TEMPERATURE MEASUREMENTS IN PERMAFROST

by

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16. Abstract

This report focuses primarily on the use of thermistors and thermocouples as sensors for making temperature measurements in permafrost soils. Logging systems are generally recommended over permanently installed multi-sensor cables when the highest accuracy is required. Guidelines are provided for thermistor logging probe design and for the calibration of temperature sensors.

Drilling methods for producing access holes into permafrost are discussed, as are the placement methods for casings or cables and the thermal recovery period resulting from drilling related thermal disturbances.

Field measurement techniques and their efforts on accuracy are also discussed. Methods for data analysis are provided for determining the presence or absence of permafrost, temperature gradients, heat flow, and freezing point depressions. Finally, a listing of manufacturers and suppliers is provided for system components.

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I. INTRODUCTION

A. General Considerations

Three-fourths of Alaska's land area is underlain by permafrost. When permafrost is ice-rich or contains massive ground ice, severe engineering and environmental problems can occur if it is caused to thaw. Solutions to these problems include avoidance and specialized construction techniques. Application of these solutions implies a knowledge of the existence and location of the permafrost and of its properties. A variety of geophysical methods are useful in developing this knowledge. However, permafrost is defined on the basis of temperature and time so that the only sure way of detecting it is by measuring its temperature. Permafrost temperatures are also useful in assessing its physical and mechanical properties.

Permafrost problems commonly involve thawing, settlement, and erosion as a result of surface disturbance; creep or fracture as a result of mechanical loading and the presence and flow of groundwater. Some specific examples include embankment settlements and cracking due to thaw consolidation, thermal erosion of sideslopes in cut areas, creep of piles and foundations in permafrost and the formation of icings on roads and in buildings. Temperature measurements are useful in evaluating these problems and in predicting whether or not they might occur in a proposed construction project.

Permafrost is defined as earth materials (soil, rock, etc.) existing at temperatures less than 0°C continuously for more than two years (Muller, 1947). This definition is a necessary condition for ice to exist in soil, however, it is not sufficient since pressure, chemical and soil particle effects may depress the freezing point of the soil pore water. From an engineering point-of-view, permafrost is of concern only when it contains ice. When permafrost is ice-rich or contains massive ground ice, it can become mechanically unstable on thawing, producing severe engineering and environmental problems.

Information on the presence and properties of permafrost and on processes that occur in permafrost can be obtained from temperature measurements and from experiments that require temperature measurements. For example, the presence or absence of permafrost can be determined from measured temperatures by noting whether or not these temperatures are less than 0 °C for more than two years. Questions on whether the permafrost is aggrading, or degrading or in equilibrium with the present climate can be resolved by analyzing the temperature profile through the permafrost. The position of the permafrost table and base (0 °C) can be noted on a temperature profile. In addition, the position of the ice-bearing permafrost table or base can be determined from changes in slope of the temperature profile or from borehole heating experiments. The mean annual temperature at the permafrost table is usually obtained by extrapolating the linear portion of the deep temperature profile to the surface. Freezing-point-depression (FPD) of the soil pore water at the permafrost table or base can be determined from the temperature profile. The local temperature gradient can be calculated from the measured temperature profile and, if the thermal conductivity of the soil is known, the local heat flow can be calculated. Under certain conditions, the thermal conductivity can be estimated from changes in the slope of the permafrost temperature profile through its base and from borehole heating experiments. The presence of massive ground ice can, in principal, be obtained from changes in the thermal gradient. Additional thermal properties (e.g. thermal diffusivity) can sometimes be determined from the ice content, gradients in the temperature profile and a knowledge of the thermal conductivity. Thermal properties can be determined by several other methods including repeated measurements of the temperature profile over a period of time.

The above properties of permafrost can be obtained more or less directly from the thermal regime of the permafrost or by analyses and interpretation of it. Additional information can be inferred from the lithology (soil profile). For example, if the lithology is known (say from information obtained during drilling), then it can be combined with the temperature data to predict the mechanical properties of the permafrost in a general way.

In addition to obtaining the properties of permafrost from measurements of its thermal regime, it is often possible to obtain information on physical processes and, sometimes, to evaluate them quantitatively. Common examples include heat and moisture transport processes during refreezing of the active layer, flow of groundwater (horizontal, vertical, and combined flow) and salt transport processes in saline permafrost.

The above constitutes a partial statement of what can be accomplished with information on the thermal regime of permafrost in terms of determining its presence, properties, and the transport processes occurring within it. Obviously not all these properties and processses can always be determined. Nevertheless, it is clear that the analyses and interpretation of the measured thermal regime is a powerful method for studying permafrost.

Unfortunately, most of the methods for obtaining temperature measurements in permafrost and for analyzing and interpreting these measurements are widely scattered throughout the literature and are not common knowledge among scientists and engineers.

The purpose of this report is to collect the specialized information from the current literature which is necessary for obtaining, reducing, and analyzing temperature measurements in permafrost and to present this information in a way that will be useful to engineers and scientists who are not familiar with the methods used in this field.

B. Assumptions and Other Considerations

There are a number of general assumptions, requirements, and considerations associated with making temperature measurements under difficult field conditions that may influence the choice of the temperature measuring system. The need for simplicity, reliability, and ruggedness of the temperature measuring system is obvious. It should also be lightweight, compact, and portable. Air temperature extremes commonly range from +30°C to -50°C. Wind, rain, blowing snow, salt water spray, etc., are additional factors to be considered.

It is assumed that electrical power is not available and only self-contained, battery powered systems are considered. Some familiarity with the principles and methods of temperature measurements (e.g. Benedict, 1977) is also assumed so that the report can focus primarily upon temperature measurements in permafrost.

The thickest ice-bearing permafrost in Alaska is 629 m (Osterkamp and Payne, 1981). Temperature measurements through this thick permafrost present special problems. However, it is thought that the main interests of users of this report will be focused on the top 50 m of permafrost. Therefore most of the general comments will be directed toward this relatively shallow geotechnical application.

Naturally-occurring permafrost temperatures are usually in the range from 0 to -20°C although some investigators calibrate their temperature measuring systems from +30 to -30°C (Raspet, et al., 1966; Hansen, 1963) which spans the range of temperatures normally found in the active layer and permafrost. The timing and frequency of the required temperature measurements should be considered since these may dictate the environmental conditions encountered and the type of system to be used.

Required accuracy should be considered with particular attention to the analyses and use of the data. Cost and complexity of the temperature measuring system, including the calibration system, increase strongly with the required accuracy. Instrumentation must be selected that can attain the desired accuracy and that meets the other noted requirements. The temperature range of interest is relatively narrow but contains a primary fixed point and several secondary fixed points useful for calibration purposes. Calibration can be accomplished by using fixed points or by comparison to a temperature standard. Except for the ice-point (IP), fixed points, temperature standards and their associated equipment are very expensive.

Permafrost conditions and the type of temperature information desired can influence the choice of a temperature measuring system. For example, temperatures at the permafrost table can be obtained with a probe forced through the active layer. Subsea permafrost near the sea bed often does not contain ice because of salty pore water so that it can be probed or drilled with relatively inexpensive methods (Osterkamp and Harrison, 1982).

Multi-sensor cables require drill holes and cable logging systems usually require cased drill holes. Ideally, a drilling method that reduces the thermal disturbance of the permafrost should be selected. However, drill holes for temperature measurements are often obtained from oil and mineral exploration efforts, water well drilling, geotechical exploration, etc., where no control can be exercised over the drilling method and the thermal disturbance introduced into the permafrost.

All of the above noted factors should be taken into consideration when selecting a temperature measuring system. However, the requirements for drilling, accuracy, and manpower for obtaining, reducing, and analyzing the data are the most important.

II. INSTRUMENTATION

A. General Considerations

Potential temperature sensors for permafrost temperature measurements include mechanical devices (e.g. liquid-in-glass thermometers), resistance devices (e.g. thermistors, resistance temperature devices or RTD's), voltage devices (e.g. thermocouples, integrated circuit devices), and others. Chinese investigators have used liquid-in-glass thermometers both as single sensors and as strings of sensors for drill hole temperature measurements in permafrost (Qui Guoqing, pers. comm.). Misener and Beck (1960) suggest the use of maximum thermometers for some temperature measurements in permafrost. Misener and Beck (1960), Robertson et al. (1966), Raspet et al. (1966), Lachenbruch et al. (1962), Hansen (1963), Judge (1973), Reiter et al. (1980), and Osterkamp and Harrison (1982) have described a variety of methods using thermistor sensors. The use of thermocouples in permafrost temperature measurements has been described by Johnston (1963) and Jurick (1977).

In recent years, thermistors have become the most widely used sensors for precision temperature measurements in permafrost. Thermistors are small, rugged, reliable, and inexpensive sensors and can be calibrated to a high degree of precision. Close fitting interpolation equations exist for relating thermistor resistance to temperature (e.g. Steinhart and Hart, 1968). In addition, it is possible to make very precise resistance measurements under field conditions. Thermocouples are often used in multisensor cable installations where reliability and low cost are important and where high precision is not necessary. While other types of sensors could be useful in permafrost temperature measurements, there does not appear to have been any concerted effort to adopt them for this purpose. Therefore, this report will focus primarily on the use of thermistors and, to a lessor extent, on the use of thermocouples as temperature sensors in permafrost. However, much of the discussion will apply to all types of potential temperature sensors.

Permafrost temperature measurements are usually made with a logging method or with multisensor cables. Commercially available logging systems and multisensor cables and those that can be constructed from components are described in Appendix A. The drill hole may be open or cased, however, a cased hole is preferred. There is little danger of a logging cable becoming stuck and multisensor cables can be recovered and replaced when the hole is cased. However, some geotechnical applications preclude the use of a cased hole. With the logging method, a sensor is attached to the end of a cable which is lowered in increments down the drill hole. The sensor is measured at each depth to determine the temperature. With a multisensor cable, the cable is placed in the drill hole, usually at the time of drilling, and left as a semi-permanent installation to be measured at later times.

The logging method has several advantages in comparison to the multisensor cable installation. Logging depths and spacings can be selected by the observer, measured precisely, and varied as desired. This is particularly useful when the temperature at some unknown depth is of interest; for example, at the base of the permafrost. Since a single sensor is used, which is removed from the hole after each logging, then its calibration can be checked repeatedly (e.g. in an ice bath). This allows detection of sensor drift or calibration changes. It is simpler to calibrate a single sensor on the end of a cable compared to a number of sensors on a long cable. The logging method can also be used to obtain a continuous temperature profile in the permafrost (Conaway, 1977; Reiter et al., 1980). For the above noted reasons, the logging method is usually used when the highest accuracy and greatest detail is required.

A disadvantage of the logging method is that a longer time is required to obtain a temperature profile in a drill hole. Typically about 3-5 minutes are required for the sensor to equilibrate at each depth. This is an important factor when the measurements must be made under very adverse conditions. A time series of the temperature profile using the logging method cannot be conveniently obtained, except at one depth. This may be a consideration for investigations of permafrost temperatures in the depth of annual temperature variations. The logging cable must be carried to the drill hole for each measurement of the temperature profile. Set-up of the logging cable may be somewhat difficult in deep drill holes since the cable is usually suspended in the hole on a pulley which must be mounted over the hole. If the hole is not cased then it can cave or freeze shut and therefore be lost for logging purposes. A common problem with open holes is that ground water often seeps into the hole from above the permafrost table and then freezes on the side of the hole just below the table. This can cause the hole to freeze shut just below the permafrost table in a single thaw season. Convection in a drill hole can cause the measured permafrost temperature to be colder than ambient temperatures. This problem may exist over the depth of annual temperature variations in small (a few cm diameter) holes and at all depths in large diameter holes. Convection can be almost eliminated in very small (<1 cm diameter) tubing placed in permafrost for logging temperatures (Osterkamp and Harrison, 1982). With the logging method, access to holes under buildings or busy roads may be restricted.

An advantage of multisensor cables is that very little time is required to measure all the sensors on the cable, typically <1 minute per sensor, because the sensors are already equilibrated with their surroundings. With the sensors connected to a switch and using a digital measuring instrument, several sensors per minute can be measured. It is usually easier for inexperienced personnel to master the details of multisensor cable measurements. There are only short lead wires to carry to connect the measuring instrument to the cable. If a hole containing a multisensor cable, caves, shears, or freezes shut, then this should not affect the cable except possibly when high freeze-back pressures are developed or large motions are involved. In small diameter holes, a multisensor cable normally fills a substantial portion of the hole or casing which may hinder or prevent convection.

A disadvantage of multisensor cables is that the measurement depths and spacings are fixed although this can be alleviated somewhat by moving the cable up or down in the hole if provisions have been made to do so. Calibration changes are not as easily detected as for single sensor logging cables. Since the sensors on a cable are calibrated independently and also drift independently, then the accuracy of the temperature profile may not, in general, be as good as for a logging system. If the data reduction is done by hand then more time may be required to reduce the data since each sensor may have a different calibration.

