I)+RRF:NEXT I
```

```
549   GOSUB 4900
550   LP1=0:BEEP:INPUT "Penetration at # ";PP
560   BEEP:INPUT "How mwny points ";NB
561   BEEP:PRINT:INPUT "Heat pulse at point # ";PPP
562   BEEP:INPUT "How mwny points ";NBB:PRINT
563   PRINT:PRINT "Calculate and plot for every N'th point. ":INPUT " N ";SSTP
564   IF SSTP=0 THEN SSTP=1
565   IF TUN=1 GOTO 599
572   XX1=25+(PP-1)*5:XX2=(PPP-1)*5:YY1=234+Q*24-120*H1(PP):
      YY2=234+Q*24-120*H1(PPP):   XX3=25+(PP-1+NB)*5:   XX4=25+(PPP-
      1+NBB)*5:   YY3=234+Q*24-120*H1(PP+NB):   YY4=234+Q*24-
      120*H1(PPP+NBB)
573   IRCLE(XX1,YY1),6:CIRCLE(XX2,YY2),6:LINE  (XX1,  YY1-3)-(XX1,YY1+3):
      LINE (XX2, YY2-3)-(XX2, YY2+3): LINE (XX1-4,YY1)-XX1+4),YY1): LINE
      (XX2-4,YY2)-(XX2+2, YY2): CIRCLE (XX3, YY3),3: CIRCLE (XX4, YY4),3:
      CIRCLE (XX3, YY3),5: CIRCLE (XX4, YY4),5
574   FOR I= 1 TO 15:PRINT:NEXT:PRINT "Acceptable ? (y/n)":BEEP
575   POT$=INKEY$:IF POT$="" GOTO 575
576   IF POT$="Y" OR POT$="y" GOTO 599
577   IF POT$="N" OR POT$="n" GOTO 579
578   IF POT$<>"N" GOTO 575
579   CLS:GOTO 549
580   BEEP:PRINT:PRINT"Original values: ":PRINT"Penetration # ";PP:",",:PRINT
      NB; "points"
581   PRINT"Heat pulse #";PPP;",",:PRINT NBB;" points":PRINT "Delay (fric) :
      ";DELAY1, "Delay (pulse) : ";DELAY:PRINT
583   GOTO 550
599   TUN=1:GOSUB 2720
600   IF LOOP1<>0 GOTO 607
605   RR=NB-NBB:IF RR>=0 THEN RR=NB ELSE RR=NBB:GOTO 610
607   RR=PPP+NBB
610   IF LOOP1<>0 GOTO 630
620   DELAY=0:DELAY1=0:GOTO 640
630   BEEP:PRINT "Input delay time T, T=T*15 Sec.":PRINT:INPUT "Delay
      (frictn)";DDLY1:   PRINT:   BEEP:   INPUT   "Delay   (pulse)
      ";DDLY:PRINT:DELAY=DDLY:DELAY1=DDLY1
635   PRINT:PRINT"Any changes about these numbers ? (y/n)"
636   EDC$=INKEY$:IF EDC$="" GOTO 636
637   IF EDC$="Y" OR EDC$="y" GOTO 580
638   IF EDC$="N" OR EDC$="n" GOTO 640
639   IF EDC$<>"N" GOTO 636
640   IF LOOP1<>0 GOTO 670
650   GOSUB 2100
660   REM CALCULATION OF F FUNCTION
670   K1=(K/(5.79-3.67*K+1.016*(K*K)))*.000001  'DIFFUSIVITY
680   ALPHA1=2*(5.79-3.67*K+1.016*K*K)/3.116   '3.116:probe's rho*c
681   ALPHA=2
685   LOOP2=LOOP2+1
```

```
690  PRINT:PRINT"Delay (friction) = ";:PRINT USING "+##.###";DELAY1,:
     PRINT ,: PRINT ,:PRINT "Delay (pulse) = ";:PRINT USING
     "+##.###";DELAY;: PRINT "(Sec.)": PRINT
700  PRINT"ALPHA                                              =";:PRINT
     USING"##.###";ALPHA1,:PRINT,:PRINT,:PRINT"Diffusivity
     =";K1:PRINT
710  TAU=A2/K1:NNN=0
720  PRINT "Time constant = ";:PRINT USING "###.#";TAU;:PRINT "
     (Sec.)":PRINT
721  IF LP1<>0 GOTO 725
722  GOSUB 11000:GOSUB 11230:GOTO 980
725  BIG=NB-NBB:IF BIG>0 THEN BIG=NB ELSE BIG=NBB
726  K1=(K/3.4)*0.000001 'take ALPHA=2, 5.79-3.67K+1.016KK=3.4
727  RER1=1:RER2=1:RER3=1:RER4=1:RER5=1:RER6=1
728  RER7=1:RER8=1:RER9=1:RER10=1:RER11=1:RER12=1
730  FOR T=1 TO RR STEP SSTP
735  IF T>BIG AND T<PPP GOTO 945
736  IF DDLY>0 OR DDLY=0 GOTO 738
737  DELAY=TRD
738  T1=((T*15+DELAY)*K1)/A2  'Time constant of heat pulse decay
739  T11=((T*15+DELAY1)*K1)/A2   'Time constant of frictional decay
755  T>=PPP GOTO 830
760  IF T1>=18.5 GOTO 770
761  IF T1>=8.5 AND T1<18.5 GOTO 780
762  IF T1>=3.6 AND T1<8.5 GOTO 790
763  IF T1>=1.6 AND T1<3.6 GOTO 800
764  IF T1>=0.6 AND T1<3.6 GOTO 810
765  REM F functin for tau<0.6
766  FOR J=RER1 TO 100:JIAN=ABS(T1-FT1(J,1))
767  IF JIAN>0.005 GOTO 769
768  RER1=J:F(T)=FT1(J,2):GOTO 830
769  NEXT J
770  REM F functin for tau>18.5
772  FOR J=RER2 TO 100:JIAN=ABS(T1-FT6(J,1))
774  IF JIAN>0.2 GOTO 777
775  RER2=J:F(T)=FT6(J,2):GOTO 830
777  NEXT J
780  REM F functin for tau 8.5 to 18.5
782  FOR J=RER3 TO 100:JIAN=ABS(T1-FT5(J,1))
784  IF JIAN>0.1 GOTO 787
785  RER3=J:F(T)=FT6(J,2):GOTO 830
787  NEXT J
790  REM F functin for tau 8.5 to 3.6
792  FOR J=RER4 TO 100:JIAN=ABS(T1-FT4(J,1))
794  IF JIAN>0.05 GOTO 797
795  RER4=J:F(T)=FT4(J,2):GOTO 830
797  NEXT J
800  REM F functin for tau 1.6 to 3.6
802  FOR J=RER5 TO 100:JIAN=ABS(T1-FT3(J,1))
```

```
804    IF JIAN>0.02 GOTO 807
805    RER5=J:F(T)=FT3(J,2):GOTO 830
807    NEXT J
810    REM F functin for tau 0.6 to 1.6
812    FOR J=RER6 TO 100:JIAN=ABS(T1-FT2(J,1))
814    IF JIAN>0.01 GOTO 817
815    RER6=J:F(T)=FT2(J,2):GOTO 830
817    NEXT J
830    IF T1>=18.5 GOTO 840
831    IF T1>=8.5 AND T1<18.5 GOTO 850
832    IF T1>=3.6 AND T1<8.5 GOTO 860
833    IF T1>=1.6 AND T1<3.6 GOTO 870
834    IF T1>=0.6 AND T1<3.6 GOTO 880
835    REM F functin for tau<0.6
836    FOR J=RER1 TO 100:JIAN=ABS(T11-FT1(J,1))
837    IF JIAN>0.005 GOTO 769
838    RER7=J:F(T)=FT1(J,2):GOTO 910
839    NEXT J
840    REM F functin for tau>18.5
842    FOR J=RER2 TO 100:JIAN=ABS(T11-FT6(J,1))
844    IF JIAN>0.2 GOTO 777
845    RER8=J:F(T)=FT6(J,2):GOTO 910
847    NEXT J
850    REM F functin for tau 8.5 to 18.5
852    FOR J=RER3 TO 100:JIAN=ABS(T11-FT5(J,1))
854    IF JIAN>0.1 GOTO 787
855    RER9=J:F(T)=FT6(J,2):GOTO 910
857    NEXT J
860    REM F functin for tau 8.5 to 3.6
862    FOR J=RER4 TO 100:JIAN=ABS(T11-FT4(J,1))
864    IF JIAN>0.05 GOTO 797
865    RER10=J:F(T)=FT4(J,2):GOTO 910
867    NEXT J
870    REM F functin for tau 1.6 to 3.6
872    FOR J=RER5 TO 100:JIAN=ABS(T11-FT3(J,1))
874    IF JIAN>0.02 GOTO 807
875    RER11=J:F(T)=FT3(J,2):GOTO 910
877    NEXT J
880    REM F functin for tau 0.6 to 1.6
882    FOR J=RER6 TO 100:JIAN=ABS(T11-FT2(J,1))
884    IF JIAN>0.01 GOTO 817
885    RER12=J:F(T)=FT2(J,2):GOTO 910
887    NEXT J
910    NNN=NNN+1:PRINT LOOP;:PRINT "-";:PRINT T,
920    PRINT "T=";:PRINT USING "##.####";T11,:PRINT,
930    PRINT "F=";:PRINT USING "##.####";F1(T),:PRINT,
935    IF T>PPP GOTO 944
939    PRINT "T(pulse) =";:PRINT USING "##.####";T1,:PRINT,
940    PRINT "F(pulse) =";:PRINT USING "##.####";F(T):GOTO 945
```

```
944   PRINT
945   NEXT T
960   FOR I=1 TO 4:PRINT:NEXT I
970   IF LP1<>0 GOTO 975
971   DELAY=DDLY:DELAY1=DDLY1
972   GOSUB 11000:GOSUB 11230:GOTO 980
975   GOSUB 2100
980   REM CHANGE IRRATIONAL POINTS
990   BEEP:PRINT "Changes of irrational points ? (y/n)"

