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CHAPTER D1

WATER TEMPERATURE—INFLUENTIAL FACTORS, FIELD MEASUREMENT, AND DATA PRESENTATION

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BOOK 1

COLLECTION OF WATER DATA BY DIRECT MEASUREMENT modified by heat exchange as it moves through the unsaturated zone. Moreover, residence time of infiltrated water in the unsaturated zone may be fairly long because the infiltrating water generally displaces soil water already in place (Warrick and others, 1971). Thus, infiltration at land surface will result in water just above the capillary fringe being recharged to the ground-water body. Schneider (1962) inferred the effects of recharge from precipitation on the basis of deviation of a few tenths of a degree Celsius in the seasonal water-temperature trends for two wells tapping a shallow aquifer.

Temperature differences within the ground-water flow system due to recharge diminish within the aquifer with distance from the recharge source. The rate at which such temperature differences are dissipated depends upon the thermal conductivity and heat capacity of the solid-fluid complex comprising the aquifer and upon the velocity of the fluid as it affects heat dispersion. The various modes of heat transfer have been described in detail by Bear (1972, p. 641-643).

Ground-water movement results in areal temperature variations—due both to the effects of local recharge of water of different temperature than that of the ground water and to the interception of geothermal heat and its lateral transfer in the moving ground water. Supkow (1971) attributed much of the areal ground-water-temperature variation at the water table for Tucson basin (about 14°C) to these causes. Moreover, Cartwright (1968) and Birman (1969) proposed the use of temperature measurements at shallow depths to prospect for ground water, based at least in part on the effects of moving ground water on the geothermal gradient. The geothermal gradient also may be distorted by vertical ground-water movement. As noted by Sorey (1971), measured ground-water temperatures sometimes deviate by a few tenths of a degree Celsius from that described by a linear geothermal gradient.

Schoeller (1962) mentioned some secondary factors which under normal circumstances bring about only negligible changes in the temperature of the ground-water-flow regime. These include heat generated by friction of ground-water flow within the porous medium, temperature changes caused by the expansion of water brought up from great depths, and heat generated by chemical reactions. With regard to this latter factor, Hanshaw and Bredehoeft (1968) and Back and Hanshaw (1971) postulated that endothermic and exothermic chemical reactions can produce marked temperature changes in ground water. Lovering and Morris (1965) discussed the possibility that ground-water temperatures can be raised significantly by oxidation of sulfide deposits.

The injection or infiltration of radioactive or other polluting materials into the ground-water system may also result in a temperature anomaly. A dramatic change in the temperature of a spring near St. Louis, Mo., is attributed to a rise and fall of bacterial activity. The bacteria have been traced to organic matter leached from a nearby landfill (A. B. Carpenter, oral commun., 1973).

Part 2. Field Measurement

Two major factors need to be considered in planning and conducting field measurements of temperature. These factors are (1) proper selection of instruments and (2) proper field application and procedures. Discussions in this section, therefore, include, first, a description of equipment and, secondly, recommendations of methods and procedures for measuring temperature in the field.

Instruments

Instruments for measuring temperature consist of two basic parts—a sensor and a scaling device. The two components combined form a thermometer. For example, consider a mercury-filled thermometer. The mercury is a material that expands upon heating, and, when contained in a tube of glass that has a uniform bore, it becomes a sensor with approximately uniform response to temperature changes. When an etched scale is added to the mercury-in-glass sensor, the combined system becomes a thermometer. Some of the sensors used in temperature measurement and some of the thermometers which incorporate them are discussed in the subsections that follow.

Temperature sensors

A temperature sensor is a device which responds to the stimulus of heat and transmits a resulting signal. Even within the relatively narrow band of the temperature spectrum where the majority of water-temperature measurements are made, there are several well-established physical principles which are the basis for temperature sensors. It is therefore important that the potential user have an understanding of these sensors and of the physical principles underlying their operation, for this will help him make the proper selection when he has a temperature-measuring application. Only when one has an adequate understanding of temperature sensors can factors, such as sensitivity, accuracy, speed of response, expected useful life, cost and resistance to corrosion, sensitivity to vibration, and other conditions, be thoroughly evaluated. The material for this section on temperature sensors was obtained from Considine (1957) and Kallen (1961).

Liquid-in-glass

The liquid-in-glass sensor has been in use for over 200 years, and, although it is not generally used today for high-precision measurements, it is the most widely used device for temperature measurement. It consists typically of a thin-walled glass bulb joined to a class capillary stem closed at the opposite end. The bulb and part of the stem are filled with an expansive liquid. Almost any liquid can be used; however, the liquids most commonly used are mercury, mercury-thallium, gallium, alcohol, toluol, pentane, and the silicones. The better grades of sensors with metallic fillings have an inert gas under pressure above the liquid column. Nitrogen, argon, or carbon dioxide is generally used above mercury; nitrogen above mercury-thallium. This gas under pressure helps to prevent separations of the liquid in the capillary tube.