The instruments used for determining temperatures in permafrost are those generally used for measuring electrical resistances (R) and the small voltages of a thermocouple (electromotive force or emf). These include Wheatstone bridges, Kelvin bridges, digital volt meters (DVM), digital multimeters (DMM), potentiometers, and a variety of electronic indicators. Some of these instruments are direct reading in temperature while others read only resistance or the emf which must be converted to temperature.

Bridges and potentiometers utilize the null method of measurement and are available as battery powered, portable, precision measuring instruments. They usually have low temperature coefficients and can be sealed against moisture. A disadvantage is that they require manual balancing for each reading which is tedious and difficult to do for long times under adverse ambient conditions. DVM's and DMM's are also available as battery powered, portable, precision measuring instruments. Their digital readout does not require manipulation by the observer and it has the advantage that changes in readings can be conveniently monitored. However, these instruments appear to be more susceptible to extremes of temperature and moisture. Consequently, bridges and potentiometers are usually used for the most precise temperature measurements in permafrost.

B. Thermistor Temperature Measurements

1. Thermistors

Thermistors are semiconductors manufactured by sintering mixtures of oxides of nickel, manganese, iron, cobalt, copper, magnesium, titanium, and other metals. The resistance of thermistors increases with decreasing temperature and the change in resistance with temperature is large (i.e., they have large negative temperature coefficients). The temperature coefficient is defined as

$$\alpha \equiv \frac{1}{R}\frac{dR}{dT} \qquad (2.1)$$

where R is the resistance in ohms and T is the temperature in °C. Typically α ranges from about 1 to $8\%\text{-}^{\circ}C^{-1}$. For example, a thermistor with a nominal resistance of 10,000 ohms at 0 °C and a resistance change of 500 ohms per °C at 0°C would have $\alpha = 5\%\text{-}^{\circ}C^{-1}$.

Thermistors cannot be manufactured with identical R vs T curves and therefore are not completely interchangeable, at least when high precision is required. However, several manufacturers offer thermistors, at additional cost, which are commonly interchangeable at the ±0.1°C level with some at the ±0.05°C level over small temperature ranges. It is also possible to cull a number of thermistors (e.g. by measuring their IP resistance) to obtain a set with their IP resistance within a selected range, although this procedure is time consuming and requires a large number of thermistors.

The long term stability of thermistors is of concern for precise mesurements, particularly when they are used in permanent installations. A number of laboratory studies (see e.g. Osterkamp [1970]), have been performed to identify factors which have an adverse affect on thermistor stability. These factors include their use over a large temperature range, thermal and mechanical shock, and exceeding the specified maximum power rating. Generally, the larger the temperature span and the higher the temperature, the greater the drift. Since permafrost temperatures are low and their range small then drift is not usually a problem. Lachenbruch et al. (1962) found that for permafrost temperature data obtained with thermistors below the 300' depth, the standard error from a straight line diminished from 0.05°C to 0.02°C over an 8-year period. Beck (1956) determined that, under field conditions over a temperature range of 10°C, relative temperatures could be relied upon to 0.02°C for at least seventeen months. Judge's (1973) experience with glass bead thermistors used for drill hole logging in the temperature range from -40 to +40°C was that no calibration drift >0.02°C had been observed in a period of four years. Thermistors which drift <0.01°C over 100 months when used at low temperatures (<25°C) are available.

The time constant, τ , of a thermistor is the time required for the thermistor to change its temperature 63% of the difference between its original temperature and a temperature impressed upon it in a step change. τ depends on the thermistor and on the medium surrounding the thermistor. It appears that thermistors with τ = 1-20 sec in still air are generally used for permafrost temperature measurements. When thermistors are incorporated in a single or multisensor cable and placed semi-permanently in a drill hole, there is little concern with τ . The thermistor will eventually come to equilibrium with its surroundings and the times required for temperature changes in permafrost are usually very large compared to τ. However, when thermistors are incorporated into probes, as in logging cables or otherwise, it is desirable to have τ as small as possible to avoid having to wait for equilibration when the probe is inserted or the cable lowered to a new depth. In these cases, τ for the probe assembly must be considered rather than τ for the thermistor alone.

A thermistor is subject to self-heating (Joule heating) when a current flows through it, as in the measuring process. The power supplied to the thermistor is

$$P = IV \qquad (2.2)$$

where I is the current and V is the voltage drop across the thermistor. The power dissipated by heating in the thermistor is

$$H = \delta(T-T_o) \qquad (2.3)$$

where T is the thermistor temperature and T_o is the ambient temperature. The dissipation constant, δ, is usually defined as the power, in mW, which will raise the thermistor 1°C above T_o. Values for δ depend upon the medium surrounding the thermistor and commonly range from 10^{-2} mw-°C^{-1} to more than 10^{2} mw-°C^{-1} for thermistors suspended in still air. However, it is the value of δ for a cable or probe that must be considered rather than δ for the thermistor alone. The maximum permissible current for a given self-heating temperature increase, $T-T_o$, is from Eq. 2.2 and 2.3,

$$I_m = \left(\frac{\delta(T-T_o)}{R}\right)^{1/2} \tag{2.4}$$

As an example, suppose it is desired to measure temperature to an accuracy of 0.10°C using a probe with $\delta = 1$mW-°C^{-1} and $R = 10^4$ ohms at the temperature to be measured. As a rule-of-thumb, $T-T_o$ should be held to one-half the desired accuracy or 0.05°C. Then Eq. 2.4 shows that $I_m = 71\,\mu A$.

Thermistors with large α, R, δ, and small τ are the most desirable for temperature logging systems. The values for δ and R may be influenced by the choice or availability of the measuring instrument. Glass and epoxy covered beads and probes are commonly used.

2. Thermistor Probes and Cables

Current logging systems incorporate the thermistor or thermistor probe into a probe assembly attached to a cable. This assembly protects the thermistor and electrical connections from corrosive fluids in the drill hole and from large hydrostatic pressure in deep drill holes. Suitable probe assemblies have been described by Misener and Beck (1960), Judge (1973), Reiter et al. (1980), and Osterkamp and Harrison (1982). These probe assemblies may be demountable or permanently attached to the cable. Demountable probes allow the thermistor to be replaced if it drifts or fails, however, they are relatively bulky. Probes that are permanently attached to the cable can be made very small, about the same size as the cable, such that they can be put down very small diameter tubing (Osterkamp and Harrison, 1982). Small probes have the potential for relatively small τ. They are manufactured by attaching a thermistor to the end of a cable and then sealing the thermistor and leads into a suitably sized (slip fit) metal tube which has one end closed. Epoxy is used to make the seal and the thermistor is held in contact with the closed end of the tube until the epoxy hardens.

It is desirable to keep τ for the probe as small as possible since this lessens the time required for the probe to equilibrate at each depth. While measurements taken during equilibration can be extrapolated to obtain the <u>in situ</u> temperature (Osterkamp and Harrison, 1975), this procedure requires more work during data reduction. Equlibration, as the term is used here, relates to the value of τ for the probe, the sensitivity of the measuring instrument, and the temperature difference between stations. For an instrument with a sensitivity of one ohm, the corresponding temperature sensitivity is about 0.002°C for a thermistor with $\alpha = 5\%\text{-}^{\circ}C^{-1}$. Suppose that the temperature difference between stations is 0.2 °C. Then the above sensitivity (0.002 °C) is about 1% of the temperature difference (0.2 °C). If an exponential approach to equilibrium is assumed, then $\cong 5\ \tau$ will be required for the probe to approach within 1% (0.002 °C) of the temperature change. This approximate analysis shows that if $\tau = 1$ minute then about five minutes will be required for the probe to equilibrate. It is found that when thermistors with $\tau \cong 1\text{-}10$ sec in still air are incorporated into the probe designs noted above that $\cong$2-5 minutes are required for the probes to equilibrate under typical drill hole conditions. The experimental approach for obtaining the equilibrium temperature at a given depth is to adopt the criterion that if no change in thermistor R can be detected in an arbitrary time period (usually 1-3 minutes) then the probe has equilibrated. However, as the above example illustrates, τ for the probe, instrument sensitivity and the temperature difference between measuring stations should be taken into account when adopting such a criterion.

Both τ and δ of a probe will be larger than for the thermistor element because of the mass involved in the probe. If a thermistor probe (e.g. Fenwall K212E) is incorporated into a probe assembly then, depending upon construction details, it may be possible to use the probe values for τ and δ to evaluate its expected performance in a drill hole and to determine I_m. When a thermistor element is incorporated into a probe assembly then τ and δ must be measured or estimated.

Guidelines for probe design can be obtained by considering the heat balance for a probe in a borehole. Since the probe is in motion between measurement levels and there is probably some motion of the probe while it is held at a given depth then the heat transfer is by convection. This approach neglects conduction along the wires and radiative transfer. The rate of heat transfer is

$$m\,c\,\frac{dT}{dt} = h\,A\,(T_f - T) \tag{2.5}$$

where m is the mass of the probe, c is its specific heat capacity, h is the convective heat transfer coefficient, A is the surface area of the probe, T_f is the fluid temperature at time t and T is the probe temperature at time t. With conditions appropriate for a step change (i.e., a sudden change of depth),

$$T_f - T = (T_f - T_i)e^{-t/\tau} \tag{2.6}$$

where T_i is the initial probe temperature and the probe time constant

$$\tau = \frac{mc}{hA} \tag{2.7}$$

Eqs. 2.6 and 2.7 show that the probe response is governed by the quantities on the right hand side of Eq. 2.7, at least in this approximate treatment. The probe mass is ρv where ρ is its density and v is its volume. Therefore the probe material should be chosen so that the product ρvc is minimized and the quantity hA is maximized. Using these criteria, lead appears to be a more desirable probe material followed by aluminum, copper, brass, silver, and stainless steel which are about equal. Since it is desirable to conduct heat away from the probe as fast as possible then copper, silver, and aluminum should be desirable probe materials. However, stainless steel appears to be commonly used, possibly because of its corrosion resistance.

Probes should be constructed so that the thermistor is in contact with the probe tip. A dab of thermally conductive grease or a drop of oil helps ensure this contact.

Temperature logging cables usually have two, three, or four conductors (leads). Two conductor cables are small and light but do not permit measurements of conductor resistance with the cable in the drill hole. Therefore, direct corrections cannot be made for changes in lead resistance with temperature, which are required for precise measurements with long cables. For example, 26 AWG copper wire has a resistance change of 1 ohm per 100 m for a temperature change from 20 °C to 0 °C which corresponds to a temperature correction of a few thousandths degree Celsius. However, a 1 km cable would require temperature corrections of a few hundredths degree Celsius. In addition, changes in insulation resistance can also produce errors in the measurements and these changes cannot be determined with two conductor cables and a non-demountable probe.

Three conductor cables with two leads connected to one side of the thermistor and one lead to the other side allow a direct measurement of the series resistance of the two leads and, therefore, a correction for changes in lead resistance with temperature. Changes in insulation resistance still cannot be determined with non-demountable probes.

There are two configurations that are normally used with four conductor cables. With one configuration, two leads are connected to one side of the thermistor, one lead to the other side, and one lead is left open. This configuration allows the lead resistance and the insulation resistance to be measured with a two-terminal instrument via a switching arrangement. Then the true thermistor resistance is calculated from (Judge, 1973)

$$R = R_m - R_s - r_s + R_m^2/R_o \qquad (2.8)$$

where R_m is the measured thermistor resistance, R_s is the series lead resistance, R_o is the insulation resistance (open-circuit), and r_s is the difference between R_s and R_m. With the other four conductor configuration, two leads are attached to each side of the thermistor for measurements with a four terminal instrument. This method allows the lead resistance to be eliminated from the measurement. It is ideally suited for use with low resistance thermistors and platinum resistance elements.

Wire sizes for logging cables are selected to minimize size, weight, and stiffness of the cable while minimizing corrections for lead resistance. As wire size increases, the lead temperature corrections decrease but cable size, weight, and stiffness increase. Apparently 26 AWG wire is a compromise size used for many logging cables (e.g. Judge, 1973).

Wire insulation is usually plastic (polyethylene, polypropylene, polyolefin) with jackets of PVC, nylon and polypropylene. For extreme conditions of temperature and corrosion, teflon insulation and jackets are sometimes used although they are more expensive. Belden cable catalog gives a detailed comparison of cable insulation and jacket materials.

According to Beck (1963), the insulation resistance should be on the order of 2000 times the thermistor resistance to attain an accuracy of 0.01°C. For a sensor resistance of 10 KΩ this criterion requires a cable insulation resistance of 20 MΩ. Therefore, the cable and the resistance of the sensor should be selected to meet this requirement.

Logging cables are usually shielded and include a wire braid for strength and resistance to abrasion. Breaking strengths are about 50-150 lbs while cable weights are on the order of 10-20 lbs per thousand feet.