1000  COR$=INKEY$:IF COR$="" GOTO 1000
1020  IF COR$="Y" OR COR$="y" GOTO 1050
1030  IF COR$="N" OR COR$="n" GOTO 1330
1040  IF COR$<>"N" GOTO 1000
1050  PRINT:PRINT"Change points in Frictional decay or in Pulse decay curve ?"
1060  PRINT:PRINT "Type F or P"
1070  ANSWER$=INKEY$:IF ANSWER$="" GOTO 1070
1090  IF ANSWER$="F" OR ANSWER$="f" GOTO 1120
1100  IF ANSWER$="P" OR ANSWER$="p" FOTO 1220
1110  IF ANSWER$<>"P" GOTO 1070
1120  PRINT:INPUT "Which point (right most point is #1) ";FP:FP=1+(FP-
      1)*SSTP:PRINT
1130  PRINT "Original value =";H(FP),"   New value =";:INPUT FCH
1150  FOR I=1 TO NB STEP SSTP:IF I<>FP GOTO 1170
1160  GG(I)=FCH:GOTO 1180
1170  GG(I)=H(I)
1180  NEXT I
1185  IF LP1=1 THEN LP1=0
1190  FOR I=1 TO NB STEP SSTP:H(I)=GG(I):NEXT I
1200  HD1=H(1):GOTO 970
1220  PRINT:INPUT "Which point (right most point is #1) "; FPP: FPP = 1 +
      (FPP-1)*SSTP:PRINT
1230  PRINT "Original value =";HH(FPP),"  New value =";:INPUT FCHH
1250  FOR I=1 TO NBB STEP SSTP:IF I<> FPP GOTO 1270
1260  GG(I)=FCHH:GOTO 1280
1270  GG(I)=HH(I)
1280  NEXT I
1285  IF LP1=1 THEN LP1=0
1290  FOR I=1 TO NBB STEP SSTP:HH(I)=GG(I):NEXT I
1300  HD=HC(1):GOTO 970
1330  PRINT:DIFF=ICPT1-ICPT:HD=HC(1):HD1=H(1)
1340  IF ABS(DIFF)<0.002 GOTO 1460  'Torelance of two inf.times
1345  IF LOOP=0 GOTO 1355
1350  FD=F(1)*SLOPE1+ICPT1
1451  FD1=F1(1)*SLOPE+ICPT:GOTO 1360
1355  IF DDLY<0 THEN DDY=0 ELSE DDY=DDLY
1356  IF DDLY1<0 THEN DDY1=0 ELSE DDY1=DDLY1
1358  FD=F(1+DDY)*SLOPE1+ICPT1
1359  FD1=F1(1+DDY1)*SLOPE+ICPT:GOTO 1360
```

```
1360 FDD=FD-HD:FDD1=FD1-HD1
1370 IF ABS(FDD)>0.15 GOTO 2900
1380 IF ABS(FDD1)>0.15 GOTO 2900
1390 IF DIFF<-0.005 GOTO 2870
1400 IF DIFF<0.005 GOTO 1420
1410 IF FDD<0 AND FDD1>0 GOTO 2890
1420 IF FDD=0 GOTO 1440
1430 DL=DELAY:IF FDD>0 THEN DELAY=DELAY+200*ABS(FDD) ELSE DELAY=DELAY-200*ABS(FDD): IF DDLY >=0 OR DDLY=0 GOTO 1440
1435 TRD= DELAY-DL
1440 IF FDD1=0 GOTO 1460
1450 DL1=DELAY1:IF FDD1>0 THEN DELAY1=DELAY1+400*ABS(FDD1) ELSE DELAY1 =DELAY1 - 400*ABS(FDD1): GOTO 1460 'Adjust delay for frictional decay
1460 SS=0:SS1=0:NBBN=0
1461 IF LP1<>1 GOTO 1470
1462 DDD=DL:IF DDLY<0 THEN DDD=0
1470 FOR T=1 TO NBB STEP SSTP
1471 NBBN=NBBN+1
1475 TT=((T*15+DDD)*K1)/(0.00472^2)
1480 KKT1=(QQ*ALPHA1*K*F(T)*0.000001)/(2*3.4*A2*PI*(HC(T)-ICPT))
1485 KKT=(QQ*ALPHA1*K*0.000001)/(3.4*2*A2*PI*SLOPE1)
1490 SS=SS+KKT:SS1=SS1+KKT1:NEXT T
1500 PRINT "K(slope)=";SS/NBBN,"K(point)=";SS1/NBBN:PRINT
1510 DDD=DL:PRINT "LOOP #";LOOP,:PRINT "Previous K =";: PRINT USING "##.###";K
1520 SS=SS/NBBN:PRINT "Conductivity K=";:PRINT USING "##.###";SS
1530 DIF=K-SS:DIF=ABS(DIF)
1540 BEEP:PRINT "Continue ? (y/n)":PRINT
1550 CTNU$=INKEY$:IF CTNU$="" GOTO 1550
1560 IF CTNU$="Y" OR CTNU$="y" GOTO 1590
1570 IF CTNU$="N" OR CTNU$="n" GOTO 2090
1580 IF CTNU$<>"N" GOTO 1550
1590 IF DIF<0.02 GOTO 2080
1610 K=SS:CLOSE:BEEP:LOOP=LOOP+1:GOTO 660
1620 CLS:BEEP:BEEP:PRINT "Printer ready ?": PRINT: LINE INPUT "Heading for printer :"; HEP$: IF HEP$="" THEN HEP$=DA$
1630 LPRINT:LPRINT:LPRINT HEP$;"    ";DATE$
1631 LPRINT:LPRINT
1640 CLS:PRINT:PRINT:PRINT "Channel # "; TN," Conductivity K = ";: PRINT USING "##.###";SS,
1650 LPRINT "Channel # ";TN,"Conductivity K = ";
1655 LPRINT USING "##.###";SS,
1660 IF CMP=0 GOTO 1680
1670 PRINT "(Manually terminated)"
1675 LPRINT"(Manually terminated)":GOTO 1690
1680 PRINT:LPRINT
```

```
1690 PRINT:PRINT SPC (15);"ALPHA =";PRINT USING "##.###"; ALPHA,: PRINT,: PRINT "Q = ";QQ;" (Jole/M)"
1700 LPRINT:LPRINT SPC (15);"ALPHA =";LPRINT USING "##.###"; ALPHA,: LPRINT,: LPRINT "Q = ";QQ;" (Jole/M)"
1710 PRINT:PRINT SPC(15);"Infinite temp. ";:PRINT USING "##.###"; TOTAL,: PRINT,
1720 LPRINT:LPRINT SPC(15);"Infinite temp. ";:LPRINT USING "##.###"; TOTAL,: LPRINT,
1730 PRINT"Temp. reference point : ";:PRINT TRR
1740 LPRINT"Temp. reference point : ";:LPRINT TRR
1750 PRINT:PRINT SPC(15);
1755 PRINT"Standard deviation of inf. temp. :";SIGICPT
1760 LPRINT:LPRINT SPC(15);
1765 PRINT"Standard deviation of inf. temp. :";SIGICPT
1770 PRINT:PRINT SPC(15);
1775 PRINT"Standard deviation of K fitting :";SIGICPT1
1780 LPRINT:LPRINT SPC(15);
1785 PRINT"Standard deviation of K fitting :";SIGICPT1
1790 PRINT:PRINT SPC(15);"Delay (fric)";
1795 PRINT USING"###.#";DL1,:PRINT,
1799 LPRINT:LPRINT SPC(15);"Delay (fric)";
1800 PRINT USING"###.#";DL1,:LPRINT,
1801 IF LOOP1<>1 GOTO 1810
1802 IF DDLY1<0 THEN DL=0
1805 PRINT "Delay (pulse)";:PRINT USING "###.#";DL
1807 LPRINT "Delay (pulse)";
1808 LPRINT USING "###.#";DL:GOTO 1830
1810 IF DDLY>=0 GOTO 1813
1811 DL=TRD
1813 PRINT "Delay (pulse) ";:PRINT USING "###.#";DL
1820 LPRINT "Delay (pulse) ";:LPRINT USING "###.#";DL
1830 PRINT:PRINT SPC(15);"LOOP ";LOOP,: PRINT "Ifn. temp. diff. ";: PRINT USING "+##.####"; DIFF
1840 LPRINT:LPRINT SPC(15);"LOOP ";LOOP,: LPRINT "Ifn. temp. diff. ";: LPRINT USING "+##.####"; DIFF
1850 PRINT:PRINT SPC(15);"Penetration at ";PP,: PRINT "Heat pulse at ";PPP
1860 LPRINT:LPRINT SPC(15);"Penetration at ";PP,: LPRINT "Heat pulse at ";PPP
1870 BEEP:BEEP:BEEP
1871 PRINT:PRINT SPC(15);
1872 PRINT "Compute for every ";SSTP; " point"
1873 LPRINT:LPRINT SPC(15);
1875 PINT "Compute for every ";SSTP; " point"
1880 FOR I=1 TO 8:LPRINT:NEXT I
1890 BEEP:PRINT:PRINT "Store F(A,T) on disk ? (y/n)"
1900 REC$=INKEY$:IF REC$="" GOTO 1900
1920 IF REC$="Y" OR REC$="y" GOTO 2070
1930 IF REC$="N" OR REC$="n" GOTO 1950
1940 IF REC$<>"N" GOTO 1900
```

```
1950 PRINT:LINE INPUT "File name for F(A,T) of pulse decay : "; FFF$: PRINT: FFF$= "B:"+FFF$
1960 CLOSE:OPEN "O",#2,FFF$:CLOSE:OPEN "A",#2,FFF$
1970 FOR I=1 TO RR STEP SSTP:PRINT #2,F(I):NEXT I
1980 PRINT:LINE INPUT "File name for F(A,T) of frictional heat decay : "; FRC$: PRINT: FRC$= "B:"+FRC$
1990 CLOSE:OPEN "O",#1,FRC$:CLOSE:OPEN "A",#1,FRC$
2000 FOR I=1 TO RR STEP SSTP:PRINT #1,F1(I):NEXT I
2010 PRINT:LINE INPUT "File name for Temp. of pulse decay : "; TTT$: PRINT: TTT$ = "B:"+TTT$
2020 CLOSE:OPEN "O",#2,TTT$:CLOSE OPEN "A",#2,TTT$
2030 FOR I=1 TO NBB STEP SSTP:PRINT #2,HH(I):NEXT I
2040 PRINT:LINE INPUT "File name for Temp. of frictional heat decay : "; TRC$: PRINT: TRC$ = "B:"+TRC$
2050 CLOSE:OPEN "O",#1,TRC$:CLOSE:OPEN "A",#1,TRC$
2060 FOR I=1 TO NB STEP SSTP:PRINT #1,H(I):NEXT I
2070 GOTO 2920
2080 IF ABS(DIFF)<0.005 GOTO 1620 ELSE GOTO 1610
2090 CMP=1:GOTO 1620

