MARINE HEAT FLOW MEASUREMENT

CENTRE FOR NEWFOUNDLAND STUDIES

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CHANGLE FANG
MARINE HEAT FLOW MEASUREMENT

by

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A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirement for the degree of Doctor of Philosophy

Department of Earth Sciences
Memorial University of Newfoundland
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St. John's

Newfoundland
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.
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).

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.

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.

Keeping real time information.

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.
During the course of this thesis program, I received the advice and assistance of numerous people. First, I wish to extend my most sincere thanks to Dr. J.A. Wright, the chairman of my supervising committee, who has supervised me during the whole project. His supervision was a constant encouragement. I wish to thank Dr. H. Miller and Dr. G. Quinlan who are also members of my Supervisory Committee. Their help in the data interpretation and in the relevant geophysical studies was invaluable.

The support and encouragement of Dr. K. Louden during the stage of developing the data processing programs and in the data interpretation is greatly appreciated. Discussions with Dr. R. Hyndman, Dr. E. Davis and Dr. Heiner Villerger about the reduction of thermal conductivity were a great help in developing the complete data processing software.

I wish to thank all the crew members of the scientific research vessels C.S.S. Hudson, C.S.S. Dawson and Navimar UN. Without their excellent skill and efficiency, the sea tests could not have been successful. I am grateful to Mr. Jim Everard and John Clarke who made the thermal strings and other mechanical parts. I appreciate the help of all my fellow graduate students from various countries in the geophysics discipline. The discussions with them often was a source of progress. Special thanks are given to my compatriots, the graduate
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Chapter 1  Introduction

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 deter-
mining 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 $\nabla T$ 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°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 \(\varepsilon\) (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, \( \int_V \varepsilon \, dV \), 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 \( \rho \) is density. Thus

\[ \int_S q_n \, ds = \int_V (\varepsilon - \rho c \frac{\partial T}{\partial t}) \, dV \]

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

\[ \int_S q_n \, ds = \int_V \text{div} \, q \, dV \]

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

\[ \int_V (K \nabla^2 T + \varepsilon - \rho c \frac{\partial T}{\partial t}) \, dV = 0 \]

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.

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<td>conduction</td>
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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 $\lambda$ 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, Srokhtin (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 pro-
duced, 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:

$$C = \ln \int_0^t \frac{T(t)}{10} \, dt$$
Table 1.2 Correlation of TTI with important stages

<table>
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<th>Stage</th>
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<tr>
<td>Onset of oil generation</td>
<td>15</td>
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<tr>
<td>Peak oil generation</td>
<td>75</td>
</tr>
<tr>
<td>End of oil generation</td>
<td>160</td>
</tr>
<tr>
<td>Upper TTI limit for occurrence</td>
<td>-1500</td>
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<tr>
<td>of wet gas</td>
<td></td>
</tr>
<tr>
<td>Last known occurrence of dry gas</td>
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</tr>
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</table>

where \( t \) is time in Ma and

\[ T \text{ is the paleotemperature in degrees Celsius in specific sedimentary strata.} \]

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 \( \beta \).
After the extension, the temperature variation is

\[ T = T_1, \quad 0 < \frac{z}{a} < \left( 1 - \frac{1}{\beta} \right) \]

\[ T = T_1 \beta \left( 1 - \frac{z}{a} \right), \quad \left( 1 - \frac{1}{\beta} \right) < \frac{z}{a} < 1. \]

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

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

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 \( \beta \) 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 Labra-
dor 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 appearance (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
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 $\text{Ni}_{0.6}\text{Mn}_{0.4}^{+2}\text{Mn}_{2}^{+3}\text{O}_4$. (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 ($5\%/\degree C$ at $0\degree C$);
2. they are available in a wide range of resistances, from $10$ ohms to $10^7$ ohms at $25\degree C$, 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 $\sigma$ is the electric conductivity, $A(T)$ is a slowly varying function of temperature, $\Delta E$ 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

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<th>R</th>
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<td>11.39K</td>
<td>79</td>
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</table>

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.)

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

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 $T_0$ 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 $T_0$ and immersed in a half-space of conductivity $K$, specific heat $c$ and density $\rho$, initially at temperature zero.

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

$$\frac{T(\alpha, t)}{T_0} = F(\alpha, \tau)$$

where

$$F(\alpha, \tau) = \frac{4\alpha}{\pi^2} \int_0^\infty \frac{\exp(-\tau u^2)}{u \left\{ [u J_0(u) - \alpha J_1(u)]^2 + [u Y_0(u) - \alpha Y_1(u)]^2 \right\}} du \ , \quad (2.1)$$

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

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

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. $\tau$ defines the thermal time constant of the probe and $\alpha$ is twice the ratio of the heat capacity of sediment to that of
probe material.

Unfortunately, it is not possible to evaluate $F(\alpha, r)$ 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 $F(\alpha, r)$, two approximate methods of calculating thermal conductivity by in situ measurement exist. They are now briefly discussed.

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

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

On the sea floor and using a steel thermal probe, $\alpha$ 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

$$F_0 = \frac{1}{2\alpha r}$$

and the asymptotic temperature at large time ($\tau > 10$) $T_0$ is

$$T_0 = T_0 F_0 = \frac{T_o}{2\alpha r}$$

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

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 $T_0$ and $T$. 
Thus the slope of the measured temperature versus the reciprocal time \( \frac{1}{t} \) gives the reciprocal conductivity \( \frac{1}{K} \) for \( \tau \) 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 \( T_\alpha \) for the asymptotic solution at the same time range. There are different ways to define the correction factor. The following are the self-consistent \( \tau \) method and the empirical \( k - K \) method.
(1) Self-consistent \( \tau \) 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 \( \tau \) and \( 2\tau \), that is, \( \frac{F(\alpha, \tau)}{F(\alpha, 2\tau)} \). Lister (1979) has suggested the correction function \( L(\alpha, \tau) \):

\[
L(\alpha, \tau) = 2\alpha \tau F(\alpha, \tau) = \frac{F(\alpha, \tau)}{F_s(\alpha, \tau)}
\]

The measured temperature \( T \) can be written as:

\[
T = F(\alpha, \tau) = \frac{F_s(\alpha, \tau)}{F_s(\alpha, \tau)} F(\alpha, \tau) = \frac{Q}{4\pi K} L(\alpha, \tau).
\]

- 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 \( \alpha \) and \( \tau \) are known. \( \alpha \) can be taken to be equal to 2 with little error (<2%, Lister, 1979, Hyndman et al., 1979). Information relating to the value \( \tau \) 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:

\[
R(\theta, 2, \tau) = \frac{\theta F(\alpha, 2\tau)}{F(\alpha, \tau)}
\]

The \( R \)-ratio tends downwards toward unity as \( \tau \) approaches infinity. \( \theta \) 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 \( \tau \). Thus, a graph comparing \( R \) and \( L \) has been suggested by Lister (1979, Fig. 2) with \( \tau \) 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 \( C(\alpha, \tau) \):

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

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 \( \alpha \) 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 x 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

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 (CDP18S829)**

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-cadmium 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 stabilized 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 $\mu$s 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
significant bit). To this end, the expression for $V_{in}$ can be written as

$$\text{Fig. 3.7 Basic structure of the sample and hold circuit}$$
\[ V_{in} = V_{ref} \times \left( \frac{b_1}{2} + \frac{b_2}{2^2} + \cdots + \frac{b_n}{2^n} \right) . \]

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 \( 1/2 \ V_{ref} \), \( 1/4 \ V_{ref} \), \( 1/8 \ V_{ref} \) \( \ldots \) \( 1/2^n \ V_{ref} \). After the last comparison, it is valid that

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

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>
<thead>
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<th>Table 3.1 ADC Input/Output Relationship</th>
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<td>Analog Input</td>
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<tr>
<td>+2.500000V</td>
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<tr>
<td>+1.250000V</td>
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<tr>
<td>+0.625000V</td>
</tr>
<tr>
<td>\ldots</td>
</tr>
<tr>
<td>+0.000076V</td>
</tr>
<tr>
<td>+00000000V</td>
</tr>
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</table>
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 I = 6, the instructions are for input-output operations.

![Fig. 3.8 One-byte Instruction Format](image)

When I = 6 and 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 meas-
urements. Moreover, these individual measurements are the reading differences between power 'on' and 'off' to the thermistor string (Fig. 3.9).

![Diagram of 15 channel ADC and power supply to the thermistor string]

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 resetting 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
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 hydro-
phone 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 \times (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 \times (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
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;
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;

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).

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.

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.

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
Establish at INITIALIZATION

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
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 7FFFFH 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 stabilizing are saved, thus some infor-
![Memory Map of the HF1601 Heat Flow Probe](image)

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
<table>
<thead>
<tr>
<th>line number</th>
<th>time/tilt</th>
<th>temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINE 01</td>
<td>0000</td>
<td>778F 7689 74B9 768D 7919 7558 7686 7C4E 7E3D 80C0 84C3 8C63 9C55 DCA4</td>
</tr>
<tr>
<td>LINE 02</td>
<td>0000</td>
<td>7792 7689 74B5 768D 7918 7556 768B 7C4E 7E3D 80C9 84C6 8C62 9C55 DCA0</td>
</tr>
<tr>
<td>LINE 03</td>
<td>0000</td>
<td>0100</td>
</tr>
<tr>
<td>LINE 04</td>
<td>0000</td>
<td>0100</td>
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<td>LINE 05</td>
<td>0000</td>
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<td>LINE 06</td>
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<td>LINE 07</td>
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<td>LINE 08</td>
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<td>0100</td>
</tr>
<tr>
<td>LINE 23</td>
<td>0000</td>
<td>0100</td>
</tr>
<tr>
<td>CONDUCTIVITY</td>
<td>0000</td>
<td>0100</td>
</tr>
</tbody>
</table>

**Fig. 4.9** Displaying format on the ship's monitor
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:

\[ R_{\text{thermistor}} = \frac{V_{\text{thermistor}}}{V_{\text{reference}}} \times R_{\text{reference}} \]

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)

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

(5.1)

\[ \tau = 0, \quad F(\alpha, \tau) = 1; \quad \tau = \infty, \quad F(\alpha, \tau) = 0 \]

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

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

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

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

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

where $h_0 = 0$, $h_m = 1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{m}$, and $\gamma = 0.57721566490$
THERMAL GRADIENT AND CONDUCTIVITY REDUCTION
LABRADOR SHELF #17

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 $u = 0, 0.1, 0.2, \ldots, 15$ and $m = 0, 1, 2, \ldots, 15$.

In the $F(\alpha,\tau)$ function, $\tau = \frac{kt}{a^2}$ describes the thermal time constant of a probe of radius $a$ in sediment of diffusivity $k$. $\alpha = \frac{2\pi a^2 \rho c}{S}$ 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 $\alpha$ and $\tau$ can be estimated by empirical relations between these parameters and the conductivity $K$ for ocean sediments (Hyndman et al., 1979) as follows

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

That is

\[ \tau = \frac{kt}{(5.79 - 3.67K + 1.016K^2) a^2} \quad \text{(5.2)} \]

\[ \alpha = \frac{2(5.79 - 3.67K + 1.016K^2)}{\rho c} \quad \text{(5.3)} \]

In (5.3), $\rho c$ 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

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

(5.4)

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

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

(5.5)

When $\alpha$ is about 2 and at large $\tau$ ($\tau > 10$), 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 $T_o$,

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

(5.6)
Let $T$ be the temperature above the ambient at any moment after frictional heating or pulse heating. It has been stated that

$$\frac{T}{T_0} = F(\alpha, \tau) \quad \text{or} \quad \frac{T}{T_0} \times F(\alpha, \tau) = 1$$

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

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

Renaming $T$ as $\Delta T$ and comparing (5.6) and (5.7),

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

or

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

where $Q$ is the heat supplied to the probe per unit time per unit length and $t$ is the time elapsed at $\Delta T$. 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 $\Delta T$ at all the points after the heat pulse and
(ii) an estimation of conductivity $K$ for determining $\alpha$ and $\tau$ using the empirical relations in equations (5.2) and (5.3).

The second requirement suggests that the reduction of thermal conductivity for \textit{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 $\alpha$, $\tau$ 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 nonlinearly 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

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

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

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

or

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

(5.10)
1. Thermal string (14 thermistors)  
2. Styrofoam insulation  
3. Glass container  
4. Ice-water mixture  
5. Platinum resistance thermometer  
6. Mineral oil  
7. Metal oil container

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

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

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

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

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

That is

$$\begin{align*}
\sum (R - R_i) &= 0 \\
\sum (R - R_i)(T_i + C)^{-1} &= 0 \\
\sum (R - R_i)(T_i + C)^{-2} &= 0
\end{align*}$$ \hspace{1cm} (5.13)

Rename $T$ for $T_i$. From (5.13),

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

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

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

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

$$A \sum (T + C)^{-2} + B \sum (T + C)^{-3} = \sum [R_i (T + C)^{-2}]$$ \hspace{1cm} (5.17)
Let $\bar{R} = \left( \sum_{i=1}^{n} R_i \right)/n$. From (5.15),

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

(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:

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

(5.19)

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

(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 $C$, $C_{\text{max}}$ and $C_{\text{min}}$, 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 $C_{\text{min}}$ or $C_{\text{max}}$ using the "optimum seeking method". If $C_{\text{max}}$ should be changed, the new $C_{\text{max}}$ is

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

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

$$C_{\text{min}} + 0.382(\text{max} - C_{\text{min}})$$
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:

\[ A = -5.493939; \quad B = 5811.403; \quad C = 342.7457 \]

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

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

that is:

\[ T = \frac{5811.403}{\ln R + 5.493939} - 342.7457 \quad (5.21) \]

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>
<thead>
<tr>
<th>location</th>
<th>Station</th>
<th>Date</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water Depth</th>
</tr>
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<td>47° 36.72</td>
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<td></td>
<td>48° 08.62</td>
<td>59° 16.19</td>
<td>151m</td>
</tr>
<tr>
<td></td>
<td>HF #38</td>
<td></td>
<td>48° 08.77</td>
<td>59° 15.93</td>
<td>151m</td>
</tr>
</tbody>
</table>
HEAT FLOW: ST. GEORGE'S BAY #30, JUNE 1984