Cable markings for depth measurements are not usually necessary in deep holes where cable depth counters are normally used. However, corrections for cable stretch, while hanging in a fluid-filled hole, should be made for the most precise measurements since the error in depth measurements can be on the order of 3/4' in 100' (Judge, 1973). A precision metal surveyors tape is usually used to mark the cable at the desired intervals. Numbered, plastic, adhesive marking tabs can be attached at the marks. A piece of clear heat shrink tubing can be shrunk into place over the tabs to protect them from wear and tear and also from the drill hole fluid.

Multisensor cable requirements for insulation and jacket material are the same as for logging cables. However, the need for an impervious jacket is greater since multisensor cables are often left as semi-permanent installations in the permafrost for several years or more. For this reason, PVC or rubber may be specified for the jacket material.

Raspet et al. (1966) and Judge (1973) provide detailed descriptions for the fabrication of multisensor cables using thermistors. The process consists of marking the cable at the desired thermistor positions, cutting the jacket open for a short distance lengthwise, locating the two conductors, removing a short piece of insulation from the conductors, soldering or mechanically attaching the thermistor wires to the conductors, and insulating and sealing the thermistor in the cable. A common wire is normally used so that the number of thermistors in the cable is one less than the number of conductors. The series lead resistance can be measured by connecting one conductor to the bottom of the common conductor. Precautions must be taken to position the thermistor correctly, to avoid overheating the thermistor if it is soldered in place, and to make the thermistor and the cut in the cable jacket waterproof. It is desirable to measure the shorted resistance of the two conductors before installing the thermistor and to check the electrical connections of the thermistor before sealing it in the cable. It may be desirable to attach an electrical connector plug to the top of the cable to facilitate measurements. Some provision may also be necessary for supporting the cable in the hole.

Both short cables and cables exceeding a kilometer in length have been constructed using these procedures. Alternative procedures for very short holes (a few meters in depth) involve attaching the thermistors to wooden or plastic rods and installing these in either cased or open holes (McGaw et al., 1978), as noted previously.

3. Resistance Temperature Measurements

Wheatstone bridges and DVMs or DMMs are the most commonly used instruments to measure thermistor resistance under field conditions. A large variety of direct reading meters are available and most of these provide accuracies in the 0.1-1.0°C range. Most meters make two terminal resistance measurements and can be equipped with an external switching arrangement to measure three conductor cables. Some meters are designed to make four terminal resistance measurements to very high precision. These four terminal measurements have the advantage that lead resistance is eliminated. Meters usually have overranging capabilities (i.e., a 4-1/2 digit instrument set on the 10^4 scale may be capable of measuring up to 19,999 ohms with five digits indicated). An estimate of the temperature sensitivity and accuracy can be made if α, near the measured temperature, is known. As an example, a 4-1/2 digit DVM with an accuracy of ±(0.01% of range + 1 digit) when set on the 10^4 ohm scale to measure a thermistor resistance of 10^4 ohms with $\alpha = 5\%\text{-}°C^{-1}$ would have an accuracy of ±0.004°C. The accuracy of a DVM is also affected by the temperature coefficient of the instrument and by any temperature gradients in the instrument. Experience suggests that temperature gradients in an instrument, such as those brought about by transferring an instrument from a heated vehicle to the cold environment, may seriously affect its accuracy. Manufacturers specifications can be used to evaluate changes in accuracy with instrument temperature. An empirical estimate of the magnitude of these errors can be made by placing the instrument in a refrigerator or deep freeze while monitoring the resistance of a fixed resistor left at room temperature. Since permafrost temperature measurements are often made under ambient conditions quite different from those existing at the time of calibration, when high accuracy is desired, corrections for instrument temperature must be made.

The current passed through a thermistor sensor must be limited because of the problem of self-heating as noted above. This measuring current of the instrument can be determined from the manufacturer's specification and Eq. 2.4 used to evaluate the self-heating which should be limited to 1/2 the desired accuracy. Self-heating is manifested by a decrease in the indicated thermistor resistance with time, usually for a few minutes, immediately after the measuring instrument is connected to the thermistor.

Many DVMs and DMMs are small, light, and easily portable with the advantage of a digital readout and continual upgrading of the measurement without any action on the part of the observer. However, they are somewhat sensitive to adverse ambient conditions (especially cold temperatures and high moisture) and rough handling which cannot always be avoided. These problems can be reduced by placing the meters in a sealed and insulated box. However, Wheatstone bridges are usually favored for the most precise temperature measurements under adverse field conditions.

Direct current bridge methods commonly used to measure thermistor resistance usually employ the two terminal Wheatstone bridge. The balance condition gives the thermistor resistance

$$R_t = (R_1/R_2)\ R_s \qquad (2.9)$$

where R_s is the slidewire resistance and R_1 and R_2 are resistances in the opposite arms of the bridge. R_t depends only on R_s and the multiplier R_1/R_2. Since this is a null measurement, its accuracy depends on the sensitivity of the galvanometer, accuracy of the known resistors, accuracy and condition of the slidewire (or step resistors where used) and the presence of contact resistances. The slidewire contact resistance may be somewhat variable, depending on the condition of the slide, in older bridges and in bridges used under corrosive conditions. The ability of the observer to balance the bridge accurately and repeatedly under extreme ambient conditions for periods of several hours may also be a factor. When three or four conductor cables are used to obtain lead wire and insulation resistance, then a switching arrangement is used (Beck, 1963; Judge,1973) as noted previously. Although more sophisticated bridges exist for the purpose of evaluating or eliminating lead resistance (Luppold, 1969) these do not appear to be commonly used for permafrost temperature measurements.

The measuring current through the thermistor should be measured or obtained from the manufacturers specifications of the measuring instrument and used to evaluate the self-heating with Eq. 2.4. If the measuring current through the thermistor is too high it may be possible to replace the bridge battery with lower voltage batteries or to place a variable resistor across the bridge batteries. However, reduction of bridge voltage will usually reduce the sensitivity of the bridge.

The bridge should have a sensitive null detector for high precision measurements. It is also desirable that high precision, low temperature coefficient resistances be used in the bridge to reduce its temperature coefficient.

The slidewire of a bridge may become stiff when ambient temperatures are very cold. To protect the bridge from rough handling, moisture, etc., it may be desirable to place it in a sealed and insulated box. With reasonable care a Wheatstone bridge can be a relatively simple, portable, reliable, and precision instrument for making temperature measurements in permafrost even under adverse ambient conditions.

C. Thermocouple Temperature Measurements

1. Thermocouples

Thermocouples are junctions of dissimilar metals that produce an emf which depends on the difference in temperature between the measuring junction and the reference junction. If the temperature of the reference junction is known then the temperature of the measuring junction can be determined by measuring the emf generated in the circuit. Since thermocouples are primarily used in multisensor cables, their use for permafrost temperature measurements will be discussed in that context.

Type T thermocouples are recommended for temperature measurements in permafrost. These are made from copper-constantan wires which are resistant to corrosion and moisture. It is the only thermocouple type for which limits of error are established in the subzero temperature range. The Seebeck coefficient is 38.0 $\mu V\text{-}^{\circ}C^{-1}$ or 21.3 $\mu V\text{-}^{\circ}F^{-1}$ at the IP. Standard limits of error for type T thermocouples are ±1 1/2°F from -75 to 200°F and with special limit wire, ±3/4°F. The ADOTPF has used type T thermocouples with special limit, nylon insulated wire and type T shielded extension wire when necessary (Jurick, 1977). Extension wires are inserted between the measuring junction and the reference junction and have approximately the same thermoelectric properties as the thermocouple wires with which they are used. Advantages in using extension wires include improvements in the mechanical or physical properties of the thermoelectric circuit (e.g. flexibility and electrical resistance) and cost reductions. Johnston (1963) recommends teflon insulation with an outer jacket of asbestos for wires subjected to flexing at below freezing air temperatures. For most ground temperature installations, 20 AWG size wire is recommended.

Fabrication of the junctions can be done by twisting and/or soldering the wires together or by crimping a special tip around the ends of the wires with a special crimping pliers. Crimped junctions are entirely satisfactory for ground temperature measurements although soldered junctions are the most durable.

2. Cables and Circuits

Multisensor thermocouple cables can be constructed in several ways. A common wire is not usually used so that each junction requires a pair of wires. In one method, a number of thermocouple junctions, formed from wire pairs, are taped together at the desired spacing. Johnston (1963) recommends placing the wire pairs for each measuring junction, taped together, in a pipe or in a plastic hose. The pipe or hose is sealed and filled with oil and then placed in a drill hole. Thermocouple cables with individual pairs of thermocouple wires are also available. When these cables are opened, a wire pair can be isolated, the thermocouple junction formed and then insulated and sealed in the same manner as multisensor thermistor cables.

The ideal circuit for a multisensor cable of type T thermocouples is shown in Figure 1. This circuit requires separate reference junctions for each measuring junction and is used when the highest accuracies are desired. A modified form of the ideal circuit (Johnston, 1963) which uses one reference junction is shown in Figure 2. It avoids the use of extension wires, in the usual sense, and is simpler than the ideal circuit. This circuit ties all the constantan wires to a common point, mechanically (the wires should not be soldered), which then allows the use of a single constantan lead wire and reference junction. A potential problem with the modified circuit occurs when uninsulated thermocouples are installed in contact with the soil. Since different soil levels may be at different electrical

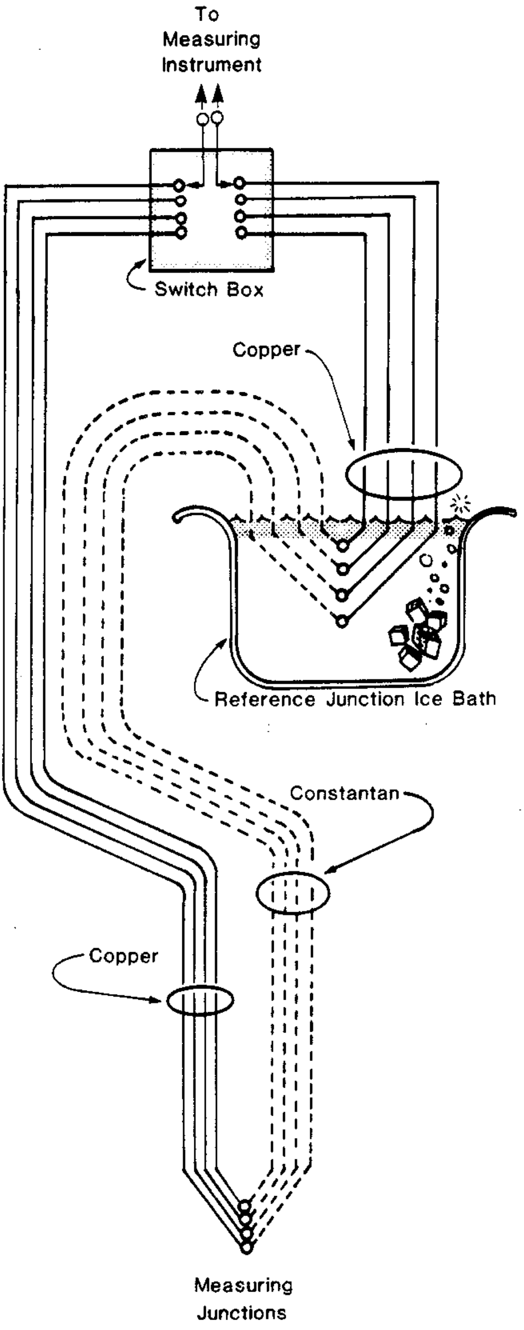

Figure 1. Ideal circuit for a multisensor cable of type T thermocouples. The reference junctions should be sealed and then placed in the same ice bath at the time the measurements are made. Copper lead wires are used to connect the measuring instrument to the switch

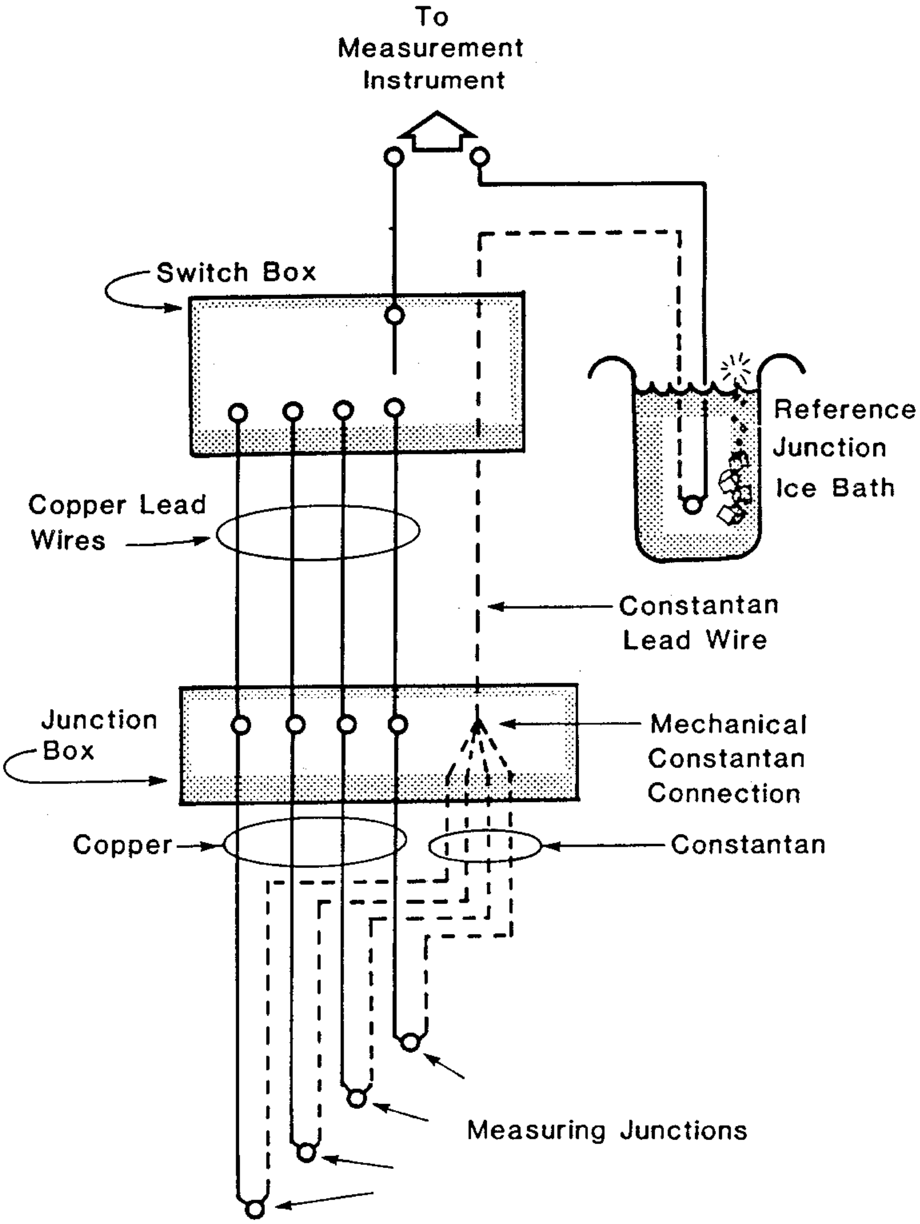

Figure 2. A modified form of the ideal circuit which uses only one reference junction. Copper lead wires are used to connect the measuring instrument to the switch

potentials, this procedure may superimpose an emf in addition to that of the thermocouple. The problem can be avoided by electrically isolating each thermocouple from the surrounding soil or by installing the thermocouples in oil-filled pipes or hoses as recommended above. With type T thermocouples, this modified circuit has the advantage of switching only the copper lead wires. Special thermocouple switches are available that switch both the copper and constantan leads. When these are used in the junction box, precautions should be taken to keep the switches at constant temperature during the time of measurement. A number of other specialized thermocouple circuits are described by Benedict (1977).

Grounding and shielding the thermocouple circuits may be desirable under certain conditions. For example, electrical noise may be produced by external electric and magnetic fields, unwanted and unknown emfs may be generated when the thermocouples are in contact with different earth potentials, and noise may be produced when there are different ground potentials between the instrument and the measuring junction. These latter problems can be minimized by grounding the thermocouple and its shielding at a single point, preferably at the measuring junction or as close as practical to it. Several possible grounded thermocouple circuits are shown in Benedict (1977) and ASTM (1981).

Since a thermocouple is a differential measuring device which produces an emf that depends on the difference between the temperature of its two junctions, then the reference junction should be maintained at a known and fixed temperature. This can be accomplished by placing the reference junction in an ice bath, by replacing the reference junction with an electronic reference junction or by other methods (ASTM, 1981). Battery powered electronic reference junctions are available, however, there is little or no information on their field use for permafrost temperature measurements. Ice baths are widely used, however, care must be taken to prepare and use them properly (see Chapter III). Errors can arise because of floatation of the ice, insufficient immersion depth, and galvanic currents which can occur when water comes in contact with the wires of bare reference junctions.

Uncertainties can be introduced into thermocouple temperature measurements by the thermocouple wire, measuring junction, extension wires, reference junction, and by other effects (e.g. noise or unknown emfs in the circuit) (Benedict, 1977; ASTM, 1981). Special type T thermocouple and extension wire can be obtained with ±3/4 °F limits of error, as noted above. Each junction has its own peculiarities but the associated uncertainties in temperature are very small. The use of extension wires can introduce extraneous emfs into the thermocouple circuit which can amount to errors of several degrees Celsius. Such large errors can be minimized by calibrating with the extension wires in place, using the same wires in the field and by maintaining their extremities at the same temperatures in the laboratory and in the field. Selector switches can introduce uncertainties of 1.5°F which can be minimized by keeping the switch at a uniform temperature that is the same in the field as in the laboratory during calibration. These switch-related uncertainties can be eliminated entirely by placing the switch in the copper wires only as in Figure 2.

Johnston (1963) states that it should be possible to obtain thermocouple temperatures accurate to at least ±0.5°F and in many cases to ±0.3°F. Jurick (1977) states that the accuracy of ADOTPF thermocouple installations was ±0.3°F at best and occasionally much worse.

The reliability of thermocouple installations is excellent. For example, since 1970 only 8 thermocouples out of 869 were found to be defective in ADOTPF installations versus 7 defective thermistors out of 224 (Jurick, 1977).

3. EMF Temperature Measurements

Portable meters and potentiometers are used to measure thermocouple emfs under field conditions although other instruments can be used (e.g. millivoltmeters, portable chart recorders). The instrument chosen for these measurements should be relatively simple, compact, lightweight, accurate, and not strongly affected by extremes in ambient conditions. Generally, it is more difficult to make the emf measurements required for thermocouple sensors compared to the resistance measurements required for thermistor sensors of comparable accuracy. Direct reading temperature meters are available for use with thermocouple sensors with stated accuracies ranging from a few tenths degree to a few degrees. However, many of these instruments have electronic reference junction compensators. Jurick (1977) found that these instruments gave satisfactory results only when used at or near normal room temperatures and that during field use when the instruments were subjected to cold ambient temperatures, errors of several degrees were observed. The problem could be partially alleviated by placing them in a sealed and insulated box.

Two types of DVMs are generally available; integrating and successive approximation types. The integrating type is less susceptible to errors from electrical noise interference. Typical uncertainties are on the order of ±(0.05% of range +1 digit).

Portable precision potentiometers may be obtained with typical limits of error of ±(0.03% of reading +3 μV). Since most permafrost measurements are in the microvolt range then the limit of error is on the order of ±3 μV which corresponds to a temperature error less than ±0.2°C. Johnston (1961a,b) gives additional information on the field use of instruments for measuring thermocouples.

III. CALIBRATION

Calibration of a thermistor consists of a determination of its electrical resistance, R, at a number of known temperatures. A means for interpolating the R values over the temperature range of interest and for converting these R values to temperature is required. Known temperatures are provided by fixed points or by comparison to temperature standards in a controlled temperature environment. Equations are available for interpreting and converting thermistor R values to temperature. Procedures for thermocouples are similar except that it is the emf which is measured rather than R. Additional general information on the calibration of temperature sensors can be found in Benedict (1977) and ASTM (1981).

A. International Practical Temperature Scale--1968

Current temperature measurements in science and industry are based on the International Practical Temperature Scale of 1968 (IPTS-68) adopted by the International Committee of Weights and Measures (CIPM, 1969). The IPTS-68 is an empirical scale chosen in such a way that the temperatures measured on it closely approximate thermodynamic temperatures. The thermodynamic temperature, T, has units of kelvin, K, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple-point of water (TPW) (i.e., the TPW is defined as 273.16 K). The Celsius temperature is defined by

$$T(°C) = T(K) - 273.15\ K \qquad (3.1)$$

Temperature differences may be expressed as kelvins or degrees Celsius.

IPTS-68 consists of a series of fixed points to which numerical values have been assigned, designated standard instruments and standard interpolation equations for defining the scale between the fixed points. The defining fixed points are established by realizing (creating experimentally) specified equilibrium states between the phases of certain substances. The most important fixed point for permafrost temperature measurements is the TPW, the equilibrium temperature between the solid, liquid and vapor phases of pure water at a pressure of 4.58 mm of Hg (TPW = 273.16K = 0.0100°C). A specially constructed platinum resistance thermometer (PRT) is the standard interpolating instrument in the range of permafrost temperatures. Interpolation between fixed point temperatures is provided by formulae which establish the relation between the resistance of the PRT and values of the IPTS-68 (CIPM, 1969).

There are several possible methods, based on the IPTS-68, for calibrating and maintaining the accuracy of a permafrost temperature measuring system. All methods rely on either fixed points or on a controlled temperature environment (usually a liquid bath) with a standard thermometer for determining the temperatures.

B. Fixed Points

The only primary fixed point in the range of temperatures usually found in permafrost is the TPW defined as 0.0100°C. Several useful secondary fixed points are shown in Table 3.1 (CIPM, 1969). The IP (0.000°C) is an inexpensive and convenient fixed point for calibration purposes and for verifying calibrations in the field. It is also used extensively as the reference junction environment for thermocouple systems.

The IP is realized in an ice bath which consists of a mixture of pure ice and pure, air-saturated water at a pressure of one atmosphere. An ice bath can be prepared by grinding ice, made from distilled or deionized water, into millimeter-sized chips with a commercial blender and placing this ice in a well-insulated container. Stainless steel or glass vacuum flasks about 10-15 cm in diameter and 30 cm or more in depth are commonly used. Pure water (distilled or deionized) should be added to the flask until the ice begins to float. More ice should be added and the mixture compressed to form a tightly packed slush. Any excess water should be decanted so that the water level is about 10% of the depth of ice below the ice surface and the ice should rest on the bottom of the flask. If the ice is allowed to float then care must be taken to place the device being calibrated entirely within the ice-water mixture. Gross errors (e.g. 4°C) can result if these precautions are not followed. The mixture should be allowed to equilibrate for about 1/2 hour before using it as an ice bath.

TABLE 3.1. Secondary reference points.

Sublimation point of carbon dioxide	-78.476 C
Melting point of mercury	-38.862 C
Triple point of phenoxybenzene	+26.87 C
Melting point of gallium	+29.771 C

Precautions should be taken to wash and rinse all containers, utensils, hands, temperature sensors, etc., in pure water to prevent contamination of the bath. The temperature of the ice bath is affected primarily by pressure and by the purity of the ice and water. At a distance h mm below the surface of the water in an ice bath, the temperature T, in °C, is

$$T = -1.32\times10^{-5}(P-760)-7.2\times10^{-7}\ h - 55(K-0.7\times10^{-6}) \quad (3.2)$$

where P is the atmospheric pressure in mm of Hg and K is the specific electrical conductance of the water in the bath in μmhos-cm^{-1} measured at 0°C (Beattie et al., 1937). Equation 3.2 shows that normal atmospheric pressure variations and immersion depths should not require corrections exceeding 0.001°C. However, the use of tap water in the ice bath could lead to errors on the order of several hundredths degrees Celsius. Osterkamp (1977) found that carefully prepared ice baths were routinely within 0.001°C of 0°C.

Thermal conduction of heat from the laboratory into a sensor in an ice bath (e.g., along the metal wires) can affect the calibration if the immersion depth is insufficient. A similar problem also exists for the immersion of a thermocouple reference junction in an ice bath. It has been established experimentally that about 15-25 cm of immersion depth are required to prevent this problem for precise calibrations (Caldwell, 1965; Osterkamp, unpublished research).

Under field conditions, an expedient ice bath can sometimes be formed by a pool of snow slush and water. If a sample of the water is obtained, its electrical conductivity can be measured in the laboratory and the ice bath corrected for water contamination.

Commercial suppliers of TPW cells and freezing and melting point cells are listed in Appendix B.

Permafrost temperature measuring systems can be calibrated to high accuracies using fixed point cells. The procedure involves a determination of thermistor resistances in several fixed point cells. An interpolation and conversion equation (Sec. 3.4) is then used with the constants in the equation determined by the known temperatures of the fixed points. The accuracy of the fixed point method can be better than 0.01°C. However, the method is somewhat limited in that it can be used only with sensors designed to be inserted into the fixed point cells and it cannot be used to calibrate multisensor cables. Further details are given in Sec. 3.4.

C. Comparison Methods

The most common method of calibrating thermistors or other sensors of permafrost temperature measuring systems is by comparison to a standard thermometer in a well-stirred liquid bath. The accuracy of this method depends on the accuracy of the standard thermometer and on the ability of the observer to bring the thermistor and the standard thermometer to the same temperature in the bath. Circulating controlled temperature baths are available that can maintain temperatures constant to ±0.01°C or better. Raspet et al. (1966) describe a bath that can maintain temperatures constant to ±0.002°C.

Choice of a standard thermometer depends on the desired level of accuracy. For the most precise work, where an accuracy on the order of 0.01°C is desired, the standard thermometer is a PRT. An instrument for measuring the resistance of the PRT such as a Mueller bridge or a precision potentiometer (Benedict, 1977) is necessary. The PRT should be calibrated periodically in a primary standards laboratory or at the National Bureau of Standards (NBS). Therefore a second PRT is usually necessary so that one can be used while the other is in transit for calibration. It is also necessary to maintain current, voltage, and resistance standards (depending on the measuring instruments) that are periodically certified by a primary standards laboratory or NBS. Considerable expense and effort must be devoted to maintaining a temperature calibration system of this accuracy.

Several standard thermometers meet requirements for accuracies in the 0.01 to 0.1°C range. For example, the YSI Model 777 Thermolinear Thermometer has an accuracy of ±0.05°C and a resolution of 0.003°C. Suitable liquid-in-glass thermometers can be calibrated to an accuracy of a few hundredths degree Celsius by NBS (Wise, 1976; Osterkamp, 1977). Accuracies in the 0.1 to 1.0°C range can be attained by using precision calibrated thermistors, platinum sensors, liquid-in-glass thermometers, or standard thermocouples as the standard thermometers.

The experimental procedure for calibration by comparison with a standard thermometer involves placing the standard thermometer and the thermistor in close proximity in a well-stirred, refrigerated, controlled temperature bath. At each calibration temperature the reading of the standard thermometer and the resistance of the thermistor is obtained. If the temperature variations in the bath are too great to achieve the desired level of temperature stability, then a large mass of material can be used to damp the temperature variations. For example, a solid iron bar (0.3 m long by 0.2 m in diameter) standing on end in the bath might be used with several holes drilled symmetrically on a circle on the end. The standard thermometer can be placed in one hole and the thermistors in the other holes. Alternatively, both the standard thermometer and the thermistor could be placed in the same hole. Raspet et al. (1966) decribe methods for calibrating individual thermistors in a controlled temperature bath and multisensor cables in an IP bath.

If the thermistor and the resistance measuring instrument are calibrated as a unit and then used together in the field then it is not necessary to convert the measured thermistor resistance to true resistance. However, if more than one measuring instrument is used, then either each instrument must be calibrated with the thermistor or the resistance accuracy of each instrument must be determined. The latter can be done by measuring standard resistances, traceable to NBS, over the resistance range where the bridge will be used. These considerations are usually necessary only where high accuracy, on the order of a few hundredths degree Celsius, is desired.

Corrections to field data, for the temperature coefficient of the measuring instrument, are also required for high accuracy. Very low temperature coefficient resistors (2 $\text{ppm-}^\circ\text{C}^{-1}$) spanning the desired resistance range can be obtained and sealed into a small unit. These resistors should be measured at the time of calibration and again when field measurements are made. The difference represents the change in the system in going from the laboratory to the field environment and can be added or subtracted, as necessary, to the measured thermistor resistance. These measurements also serve to detect the existence of gross errors or any changes in the measuring system.

D. Conversion and Interpolation Methods

Several manufacturers offer thermistors that are interchangeable within ±0.1°C and some within 0.05°C, as noted previously. The calibration of these thermistors can be verified at one fixed temperature, preferably the IP. This procedure makes it relatively simple and inexpensive to achieve accuracies on the order of ±0.1°C. However, when the thermistors are not interchangeable and when greater accuracies are required, then the thermistors must be specially calibrated. The calibration procedure produces a set of calibration points which are the thermistor resistances and their corresponding temperatures. It is impossible, in a practical sense, to obtain enough calibration points to define a continuous relationship between thermistor resistance and temperature. Therefore a method is needed to convert thermistor resistance to temperatures and to interpolate between calibration points. Calibration tables and equations are usually used for conversion and interpolation procedures.

Several equations describe the relationship between temperature and thermistor resistance (Roberston et al., 1966; Steinhart and Hart, 1968; Johnson, 1970; Judge, 1973). However, the relatively simple and precise equation of Steinhart and Hart (1968) is recommended over other equations. In this equation, the reciprocal of the temperature, in kelvins,

$$1/T = A + B \log R + C (\log R)^3 \qquad (3.3)$$

where A, B, and C are constants and R is the thermistor resistance at T. Equation 3.1 can be used to convert the thermodynamic temperature, T, to Celsius temperature. Equation 3.3 has the desirable feature of converting the measured thermistor resistance directly to temperature without the need for an inversion procedure. It has been tested against about one hundred other relationships and was consistently found to be the best. Over a range of 35°C it could be fit to nine calibration points to better than 0.001°C. Reducing the number of calibration points to three, allowed a fit to 0.003°C. Therefore, only a few calibration points are needed to determine the coefficients. These features make it possible to use three fixed points (mercury, ice, and gallium) and Eq. 3.3 to calibrate thermistors to an accuracy of 0.01°C or better from -40 to +30°C.

Steinhart and Hart (1968) have also shown that the best experimental strategy is to extend the calibration range outside the range in which measurements are to be made. Extrapolations beyond the calibration range deteriorate rapidly in accuracy.

When three calibration points are available, Eq. 3.3 can be used to algebraically determine the three coefficients, A, B, and C, for each thermistor. If a greater number of calibration points are available, then a computer least squares fitting program can be used to determine the coefficients. A separate set of coefficients are usually determined for each measuring instrument for very precise measurements.

For a relatively small temperature range (<10°C) and accuracies on the order of 0.05°C, Eq. 3.3 can be used with just two coefficients, A and B (i.e., °C=0). The resulting equation is somewhat simpler to use.

Once the coefficients have been determined, then thermistor temperatures can be calculated directly using Eq. 3.3. Alternatively, when less accuracy is required, a graph or a table of thermistor resistances vs. temperatures can be produced using Eq. 3.3. Robertson et al. (1968) have developed a procedure involving interpolation of tabulated resistance and temperature values which allows temperatures to be determined to an uncertainty of 0.01°C.

E. Thermocouple Considerations

The above comments on the IPTS-68, fixed points, and comparison methods of calibration also apply to thermocouples. One special problem with the calibration of thermocouples is the galvanic action that may be set up when water in an ice bath comes in contact with bare thermocouple wires. The use of insulated wires or thermowells can eliminate this error.

Required thermocouple accuracies are not usually high, typically on the order of 1/2-1°C. The utility of thermocouples is that, with special limit wires, they are interchangeable at this level of accuracy so that calibration is not necessary. However, because of commercial variability of the wire, an important criterion for an accurate thermocouple system design is that all of the thermocouple wire should come from the same lot. Sufficient wire should be ordered at the beginning of a project to insure that replacement or additional wire will not need to be obtained from other lots or manufacturers. Such wire may be within specified error limits but may have significantly different thermoelectric properties from the original wire.

The usual procedure with thermocouples is to use reference tables (Powell et al., 1974; ASTM, 1981) to convert the measured emfs to temperature. The most precise reference tables for thermocouples (Powell et al., 1974) have been generated using a variety of data on standard thermocouple wires. A power series expansion of the form

$$E = a_1T^1 + a_2T^2 + a_3T^3 + \ldots., \quad (3.4)$$

where E is the thermocouple emf in microvolts, T is the temperature in degrees Celsius and the a's are coefficients determined by the fit of Eq. 3.4 to the data, was used to relate E to T. For type T thermocouples, fourteen coefficients are required in the temperature range from -270 to 0°C and eight coefficients in the range from 0 to 400°C. Table 3.2 was generated using these coefficients but with E rounded off to the nearest microvolt.

TABLE 3.2. Type T thermocouples--thermoelectric voltage as a function of temperature (°C), reference junctions at 0°C.

°C	0	1	2	3	4	5	6	7	8	9	10
					Thermoelectric Voltage in Absolute Millivolts						
-60	-2.152	-2.185	-2.218	-2.250	-2.283	-2.315	-2.348	-2.380	-2.412	-2.444	-2.475
-50	-1.819	-1.853	-1.886	-1.920	-1.953	-1.987	-2.020	-2.053	-2.087	-2.120	-2.152
-40	-1.475	-1.510	-1.544	-1.579	-1.614	-1.648	-1.682	-1.717	-1.751	-1.785	-1.819
-30	-1.121	-1.157	-1.192	-1.228	-1.263	-1.299	-1.334	-1.370	-1.405	-1.440	-1.475
-20	-0.757	-0.794	-0.830	-0.867	-0.903	-0.940	-0.976	-1.013	-1.049	-1.085	-1.121
-10	-0.383	-0.421	-0.458	-0.496	-0.534	-0.571	-0.608	-0.646	-0.683	-0.720	-0.757
- 0	-0.000	-0.039	-0.077	-0.116	-0.154	-0.193	-0.231	-0.269	-0.307	-0.345	-0.383
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234	0.273	0.312	0.351	0.391
10	0.391	0.430	0.470	0.510	0.549	0.589	0.629	0.669	0.709	0.749	0.789
20	0.789	0.830	0.870	0.911	0.951	0.992	1.032	1.073	1.114	1.155	1.196
30	1.196	1.237	1.279	1.320	1.361	1.403	1.444	1.486	1.528	1.569	1.611
40	1.611	1.653	1.695	1.738	1.780	1.822	1.865	1.907	1.950	1.992	2.035

Equation 3.4 may be approximated by quadratic, cubic and quartic equations (two, three and four coefficients). Table 3.3 gives the coefficients for these approximations and the expected error. The error range given in the table is the difference between the voltage as obtained from the full set of coefficients and the respective reduced order approximations.

It is also desirable to have the temperature as a function of voltage. These data are given in Table 3.4 in steps of ten microvolts from -2.10 to +1.60 mv (about -58 to +37°C). A power series expansion of the form

$$T = a_1E^1 + a_2E^2 + a_3E^3 + a_4E^4, \quad (3.5)$$

where the a's are coefficients determined from the data, can be used as a reduced order approximation to Table 3.4. The coefficients for quadratic, cubic and quartic approximations and the expected error range is given in Table 3.5. Table 3.5 suggests that the quartic approximation in the temperature range from -200 to 0°C is sufficiently precise for most purposes ±0.3°C). All of the digits in the coefficients should be used to prevent rounding off errors in the calculations. Benedict (1977) and ASTM (1981) discuss other specialized methods useful for calibration of thermocouples.

TABLE 3.3. Type T thermocouples--quadratic, cubic, and quartic approximations to the data as a function of temperature (°C) in selected temperature ranges. The expansion is of the form $E = a_1T+a_2T^2+a_3T^3+a_4T^4$ where E is in microvolts and T is in degrees Celsius.

Temperature Range (°C)	a_1		a_2		a_3		a_4		Error Range (μV)
	Argument	Exp	Argument	Exp	Argument	Exp	Argument	Exp	Exact-Approx.
I. Quartic Equation									
-200 to 0	3.8749056	+1	4.5149809	-2	-4.7759448	-5	-2.5773959	-8	-0.14 to 0.13
-200 to 400	3.8621703	+1	4.5433050	-2	-3.4731838	-5	1.4661300	-8	-7.00 to 3.50
0 to 400	3.8468407	+1	4.6651731	-2	-3.7375793	-5	1.5999833	-8	-0.90 to 0.90
II. Cubic Equation									
-200 to 0	3.8795175	+1	4.6406525	-2	-3.7515430	-5	...	...	-0.40 to 0.45
-200 to 400	3.8419940	+1	4.5812964	-2	-2.8715275	-5	...	...	-24 to 19
0 to 400	3.8666983	+1	4.3739444	-2	-2.4974186	-5	...	...	-5 to 3
III. Quadratic Equation									
-200 to 0	3.9460429	+1	5.6897673	-2	...	...	...	...	-10 to 14
-200 to 400	3.7311396	+1	3.9301943	-2	...	...	...	...	-350 to 300
0 to 400	4.0381232	+1	2.9943775	-2	...	...	...	...	-75 to 55

TABLE 3.4. Type T thermocouples--temperature (°C) as a function of thermoelectric voltage, reference junctions at 0 °C.

mV	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	.10
	Temperatures in Degrees C (IPTS 1968)										
-2.00	-55.39	-55.69	-55.99	-56.29	-56.60	-56.90	-57.20	-57.50	-57.80	-58.11	-58.41
-1.90	-52.41	-52.70	-53.00	-53.30	-53.60	-53.90	-54.20	-54.49	-54.79	-55.09	-55.39
-1.80	-49.45	-49.74	-50.04	-50.33	-50.63	-50.92	-51.22	-51.52	-51.81	-52.11	-52.41
-1.70	-46.51	-46.81	-47.10	-47.39	-47.68	-47.98	-48.27	-48.56	-48.86	-49.15	-49.45
-1.60	-43.61	-43.90	-44.19	-44.48	-44.77	-45.06	-45.35	-45.64	-45.93	-46.22	-46.51
-1.50	-40.72	-41.01	-41.30	-41.59	-41.87	-42.16	-42.45	-42.74	-43.03	-43.32	-43.61
-1.40	-37.87	-38.15	-38.44	-38.72	-39.01	-39.29	-39.58	-39.86	-40.15	-40.44	-40.72
-1.30	-35.03	-35.31	-35.60	-35.88	-36.16	-36.44	-36.73	-37.01	-37.30	-37.58	-37.87
-1.20	-32.22	-32.50	-32.78	-33.06	-33.34	-33.62	-33.90	-34.18	-34.47	-34.75	-35.03
-1.10	-29.42	-29.70	-29.98	-30.26	-30.54	-30.82	-31.10	-31.38	-31.66	-31.94	-32.22
-1.00	-26.65	-26.93	-27.21	-27.48	-27.76	-28.04	-28.31	-28.59	-28.87	-29.15	-29.42
-0.90	-23.91	-24.18	-24.45	-24.73	-25.00	-25.28	-25.55	-25.83	-26.10	-26.38	-26.65
-0.80	-21.18	-21.45	-21.72	-21.99	-22.27	-22.54	-22.81	-23.08	-23.36	-23.63	-23.91
-0.70	-18.47	-18.74	-19.01	-19.28	-19.55	-19.82	-20.09	-20.36	-20.63	-20.90	-21.18
-0.60	-15.78	-16.04	-16.31	-16.58	-16.85	-17.12	-17.39	-17.66	-17.93	-18.20	-18.47
-0.50	-13.10	-13.37	-13.64	-13.90	-14.17	-14.44	-14.70	-14.97	-15.24	-15.51	-15.78
-0.40	-10.45	-10.71	-10.98	-11.24	-11.51	-11.77	-12.04	-12.31	-12.57	-12.84	-13.10
-0.30	-7.81	-8.08	-8.34	-8.60	-8.87	-9.13	-9.39	-9.66	-9.92	-10.19	-10.45

TABLE 3.4. (continued)

mV	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	.10
-0.20	-5.19	-5.45	-5.72	-5.98	-6.24	-6.50	-6.76	-7.03	-7.29	-7.55	-7.81
-0.10	-2.59	-2.85	-3.11	-3.37	-3.63	-3.89	-4.15	-4.41	-4.67	-4.93	-5.19
-0.00	0.00	-0.26	-0.52	-0.78	-1.03	-1.29	-1.55	-1.81	-2.07	-2.33	-2.59
0.00	0.00	0.26	0.52	0.77	1.03	1.29	1.55	1.80	2.06	2.32	2.58
0.10	2.58	2.83	3.09	3.35	3.60	3.86	4.12	4.37	4.63	4.88	5.14
0.20	5.14	5.39	5.65	5.91	6.16	6.42	6.67	6.93	7.18	7.44	7.69
0.30	7.69	7.95	8.20	8.45	8.71	8.96	9.22	9.47	9.72	9.98	10.23
0.40	10.23	10.48	10.74	10.99	11.24	11.50	11.75	12.00	12.25	12.51	12.76
0.50	12.76	13.01	13.26	13.51	13.76	14.02	14.27	14.52	14.77	15.02	15.27
0.60	15.27	15.52	15.77	16.02	16.27	16.52	16.77	17.02	17.27	17.52	17.77
0.70	17.77	18.02	18.27	18.52	18.77	19.02	19.27	19.52	19.77	20.01	20.26
0.80	20.26	20.51	20.76	21.01	21.25	21.50	21.75	22.00	22.24	22.49	22.74
0.90	22.74	22.99	23.23	23.48	23.73	23.97	24.22	24.47	24.71	24.96	25.20
1.00	25.20	25.45	25.69	25.94	26.19	26.43	26.68	26.92	27.17	27.41	27.65
1.10	27.65	27.90	28.14	28.39	28.63	28.88	29.12	29.36	29.61	29.85	30.09
1.20	30.09	30.34	30.58	30.82	31.07	31.31	31.55	31.79	32.04	32.28	32.52
1.30	32.52	32.76	33.00	33.25	33.49	33.73	33.97	34.21	34.45	34.69	34.94
1.40	34.94	35.18	35.42	35.66	35.90	36.14	36.38	36.62	36.86	37.10	37.34
1.50	37.34	37.58	37.82	38.06	38.30	38.53	38.77	39.01	39.25	39.49	39.73

TABLE 3.5. Type T thermocouples--quadratic, cubic, and quartic approximations to the data as a function of voltage in selected temperature ranges (°C). The expansion is of the form $T = a_1E+a_2E^2+a_3E^3+a_4E^4$ where E is in microvolts and T is in degrees Celsius.

Temperature Range (°C)	a_1		a_2		a_3		a_4		Error Range (°C)
	Argument	Exp	Argument	Exp	Argument	Exp	Argument	Exp	Exact-Approx.
I. Quartic Equation									
-200 to 0	2.3837090	-2	-2.9878839	-6	-7.1945810	-10	-1.0041943	-13	-0.3 to 0.3
-200 to 400	2.6792411	-2	-1.0370271	-6	-6.1330327	-11	-1.3988385	-15	-6 to 5
0 to 400	2.5661297	-2	-6.1954869	-7	2.2181644	-11	-3.5500900	-16	-0.15 to 0.17
II. Cubic Equation									
-200 to 0	2.8388396	-2	1.1561610	-6	4.3380483	-10	...	...	-1.0 to 0.8
-200 to 400	2.8164207	-2	-9.0701000	-7	2.3070982	-11	...	...	-10 to 7
0 to 400	2.5074243	-2	-4.4920686	-7	7.9942544	-12	...	...	-0.6 to 0.7
III. Quadratic Equation									
-200 to 0	2.1878624	-2	-2.3425024	-6	...	...	...	...	-4 to 3
-200 to 400	2.7401364	-2	-4.3784364	-7	...	...	...	...	-33 to 19
0 to 400	2.3610934	-2	-2.1980131	-7	...	...	...	...	-3 to 3

IV. INSTALLATION OF SENSORS

A. Probing

Probing involves driving a hollow rod or a pipe into the permafrost and then measuring the temperature inside of the rod or pipe or in the hole after they are removed. The driver can be a sledge hammer, electrical impact drill, cathead and drop hammer, air, electrical or gasoline powered jack hammer, or a hydraulic system (Blouin et al., 1979; Osterkamp and Harrison, 1982; Esch, 1982). Standard drill rod, iron water pipe, or specially designed drive rod may be used. In one method (Osterkamp and Harrison, 1982), continuous plastic tubing inside of the drive rod was placed in subsea permafrost to depths of several tens of meters. The drive rod can be pulled up around the tubing leaving the tubing in place to be logged at a later time. Probing is possible in permafrost where there is little or no ice-bonding of the soil particles. This situation arises near the sea bed in the thawed layer of subsea permafrost which contains very salty pore water. It may also occur because of soil particle effects in warm, fine-grained permafrost. For example, in very warm permafrost (Fairbanks silt), a rod or pipe can often be driven several meters into the frozen soil. It is usually possible to reach the permafrost table and to penetrate a short distance through it (depending on the soil type) by probing through the active layer or thawed soil above the table in September. Probing in frozen coarse-grained soils is difficult or impossible with the above noted methods.

These probing methods are relatively simple, fast, and inexpensive ways of obtaining access holes for temperature measurements in the active layer, thawed zones above ice-bonded permafrost and sometimes a few meters into fine-grained permafrost. The thermal disturbance caused by probing is usually small compared to other methods of sensor installation. Time scales for the return of the hole to equilibrium are on the order of minutes to several days.

B. Drilling

Access holes for temperature measurements in permafrost are usually made by drilling. Drilling equipment includes hand augers, unsupported gasoline or electrical powerheads and augers, frame mounted lightweight portable drills, and large stationary, portable or vehicle mounted drill rigs. Drilling methods include augering, rotary with circulation of air or mud, water jetting and others. Hand augers can be used to drill small diameter holes to depths of several meters in fine-grained soils. Powerheads, of the type used for drilling post holes, allow penetration to 10 m or more in fine-grained permafrost. Frame mounted, lightweight, portable drills increase this penetration to several tens of meters (Brockett, 1982). The water jetting method can produce access holes 50 m or more in depth in fine-grained permafrost (Cederstrom and Tibbitts, 1961; Judge et al., 1976; Osterkamp and Harrison, 1982). For deeper holes, or for drilling in coarse-grained permafrost larger drill rigs are usually necessary.

Criteria for selecting a drilling method should include consideration of the surface distrubance and the thermal disturbance of the permafrost during drilling. Surface disturbance can be minimized by drilling when the ground is snow covered. It may be desirable to cover the ground surface around the drill hole with a tarpauline or plywood so that drill cuttings and debris can be removed from the drill site. Restricting sharp turns by tracked vehicles in the immediate vicinity of the drill site can help to minimize surface disturbance. If the original ground surface has been disturbed during drilling, it may be advisable to fertilize and reseed it during the clean-up phase. Fertilizer (nitrogen, 20%; phosphoric acid, 10%; potash, 10%) and grass seed (Pennlawn Red Fescue) has been used with good results in Alaska.

Thermal disturbance of the permafrost during drilling can be reduced by selection of the appropriate drilling method. However, other factors such as the season, the time required for drilling and the presence of ground water may contribute to the drilling disturbance. Holes drilled during the cold weather of early spring appear to return to equilibrium faster than holes drilled during the summer or fall. There is little data available to quantitatively assess the effect of the drilling methods and other factors on the drilling disturbance. Some general impressions are as follows. Augering usually produces very little drilling disturbance. Holes 30 m in depth can usually be augered in just a few hours and return to equilibrium on time scales of a few weeks to a few months. Rotary drilling during cold weather with air circulation to remove the cuttings usually results in a relatively small drilling disturbance with a return to equilibrium on time scales of a month to several months. Rotary drilling with water circulation to remove the cuttings causes a relatively large drilling disturbance with time scales of months to years to return to equilibrium. Very large drill rigs (for drilling oil wells) produce a drilling disturbance that may require several decades to return to equlibrium (Lachenbruch et al., 1982). Drilling experience suggests that water jetting methods produce drill holes that may require times on the order of weeks to months to return to equilibrium (Osterkamp and Harrison, 1982).

In some areas, permafrost exists with the elevation of the ground water table much higher than the permafrost base. When the base of the permafrost is penetrated, this ground water can then rise in the drill hole and may even be under pressure resulting in artesian flow from the hole (Linell, 1973). The injection of this water into the drill hole increases the time required for the hole to return to equilibrium (due to the latent heat associated with freezing that must be removed by conduction in the permafrost). In the artesian case, the water flow should be terminated so that the hole can eventually refreeze and return to equilibrium.

It is recommended that the hole be cased when using either the logging method or multisensor cables. If the drill casing is left in the hole then temperatures can be measured inside of it by logging or using multisensor cables. If the hole is open then a plastic or iron pipe, capped at the bottom, should be placed in the hole. Any subsequent caving in the hole should have little or no effect on the use of the hole for temperature measurements.

Drill cuttings should be used for back-filling, taking care to use fine material and to break chunks to keep them from bridging the hole. The pipe or casing should be filled with a non-freezing fluid; low temperature oils and diesel fuel are often used. Anti-freeze solutions are not recommended since, if a leak occurs or the pipe overflows, they can melt the permafrost when in contact with it. A logging cable can be used to log the pipe for temperature or a multisensor cable can be lowered into the pipe and left in place. It may be desirable to suspend the cable in the hole. Judge (1973) recommends the use of a Kellems cable grip to support the cable in the hole. A tripod mounted over the hole with a box containing any necessary connectors, switches, etc., may also be necessary.

Special hole finishing methods are required for very deep drill holes (e.g. abandoned oil wells or dry holes). These must be approved on a hole-by-hole basis by the Alaska Oil and Gas Conservation Commission.

C. Geotechnical Considerations

Logging and multisensor cable methods are suitable for most geotechnical applications, particularly for obtaining permafrost temperatures in undisturbed terrain. However, some geotechnical applications automatically rule out certain methods. For example, while casing of holes is usually recommended, temperature measurements in road beds that are undergoing active thaw settlement should not be made in cased drill holes since the casing may eventually protrude above the road surface. Solutions to these and other geotechnical problems utilize the principles of the foregoing sections but often in unusual ways.

Permafrost temperatures at very shallow depths may be obtained by burying one or more sensors at the desired depth. These sensors should be sealed from moisture. If a temperature profile is desired the sensors may be attached to a plastic or wooden rod which is inserted into a drill hole (McGaw et al., 1978). The drill hole may be open or preferably cased if the application allows. Sometimes the rod cannot be left in place between measurements. In these cases, the hole should be capped and filled (e.g., with a wood rod, insulation, etc.) to prevent or restrict air circulation. When the rod, carrying the sensors, is placed in the hole, sufficient time must be allowed for the sensors to equilibrate. Equilibration will normally be faster if the sensors are forced into contact with the side of the hole.

When temperatures must be measured in a horizontal hole as in a hillside or under a road or building, multisensor cables are preferred over the logging method. These installations often require running the cable some distance from the structure and/or gathering the cable ends at some central point.