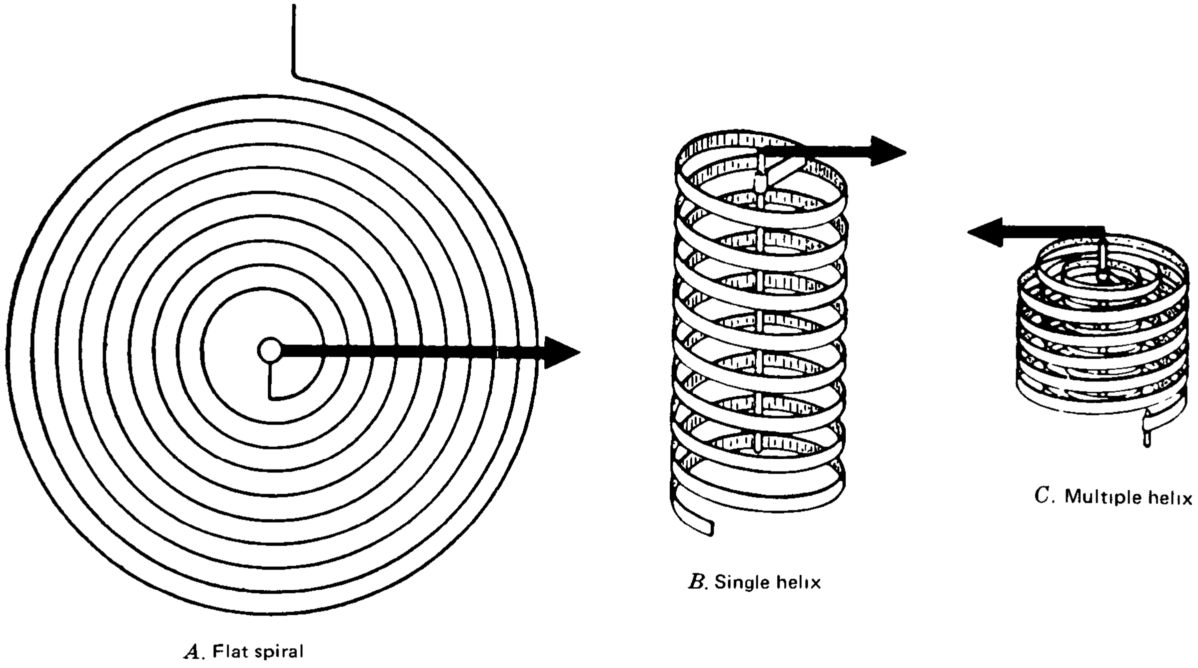
The liquid in the bulb expands or contracts in volume as its temperature rises or falls. This volume change is transmitted to the capillary tube, causing a change in the length of the liquid column in the tube. The physical principle on which this sensor operates is therefore very simple; however, the design, the choice of materials used, and the construction can be very complex and, consequently, have great influence on its quality. Although the cleanliness of the bulb, the capillary bore, and the liquid filling has a pronounced effect on the performance of the finished sensor, of equal importance is the choice of the glass from which it is manufactured and the correct annealing of the glass. If the bulb is made from unsuitable glass or the annealing is inadequate, significant changes in volume will occur, causing serious inaccuracies. Even with the best materials and design, gradual volume changes will continue for years; however, these will generally be limited to an equivalent inaccuracy of less than 0.1°C.

The capillary bores are usually round or elliptical. The smaller the capillary bore, the greater the change in elevation of the liquid level for a given change in temperature. However, there is a practical limit beyond which capillary forces will prevent a smooth advance or retreat of the liquid column. Particularly with a slowly changing temperature, the movement of the liquid meniscus may be found to occur erratically in significantly large steps.

Several factors contribute to the popularity and widespread use of the liquid-in-glass sensor. It is both simple in design and easy to use, as well as being very inexpensive. However, being made of glass, it is fragile. The thermal mass of the sensor is large; therefore, the time constant—that is, the time required to respond to a temperature change—is relatively long. The liquid-in-glass sensor is not commonly used as the basis of recording thermometers but is generally used as a part of portable nonrecording instruments.

Bimetallic

The bimetal temperature sensor is made up of two or more laminated strips of different


A. Flat spiral

B. Single helix

C. Multiple helix

Figure 8 —Principal types of elements in bimetal thermometers

metals, which, because of the different expansion rates of the components, causes it to change its curvature when subjected to a change in temperature. If one end of a straight bimetal strip is fixed, the other end deflects in direct proportion to a temperature change. The deflection for a given temperature change is proportional to the square of the length of the strip and is inversely proportional to the thickness of the strip. When the bimetal strip is wound into a spiral or helix and one end is fixed, the other end will rotate with a change in temperature.

Bimetallic elements are most commonly formed in either a flat spiral, a single helix, or a multiple helix (fig. 8). In these forms the signal transmitted is a rotary mechanical motion. If the design is proper the motion will be linear with temperature changes over the design range of the sensor.

Bimetallic sensors are rugged, but severe mechanical shock or vibration can cause distortion resulting in large shifts in their calibration. They present a large thermal mass and, consequently, have a relatively long time constant, approximately on the same order as that for liquid-in-glass sensors.

Filled-system

A filled-system temperature sensor consists of a bulb containing a gas or fluid whose physical properties change with temperature changes. These changes are transmitted to a Bourdon, bellows, or other suitable element through a connecting capillary tube. Filled-system sensors may be separated into two fundamental types—those in which the element responds to a volume change and those in which the element responds to a pressure change.

The systems that respond to volume changes are completely filled with a liquid. The liquid in the bulb expands with temperature changes to a greater degree than does the bulb metal, thereby producing a net volume change which is communicated to the detecting element.

The systems that respond to pressure changes are either filled with a gas or partially filled with a volatile liquid. Changes in gas or vapor pressure with changes in bulb temperature are communicated to the detecting element.

Filled-system temperature sensors are further classified by the Scientific Apparatus Makers Association into the following categories:

- Class I. Liquid-filled systems:
  - IA. