TERRESTRIAL HEAT FLOW
IN THE ST. LAWRENCE LOWLAND OF QUEBEC

by

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TABLE OF CONTENTS

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ABSTRACT

It was proposed to make an investigation of the terrestrial heat flow in the area about Montreal using boreholes drilled to explore for gas or oil. A fairly satisfactory D.C. thermistor bridge method of measuring temperatures at depth has been developed and three boreholes have been surveyed.

Cores from many of the holes in the area were available, and a divided-bar type of thermal conductivity apparatus was made for measuring their conductivities.

Preliminary results indicate a heat flow of about 0.8 microcalorie per square centimetre per second.

INTRODUCTION

The work described in this thesis was wholly financed by a grant from the Geological Survey of Canada held by Dr. T. H. Clark and Dr. V. A. Saull. This grant was made available in August 1958 when work was begun on the project. All the known boreholes in the area were visited, and sketches were prepared for a mercury thermometer probe and a thermister probe, both to be made in the college workshop.

Some preliminary work was done with mercury-in-glass thermometers, but with a continuing programme of field work in prospect, it was intended to develop a reliable electrical method of measuring both temperatures and temperature gradients at depth with a single probe. For a number of reasons this turned out to be a longer and more difficult job than was at first expected.

Some of the difficulties which arose could have been anticipated, especially those met in the operation of the complete apparatus in its original form. Other difficulties, such as non-availability of materials, were unavoidable, as were also those which turned up in the field due to bad weather, caving of holes and so on. However, some useful experience for future work was acquired.

Because of difficulties in developing the electrical equipment and delay in delivery of a suitable co-axial cable, little directly useful field work was done until the spring and summer of 1960, when two very successful surveys were made by Dr. Saull and the author in two boreholes near Lanoraie (Cartier Natural Gas No. 5 and Leuman No. 1). However, a shallow water well in Roxboro was surveyed with a temporary (microphone) cable on the thermistor probe in the summer of 1959. This was of no real value for heat flow measurement, but the thermistor probe and the surface equipment worked really well for the first time.

The conductivity apparatus was first assembled in the summer of 1959, and shortly afterwards the author accepted permanent employment and was no longer available for full time work on the project. Work was continued by Dr. Saull, later assisted by Mr. R. Doig, who is presently doing an M.Sc. thesis on the project. The conductivity used to derive the heat flow value quoted in this thesis was determined by Mr. Doig with this apparatus. (1).

I <u>STANDARD METHODS FOR BOREHOLE TEMPERATURE MEASUREMENT</u>

For a continuing programme of temperature measurements electrical methods have many advantages, especially their potentially greater sensitivity, over the use of mercury-in-glass thermometers. In spite of the apparent simplicity of measuring a series of temperatures in a borehole with the latter, it requires considerable organization, skill, patience, and care to get reliable results; however, the equipment is light and simple, the essentials being a pressure-proof container for the thermometers and a means of lowering it to known depths in the hole. On the other hand, the thermometers have to be handled carefully and at the same time quickly, especially in hot weather, when also some means of cooling them and their container must be available. A more serious disadvantage, however, is that should a negative temperature gradient occur in the field, it could be recorded as less significant than it may in fact be, or even missed altogether, because the thermometers obviously have to traverse the upper parts of the hole in coming to the surface from below. Furthermore, since each measurement requires a trip down and up and the thermometers have to be cooled before each descent, a complete survey of a hole is a slow operation and causes thermal and mechanical disturbances in the hole; especially in small holes, readings may not be reproducible for checking, and there is a limit to how closely spaced the readings may be. Generally, however, boreholes bigger than a few inches in diameter seem to be surprisingly insensitive to moderate thermal or mechanical disturbances because of the relatively large heat capacity and inertia of the water column, and mercury-in-glass thermometers were used up to recently for virtually all of the work done on terrestrial heat flow. The thermometers are restricted-bore maximum thermometers similar to clinical thermometers (which have in fact been used for this work), but calibrated for total immersion. It is considered good practice to use a number of thermometers in one container, half of them being inverted; but given one accurately calibrated one, there seems to be no advantage, other than an illusory gain in precision, in using any more. On the other hand, more thermometers require a larger container, with a greater combined heat capacity. A little oil or water is put in the container to improve the transfer of heat from the hole to thethermometer, and the thermometer and container are cooled to below the borehole temperature, and the thermometer set to its lowest reading. Enough air space must be left in the container to ensure that closing it will not cause an excessive pressure on the thermometer. The sealed container is lowered to the required depth: most authorities recommend a rate of lowering of about 100 ft. per minute, which is quite comfortably maintained. The time required for the thermometer to approach the temperature of the surrounding water is found by tests in the laboratory; with a single thermometer in a small container it may be quite short, probably less than 15 minutes, and about 5 minutes longer is allowed in the field* This is one of the unavoidable delays in this method, but a doubtful reading has no value. The depth to the termometer is noted and the container is then hoisted to the surface and opened with as little rough handling as possible, and the thermometer is read: if possible the reading should be done independently by two people, taking care to see that the mercury thread is continuous to the restriction. In warm weather it will probably be found that the second person's reading is systematically higher than the other's, but it should not differ from it by more than a single division, and the first reading is taken as the measured temperature.

* This depends to some extent on its sensitivity; it does not matter whether or not a thermometer reading to $\frac{1}{2}°$ gets to within 0.1° of the true temperature, but one being read to 0.2° would of course have to do so: like any other body, a thermometer approaches equilibrium with the surrounding medium more and more slowly as the temperature difference between them diminishes, so that unnecessarily precise readings are wasteful of time in the field.

The ambient air temperature is not important, but it is useful to note it a few times during the day; the higher it is the more quickly must the handling and reading of the thermometer be done. The readings must obviously be made before the thermometer warms up. Thermometers are available divided to 0.1°C. so that readings to 0.05°C. may be made with confidence.

ELECTRICAL METHODS

Most of the electrical methods used fall into one or other of two classes, thermocouples and resistance thermometers. Their potentialities were recognized as long ago as the middle of the last century, when various workers used very sensitive (even by modern standards) thermopiles and galvanometers for studying temperatures of lava flows, stellar radiation, and so on. Kelvin used a thermocouple for measuring borehole temperatures in 1868, and was very likely the first to use an electrical method in connection with terrestrial heat flow. (2) He used the thermocouple as a means of transferring the underground temperature to the surface, where it could be measuredby other means. He had the surface junction in a vessel of cold water which he heated until he could observe no deflection of the galvanometer, and then he measured the temperature of the water with an ordinary thermometer. Near the end of the last century, Callendar used resistance thermometers to measure soil temperatures at shallow depths (down to 9 ft.) in Montreal. (3) In those days sensitive galvanometers were very delicate and quite unsuitable for large-scale field use, and the advantages of electrical methods were not fully attained.

Using a simple thermocouple with a sensitive galvanometer has the serious disadvantage that the quantity to be measured is very small and easily masked by the effects of stray thermal or other currents, insulation defects, moisture, etc. In addition, a stable known reference junction temperature is required; or corrections must be applied to the readings, measuring the reference junction temperature at the same time as the observation is made, and with comparable accuracy. An ice-point bath is generally used. A minor source of error in such a simple circuit is the Thomson effect: if in a circuit of two dissimilar metals a temperature gradient exists between the ends, heat will be transferred by the current, which acts as if it were a fluid with a finite specific heat (which may be "negative" with some metals): however, the terrestrial temperature gradient is so small that the current in a simple thermocouple circuit would be also small, and errors from this cause would be very small. A practical difficulty is that thermocouple wires are too weak to support their own weight for the lengths required for borehole temperature measuring. Resistance thermometers may be made largely free from these defects, and are at present the most reliable and otherwise satisfactory electrical thermometers for borehole work. They have, however, some disadvantages.

For high precision and stability the best type is the platinum resistance thermometer, in which the temperature-sensitive element is a coil or grid of fine platinum wire: thermometers of this type are used extensively in laboratories and in industry, and are accepted standards for calibrating other instruments. However, the resistance of the element is usually fairly small - from a few tens of ohms to a few hundreds of ohms at room temperature - so that any change in the resistance of the leads is significant. This necessitates compensating leads, which add to the bulk and weight of the equipment as well as making the electrical layout more complicated. Only a limited power may be used in the element which, also, has a small temperature coefficient of resistance (typical of metallic conductors) so that a fairly sensitive (and therefore delicate) galvanometer is required. Many borehole temperature surveys of a very high standard have been made with these thermometers, notably by Weiss in South Africa.(4,5)

Thermistors are small pieces of semi-conducting material (similar to transistor material) commonly mixtures of metallic oxides, and are made in various shapes and sizes, and with room temperature resistances ranging from some hundreds of ohms to more than a hundred kilohms. Their outstanding advantage over metallic resistances is their very high temperature coefficient of resistance - of the order of $3\frac{1}{2}$ to $4\frac{1}{2}\%$ per degree C. (this is negative, so that the higher the temperature the lower the resistance), which not only increases their sensitivity, but also does away with the need for compensating leads. However, their safe power dissipation is much less than that of a platinum element, and an even lower power must be used to get a linear relation between voltage and current, although this is not essential. Some disadvantages are that they do not have the stability of metallic elements, and they are very sensitive to thermal shock. Before being used in the field a thermistor should be aged by slow heating and cooling through the range in which it is to be used, with the measuring current flowing in it, and it should not be subjected to higher temperatures. Neglect of this precaution may not damage it, but will almost certainly alter its calibration and may impair its stability. (6,2)

A thermistor for use in deep boreholes should have a high resistance so that the resistance of the cable is insignificant compared with it, and as high a safe rate of power dissipation as possible. Its time of response would be unimportant, as even in a metal probe a thermistor will get very near thermal equilibrium before the fluid disturbances caused by lowering the probe will have died out. (7) The high resistance demands extreme care with insulation, the probe must be absolutely watertight, and there must be no moisture on the surface components; also, the same type of wire should be used for all loose wiring on the equipment to minimize unwanted thermal currents. This is very important, especially in hot weather.

Up to a certain small rate of power dissipation, a thermistor in an environment of constant temperature has a constant resistance; this rate is generally well below the maximum safe rate, and at higher rates the resistance is reduced by the self-heating of the thermistor, and it is therefore dependent on the power, on the ambient temperature, and on the rate of heat transfer between the thermistor and its surroundings. However, for a given safe power in a stable thermistor there is a unique value of resistance for a given ambient temperature, and this is fully reproducible where the heat transfer conditions between the thermistor and its environment are unchanged. Thus if a constant stable voltage were available, a thermistor could be used for temperature measurement at any safe rate of power dissipation, but the lower the power the less sensitive is the resistance to small changes in the voltage supply, and an absolutely constant voltage applied to the thermistor means that the power changes as the temperature changes, and also that the sensitivity diminishes as the resistance increases, i.e. as the temperature drops. A constant power circuit would give a more nearly uniform sensitivity, but would be a fairly complicated arrangement, so a useful method is to vary the voltage in steps when measuring a range of temperatures, keeping the voltage high enough to give the required sensitivity, and low enough to avoid excessive heating of the thermistor. This procedure, however, was found to be unnecessary when a sufficiently sensitive galvanometer was used.

II OUTLINE OF PREVIOUS WORK

To calculate the flow of heat in a substance, the temperature gradient in the direction of the flow, and the thermal conductivity, must be known. For terrestrial heat flow, the usual procedure is to measure temperatures at different depths in boreholes, so getting the temperature gradient, and then to measure in the laboratory the thermal conductivities of samples of rock from the holes. The gradient is usually not constant, but gives a curved graph of temperature versus depth, and the graph may be convex toward or away from the temperature axis. It may be stated as change of temperature per unit change of depth, or as change of depth per degree change of temperature (this is referred to as the "reciprocal gradient", or, more rarely, the geothermal step). Further, the degrees may be either Fahrenheit or Centigrade; and in addition, the units of depth are commonly feet, 100-ft. units, metres, or, for deep holes, kilometres.

Almost always the temperature has been found to increase with depth, that is, to give a positive temperature gradient; however, negative gradients are known, though these are sometimes due to artificial causes. Shaft sinking, especially, and general mining operations are valuable sources of temperature information, as are also tunnelling operations.(8) Trial borings on a tunnel line have a special value in that they differ from almost all other boreholes in being drilled in regions where there is no expectation of finding ores, oil, or gas. The bulk of information on temperature gradients is from oil-well holes or exploratory holes for oil or gas, together with a much smaller contribution from mineralized regions. In other words, most of the information is from exceptional rather than typical parts of the earth's crust. Mountains, of course, may not be typical either, and tunnels usually go through mountains, but temperature information from tunnelling operations is nevertheless very valuable. Also, an increasing amount of information is becoming available on heat flow through the ocean floors, got by measuring the temperature gradients within the top 15 or 20 feet of the sea-bottom sediments, whose conductivities are then assessed from core samples.