Multisensor cables are often installed on piles supporting roads, pipelines, bridges, etc., on permafrost. The most secure installations appear to be where a small diameter iron pipe is welded to the pile and the cable placed in the pipe. A similar installation can be used on well casing.

V. FIELD METHODS

A. General Considerations

The equipment used in the logging method can be carried to the hole site in a backpack. It consists of the sensor, cable, reel, measuring instrument, tent, pulleys, depth counter, weights, switches, timer, notebook, and other small items. Equipment for measuring a multisensor cable is lighter since it does not include the cable and some other small items. A tent is recommended for shelter while making the measurements. It can be pitched next to the hole or, in some cases, directly over the hole if it has an opening in the floor. Dome tents are desirable since their motion on windy days is minimal with the tent material in tension. Under rainy conditions, the tent helps to keep the equipment and observer dry and reasonably comfortable. When it is snowing, electrically charged snow particles falling on the null detector of a bridge or blowing across it can cause the detector to fluctuate wildly. A tent solves this problem. During sunny weather, when the sunlight falls on the measuring instrument, it can cause temperature gradients in the instrument which appear as instrumental drift. The problem is aggravated when the instrument rests on a cold surface. Placing the instrument in a tent with an insulating pad under it reduces this problem substantially. In cold weather, the observer will normally be more comfortable in a tent, especially when the wind is blowing. A tent can also be heated. Balancing a bridge a hundred or more times over several hours under trying environmental conditions will be done more precisely if the observer is reasonably comfortable.

In some geotechnical applications, it may be possible to bring a vehicle close to the hole and to make the measurements while in the vehicle. Logging can be carried out by running the cable from the vehicle to the hole and then down the hole. Multisensor cable measurements can be made by using a long extension wire from the vehicle to an electrical connector on the cable.

A measured temperature profile consists of a set of temperature and depth measurements and other information needed for data reduction. In short holes (up to ≅60 m), sensor depth can be determined from markings on the cable while it is suspended in the hole with a clamp (a heavy duty paper clip works well). In deeper holes, the cable is usually passed over a pulley with a mechanical counter. A cable weight may be used to keep the cable firmly in contact with the pulley. The added weight also helps the cable sink in mud-filled holes. According to Judge (1973), cable stretch in a hole may amount to 15 feet at a depth of 2,000 feet or about 3/4 feet at a depth of 100 feet. Misener and Beck (1960) detected permanent cable extensions of 0.5% when heavy equipment was used. For precise work, cable stretch should be taken into account. When a cable counter is used, the cable should be carefully reeled in and the depth going down compared to the depth coming up to correct for any slippage or permanent stretching.

Electrical noise is sometimes a problem and it has been found to be desirable to ground the measuring instrument and cable shield to the same point which can be the casing if it is metal. The measuring instrument should be left on during measurements. Some instruments drift substantially the first hour or so until they stabilize, especially if they have just been removed from a warm environment. The zero setting for a null detector should be checked for each reading. The instrument should be unbalanced between readings so that each reading is independent.

B. Field Calibration and Verification of Measurements

The calibration of multisensor cables can be checked by measuring each sensor at the same depth in the hole while the cable is being installed. This can also be done at a later time if provisions have been made to raise and lower the cable in the hole. For the most precise measurements, a logging system can be checked periodically with an ice bath in the field. If a second cable is available then it should be used to measure the temperature at several random depths and the data compared to that obtained with the main logging cable. The drift of a measuring instrument can be detected and corrected by measuring the low temperature coefficient resistor that was measured during calibration. For the most precise measurements, this resistor should be measured before and after each sensor measurement. The normal procedure is to measure it before and after logging and about once every 30 minutes during logging. It is desirable to measure it more frequently while the bridge is stabilizing.

Graphing the data while logging can help to detect any poor measurements since an equilibrium temperature profile should be relatively smooth except when crossing lithological changes. A small hand calculator can be used to calculate the temperature using Eq. 3.3. The resulting measured profile can be graphed between measurements while waiting for the probe to equilibrate at each depth.

VI. DATA REDUCTION AND ANALYSES

A. Data Reduction

The raw data consists of a set of resistances and depths and the times at which these were measured. A number of corrections are necessary to obtain the true *in situ* temperature profile. Depth measurements are usually made with respect to a convenient reference plane (e.g. the top of the casing), however, the usual datum plane is the ground surface. This correction requires only a simple subtraction of the height of the reference plane above the ground surface from the measured depths. Corrections for cable stretch are not required when using a cable counter.

If the measured resistances do not represent equilibrated values then a method must be found to obtain them. Since a probe may be approximated by a line heat source (or sink), this suggests that its return to equilibrium may follow a 1/t curve (i.e., a graph of resistance with reciprocal time would be linear). Osterkamp and Harrison (1976) found that this was approximately true for many of their measurements. This procedure requires recording the time that the sensor is lowered to a new depth and then a sufficient number of resistance and time values to generate a curve. Some experimentation is required to establish the time scale and the spacing of the measurements. In general, this is a laborious procedure and should be avoided when possible.

For precise work the measured resistance values should be corrected for instrument drift, temperature coefficient of the instrument, effects of temperature gradients on the instrument, etc. If a very low temperature coefficient resistor is measured at the time of calibration and then again at the time the field measurements are made, as recommended above, then corrections can be made for these errors. A sufficient number of measurements of the resistor should be made in the laboratory to establish its average resistance. The difference between the average value in the laboratory and the measured value in the field is added to the thermistor resistance if the field value is lower and subtracted from the thermistor resistance if the field value is higher.

If the calibration procedure eliminated the cable resistance (as with 3 or 4 terminal measurements), then, using the same method in the field, no additional correction for cable resistance variation with temperature is necessary. There is an error involved when using two-conductor cables, however, as noted above, when the cables are short the error is small.

When the above corrections have been applied to the raw data then the corrected thermistor resistances can be converted to temperatures using Eq. 3.2. The resulting measured temperature profile is the *in situ* profile.

The *in situ* profile may not be the equilibrium profile because of the drilling disturbance noted above which may require long time periods to dissipate. Lachenbruch and Brewer (1959) have shown that the borehole and thermal disturbance of drilling can be treated as a continuous line heat source. The axial temperature due to a constant heat source Q applied for a time, s,is

$$T = T_0 + \frac{Q}{4\pi K} \ln \left(\frac{t}{t-s}\right) \qquad (6.1)$$

where T_o is the initial temperature in the permafrost, K is the thermal conductivity, t is the time measured from the start of drilling and s is the time of drilling at a given depth. Eq. 6.1 shows that if the drill hole temperature, T, at some depth, is graphed with ln (t/t-s), then a straight line with intercept T_o (the temperature before drilling) should result. Additional details and examples are given in Lachenbruch and Brewer (1959).

Ground surface temperature disturbances (water bodies, roads, buidings, etc.) and topographical changes may distort the temperature profile by lateral heat flow and changes in surface temperature. For some purposes (e.g. heat flow measurements) it is desirable to correct the temperature profile to a flat earth condition with no surface disturbances. Lachenbruch (1957, 1968) and Gold and Lachenbruch (1973) describe the methods.

When the _in situ_ equilibrium temperature profile has been corrected for surface and topographical disturbances, then the resulting profile can be used for a variety of thermodynamic calculations and can be directly compared to other corrected equilibrium temperature profiles.

B. Data Analyses

The introduction of this report described the type of information that could be obtained from temperature profiles in permafrost. This section will describe in greater detail how to obtain this information. However, the analyses of temperature profiles in permafrost are complex tasks and only an outline of the methods can be given here. For additional details the reader should consult the references.

Permafrost is defined on the basis of temperature (<0 °C) and time (for two years or more). Therefore, a determination of its presence or absence requires temperature measurements for two years. In practice, inspection of one equilibrium temperature profile is all that is normally used. This procedure works well because ground temperatures, particularly below the depth of annual freezing, change very slowly with time. Problems arise near the permafrost table where temperatures must be monitored for a two year period to determine whether permafrost is present or absent and its level in the ground. Problems can also arise when the temperature data is of low accuracy. For example, permafrost warmer than -0.5 °C is common in Interior Alaska and, using measurements with an accuracy of ±0.5 °C, it would be difficult to decide on the presence or absence of this permafrost. More accurate measurements are needed in these cases.

Figure 3 is an example of temperature profiles in warm permafrost. The ice-bearing permafrost base (≅25 m depth) can be determined from the equilibrium temperature profile obtained after the drilling disturbance had dissipated. However, consider the profile measured eight days after drilling. It demonstrates that the approximate depth to the ice-bearing permafrost base (25-26 m) can also be determined very soon after drilling from the change in slope of the temperature curve. The reason is that, as long as any ice remains, then the temperature around the

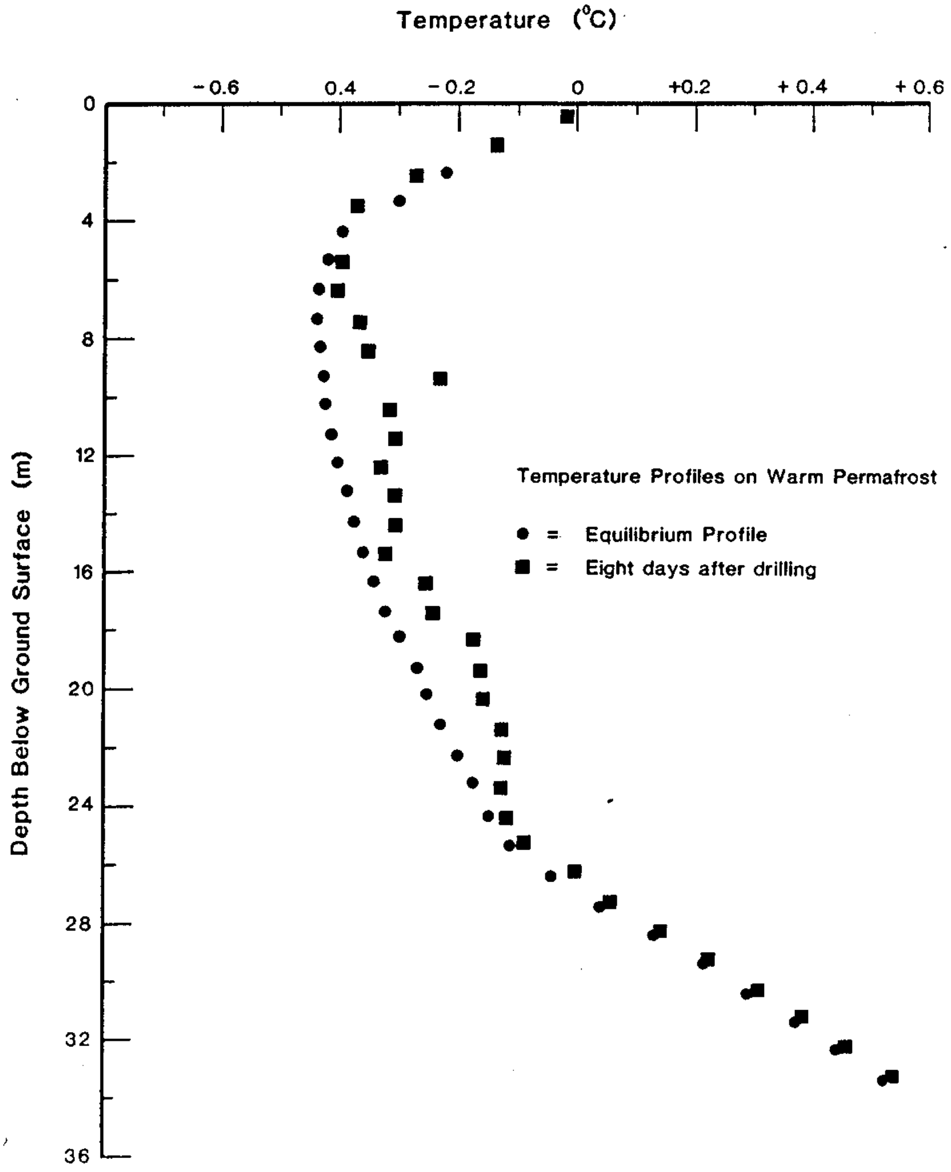

Figure 3. Temperature profiles in warm permafrost. The temperature differences between the two profiles are caused by the drilling disturbance

drill hole must remain at the melting point of the ice-water-soil mixture. The position of the permafrost table (its top surface) is more difficult to determine from these temperature data. It is usually obtained from probing and temperature measurements during late summer or early fall.

Temperature gradients can be obtained directly from the temperature profiles. This determination is best made with an equilibrium temperature profile. However, Lachenbruch and Brewer (1959) have shown that, in a very disturbed hole, the gradient defined by a least squares line, 67 days after the completion of drilling, was only 5% greater than the probable equilibrium value. At this time, the measured temperatures were still about 2°C greater than the equilibrium value.