2100 REM SUBROUTINE OF LEAST SQUARE FITTING
2110 SCREEN 100:SCREEN 105:KEY OFF:CLS 'Change if use IBM PC
2120 SCAL=0:FOR I=1 TO NB:SCAL=SCAL+H(I):NEXT I
2130 SCAL=(SCAL/NB)*300+175 'Auto adjust on screen
2140 LINE (60,300)-(580,300):LINE (60,30)-(60,300)
2150 FOR I=1 TO NB STEP SSTP
2155 X(I)=F1(I)*1000+60:Y(I)=SCAL-H(I)*300
2160 CIRCLE (X(I),Y(I)),0.5:NEXT I ,Display frictional decay
2180 SSX=0:SSY=0:SX=0:SY=0:SXY=0:SIG=0:NBN=0
2190 FOR I=1 TO NB STEP SSTP
2195 NBN=NBN+1
2200 SSX=SSX+F1(I)^2:SSY=SSY+H(I)^2
2210 SX=SX+F1(I):SY=SY+H(I):SXY=SXY+F1(I)*H(I):NEXT I
2230 ASSX=SSX/NBN:ASSY=SSY/NBN:ASX=SX/NBN: ASY= ASY/NBN: ASXY = SXY/NBN
2240 SIGX=ASSX-(ASX*ASX):SIG=ASSY-ASY*ASY
2250 SLOPE=(ASXY-ASX*ASY)/SIGX 'Slope of frictional decay
2260 ICPT=ASY-(SLOPE*ASX) 'Temp. at infinite time
2280 FOR I=1 TO NB STEP SSTP:LSUMM= SLOPE*F1(I) + ICPT-H(I): SIG-SIG + SUMM*SUMM: NEXT I
2300 SIG=SIG/(NBN*NBN):SIGSLP=SIG/SIGX
2310 SIGICPT=SIG*ASSX/SIGX:SIGICPT=SQR(SIGICPT
2320 IF F1(I)>0.55 GOTO 2340
2330 LL=X(1)+20:GOTO 2350
2340 LL=X(2)+20
2350 LINE(60,SCAL-300*ICPT)-(LL,SCAL-300*((LL-60) * SLOPE / 1000 + ICPT))
2360 FOR I=1 TO 4:PRINT:NEXT I
2370 FOR I=1 TO NBB STEP SSTP
2371 HC(I)= HH(I)-F(I+PPP-PP-1)*SLOPE
```

```
2372 X(I)=F(I)*1000+60:Y(I)=SCAL-HC(I)*300
2380 CIRCLE (X(I),Y(I)),1.5:NEXT I  'heat pulse fitting
2400 SSX=0:SSY=0:SX=0:SY=0:SXY=0:SIG=0:NBBN=0
2420 FOR I=1 TO NBB STEP SSTP
2421 SSX=SSX+F(I)^2:SSY=SSY+HC(I)^2
2425 NBBN=NBBN+1
2430 SX=SX+F(I):SY=SY+HC(I)
2440 SXY=SXY+F(I)*HC(I):NEXT I
2450 ASSX=SSX/NBBN:ASSY=SSY/NBBN
2452 ASX=SX/NBBN:ASY=SY/NBBN:ASXY=SXY/NBBN
2460 SIGX=ASSX-ASX^2:SIGY=ASSY-ASY^2
2480 ICPT1=ASY-SLOPE1*ASX  'Inf. temp. of pulse decay
2500 FOR I=1 TO NBB STEP SSTP
2510 SUMM = SLOPE1*F(I)+ICPT-HC(I)
2515 SIG=SIG+SUMM^2:NEXT I
2520 SIG=SIG/NBBN^2:SIGSLP1=SIG/SIGX
2530 SIGICPT1=SIG*ASSX/SIGX
2535 SIGICPT1=SQR(SIGICPT1)
2540 IF F(1)>0.55 GOTO 2560
2550 LL=X(1)+20:GOTO 2570
2560 LL=X(2)+20
2570 LINE(60,SCAL-300*ICPT1)-(LL,SCAL-300*((LL-60) * SLOPE1 / 1000 + ICPT1))
2580 FOR I=1 TO 17:PRINT:NEXTI
2590 PRINT SPC(40);"Channel:";TN" Reference ";:PRINT TRR
2600 PRINT SPC(40);"Channel:";TN"Temp. (frc)";
2605 PRINT USING "##.####"; ICPT
2610 PRINT SPC(40);"Channel:";TN"Temp. (pls)";
2620 PRINT USING"##.####";ICPT1:PRINT:TOTAL=ICPT
2630 PRINT SPC(40);"Channel:";TN;"Inf.temp. ";
2635 PRINT USING "##.####"; TOTAL
2640 LOOP1=LOOP1+1
2650 IF LOOP2<>0 GOTO 2710
2660 BEEP:BEEP:PRINT:PRINT "Change of the delay times ? (present delay = 0) (y/n)": PRINT
2670 CHG$=INKEY$:IF CHG$="" GOTO 2670
2680 IF CHG$="Y" OR CHG$="y" GOTO 630
2690 IF CHG$="N" OR CHG$="n" GOTO 2860
2700 IF CHG$<>"N" GOTO 2670
2710 RETURN
2720 REM SUBROUTIN OF FINDING DATA POINTS
2730 FOR I=1 TO 119
2740 KIK=I-PP:IF I<PP GOTO 2780
2750 H(KIK)=H1(I)  'Temp. of frictional decay
2760 IF KIK<>1 GOTO 2780
2770 HD1=H(KIK)
2780 NEXT I
2790 FOR I=1 TO 119
2800 KIK=I-PPP:IF I<PPP GOTO 2840
```

```
2810   HH(KIK)=H1(I)  'Temp. of pulse decay
2820   IF KIK<>1 GOTO 2840
2830   HD=HH(KIK)
2840   NEXT I
2842   FOR I=1 TO 119:HC(I)=HH(I):HEXT I
2850   RETURN
2860   LOOP2=1:GOTO 2710
2870   IF FDD>0 AND FDD1<0 GOTO 2890
2880   GOTO 1420
2890   BEEP:BEEP:BEEP:PRINT:PRINT "Do not converge !";
2990   PRINT"Change initiate points !":PRINT
2995   IF LOOP2=1 THEN LOOP2=0
2910   GOTO 550
2920   CLS:GOSUB 9020:PRINT:PRINT "Another channel ?  (y/n)"
2930   CTU$=INKEY$:IF CTU$="" GOTO 2930
2940   IF CTU$="Y" OR CTU$="y" GOTO 200
2950   IF CTU$="N" OR CTU$="n" GOTO 20
2960   IF CTU$<>"N" GOTO 2930
3000   REM ROUTINE OF FAST GRADIENT ESTIMATE
3001   DIM X(14),Y(14):M=14
3005   DIM J(120),W(120),L(14),H(14),HEAT(1665),H1(120)
3010   CLOSE:CLS:GOSUB 9020:PRINT SPC(10);"Thermal gradient calculation and
       plooting": FOR I=1 TO 5: PRINT: NEXT I: PRINR SPC(10); "Mount disk on
       drive B": PRINT SPC(10); "Press any key to continue"
3020   KK$=INKEY$:IF KK$="" GOTO 3020
3030   CLS:BEEP:FILES "B:":FOR I=1 TO 4:PRINT
3040   MEXT I: PRINT SPC(10);" ";
3042   LINE INPUT "Which data file ? ";NW$
3044   NW$= "B:"+NW$
3050   BEEP:PRINT:LINE INPUT"Name of new data file: ";G$
3052   G$="B:"+G$
3055   PRINT:BEEP:INPUT" Probe length (in meter)";LENGH
3056   IF LENGH=0 THEN LENGH=7.5
3060   BEEP:BEEP:PRINT:PRINT" Printer ready ?";:PRINT SPC(8);: LINE INPUT"
       Heading of the print :";PG$: IF PG$="" THEN PG$=NW$
3070   LPRINT"Thermal gradient of ";PG$:LPRINT:LPRINT
3071   PRINT"Is ";NW$;" a Random file or a Serial file ? (type R or S)"
3072   RS$=INKEY$:IF RS$="" GOTO 3072
3073   IF RS$="R" OR RS$="r" GOTO 3077
3074   IF RS$="S" OR RS$="s" GOTO 3079
3075   IF RS$<>"S" GOTO 3072
3077   PRINT:PRINT"Loading from random file ";
3078   PRINT NW$;"...":GOTO 3090
3079   PRINT:PRINT"Loading from serial file ";
3080   PRINT NW$;"...":GOTO 5900
3090   OPEN "O",#2,G$:CLOSE:GOSUB 5500
3210   OPEN "R",#1,NW$
```

```
3220 FIELD #1,4 AS L$,8 AS T$,4 AS R$,8 AS D1$,8 AS D2$,8 AS D3$,8 AS D4$,8 AS D5$,8 AS D6$,8 AS D7$,8 AS D8$,8 AS D9$,8 ASA D10$,8 AS D11$,8 AS D12$,8 AS D13$,8 AS D14$
3260 AVRG=0:FOR I=1 TO 80:GET #1,I: J(I)=CVS(D1$): AVRG=AVRG+J(I): NEXT I
3270 AVRG=AVRG/80:AVRG=(5811.403/(LOG(AVRG)+5.493939))-342.7457: Q = AVRG/0.2-1
3280 FOR I=1 TO 80:J(I)=5811.403/(LOG(J(I))+5.493939))-3.42.7457 'Simulate R-T relation of thermistor
3290 J(I)=234+Q*24-120*J(I):NEXT I
3310 FOR I=1 TO 79:X1=70+(I-1)*6
3315 X2=X1+6:Y1=J(I):Y2=J(I+1)
3320 LINE (X1,Y1)-(X2,Y2):NEXT I
3321 BEEP:BEEP:INPUT"Which point for tem. reference ";TR:IF TR=0 THEN TR=1
3322 XX1=70+(TR-1)*6:YY1YY1=J(TR)
3323 CIRCLE (XX1,YY1),3:CIRCLE (XX1,YY1),6
3340 BEEP:INPUT"Which point for gradient calculation ";F
3341 XX1=70+(F-1)*6:YY1=J(F):CIRCLE (XX1,YY1), 6: LINE (XX1,YY1-3)-(XX1,YY1)+3
3342 BEEP:PRINT"Are these points aceptable ? (y/n)"
3343 GGP$=INKEY$:IF GGP$="" GOTO 3343
3344 IF GGP$="Y" OR GGP$="y" GOTO 3350
3345 IF GGP$="N" OR GGP$="n" GOTO 3347
3346 IF GGP$<>"N" GOTO 3343
3347 CLS:GOSUB 5500:GOTO 3343
3350 OPEN "A",#2,G$
3360 FIELD #1,4 AS L$,8 AS T$,4 AS R$,8 AS D1$,8 AS D2$,8 AS D3$,8 AS D4$,8 AS D5$,8 AS D6$,8 AS D7$,8 AS D8$,8 AS D9$,8 ASA D10$,8 AS D11$,8 AS D12$,8 AS D13$,8 AS D14$
3370 FOR K=1 TO 14:FOR I=1 TO 80
3390 IF I<>TR THEN 3570
3400 GET #1,I:GOSUB 5000
3570 NEXT I:H(K)=J(TR):NEXT K
3600 FOR K=1 TO 14:FOR I=1 TO 80
3620 IF I>F THEN 3830
3630 GET #1,I
3640 IF I<F THEN 3820
3650 GOSUB 5000
3810 L(K)=J(I):D=H(K)-H(1):L(K)=L(K)-D:PRINT #2,L(K)
3820 NEXT I
3830 NEXT K
3840 MIN=L(1):FOR I=1 TO 14:PS=L(I)-MIN:IF PS>0 GOTO 3845
3841 MIN=L(I)
3845 NEXT I
3850 CLS:PRINT:PRINT:FOR I=14 TO 1 STEP -1
3860 IF I=1 THEN 3890
3870 IF I<>14 THEN 3900
3880 STR=(L(I)-MIN)*30:PRINT I,L(I),
```

```
3885    PRINT "    TOP",SPC(STR);"*":GOTO 3910
3890    STR=(L(I)-MIN)*30:PRINT I,L(I),
3895    PRINT"BOTTOM",SPC(STR);"*":GOTO 3910
3900    STR=(L(I)-MIN)*30:PRINT I,L(I),,SPC(STR);"*"
3910    NEXT I
3920    FOR I=14 TO 1 STEP -1
3930    IF I=1 THEN 3960
3940    IF I<>14 THEN 3970
3950    STR=(L(I)-MIN)*30:LPRINT "Channel ";I,: LPRINT USING "##.####";
        L(I),: LPRINT "    TOP", ,: LPRINT SPC(STR); "*": GOTO 3980
3960    STR=(L(I)-MIN)*30:LPRINT "Channel ";I,: LPRINT USING "##.####";
        L(I),: LPRINT "BOTTOM" ,: LPRINT SPC(STR); "*": GOTO 3980
3970    STR=(L(I)-MIN)*30:LPRINT "Channel ";I,: LPRINT USING "##.####";
        L(I),: LPRINT, ,: LPRINT SPC(STR); "*"
3980    NEXT I
3990    BEEP:BEEP:PRINT:PRINT"Press any key to continue."