It would be consistent and convenient to use the C.G.S. system throughout, but as the foot is used almost exclusively in field work, a useful expression of the temperature gradient is degrees C. per hundred feet, positive when the temperature increases downward, and for the reciprocal gradient, feet per degree C. Perhaps the only justification for using the Fahrenheit scale is that for some reason (possibly because clinical thermometers show degrees F.) suitable Centigrade thermometers are more difficult to get than Fahrenheit ones; but a good deal of published work on terrestrial heat flow uses the Fahrenheit scale, and where such is directly referred to in the following it is converted to Centigrade units.

A commonly quoted value for a terrestrial temperature gradient is 1°C. per hundred feet, a very convenient figure which is fairly representative of regions of flat terrain, where many determinations have averaged about 0.032°C./metre within a fairly small range - this is about 0.98°C./100 ft., or 107 ft./deg.C. However, values ranging from 468 ft./deg.C. to 205 ft./deg C. have been recorded in Canada. (9)

Thermal conductivities are expressed in a variety of units, but in geophysics there is a trend towards the exclusive use of the C.G.S. system, in which the unit of thermal conductivity is one calorie per square centimetre per second per unit temperature gradient. The unit temperature gradient is 1°C. per centimetre, so that the thermal conductivity is expressed in cals./cm.deg.C.sec. In the same system, heat flow is expressed in cals/sq.cm.per second, but the terrestrial heat flow is so small that it is usually expressed in microcalories per square centimetre per second.

Another important property of a substance, incorporating its density, its specific heat and its conductivity, is its thermal diffusivity. On this depends the rate at which a body comes to thermal equilibrium with its surroundings. It is the ratio of two quantities, one proportional to the heat stored in a volume of the substance, and the other proportional to the heat conducted by an equal volume of the substance in a given time; the heat units cancel, and it is expressed in cm.^{2}/sec.

Rocks have thermal conductivities ranging from 0.003 to 0.014 cal./cm/deg.C.sec. most of them being near the middle of the range, about 0.006 or so, and a world-wide average of heat flow values is 1.23 microcalories/cm.^{2}/sec.(Bullard and Kuiper). For example, a temperature gradient of 0.98°C./100 ft. (0.032°C./metre) in a medium of conductivity 0.004 cals./cm.deg.C.sec. would give a heat flow of:-

$$32 \times 10^{-3} \times 10^{-2} \times 4 \times 10^{-3} =$$
$$128 \times 10^{-8} = 1.28 \times 10^{-6} \text{ cals./cm}^2\text{/sec.} =$$
$$1.28 \text{ micro-calories/sq.cm./sec.}$$

The usual procedure for getting temperature gradients in a borehole is to take temperature readings at known depths, and then to assume that the fluid column in the hole has been at the same temperature as the surrounding bulk rock, and that the quantity of heat abstracted by the measuring instrument is small. The instrument is left at the position whose temperature is to be measured until it has come to an equilibrium with its environment, (and it is assumed to be then at rock temperature). Provided that there has been no recent movement of the fluid in the hole, the temperature so measured will be very close to the rock temperature. The fluid column in a liquid filled borehole is much more likely to be stable, and is also less easily disturbed by lowering the measuring instrument, than that in an air- or gas-filled hole. Also, the relatively large thermal capacity of the liquid tends to minimize the thermal disturbance during measurement. Boreholes almost always contain water, with more or less suspended mud at depth. There is no general agreement about the time required for the liquid column in a hole to come to equilibrium after a disturbance. It depends on the magnitude and duration of the disturbance, and on the diffusivity of the surrounding rock. Krige (10) considers that it will have attained rock temperature within two months after drilling has been stopped, and considers a result got at sixteen days after drilling to be of "reduced value". Others give estimates "of the order of a month", and yet others estimate from ten to one hundred times the drilling time; by "drilling time" is meant the period between the time when the position in question was drilled and the time when drilling was stopped; thus the bottom of a hole should come to equilibrium sooner than the higher parts of it (11,12). Drilling is a very severe disturbance. It generates a good deal of heat, which is disposed of by the circulation of the drilling mud, but this seriously disturbs the temperature gradient. Movement of the liquid column in the hole after the thermal effects of drilling have gone away may be caused by either avoidable or known mechanical disturbances, or, more rarely, by convection currents.

Many prominent workers have examined the possible effects of convection currents and the circumstances in which they may exist, but it has been found that they are not likely to exist under normal circumstances, or, if they do exist, that they are too slow to have a measurable effect on the temperatures in the hole. Van Orstrand found no evidence of convection in deep holes up to eight inches in diameter, and Misener and Beck cite a case in which temperatures were measured in a 4500 ft. hole when dry, and again two years later when the hole was full of water, with the same result in each case.(2)

An incompressible, non-viscous fluid would be unstable in the normal terrestrial temperature gradient; but if a fluid has a sufficiently high specific gravity, and also is sufficiently compressible for the hydrostatic pressure to cancel the tendency of the liquid to expand with increasing temperature, there will be an increase of density downward, with a tendency towards stability. This by itself, however, is not enough. Jeffreys ("The Earth" 2nd. ed. p.138) gives the critical gradient below which convection is not possible in a non-viscous fluid as $\frac{gaT}{C_p}$, where:

g is the acceleration of gravity,

a is the thermal coefficient of expansion of the fluid,

T is the absolute temperature, and

C_p is the specific heat at constant pressure.

With a higher gradient convection could occur. A. L. Hales showed (13) that viscosity would increase the critical gradient by $\frac{Cuk4}{ga\bullet}$ where:

u is the kinematic viscosity (cm.^{2}sec.$^{-1}$)

k is the thermal diffusivity (cm.^{2}sec.$^{-1}$)

a is the thermal coefficient of expansion of the fluid, °C^{-1},

$\bullet$ is the radius of the hole (cm.), and

C is a constant whose value depends on the proportions of the system: for a tube whose diameter is small compared with its length, C is 216. Thus the complete expression for the critical temperature gradient is:

$$\frac{gaT}{C_p} + \frac{216\ uk}{g\ a\ \bullet^4}$$

both parts of this expression have the units deg. K.L^{-1} (the specific heat C_p is in ergs/°K/gm.), and the second part is many times greater than the first. It is evident that the critical gradient decreases rapidly as the radius of the hole increases; and it also decreases with rising temperature, since C_p, k, v and a are temperature-dependent. For water at 25°C. (298°K.) typical values of the quantities in the expression are:-

$a = 2.6 \times 10^{-4}/°K$

$C_p = 4.2 \times 10^7$ ergs/°K/gm

$u = 8.9 \times 10^{-3}$ cm.^{2}/sec., and

$k = 1.49 \times 10^{-3}$cm.^{2}/sec.

Taking g as 981 cm./sec.^{2}, the critical gradient in a hole 5 cm. in diameter would be:

$$\frac{981 \times 2.6 \times 10^{-4} \times 298}{4.2 \times 10^{7}} + \frac{216 \times 8.9 \times 10^{-3} \times 1.49 \times 10^{-3}}{981 \times 2.6 \times 10^{-4} \times (2.5)^{4}}$$

$$= \frac{9.81 \times 2.6 \times 2.98}{4.2} \times 10^{-7} + \frac{2.16 \times 8.9 \times 1.49 \times 16}{9.81 \times 2.6 \times 6.25} \times 10^{-4}$$

$$= 18.097 \times 10^{-7} + 2.875 \times 10^{-4}$$

$$= 2.893 \times 10^{-4} \text{ deg.K./cm.}$$

$$= 0.029^{\circ}/\text{metre, or } 29^{\circ}/\text{km.}$$

This is about the normal terrestrial gradient, so that holes of greater diameter than 5 cm. might be expected to be unstable at this temperature. Misener and Beck have plotted graphs showing the relations between the critical gradient, the diameter of the hole, and the temperature. However, as mentioned above, convection currents have rarely been found to interfere with temperature measurements even in deep boreholes of fairly large diameter. This may be due in part to an added increase of density downward caused by suspended solids. Even if the fluid in a hole were in a state of steady convection, it is conceivable that a thermometer in the fluid column would show a temperature pretty close to rock temperature, but in such a hole the rock temperature gradient might be flattened by long-continued transfer of heat from bottom to top. Also, the steeper the original gradient (i.e. the gradient prevailing before the hole was drilled) the more pronounced would be this flattening. Perhaps the only check on whether this is happening or not would be to extrapolate the temperature readings in the hole and see if they approach the mean annual temperature near the surface, but this is unsatisfactory in that it is only applicable to measurements made in undisturbed regions and not to measurements made in regions such as those in which oil or gas exploration holes are usually drilled. Thus without definite knowledge of the absence of convection currents an abnormally flat gradient could be attributed to steady continued convection, or could in fact be a genuine naturally flat gradient. Another source of errors is local circulation in the hole caused by too rapid movement of the probe. This is fairly easily detected when an electrical method is used - readings taken on the way down should be reproduced on the way back up, and such reproducible readings may be accepted with confidence.

For precise work, the boreholes should be surveyed for verticality of corrections made where necessary. In fairly short holes, a degree or two out of plumb makes very little difference. An error of 1% in depth would require about 8° deviation, from vertical, but deep oil well holes have been known to deviate by more than this at depth.(14)

III GEOLOGY

The area studied is part of the St. Lawrence Lowland, which is a large trough of Lower Palaeozoic sedimentary rocks lying unconformably on the pre-Cambrian Grenville group. The long axis of the trough is roughly parallel with and southeast of the St. Lawrence River. Its northwestern side is faulted against the Laurentian uplands, and its southeastern boundary is marked by a series of thrust faults associated with the Appalachian and Adirondack Mountains. At the northeastern end of this boundary the sedimentary beds of the trough are overturned and there is considerable deformation. This is less severe to the southwest, where the boundary is an overthrust fault zone with little deformation.(15)

In sequence downward, the rock groups of the trough are:-

Richmond - non-marine shale changing downward to calcareous shale and marine limestone.

Lorraine - mostly shales and sandstones.

Utica - black shale.

Trenton - limestone of irregular qualities, with some interbedded shale.

Black River - limestone changing downward to dolomite.

Chazy - fossiliferous limestone changing downward to sandstone and shale.

Beekmantown - dolomite becoming sandy downward.

Potsdam - orthoquartzite sandstone and conglomerate, lying on pre-Cambrian basement.

The upper groups do not extend to the northwestern limit of the trough, but in the opposite direction all except the upper groups are covered by the hanging wall of the Appalachian thrust. Also, the older groups (below the Trenton) end successively in a direction northeast from the centre of the trough, so that near Montreal there are four groups between the pre-Cambrian and the Trenton, but near Quebec the Trenton lies directly on the pre-Cambrian. A few miles apart on a line roughly at right angles to the axis of the trough, crossing the St. Lawrence near Montreal, are the Tertiary Monteregian intrusives, from Shefford in the east to Oka in the west. The Oka intrusive shows only a small outcrop, unlike the others which form conspicuous hills in the St. Lawrence plain.

Faults in the trough are in two nearly perpendicular directions, parallel with and across the axis. Some of the faults in the latter direction, in association with minor anticlinal features, are likely traps for gas or oil, and many of the holes were drilled in such locations.

Gas is found in almost all formations, in quantities ranging from mere puffs to some hundreds of thousands of cubic feet per day, but those groups from the Trenton inclusive upward are of particular interest as potential or actual producers of gas or oil. Oil is less common than gas. Vugs are found in the Beekmantown, and small drops of oil are found in some places in the upper Trenton formations. Most of the overlying shales smell of oil when freshly broken.

At least two holes, however, were drilled in locations and in formations where there was little reason to expect oil or gas, and these were of special interest in connection with the heat flow study. One of them, the Mallet well near Ste. Therese, was stopped at 3035 ft. in the Potsdam, having entered that formation at 1334 ft. The other, drilled near Oka in 1956, is wholly in the Grenville. Unfortunately, both of these were found to be blocked, the Mallet at the surface, and the Oka hole at about 35 ft.

Outcrops are numerous in the area, but the overburden in some places is 200 ft. deep.

Many of the holes were found to have caved at fairly shallow depths, even holes drilled a relatively short time previously, less than a year in one case; other older holes were still usable. In general, the younger shales do not seem to be very competent rocks, and the age of a borehole (i.e. the length of time since it was drilled) is not a reliable indication as to whether or not the hole is clear at depth. The best way to find out if a hole is clear is to try making a set of temperature measurements in it, so that the temperatures are not needlessly disturbed before use. Probing a hole just to see if it is clear might upset the temperature gradient, and reliable rock temperature measurements cannot be made for some time afterwards.

IV PRELIMINARY FIELD WORK

Thermometers

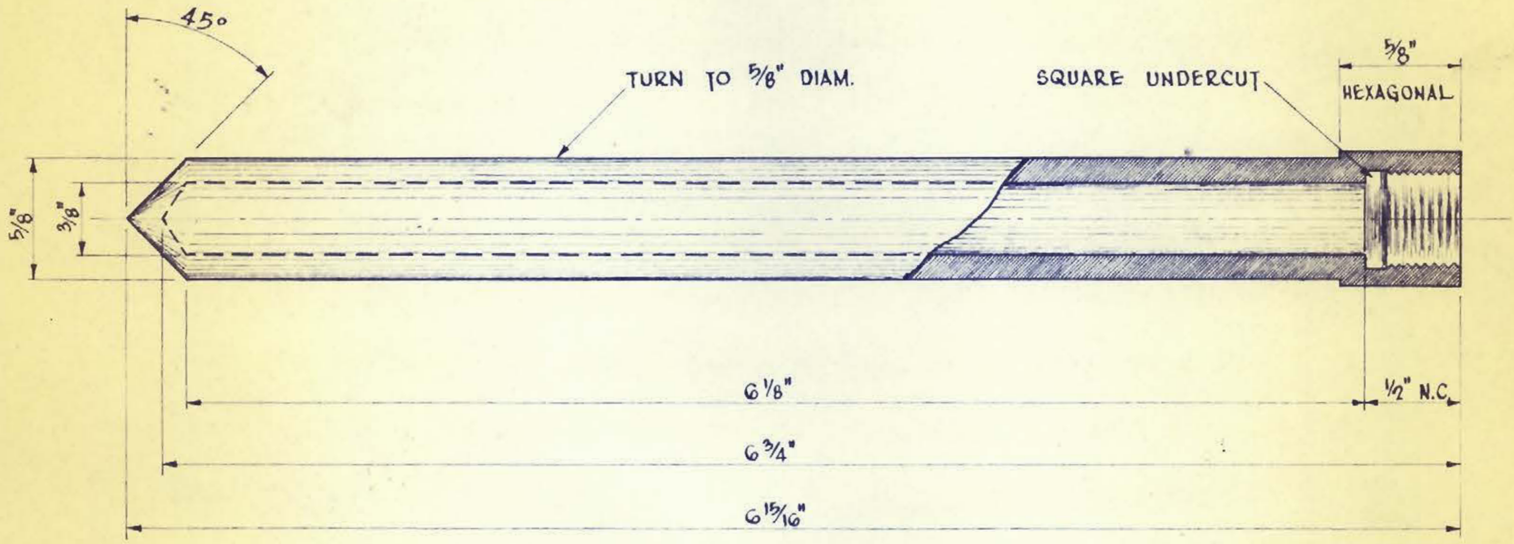
It was intended to begin field work with special Centigrade thermometers divided to fifths of degrees, but these were not available for some months after being ordered, and work was begun with locally purchased thermometers divided to single Fahrenheit degrees, marked for total immersion, about $5\frac{3}{4}$ ins. long and 5/16 in. in diameter. When the specially ordered ones were finally delivered, they were no longer required and the only interesting work done with them was a rough survey of a well at Mascouche, in which three of them were lowered together to1538 ft., exposed to the water pressure in the well. Two of them gave credible readings for the temperature at that depth, but the third one showed a quite improbable value.

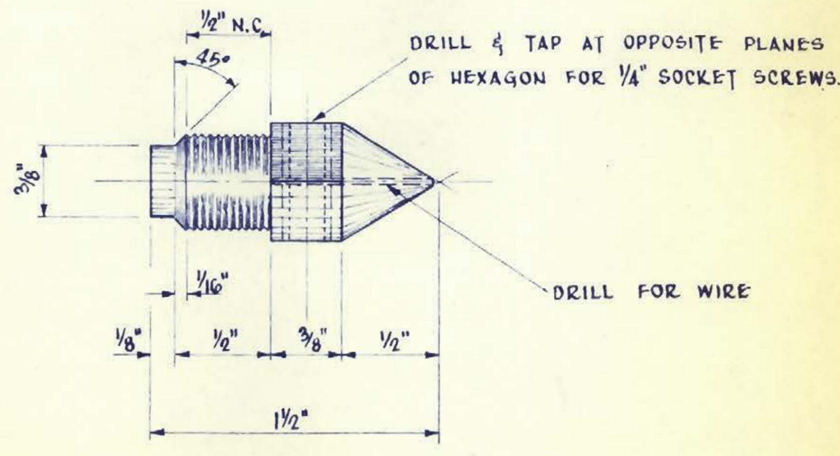
Thermometer Container (Fig.1)

Only one of the Fahrenheit thermometers was used at a time, and a brass container was made for it from a length of 5/8 in. hexagonal rod turned circular for most of its length, but left hexagonal at its open end, which was threaded internally ($\frac{1}{2}$ in. N.C.) to take the plug. The plug was drilled and tapped through two opposite flats to take two 3/16 in. Allen screws for clamping the piano wire used for lowering the container - the end of the wire fitted into a small axial hole drilled into the plug to just past the two tapped holes. A light spiral spring was placed in the bottom of the container to push the thermometer up when the plug was removed. This saved having to tilt the tube (and the thermometer) and avoided spilling oil from it. No. 10 piano wire (0.024" diam. and weighing 1 lb. per 690 ft.) was used to lower it into the well. Tests showed that a delay of thirteen minutes was just long enough for the thermometers to show correctly the temperature of a bath at 40°C. (the only one at hand) starting with the thermometer and container at about 20°C. In the field a minimum of twenty minutes was allowed at each depth - this was in addition to the time taken to lower it to depth.

FIG.1

Container for mercury thermometer.





PLUG

Cable Reel and Footage Counter

The wire was carried on a light portable reel (intended for seismic field work) which was held down on the ground with iron pegs, and a hook fitting into holes drilled in one flange of the reel held the thermometer at any required depth. From the reel, the wire went over a measuring pulley one foot in circumference coupled to a "Veeder" counter reading to tenths of revolutions, so that the depth to the probe could be read to one tenth of a foot. The pulley, bearings, and counter were mounted on a one-inch plywood base, with a simple coil-spring flexible coupling between the pulley and the counter. The counter was a non-reset type (the reset type is not guaranteed to count down accurately, and counting down provides an easy check on errors in the depth measurement) reading to 999.9. A certain amount of trouble arose from slipping of the wire on the pulley, especially on the way up when the wire was wet. This was almost eliminated by taking a complete turn of the wire around the pulley, but care was required at any kinks in the wire. Usually the counter showed a small negative footage when the probe came to the surface. This was especially noticeable early in the work, and more so with the electric cable than with the piano wire, so it was probably caused by stretch in the wire or cable.

The measuring unit was mounted on uprights a few feet over the collar of the hole. Two types of uprights were made because some of the holes had plain casing pipes projecting over the surface, and others ended in standard flanges with bolt-holes. For those holes with plain pipes, two angle-iron uprights were made with slotted plates at their tops to take the measuring unit. Cross-pieces near their lower ends were drilled for long studs which clamped the uprights around the pipe, centering them at the same time. This arrangement was very satisfactory, though it would be better made of light alloy members. For use with flanged casing pipes, the measuring unit was mounted on two-one-inch pipe uprights with studs welded in the end - the lower ones to go into the flange bolt-holes, and the upper ones to take the measuring unit. In some cases (as at St. Hyacinthe) where there was a drilling shack around the collar of the hole, the uprights were not required and the whole of the surface equipment was mounted directly on the floor of the shack.

Thermistor Probe and Equipment

In an attempt to get some results before the weather made field work difficult, a few surveys were attempted late in 1958 with the first thermistor probe, a small Leeds Northrup Wheatstone bridge (#4760) and a $\frac{1}{4}$ ma. per division Weston galvanometer. Because of the high resistance of the thermistor, the bridge was used at a 100:1 ratio, so that the smallest step was 100 ohms. This was just discernible on the galvanometer with the maximum safe voltage across the bridge. On account of the low sensitivity of the galvanometer, the voltage was kept near the maximum for the safe power dissipation of the thermistor (10mw.). This was done by tapping from a group of dry cells, since the voltage had to be changed as the resistance of the thermistor changed. About 45 volts was required at low temperatures. The whole arrangement was about as sensitive as the mercury thermometers, but in any case none of the surveys was of any direct value because of blocked holes and/or equipment trouble, such as leaky cable glands and defective cable insulation (this was later found to be so bad that this particular cable was abandoned for this application). However, some useful experience was gained in handling the field equipment.

V ELECTRICAL FIELD EQUIPMENT

As originally designed the field equipment was to comprise a thermistor and a thermopile in series with each other in a single long probe with the thermistor at its lower end. The thermistor was to be used with alternating current for the temperature measurement when the thermopile would be merely an extra, nearly constant, impedance in the circuit; and the temperature gradient would be got from the thermopile output by a direct current potential measurement, not affected by the high resistance of the theristor; thus both the temperature and the local temperature gradient at depth would be obtainable with just one two-conductor cable down the borehole. Using alternating current was expected to have many advantages, especially those of minimizing the effects of stray currents and of being satisfactorily amplified with available equipment. This latter naive belief was not justified.

Essentially what is required for the temperature measurement with such a circuit is a means of measuring the resistance of the circuit an even number of times, reversing the polarity between the measurements and meaning the results to eliminate the effect of the thermopile output. Theoretically both the temperature and the gradient could be got from these resistance measurements, but it would demand a rigid control of procedure and would be difficult to reproduce. The gradient, therefore, would be got by disconnecting the A.C. supply and measuring the thermopile output with a suitable potentiometer. Low frequency alternating current immediately suggests itself as offering a few important advantages for the temperature measurement, provided that a clean symmetrical wave form can be got, one advantage, important becuase of the thermopile in the circuit, being the automatic assurance that the power in every half cycle is the same. From one point of view, the lower the frequency the better, but it is not easy to get a good wave form, free from harmonics, at very low frequencies without heavy and bulky equipment. The thermopile, and possibly also to some extent the bridge network to be used for measuring the resistance, would be highly inductive and hence frequency sensitive, and the effects of this would be least at low frequencies.

It was thought that a modified Wheatstone bridge with a variable condenser shunting either the variable arm or the unknown (depending on whether the cable and probe should be more capacitive than inductive or vice versa) would be satisfactory, and as it was at first intended to use a headphone as a detector, a frequency of about 1200 c.p.s. was chosen. This was later changed to 500 c.p.s. and an oscillator was built with plug-in tuners for these frequencies. An available high-gain amplifier with output meter was used instead of phones and suitable tuners were made for it also.

The delivery time for suitable thermocouple wire was about two months, so it was decided to start work by using the thermistor alone with direct current, making only temperature measurements, and getting the temperature gradient from these in the usual way.

The thermistor used was a "Stantel" F15 (Standard Telephone and Cable Co. Ltd.). This was a directly heated bead-type thermistor with a resistance of about 100K at 20°C., a temperature coefficient of resistance of about 4% per degree Centigrade, and a maximum safe power dissipation of 10 milliwatts.

Some special co-axial cable developed specifically for work in bore-holes was on order, but the delivery time was very long (some months) and the only cable available at the time, strong enough to support its own weight and that of the probe without excessive stretch at an expected depth of about 3000 ft., was a loosely twisted pair used for seismic field work, so the thermistor probe, and, later, the thermopile were designed for use with this cable, with provision for adapting them to the co-axial cable when it should be available. Each conductor had four steel and three copper strands in a tough plastic covering with an outside diameter of 0.065 in. Tested as a parallel pair, a sample broke at a tension of 270 lbs. with an elongation of about 0.07 in. in 10 ins. A typical readily available co-axial microphone cable broke at 53 lbs. after an extension of some inches in a length of about 3 feet. 1500 ft. of the pair had a series resistance of about 92 ohms.

The Thermistor Probe

A few different patterns of probe were made before a really satisfactory one evolved. Each was in two main parts, the stem which enclosed the thermistor, and the cap which carried the glands and electrical connections for the cable. The first one made had two separate glands, one for each conductor. Both the stem and the cap were made of brass, and screwed together with 1" x 14 threads, the cap being the male part. Brass is very suitable for such items as these, being fairly strong and at the same time easily machined to a good finish. Its special advantage in this case was its high thermal conductivity (about 0.29 c.g.s. units). Each joint face and the corresponding thread were machined at the same setting, and the only jointing used was some sealing compound wiped over the threads and joint faces. The arrangement of the cable glands was the principal weakness of this design. The workshop facilities available were inadequate to make a really good job of these, and it was very difficult to seal the glands without damaging the insulation of the cable. Graphited yarn was used for packing, simply because there was some at hand. The glands were positioned so as not to project outside the diameter of the probe ($1\frac{1}{4}$"), and they had to be inclined away from each other so that they could be screwed into the stuffing boxes, and so were out of line with the cable which was thus prone to damage here, especially when the probe got snagged in a hole. The thermistor was mounted on a block of "Teflon" located by a dowel in the stem of the probe, and carrying two contacts which matched with two spring-loaded contacts in the cap (also located by a dowel).

A second probe was made, using the stem part of the first one, but in this one the two conductors were in the one gland, about 1/8" apart, parallel with each other (and with the axis of the probe). The packing was solid soft rubber cut from 3/8" sheet, and was drilled for the conductors with the gland in place in the stuffing box. The gland was forced down by a hollow 5/8" x 20 screw through which the cable passed, and was prevented from turning by small projections, solid with the gland, which fitted into grooves cut in the wall of the stuffing box.

This packing was quite successful, but the grooves in the brass cap and the gland itself wore loose after repeated assembly, so a new cap, gland,and screw were made from 18-8 stainless steel. Solid rubber was found quite effective as packing material, but the success of the whole sealing arrangement depends on having the rubber cut accurately to shape, so that the stuffing box is completely full of rubber before the gland is loaded. Solid rubber is almost incompressible when restrained laterally, and a high pressure can be produced in the packing with very little deformation, and hence little likelihood of damaging the cable insulation. All the cable holes should be a push fit on the conductors, and the gland a neat fit in the stuffing box; otherwise the rubber will flow when the packing is compressed, and may damage the insulation. As before, brass was used for the stem of the probe because of the low thermal conductivity of the stainless steel (about 1/14 that of brass), but because of the difference in coefficients of thermal expansion (brass 20×10^{-6}/degree C., 18-8 stainless steel $16 \times 10^{-6}/°C$) an aluminium ring 3/16" thick was fitted between the joint faces. This has a sufficiently high coefficient to seal effectively while the probe is warming up, and is also fairly soft. Some changes were also made to the internal connections for the thermistor, replacing the spring-loaded contacts with demountable screwed connections, so that the stem now served only to provide mechanical protection for the thermistor.

The exterior of the new cap was machined to accommodate later on an oil seal and a rigid mechanical connection for the thermopile, which was being assembled at about this time.

This probe served very well, but unfortunately none of the holes in which it was tried were open to any useful depth, and it was also discovered, during an unsuccessful trial of the thermopile alone, (i.e. without a thermistor) that the insulation of the twin cable was seriously at fault for its whole length. At first the direct electrical effect of this on the thermistor readings was small, but it was disastrous to the thermopile readings which were only tens of microvolts. It offered, however, a plausible explanation for small water leakages into the probe, previously attributed to the packing. Later the cable became completely saturated and quite useless.

The gland and cap were bored out to take a heavy microphone cable of the same diameter as the special co-axial cable on order, but not yet available. The holes for the twisted pair cable had been located so that they would just clean out when this was done - and one very successful temperature survey was made in a shallow well at Roxboro. A separate gradient survey with the thermopile alone (also using microphone cable) was an immediate failure because of a leaky gland. This was the last time the thermopile was used to date.

Soon after this, the whole cap was remodelled. A plain cylindrical brass cap with a single gland secured by four studs and nuts was made for the special borehole cable, which had now arrived. No provision was made for connection with the thermopile. The thermistor leads were soldered directly to the conductors of the cable, and the stuffing box was made big enough to take standard thick wall rubber tubing for packing. This was the probe used for the successful surveys in Lounan No. 1 and Cartier Natural Gas No. 5.

When assembling the probe, enough heat transfer oil is put in the stem to immerse the bead end of the thermistor, leaving enough air space to obviate any excessive rise in pressure when the cap is screwed in place.

The Thermopile

This consists of two sets of junctions five feet apart, at either end of a thin-walled stainless steel tube half an inch in diameter. The junctions are surrounded by copper rings of the same diameter as the thermistor probe ($1\frac{1}{4}$") and are insulated electrically from them by layers of thin linen. Each set has 32 junctions arranged in two layers of 16, all the elements being in series. The external connections (to the borehole cable and the thermistor leads) are made on a "Plexiglass" block at the upper end so that they are all in the same temperature zone, and easily accessible without disturbing the junctions. The length of the thermopile was governed by the output required, while keeping physical dimensions as small as was practicable. The longer it is the larger the output to be expected - and the length chosen (5 ft.) is about as long as can be handled easily in the field.

Stainless steel was used for all the external parts except the copper rings about the junctions. In this case, its low thermal conductivity is advantageous in minimizing axial heat transfer between the junctions. As there was some doubt about the behaviour of a long thin-walled tube if deformed under pressure, the thermopile was to be filled with oil. (Actually there was little free space in it, as it was almost completely full of wires), and a special seal was devised for the lower end which was attached to the cap of the thermistor probe. This seal had two circular section spring steel rings in a groove in the thermistor cap, and these were compressed to leave gaps of about 0.010" by the end fitting of the thermopile. The ring gaps were 180° apart and located by a small dowel, and it was expected that this seal would permit equalizing to a satisfactory extent the pressure inside the thermopile with that outside; the whole arrangement is simple and avoids the complication of flexible members, etc. It should be effective with the probe in any attitude (while being carried in the field, for example).

Any water entering the probe through the seal would collect around the thermistor cap where there was room for more than enough water to fill the whole thermopile proper without wetting the lower junctions. However, as an additional precaution all the internal connections were varnished over during assembly. A gland using rubber packing and secured by four small (#5) screws was fitted at the top for the borehole cable. This gland would not have to seal against any very high pressure, unlike the thermistor gland which is still exposed to the unbalanced pressure of the water column in the borehole.

Iron "Constantan" thermocouple wire (No. 9B3N4, Honeywell Controls Ltd.) was used. This has the two conductors side by side in tough polyvinyl insulation, and is the smallest iron constantan pair supplied with this covering. These metals give the highest em.f. of any of the common thermocouple metals - about 0,05 m.v. for a 1°C. temperature between the junctions at moderate temperatures. The lowest temperature gradient found mentioned in the literature of Eastern Canada is 1°F. in 260 ft. - this is the vertical gradient inferred from an inclined drill hole in Debrite mine in the Timmins area (Misener and Thomson), "Temperature Gradients in Ontario and Quebec", Trans. C.I.M.M. Vol. 53, 1950). About the same area, the highest gradient mentioned is 1°F. in 116 ft. and Misener has recorded an average gradient of 1°F. in 115 ft. in the Sudbury area ("Temperature Gradients in the Canadian Shield", Trans. C.I.M.M. Vol. 52, 1949). Taking the least favourable of these:-

10°F. in 260 ft. = 1°C. in 468 ft. and this gradient would give 0.0107°C. difference in temperature between the junction of a five-foot thermopile in equilibrium. For one pair of junctions, this would give an em.f. of 0.05 x 0.0107 μ.v., and for 32 pairs in series, 32 x 0.05 x 0.0107 in.v. = 1712 x 10^{-5} μ.v. = 17.1 μ.v., which would be well within the range of the A.C. microvolt amplifier to be used with the thermopile.

This would be the worst condition to be expected, as even for the area discussed in the paper, an area whose rock types and geological history are very different from those of the St. Lawrence Lowlands, the 1°F. in 260 ft. was the lowest of a number of exceptionally low values. However, in the first reference above, Misener and Thomson recorded a gradient of 1°F. in 114 ft. (1°C. in 205 ft.) in a demonstration oil well drilled in Toronto through strata similar to those of the St. Lawrence Lowlands. This gradient would give about 38 μv. in the thermopile.

No appreciable error was expected from axial conduction of heat in the probe. It is of small cross-section (about 1.26 sq. cm.) and the metal used has a low conductivity. The metallic cross-sectional area (including the wires) is about 0.6 sq. cm. and the rest is oil and polyvinyl chloride, both poor conductors (about 4×10^{-4} c.g.s. units). Because of the distribution of the metal in the cross-section (the iron and constantan are fairly good conductors and are in good thermal contact with the water at each end) a mean thermal conductivity of 0.03 c.g.s. units may be assigned to the whole cross-section. The temperature difference between the ends will be small, say 0.01°C., and the heat flow correspondingly small (this applies also to errors which might be expected from the Thomson effect (see p. 26) so that in the short time spent in one survey of a borehole, there should not be sufficient heat flow to cause any noticeable inequilibrium. The fluid in the borehole would have a conductivity of about 0.0014 c.g.s. units. The volume of the probe will displace some of the water column uniformity with little disturbance of the gradient. Also in a hole with a nearly constant gradient, the probe having once come near equilibrium would thereafter be heated or cooled more or less uniformly, but once the reading has become steady at a particular depth, it is unlikely to give a false gradient value. Bullard has investigated a similar case in some detail (18). Before being used in the field the thermopile should be checked in a zero gradient (an ice point bath large enough to accommodate the probe,(or two separate small ones) for zero output, and thereafter the readings may be converted to temperature differences by use of published tables. Errors could arise from imperfect welding of junctions, so that zero output might not mean zero gradient.

Some preliminary work was done with a small Wheatstone bridge, dry batteries, and a Weston galvanometer (see p.19), but this was not sufficiently sensitive, and in any case required a fairly large current in the thermistor. To get greater sensitivity with direct current in the thermistor, a 1.1 megohm General Radio resistance box (#1432P) was inserted in the variable arm of the L.N. bridge, and a d'Arsonval galvanometer with a sensitivity of 0.0033 μa/mm at 1 metre was used instead of the Weston meter. The bridge could now be used at 1:1 ratio, and single ohms were available on its variable arm (the smallest step on the General Radio box is 10 ohms). This arrangement was very satisfactory, and reliable ice point resistances were got with as low as 2v. across the bridge. A 6 volt lead acid battery provided the current. For field use, the galvanometer, scale and lamp were enclosed in a large light-proof wooden box painted a sombre (and prophetic) black - the galvanometer suspension did not survive the first field trip. Nonetheless, the apparatus could be used satisfactorily in the field, provided that there should be fairly easy access to the borehole (there was not in this case) and that the bush should be cleared to give plenty of room for setting up.

After this, the d'Arsonval galvanometer was replaced by a "Rubicon" galvanometer, which is an excellent instrument for this work. It is inherently less sensitive than the d'Arsonval, but in practice is quite as good as it because of the excellent scale and illumination, especially when used as a null detector, as in this case. This was the final form of the D.C. equipment. Some changes were made to the footage counter when the new co-axial cable was used, but the electrical equipment was substantially the same.

The principal reason for the fact that the thermopile and thermistor were never used in series with each other as a single unit was the failure to develop a satisfactory A.C. bridge method within the time available. There were a number of reasons for this, but the main one was the failure to appreciate the significance of the difficulties when they arose. A lot of time was spent in making up different bridge arrangements, the last bridge being an elaborately shielded Wheatstone bridge with two isolating transformers and a Wagner earth. In all cases it was found very difficult to get a minimum on the output meter (a null was never got) and the final result of a balance was that the variable arm was only a fraction of the unknown resistance (in the ratio of about 35:100). Also reproducibility was poor. It was found that some of these features were largely effects of the length of the cable, and were substantially unchanged when different lengths were unwound from the reel. One attempt to resolve the difficulty was made by putting another reel of cable in the variable arm. This was only partially successful, and also was a bit clumsy and scarcely acceptable for field use.

In view of the very short electrical length of the line even at the higher frequency used, trouble from resonance was not anticipated. However, the indications are that the trouble is caused by some transmission line effect, such as a high standing wave ratio, as would prevail in a badly unmatched line such as this is. Because the resistance of the probe would be changing over a fairly wide range, the reflection coefficient, and therefore the magnitude of the reflected wave would also be changing. With a sufficient knowledge of the properties of the line, the reflection coefficient would be calculable from the field observations, and from this the resistance of the lower termination (in the borehole) would be available. It is felt that further work would be justified.

VI CALIBRATION OF THERMISTOR AND REDUCTION OF FIELD RESULTS

The most convenient and rapid accurate way of calibrating a thermistor for field use is direct comparison with a standard platinum resistance thermometer. This is not an absolute calibration, but it is reliable and can be as accurate as one desires to make it. Plotting the logarithm of the resistance against the reciprocal of the temperature should give a very nearly straight line, showing any irregular values which should be discarded. The number of fixed points available in the required temperature range is quite limited, and the thermistor should not be heated to higher temperatures. Commercially pure acetophenone has a melting point of 19.60°C. but this is seriously affected by impurities, a common drawback with organic substances, and the liquid is messy stuff to handle, having, also, an unpleasant smell. Carbon disulphide has a boiling point of 46.2°C. but it is a serious fire hazard unless proper precautions are taken, and is not easily handled. A possibly useful fixed point might be the melting point of a low-temperature eutectic alloy, such as Rose's metal, provided that the same unique sample were always used, and that there were no reaction with the metal of the thermistor probe, as the thermistor is almost always calibrated when assembled in the probe, especially for checking before and after a field trip, for which fixed points are particularly useful. The triple point of water provides an absolute fixed point, but commercially available apparatus is too small to accommodate a bulky probe in the temperature cell. Practically, then, the one fixed point used is the common ice point.

The ice point bath should be a mixture of finely divided ice and distilled water, well mixed. Ice taken in lumps from a freezer is likely to be supercooled, and a vessel of water and ice lumps will have unstable zones of different temperatures in it (this is observable with a thermistor inserted directly, i.e. not enclosed in a probe, into such a bath). The temperature differences may be of the order of whole degrees. What is required is as close an approach as is possible to a mass consisting everywhere of ice and water in equilibrium with each other. A successful bath is a large vacuum flask to contain the probe with plenty of room all around it, packed with almost solidly rammed shavings planed from a block of ice. This is wetted to saturation with water (saturation is easily noted by the colour of the mass) and a glass tube reaching to the bottom of the flask is used to draw off excess water. The ice should be rammed gently at intervals, and fresh water added. In really precise work, a correction would probably be made for barometric pressure, but this is not necessary for the present purpose.

The other temperatures for the calibration may be got by placing the thermistor probe and one junction of a thermocouple side by side in a well stirred temperature bath. The temperature of the bath is varied by allowing it to cool, and may be stopped for short periods at different values by switching on the heaters. Simultaneous readings are taken of the resistance of the thermistor and the output of the thermocouple; the latter are then translated to temperature values, and conversion of the resistance readings to temperature values may be done from the relation $R_t = ae^{\frac{-b}{T}}$, where "a" and "b" are constants, and "T" the temperature in degrees Kelvin. In fact, however, "a" is not truly constant over a wide range of temperature, so values for "b" are calculated from closely-spaced pairs of calibration readings, and the average of these values is used to calculate "a" from a set of readings near the middle of the range. A less precise, but quite sufficiently accurate, method is to use the relation $R_T = R_{273}\, E^{\left(\frac{B}{T} - \frac{B}{273}\right)}$ so that $B = \dfrac{-\log \frac{RT}{RO} \times 273 \times T}{\theta \times \log E}$ where "θ" is the temperature in degrees Centigrade at which the thermistor has the resistance R_t and R_0 is the ice point resistance of the thermistor. "B" is positive and has the dimensions of temperature. With "B" known, any resistance value of this particular thermistor within the range can be expressed as a temperature by rearranging the expression to read

$$T = \frac{B \log E}{\frac{B\log E}{273} + \log \frac{RT}{RO}}$$

. R_T is the only variable, and for the thermistor used in Lounan #1 and Cartier Natural Gas #5, the expression for the temperature became:

$$T = \frac{1625.98}{5.95597 \pm \log \frac{RT}{RO}}$$

which gives the temperature in degrees Kelvin. Logarithms are to the base 10. This method is rather faster than the first procedure above. A convenient way of handling the arithmetic is to tabulate the values as shown below:-

TABLE No. 1 LOUNAN No. 1

R_o = 259025

Depth	°K	R_T	R_T/R_o	log R_T/R_o	Denominator
50	280.521	179325	0.69231	$\bar{1}$.84031	5.79628
100	280.924	175925	0.67918	$\bar{1}$.83198	5.78795
150	281.370	172250	0.66499	$\bar{1}$.82282	5.77879
200	281.622	170225	0.65718	$\bar{1}$.81765	5.77362
250	281.944	167650	0.64723	$\bar{1}$.81105	5.76702
300	282.270	162075	0.63739	$\bar{1}$.80440	5.76037
350	282.664	158875	0.62571	$\bar{1}$.79637	5.75234
400	283.090	155835	0.61336	$\bar{1}$.78771	5.74368
450	283.504	155835	0.60162	$\bar{1}$.77931	5.73528
500	283.952	152615	0.58919	$\bar{1}$.77026	5.72623
550	284.427	149295	0.57637	$\bar{1}$.76070	5.71667
600	284.892	146125	0.56413	$\bar{1}$.75138	5.70735

TABLE No. 2 CARTIER NATURAL GAS No. 5

25	281.996	167235	0.64563	T.80998	5.76595
50	281.459	171525	0.66219	T.82099	5.77696
62	281.308	172755	0.66694	%.82409	5.78006
71	281.305	172780	0.66704	T.82416	5.78013
80	281.295	172860	0.66735	T.82436	5.78033
88	281.312	172725	0.66683	T.82401	5.77998
100	281.295	172860	0.66735	T.82436	5.78033
150	281.318	172675	0.66663	T.82388	5.77985
200	281.397	172025	0.66413	T.82226	5.77823
250	281.627	170175	0.65698	T.81754	5.77351
300	281.922	167825	0.64791	T.81151	5.76748
350	282.256	165200	0.63778	T.80467	5.76064
400	282.617	162425	0.62706	T.79731	5.75328
450	282.988	159635	0.61629	T.78978	5.74575
500	283.350	156950	0.60593	T.78243	5.73840
550	283.746	154085	0.59487	T.77442	5.73039
600	284.129	151375	0.58440	T.76671	5.72268
650	284.555	148415	0.57297	T.75813	5.71410
700	284.925	145900	0.56327	T.75071	5.70668
750	285.418	142625	0.55062	T.74085	5.69682
798	285.847	139840	0.53987	T.73230	5.68827

TABLE No. 3 ROXBORO

Depth	25	50	75	100	125	150	175	200	225	234	ft.
Temp.	8.57	9.01	8.99	8.94	8.90	8.90	8.92	8.95	9.02	9.04	°C.

VII CONDUCTIVITY APPARATUS AND MEASUREMENTS

The common method of measuring rock conductivities uses the divided bar type of apparatus developed by A. E. Benfield (17). In this method, a specimen of the rock is inserted between the two near ends of two brass rods of known conductivity (determined by calibration with discs of material of known conductivities), the remote ends being maintained at different temperatures, one about 20°C. higher than the other. From a knowledge of the temperature gradients in the rods, the conductivity of the specimen can be found in terms of that of the material of the rods. Because of the unknown temperature drop across the interfaces between the rods and the specimen, a number of samples of different thicknesses are investigated, and it is assumed that the interfaces in each case behave in the same way, A solution of glycerine in water is applied to each face when inserting the specimen, and the upper bar is weighted to promote good contact.

The determination of the specimen's conductivity is done as follows: The near end face temperatures are calculated by extrapolation from the measured gradients in the rods. Let the difference between the two temperatures be "T"; this is the sum of temperature drops in the specimen and in the two interfaces. Let the drop in the two interfaces together be "L". If "S" is the thickness of the specimen and "G" the temperature gradient in it, then $T = L + GS$. Assuming that the interfaces behave as conductors in a similar fashion to the brass and the specimen, the magnitude of "L" depends on the heat flowing, which (neglecting radial heat losses) is proportional to the gradient in, and conductivity of, the brass. In other words, $L = KG_b$

So, $\frac{T}{G_b} = K + k_b \times \frac{S}{k_v}$, where k_b is the conductivity of the brass, k_v that of the rock specimen and K a quantity involving the thickness (conductivity of interfaces.) Plotting $\frac{T}{G_b}$ against S should give a straight line (with intercept K) whose slope will be $\frac{k_b}{k_v}$, so that with k_b known, k_v can be found.

This is not a perfect means of assessing the conductivity of bulk rock in situ at depth. The effect of pressure directly on the thermal conductivity is fairly small (Bridgeman et al.), but its indirect effect by way of changing water content may be considerable. Also, in the case of badly fissured rock at depth, the conductivity of a solid sample can scarcely be thought to be representative. There is a growing interest in means of measuring conductivity in situ by transient methods using heating probes, but for the present it was thought that a value obtained by a generally accepted method would be better than no value, the probable outcome of attempting to develop an in situ method in a limited time.

Dr. A. E. Beck, of the University of Western Ontario, has devised a form of divided bar apparatus in which the remote end temperatures of the bars are maintained constant by means of water sprayed against them from a series of fine jets housed in each. Among the advantages claimed for this apparatus is the fact that it attains its equilibrium condition in a matter of minutes after changing a specimen, and within about 20 minutes from starting cold. This is certainly borne out in practice. However, its successful use demands a rigid control of both temperatures; without this, no results of value can be got. Dr. Beck has described this in a paper published in 1957 (18) and very kindly supplied sketches and information from which the apparatus used here was built. Some small detail changes were made, and two sets of bars, one pair incorporating guard rings, and the other pair being solid brass. So far lack of time has not permitted comparative tests with the two sets as the apparatus is not yet fully satisfactory with the first pair of bars used (those with guard rings). Some runs have been made with core samples, but these have not been fully satisfactory, nor has there been an opportunity to calibrate the bars themselves.

FIG.2

Sprayer head for divided-bar apparatus.

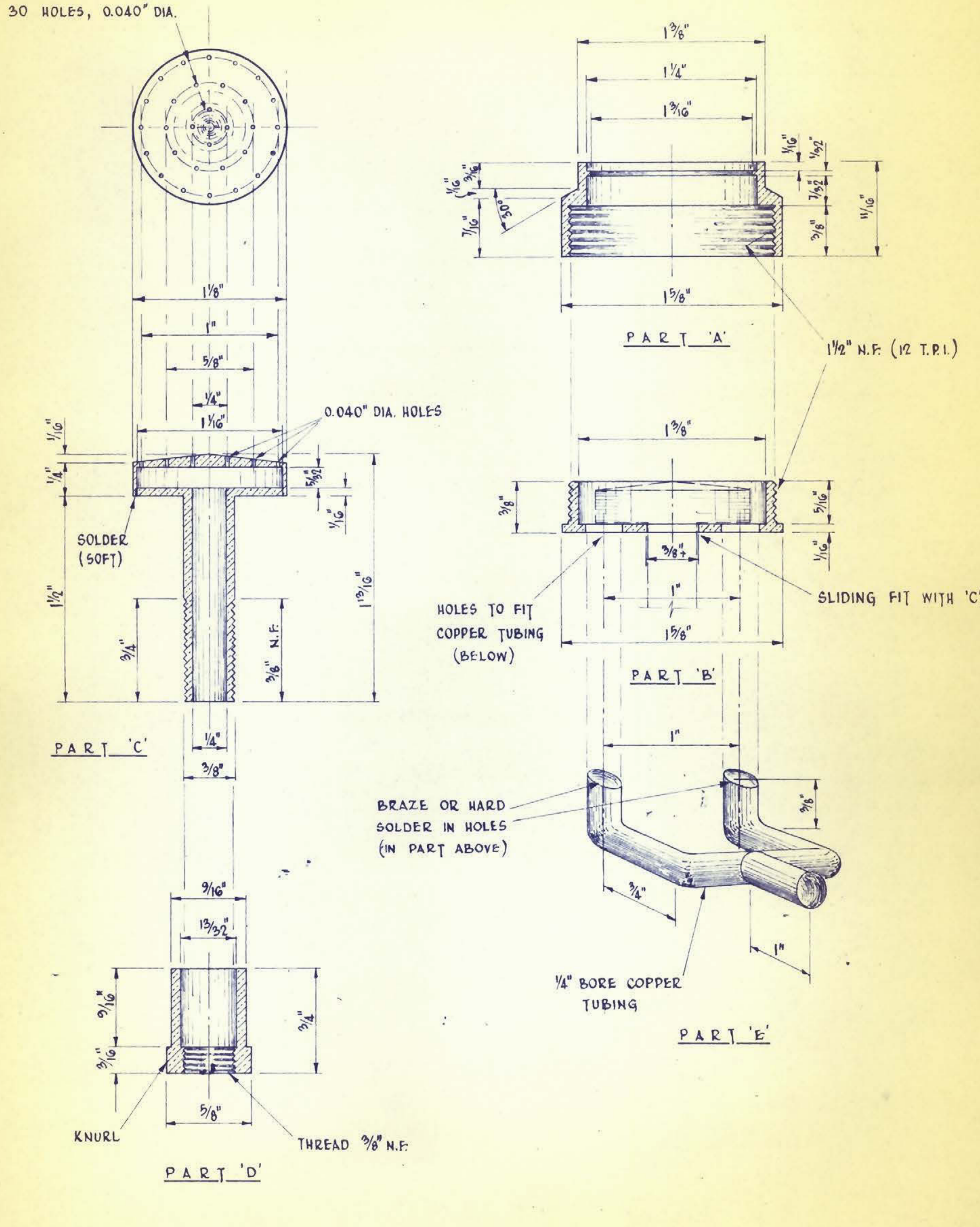
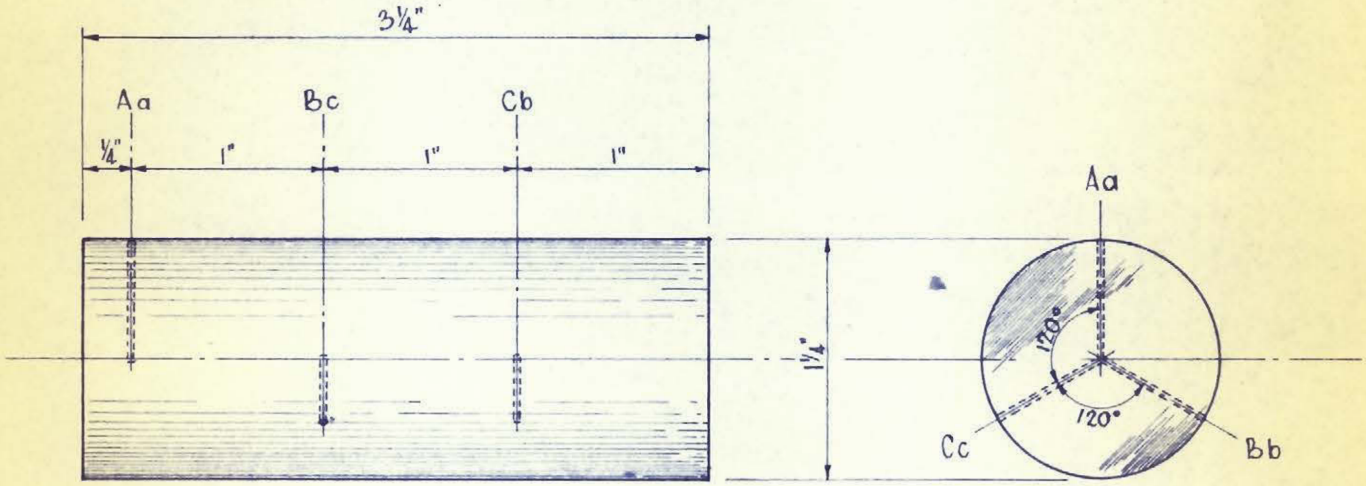


FIG.3

Solid bar for divided-bar apparatus.

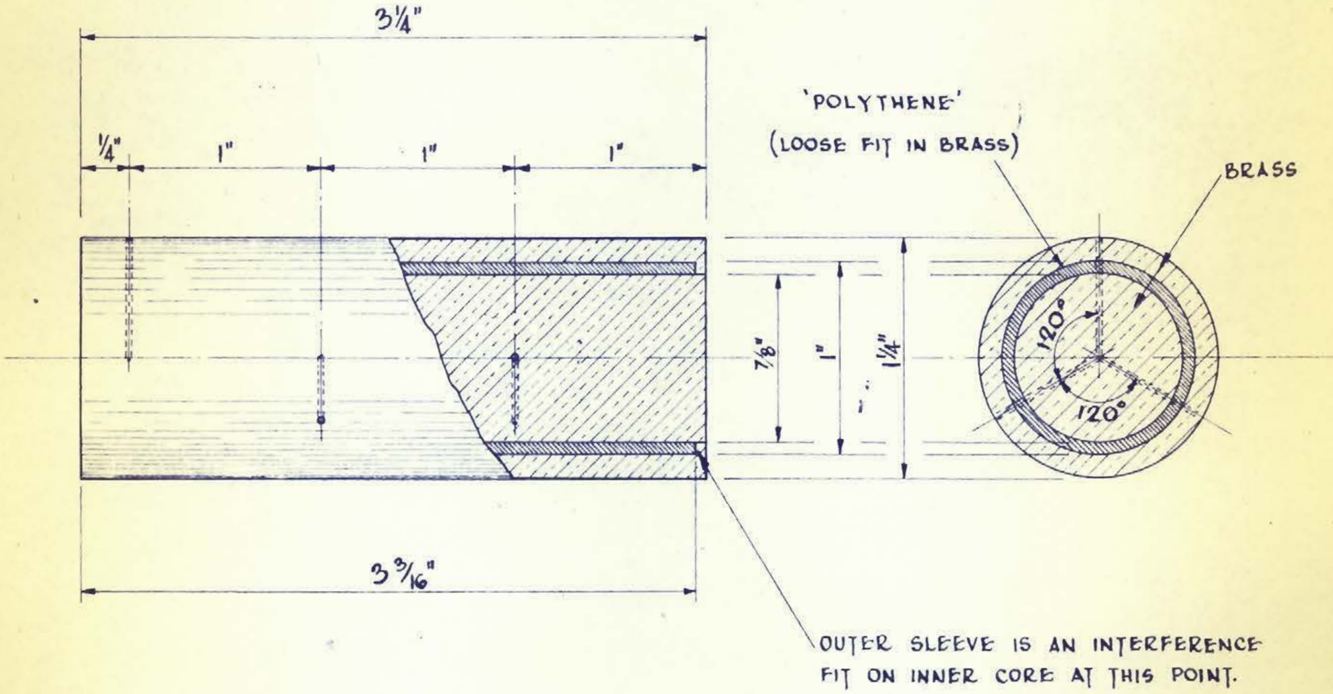


• HOLES ARE 0.055" DIA. AND 21/32" DEEP, AT 120° APART IN END VIEW.

• TWO BARS ARE TO BE MADE, THE LETTERS 'A', 'B', 'C' REFER TO ONE, AND THE LETTERS 'a', 'b', 'c' REFER TO THE OTHER – THE DIFFERENCE IS IN THE ORDER OF THE HOLES.

FIG.4

Guard-ring bar for divided-bar apparatus.



Each bar has a shower consisting of an enclosed brass sprayer with 30 holes 0.040" in diameter, arranged in three rings - these direct water against the end face of the bar, and the head of the shower is made convex (or, rather, conical) to ensure that the inner rings are not obstructed by the discharge from the outer holes. Provision is made for drainage back to the reservoirs. Actually, the water is not sprayed against the bars as the jets coalesce into a sort of mushroom shape on leaving the holes, but the combined area of the holes is much less than that of the feed, so that there is little doubt that all the holes supply the face with water, provided of course that the water is clean, and mone of the holes is blocked. **Fig.**2

Each shower has its own closed circuit, two pumps being mounted on one shaft, driven by a half horsepower electric motor. The pumps are small vane-type pumps (being fuel pumps for heavy oil engines, surplus stock) and are not perhaps the best type for use with water. However, they have behaved very well to date and have the virtue that any particles in the circuit will be pretty finely comminuted before getting to the showers. The pumps supply the showers directly - this simplifies the plumbing, and no difficulty has arisen from excessive pressures in the rubber pipes used between all the elements.

As first set up the upper end was the hot end, and was controlled by a thermistor controller ("Thermistemp" model 71) to one hundredth of a degree C. It was thought that if there was a sufficient volume of water in the cool end circuit, the resulting slow rise in its temperature would make very little difference in the course of a run. This was found to be far from the truth, and the first results were quite useless. Gradients in the bars were anything but comparable, and a really steady state was never obtained.

The temperature differences along the bars were measured with copper constantan thermocouples so arranged that any pair could be connected differentially. They were numbered 1 to 6 from the top down, and the readings were made with a Leeds Northrup D.C. microvolt amplifier (it is necessary to be able to read microvolts). The temperature of the hot end was estimated from the controller setting by extrapolating backwards from the measured gradient in the bar. The hot reservoir was controlled at 45°C., and the cool one rose slowly from room temperature (28°C) to 31.2°C over about 4 hours.

Three core samples of different thicknesses were used - the thickness is the mean of 4 measurements around the circumference, and the faces were quite flat:-

thin sample	0.214"	= 0.544 cm.
medium sample	0.357"	= 0.907 cm.
thick sample	0.447"	= 1.135 cm.

In this first run the performance was so obviously poor that the figures were not processed further. Typical results were:

thin specimen:

thermocouples	1 - 6	12.25°C.
"	1 - 3	2.25°C.
"	4 - 6	1.75°C.
"	3 - 4	7.75°C.
"	1 - 6	12.25°C.

The discrepancy between 1 - 3 and 4 - 6 is to be noted. It was not due to misreading of the instrument. This is the best of the three for the first run. The repeat of 1-6 shows that the apparatus was in a steady state. Each value above is a mean of several readings, all agreeing closely with each other.

medium specimen:

thermocouples	1 - 3	2.12°C
"	4 - 6	1.38°C
"	3 - 4	10.06°C
"	1 - 6	13.12°C

thick specimen:

thermocouples	3 - 4	11.45°C.
"	1 - 3	1.88°C.
"	1 - 6	12.02°C.
"	4 - 6	1.38°C.
"	3 - 4	10.11°C.

It was then realized that a close control over both temperatures was necessary, and the apparatus was rearranged to provide this. As now arranged the upper end was the cold end, and both ends were controlled, the hot end at 47.5°C. and the cold end 30.4° to 31°C. - mean 30.7°C. Another change was that oil baths were used instead of water reservoirs. The oil had a much lower specific heat and responded faster to control; and the pumps ran very well. No trouble arose from high pressures. The thermocouple junctions are numbered as before, from top to bottom, and the results were much more satisfactory though could be better still. The following is a summary of the readings:

Thin specimen:

1 - 6	9.75°C
1 - 3	1.50°C
4 - 6	1.35°C
3 - 4	6.97°C.

Thick specimen:

3 - 4	8.18°C.
1 - 6	9.85°C.
1- 3	0.82°C.
4 - 6	1.07°C.

Medium specimen:

3 - 4	8.17°C.
1 - 3	0.82°C.
4 - 6	1.00°C.
1 - 6	9.60°C.

These are all fairly consistent.

Extrapolating for end temperatures gives:

Thin specimen	hot face	45.82°C.
Drop across specimen 5.55°	cold face	39.27°C.
Medium specimen	hot face	46.26°C.
Drop across specimen 7.56°	cold face	38.70°C.
Thick specimen	hot face	46.18°C
Drop across specimen 8.74°	cold face	38.44°C

These figures were not processed further, as the core was from an unknown hole and values for cores representative of the Lounan and Cartier holes became available from R. Doig's work with this apparatus (1).

VIII DISCUSSION OF RESULTS

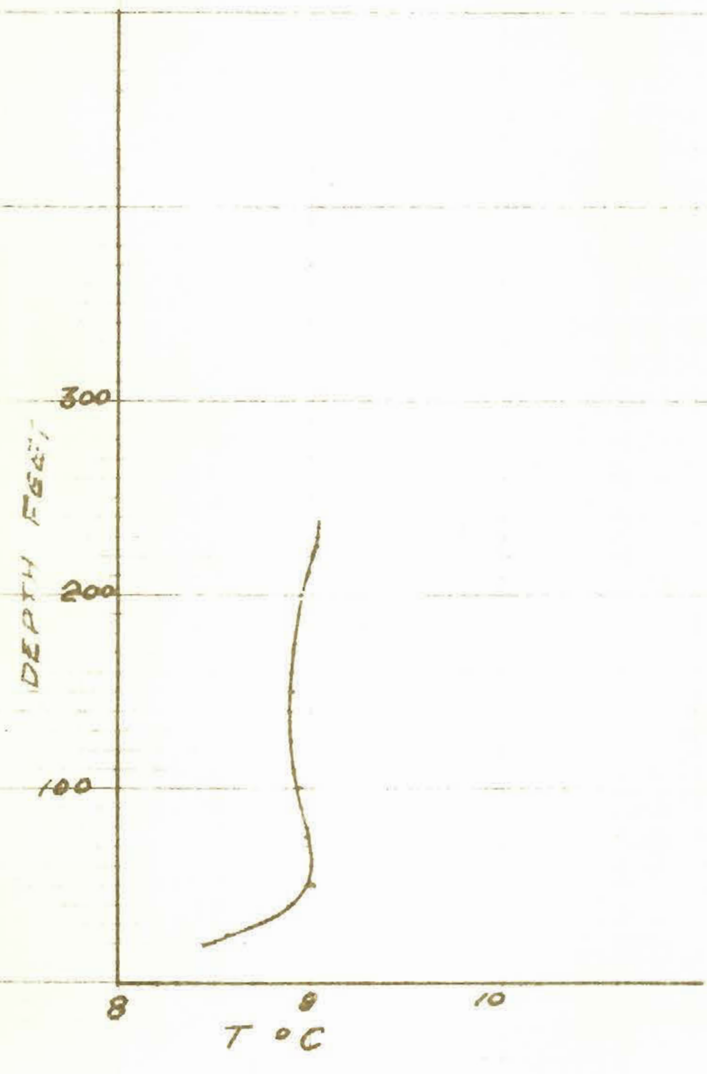
The virtual absence of a temperature gradient below about 30 feet in the Roxboro well is possibly caused by circulation of groundwater. This well supplied the locality with water until a few months before the survey, and there are other wells nearby. The local rock is a fairly thinly-bedded limestone. It was not intended to use this well for heat flow work, but it was the first really successful survey with the thermistor probe. A notable feature was excellent reproduction of check measurements at a few places on the way up. The well is about 8 in. in diameter, and no special precautions were taken to avoid disturbing it. The same reproducibility of readings was evident in the other boreholes surveyed - Lounan No. 1 and Cartier Natural Gas No. 5.

Both of the latter holes show temperature gradients steepening with depth (i.e. convex towards the depth axis.) This is the common state of affairs and is generally attributed to poorer conductivity at depth, because there is less interstitial water in rock at depth than near the surface. The conspicuous negative gradient near the top of Cartier Natural Gas No. 5 resembles the effect of a glacial age on near-surface bed-rock, but available information is that there is 200 ft. of overburden on the bed-rock here. It is not known to what depth the casing extends.

Lounan No. 1 gives a fairly typical temperature-depth graph, with a few not very conspicuous points of inflection, and the rock is a not very competent (to judge from progressive blocking of the hole since it was first visited in 1958) thinly-bedded sandstone and shale. The mean of three fairly straight portions selected by inspection from the temperature-depth graph gives a gradient of $0.79^{\circ}C/100$ ft, and taking an average conductivity of 0.003 c.g.s. units for a mixture of sandstone and shale, a heat flow value of approximately 0.79 microcalorie/cm^2/sec. results.

Cartier Natural Gas No. 5, treated similarly, gives the same mean gradient (the two holes are within a few miles of each other) so that an approximate value for the heat flow in the locality is 0.8 microcalorie/ cm^2/sec.

ROXBORO

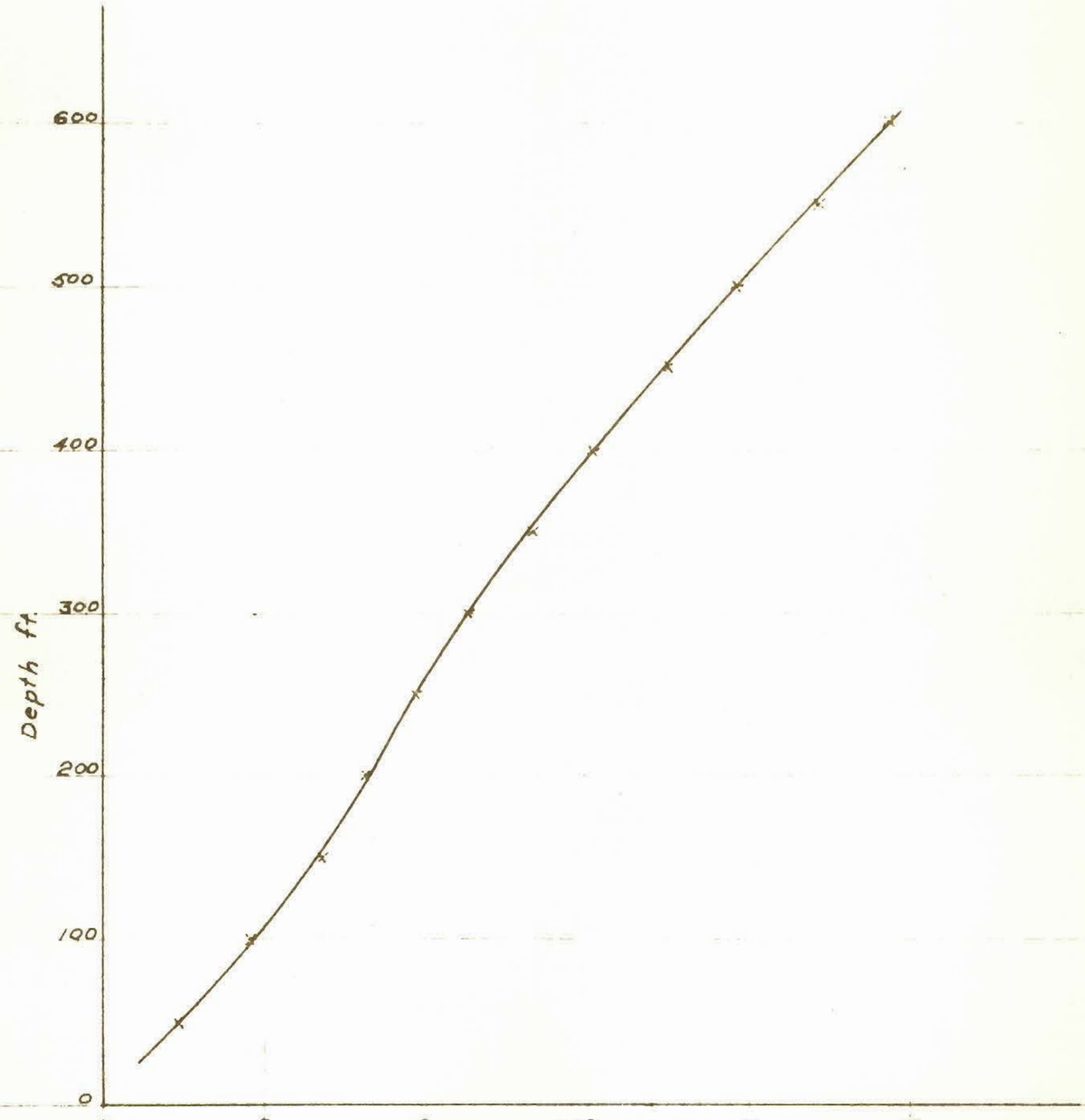


TEMPERATURE-DEPTH GRAPH for a water well at Roxboro, Mtl.

LOUNAN Nº 1

TEMPERATURE-DEPTH GRAPH

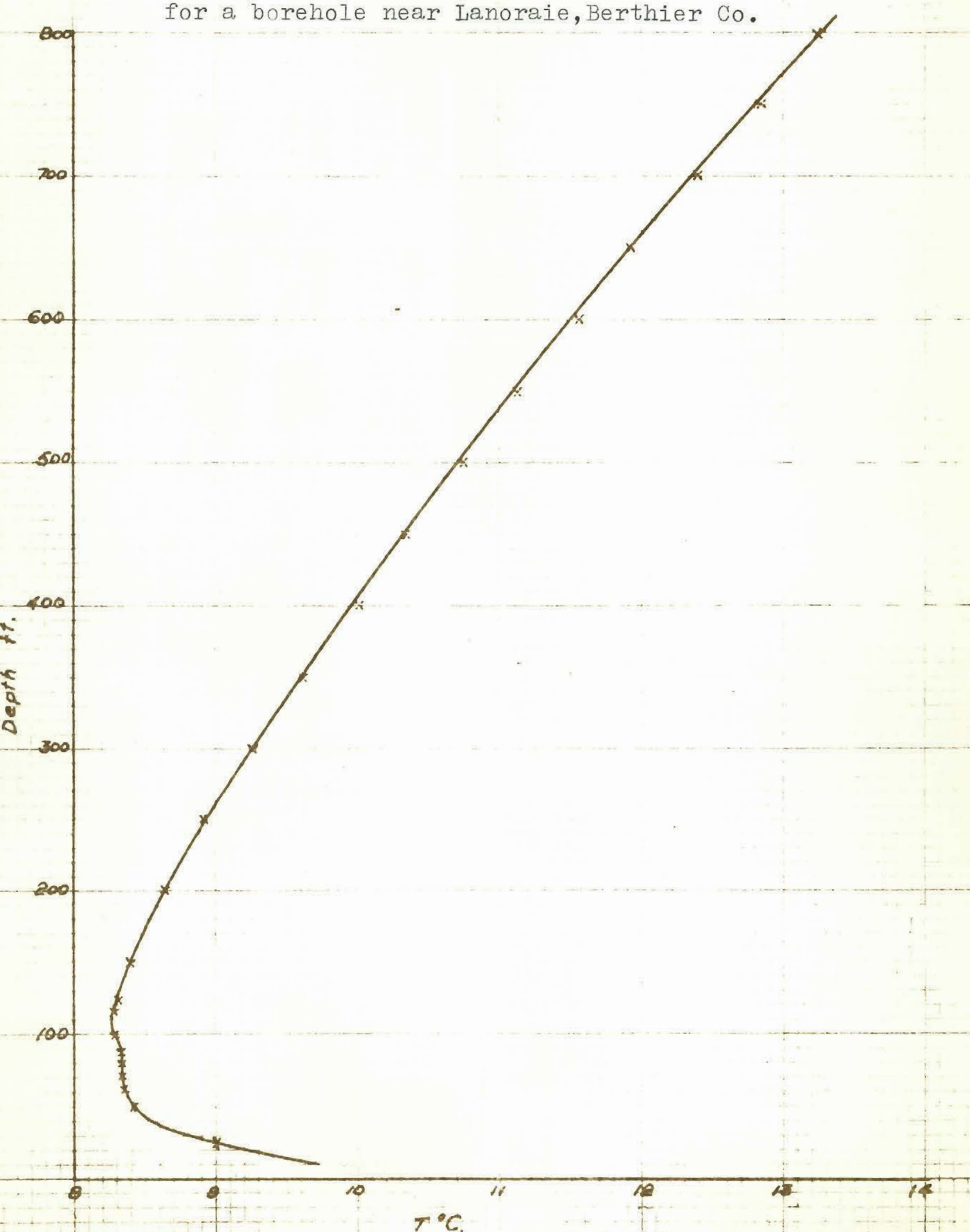
for a borehole near Lanoraie, Berthier Co.



CARTIER NATURAL GAS Nº 5

TEMPERATURE-DEPTH GRAPH

for a borehole near Lanoraie, Berthier Co.



IX REVIEW

In reviewing the work covered by this thesis, it becomes apparent that relatively little was accomplished towards evaluating the heat flow in the St. Lawrence Lowland, and that the original object in designing the field equipment was not realized. This object was to get both temperature and temperature gradient data to the surface with a single two-conductor cable from a fairly simple probe in the borehole. However, a reliable and fairly simple method was developed for measuring temperatures at any depths likely to be met with in the field, so that the terrestrial temperature gradient could be got in the classical way, by interpolating from temperature readings taken at known depths.

That more heat flow values were not obtained was largely due to the lack of usable boreholes - this results from a number of causes, one major cause being avoidable. This is the great haste with which recently drilled holes are destroyed by drawing the casing, plugging with concrete, or otherwise, which is unfortunately required by government regulation. No hole should be destroyed without having a temperature survey made in it: if required, a copy of this could be lodged with the appropriate government department, in the same way as are the cores and drilling log. This would ensure that some of the most valuable information available from the hole, and available from no other source, would be recorded. Once a hole is destroyed, it cannot be re-entered, practically speaking, and an unsuccessful gas or oil exploration hole is an ideal source of temperature information. More than 100 deep holes have been drilled in the Lowland area, and others are being drilled, but not more than five of any depth were found available for temperature surveys.

Inadequate workshop facilities offer another major obstacle to early success in experimental work. The effect of this could be greatly reduced by some sort of recognized liaison with a department having the required facilities (in personnel and in machinery) whereby that department could be requested to estimate for and carry out work for other departments with the minimum delay. Unofficial back-door negotiations do not usually produce satisfactory results.

Far too much attention was given to making the borehole equipment physically small. Results in the field showed that the boreholes used were not at all easily disturbed, and results were quite reproducible in all cases where the equipment worked satisfactorily. Small equipment offers some advantages in minimizing thermal and mechanical disturbances in the boreholes, but involves liabilities far outweighing these, such as especially lack of reliability, and in the case of a thermopile, small output (easily drowned by spurious effects). Another major disadvantage of small equipment is difficulty of manufacture with often limited facilities. The smaller a particular item is made, the more serious do the disadvantages become. Even in the design stage there is the difficulty of having to design for built-in defects in workmanship.

The difficulties met with in the use of mercury-in-glass thermometers have been mentioned above. Early workers used thermometers with metal indices enclosed in the capillaries, similar to the common greenhouse thermometer. This type fell into disuse because of the ease with which a reading could be lost by careless handling, and because of the greater accuracy of the restricted bore type now used, but they were widely used for scientific work in the past, notably for sea-water temperature measurements in the "Challenger" expeditions of the last century. One method of using mercury thermometers overcame some of the difficulties by using a number (up to ten) of split thermometer containers which were fixed on the cable at 200 ft. intervals as it was lowered; thus all the temperature measurements could be made in one descent. But, with a number of containers in the hole at once, the water column would be displaced from the bottom upwards, and in a small hole this displacement could be considerable. Also the method is less likely to record a reversed gradient satisfactorily than the usual method of lowering one container at a time, because of the necessarily slower lowering and raising of the cable. Nonetheless, this equipment has given very satisfactory results under different conditions, especially notable being a check survey made within two hours of a previous survey in the same hole, giving a correspondence of average readings (there are a number of thermometers in each container) at the check positions within .01°C.

A real disadvantage of electrical resistance methods of temperature measurement is that the quantity actually measured in the field is small (currents of the order of tens of microamperes or less) and liable to serious interference from stray currents, general electrical noise, electrochemical effects and above all, insulation defects. An electrical method which does not depend on voltage or current measurement uses as a temperature-sensing element an oscillating device whose frequency is temperature-sensitive, and the frequency is measured at the surface. This has the advantage that, provided that the signal can be detected, its strength is relatively unimportant, and the frequency will be easily detectable regardless of stray currents and other common interferences. This method has been used for borehole temperature measurement in South Africa (19) using a mechanical vibrating system maintained in vibration at its natural frequency by a two-tube oscillator and a suitable feed-back arrangement. The vibrating element was a steel wire stretched from end to end of a brass cylinder, so that the tension of the wire (and hence its natural frequency) rose as the temperature rose. This apparatus has two outstanding advantages: only one insulated conductor was required from the probe to the surface, and the measured quantity (frequency) was independent of changes in the electrical equipment (tubes, batteries, etc.). The frequency at 18°C. was about 110 c.p.s. and at 54°C. about 430 c.p.s. In the paper referred to above, describing this apparatus, the quoted correspondence with mercury thermometers was not good, but they did not correspond very well with each other anyway. Some minor criticisms of the device are that the probe has a greater heat capacity than a simple thermistor probe, and that the temperature shown is not really a point temperature, but rather a mean temperature over the length of the brass cylinder. This, however, is unimportant. Presumably, also, the tubes dissipate some heat (the instrument was built before transistors became available).

Temperature Gradient Measurements

It seems that until quite recently, little attention was given to direct measurements of terrestrial temperature gradients. Bullard's work on gradients in ocean-bottom sediments from "Discovery II" (16.) and similar work by the Scripps Institution from La Jolla used a thermopile probe carrying its own recording mechanism, so that there was no need to transmit a signal to the surface. In this case, of course, there was no limit, within reason, to the size of recording unit. Misener & Beck (2.) mention a 100 junction thermopile for borehole use, and a 200 junction thermopile is being prepared by another group for the same purpose.

Compared with the classical method of getting the temperature gradient by interpolation from temperature measurements, the use of a thermopile has the advantage, provided that it is sensitive enough, that errors due to slipping of the counter or stretching of the cable have no effect on the value of the gradient, but only on the allocation of that gradient to a specific depth. This latter is rarely so important that small inaccuracies in positioning the probe cannot be tolerated. On the other hand, a thermopile would be more seriously affected by any stable local motion in the water column in the borehole (e.g. a convection cell at depth or local circulation of ground water).

As mentioned above, too much effort was devoted to making the probe as small as was thought practicable - this reduced the output of the thermopile, but as it was intended to use a Leeds Northrup D.C. microvolt amplifier, the low output was considered acceptable. One point, however, was overlooked: the amplifier was designed for a source resistance of not more than 1000 ohms, and with a very high resistance, such as that of the thermistor, in series with the thermopile, the response of the amplifier would be very slow and quite unreliable (especially at thermistor resistances of the order of 100 K). This was later verified in the laboratory. Thus, the original idea of using the thermopile in series with the thermistor would not have worked for this reason, even if it had not failed for other reasons. Also, it is bad in principle to depend on readings of a few tens of microvolts. Such readings can be accepted with confidence only if it is known that the insulation everywhere in the system is perfect, and that there are no stray currents from any cause whatever. These conditions are very difficult to secure, as was demonstrated when the thermopile was used alone in the Lounan No. 1 well at **Lanoraie.**

<u>Conductivity Apparatus</u> **Fig.** 2,3 &4

Two sets of bars were made for the divided-bar conductivity apparatus, one set incorporating guard rings and the other being a pair of plain solid bars. To date, only the guard ring bars have been used, but as there is some doubt about the value of the guard rings, a comparison of the performances of the two types of bars would be of some value. The precision obtainable with the apparatus possibly does not justify the complexity and expense of the guard ring bars. Also, the sprayers were made with 30 holes 0.040" diameter in each. It is now felt that fewer larger holes would be a better arrangement, because with the small holes there is a greater danger of loss of symmetry from clogging of some of the holes than there would be if the holes were larger.

So much trouble arose in trying to develop a satisfactory A.C. bridge method, and even in securing reliable performance of the D.C. equipment, that some thought was given to a frequency method of measuring at least temperatures, if not temperature gradients also; but there was not enough time to design and build a device similar to the oscillator described above (19). However, quite independently of this, Dr. Saull suggested a simple R.C. oscillator with a thermistor, or if necessary, a number of them in parallel, as the R in the tank circuit, and proposed further work on these lines. A rather more advanced thermistor oscillator was designed and built by Mr. R. Doig for further work on the heat flow project.(1)

APPENDIX

A number of boreholes in the area were visited in the autumn of 1958, but many of them were found to be useless for temperature measurements, usually because of having been blocked either intentionally (by drawing the casing or by concreting) or accidentally. Some of the holes open at the surface were found to be blocked lower down, sometimes at quite shallow depths. Those holes actually producing gas were discarded, at any rate for the moment, because of the difficulty of ensuring that the measurements could be made without any excape of gas during the operation and for some time before it. This would not matter in the case of a well drilled down below the source of gas, but would seriously interfere with results in higher portions of the holes.

The following is a summary of the results of this preliminary examination. The numbers are those on the accompanying map which is published by the Quebec Department of Mines to go with "Data on Wells Drilled for Gas and Petroleum in the St. Lawrence Lowlands Area" by De Blois. This publication gives such information as location, collar elevation, depth, owner, driller and result for each well, together with a condensed log, for each hole shown.

1 Montreal #1 - this ends in an open 3" pipe socket about one foot above ground level. It appears to be open, there is no gas or water flowing from it, and access is fairly easy. It is supposed to be about 2400 ft. deep, but about 300 ft. of drill rod was lost in it.

7 Bald Mountain No. 1 Berthierville - this has been plugged with concrete.

12 Bald Mountain No. 2 Louiseville - also plugged.

40 and 41 Madeleine No. 1 and Madeleine No. 2 - these are both producing gas so that even if it were decided to use them, this would involve

dismantling pipe fittings and so on. They are both easily accessible.

42 Eastern Canada No. 1 - this ends in a 12" casing reduced to $3\frac{1}{2}$" with a horizontal pipe and stop valve about 4 ft. over ground level. All of this is easily dismantled, and there is little or no gas pressure. This well was dynamited at the Black River level, and is not likely to be open below this.

46(a) Eastern Canada No. 6 - this is open, ending with a 10" diameter flange with $8\frac{3}{4}$" holes, on a 4" bore pipe, only about 6" above ground level. It should be about 2600 ft. deep, from the Chazy to the Potsdam. This was visited again in December, but was found to be blocked at about 21 feet. This blockage was not solid, and 478 ft. was reached before a solid blockage. The thermistor probe was damaged at the first blockage so that no temperature readings were made, and the probe got snagged many times on the way up. No gas or water flowing from the hole, but the cable and probe were coated with thick oil on coming to the surface.

49 Quonto-International No. 1 Mascouche - this is a 3" (approx.) pipe in a pit at about ground level. When first examined, it was closed by a tight wooden plug, seeping gas through the grain. This well was surveyed with mercury thermometers in the summer of 1960 (see L 17).

51(a) Laduboro No. 2 LaBaie - Yamaska - this had just been started, and was still in drift at 46 ft. The result was a dry hole, but it has not been revisited, and its present condition is not known. Access is easy.

67 Lozo and Joseph No. 1 - this is caved in at the surface and cannot be entered.

68 Lozo and Joseph No. 2 - this was not actually visited - access is a bit awkward (through bush) and ground is marshy when river level is high. However, a local resident assured us that it was fitted with a stop-valve, and was in good condition. Not known whether it is actually producing gas or not.

69 Mohr No. 1 - this is blocked (intentionally) by rubble at about 10 ft. from top of pipe, which stands about five feet above ground.

76 Oil Selections No. 3

77 Oil Selections No. 4

90 Oil Selections No. 29

91 Oil Selections No. 30

92 Oil Selections No. 31

No number Oil Selections No. 28

All of these Oil Selections wells are producing gas, some of them plentifully. All have stop valves, but some end in screwed fittings and others in standard flanges. Some of them would be difficult to enter - fittings seized up and rusted over.

95 No. 1 St. Hyacinthe - when this was first visited, drilling had been suspended, it was thought temporarily, a few months previously. The rig (cable tool) was still in place, with a shack built around the collar of the hole. The hole ended in a $6\frac{1}{2}$" bore pipe a foot or so below the timber deck of the shack. Access was easy and it was easy to work at. This was visited later with a mercury thermometer (see later).

113 St. Lawrence River No. 1 - this has a production casing inside the borehole casing, ending in a large (9") "T" piece with the stem horizontal, extended about 6 ft. and reduced to about 3" - the top of the "T" is closed by a split cap - no indication of gas under pressure. All fittings could be easily dismantled.

117 No. 1 Nicolet - this has a production casing inside the borehole casing, which stands about 1 ft. above ground level. Inside this again was a loose pipe, probably drilled rod, whose upper end was plugged with concrete. There was a tripod over the hole, and it looked as if the drill string was still there. This is supposed to be about 3300 ft. deep. In any case, in its then condition it was of no use, and was not revisited.

514 Coupal No. 1 - this ends in a $4\frac{1}{2}$" drain, socket closed with a square-headed ($1\frac{3}{4}$" sq.) plug, and stands about a foot above ground, which is pretty wet. Gas bubbles seeping through mud about the pipe. Should be about 1300 ft. deep.

515 Lounan No. 1 - this ends in a pipe about $4\frac{1}{2}$" drain, standing in grass about 2 feet above ground. It was visited numerous times, first with a mercury thermometer, when it was found blocked at about 80 ft. This was cleared by putting some heavy weights on the probe, and greatest depth was 895 ft., where it seemed to be blocked solidly; snagged a few times on the way up too. This has been revisited recently, and maximum depth reached was 624 ft. Access is awkward for equipment - about 100 yards in bush from roadway.

516 Mallet No. 1 - this is a $2\frac{1}{2}$" (approx.) diameter pipe quite flush with ground level in a field. The top is filled with mud and clay, but it might just possibly be open at depth, though this is unlikely. Should be more than 3000 ft. deep, the bottom 1600 ft. being in Potsdam.

521 Senigon No. 1 - this is a pipe about $4\frac{1}{2}$" in diameter standing about a foot over surface in wet ground. The whole area smells of H_2S (hole is in black shale all the way), and well flows very cold water, about 5 gals./min. (this is only an estimate) never freezing or going dry, according to the owner. This should be about 2200 ft. deep, but was visited (unsuccessfully) with a thermistor probe, when the maximum depth reached was 238 ft. - this is probably where the water comes from.

524 Ste. Rosalie No. 1 and 525 St. Rosalie No. 2 - these are near each other, and in a locality where there is a dip of about 45° (there is an outcrop nearby). No. 1 is a 3" diameter pipe flush with the ground, and seems to have the drill rods still in place. No. 2 is similar, about 3" diameter with 2" rods still in place, but stands about a foot above ground level. Neither of these has been revisited, and in the condition

when first seen, would not be easy to use for temperature measurements.

A well which has not been identified with certainty, but which is probably No. 39, Cartier Natural Gas No. 5, was examined and found to be clear and probably useful. It is near Lounan, and is one of a group of at least five wells in the same locality (East of the Mohr well and west of Lounan) the remainder of which have been blocked intentionally - this one was probably overlooked, and has recently been found open to 808 feet. Another nearby, west of this one, is fitted with a gate valve, above which the pipe has been filled with rubble. The valve spindle is missing, but if the gate were still in place, this well might be open. Some of these do not seem to be marked on the map.

Oka - there is a hole here apparently not noted on the map (drilled by Oka Oil Co.,) supposed to be 1700 feet deep, all in pre-Cambrian. This was not found on first visit (a water well in drift was mistaken for it) but was found some time later: ends in concrete base for drilling rig (ground is sandy nearby), about $2\frac{1}{2}$" bore. Owner of land says casing extends to about 35 ft. This hole was found to be blocked at 35.8 ft. Cores are $1\frac{1}{4}$" in diameter, and were stored in shack nearby. These have since been taken to McGill. This well was revisited about Christmas 1959, but was found blocked fairly solidly at about 25 ft. This and the Mallet well (No. 516 above) would be particularly valuable for temperature measurements.

Cap Sante - a well drilled here by the Bald Mountain Co. was caved and concreted over in the first week of December 1958. This was not visited, but information was obtained by telephone from Bald Mountain Co. It is not known whether this is No. 8 or No. 163 on map.

A well near Yamachiche, apparently not noted on the map, was visited. This was a small privately drilled one, probably not very deep, but running water plentifully, and supplying the owner's cottage with enough gas for light and heat. The gas was under a fairly low pressure (contained by an inverted 40 gal. oil drum floating in the well, loaded by a few large stones). There was a lot of travertine about the well from the overflow. Many small privately sunk wells get gas just at bed rock, so this well is probably of very little use for heat flow.

In many cases where wells are in privately owned fields, the owners of the fields have been anxious to have the use of the fields again, and in many cases would like to have the casing drawn and the well ploughed over, so that the fact that a hole has been in the condition noted above may not mean that it still is so. This would probably apply to Eastern Canada No. 6 and Laduboro No. 2 more than to others.

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