The mean annual ground surface temperature (MAST) is obtained by extrapolating the lower linear portion of the equilibrium temperature profile to the surface. For example, the permafrost in Fig. 3 has a MAST $\cong -0.72°C$. The relationship between mean annual air temperature (MAAT) and MAST is not usually known. It is difficult to determine because of surface effects (e.g. snow cover, vegetation) and the presence of the active layer. In addition, the numerical modeling results of Goodrich (1978) suggest that the effect of a snow cover and the active layer may be to displace the true MAST from the extrapolated value.

Permafrost thicknesses, determined by the position of the 0°C isotherm, do not usually correspond to the thicknesses of ice-bearing or ice-bonded permafrost which may be up to 60 m less than the permafrost thicknesses on Alaska's North Slope (Osterkamp and Payne, 1981). The temperature difference between 0°C and the base of the ice-bearing or ice-bonded permafrost is the freezing-point-depression (FPD) of the soil pore water. If it is assumed that the factors producing FPD are additive, then the equilibrium temperature (FPD) of a soil-water-ice system is given by (Osterkamp, 1975)

$$T_o = 0.0100 - T_p - T_c - T_s \tag{6.2}$$

where T_p, T_c, and T_s are the separate FPD for pressure, chemical and soil particle effects. Neglecting air saturation and atmospheric pressure variations from one atmosphere of pressure,

$$T_o \cong -T_p - T_c - T_s \tag{6.3}$$

If the system is water saturated, the pressure on the ice and water phases equal and, if equlibrium prevails, then the pressure term becomes

$$T_p = 0.0075\ P \tag{6.4}$$

where P is the pressure in atmospheres on the ice and water in the pore spaces. For example, if P is assumed to be the hydrostatic pressure then T_p = 0.44 °C at a depth of 600 m.

T_c depends on the type and concentration of solute in the soil pore water. When the solute concentration is known, the FPD value can be calculated from it or obtained from the phase diagram.

The FPD term associated with soil particle effects is given by (Anderson et al., 1973)

$$T_s = \left(\frac{W}{a}\right)^b \qquad (6.5)$$

where W is the fractional unfrozen water content and a and b are empirically determined constants related to the specific surface area of the soil. For saturated silts and coarser-grained soils T_s = 0.01°C or less while for clays T_s could exceed several degrees Celsius.

Figure 3 shows that $T_o \cong -0.12$°C for base of the ice-bearing permafrost at this site. At this depth, $T_p \cong 0.02$°C, and, therefore, the sum of T_c and T_s must be $\cong 0.10$°C. However, information on the solute type and concentration or on T_s are not available to help separate chemical and soil particle effects at this site.

Gold and Lachenbruch (1973) have shown that, for saturated materials, the water content (volume fraction) is

$$\phi = 0.72 \ln \left(\frac{G_t}{G_f}\right) \qquad (6.6)$$

where G_t and G_f are the geothermal gradients in the thawed soil under the permafrost and in the permafrost respectively. If the permafrost thickness is in equilibrium with the climate, then G_t and G_f can be obtained from the temperature profiles. The equilibrium condition probably holds for most of the deeper permafrost on Alaska's North Slope but not for most of the discontinuous permafrost south of the Brooks Range (Osterkamp, 1983). Since the geothermal gradients are related to the thawed and frozen thermal conductivities then

$$\frac{K_f}{K_t} \cong 4^{\phi} . \tag{6.7}$$

Gold and Lachenbruch (1973) also provide other relationships of the thermal conductivity and thermal diffusivity to ϕ. Equations 6.6 and 6.7 do not apply to the temperature profile in Figure 3 since this permafrost is not in equilibrium with present climate.

If the thermal properties of the thawed and frozen material are known (e.g. from direct measurements) then the heat flow into the base of the permafrost and in the permafrost can be determined from the heat conduction equation

$$Q_t = -K_t \, G_t \tag{6.8}$$

and

$$Q_f = -K_f \, G_f \tag{6.9}$$

where Q_t and Q_f are the heat fluxes in the thawed and frozen material respectively.

The above is a sketch of some of the analyses that can be applied to permafrost temperature profiles. Another large class of analyses, that will not be included here, involve the application of the theory of heat conduction to permafrost. This is possible because the ice in the pore spaces of permafrost largely blocks the transport of matter (water or moisture) which insures that the heat transport will be conductive. This fact has been exploited by many investigators to determine the effects of natural processes and anthropogenic activities on permafrost (see Gold and Lachenbruch, 1973).

VII. SUMMARY

This report focuses primarily on the use of thermistors and, to a lesser extent, on the use of thermocouples as sensors for making temperature measurements in permafrost. However, much of the material applies to all types of temperature sensors and systems for temperature measurement. Logging systems are generally recommended over semi-permanent multi-thermistor cable installations when the highest accuracy is required. Care must be taken in the selection of thermistor sensors to ensure that proper time constants and dissipation constants are obtained and that the thermistors are compatible with the cable and measuring instruments. Guidelines for thermistor probe design show that the product of probe density, volume, and specific heat capacity should be minimized to minimize the probe time constant. Logging cables are selected to minimize size, weight, and stiffnes while minimizing corrections for lead resistance. Three and four conductor cables allow elimination of, or corrections for, lead resistance.

Wheatstone bridges, digital volt meters and potentiometers are commonly used to measure thermistor resistances and thermocouple voltages under field conditions. Bridges and potentiometers are somewhat more reliable under adverse field conditions.

Calibration of temperature sensors can be accomplished using the fixed point method or the comparison method. High accuracy can be achieved with both methods. A polynomial equation relating the reciprocal of thermistor temperature to odd powers of the log of thermistor resistance is recommended for converting thermistor resistances to temperatures and to interpolate between calibration points.

Drilling methods for producing access holes in permafrost should be selected to minimize the thermal disturbance of the permafrost during drilling and the surface disturbance. The holes should be cased with small diameter plastic or iron pipe after drilling for both logging and multisensor cable systems. In certain geotechnical applications, such as measuring temperatures under roads on permafrost that may be subjected to thaw consolidation, it may be desirable to leave the hole uncased.

The care taken by the observer in making the permafrost temperature measurements is a significant factor in obtaining high quality data. A vehicle or a tent should be used while taking the measurements, both to protect the observer and the measuring system. Corrections for thermistor depth, cable temperature, instrument drift and equilibration of the thermistor in the hole are required for high accuracy. The measured in situ temperature profile may represent the effects of lateral heat flow and other thermal disturbances to the permafrost. A variety of methods for data analyses and for obtaining the equilibrium temperature profile in the permafrost are available. Discussions and/or references are provided for the techniques of determining the presence or absence of permafrost, position of the permafrost table or base, position of the ice-bearing permafrost table or base, temperature gradients, thermal properties, heat flow, mean annual surface temperature, freezing-point-depression of the soil pore water and for application of the theory of conductive heat transfer to permafrost.

Construction details are provided for a relatively inexpensive temperature logging system for permafrost temperature measurements. A list of manufacturers and suppliers is provided for permafrost temperature measuring systems and components.

VIII. ACKNOWLEDGEMENTS

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X. APPENDICES

APPENDIX A. Permafrost Temperature Measuring Systems For Geotechnical Applications

The two commercially available logging systems noted in Appendix B (Fluid Dynamics Corporation and Epic, Inc.) should be adequate for most temperature measurements for geotechnical purposes in permafrost. However, the use of the Epic system has not yet been reported and it is limited to temperature measurements warmer than -5°C. The Fluid Dynamics system has been used extensively in permafrost, however, it is designed primarily for logging deep drill holes. A relatively inexpensive system for shallow geotechnical applications can be constructed as follows. A thermistor that has $\tau \leq 10$s and $\delta \cong 1$ mw-°C^{-1} or greater should be used. Thermistor resistance at the IP should be 1.0-1.4x10^{4} ohms. The thermistor should be sealed in a small-diameter, thin-walled metal tube (see Chapter II) and attached to a small-diameter, two conductor, shielded cable with 22-26 AWG wire about 50 m in length. The cable should be marked at the desired intervals and then wound on a reel--the metal reels usually used for shipping the cable are satisfactory.

The measuring instrument should have a measuring current on the order of 30 μA or less to avoid thermistor self-heating. A 4-1/2 digit DVM with low measuring current (e.g. HP3465B) or a Wheatstone bridge (e.g. L & N 4289-2 or 3 with reduced voltage for the bridge power supply) should meet this low current requirement. Calibration of the system can be carried out by the comparison method, using a mercury-in-glass thermometer (e.g. Brooklyn Thermometer Co.) in a refrigerated controlled temperature bath. Both the thermometer and the thermistor should also be calibrated at the IP.

Attainable field accuracy with this system depends primarily on the care taken by the observer during calibration and use of it and on the severity of field conditions but should be about 0.05 °C.

Thermistor cables can be constructed using the detailed instructions of Judge (1973). If accuracies greater than ±0.1 °C are not required, then thermistors, interchangeable at this level, can be used (e.g. Yellow Springs Instrument Co., Inc., or Fenwall Electronics). The value for τ of the thermistors is not important in these cable installations, however, $\delta \cong 1$ mW-°C^{-1} should still be used. Then, the DVM and bridge requirements are the same as for the logging system described above provided the IP resistance is the same. It is recommended that the cable be checked in a large ice bath prior to use. Installation should be in oil-filled plastic pipe, iron pipe or casing unless thaw settlement will be a problem, as noted previously.

Thermocouple cables can be constructed using the detailed instructions of Johnston (1963). With special limit wire, accuracies approaching 0.5 °C should be attainable. The circuitry shown in Figure 2 is recommended, where only the copper wires are switched and a single IP is required. A DVM capable of resolving a few microvolts (e.g. HP3465B) or a potentiometer (e.g. L & N 8686-3) are suitable thermocouple measuring instruments. It is recommended that the cable be installed in an oil filled plastic pipe, iron pipe or casing except possibly where thaw settlement will be a problem.

APPENDIX B. Manufacturers and Suppliers

1. Logging Systems

(a) Fluid Dynamics Corporation
66 South Holman Way
Golden, CO 80401
[Also sells components for logging systems]

(b) Epic, Inc.
150 Nassau Street
New York, NY 10038

Companies that manufacture geophysical borehole logging tools often make a temperature probe and associated cable and measuring instruments.

2. Thermistors

(a) Fenwall Electronics
63 Fountain Street
Framingham, MA 01701

(b) Industrial Division
Yellow Springs Instrument Co., Inc.
Yellow Springs, OH 45387

3. Thermocouples

(a) Omega Engineering, Inc.
One Omega Drive, Box 4047
Stamford, CN 06907

(b) Leeds and Northrup
North Wales, PA 19454

(c) Industrial Division
Yellow Springs Instrument Co., Inc.
Yellow Springs, OH 45387

4. Cables

(a) Belden Corporation
P.O. Box 1327
Richmond, IN 47374

- (b) Berk-Tek, Inc.
  Box 60, R.D. 1
  Reading, PA 19607

- (c) Custom Cable Company
  5310 Glenmont
  Houston, TX 77036

5. Reels

- (a) Fluid Dynamics Corporation
  66 South Holman Way
  Golden, CO 80401

- (b) Edgar Sharpe & Associates LTD.
  1983 Kipling Avenue North
  Rexdale, Ontario, CANADA M9W 4J4

6. Portable Wheatstone Bridges

- (a) Leeds and Northrup
  North Wales, PA 19454

- (b) Richard Brancker Research, LTD.
  27 Monk Street
  Ottawa, Ontario, CANADA K1S 3Y7

- (c) General Radio
  300 Baker Avenue
  Concord, MA 01742

7. Digital Volt Meters

- (a) Hewlett- Packard
  1820 Embarcadero Road
  Palo Alto, CA 94303

- (b) Data Precision Corporation
  Audubon Road
  Wakefield, MA 01880

- (c) John Fluke Mfg. Co., Inc.
  P.O. Box 7428
  Seattle, WA 98133

8. Potentiometers

(a) Leeds and Northrup
North Wales, PA 19454

9. Fixed-Point Apparatus and Platinum Resistance Thermometers

(a) Industrial Division
Yellow Springs Instrument Co., Inc.
Yellow Springs, OH 45387

(b) Leeds and Northrup
North Wales, PA 19454

(c) Trans-Sonics
P.O. Box 326
Lexington, MA 02173

[Triple-point-of-water cells only]

10. Calibration Instruments

(a) Mueller bridges and resistance measuring potentiometers

Leeds and Northrup
North Wales, PA 19454

(b) Temperature standards

Industrial Division
Yellow Springs Instrument Co., Inc.
Yellow Springs, OH 45387

(c) Precision thermometers

Brooklyn Thermometer Co.
90 Verdi Street
Farmingdale, NY 11735

11. Low Temperature Coefficient Resistors

(a) Tel Labs
154 Harvey Road
Londonderry, NH 03053

12. Switches, Standards, Miscellaneous

(a) Leeds and Northrup
(b) Omega Engineering, Inc.
(c) Yellow Springs Instrument Co., Inc.
(d) General Radio