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

<table>
<thead>
<tr>
<th>Location</th>
<th>Station</th>
<th>Date</th>
<th>Lat. (° N)</th>
<th>Long. (° W)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 5</td>
<td>5-1</td>
<td>223,1984</td>
<td>58° 00.84</td>
<td>48° 23.36</td>
<td>3435</td>
</tr>
<tr>
<td></td>
<td>5-2</td>
<td></td>
<td>58° 03.73</td>
<td>48° 21.92</td>
<td>3435</td>
</tr>
<tr>
<td>Site 2</td>
<td>2-1</td>
<td>231,1984</td>
<td>58° 30.82</td>
<td>57° 56.17</td>
<td>2614</td>
</tr>
<tr>
<td></td>
<td>2-2</td>
<td></td>
<td>58° 30.71</td>
<td>57° 54.57</td>
<td>2623</td>
</tr>
<tr>
<td></td>
<td>2-3</td>
<td></td>
<td>58° 30.43</td>
<td>57° 53.47</td>
<td>2623</td>
</tr>
<tr>
<td></td>
<td>2-4</td>
<td></td>
<td>58° 30.10</td>
<td>57° 52.42</td>
<td>2655</td>
</tr>
<tr>
<td></td>
<td>2-5</td>
<td></td>
<td>58° 29.65</td>
<td>57° 51.16</td>
<td>2646</td>
</tr>
<tr>
<td></td>
<td>2-6</td>
<td></td>
<td>58° 29.04</td>
<td>57° 49.79</td>
<td>1472</td>
</tr>
<tr>
<td>Hopedale Saddle</td>
<td>HS-1</td>
<td>235,1984</td>
<td>55° 49.90</td>
<td>58° 40.52</td>
<td>573</td>
</tr>
<tr>
<td></td>
<td>HS-2</td>
<td></td>
<td>55° 48.49</td>
<td>58° 40.47</td>
<td>594</td>
</tr>
<tr>
<td></td>
<td>HS-3</td>
<td></td>
<td>55° 47.55</td>
<td>58° 41.37</td>
<td>594</td>
</tr>
<tr>
<td></td>
<td>HS-4</td>
<td></td>
<td>55° 46.55</td>
<td>58° 42.02</td>
<td>607</td>
</tr>
<tr>
<td></td>
<td>HS-17</td>
<td>236,1984</td>
<td>55° 38.39</td>
<td>58° 44.47</td>
<td>657</td>
</tr>
<tr>
<td></td>
<td>HS-18</td>
<td></td>
<td>55° 38.19</td>
<td>58° 43.24</td>
<td>641</td>
</tr>
<tr>
<td></td>
<td>HS-19</td>
<td></td>
<td>55° 38.19</td>
<td>58° 41.31</td>
<td>641</td>
</tr>
</tbody>
</table>
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:

\[ T = 0 \quad \text{when} \quad t = 0 \]

\[ T = T_0(t) \quad \text{at} \quad z = 0 \quad (z: \text{depth,} \quad z = 0 \text{is the water-sediment interface}) \]

The temperature distribution in the solid is expressed as

\[ \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} \quad (7.1) \]

where \( k \) is diffusivity of the solid. For the perturbing influence, take \( T_0(t) \) to be a periodic function with frequency \( \omega \). A standard solution is of the form

\[ T = U \, e^{i(\omega t - \phi)} \quad (7.2) \]

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

Substituting (7.2) into (7.1)

\[ \frac{\partial^2 U}{\partial z^2} = \frac{i \omega}{k} U \quad (7.3) \]

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

\[ T = A \ e^{-Kz} \cos(\omega t - Kz - \phi) \] \hspace{1cm} (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 \( k \approx 0.23 \times 10^{-6} \text{m}^2 \text{s}^{-1} \) for the daily temperature variation \( S = 0.5 \text{m} \), for an annual variation \( S = 9.5 \text{m} \).

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.

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 $\omega$. 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 per-
turbation 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 °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
Fig. 7.1b  Bottom water temperature record of Belle Bay 1 and Bay d'Espoir
Table 7.1 Thermal gradient at Belle Bay 2

<table>
<thead>
<tr>
<th>Station</th>
<th>Gradient (no correction)</th>
<th>Gradient (corrected*)</th>
<th>Correction (mKm⁻¹)</th>
<th>Correction (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2-1</td>
<td>63.5</td>
<td>69.4</td>
<td>+5.9</td>
<td>8°C</td>
</tr>
<tr>
<td>B2-2</td>
<td>70.1</td>
<td>73.1</td>
<td>+3</td>
<td>4°C</td>
</tr>
<tr>
<td>B2-3</td>
<td>67</td>
<td>69.8</td>
<td>+2.8</td>
<td>4°C</td>
</tr>
<tr>
<td>B2-4</td>
<td>67.7</td>
<td>65.6</td>
<td>-2</td>
<td>3°C</td>
</tr>
<tr>
<td>B2-5</td>
<td>63.6</td>
<td>65.1</td>
<td>+1.5</td>
<td>2.5°C</td>
</tr>
<tr>
<td>B2-6</td>
<td>65</td>
<td>65.5</td>
<td>+0.5</td>
<td>&lt;1°C</td>
</tr>
<tr>
<td>average</td>
<td></td>
<td></td>
<td></td>
<td>3.5°C</td>
</tr>
</tbody>
</table>

*: 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⁻¹K⁻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⁻¹K⁻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

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

where \( q_u \) is the undisturbed thermal gradient at great depth and

\[ Q(p) = \frac{1}{2} p^2 - \left( 1 + \frac{p^2}{2} \right) \text{erf} \left( \frac{p}{\sqrt{2}} \right) - \frac{1}{\sqrt{\pi}} p e^{-\frac{p^2}{4}} \]

and

\[ p = \frac{V_t}{\sqrt{kt}} \]

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

<table>
<thead>
<tr>
<th>Sedimentation rate (mm/year)</th>
<th>( q_0 / q_u )</th>
<th>Correction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.9998</td>
<td>+0.02</td>
</tr>
<tr>
<td>0.1</td>
<td>0.998</td>
<td>+0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>0.982</td>
<td>+1.8</td>
</tr>
<tr>
<td>1.0</td>
<td>0.963</td>
<td>+3.7</td>
</tr>
<tr>
<td>2.0</td>
<td>0.927</td>
<td>+7.3</td>
</tr>
<tr>
<td>5.0</td>
<td>0.825</td>
<td>+17.5</td>
</tr>
</tbody>
</table>

\( q_o \): 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/m² (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/m² and 45 mW/m² (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 ($4.9 \times 10^{-9}$ 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

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

\[T = 0, \; \text{for} \; t = 0\]

\[T = T_0 + bt \; \text{at} \; z = 0\]

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

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

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

\[
T = 4bt \, i^2 \text{erfc} \, \frac{z}{2\sqrt{kt}} \tag{7.5}
\]
where

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

and

\[ \text{ierfc} (y) = \frac{1}{\sqrt{\pi}} e^{-y^2} - y^2 \text{erfc} (y) \]

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

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

<table>
<thead>
<tr>
<th>Station</th>
<th>Gradient (mK/m)</th>
<th>Mean gradient (mK/m)</th>
<th>Heat flux* (mW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1-20</td>
<td>93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1-21</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1-22</td>
<td>91.3</td>
<td>86±5.9</td>
<td>74±13</td>
</tr>
<tr>
<td>B1-23</td>
<td>79.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1-24</td>
<td>83.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Table 7.4 also gives an estimation of heat flow value of 74 mW/m², 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⁻¹K⁻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/m²).

<table>
<thead>
<tr>
<th>Table 7.5 Thermal gradient at Bay d’Espoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>E10</td>
</tr>
<tr>
<td>E11</td>
</tr>
<tr>
<td>E12</td>
</tr>
<tr>
<td>E13</td>
</tr>
<tr>
<td>E14</td>
</tr>
<tr>
<td>E15</td>
</tr>
<tr>
<td>E16</td>
</tr>
<tr>
<td>*: conductivity 0.8 W/Km, +10% correction</td>
</tr>
</tbody>
</table>

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.
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>
<thead>
<tr>
<th>Station</th>
<th>Gradient (mK/m)</th>
<th>Conductivity (Wm⁻¹K⁻¹)</th>
<th>Heat flow (mW/m²)</th>
<th>Mean heat flow (mW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>48.3</td>
<td>1.48</td>
<td>71.5</td>
<td></td>
</tr>
<tr>
<td>2-2</td>
<td>54.2</td>
<td>1.27</td>
<td>68.8</td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>43.9</td>
<td>1.49</td>
<td>65.4</td>
<td></td>
</tr>
<tr>
<td>2-4</td>
<td>44.4</td>
<td>1.43*</td>
<td>63.5</td>
<td>69±5</td>
</tr>
<tr>
<td>2-5</td>
<td>53.8</td>
<td>1.33</td>
<td>71.6</td>
<td></td>
</tr>
<tr>
<td>2-6</td>
<td>50.7</td>
<td>1.43*</td>
<td>72.5</td>
<td></td>
</tr>
<tr>
<td>5-1</td>
<td>83.3</td>
<td>0.89</td>
<td>74.7</td>
<td>73±3</td>
</tr>
<tr>
<td>5-2</td>
<td>74.4</td>
<td>0.95</td>
<td>71.1</td>
<td></td>
</tr>
</tbody>
</table>

*: 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: \( Q(t) = 63 \pm 2 \text{ mW/m}^2 \), \( D(t) = 5140 \pm 70 \text{ m} \);
Site 5: \( Q(t) = 66 \pm 2 \text{ mW/m}^2 \), \( D(t) = 5025 \pm 60 \text{ m} \).

<table>
<thead>
<tr>
<th>Age</th>
<th>Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td></td>
</tr>
<tr>
<td>0-70</td>
<td>( D(t) = 2500 + 350 \ t^{0.5} )</td>
</tr>
<tr>
<td>( &gt;20 )</td>
<td>( D(t) = 6400 - 3200 \ e^{-\frac{t}{62.8}} )</td>
</tr>
<tr>
<td>Heat Flow</td>
<td></td>
</tr>
<tr>
<td>0-120</td>
<td>( Q(t) = \frac{473}{t^{0.5}} )</td>
</tr>
<tr>
<td>( &gt;60 )</td>
<td>( Q(t) = 37.5 + 67 \ e^{-\frac{t}{62.8}} )</td>
</tr>
</tbody>
</table>

\( t \) is in millions of years, \( D(t) \) is in meters, \( Q(t) \) is in mW/m\(^2\). The decay of the radioactive elements contributes 4 mW/m\(^2\) 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>
<thead>
<tr>
<th>Location</th>
<th>Magnetic anomaly number</th>
<th>age of magnetic anomaly</th>
<th>Heat flow measured (mW/m(^2))</th>
<th>Heat flow predicted by age (mW/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 2</td>
<td>26 - 27</td>
<td>55 - 60</td>
<td>60±5</td>
<td>63±2</td>
</tr>
<tr>
<td>Site 5</td>
<td>23 - 24</td>
<td>50 - 55</td>
<td>73±3</td>
<td>66±2</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Location</th>
<th>Water depth (measured)</th>
<th>basement depth *</th>
<th>basement depth (magnetic)</th>
<th>basement depth (heat flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 2</td>
<td>2630 m</td>
<td>3585 m</td>
<td>5140±70 m</td>
<td>4900±260 m</td>
</tr>
<tr>
<td>Site 5</td>
<td>3230 m</td>
<td>4270 m</td>
<td>5025±60 m</td>
<td>4770±420 m</td>
</tr>
</tbody>
</table>

*: 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

<table>
<thead>
<tr>
<th>Station</th>
<th>Gradient (mK/m)</th>
<th>Conductivity (Wm⁻¹K⁻¹)</th>
<th>Heat flow (mW/m²)</th>
<th>Mean Heat flow (mW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS-1</td>
<td>31.3</td>
<td>0.96</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>HS-2</td>
<td>24.1</td>
<td>0.92</td>
<td>22.3</td>
<td></td>
</tr>
<tr>
<td>HS-3</td>
<td>31.5</td>
<td>1.06</td>
<td>33.3</td>
<td></td>
</tr>
<tr>
<td>HS-4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>28.3±4</td>
</tr>
<tr>
<td>HS-17</td>
<td>24.9</td>
<td>1.02</td>
<td>25.4</td>
<td></td>
</tr>
<tr>
<td>HS-18</td>
<td>33.4</td>
<td>0.85</td>
<td>28.5</td>
<td></td>
</tr>
<tr>
<td>HS-19</td>
<td>33.6</td>
<td>0.90</td>
<td>30.2</td>
<td></td>
</tr>
</tbody>
</table>

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/m² (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 \textit{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.

3.2 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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Wright, J.A. and Fang, C.L. *A microprocessor instrument for real-time marine heat flow measurement.* (In preparation), 1985

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

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 sys-
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
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.

![CDP1802 Microprocessor Diagram](image)

**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 of 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 ; 0001 ..**********************************************************************
0000 ; 0002 ..NAME: HE1601P
0000 ; 0003 ..DESC: HEAT FLOW MEASUREMENT
0000 ; 0004 ..DATE: 16/05/1984
0000 ; 0005
0000 ; 0006 .. HF1601 IS DESIGNED FOR MEASURING
0000 ; 0007 .. MARINE HEAT FLOW. 16 CHANNELS.
0000 ; 0008 .. SAMPLING RATE 15 SEC. DATA STORE IN
0000 ; 0009 .. RAM. UNDERWATER TELEMETRY.
0000 ; 0010 .. 4 DATA STORE FOR PREPENETRATION.
0000 ; 0011 .. 18 MINUTES FOR THERMAL GRADIENT
0000 ; 0012 .. AND CONDUCTIVITY MEASUREMENTS.
0000 ; 0013 .. THIS PROGRAM IS LINKED TO UT62 FOR
0000 ; 0014 .. DELAY, SUBROUTINE CALL AND
0000 ; 0015 .. RETURN. TYPE DATA VIA RS 232C.
0000 ; 0016
0000 ; 0017 ..**********************************************************************
0000 ; 0018 .. SYSTEM EQUATES
0000 ; 0019 ..**********************************************************************
0000 ; 0020 .. REGISTER ASSIGNMENTS
0000 ; 0021
0000 ; 0022
0000 ; 0023 CLOCK=#00 ..CLOCK COUNTER
0000 ; 0024 RAMPT=#01 ..RAM POINTER FOR DATA
0000 ; 0025 SP=#02 ..STACK POINTER
0000 ; 0026 PC=#03 ..PROGRAM COUNTER
0000 ; 0027 CALL=#04 ..CALL ROUTINE COUNTER
0000 ; 0028 RETN=#05 ..RETURN ROUTINE COUNTER
0000 ; 0029 LINK=#06 ..SUBROUTINE DATA LINK
0000 ; 0030 CHANL=#07 ..CHANNEL.0. CHANNEL COUNTER
0000 ; 0031 ..CHANNEL.1. FOR 8 TIMES COUNTER
0000 ; 0032 MINUTE=#08 ..MINUTE.0. MINUTE COUNTER
0000 ; 0033 ..MINUTE.1. Grad T OR K FLAG
0000 ; 0034 DELAY=#0C ..DELAY ROUTINE COUNTER
0000 ; 0035 AUX=#0E ..AUX.1 HOLDS TIME CONSTANT
0000 ; 0036 MOTION=#0D ..MOTION.0 MOTION FLAG
0000 ; 0037
0000 ; 0038
0000 ; 0039 .. RAM/ROM ALLOCATIONS
..**************************************************************
ORG HF1801

7100;

..DISABLE INTERRUPTS

.. INITIALIZE UT 62 MONITOR

LBR INIT1
INIT1=#83F3

.. STORE A/D SUBROUTINE
.. (PART OF A/D ROUTINE INTO #1300-#1307)

..**************************************************************

..**************************************************************
REGISTER INITIALIZATION

..**************************************************************
RESTAT
LDI $14; PHI RAMPT ..R1=#1400.
LDI #28; PHI AUX.1 ..BAUD RATE 300.
LDI #00; PLO MOTION ..MOTION FLAG
NOP .."J", J=0.
16 CHANNEL A/D CONVERSION, 8 TIMES

RESET: SEX PC

OUT 1, #30..PULSE #613062
OUT 2, #00..RESET J.
LDI #00; PLO MINUTE.0..T=0.
LDI #02; PHI MINUTE.1..K=2.
INC MOTION ..J=J+1.