4000    KKK$=INKEY$:IF KKK$="" THEN 4000
4030    FOR I=1 TO 14:X(I)=300*L(I)-250:Y(I)+15*(14-I):NEXT I
4031    MAX=X(1):IF MAX<0 GOTO 4040
4032    FOR I=1 TO 14:DS=X(I)-MAX:IF DS<0 GOTO 4034
4033    MAX=X(I):II=I:MXX=X(I)-500
4034    NEXT I
4035    IF MAX<500 GOTO 4100
4036    FOR I=1 TO 14:X(I)=X(I)-MXX:NEXT I:GOTO 4100
4040    MIN=X(1):FOR I=1 TO 14:DS=X(I)-MIN:IF DS>0 GOTO 4060
4050    MIN=X(I):MMIN=200-X(I)
4060    NEXT I
4070    IF MIN>100 GOTO 4100
4080    FOR I=1 TO 14:X(I)=X(I)+MMIN:NEXT I
4100    GOSUB 5700
4140    FOR I=1 TO M
4150    CIRCLE (X(I)+100,50+Y(I)),4,1:NEXT I
4160    FOR I=1 TO M
4170    LINE (X(I)+98,50+Y(I))-(X(I)+102,50+Y(I))
4180    LINE (X(I)+100,48+Y(I))-(X(I)+100,52+Y(I)):NEXT I
4190    BEEP:INPUT"How many points are in calculation ";N
4200    FOR I=1 TO N:X(I)=300*(L(I)-L(N)):Y(I)=15*(N-1):NEXT I
4210    SXX=0:SSY=0:SX=0:SY=0:SXY=0:SIG=0
4230    FOR I=1 TO N
4240    SSX=SSX+X(I)^2:SSY=SSY+Y(I)^2:SX=SX+X(I)
4245    SY=SY+Y(I):SXY=SXY+X(I)*Y(I)
4250    NEXT I
4260    ASSX=SSX/N:ASSY=SSY/N
4265    ASX=SX/N:ASY=SY/N:ASXY=SXY/N
4270    SIGX=ASSX-ASX^2:SIGY=ASSY-ASY^2
4280    SLOPE=(ASXY-ASX*ASY)/SIGX
4290    ICPT=ASY-SLOPE*ASX
4300    FOR I=1 TO N
```

```
4310 SUM=SLOPE*X(I)+ICPT-Y(I):SIG=SIG+SUM^2:NEXT I
4320 SIG=SIG/(N*N)
4330 SIGSLP=SIG/SIGX:SIGSLP=SQR(SIGSLP)
4350 SIGICPT=SIG*ASSX/SIGX:SIGICPT=SQR(SIGICPT)
4370 GOSUB 5700
4470 FOR I=1 TO N:CIRCLE(X(I)+100,50+Y(I)),4:NEXT
4490 FOR I=1 TO N
4500 LINE(X(I)+98,50+Y(I))-(X(I)+102,50+Y(I))
4510 LINE(X(I)+100,48+Y(I))-(X(I)+100,52+Y(I)):NEXT I
4520 L=0
4530 FOR I=1 TO N
4540 IF X(I)>=L THEN 4550 ELSE 4560
4550 L=X(I)
4560 NEXT I
4570 L=L+110
4580 LINE(100,50+ICPT)-(L,(L-100)*SLOPE+ICPT+50)
4590 G=(0.1/SLOPE)*(7.5/LENGH)
4600 PRINT SPC(18);"Least-square-fitting of thermal gradient"
4610 PRINT:PRINT:PRINT SPC(11);"0"
4630 PRINT SPC(62);"Temp."
4640 FOR I=1 TO 12:PRINT:NEXT I
4670 PRINT SPC(30);"Geothermal gradient: ";
4675 PRINT USIMG "##.####";G;:PRINT
4680 LPRINT:LPRINT:LPRINT"Geothermal gradient :";LPRINT USING
     "####.#"; 1000*G;: LPRINT " (mK/M) [ at point ";F; ",";: LPRINT "from
     channel 1 to channel "; N; ", probe length : "; LENGH; " M ]";
4681 LPRINT "Temp. reference point:"; TR
4690 FOR I=1 TO 8:LPRINT:NEXT I
4700 PRINT SPC(9);"(M)"
4710 PRINT SPC(30);"Slope : ";:PRINT USING "##.####"; SLOPE/0.1
4720 PRINT " +/-";:PRINT USINR "##.####";SIGSLP/0.1
4730 PRINT SPC(9);"DEPTH";SPC(16); "Intercept : ";:PRINT USING
     "##.####"; ICPT/30
4740 PRINT " +/-";PRINT USING "##.####";SIGICPT/30
4741 PRINT"Press any key to continue"
4750 S$=INKEY$:IF S$="" GOTO 4750
4770 CLS:PRINT:PRINT"Continue with gradient estimation ? (y/n)"
4780 GRD$=INKEY$:IF GRD$="" GOTO 4780
4790 IF GRD$="Y" OR GRD$="y" GOTO 3010
4800 IF GRD$="N" OR GRD$="n" GOTO 20
4810 IF GRD$<>"N" GOTO 4780
4900 PG$=DA$:GOSUB 5500:AVRG=0
4905 FOR I=1 TO 79:AVRG=AVRG+H1(I):NEXT:AVRG=AVRG/79
4910 Q=AVRG/0.2-1:FOR I=1 TO 79:J(I)=234+Q*24-H1(I)*120:NEXT
4920 FOR I=1 TO 78:X1=70+(I-1)*6:X2=X1+6:Y1=J(I)
4921 Y2=J(I+1):LINE(X1,Y1)-(X2,Y2):NEXT I
4930 RETURN
```

```
5000 ON K GOTO 5010, 5020, 5030, 5040, 5050, 5060, 5070, 5080, 5090, 5100,
     5110,5120, 5130, 5140
5010 J(I)=CVS(D1$):GOTO 5150
5020 J(I)=CVS(D2$):GOTO 5150
5030 J(I)=CVS(D3$):GOTO 5150
5040 J(I)=CVS(D4$):GOTO 5150
5050 J(I)=CVS(D5$):GOTO 5150
5060 J(I)=CVS(D6$):GOTO 5150
5070 J(I)=CVS(D7$):GOTO 5150
5080 J(I)=CVS(D8$):GOTO 5150
5090 J(I)=CVS(D9$):GOTO 5150
5100 J(I)=CVS(D10$):GOTO 5150
5110 J(I)=CVS(D11$):GOTO 5150
5120 J(I)=CVS(D12$):GOTO 5150
5130 J(I)=CVS(D13$):GOTO 5150
5140 J(I)=CVS(D14$):GOTO 5150
5150 J(I)=(5811.403/(LOG(J(I))+5.493939))-342.7457
5160 RETURN
5200 PRINT:PRINT"Loading from random file  ";DA$:GOSUB 9000
5201 CLOSE:OPEN "R",#1,DA$
5202 FIELD #1,4 AS L$,8 AS T$,4 AS R$,8 AS D1$,8 AS D2$,8 AS D3$,8 AS D4$,8
     AS D5$,8 AS D6$,8 AS D7$,8 AS D8$,8 AS D9$,8 ASA D10$,8 AS D11$,8 AS
     D12$,8 AS D13$,8 AS D14$
5208 FOR I=1 TO 120:GET #1,I
5209 ON TN GOTO 5210, 5220, 5230, 5240, 5250, 526O, 5270, 5280, 5290, 5300, 5310,
     5320, 5330, 5340
5210 H1(I)=CVS(D1$):GOTO 5350
5220 H1(I)=CVS(D2$):GOTO 5350
5230 H1(I)=CVS(D3$):GOTO 5350
5240 H1(I)=CVS(D4$):GOTO 5350
5250 H1(I)=CVS(D5$):GOTO 5350
5260 H1(I)=CVS(D6$):GOTO 5350
5270 H1(I)=CVS(D7$):GOTO 5350
5280 H1(I)=CVS(D8$):GOTO 5350
5290 H1(I)=CVS(D9$):GOTO 5350
5300 H1(I)=CVS(D10$):GOTO 5350
5310 H1(I)=CVS(D11$):GOTO 5350
5320 H1(I)=CVS(D12$):GOTO 5350
5330 H1(I)=CVS(D13$):GOTO 5350
5340 H1(I)=CVS(D14$):GOTO 5350
5350 H1(I)=(5811.403/(LOG(H1(I))+5.493939))-342.7457
5365 NEXT I:CLOSE:RETURN
5500 CLS:SCREEN 100:SCREEN 105
5510 LINE (20,32)-(20,272),1:LINE(20,272)-(620,272),1
5520 FOR I=0 TO 595 STEP 5:X1=25+I:Y1=270
5530 X2=X1:Y2=274:LINE(X1,Y1)-(X2,Y2):NEXT I
5540 FOR I=0 TO 595 STEP 20:X1=25+I:Y1=268
5550 X2=X1:Y2=274:LINE(X1,Y1)-(X2,Y2):NEXT I
5560 FOR I=0 TO 192 STEP 48:X1=17:Y1=32+I
```