PHASE1: LDI #00; PLO RA; PHI CHANL ..M=0.
LDI #10; PHI RA ..RA=#1000.
N0P; N0P

REPEAT: SEX PC; OUT 1, #30
OUT CHOPPR, #00
CHOPPR=#4 ..CHOPPR ON.
LDI #00; PLO CHANL ..N=0.

HIGH: SEP CALL; A(A/D)
INC CHANL ..N=N+1.
A(A/D)=#0290
GLO CHANL; SDI #10 ..N=16?
BNZ HIGH

LOW: SEP CALL; A(A/D)
INC CHANL ..N=N+1.
GLO CHANL; SDI #10
BNZ LOW

SUBTRACTION (CHOPPER ON) - (CHOPPER OFF)

LDI #00; PHI CHANL ..M=0.
PLO CHANL; PLO RB; PLO RA ..N=0.
LDI #10; PHI R9; PHI RA ..RA=#1000
LDI #20; PLO R9 ..R9=#1020
LDI #12; PHI RB ..RB=#1200.
SEX R9

SEX PC; OUT 1, #30
OUT CHOPPR, #00
CHOPPR OFF.
LDI #00; PLO CHANL ..N=0.

GHI CHANL; ADI #01; PHI CHANL ..M+1.
SDI #08; BNZ REPEAT ..M=8?
SEX PC; OUT 1, #30
OUT TELE, #00; NOP

TELE=#7 ..TELE ON.
0096  5B1B;     0138  STR RB; INC RB
0098  17;        0139  INC CHANL  ..N=N+1.
0099  87FD10;    0140  GLO CHANL; SDI #10 ..N=16?
009C  3A8E;      0141  BNZ DOSUB
009E  97FC01B7;  0142  GHI CHANL; ADI #01; PHI CHANL ..M+1.
00A2  F800A7F6;  0143  LDI #00; PLO CHANL; SHR ..N=0. DF=0.
00A6  8AFC20AA;  0144  GLO RA; ADI #20; PLO RA ..RA=RA+#20.
00AA  9A7C00BA;  0145  GHI RA; ADCI #00; PHI RA
00AE  F800F6;    0146  LDI #00; SHR ..DF=0.
00B1  89FC20A9;  0147  GLO R9; ADI #20; PLO R9 ..R9=R9+#20.
00B5  997C00B9;  0148  GHI R9; ADCI #00; GHI R9
00B9  97FD08;    0149  GHI CHANL; SDI #08 ..M=8?
00BC  3A8E;      0150  BNZ DOSUB
00BE  ;          0151
00BE  ;          0152
00BE  ;          0153
00BE  ;          0154
00BE  ;          0155
00BE  ;          0156
00BE  ;          0157
00BE  ;          0158
00BE  B7A7;      0159
00C0  AAA9;      0160
00C2  F812BABB9; 0161
00C6  F800AF;    0162
00C9  89FC20A9;  0163
00CD  E9;        0164
00CE  0AF460;    0165
00D1  5A1A;      0166
00D3  0A74;      0167
00D5  5AC4;      0168
00D7  3BDA;      0169
00D9  1F;        0170
00DA  292A;      0171
00DC  97FC01;    0172
00DF  B7FD07;    0173
00E2  3AC9;      0174
00E4  17;        0175
00E5  DCFFDCFF;  0176
00E9  DCFFDC80;  0177
00ED  C4C4C4;    0178
00F0  ;          0179
00F0  ;          0180
00F0  ;          0181
00F0  F803AB;    0182
00F3  2B;        0183
00F4  1A;        0184
00F5  8FF8AF;    0185
00F8  0A765A;    0186

AVERAGE

DO SUMS FOR 8 TIMES, DIVIDED BY 8

DO SUMS

PHI CHANL; PLO CHANL ..N=0,M=0.
PLO RA; PLO R9 ..RA=R9=#1200.
LDI #12; PHI RA; PHI R9
AGAIN: LDI #00; PLO RF ..RF.0=0.
AVERAGE: GLO R9; ADI #20; PLO R9 ..R9+#20.
SEX R9

LDN RA; ADD; IRX ..L BYTE ADD.
STR RA; INC RA

LDN RA; ADC ..H BYTE ADD WITH

STR RA; NOP ..CARRY.

BNF GO ..OVERFLOW?
INC RF ..YES.

GO: DEC R9; DEC RA ..R9-1,RA-1.

DEC R9; DEC RA ..R9-1,RA-1.

GHI CHANL; ADI #01 ..M=M+1.
PHI CHANL; SDI #07 ..M=8?
BNZ AVERAGE ..NO.
INC CHANL ..YES. N=N+1.
DELAY, #FF; DELAY, #FF

DELAY, #FF; DELAY. #80

NOP; NOP; NOP

DIVIDED BY 8

LDI #03; PLO RB ..RB AS "S".
DIVIDE: DEC RB ..S=S-1.

INC RA ..RA POINTS TO LOW BYTE.
GLO RF; SHR; PLO RF ..OVERFLOW OUT

LDN RA; SHRC; STR RA ..HIGH BYTE
00FB ; 0187
00FB 2A; 0188
00FC OA765A; 0189
00F0 ; 0190
00F0 8BCA00F3; 0191
0100 87FD10; 0192
0106 3214; 0193
0108 1A1A; 0194
010A 8A99AB9; 0195
010E F800B7; 0196
0111 C000C8; 0197
0114 ; 0198
0114 ; 0199
0114 ; 0200
0114 ; 0201
0114 ; 0202
0114 F800A7; 0203
0117 F812BA; 0204
011A F81FAA; 0205
011D 88; 0206
011E 3A45C4; 0207
0121 98F6; 0208
0123 3333C4; 0209
0126 D483F0; 0210
0129 ; 0211
0129 5455D50; 0212
012D 2E; 0213
012E 0D0A; 0214
0130 00; 0215
0131 3045; 0216
0133 D483F0; 0217
0136 434F4E44; 0218
013A 55435449; 0219
013E 58495459; 0220
0142 0D0A; 0221
0144 00; 0222
0145 80F6; 0223
0147 334F; 0224
0149 905A2A; 0225
014C 805A1A; 0226
014F ; 0227
014F ; 0228
014F ; 0229
014F 17; 0230
0150 0A2A51; 0231
0153 87FD20; 0232
0156 325B; 0233
0158 11; 0234
0159 304F; 0235

...RIGHT SHIT WITH CARRY.
DEC RA ..RA POINTS TO LOW BYTE.
LDN RA; SHRC; STR RA ..LOW BYTE
...RIGHT SHIT WITH CARRY.
GLO RB; LBNZ DIVIDE ..S=0? NO.
GLO CHANL; SDI #10 ..YES, N=16?
BZ ENDAVE ..YES, DATA STROE.
INC RA; INC RA ..NO, RA=RA+2.
GLO RA; PLO R9; GHI RA; PHI R9 ..RA=R9.
LDI #00; PHI CHANL ..N=0.
LBR AGAIN ..NEXT CHANNEL.

ENDAVE: LDI #00; PLO CHANL ..N=0.
LDI #12; PHI RA
LDI #1F; PLO RA ..RA=#121F.
GLO MINUTE ..TEST T.
BNZ EVEN; NOP ..T NOT 0.
GHI MINUTE; SHR ..T=0, TEST K.
BDF TITLE2; NOP ..K=1, TO CONDUCT.
TITLE1: SEP CALL; A(OSTRNG) ..K=0, TELE
OSTRNG=#83F0 .."TEMP".
OSTRNG = #83F0 .."TEMP"
,'T' TEMP'
,T'0D0A'
,#00

BR EVEN

TITLE2: SEP CALL, A(OSTRNG) ..K=1,
,T'CONDUCTIVITY' ..TELE
, .."CONDUCTIVITY".
,T'0D0A'
,#00

EVEN: GLO CLOCK; SHR ..IF CLOCK EVEN.
BDF STORE ..STORE CLOCK, IF ODD.
GHI CLOCK; STR RA; DEC RA; STR TILT.
GLO CLOCK; STR RA; INC RA

STORE: INC CHANL ..N=N+1.
LDN RA; DEC RA; STR RAMPT ..DATA STR.
GLO CHANL; SDI #20 ..N=32?
BZ ADTEST ..YES, RAM < #7FFF?
INC RAMPT
BR STORE
ADTEST: LDI #00; SHR
GHI RAMPT: SDI #7D ..IF RAMPT >
BNF HIADRS ..#7FF GO TO #D000.
BNZ INC1

GLO RAMPT; SDI #FF

BNZ INC1

BR TRANSM

INC1: INC RAMPT

BR TRANSM

HIADRS: GHI RAMPT; SDI #FF ..#FFFF?
BNZ INC2 ..NO, GO ON.

GLO RAMPT; SDI #FF

BZ END ..YES, END.

INC2: INC RAMPT

BR TRANSM

END: SEP CALL, A(OSTRNG) ..TELE
'T' 'RAM FULL' .."RAM FULL"

'T' '0D0A'

,#00

NOP; NOP

STOP: BR STOP; NOP ..PROGRAM HALTS.

DATA TRANSMISSION VIA TELEMETRY

TRANSIM: GLO MINUTE; PHI RF ..TELE "T".

SEP CALL, A(TYPE2)

TYPE2=#81AE

SEP CALL, A(TYPE6)

TYPE6=#81A2

'T' ..TELE ONE SPACE.

LDI #10; PLO CHANL ..N=16.

LDI #12; PHI RA ..RA=#121F.

LDI #1F; PLO RA

TELEOU: LDN RA; PHI RF
01A9  D481AE;  0285  SEP CALL, A(TYPE2)
01AC  2A0ABF;  0286  DEC RA; LDN RA; PHI RF
01AF  D481AE;  0287  SEP CALL, A(TYPE2)
01B2  2A;  0288  DEC RA
01B3  D481A2;  0289  SEP CALL, A(TYPE6)
01B6  20;  0290  ,T’  ..TYPE ONE SPACE.
01B7  27873AA7;  0291  DEC CHANL; GLO CHANL; BNZ TELEOU
01BB  D483F0;  0292  SEP CALL, A(OSTRNG)
01BE  0D0A;  0293  ,’0D0A’
01C0  00;  0294  ,#00
01C1  ;  0295
01C1  ;  0296  4 DATA PREPENETRATION
01C1  ;  0297
01C1  ;  0298  ***********************
01C1  ;  0299
01C1  8DFD08;  0300  GLO MOTION; SDI 08 ..J=8?
01C4  3AEF;  0301  BNZ WAIT1 ..NO.
01C6  2DC4C4;  0302  DEC MOTION; NOP; NOP ..J==J-1.
01C9  F860A7;  0303  LDI #60; PLO CHANL ..N==#60.
01CC  2127;  0304  DEC: DEC RAMPT; DEC CHANL
01CE  873ACC;  0305  GLO CHANL; BNZ DEC ..RAMPT-#60.
01D1  81AA;  0306  GLO RAMPT; PLO RA
01D3  91BA;  0307  GHI RAMPT; PHI RA ..RA==RAMPT
01D5  F820A7;  0308  LDI #20; PLO CHANL ..N==#20.
01D8  2A27;  0309  DEC1: DEC RA; DEC CHANL
01DA  873AD8;  0310  GLO CHANL; BNZ DEC1 ..RAMPT-#20.
01DD  F860A7;  0311  LDI #60; PLO CHANL ..N==#60.
01E0  415A1A;  0312  COPY: LDA RAMPT; STR RA; INC RA ..R(1)==R(A).
01E3  2787;  0313  DEC CHANL; GLO CHANL ..N==0?
01E5  3AE0;  0314  BNZ COPY ..COPY #80 BYTES.
01E7  8AA1;  0315  GLO RA; PLO RAMPT ..RAMPT==RA.
01EB  9AB1;  0316  GHI RA; PHI RAMPT
01ED  30EF;  0317  BR WAIT1
01EF  C4C4;  0318  NOP; NOP
01F1  36EF;  0319  WAIT1: B3 WAIT1 ..15 SECONDS?
01F1  10;  0320  INC CLOCK
01F2  ;  0321
01F2  ;  0322
01F2  ;  0323  ***********************
01F2  ;  0324  .. MOTION DETECTION
01F2  ;  0325
01F2  ;  0326  ***********************
01F2  34FF;  0327  B1 ALERT ..EF1 AS MOTION FLAG.
01F4  ;  0328
01F4  ;  0329  ***********************
01F4  ;  0330  .. MEASUREMENT COMPLETION
01F4  ;  0331
01F4  98F6;  0332  GHI MINUTE; SHR ..K==1?
01F6  CB021B;  0333  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 51454D50; 0342 ,T'TEMP.END'
0212 2E454E44; 0343 ,
0216 0D0A; 0344 ,T'D0A'
0218 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 20154E44; 0356 ,
023B 0D0A; 0357 ,T'D0A'
023D 00; 0358 ,#00
023E E4C4C4C4; 0359 NOP; NOP; NOP; NOP;
0242 C4C4; 0360 NOP; 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 ..HEAT PULSE
024E ; 0366 ..******************************
024E ; 0367 ..PHASE DETECTION
024E ; 0368 ..
024E : 0369 ..
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
HEAT PULSE

Pulse: B3 Pulse  ...15 seconds

INC Clock
SEX PC; OUT 1, #30
OUT 5, #00
DELAY, #FF; DELAY, #FF
DELAY, #FF; DELAY, #FF
NOP; NOP; NOP; NOP
NOP; NOP; NOP; NOP

WAIT3: B3 WAIT3  ...HEAT PULSE 15 SEC.

NOP
SEX PC; OUT, #30
OUT 5, #00  ...HEAT PULSE OFF.
BR OFF2
NOP; NOP

SUBROUTINE FOR A/D CONVERSION

A/D: LDI #13; PHI R9  ...#1304 FOR STR N.
LDI #04; PLO R9
GLO CHANL; STR R9
LBR RAM
RAM=#1300

RETURN: DELAY, #10
SEX PC; OUT 1, #30  ...CONVER PULSE
OUT 8, #30  ...#513066
DELAY, #15
OUT 1, #08  ...I/O INTERFACE.
NOP; NOP

SEX RA

INP PORT(A)  ...INPUT LOW BYTE.
PORT(A) = C
IRX
INP PORT(B)  ...INPUT HIGH BYTE.
PORT(B) = E
IRX
SEP RETN  ...RETURN TO MAIN PROG.

NAME: HF1601T
.. TYPE DATA IN RAM #1400-#7FFF AND #D000-#FFFF. FORMAT: 1. DATA No.: 2. TILT(ODD No.), TIME(EVEN No.); 3. REFERENCE; 4. 14 CHANNEL DATA.
.. RUN THIS PROGRAM TYPE *P0600.

.. Date: 23/10/1983

**DIS;** .0 ...DISABLE INTERRUPTS.

..**START3**

..**DATA**
085A 3A30; 0481 BNZ NEXT
085C 873A30; 0482 GLO R7; BNZ NEXT
085F 2D8D; 0483 DEC RD; GLO RD ..TWICE?
0861 3271; 0484 BZ FINISH ..YES. STOP.
0863 F801B7; 0485 LDI #01; PHI R7 ..NO. R7=#0180.
0866 F880A7; 0486 LDI #80; PLO R7
0869 F8D0B1; 0487 LDI #D0; PHI R1 ..R1=#D000.
086C F800A1; 0488 LDI #00; PLO R1
086F 3030; 0489 BR NEXT ..TYPE DATA #D000-#FFFF.
0871 C087F0; 0490 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))→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.

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<th>OP CODE</th>
<th>OPERATION</th>
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<td>MEMORY REFERENCE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOAD VIA N</td>
<td>LDN</td>
<td>0N</td>
<td>M(R(N))→D; FOR NOT 0</td>
</tr>
<tr>
<td>LOAD ADVANCE</td>
<td>LDA</td>
<td>4N</td>
<td>M(R(N))→D; R(N)+1→R(N)</td>
</tr>
<tr>
<td>LOAD VIA X</td>
<td>LDX</td>
<td>F0</td>
<td>M(R(X))→D</td>
</tr>
<tr>
<td>LOAD VIA X AND ADVANCE</td>
<td>LDXA</td>
<td>72</td>
<td>M(R(X))→D; R(X)+1→R(X)</td>
</tr>
<tr>
<td>LOAD IMMEDIATE</td>
<td>LDI</td>
<td>F8</td>
<td>M(R(P))→D; R(P)+1→R(P)</td>
</tr>
<tr>
<td>STORE VIA N</td>
<td>STR</td>
<td>5N</td>
<td>D→M(R(N))</td>
</tr>
<tr>
<td>STORE VIA X AND DECREMENT</td>
<td>STXD</td>
<td>73</td>
<td>D→M(R(X)); R(X)-1→R(X)</td>
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<tr>
<td>REGISTER OPERATION</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INCREMENT REG N</td>
<td>INC</td>
<td>1N</td>
<td>R(N)+1→R(N)</td>
</tr>
<tr>
<td>DECREMENT REG N</td>
<td>DEC</td>
<td>2N</td>
<td>R(N)-1→R(N)</td>
</tr>
<tr>
<td>INCREMENT REG X</td>
<td>IRX</td>
<td>60</td>
<td>R(X)+1→3R(X)</td>
</tr>
<tr>
<td>GET LOW REG N</td>
<td>GLO</td>
<td>8N</td>
<td>R(N).0→D</td>
</tr>
<tr>
<td>PUT LOW REG N</td>
<td>PLO</td>
<td>AN</td>
<td>D→R(N).0</td>
</tr>
</tbody>
</table>
### Logic Operations

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<th>Instruction</th>
<th>Mnemonic</th>
<th>Op Code</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Get High Reg N</td>
<td>GHI</td>
<td>9N</td>
<td>$R(N).1 \rightarrow D$</td>
</tr>
<tr>
<td>Put High Reg N</td>
<td>PHI</td>
<td>BN</td>
<td>$D \rightarrow R(N).1$</td>
</tr>
<tr>
<td><strong>OR</strong></td>
<td>OR</td>
<td>F1</td>
<td>$M(R(X)) ; OR ; D \rightarrow D$</td>
</tr>
<tr>
<td><strong>OR Immediate</strong></td>
<td>ORI</td>
<td>F9</td>
<td>$M(R(P)) ; OR ; D \rightarrow D$</td>
</tr>
<tr>
<td><strong>EXCLUSIVE OR</strong></td>
<td>XOR</td>
<td>F3</td>
<td>$M(R(X)) ; XOR ; D \rightarrow D$</td>
</tr>
<tr>
<td><strong>EXCLUSIVE OR Immediate</strong></td>
<td>XRI</td>
<td>FB</td>
<td>$M(R(P)) ; XOR ; D \rightarrow D$</td>
</tr>
<tr>
<td><strong>AND</strong></td>
<td>AND</td>
<td>F2</td>
<td>$M(R(X)) ; AND ; D \rightarrow D$</td>
</tr>
<tr>
<td><strong>AND Immediate</strong></td>
<td>ANI</td>
<td>FA</td>
<td>$M(R(P)) ; AND ; D \rightarrow D$</td>
</tr>
<tr>
<td><strong>SHIFT RIGHT</strong></td>
<td>SHR</td>
<td>F6</td>
<td>$SHIFT ; D ; RIGHT,$</td>
</tr>
<tr>
<td><strong>SHIFT Right with Carry</strong></td>
<td>SHRC</td>
<td>76</td>
<td>$SHIFT ; D ; LEFT,$</td>
</tr>
<tr>
<td><strong>SHIFT LEFT</strong></td>
<td>SHL</td>
<td>FE</td>
<td>$SHIFT ; D ; LEFT,$</td>
</tr>
<tr>
<td><strong>SHIFT Left with Carry</strong></td>
<td>SHLC</td>
<td>7E</td>
<td>$SHIFT ; D ; LEFT,$</td>
</tr>
</tbody>
</table>

### Arithmetic Operations

<table>
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<tr>
<th>Instruction</th>
<th>Mnemonic</th>
<th>Op Code</th>
<th>Operation</th>
</tr>
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<tbody>
<tr>
<td>Add</td>
<td>ADD</td>
<td>F4</td>
<td>$M(R(X))+D \rightarrow DF,D$</td>
</tr>
<tr>
<td>Add Immediate</td>
<td>ADI</td>
<td>FC</td>
<td>$M(R(P))+DS\rightarrow DF,D; ; R(P)+1\rightarrow R(P)$</td>
</tr>
<tr>
<td>Add with Carry</td>
<td>ADC</td>
<td>74</td>
<td>$M(R(X))+D+DF\rightarrow DF,D$</td>
</tr>
<tr>
<td>Add with Carry, Immediate</td>
<td>ADC1</td>
<td>7C</td>
<td>$M(R(P))+D+DF\rightarrow DF,D; ; D; ; R(P)+1\rightarrow R(P)$</td>
</tr>
<tr>
<td>Subtract D</td>
<td>SD</td>
<td>F5</td>
<td>$M(R(X))-D \rightarrow DF,D$</td>
</tr>
<tr>
<td>Subtract D Immediate</td>
<td>SDI</td>
<td>FD</td>
<td>$M(R(P))-D \rightarrow DF,D; ; R(P)+1\rightarrow R(P)$</td>
</tr>
<tr>
<td>Subtract D with Borrow</td>
<td>SDB</td>
<td>75</td>
<td>$M(R(X))-D-DF \rightarrow DF,D$</td>
</tr>
<tr>
<td>Subtract D with Borrow, Immediate</td>
<td>SDBI</td>
<td>7D</td>
<td>$M(R(P))-D-\overline{DF} \rightarrow DF,D; ; R(P)+1\rightarrow R(P)$</td>
</tr>
<tr>
<td>Subtract Memory</td>
<td>SW</td>
<td>F7</td>
<td>$D-M(R(X)) \rightarrow DF,D$</td>
</tr>
<tr>
<td>Subtract Memory, Immediate</td>
<td>SMI</td>
<td>FF</td>
<td>$D-M(R(P)) \rightarrow DF,D; ; R(P)+1\rightarrow R(P)$</td>
</tr>
</tbody>
</table>
### INSTRUCTION | MNEMONIC | OP CODE | OPERATION
--- | --- | --- | ---
SUBTRACT MEMORY WITH BORROW | SMB | 77 | D-M(R(X))-DF →DF,D
SUBTRACT MEMORY WITH BORROW, IMMEDIATE | SMBI | 7F | D-M(R(P))-DF →DF,D; R(P)+1→R(P)

### BRANCH INSTRUCTIONS - SHORT BRANCH

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<th>BRANCH INSTRUCTIONS</th>
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<th>SHORT BRANCH IF D=0</th>
<th>SHORT BRANCH IF D NOT 0</th>
<th>SHORT BRANCH IF DF=1</th>
<th>SHORT BRANCH IF DF=0</th>
<th>SHORT BRANCH IF Q=1</th>
<th>SHORT BRANCH IF Q=0</th>
<th>SHORT BR IF EF1=1</th>
<th>SHORT BR IF EF1=0</th>
<th>SHORT BR IF EF2=1</th>
<th>SHORT BR IF EF2=0</th>
<th>SHORT BR IF EF3=1</th>
<th>SHORT BR IF EF3=0</th>
<th>SHORT BR IF EF4=1</th>
<th>SHORT BR IF EF4=0</th>
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<tr>
<td></td>
<td>BR</td>
<td>BZ</td>
<td>BNZ</td>
<td>BDF</td>
<td>BNF</td>
<td>BQ</td>
<td>BNQ</td>
<td>B1</td>
<td>BN1</td>
<td>B2</td>
<td>BN2</td>
<td>B3</td>
<td>BN3</td>
<td>B4</td>
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<td></td>
<td>30</td>
<td>32</td>
<td>3A</td>
<td>33</td>
<td>3B</td>
<td>31</td>
<td>39</td>
<td>34</td>
<td>3C</td>
<td>35</td>
<td>3D</td>
<td>36</td>
<td>3E</td>
<td>37</td>
<td>3F</td>
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</tr>
<tr>
<td></td>
<td>M(R(P))→R(P.0</td>
<td>IF D=0, M(R(P))→R(P.0 ELSE R(P)+1→R(P)</td>
<td>IF D NOT 0, M(R(P))→R(P) ELSE R(P)+1→R(P)</td>
<td>IF DF=1, M(R(P))→R(P.0 ELSE R(P)+1→R(P)</td>
<td>IF DF=0, M(R(P))→R(P.0 ELSE R(P)+1→R(P)</td>
<td>IF Q=1, M(R(P))→R(P.0 ELSE R(P)+1→R(P)</td>
<td>IF Q=0, M(R(P))→R(P.0 ELSE R(P)+1→R(P)</td>
<td>IF EF=1, M(R(P))→R(P.0 ELSE R(P)+1→R(P)</td>
<td>IF EF1=0, AS ABOVE</td>
<td>IF EF2=1, AS ABOVE</td>
<td>IF EF2=0, AS ABOVE</td>
<td>IF EF3=1, AS ABOVE</td>
<td>IF EF3=0, AS ABOVE</td>
<td>IF EF4=1, AS ABOVE</td>
<td>IF EF4=0, AS ABOVE</td>
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### BRANCH INSTRUCTIONS - LONG BRANCH

<table>
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<tr>
<th>BRANCH INSTRUCTIONS</th>
<th>LONG BRANCH</th>
<th>LONG BR IF D=0</th>
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<tr>
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<td>LBR</td>
<td>LBZ</td>
</tr>
<tr>
<td></td>
<td>C0</td>
<td>C2</td>
</tr>
<tr>
<td></td>
<td>M(R(P))→R(P.1, M(R(P))→R(P.0</td>
<td>IF D=0, M(R(P))→R(P.1 M(R(P)+1)→R(P.0 ELSE R(P)+2→R(P)</td>
</tr>
<tr>
<td>INSTRUCTION</td>
<td>MNEMONIC</td>
<td>OP CODE</td>
</tr>
<tr>
<td>-------------</td>
<td>----------</td>
<td>---------</td>
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<tr>
<td>LONG BR IF D NOT 0</td>
<td>LBNZ</td>
<td>CA</td>
</tr>
<tr>
<td>LONG BR IF DF = 1</td>
<td>LBDF</td>
<td>C3</td>
</tr>
<tr>
<td>LONG BR IF DF = 0</td>
<td>LBNF</td>
<td>CB</td>
</tr>
<tr>
<td>LONG BR IF Q = 1</td>
<td>LBQ</td>
<td>C1</td>
</tr>
<tr>
<td>LONG BR IF Q = 0</td>
<td>LBNQ</td>
<td>C9</td>
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**CONTROL INSTRUCTIONS**

<table>
<thead>
<tr>
<th>NO OPERATION</th>
<th>NOP</th>
<th>C4</th>
<th>CONTINUE</th>
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<tbody>
<tr>
<td>SET P</td>
<td>SEP</td>
<td>DN</td>
<td>N→P</td>
</tr>
<tr>
<td>SET X</td>
<td>SEX</td>
<td>EN</td>
<td>N→X</td>
</tr>
<tr>
<td>SET Q</td>
<td>SEQ</td>
<td>7B</td>
<td>1→Q</td>
</tr>
<tr>
<td>RESET Q</td>
<td>REQ</td>
<td>7A</td>
<td>0→Q</td>
</tr>
<tr>
<td>PUSH X,P TO STACK</td>
<td>MARK</td>
<td>79</td>
<td>(X,P)→T; (X,P)→M(R(2)) THEN P→X; R(2)→R(2)</td>
</tr>
</tbody>
</table>

**INTERRUPT CONTROL**

| EXTERNAL INTERRUPT ENABLE | XIE | 680A | 1→XIE |
| EXTERNAL INTERRUPT DISABLE | XID | 680B | 0→XIE |
| COUNTER INTERRUPT ENABLE | CIE | 680C | 1→CIE |
| COUNTER INTERRUPT DISABLE | CID | 680D | 0→CIE |
| RETURN | RET | 70 | M(R(X))→X,P; R(X)+1→R(X); 1→IE |
| DISABLE | DIS | 71 | M(R(X))→X,P; R(X)+1→R(X); 0→IE |
| SAVE | SAV | 78 | T→M(R(X)) |

**INPUT-OUTPUT BYTE TRANSFER**

<p>| OUTPUT 1 | OUT 1 | 61 | M(R(X))→BUS; R(X)+1→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 |</p>
<table>
<thead>
<tr>
<th>INSTRUCTION</th>
<th>MNEMONIC</th>
<th>OP CODE</th>
<th>OPERATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT 1</td>
<td>INP 1</td>
<td>69</td>
<td>BUS→M(R(X)); BUS←; N LINES=1</td>
</tr>
<tr>
<td>INPUT 2</td>
<td>INP 2</td>
<td>6A</td>
<td>AS ABOVE; N LINES=2</td>
</tr>
<tr>
<td>INPUT 3</td>
<td>INP 3</td>
<td>6B</td>
<td>AS ABOVE; N LINES=3</td>
</tr>
<tr>
<td>INPUT 4</td>
<td>INP 4</td>
<td>6C</td>
<td>AS ABOVE; N LINES=4</td>
</tr>
<tr>
<td>INPUT 5</td>
<td>INP 5</td>
<td>6D</td>
<td>AS ABOVE; N LINES=5</td>
</tr>
<tr>
<td>INPUT 6</td>
<td>INP 6</td>
<td>6E</td>
<td>AS ABOVE; N LINES=6</td>
</tr>
<tr>
<td>INPUT 7</td>
<td>INP 7</td>
<td>6F</td>
<td>AS ABOVE; N LINES=7</td>
</tr>
</tbody>
</table>
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"
31 PRINT "5). Infinite-time temperature reduction": PRINT: PRINT "6). Interactive 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:"BYE!":PRINT:PRINT:END
200 REM ROUTINE OF CALCULATING CONDUCTIVITY
210 CLEAR:CLOSE:DIM J1(200),JO(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:SPC(12);"THERMAL CONDUCTIVITY AND GRADIENT CALCULATION": PRINT: PRINT SPC(12);"!! Start with
265 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
CLOSE:OPEN"R",#1,",F-T6.DAT":FIELD #1,8 AS T$,8 AS F$
FOR J=1 TO 100:GET #1,J:FT6(J,1)=CVS(T$):FT6(J,2)=CVS(F$):NEXT
LOOP=0:LOOPS1=0:LOOPS2=0:LP1=0:CLOSE
PRINT:PRINT "Loading F function for K=0.8...":PRINT:GOSUB 9000
OPEN "I", #1,"A;F0.8"
FOR I=1 TO 120:INPUT #1,F(I):F1(I)=F(I):NEXT I:CLOSE:K=0.8
PI=3.141593:E=2.718282:A2=.004725
DU=.1:PI2=PI:2:CM=0:TUN=0
BEEP:BEEP:CLS:FOR I=1 TO 6:PRINT:NEXT I:PRINT SPC(20);"Press any key to continue"
MM$=INKEY$:IF MM$="" GOTO 340
CLS:FILES "B:"
PRINT:PRINT "Loading from serial data file ";DA$:GOSUB 9000
CLOSE:OPEN "I", #1,DA$:FIRST=0
IF TN=14 THEN FITT=1665 ELSE FITT=TN+119
FOR I=1 TO FITT:INPUT #1,HEAT(I) 'Input data from 1 to this channel NEXT I
IF TN<>14 GOTO 530
FOR I=1 TO 119:KK=(TN-1)*119+I:HI(I)=HEAT(KK):NEXT I 'This channel
PRINT:BEEP:PRINTC"Heat quantity Q (Joule/M) = ";QQ
FOSUB 4900
IF DD$="Y" OR DD$="y" GOTO 543
IF DD$="N" OR DD$="n" GOTO 532
IF DD$<"S" OR DD$="" GOTO 389
IF RS$="R" OR RS$="r" GOTO 387
IF RS$="S" OR RS$="s" GOTO 389
IF RS$="" GOTO 382
PRINT:"Is it acceptable? (y/n)";BEEP
DD$=INKEY$:IF DD$="" GOTO 536
IF DD$="Y" OR DD$="y" GOTO 543
IF DD$="N" OR DD$="n" GOTO 532
IF DD$<"S" OR DD$="" GOTO 389
CLOSE:OPEN "R", #1,DA$
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 AS D10$,8 AS D11$,8 AS D12$,8 AS D13$,8 AS D14$
FOR S=1 TO TRR:GET #1,S:S1(S)=CVS(D1$):NEXT S: RRF =
(5811.403/(LOG (S1(TRR))) + 5.493939))·342.7457
RRF=RRF-H1(TRR):FOR I=1 TO 119:H1(I)=H1(I)+RRF:NEXT I
GOSUB 4900

LP1=0:BEEP:INPUT "Penetration at # ";PP

BEEP:INPUT "How many points ";NB

BEEP:PRINT:INPUT "Heat pulse at point # ";PPP

BEEP:INPUT "How many points ";NBB:PRINT

PRINT:PRINT "Calculate and plot for every N'th point. ":INPUT "N ";SSTP

IF SSTP=0 THEN SSTP=1

IF TUN=1 GOTO 599

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(PPP+NB):
YY4=234+Q*24-120*H1(PPP+NBB)

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,YY1-4)-XX1+4),YY1):
LINE (XX2-4,YY2-4)(XX2+2, YY2): CIRCLE (XX3, YY3),3: CIRCLE (XX4, YY4),3:
CIRCLE (XX3, YY3),5: CIRCLE (XX4, YY4),5

FOR I=1 TO 15:PRINT:NEXT:PRINT "Acceptable! (y/n)" :BEEP

POT$=INKEY$:IF POT$="y" GOTO 575

IF POT$="Y" OR POT$="y" GOTO 599

IF POT$="N" OR POT$="n" GOTO 579

IF POT$<"N" GOTO 575

CLS:GOTO 549

BEEP:PRINT:PRINT "Original values: ":PRINT "Penetration ";PP:" ,",:PRINT NB; "points"

PRINT "Heat pulse ";PPP," ":PRINT NBB; " points":PRINT "Delay (fric) : ":DELAY1, "Delay (pulse) ": DELAY:PRINT

GOTO 550

TUN=1:GOSUB 2720

IF LOOP1<>0 GOTO 607

RR=NB-NBB:IF RR>=0 THEN RR=NB ELSE RR=NBB:GOTO 610

RR=PPP+NBB

IF LOOP1<>0 GOTO 630

DELAY=0:DELAY1=0:GOTO 640

BEEP:PRINT "Input delay time T, T=T*15 Sec." :PRINT:INPUT "Delay (fricn)":DDLY1: PRINT: BEEP: INPUT "Delay (pulse) ":DDLY:PRINT:DELAY=DDLY:DELAY1=DDLY1

PRINT:PRINT "Any changes about these numbers? (y/n)"

EDC$=INKEY$:IF EDC$="y" GOTO 636

IF EDC$="Y" OR EDC$="y" GOTO 580

IF EDC$="N" OR EDC$="n" GOTO 640

IF EDC$<"N" GOTO 636

IF LOOP1<>0 GOTO 670

GOSUB 2100

REM CALCULATION OF F FUNCTION

K1=(K/(5.79-3.67*K+1.016*K*K))*0.000001 'DIFFUSIVITY

ALPHA1=2*(5.79-3.67*K+1.016*K*K)/3.116 '3.116:probe's rho*c

ALPHA=2

LOOP2=LOOP2+1
PRINT: PRINT "Delay (friction) = "; PRINT USING " +##.###"; DELAY1: PRINT "; PRINT "Delay (pulse) = "; PRINT USING "+##.###"; DELAY2: PRINT "(Sec.)": PRINT
PRINT "ALPHA = "; PRINT USING "+##.###"; ALPHAS1: PRINT; PRINT; PRINT "Diffusivity = "; K1: PRINT
TAU = A2/K1: NNN = 0
PRINT "Time constant = "; PRINT USING "+##.##": TAU: PRINT "(Sec.)": PRINT
IF LP1 <> 0 GOTO 725
GOSUB 11000: GOSUB 11230: GOTO 980
BIG = NB - NBB: IF BIG > 0 THEN BIG = NB ELSE BIG = NBB
K1 = (K/3.4) * 0.000001 'take ALPHA = 2, 5.79 - 3.67K + 1.016KK = 3.4
RER1 = 1: RER2 = 1: RER3 = 1: RER4 = 1: RER5 = 1: RER6 = 1
RER7 = 1: RER8 = 1: RER9 = 1: RER10 = 1: RER11 = 1: RER12 = 1
FOR T = 1 TO RR STEP SSTP
IF T > BIG AND T < PPP GOTO 945
IF DDLY > 0 OR DDLY = 0 GOTO 738
DELAY = TRD
T1 = (T*15 + DELAY) * K1 / A2 'Time constant of heat pulse decay
T11 = (T*15 + DELAY1) * K1 / A2 'Time constant of frictional decay
T > =PPP GOTO 830
IF T1 > =18.5 GOTO 770
IF T1 > =8.5 AND T1 < 18.5 GOTO 780
IF T1 > =3.6 AND T1 < 8.5 GOTO 790
IF T1 > =1.6 AND T1 < 3.6 GOTO 800
IF T1 > =0.6 AND T1 < 3.6 GOTO 810
REM F function for tau < 0.6
FOR J = RER1 TO 100: JIAN = ABS(T1 - F(T1(J,1)))
IF JIAN > 0.005 GOTO 769
RER1 = J: F(T) = F(T1(J,2)): GOTO 830
NEXT J
REM F function for tau > 18.5
FOR J = RER2 TO 100: JIAN = ABS(T1 - F(T6(J,1)))
IF JIAN > 0.2 GOTO 777
RER2 = J: F(T) = F(T6(J,2)): GOTO 830
NEXT J
REM F function for tau 8.5 to 18.5
FOR J = RER3 TO 100: JIAN = ABS(T1 - F(T5(J,1)))
IF JIAN > 0.1 GOTO 787
RER3 = J: F(T) = F(T6(J,2)): GOTO 830
NEXT J
REM F function for tau 8.5 to 3.6
FOR J = RER4 TO 100: JIAN = ABS(T1 - F(T4(J,1)))
IF JIAN > 0.05 GOTO 797
RER4 = J: F(T) = F(T4(J,2)): GOTO 830
NEXT J
REM F function for tau 1.6 to 3.6
FOR J = RER5 TO 100: JIAN = ABS(T1 - F(T3(J,1)))
IF JIAN > 0.02 GOTO 807
RER5 = J: F(T) = FT3(J, 2): GOTO 830
NEXT J
REM F function for tau 0.6 to 1.6
FOR J = RER6 TO 100: JIAN = ABS(T1 - FT2(J, 1))
IF JIAN > 0.01 GOTO 817
RER6 = J: F(T) = FT2(J, 2): GOTO 830
NEXT J
IF T1 >= 18.5 GOTO 840
IF T1 >= 8.5 AND T1 < 18.5 GOTO 850
IF T1 >= 3.6 AND T1 < 8.5 GOTO 860
IF T1 >= 1.6 AND T1 < 3.6 GOTO 870
IF T1 >= 0.8 AND T1 < 3.6 GOTO 880
REM F function for tau < 0.6
FOR J = RER1 TO 100: JIAN = ABS(T11 - FT1(J, 1))
IF JIAN > 0.005 GOTO 769
RER7 = J: F(T) = FT1(J, 2): GOTO 910
NEXT J
REM F function for tau > 18.5
FOR J = RER2 TO 100: JIAN = ABS(T11 - FT6(J, 1))
IF JIAN > 0.2 GOTO 777
RER8 = J: F(T) = FT6(J, 2): GOTO 910
NEXT J
REM F function for tau 8.5 to 18.5
FOR J = RER3 TO 100: JIAN = ABS(T11 - FT5(J, 1))
IF JIAN > 0.1 GOTO 787
RER9 = J: F(T) = FT5(J, 2): GOTO 910
NEXT J
REM F function for tau 8.5 to 3.6
FOR J = RER4 TO 100: JIAN = ABS(T11 - FT4(J, 1))
IF JIAN > 0.05 GOTO 797
RER10 = J: F(T) = FT4(J, 2): GOTO 910
NEXT J
REM F function for tau 1.6 to 3.6
FOR J = RER5 TO 100: JIAN = ABS(T11 - FT3(J, 1))
IF JIAN > 0.02 GOTO 807
RER11 = J: F(T) = FT3(J, 2): GOTO 910
NEXT J
REM F function for tau 0.6 to 1.6
FOR J = RER8 TO 100: JIAN = ABS(T11 - FT2(J, 1))
IF JIAN > 0.01 GOTO 817
RER12 = J: F(T) = FT2(J, 2): GOTO 910
NEXT J
NNN = NNN + 1: PRINT LOOP; PRINT "-"; PRINT T,
PRINT "T="; PRINT USING "##.####"; T11; PRINT,
PRINT "F="; PRINT USING "##.####"; F1(T); PRINT,
IF T > PPP GOTO 944
PRINT "T(pulse) ="; PRINT USING "##.####"; T1; PRINT,
PRINT "F(pulse) ="; PRINT USING "##.####"; F(T): GOTO 945
PRINT
NEXT T
FOR I=1 TO 4:PRINT:NEXT I
IF LP1<>0 GOTO 975
DELAY=DDLY:DELAY1=DDLY1
GOSUB 11000:GOSUB 11230:GOTO 980
GOSUB 2100
REM CHANGE IRRATIONAL POINTS
BEEP:PRINT "Changes of irrational points? (y/n)"
COR$=INKEY$:IF COR$="" GOTO 1000
IF COR$="Y" OR COR$="y" GOTO 1050
IF COR$="N" OR COR$="n" GOTO 1330
IF COR$>"N" GOTO 1000
PRINT:PRINT "Change points in Frictional decay or in Pulse decay curve?"
PRINT:PRINT "Type F or P"
ANSWER$=INKEY$:IF ANSWER$="" GOTO 1070
IF ANSWER$="F" OR ANSWER$="f" GOTO 1120
IF ANSWER$="P" OR ANSWER$="p" GOTO 1220
IF ANSWER$>"P" GOTO 1070
PRINT:INPUT "Which point (right most point is #1) " ;FP:FP=1+(FP-1)*SSTP:PRINT
PRINT "Original value =" ;H(FP), " New value =" ;INPUT FCH
FOR I=1 TO NB STEP SSTP:IF I<>FP GOTO 1170
GG(I)=FCH:GOTO 1180
GG(I)=H(I)
NEXT I
IF LP1=1 THEN LP1=0
FOR I=1 TO NB STEP SSTP:H(I)=GG(I):NEXT I
HD=H(1):GOTO 970
PRINT:INPUT "Which point (right most point is #1) " ;FPP:FPP=1+(FPP-1)*SSTP:PRINT
PRINT "Original value =" ;HH(FPP), " New value =" ;INPUT FCHH
FOR I=1 TO NBB STEP SSTP:IF I<>FPP GOTO 1270
GG(I)=FCHH:GOTO 1280
GG(I)=HH(I)
NEXT I
IF LP1=1 THEN LP1=0
FOR I=1 TO NBB STEP SSTP:HH(I)=GG(I):NEXT I
HD=HC(1):GOTO 970
PRINT:DIFF=ICPT1-ICPT:HD=HC(1):HD1=H(1)
IF ABS(DIFF)<0.002 GOTO 1480 'Tolerance of two inf.times
IF LOOP=0 GOTO 1355
FD=F(1)*SLOPE1+ICPT1
FD1=F1(1)*SLOPE1+ICPT1:GOTO 1360
IF DDLY<0 THEN DDY=0 ELSE DDY=DDLY
IF DDLY1<0 THEN DDY1=0 ELSE DDY1=DDLY1
FD=F(1+DDY)*SLOPE1+ICPT1
FD1=F1(1+DDY1)*SLOPE1+ICPT1:GOTO 1360
FDD = FD - HD: FDD1 = FDI - 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 * ALPHAI * K * F(T) * 0.000001) / (2 * 3.4 * A2 * PI * (HC(T) - ICPT))
1485 KKT = (QQ * ALPHAI * 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 "##.###"; SS
1520 K = 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$: IF CTNU$ = "Y" GOTO 1550
1560 IF CTNU$ = "N" GOTO 1590
1570 IF CTNU$ = "y" GOTO 1590
1580 IF CTNU$ = "n" GOTO 2090
1590 IF DIF < 0.02 GOTO 2080
1600 K = SS: CLOSE: BEEP: LOOP = LOOP + 1: GOTO 660
1610 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 = ";
1660 LPRINT USING "##.###"; SS,
1680 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;
1700 LPRINT:LPRINT SPC (15);"Q = ";Q;" (Jole/M)
1710 PRINT:PRINT SPC(15);"Infinite temp. ";PRINT USING "##.#####"; TOTAL:
1720 LPRINT:LPRINT SPC(15),"Infinite temp. ";LPRINT USING "##.###";
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 :";SIGICPT
1780 LPRINT:LPRINT SPC(15);
1785 PRINT"Standard deviation of K fitting :";SIGICPT
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
1835 USING "+###.####": DIFF
1840 LPRINT:LPRINT SPC(15);"LOOP ",:LOOP,: LPRINT "Ifn. temp. diff. ":
1845 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);
1874 FOR I=1 TO 8:LPRINT:NEXT I
1880 BEEP:BEEP:PRINT "Store F(A,T) on disk (y/n)"
1890 REC$=INKEY$:IF REC$="" GOTO 1900
1900 IF REC$="Y" OR REC$="y" GOTO 2070
1910 IF REC$="N" OR REC$="n" GOTO 1950
1920 IF REC$<>"N" GOTO 1900
PRINT: LINE INPUT "File name for F(A,T) of pulse decay : "; FFF$: PRINT: FFF$ = "B:" + FFF$

CLOSE: OPEN "O", #2, FFF$: CLOSE: OPEN "A", #2, FFF$

FOR I = 1 TO RR STEP SSTP: PRINT #2, F(I): NEXT I
PRINT: LINE INPUT "File name for F(A,T) of frictional heat decay : "; FRC$: PRINT: FRC$ = "B:" + FRC$

CLOSE: OPEN "O", #1, FRC$: CLOSE: OPEN "A", #1, FRC$
FOR I = 1 TO RR STEP SSTP: PRINT #1, F(I): NEXT I
PRINT: LINE INPUT "File name for Temp. of pulse decay : "; TTT$: PRINT: TTT$ = "B:" + TTT$

CLOSE: OPEN "O", #2, TTT$: CLOSE: OPEN "A", #2, TTT$
FOR I = 1 TO NBB STEP SSTP: PRINT #2, H(I): NEXT I
PRINT: LINE INPUT "File name for Temp. of frictional heat decay : "; TRC$: PRINT: TRC$ = "B:" + TRC$

CLOSE: OPEN "O", #1, TRC$: CLOSE: OPEN "A", #1, TRC$
FOR I = 1 TO NBB STEP SSTP: PRINT #1, H(I): NEXT I
GOTO 2920
IF ABS(DIFF) < 0.005 GOTO 1620 ELSE GOTO 1610

REM SUBROUTINE OF LEAST SQUARE FITTING
SCREEN 100: SCREEN 105: KEY OFF: CLS 'Change if use IBM PC
SCAL = 0: FOR I = 1 TO NB: SCAL = SCAL + H(I): NEXT I
SCAL = (SCAL/NB)*300 + 175 'Auto adjust on screen
LINE (60, 300) - (580, 300) : LINE (60, 30) - (80, 300)
FOR I = 1 TO NB STEP SSTP
X(I) = F(I)*1000 + 60: Y(I) = SCAL - H(I)*300
CIRCLE (X(I), Y(I)), 0.5: NEXT I , Display frictional decay
SSX = 0: SSY = 0: SX = 0: SY = 0: SXY = 0: SIG = 0: NBN = 0
FOR I = 1 TO NB STEP SSTP
NBN = NBN + 1
SSX = SSX + F(I)^2: SSY = SSY + H(I)^2
SX = SX + F(I): SY = SY + H(I): SXY = SXY + F(I)*H(I): NEXT I
ASSX = SSX/NBN: ASSY = SSY/NBN: ASX = SX/NBN: ASY = SY/NBN: ASXY = SXY/NBN
SIGX = ASSX - (ASX*ASY): SIG = ASSY - ASX*ASY
SLOPE = (ASXY - ASX*ASY)/SIGX 'Slope of frictional decay
ICPT = ASY - (SLOPE*ASX) 'Temp. at infinite time
FOR I = 1 TO NB STEP SSTP: LSUMM = SLOPE*F(I) + ICPT*H(I): SIG = SIG + SLOM*SUMM: NEXT I
SIGCPT = SIG*ASSX/SIGX: SIGCPT = SQR(SIGCPT)
IF F(I) > 0.55 GOTO 2340
LL = X(I) + 20: GOTO 2350
LL = X(2) + 20
LINE(60, SCAL - 300 + ICPT) - (LL, SCAL - 300 - (LL - 60) * SLOPE / 1000 + ICPT))
FOR I = 1 TO 4: PRINT: NEXT I
FOR I = 1 TO NBB STEP SSTP
HC(I) = HH(I) - F(I + 1)*SLOPE
X(l) = F(I) * 1000 + 60; Y(I) = SCAL - HC(I) * 300

CIRCLE (X(l), Y(l)), 1.5: NEXT I 'heat pulse fitting

SSX = 0; SSY = 0; SX = 0; SY = 0; SXY = 0; SIG = 0; NBBN = 0

FOR I = 1 TO NBB STEP SSTP
  SSX = SSX + F(I)^2; SSY = SSY + HC(I)^2
  NBBN = NBBN + 1
END

SX = SX + F(I); SY = SY + HC(I)

ASSX = SSX / NBBN; ASSY = SSY / NBBN

ASX = SX / NBBN; ASY = SY / NBBN; ASXY = SXY / NBBN

SIGX = ASSX - ASX^2; SIGY = ASSY - ASY^2

ICPT1 = ASY - SLOPE1 * ASX 'Inf. temp. of pulse decay

FOR I = 1 TO NBB STEP SSTP
  SUMM = SLOPE1 * F(I) + ICPT - HC(I)
END

SIG = SIG + SUMM^2: NEXT I

SIG = SIG / NBBN^2: SIGSLOPE1 = SIG / SIGX

SIGICPT1 = SIG * ASSX / SIGX

SIGJCPT1 = SQR(SIGICPT1)

IF F(I) > 0.55 GOTO 2560

LL = X(1) + 20: GOTO 2570

LINE(60, SCAL - 300 * ICPT1) - (LL, SCAL - 300 * (LL - 60) * SLOPE1 / 1000 + ICPT1)

FOR I = 1 TO 17: PRINT: NEXT I

PRINT SPC(40); "Channel:"; TN" Reference "; PRINT TRR

PRINT SPC(40); "Channel:"; TN" Temp. (frc)";

PRINT USING "##-####"; JCPT

PRINT SPC(40); "Channel:"; TN" Temp. (pis)";

PRINT USING "##-####"; ICPT1: PRINT: TOTAL = ICPT

LOOP1 = LOOP1 + 1

IF LOOP2 <> 0 GOTO 2710

BEEP: BEEP: PRINT: PRINT "Change of the delay times ? (present delay = 0) (y/n)"; PRINT

CHG$ = INKEY$: IF CHG$ = "" GOTO 2670

IF CHG$ = "Y" OR CHG$ = "y" GOTO 630

IF CHG$ = "N" OR CHG$ = "n" GOTO 2860

IF CHG$ <> "N" GOTO 2670

RETURN

REM SUBROUTIN OF FINDING DATA POINTS

FOR I = 1 TO 119

KIK = I - PP: IF I < PP GOTO 2780

H(KIK) = H1(I) 'Temp. of frictional decay

IF KIK <> 1 GOTO 2780

HD1 = H(KIK)

NEXT I

FOR I = 1 TO 119

KIK = I - PPP: IF I < PPP GOTO 2840
HH(KIK) = Hl(I)  "Temp. of pulse decay"

IF KIK <> 1 GOTO 2840

HD = HH(KIK)

NEXT I

FOR I = 1 TO 119: HC(I) = HH(I): NEXT I

RETURN

LOOP2 = 1: GOTO 2710

IF FDD > 0 AND FDD1 < 0 GOTO 2890

GOTO 1420

BEEP: BEEP: BEEP: PRINT: PRINT "Do not converge!"

PRINT "Change initiate points!": PRINT

IF LOOP2 = 1 THEN LOOP2 = 0

GOTO 550

CLS: GOSUB 9020: PRINT: PRINT "Another channel ? (y/n)"

CTU$ = INKEY$: IF CTU$ = "" GOTO 2930

IF CTU$ = "Y" OR CTU$ = "y" GOTO 200

IF CTU$ = "N" OR CTU$ = "n" GOTO 20

IF CTU$ <> "N" GOTO 2930

REM ROUTINE OF FAST GRADIENT ESTIMATE

DIM X(14), Y(14): M = 14

DIM J(120), W(120), L(14), H(14), HEAT(1665), H1(120)

CLOSE: CLS: GOSUB 9020: PRINT SPC(10); "Thermal gradient calculation and ploting": FOR I = 1 TO 5: PRINT: NEXT I: PRINT SPC(10); "Mount disk on drive B": PRINT SPC(10); "Press any key to continue"

KK$ = INKEY$: IF KK$ = "" GOTO 3020

CLS: BEEP: FILES "B:" FOR I = 1 TO 4: PRINT

MEXT I: PRINT SPC(10); ",NW$

LINE INPUT "Which data file ?: "; NW$

NW$ = "B:" + NW$

BEEP: PRINT: LINE INPUT "Name of new data file: "; G$

G$ = "B:" + G$

PRINT: BEEP: INPUT " Probe length (in meter) "; LENC

IF LENC = 0 THEN LENC = 7.5

BEEP: BEEP: PRINT "Printer ready ?": PRINT SPC(8);: LINE INPUT "Heading of the print : "; PG$: IF PG$ = "" THEN PG$ = NW$

LPRINT "Thermal gradient of "; PG$: LPRINT: LPRINT

PRINT "Is "; NW$; " a Random file or a Serial file ? (type R or S)"

RS$ = INKEY$: IF RS$ = "" GOTO 3072

IF RS$ = "R" OR RS$ = "r" GOTO 3077

IF RS$ = "S" OR RS$ = "s" GOTO 3079

IF RS$ <> "S" GOTO 3072

PRINT: PRINT "Loading from random file ";

PRINT NW$; "...": GOTO 3090

PRINT: PRINT "Loading from serial file ";

PRINT NW$; "...": GOTO 5900

OPEN "O", #2, G$: CLOSE: GOSUB 5500

OPEN "R", #1, NW$
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 AS A D10$,8 AS D11$,8 AS D12$,8 AS D13$,8 AS D14$

AVRG=0: FOR I=1 TO 80: GET #1,1: J(I)=CVS(D1$): AVRG=AVRG+J(I): NEXT I

AVRG=AVRG/80: AVRG=(5811.403/(LOG(AVRG)+5.493939))-342.7457: Q = AVRG/0.2-1

FOR I=1 TO 80: J(I)=5811.403/(LOG(J(I))+5.493939})-3.42.7457 'Simulate R-T relation of thermistor

J(I)=234 + Q*$24-120*J(I): NEXT I

FOR I=1 TO 79: X1=70+(1-1)*6

X2=X1+6: Y1=J(I): Y2=J(I+1)

LINE (X1,Y1)-(X2,Y2): NEXT I

BEEP:BEEP:BEEP: INPUT"Which point for tem. reference "; TR: IF TR=0 THEN TR=1

XX1=70+(TR-1)*6: YY1=J(TR)

CIRCLE (XX1,YY1),3:CIRCLE (XX1,YY1),6

BEEP:INPUT"Which point for gradient calculation ";F

XX1=70+(F-1)*6: YY1=J(F): CIRCLE (XX1,YY1), 6: LINE (XX1,YY1-3)-(XX1,YY1)+3

BEEP:PRINT"Are these points acceptable? (y/n)"

GGP$=INKEY$: IF GGP$="" GOTO 3343

IF GGP$="Y" OR GGP$="y" GOTO 3350

IF GGP$="N" OR GGP$="n" GOTO 3347

IF GGP$<>"N" GOTO 3343

CLS: GOSUB 5500: GOTO 3343

OPEN "A",#2,G$

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 AS A D10$,8 AS D11$,8 AS D12$,8 AS D13$,8 AS D14$

FOR K=1 TO 14: FOR I=1 TO 80

IF I<>TR THEN 3570

GET #1,1: GOSUB 5000

NEXT I: H(K)=J(TR): NEXT K

FOR K=1 TO 14: FOR I=1 TO 80

IF I>F(K) THEN 3840

IF I<>TR THEN 3570

GOSUB 5000

L(K)=J(I): D=H(K)-H(1): L(K)=L(K)-D PRINT #2, L(K)

NEXT I

NEXT K

MIN=L(1): FOR I=1 TO 14: PS=L(I)-MIN: IF PS>0 GOTO 3845

MIN=L(I)

NEXT I

NEXT K

CLS: PRINT: PRINT: FOR I=14 TO 1 STEP -1

IF I=1 THEN 3890

IF I<>14 THEN 3900

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

KKK$ = INKEY$: IF KKK$ = " " THEN 4000
FOR I = 1 TO 14: X(I) = 300 * L(I) - 250: Y(I) = 15 * (14 - I): NEXT I
MAX = X(I): IF MAX < 0 GOTO 4040
FOR I = 1 TO 14: DS = X(I) - MAX: IF DS < 0 GOTO 4034
MAX = X(I): II = I: MXX = X(I) - 500
FOR I = 1 TO 14: X(I) = X(I) - MXX: NEXT I
GOSUB 5700
FOR I = 1 TO M
CIRCLE (X(I) + 100, 50 + Y(I)), 4, 1: NEXT I
FOR I = 1 TO M
LINE (X(I) + 98, 50 + Y(I)) - (X(I) + 102, 50 + Y(I))
LINE (X(I) + 100, 48 + Y(I)) - (X(I) + 100, 52 + Y(I)): NEXT I
BEEP: PRINT " How many points are in calculation " : X
FOR I = 1 TO N: X(I) = 300 * L(I) - L(N)): Y(I) = 15 * (N - 1): NEXT I
SXX = 0: SYY = 0: SX = 0: SY = 0: SXY = 0: SIG = 0
FOR I = 1 TO N
SSX = SXX + X(I)^2: SYY = SYY + Y(I)^2: SX = SX + X(I)
SY = SY + Y(I): SXY = SXY + X(I) * Y(I)
NEXT I
ASSX = SSX / N: ASSY = SYY / N
ASX = SX / N: ASY = SY / N: ASXY = SXY / N
SIGX = ASSX - ASX^2: SIGY = ASSY - ASY^2
SLOPE = (ASXY - ASX * ASY) / SIGX
ICPT = ASY - SLOPE * ASX
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 I
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 ELSE
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);"O"
4630 PRINT SPC(62);"Temp."
4640 FOR I=1 TO 12:PRINT:NEXT I
4670 PRINT SPC(30);"Geothermal gradient: ";
4680 LPRINT:LPRT:LPRT:"Geothermal gradient ";LPRINT USING "###.####";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
4740 PRINT "+/-" ;PRINT USING "##.####";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 SS=INKEY$;IF SS="" GOTO 4750
4770 CLS:PRINT:PRINT"Continue with gradient estimation ? (y/n)"
4780 GRD$=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+HI(I):NEXT:AVRG=AVRG/79
4910 Q=AVRG/0.2-1:FOR I=1 TO 79:J(I)=234+Q*24+HI(I)*120:NEXT
4920 FOR I=1 TO 78:X(1)=70+(I-1)*6:X2=X1+6:Y1=Y(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 AS 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, 5260, 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 = 288
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
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$;:PRINT "TIME ":PRINT
5630 RETURN
5700 CLS:SCREEN 100:SCREEN 105:LINE (100,50)-(559,50)
5720 FOR I=0 TO 420 STEP 15:LINE(115+I,148)-(115+I,50):NEXT I
5740 FOR I=0 TO 375 STEP 75:LINE(175+I,146)-(175+I,50):NEXT I
5760 FOR I=0 TO 300 STEP 150:LINE(250+I,144)-(250+I,50):NEXT I
5770 LINE (100,50)-(100,275)
5790 FOR I=0 TO 180 STEP 30:LINE (98,I+1)-(100,I+1):NEXT I
5800 RETURN
5900 OPEN "O",#2,G$: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(X:X1,YY1-3)-(XX1,YY1+3):
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 ".",#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 processed?"
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$(82,#1)
6270 PRINT "Name the new data file ":PRINT:PRINT
6280 PRINT:PRINT:PRINT "Press any key to continue"
6290 MNM$=INKEY$:IF MM$="" 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$="0123456789ABCDEF"
6350 FOR H=1 TO 120:FOR K=1 TO 17
6360 A$=INPUT$(5,#1):X=0
6370 FOR I=1 TO 5 'Hex to decimal conversion
6380 IF I=5 GOTO 6490
6390 B$=MID$(A$,I,1)
6400 FOR J=1 TO 16:D$=MID$(C$,J,1)
6410 IF B$=D$ GOTO 6470
6420 NEXT J
6430 X=X+(J-1)*16^((4-I)
6440 NEXT I
6450 THR$(K,H)=X
6460 NEXT K
6470 A$=INPUT$(1,#1):PRINT H;:PRINT " ":NEXT H
6480 REM RESISTANCE CALCULATION
6490 REM Reference resistor = 10000 ohm
6500 FOR J=1 TO 120:FOR I=1 TO 17
6510 THR$(I,J)=THR$(I,J)/THR$(3,J)*10000
6520 OPEN "R",#,2,NW$
6530 FIELD #1,4 AS L$,8 AS T$,4 AS R$,8 AS D1$,8 AS D2$,8 AS D3$,8 AS D4$,8
6540 AS D5$,8 AS D6$,8 AS D7$,8 AS D8$,8 AS D9$,8 AS D10$,8 AS D11$,8 AS D12$,8 AS D13$,8 AS D14$
6550 FOR J=1 TO 80:FOR I=1 TO 17
6560 PRINT THR$(I,J)
6570 ON I GOTO 6690, 6700, 6710, 6720, 6730, 6740, 6750, 6760, 6770, 6780, 6790,
6800, 6810, 6820, 6830, 6840, 6850
6590 LSET I$=MK$(THR$(1,J)):GOTO 6870
6600 LSET J$=MK$(THR$(2,J)):GOTO 6870
6610 LSET R$=MK$(THR$(3,J)):GOTO 6870
6620 LSET D1$=MK$(THR$(4,J)):GOTO 6870
6630 LSET D2$=MK$(THR$(5,J)):GOTO 6870
6640 LSET D3$=MK$(THR$(6,J)):GOTO 6870
LSET DS=MKS$(THRM(7,J)):GOTO 6870
LSET DS=MKS$(THRM(8,J)):GOTO 6870
LSET DS=MKS$(THRM(9,J)):GOTO 6870
LSET DS=MKS$(THRM(10,J)):GOTO 6870
LSET DS=MKS$(THRM(11,J)):GOTO 6870
LSET DS=MKS$(THRM(12,J)):GOTO 6870
LSET DS=MKS$(THRM(13,J)):GOTO 6870
LSET DS=MKS$(THRM(14,J)):GOTO 6870
LSET DS=MKS$(THRM(15,J)):GOTO 6870
LSET DS=MKS$(THRM(16,J)):GOTO 6870
LSET DS=MKS$(THRM(17,J)):GOTO 6870
NEXT I
PUT #2,;NEXT J
FOR I=1 TO 3:BEEP:NEXT I
PRINT."Display Temp.-time relationship ? (y/n)"
F$=INKEY$:IF F$="" GOTO 6980
IF F$="Y" OR F$="y" GOTO 7040
IF F$="N" OR F$="n" GOTO 20
IF F$>">""N"" GOTO 6980
CLOSE:DIM B(120),J(120),S(120),L(14),H(14):CLS
PRINT."Temperature-Time relation display"
FOR I=1 TO 5:PRINT:NEXT I
PRINT."Which data file ?"
PRINT.PRINT.PRINT.RPR SC(22);
PRINT."Press any key to continue"
MMMS=INKEY$:IF MMMS="" GOTO 8100
CLS:BEepy:FILES "B":PRINT:PRINT:PRINT
LINE INPUT"Name the new file: ";OBJ$
OBJ$=" B:"+OBJ$
PRINT:"Store new (Serial) data file on disk ? (y/n)"
BNB$=INKEY$:IF BNB$="" GOTO 8140
IF BNB$="Y" OR BNB$="y" GOTO 8190
IF BNB$="N" OR BNB$="n" GOTO 8180
IF BNB$>">""N"" GOTO 8140
OPEN "O",#2,OBJ$:CLOSE:OPEN"A",#2,OBJ$
8250  GOSUB 5500
8390  OPEN "R",#1,N\\$
8400  FIELD #1,4 AS L4,8 AS T4,8 AS R4,8 AS D14,8 AS D24,8 AS D34,8 AS D44,8
   AS D54,8 AS D64,8 AS D74,8 AS D84,8 AS D94,8 AS D104,8 AS D114,8 AS D124,8
   AS D134,8 AS D144
8410  AVRG=0:FOR I=1 TO 120:GET #1,1
8412  B(I)=CVS(D14):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
8650  IF I<>RF THEN
8660  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<>I 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$:RETURN
9500  REM ROUTINE OF INFINITE-TIME TEMP.
9510  DIM J1(200),J0(200),Y0(200),Y1(200),F(100), F1(100), X(40), Y(40), HEAT(1105),
   H1(80), H(80), J(80), S1(79)
9520  GOSUB 9020:CLS:PRINT:PRINT:PRINT:FLG=0
9525  PRINT SPC(15);"INFINITE-TIME TEMPERATURE"
9530  FOR I=1 TO 5:PRINT:NEXT I
9535  PRINT SPC(20);"Which data file?":PRINT
9540  PRINT:PRINT SPC(20);"Mount disk on drive B:";
9545  PRINT SPC(20);"Press any key to continue"
9550  PR$=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$;
PRINT " a random or a serial file? (type R or S)"
RS$=INKEY$:IF RS$="" GOTO 9580
IF RS$="R" OR RS$="r" GOTO 9620
IF RS$="S" OR RS$="s" GOTO 9630
IF RS$<>"S" GOTO 9580
GOSUB 5200:FLG=1:GOTO 9632
GOSUB 10390
GOSUB 4900
GOSUB 4900
BEEP:INPUT"Temp. reference point ";TRR
IF TRR=0 THEN TRR=1:XX1=70+(TRR-1)*6:YY1=234+Q*24-120 + H1(TRR): CIRCLE (XX1, YY1), 3: CIRCLE (XX1, YY1), 5
PRINT "Is it acceptable? (y/n)"; BEEP
DD$=INKEY$:IF DD$="" GOTO 9636
IF DD$="Y" OR DD$="y" GOTO 9640
IF DD$="N" OR DD$="n" GOTO 9632
IF DD$<>"N" GOTO 9636
CLOSE:OPEN "R",#1,DA$
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 AS D10$,8 AS D11$,8 AS D12$,8 AS D13$,8 AS D14$
FOR S=1 TO TRR:GET #1,S:S1(S)=CVS(D1$): NEXT S: RRF=5811.403/(LOG(S1(TRR))+5.493939)-342.7457
RRF=RRF-H1(TRR):FOR I=1 TO 79:H1(I)=RRF: NEXT I
GOSUB 4900
BEEP:INPUT"Penetration at point ";PP
INPUT"How many points";NB:GOSUB 10460:BEEP
INPUT "Process data for every N'th point "; SSTP:IF SSTP=0 THEN SSTP=1
XX1=70+(PP-1)*6:YY1=234+Q*24-120 + H1(PP): XX2=70 + (PP-1+NB)*6:YY2 = 234+Q*24-120* H1(PP+NB)
CIRCLE (XX1,YY1),6:LINE(XX1,YY1-3)-(XX1, YY1+3): LINE (XX1-4, YY1)-(XX1+4, YY1): CIRCLE (XX2, YY2), 3: CIRCLE (XX2, YY2),5
FOR I=1 TO 18:PRINT:NEXT I:PRINT "Are these acceptable? (y/n)"; BEEP
POT$=INKEY$:IF POT$="" GOTO 9654
IF POT$="Y" OR POT$="y" GOTO 9660
IF POT$="N" OR POT$="n" GOTO 9644
IF POT$<>"N" GOTO 9654
INPUT"Delay (~*15 sec., input N)= ";DELAY1
DELAY1=ABS(DELAY1)
BEEP:PRINT"Conductivity = 0.8 ? (y/n)"
POT$=INKEY$:IF POT$="" GOTO 9680
IF POT$="Y" OR POT$="y" GOTO 9720
IF POT$="N" OR POT$="n" GOTO 9740
IF POT$<>"N" GOTO 9680
CLOSE:OPEN "I",#1,"F0.8" OPEN "I",#2,"J1.DAT" OPEN "I",#3,"Y0.DAT" OPEN "I",#4,"Y1.DAT"
FOR I=1 TO 80:INPUT #1,F1(I)NEXT I
CLOSE:K=0.8:GOTO 10025
PRINT "; ;INPUT"K = ";K
CLOSE:OPEN"I",#1,"J0.DAT":OPEN"I",#2,"J1.DAT"
OPEN "I",#3,"Y0.DAT":OPEN"I",#4,"Y1.DAT"
FOR U=1 TO 110
INPUT #1,JO(U):INPUT #2,J1(U)
INPUT #3,YO(U):INPUT #4,Y1(U)
NEXT U 'Input bessel data
K1=(K/(5.79-3.67*K+1.016*K^2))*0.000001
ALPHA=2*(5.79-3.67*K+1.016*K*K)/3.116
PRINT PRINT "Delay = ";
PRINT USING "+##.###";DELAY1*15;
PRINT " (Sec.)"
TAU=0.00472^2/K1:NNN=0;PI=3.141593
E=2.718282:A2=0.004725^2:PI2=PI^2
PRINT"Time constant= ";PRINT USING"###.#";TAU
PRINT " (Sec.)":PRINT
FOR T=1 TO NB+DELAY1
T11=(T*15*K)/A2
SUM1=0
FOR U=0 TO 10 STEP 0.1 ' Calculation
UA=U*10+1
AA=U*JO(UA)-ALPHA*J1(UA)
BB=U*YO(UA)-ALPHA*Y1(UA)
S=AA^2+BB^2