```
5570    X2=23:Y2=Y4:LINE(X1,Y1)-(X2,Y2):NEXT I
5580    PRINT SPC(25);"HEAT FLOW         ";PG$
5590    PRINT SPC(25);"Station #  ";STATION$
5600    PRINT "    TEMP."
5610    FOR I=1 TO 17:PRINT:NEXT I
5620    S$=SPACE$(73):PRINT S$;:PRINT "TIME ":PRINT
5630    RETURN
5700    CLS:SCREEN 100:SCREEN 105:LINE (100,50)-(559,50)
5720    FOR I=0 TO 420 STEP 15:LINE(115+I,48)-(115+I,50):NEXT I
5740    FOR I=0 TO 375 STEP 75:LINE(175+I,46)-(175+I,50):NEXT I
5760    FOR I=0 TO 300 STEP 150:LINE(250+I,44)-(250+I,50):NEXT I
5770    LINE (100,50)-(100,275)
5790    FOR I=0 TO 180 STEP 30:LINE (98,80+I)-(100,80+I):NEXT
5800    RETURN
5900    OPEN "O",#2,G$:CLOSE
5909    TN=1:DA$=NW$:GOSUB 10390
5910    GOSUB 4900
5911    INPUT "Which point for gradient calculation  ";F
5912    XX1=70+(F-1)*6:YY1=234+Q*24-120*H1(F)
5913    CIRCLE  (XX1,YY1),6:LINE(XX1,YY1-3)-(XX1,YY1+3):  LINE  (XX1-4,YY1)-
        (XX1+4,YY1)
5914    FOR I=1 TO 19:PRINT:NEXT:PRINT"Is this acceptable ?  (y/n)"
5915    POT$=INKEY$:IF POT$="" GOTO 5915
5916    IF POT$="Y" OR POT$="y" GOTO 5920
5917    IF POT$="N" OR POT$="n" GOTO 5910
5918    IF POT$<>"N" GOTO 5915
5920    CLOSE:OPEN "I",#1,NW$
5925    FOR I=1 TO 1105:INPUT #1,HEAT(I):NEXT I
5928    FOR J=1 TO 14:KKK=(J-1)*79+F
5931    L(J)=HEAT(KKK):NEXT J:GOTO 3850

6000    REM ROUTINE OF HEX TO DECIMAL
6001    REM CALCULATE RESISTANCE. 20 min. DATA
6010    DIM THRM(17,80):GOSUB 9020
6020    CLS:KEY OFF:PRINT:PRINT:PRINT
6030    PRINT "RAW DATA PROCESSING"
6090    FOR I=1 TO 5:PRINT:NEXT I
6100    PRINT SPC(18);"Which data file is to be pocessed ?"
6101    PRINT:PRINT:PRINT SPC(22);
6102    PRINT "Mount disk on drive B":PRINT SPC(22);
6103    PRINT "Press any key to continue"
6110    MM$=INKEY$:IF MM$="" GOTO 6110
6120    CLS:BEEP:FILES "B:":PRINT:PRINT:PRINT
6130    LINE INPUT"   Type file name:  ";Q$:Q$="B:"+Q$
6140    OPEN Q$ FOR INPUT AS #1
6150    PRINT:PRINT "Start from which line ?";
6155    PRINT "  (in hexadecimal format ####)"
6160    LINE INPUT "  Type line number : ";Y$
6180    FOR I=1 TO 1200:N$=INPUT$(4,#1)
```

```
6190   IF N$=Y$ THEN GOTO 6250
6200   M$=INPUT$(82,#1):NEXT I:PRINT
6210   PRINT "Line number error":GOSUB 9010:CLOSE #1
6220   GOTO 6140
6250   PRINT:PRINT N$;:PRINT "  found":PRINT
6260   M$=INPUT$(82,#1)
6280   PRINT "Name the new data file :":PRINT:PRINT
6285   PRINT:BEEP:PRINT "Press any key to continue"
6290   MNM$=INKEY$:IF MMM$="" GOTO 6290
6300   CLS:FILES "B:":PRINT:PRINT:PRINT
6310   LINE INPUT "   Type new file name :  ";NW$
6315   NW$="B:"+NW$
6320   CLS:PRINT"Source data file: ";Q$;:PRINT" line #";Y$
6325   PRINT:PRINT:PRINT"New data file: ";NW$
6330   FOR I=1 TO 5:PRINT:NEXT I
6335   PRINT"Processing takes 12 minutes":PRINT:PRINT
6340   C$="0123456789ABCDEF"
6360   FOR H=1 TO 120:FOR K=1 TO 17
6380   A$=INPUT$(5,#1):X=0
6400   FOR I=1 TO 5  'Hex to decimal conversion
6410   IF I=5 GOTO 6490
6420   B$=MID$(A$,I,1)
6430   FOR J=1 TO 16:D$=MID$(C$,J,1)
6450   IF B$=D$ GOTO 6470
6460   NEXT J
6470   X=X+(J-1)*16^(4-1)
6480   NEXT I
6490   THRM(K,H)=X
6500   NEXT K
6510   A$=INPUT$(1,#1):PRINT H;:PRINT " ";:NEXT H
6520   REM RESISTANCE CALCULATION
6530   REM reference resistor = 10000 ohm
6580   FOR J=1 TO 120:FOR I=1 TO 17
6600   THRM(I,J)=(THRM(I,J)/THRM(3,J))*10000
6610   NEXT I:NEXT J
6630   OPEN "R",#2,NW$
6640   FIELD #1,4 AS L$,8 AS T$,4 AS R$,8 AS D1$,8 AS D2$,8 AS D3$,8 AS D4$,8
       AS D5$,8 AS D6$,8 AS D7$,8 AS D8$,8 AS D9$,8 ASA D10$,8 AS D11$,8 AS
       D12$,8 AS D13$,8 AS D14$
6650   FOR J=1 TO 80:FOR I=1 TO 17
6670   PRINT THRM(I,J)
6680   ON I GOTO 6690, 6700, 6710, 6720, 6730, 6740, 6750, 6760, 6770, 6780, 6790,
       6800, 6810, 6820, 6830, 6840, 6850
6690   LSET I$=MKS$(THRM(1,J)):GOTO 6870
6700   LSET J$=MKS$(THRM(2,J)):GOTO 6870
6710   LSET R$=MKS$(THRM(3,J)):GOTO 6870
6720   LSET D1$=MKS$(THRM(4,J)):GOTO 6870
6730   LSET D2$=MKS$(THRM(5,J)):GOTO 6870
6740   LSET D3$=MKS$(THRM(6,J)):GOTO 6870
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6750   LSET D4$=MKS$(THRM(7,J)):GOTO 6870
6760   LSET D5$=MKS$(THRM(8,J)):GOTO 6870
6770   LSET D6$=MKS$(THRM(9,J)):GOTO 6870
6780   LSET D7$=MKS$(THRM(10,J)):GOTO 6870
6790   LSET D8$=MKS$(THRM(11,J)):GOTO 6870
6800   LSET D9$=MKS$(THRM(12,J)):GOTO 6870
6810   LSET D10$=MKS$(THRM(13,J)):GOTO 6870
6820   LSET D11$=MKS$(THRM(14,J)):GOTO 6870
6830   LSET D12$=MKS$(THRM(15,J)):GOTO 6870
6840   LSET D13$=MKS$(THRM(16,J)):GOTO 6870
6850   LSET D14$=MKS$(THRM(17,J)):GOTO 6870
6870   NEXT I
6880   PUT #2,:NEXT J
6910   FOR I=1 TO 3:BEEP:NEXT I
6940   PRINT:PRINT"Display Temp.-time relationship ? (y/n)"
6980   F$=INKEY$:IF F$="" GOTO 6980
7000   IF F$="Y" OR F$="y" GOTO 7040
7010   IF F$="N" OR F$="n" GOTO 20
7020   IF F$<>"N" GOTO 6980
7040   CLOSE:DIM B(120),J(120),S(120),L(14),H(14):CLS
7050   PRINT:PRINT:GOSUB 9020:GOTO 8130
8000   REM ROUTINE OF T-t DISPLAY AND PLOT
8005   DIM B(120),J(120),S(120),L(14),H(14)
8010   GOSUB 9020:CLOSE:CLS:KEY OFF:PRINT SPC(18);
8020   PRINT"Temperature-Time relation display"
8030   FOR I=1 TO 5:PRINT:NEXT I
8090   PRINT SPC(25);"Which data file ?"-
8091   PRINT:PRINT:PRINT:PRINR SPC(22);
8092   PRINT "Mount disk on drive B":PRINT SPC(22)
8093   PRINT "Press any key to continue"
8100   MMM$=INKEY$:IF MMM$="" GOTO 8100
8110   CLS:BEEP:FILES "B:":PRINT:PRINT:PRINT
8120   LINE INPUT "Type data file name:  ";NW$
8125   NW$="B:"+NW$
8130   PRINT:PRINT "Store new (Serial) data file on disk ? (y/n)"
8140   BNB$=INKEY$:IF BNB$="" GOTO 8140
8150   IF BNB$="Y" OR BNB$="y" GOTO 8190
8160   IF BNB$="N" OR BNB$="n" GOTO 8180
8170   IF BNB$<>"N" GOTO 8140
8180   STR=0:GOTO 8200
8190   STR=1:BEEP:LINE INPUT"Name the new file: ";OBJ$
8191   OBJ$="B:"+OBJ$
8200   PRINT:INPUT "Reference point (1 to 119)";RF
8201   IF RF<1 OR RF>79 THEN RF=1
8205   PRINT:BEEP:LINE INPUT "Heading : ";PG$
8210   IF PG$="" THEN PG$=NW$
8220   PRINT:BEEP:LINE INPUT"Station # : ";STN$:CLS
8230   IF STR<>1 GOTO 8250
8240   OPEN "O".#2,OBJ$:CLOSE:OPEN"A",#2,OBJ$
```

```
8250   GOSUB 5500
8390   OPEN "R",#1,NW$
8400   FIELD #1,4 AS L$,8 AS T$,4 AS R$,8 AS D1$,8 AS D2$,8 AS D3$,8 AS D4$,8
       AS D5$,8 AS D6$,8 AS D7$,8 AS D8$,8 AS D9$,8 ASA D10$,8 AS D11$,8 AS
       D12$,8 AS D13$,8 AS D14$
8410   AVRG=0:FOR I=1 TO 120:GET #1,I
8412   B(I)=CVS(D1$):AVRG=AVRG+B(I):NEXT I
8414   AVRG=AVRG/80
8430   AVRG=5811.403/(LOG(AVRG)+5.493939)-342.7457
8431   Q=AVRG/0.2-1
8440   FOR K=1 TO 14:FOR I=1 TO 120
8460   GET #1,I:GOSUB 5000
8630   S(I)=234+Q*24-J(I)*120
8640   IF I<>RF THEN 8660
8650   L(K)=J(RF):H(K)=S(RF)
8660   NEXT I
8670   D=L(K)-L(1):C=H(K)-H(1)
8680   FOR I=1 TO 119:Y=J(I)-D
8690   IF STR<>1 GOTO 8710
8700   PRINT #2,Y
8710   X1=70+(I-1)*6:X2=X1+6:Y1=S(I)-C:Y2=S(I+1)-C
8720   LINE (X1,Y1)-(X2,Y2)
8730   NEXT I
8740   NEXT K
8750   PRINT "Press any key to continue"
8760   SS$=INKEY$:IF SS$="" GOTO 8760
8770   CLS:GOSUB 9020:PRINT:PRINT
8775   PRINT "Display another file ?  (y/n)"
8780   LLL$=INKEY$:IF LLL$="" GOTO 8780
8790   IF LLL$="Y" OR LLL$="y" GOTO 8010
8800   IF LLL$="N" OR LLL$="n" GOTO 20
8810   IF LLL$<>"N" GOTO 8780
9000   XX$="EG":PLAY "MB ML T250 O4 L2"+XX$:RETURN
9010   XXX$="ADCADECCDF":PLAY "MN L32"+XXX$:RETURN
9020   MUS$="CEG":PLAY"MB L8"+MUS$:RETURN
9500   REM ROUTINE OF INFINITE-TIME TEMP.
9510   DIM J1(200),J0(200),Y0(200),Y1(200),F(100), F1(100), X(40), Y(40), HEAT(1105),
       H1(80), H(80), J(80), S1(79)
9520   GOSUB 9020:CLS:PRINT:PRINT:PRINT:FLG=0
9525   PRINT SPC(15);"INFINITE-TIME TEMPERATURE"
9530   FOR I=1 TO 5:PRINT:NEXT I
9535   PRINT SPC(20);"Which data file ?":PRINT
9540   PRINT:PRINT SPC(20);"Mount disk on drive B:"
9545   PRINT:PRINT SPC(20);"Press any key to continue"
9550   PR$=INKEY$:IF PR$="" GOTO 9550
9560   CLS:FILES "B:":PRINT:PRINT:BEEP:BEEP
9561   LINE INPUT "Data file: ";DA$:DA$="B:"+DA$
9562   PRINT:BEEP:INPUT "Thermistor # (bottom is #1)";TN
9570   BEEP:BEEP:PRINT:PRINT "Is ";DA$;
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```
9571  PRINT " a random or a serial file ? (type R or S)"
9580  RS$=INKEY$:IF RS$="" GOTO 9580
9590  IF RS$="R" OR RS$="r" GOTO 9620
9600  IF RS$="S" OR RS$="s" GOTO 9630
9610  IF RS$<>"S" GOTO 9580
9620  GOSUB 5200:FLG=1:GOTO 9632
9630  GOSUB 10390
9632  GOSUB 4900
9633  BEEP:INPUT"Temp. reference point ";TRR
9634  IF TRR=0 THEN TRR=1:XX1=70+(TRR-1)*6:YY1=234+Q*24-120 *
      H1(TRR): CIRCLE (XX1, YY1), 3: CIRCLE (XX1, YY1), 5
9635  PRINT "Is it acceptable ? (y/n)":BEEP
9636  DD$=INKEY$:IF DD$="" GOTO 9636
9637  IF DD$="Y" OR DD$="y" GOTO 9640
9638  IF DD$="N" OR DD$="n" GOTO 9632
9639  IF DD$<>"N" GOTO 9636
9640  CLOSE:OPEN "R",#1,DA$
9641  FIELD #1,4 AS L$,8 AS T$,4 AS R$,8 AS D1$,8 AS D2$,8 AS D3$,8 AS D4$,8
      AS D5$,8 AS D6$,8 AS D7$,8 AS D8$,8 AS D9$,8 ASA D10$,8 AS D11$,8 AS
      D12$,8 AS D13$,8 AS D14$
9642  FOR S=1 TO TRR:GET #1,S:S1(S)=CVS(D1$): NEXT S: RRF= 5811.403 /
      (LOG(S1(TRR)) + 5.493939)-342.7457
9643  RRF=RRF-H1(TRR):FOR I=1 TO 79:H1(I) = RRF: NEXT I
9644  GOSUB 4900
9645  BEEP:INPUT"Penetration at point # ";PP
9647  INPUT"How many points";NB:GOSUB 10460:BEEP
9650  INPUT "Process data for every N'th point "; SSTP:IF SSTP=0 THEN SSTP=1
9651  XX1=70+(PP-1)*6:YY1=234+Q*24-120 * H1(PP): XX2=70 + (PP-1+NB)*6:
      YY2 = 234+Q*24-120* H1(PP+NB)
9652  CIRCLE (XX1,YY1),6:LINE(XX1,YY1-3)-(XX1, YY1+3): LINE (XX1-4, YY1)-
      (XX1+4, YY1): CIRCLE (XX2, YY2), 3: CIRCLE (XX2, YY2),5
9653  FOR I=1 TO 18:PRINT:NEXT I:PRINT "Are these acceptable ? (y/n)": BEEP
9654  POT$=INKEY$:IF POT$="" GOTO 9654
9655  IF POT$="Y" OR POT$="y" GOTO 9660
9656  IF POT$="N" OR POT$="n" GOTO 9644
9658  IF POT$<>"N" GOTO 9654
9660  INPUT"Delay (N*15 sec., input N)= ";DELAY1
9662  DELAY1=ABS(DELAY1)
9670  BEEP:PRINT"Conductivity = 0.8 ? (y/n)"
9680  POT$=INKEY$:IF POT$="" GOTO 9680
9690  IF POT$="Y" OR POT$="y" GOTO 9720
9700  IF POT$="N" OR POT$="n" GOTO 9740
9710  IF POT$<>"N" GOTO 9680
9720  CLOSE:OPEN "I",#1,"F0.8"
9730  FOR I=1 TO 80:INPUT #1,F1(I)NEXT I
9735  CLOSE:K=0.8:GOTO 10025
9740  PRINT"  ";:INPUT"K = ";K
9750  CLOSE:OPEN"I",#1,"J0.DAT":OPEN"I",#2,"J1.DAT"
9760  OPEN "I",#3,"Y0.DAT":OPEN"I",#4,"Y1.DAT"
```

```
9770    FOR U=1 TO 110
9780    INPUT #1,J0(U):INPUT #2,J1(U)
9785    INPUT #3,Y0(U):INPUT #4,Y1(U)
9790    NEXT U  'Input bessel data
9800    K1=(K/(5.79-3.67*K+1.016*K^2))*.000001
9810    ALPHA=2*(5.79-3.67*K+1.016*K*K)/3.116
9820    PRINT:PRINT "Delay = ";
9821    PRINT USING "+##.###";DELAY1*15;
9822    PRINT "   (Sec.)"
9830    TAU=0.00472^2/K1:NNN=0:PI=3.141593
9831    E=2.718282:A2=0.004725^2:DU=.1:PI2=PI^2
9840    PRINT"Time constant= ";:PRINT USING"###.#";TAU
9841    PRINT " (Sec.)":PRINT
9850    FOR T=1 TO NB+DELAY1
9860    T11=(T*15*K)/A2
9870    SUM1=0
9880    FOR U=0 TO 10 STEP 0.1  'F caculation
9890    UA=U*10+1
9892    AA=U*J0(UA)-ALPHA*J1(UA)
9894    BB=U*Y0(UA)-ALPHA*Y1(UA)
9900    S=AA^2+BB^2
9910    W=U:IF U=0 THEN W=0.000048
9920    S=S*W
9930    G1=(-1)*T11*U*U:IF G1<-88 THEN G1=-88
9940    V1=E^G1*DU
9950    SUM1=SUM1+V1/S
9960    NEXT U
9970    F1(T)=(4*ALPHA/PI2)*SUM1
9980    NNN=NNN+1:PRINT NNN
9990    PRINT"T=";:PRINT USING"##.####";T11:PRINT

10000   PRINT"T=";:PRINT USING"##.####";F1(T),:PRINT
10010   NEXT T
10020   FOR I=1 TO 4:PRINT:NEXT I
10025   GOSUB 11010
10260   FOR I=1 TO 17:PRINT:NEXT I
10261   PRINT SPC(40);"Channel:";TN" Temp.(frc)";:PRINT USING "##.####":
        ICPT
10262   PRINT:PRINT:PRINT:PRINT "Printer ready ? Press any key to continue ":
        BEEP: BEEP: BEEP
10263   ITT$=INKEY$:IF ITT$="" GOTO 10263
10270   LPRINT DA$,:LPRINT"     ";
10271   LPRINT DATE$:LPRINT:LPRINT
10272   LPRINT "Channel:";TN;" Infinite-time temp.(frc)";
10273   LPRINT USING"##.####";ICPT
10274   LPRINT:LPRINT"    Penetration point: ";PP;
10275   LPRINT"    ";NB;" points"
10276   LPRINT"    Estimated conductivity: ";K,
10277   LPRINT"  Delay time: ";DELAY1*15;" Sec."
```

```
10278   LPRINT"    Temp. reference point: ";TRR
10279   FOR I=1 TO 8:LPRINT:NEXT I
10280   BEEP:BEEP:BEEP
10290   PRINT:PRINT"Store F(A,T) on disk ? (y/n)"
10310   POT$=INKEY$:IF POT$="" GOTO 10310
10320   IF POT$="Y" OR POT$="y" GOTO 10375
10330   IF POT$="N" OR POT$="n" GOTO 10350
10340   IF POT$<>"N" GOTO 10310
10350   PRINT:LINE INPUT "File name for F(A,T) of frictional heat decay : ";FRC$:
        PRINT: FRC$= "B:"+FRC$
10360   CLOSE:OPEN"O",#1,FRC$:CLOSE:OPEN"A"#1,FRC$
10370   FOR I=1 TO NB+DELAY1
10371   PRINT #1,F1(I+DELAY1):NEXT I
10375   CLS:GOSUB 9020:PRINT:PRINT:PRINT
10380   PRINT SPC(25);"Continue ? (y/n)"
10381   POT$=INKEY$:IF POT$="" GOTO 10381
10382   IF POT$="Y" OR POT$="y" GOTO 9520
10383   IF POT$="N" OR POT$="n" GOTO 20
10384   IF POT$<>"N" GOTO 10381
10390   CLOSE:OPEN "I",#1,DA$
10400   IF TN=14 THEN FITT=1105 ELSE FITT=TN*79
10410   FOR I=1 TO FITT:INPUT #1,HEAT(I):NEXT I
10420   IF TN<>14 GOTO 10440
10430   FOR I=1 TO 78:KK=(TN-1)*79+I
10435   H1(I)=HEAT(KK):NEXT I:GOTO 10460
10440   FOR I=1 TO 79:KK=(TN-1)*79+I
10445   H1(I)=HEAT(KK):NEXT I
10450   RETURN
10460   FOR I=1 TO 79
10470   KIK=I-PP:IF I<PP GOTO 10490
10480   H(KIK)=H1(I)
10490   NEXT I:RETURN
11000   REM SUBROUTINE OF LEAST SQUARE FITTING
11005   IF DDLY<0 THEN DELAY=0
11006   IF DDLY1<0 THEN DELAY1=0
11010   SCREEN 100:SCREEN 105:KEY OFF:CLS
11020   SCAL=0:FOR I=1 TO NB:SCAL=SCAL+H(I):NEXT I
11030   SCAL=(SCAL/NB)*300+175  'auto adjusting screen
11040   LINE (60,300)-(580,300)
11045   LINE (60,30)-(60,300)
11050   FOR I=1 TO NB STEP SSTP
11055   X(I)=F1(I+DELAY1)*1000+60:Y(I)=SCAL+H(I)*300
11060   CIRCLE (X(I),Y(I)),0.5:NEXT I
11070   SSX=0:SSY=0:SX=0:SY=0:SXY=0:SIG=0:NBN=0
11080   FOR I=1 TO NB STEP SSTP
11090   NBN=NBN+1
11100   SSX=SSX+F1(I+DELAY1)^2:SSY=SSY+H(I)^2
11110   SX=SX+F1(I+DELAY1):SY=SY+H(I)
11115   SXY=SXY+F1(I+DELAY1)*H(I):NEXT I
```