W=U:IF U=0 THEN W=0.000048
S=S*W
Gl=(-1)*T11*U^U:IF Gl<-88 THEN Gl=-88
V1=E^Gl*DU
SUM1=SUM1+V1/S
NEXT U-
F1(T)=(4*ALPHA/PI2)*SUM1
NNN=NNN+1:PRINT NNN
PRINT"T=";PRINT USING"##.####";T11
PRINT T=";PRINT USING"##.####";F1(T)
NEXT T
FOR I=1 TO 4:PRINT:NEXT I
GOSUB 11010
FOR I=1 TO 17:PRINT:NEXT I
PRINT SPC(40);"Channel: ..T";TN;" Temp.(frc)";PRINT USING "###.###";ICPT
PRINT PRINT PRINT PRINT "Printer ready ? Press any key to continue ":
BEEP: BEEP: BEEP
ITT$=INKEY$:IF ITT$="" GOTO 10263
LPRINT DA$;LPRINT"
LPRINT DATE$;LPRINT:LPRT
LPRINT "Channel: ..T";TN;" Infinite-time temp.(frc)"
LPRINT USING"###.###";ICPT
LPRINT:LPRINT" Penetration point: ..PP;"
LPRINT " ..NB;" points"
LPRINT" Estimated conductivity: ..K,"
LPRINT" Delay time: ..DELAY1*15;" Sec."
LPRINT" Temp. reference point: ";TRR
FOR I=1 TO 8:LPRINT:NEXT I
BEEP:BEEP:BEEP
PRINT:PRINT"Store F(A,T) on disk? (y/n)"
POT$=INKEY$:IF POT$="" GOTO 10310
IF POT$="Y" OR POT$="y" GOTO 10375
IF POT$="N" OR POT$="n" GOTO 10350
IF POT$<" >""N" GOTO 10310
PRINT:LINE INPUT "File name for F(A,T) of frictional heat decay: ";FRC$:
PRINT: FRC$= "B:"+FRCS
CLOSE:OPEN"O",#1,FRC$;CLOSE:OPEN"A"#1,FRC$
FOR I=1 TO NB+DELAY1
PRINT #1,F1(I+DELAY1):NEXT I
CLS:GOSUB 9020:PRINT:PRINT:PRINT
PRINT SPC(25);"Continue? (y/n)"
POT$=INKEY$:IF POT$="" GOTO 10381
IF POT$="Y" OR POT$="y" GOTO 9520
IF POT$="N" OR POT$="n" GOTO 20
IF POT$<" >""N" GOTO 10381
CLOSE:OPEN "I",#1,DAS
IF TN=14 THEN FITT=1105 ELSE FITT=TN*79
FOR I=1 TO FITT:INPUT #1,HEAT(1):NEXT I
FOR I=1 TO 79:KK=(TN-1)*79+1
H1(I)=HEAT(KK):NEXT I:GOTO 10460
FOR I=1 TO 79:KK=(TN-1)*79+1
H1(I)=HEAT(KK):NEXT I
RETURN
KIK=I-PP:IF I<PP GOTO 10490
H(KIK)=H1(I)
NEXT I:RETURN
REM SUBROUTINE OF LEAST SQUARE FITTING
IF DDLY<0 THEN DELAY=0
IF DDLY1<0 THEN DELAY1=0
SCREEN 100:SCREEN 105:KEY OFF:CLS
SCAL=0:FOR I=1 TO NB:SCAL=SCAL+HEAT(I):NEXT I
SCAL=(SCAL/NB)*300+175 'auto adjusting screen
LINE (60,300)-(580,300)
LINE (60,30)-{ e0, 300)
FOR I=1 TO .-B STEP SSTP
X(I)=F1(I+DEL1)*1000+60:Y(I)=SCAL+HEAT(I)*300
CIRCLE (X(I),Y(I)),0.5:NEXT I
FOR I=1 TO NB STEP SSTP
SSX=0:SSY=0:SX=0:SY=0:SXY=0:SIG=0:NBN=0
LINE (60,300)-(580,300)
LINE (60,30)-(60,300)
FOR I=1 TO NB STEP SSTP
X(I)=F1(I+DEL1)*1000+60:Y(I)=SCAL+HEAT(I)*300
CIRCLE (X(I),Y(I)),0.5:NEXT I
SSX=SSX+F1(I+DEL1)*2:SSY=SSY+HEAT(I)*2
SX=SX+F1(I+DEL1):SY=SY+HEAT(I)
SXY=SXY+F1(I+DEL1)*HEAT(I):NEXT I
11120 ASSX=SSX/NBN:ASSY=SSY/NBN
11125 ASX=SSX/NBN:ASY=SSY/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*F(I+DELAY)+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 F(I+DELAY)>0.55 GOTO 11210
11200 LL=X(I)+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:ASSY=SSY/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(I+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
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:K=K+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
IF POTS<>"N" GOTO 15320
PRINT:PRINT:PRINT"Which point # ";INPUT K
PRINT:PRINT:PRINT"The old value: ";
PRINT "X= ";XX(K);" Y= ";YY(K)
INPUT "New value of X.Y ";XW,YW
PRINT "K";K
FOR I=1 TO N
IF I=K GOTO 15430
XX(I)=HX(I):YY(I)=HY(I):GOTO 15440
XX(K)=XW:YY(K)=YW
NEXT I
PRINT:PRINT:PRINT"X : ";FOR M=I TO N:PRINT XX(M);NEXT M:PRINT:PRINT"Y: ";FOR M=I TO N:PRINT YY(M);NEXT M
GOTO 15130
FOR I=1 TO N:X(I)=300•XX(I):Y(I)=30•Y'r'(I);NEXT
MAX=X(1):FOR I=1 TO N:DS=X(I)-MAX
IF DS<0 GOTO 15500
MAX=X(I):MXX=X(I)-500
NEXT I
IF MAX<500 GOTO 15530
FOR I=1 TO N:X(I)=X(I)-MXX:NEXT
MIN=X(1):FOR I=1 TO N:DS=X(I)-MIN
IF DS>0 GOTO 15550
MIN=X(I):MMIN=200-X(I)
NEXT I
IF MIN>100 GOTO 15580
FOR I=1 TO N:X(I)=X(I)+MMIN:NEXT 1
CLS:GOSUB 5700:FOR I=1 TO N:CIRCLE(100+X(I),50+Y(I)),4,1:NEXT
FOR I=1 TO N:LINE(X(I)+98,50+Y(I))-(X(I)+102,50+Y(I))
LINE(X(I)+100,48+Y(I))-(X(I)+100,52+Y(I))
NEXT I
PRINT "How many point are valid ?"
INPUT "N= ";N
FOR I=1 TO N:X(I)=300*(XX(I)-XX(N));Y(I)=30•Y'r'(I)-Y(N);NEXT
Y(I)=30•Y(I)-YY(N);:NEXT 1
CLS:GOSUB 5700:FOR I=1 TO N:CIRCLE(100+X(I),50+Y(I)),4,1:NEXT 1
FOR I=1 TO N:
LINE(X(I)+98,50+Y(I))-(X(I)+102,50+Y(I))
LINE(X(I)+100,48+Y(I))-(X(I)+100,52+Y(I))
NEXT I
NEXT I
SSX=0:SSY=0:SSX=0:SY=0:SXY=0:SIG=0
FOR I=1 TO N:SSX=SSX+X(I)*2
SSY=SSY+Y(I)*2:SSX=SSX+X(I)
SSY=SSY+Y(I):SXY=SXY+X(I)*Y(I)
NEXT I:ASSX=SSX/N:ASSY=SSY/N
ASX=SX/N:ASY=SY/N:ASXY=SXY/N
SIGX=ASSX-ASX*2:SIGY=ASSY-ASY*2
SLOPE=(ASXY-ASX*ASY)/SIGX
REM CALCULATE SLOPE AND intercept
ICPT=ASY-SLOPE*ASX
FOR I=1 TO N
SUM=SLOPE*X(I)+ICPT-Y(I)
SIG=SIG+SUM^2:NEXT I
SIG=SIG/N*N:SIGSLP=SIG/SIGX
SIGSLP=SQR(SIGSLP)
SIGICPT=SIG*ASSX/SIGX
SIGICPT=SQR(SIGICPT):L=0
FOR I=1 TO N
IF X(I)>0 THEN 15980 ELSE 15990
L=X(I)
NEXT I
L=L+110:G=0.1/SLOPE
LINE(100,50+ICPT)-(L,L-100)*SLOPE+50+ICPT
PRINT SPC(18);"Least-square-fitting of gradient"
PRINT:PRINT:PRINT SPC(11);"0"
PRINT SPC(62);"TEMP."
FOR I=1 TO 13:PRINT:NEXT I
PRINT SPC(30);"Geothermal gradient;";
PRINT USING "##.####";G:PRINT"(K/M)"
PRINT SPC(9);"(M)":PRINT:PRINT SPC(9);"Depth"
PRINT SPC(20);"Pinter ready? ";
PRINT "Press any key to continue":gosub 9000
S$=INKEY$:IF S$="" GOTO 16120
CLS:PRINT:LINE INPUT"Heading of the print:";HED$
LPRINT "Geothermal gradient: ";HED$;
LPRINT ",";DATE$:LPRINT:LPRINT:LPRINT
LPRINT "Temp. ";FOR I=1 TO N
LPRINT "(";i;")";XX(I):NEXT I:LPRINT
LPRINT "Depth: ";FOR I=1 TO N
LPRINT "(";i;")";YY(I):NEXT I:LPRINT
LPRINT "Gradient: ";
LPRINT USING "##.####";G*1000:LPRINT "MK/M"
FOR I=1 TO 8:LPRINT:NEXT I
BEEP:CLS:PRINT:PRINT SPC(19);
PRINT "Continue with gradient? (y/n)"
POT$=INKEY$:IF POT$="" GOTO 16140
IF POT$="Y" OR POT$="y" GOTO 15020
IF POT$="N" OR POT$="n" GOTO 20
IF POT$<>"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 0.94980,1.00410,2.86090,3.81990,4.78110
131 DATA 5.74440,6.70600,7.67660,8.64530,9.61580
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
140 INPUT "The trial maximum C = ";CMAX
150 INPUT "The trial minimum C = ";CMIN
160 C = CMIN: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 = I / (T(I) + C) + L
280 M = (T(I) + C)^2 - 2 + M: K = (T(I) + C)^2 - 3 + K
300 P = (RI(I)^2(1 / (T(I) + C))^2) + P
310 Q = (RI(I)^2((T(I) + C)^2 - 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 = I / (T(I) + C) + L
430 M = (T(I) + C)^2 - 2 + M: K = (T(I) + C)^2 - 3 + K
440 P = (RI(I)^2(1 / (T(I) + C))^2) + P
450 Q = (RI(I)^2((T(I) + C)^2 - 2)) + Q: NEXT I
460 B = (Q - RA * M) / (K - (L * M) / N): A = RA - ((B * L) / N)
A=';A,"B="B,"C="C
PRINTER:PRINTER:PRINT "Printer ready! press any key to continue"
FF$=INKEY$:IF FF$="" GOTO 530
PRINTER:PRINTER:PRINTER "Thermistor T-R relationship";
PRINTER:PRINTER:PRINTER "Number of points: ";N:PRINTER
PRINTER:PRINTER:PRINTER "Least square error : ";V
PRINTER:PRINTER:PRINT "Want to display! {y/n}" 
FF$=INKEY$:IF FF$="" GOTO 580
IF FF$="Y" OR FF$="y" GOTO 640
IF FF$="N" OR FF$="n" GOTO 630
IF FF$<>"N" GOTO 580
GOTO 1680
CLS:SCREEN 100:SCREEN 105:KEY OFF
LINE (0,0)-(649,340),1,B
LINE(50,50)-(50,300):LINE(50,300)-(580,300)
FOR I=1 TO 50
LINE(50+I*10,298)-(50+I*10,302)
IF I>=10 THEN 830
LINE(50+I*50,297)-(50+I*50,304)
IF I>5 THEN 830
LINE(50+I*100,296)-(50+I*100,306)
NEXT I
PRINT SPC(15);"Least square fitting of temp.-resist."
FOR I=1 TO 20:PRINT:NEXT I
PRINT SPC(70);"T (C)"
FOR I=1 TO N;R=50+T(I)*10;H=D(I)
J=328-H/300:CIRCLE(R,J),3:NEXT I
FOR I=1 TO 48;X(I)=50+I*10
Y=2.718282^((A+(B/(I+C)))
Z(I)=328-Y/300:NEXT I
FOR I=1 TO 48
LINE(X(I-1),Z(I-1))-(X(I),Z(I)):NEXT I
PRINT "Press any key to continue"
FF$=INKEY$:IF FF$="" GOTO 1040
GOTO 1270
FOR I=1 TO N;Y=(A+(B/T(I)+C))
Y=Y-R(I);Y=Y*Y;V=Y+V:NEXT I:RETURN
VMAX=V:C=CMIN:GOTO 250
VMIN=V:GOTO 370
CMAX=CMIN+(CMAX-CMIN)*0.618:C=CMAX
PRINT "New Cmax=";C,"Cmin=":GOTO 250
CMIN=CMIN+(CMAX-CMIN)*(1-0.618):C=CMAX
PRINT "New Cmin=";CMIN,"Cmax=";CMAX:GOTO 250
C=(CMAX+CMIN)/2:GOTO 410
CLS:SCREEN 100:SCREEN 105:KEY OFF
LINE(0,0)-(649,340),1,B
LINE(50,50)-(50,280):LINE(50,280)-(580,280)
FOR I=1 TO 17
1350 LINE(50+I*30,276)-(50+I*30,282)
1360 FOR W:=1 TO 10:W:=W-1
1380 LINE(50+WI*30+W*3.278)-(50+WI*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)
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

\[ T = 1 - \frac{2}{\sqrt{\pi}} \int_0^z e^{-\xi^2} d\xi \]

\[ = 1 - \text{erf} \left( \frac{z}{2\sqrt{kt}} \right) \]  \hspace{1cm} (F.1)

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

\[ T = 1, \quad \text{for } z = 0, \ t > 0 \]

\[ T = 0, \quad \text{for } z > 0, \ t = 0. \]

We notice that for a small value of \( x \), the error function \( \text{erf} (x) \) can be approximated by \( \text{erf} (x) \approx \frac{2x}{\sqrt{\pi}} \). 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 $\Delta T$ in a solution of the form

$$T = T_0 + qz - \Delta T$$

where $\Delta T$ 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:

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

where $\delta T$ is the amplitude of the temperature change.

The corrected thermal gradient at the sediment surface is then:

$$q_0 = \left[ \frac{\partial T}{\partial z} \right]_{z=0} = q + \delta T \left[ \frac{1}{\sqrt{\pi kt_1}} - \frac{1}{\sqrt{\pi kt_2}} \right]$$