```
11120  ASSX=SSX/NBN:ASSY=SSY/NBN
11125  ASX=SX/NBN:ASY=SY/NBN:ASXY=SXY/NBN
11130  SIGX=ASSX-ASX^2:SIGY=ASSY-ASY^2
11140  SLOPE=(ASXY-ASX*ASY)/SIGX
11150  ICPT=ASY-SLOPE*ASX
11160  FOR I=1 TO NB STEP SSTP
11161  LSUMM=SLOPE*F1(I+DELAY1)+ICPT-H(I)
11162  SIG=SIG+SUMM^2:NEXT I
11170  SIG=SIG/NBN^2:SIGSLP=SIG/SIGX
11180  SIGICPT=SIG*ASSX/SIGX:SIGICPT=SQR(SIGICPT)
11190  IF F1(1+DELAY1)>0.55 GOTO 11210
11200  LL=X(1)+20:GOTO 11220
11210  LL=X(2)+20
11220  LINE (60,SCAL-300*ICPT)-(LL, SCAL-300*(LL-60)* SLOPE/ 1000 + ICPT)
11225  RETURN
11230  FOR I=1 TO 4:PRINT:NEXT I
11240  FOR I=1 TO NBB STEP SSTP
11241  HC(I)=HH(I)-F(I+DELAY+PPP-PP-1)*SLOPE
11242  X(I)=F(I+DELAY)*1000+60:Y(I)=SCAL-HC(I)*300
11250  CIRCLE (X(I),Y(I)),1.5:NEXT I
11260  SSX=0:SSY=0:SX=0:SY=0:SXY=0:SIG=0:NBBN=0
11270  FOR I=1 TO NBB STEP SSTP
11271  SSX=SSX+F(I+DELAY)*F(I+DELAY)
11272  SSY=SSY+HC(I)^2:NBBN=NBBN+1
11290  SX=SX+F(I+DELAY):SY=SY+HC(I)
11291  SXY=SXY+F(I+DELAY)*HC(I):NEXT I
11300  ASSX=SSX/NBBN:ASSY=SSY/NBBN:ASX=SX/NBBN
11305  ASY=SY/NBBN:ASXY=SXY/NBBN
11310  SIGX=ASSX-ASX^2:SIGY=ASSY-ASY^2
11320  SLOPE1=(ASXY-ASX*ASY)/SIGX
11330  ICPT1=ASY-SLOPE1*ASX
11340  FOR I=1 TO NBB STEP SSTP
11341  SUMM=SLOPE1*F(I+DELAY)+ICPT1-HC(I)
11342  SIG=SIG+SUMM*SUMM:NEXT I
11350  SIG=SIG/NBBN^2:SIGSLP1=SIG/SIGX
11360  SIGICPT1=SIG*ASSX/SIGX:SIGICPT1=SQR(SIGICPT1)
11370  IF F(1+DELAY)>0.55 GOTO 11390
11380  LL=X(1)+20:GOTO 11400
11390  LL=X(2)+20
11400  LINE (60,SCAL-300*ICPT1)-(LL, SCAL-300*(LL-60)* SLOPE1/ 1000 + ICPT1)
11410  FOR I=1 TO 17:PRINT:NEXT
11420  PRINT SPC(40);"Channel:";TN;" Reference ";
11421  PRINT TRR
11430  PRINT SPC(40);"Channel:";TN;" Temp. (frc) ";
11431  PRINT USING "##.####";ICPT
11440  PRINT SPC(40);"Channel:";TN;" Temp. (pls) ";
11441  PRINT USING "##.####";ICPT1:PRINT:TOTAL=ICPT
11450  PRINT SPC(40);"Channel:";TN;" Inf. Temp. ";
11451  PRINT USING "##.####";TOTAL
```

```
11460   LOOP1=LOOP1+1:LP1=LP1+1
11461   HD=HC(1+DELAY):HD1=H(1+DELAY1)
11465   DELAY=DDLY*15:DELAY1=DDLY1*15
11470   RETURN
15000   REM SUBROUTINE OF L-S-F
15010   DIM X(14),Y(14),XX(14);YY(14),HX(14),HY(14)
15020   CLS:GOSUB 9020:PRINT:PRINT:PRINT:PRINT
15021   PRINT SPC(15);"Interactive fit of gradient"
15030   FOR I=1 TO 6:PRINT:NEXT I
15040   PRINT "How many points ?":PRINT:PRINT
15050   PRINT "N = ";INPUT N
15070   CLS:BEEP:BEEP:PRINT:PRINT
15075   PRINT"Type in values in X,Y pairs":PRINT
15080   PRINT "After each '?', type in a pair of data 'Temp., Depth' using the format: "
        :PRINT
10590   PRINT PC(10);"X,Y  where X is temp. in degree Celsius": PRINT SPC(25); "Y
        is depth in meter": PRINT
15100   FOR I=1 TO N:PRINT "# ";I
15105   INPUT XX(I),YY(I):NEXT I
15110   PRINT:PRINT:PRINT"X: ",:FOR I=1 TO N
15115   PRINT XX(I);:NEXT I:PRINT:PRINT
15120   PRINT "Y: ",:FOR I=1 TO N:PRINT YY(I):NEXT
15130   BEEP:PRINT:PRINT"Sorting...":PRINT
15135   I=1:J=1:K=1
15140   DD1=YY(I):DDX1=XX(I)
15150   DD2=YY(I+1):DDX2=XX(I+1)
15160   IF DD1>DD2 GOTO 15180
15170   TEP=DD1:DD1=DD2:DD2=TEP
15175   TEPX=DDX1:DDX1=DDX2:DDX2=TEPX
15180   HY(K)=DD1:HX(K)=DDX1:I=I+1
15190   HY(J+1)=DD2:HX(J+1)=DDX2
15200   J=J+1
15210   IF I=N GOTO 15230
15220   GOTO 15150
15230   FOR T=1 TO N:YY(T)=HY(T):XX(T)=HX(T):NEXT T
15240   I=K+1:J=K+1:K=K+1
15250   IF K=N GOTO 15280
15260   DD1=HY(I):DD2=HY(I+1):DDX1=HX(I):DDX2=HX(I+1)
15270   GOTO 15160
15280   REM
15290   PRINT:PRINT:PRINT"X :  ",
15291   FOR I=1 TO N:YY(I)=HY(I):XX(I)=HX(I)
15293   PRINT XX(I);:NEXT I:PRINT
15300   PRINT "Y: ",:FOR I=1 TO N:PRINT YY(I);:NEXT
15310   PRINT:PRINT:BEEP:BEEP
15315   PRINT "Any change of the data ?  (y/n)"
15320   POT$=INKEY$:IF POT$="" GOTO 15320
15330   IF POT$="Y" OR POT$="y" GOTO 15360
15340   IF POT$="N" OR POT$="n" GOTO 15470
```

```
15350   IF POT$<>"N" GOTO 15320
15360   PRINT:PRINT:PRINT"Which point # ";:INPUT K
15370   PRINT:PRINT:PRINT"The old value: ";
15375   PRINT "X= ";XX(K);" Y= ";YY(K)
15380   INPUT "New value of X,Y ";XW,YW
15390   PRINT "k";K
15400   FOR I=1 TO N
15410   IF I=K GOTO 15430
15420   XX(I)=HX(I):YY(I)=HY(I):GOTO 15440
15430   XX(K)=XW:YY(K)+YW
15440   NEXT I
15450   PRINT:PRINT"X: ",:FOR M=1 TO N:PRINT XX(M);
15451   NEXT M:PRINT:PRINT"Y: ",:FOR M=1 TO N
15452   PRINT YY(M);:NEXT M
15460   GOTO 15130
15470   FOR I=1 TO N:X(I)=300*XX(I):Y(I)=30*YY(I);NEXT
15480   MAX=X(1):FOR I=1 TO N:DS=X(I)-MAX
15485   IF DS<0 GOTO 15500
15490   MAX=X(I):MXX=X(I)-500
15500   NEXT I
15510   IF MAX<500 GOTO 15530
15520   FOR I=1 TO N:X(I)=X(I)-MXX:NEXT
15530   MIN=X(1):FOR I=1 TO N:DS=X(I)-MIN
15535   IF DS>0 GOTO 15550
15540   MIN=X(I):MMIN=200-X(I)
15550   NEXT I
15560   IF MIN>100 GOTO 15580
15570   FOR I=1 TO N:X(I)=X(I)+MMIN:NEXT I
15580   GOSUB 5700:FOR I=1 TO N
15585   CIRCLE (100+X(I),50+Y(I)),4,1:NEXT I
15590   FOR I=1 TO N
15595   LINE(X(I)+98,50+Y(I))-(X(I)+102,50+Y(I))
15600   LINE(X(I)+100,48+Y(I))-(X(I)+100,52+Y(I))
15601   NEXT I
15610   PRINT "How many point are valid ?"
15620   INPUT "N= ";N
15630   FOR I=1 TO N:X(I)=300*(XX(I)-XX(N))
15631   Y(I)=30*(YY(I)-YY(N)):NEXT I
15640   CLS:GOSUB 5700:FOR I=1 TO N
15641   CIRCLE(100+X(I),50+Y(I)),4,1:NEXT I
15650   FOR I=1 TO N
15651   LINE(X(I)+98,50+Y(I))-(X(I)+102,50+Y(I))
15660   LINE(X(I)+100,48+Y(I))-(X(I)+100,52+Y(I))
15661   NEXT I
15670   SSX=0:SSY=0:SX=0:SY=0:SXY=0:SIG=0
15680   FOR I=1 TO N:SSX=SSX+X(I)^2
15700   SSY=SSY+Y(I)^2:SX=SX+X(I)
15710   SY=SY+Y(I):SXY=SXY+X(I)*Y(I)
15740   NEXT I:ASSX=SSX/N:ASSY=SSY/N
```

```
15770   ASX=SX/N:ASY=SY/N:ASXY=SXY/N
15800   SIGX=ASSX-ASX^2:SIGY=ASSY-ASY^2
15820   SLOPE=(ASXY-ASX*ASY)/SIGX
15830   REM CALCULATE SLOPE AND intercept
15840   ICPT=ASY-SLOPE*ASX
15860   FOR I=1 TO N
15870   SUM=SLOPE*X(I)+ICPT-Y(I)
15880   SIG=SIG+SUM^2:NEXT I
15900   SIG=SIG/N*N:SIGSLP=SIG/SIGX
15920   SIGSLP=SQR(SIGSLP)
15930   SIGICPT=SIG*ASSX/SIGX
15940   SIGICPT=SQR(SIGICPT):L=0
15960   FOR I=1 TO N
15970   IF X(I)>=0 THEN 15980 ELSE 15990
15980   L=X(I)
15990   NEXT I
16000   L=L+110:G=0.1/SLOPE
16020   LINE(100,50+ICPT)-(L,(L-100)*SLOPE+50+ICPT)
16030   PRINT SPC(18);"Least-square-fitting of gradient"
16040   PRINT:PRINT:PRINT SPC(11);"0"
16060   PRINT SPC(62);"TEMP."
16070   FOR I=1 TO 13:PRINT:NEXT I
16100   PRINT SPC(30);"Gepthermal gradient; ";
16105   PRINT USING "##.####";G;:PRINT"(K/M)"
16110   PRINT SPC(9);"(M)":PRINT:PRINT SPC(9);"Depth"
16115   PRINT SPC(20);"Pinter ready? ";
16116   PRINT "Press any key to continue":gosub 9000
16120   S$=INKEY$:IF S$="" GOTO 16120
16121   CLS:PRINT:LINE INPUT"Heading of the print:";HED$
16122   LPRINT "Geothermal gradient: ";HED$;
16123   LPRINT "  ";DATE$:LPRINT:LPRINT
16124   LPRINT "Temp. ";:FOR I=1 TO N
16125   LPRINT "(";I;")";XX(I);:NEXT I:LPRINT
16126   LPRINT "Depth: ";:FOR I=1 TO N
16127   LPRINT "(";I;")";YY(I);:NEXT I:LPRINT
16128   LPRINT "Gradient: ";"  ";
16129   LPRINT USING "###.##";G*1000;:LPRINT" MK/M"
16130   FOR I=1 TO 8:LPRINT:NEXT I
16131   BEEP:CLS:PRINT:PRINT SPC(19);
16132   PRINT "Continue with gradient ? (y/n)"
16140   POT$=INKEY$:IF POT$="" GOTO 16140
16150   IF POT$="Y" OR POT$="y" GOTO 15020
16160   IF POT$="N" OR POT$="n" GOTO 20
16170   IF POT$<>"N" GOTO 16140
```

Appendix E: T-R Relation Program Listing

```
10    REM ROUTINE OF LEAST SQUARE FIT T-R RELATION
20    DIM RI(60),T(60),D(60),X(60),Z(60):S=0:CLS
30    KEY OFF:INPUT"How many data points ";N
40    FOR I=1 TO N:READ T(I),D(I)
50    IF D(I)<>0 GOTO 120
60    BEEP:PRINT"Resistance can not be zero !":GOTO 30
120   NEXT I
125   REM DATA LIST OF T-R RELATION OF THERMISTOR
130   DATA 0,94980,1,90410,2,86090,3,81990,4,78110
131   DATA 5,74440,6,70960,7,67660,8,64530,9,61560
132   DATA 10,58750,11,56070,12,53540,13,51130,14,48840
133   DATA 15,46670,16,44600,17,42460,18,40770,19,38990
134   DATA 20,37300,21,35700,22,34170,23,32710,24,31320
135   DATA 25,30000,26,28740,27,27540,28,26400,29,25310
136   DATA 30,24270,31,23280,32,22330,33,21430,34,20570
137   DATA 35,19740,36,18960,37,18210,38,17490,39,16800
138   DATA 40,16150,41,15520,42,14920,43,14350,44,13800
139   DATA 45,13280,46,12770,47,12290,48,11830,49,11390
160   INPUT "The trial maximum C = ";CMAX
170   INPUT "The trial minimum C = ";CMIN
180   C=CMAX:RA=0:FOR I=1 TO N:R(I)=LOG(D(I))
220   RA=RI(I)+RA:NEXT I:RA=RA/N
250   L=0:M=0:K=0:P=0:LEFT=0:RIGHT=0
260   FOR I=1 TO N:L=1/(T(I)+C)+L
280   M=(T(I)+C)^2(-2)+M:K=(T(I)+C)^2(-3)+K
300   P=(RI(I)*(1/(T(I)+C)))+P
310   Q=(RI(I)*((T(I)+C)^(-2)))+Q:NEXT I
330   B=(Q-RA*M)/(K-(L*M)/N):A=RA-((B*L)/N)
350   V=0:GOSUB 1070
360   IF C=CMAX THEN 1140 ELSE 1170
370   PRINT:PRINT"ERRmax=";VMAX,"ERRmin=";VMIN
380   E=VMAX-VMIN:PRINT"ERR=";E
390   IF ABS(E)<0.0000001 GOTO 1250
400   IF E>0 THEN 1190 ELSE 1220
410   CLS:L=0:M=0:K=0:P=0:Q=0:LEFT=0:RIGHT=0
420   FOR I=1 TO N:L=1/(T(I)+C)+L
430   M=(T(I)+C)^2(-2)+M:K=(T(I)+C)^2(-3)+K
440   P=(RI(I)*(1/(T(I)+C)))+P
450   Q=(RI(I)*((T(I)+C)^(-2)))+Q:NEXT I
460   B=(Q-RA*M)/(K-(L*M)/N):A=RA-((B*L)/N)
```

```
520   PRINT:PRINT:PRINT"A=';A,"B="B,"C="C
525   PRINT:PRINT"Printer ready ? press any key to continue"
530   FF$=INKEY$:IF FF$="" GOTO 530
531   LPRINT"Thermistor T-R relationship";
532   LPRINT:LPRINT"Number of points: ";N:LPRINT
540   LPRINT:LPRINT:LPRINT"A=';A,"B="B,"C="C
550   PRINT:PRINT"Least square error : ";V
560   PRINT:PRINT:PRINT"Want to display ? (y/n)"
580   FF$=INKEY$:IF FF$="" GOTO 580
590   IF FF$="Y" OR FF$="y" GOTO 640
600   IF FF$="N" OR FF$="n" GOTO 630
610   IF FF$<>"N" GOTO 580
630   GOTO 1680
640   CLS:SCREEN 100:SCREEN 105:KEY OFF
740   LINE (0,0)-(649,340),1,B
750   LINE(50,50)-(50,300):LINE(50,300)-(580,300)
770   FOR I=1 TO 50
780   LINE(50+I*10,298)-(50+I*10,302)
790   IF I>=10 THEN 830
800   LINE(50+I*50,297)-(50+I*50,304)
810   IF I>5 THEN 830
820   LINE(50+I*100,296)-(50+I*100,306)
830   NEXT I
840   PRINT SPC(15);"Least square fitting of temp.-resist."
860   FOR I=1 TO 20:PRINT:NEXT I
890   PRINT SPC(70);"T (C)"
900   FOR I=1 TO N:R=50+T(I)*10:H=D(I)
930   J=328-H/300:CIRCLE(R,J),3:NEXT I
960   FOR I=1 TO 48:X(I)==50+I*10
980   Y=2.718282^(A+(B/(I+C)))
990   Z(I)=328-Y/300:NEXT I
1010  FOR I=1 TO 48
1020  LINE(X(I-1),Z(I-1))-(X(I),Z(I)):NEXT I
1030  PRINT"Press any key to continue"
1040  FF$=INKEY$:IF FF$="" GOTO 1040
1060  GOTO 1270
1070  FOR I=1 TO N:Y=(A+(B/T(I)+C)))
1090  Y=Y-RI(I):Y=Y*Y:V=Y+V:NEXT I:RETURN
1140  VMAX=V:C=CMIN:GOTO 250
1170  VMIN=V:GOTO 370
1190  CMAX=CMIN+(CMAX-CMIN)*0.618:C=CMAX
1200  PRINT"New Cmax=";C,"Cmin=":GOTO 250
1220  CMIN=CMIN+(CMAX-CMIN)*(1-0.618):C=CMAX
1230  PRINT"New Cmin=";CMIN,"Cmax=";CMAX:GOTO 250
1250  C=(CMAX+CMIN)/2:GOTO 410
1270  CLS:SCREEN 100:SCREEN 105:KEY OFF
1310  LINE(0,0)-(649,340),1,B
1320  LINE(50,50)-(50,280):LINE(50,280)-(580,280)
1340  FOR I=1 TO 17
```

```
1350    LINE(50+I*30,276)-(50+I*30,282)
1360    FOR W=1 TO 10:W1=I-1
1380    LINE(50+W1*30+W*3,278)-(50+W1*30+W*3,280)
1390    NEXT W
1400    IF I>=4 THEN 1440
1410    LINE(50+I*150,276)-(50+I*150,285)
1420    IF I>2 THEN 1440
1430    LINE(50+I*300,274)-(50+I*300,287)
1440    NEXT I
1450    PRINT SPC(15);"Least square fitting of T-R"
1470    FOR I=1 TO 18:PRINT:NEXT I
1500    PRINT:PRINT:PRINT SPC(6);"0";SPC(17);"5";
1510    PRINT SPC(17);"10";SPC(17);"15";SPC(7);"T(C)"
1520    FOR I=1 TO N:R=50+T(I)*30:H=D(I)
1550    J=500-H/200:CIRCLE(R,J),3:NEXT I
1580    FOR I=1 TO 19:X(I)=50+I*30
1600    Y=2.718282^(A+(B/(I+C)))
1610    Z(I)=500-Y/200:NEXT I
1630    FOR I=1 TO 19
1640    LINE (X(I-1),Z(I-1))-(X(I),Z(I)):NEXT I
1660    PRINT"Press any key to exit"
1670    FF$=INKEY$:IF FF$="" GOTO 1670
1680    END
```

Appendix F: Correction for a step function temperature variation

The sudden temperature change of the bottom water is simulated by a step function. It is known that

$$T = 1 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{z}{2\sqrt{kt}}} e^{-\xi^2}\, d\xi$$

$$= 1 - erf\left(\frac{z}{2\sqrt{kt}}\right) \qquad \text{(F.1)}$$

satisfies the equation of conduction of heat in one dimension with the initial and boundary conditions:

$$T = 1, \qquad \text{for } z = 0,\ t > 0$$

$$T = 0, \qquad \text{for } z > 0,\ t = 0\ .$$

We notice that for a small value of x, the error function $erf\ (x)$ can be approximated by $erf\ (x) = \frac{2x}{\sqrt{\pi}}$. Thus, the solution for the correction for bottom water temperature perturbation with a step function feature may be written as a combination of solutions of type (F.1).

The influence of a sudden temperature change in the bottom water appears as a ΔT in a solution of the form

$$T = T_0 + qz - \Delta T \tag{F 2}$$

where ΔT is the solution in (F.1), T_0 is the present temperature at the sea floor and q is the measured value of thermal gradient. Note that (F.1) is normalized.

If the temperature change is not an exact step function but a ramp from t_1 to t_2, (F.2) is written as:

$$T = T_0 + qz + \delta T \left[erf \left(\frac{z}{2\sqrt{kt_1}} \right) - erf \left(\frac{z}{2\sqrt{kt_2}} \right) \right] \tag{F.3}$$

where δT is the amplitude of the temperature change.

The corrected thermal gradient at the sediment surface is then:

$$q_0 = \left[\frac{\partial T}{\partial z} \right]_{z=0} = q + \delta T \left[\frac{1}{\sqrt{\pi k t_1}} - \frac{1}{\sqrt{\pi k t_2}} \right] . \tag{F.4}$$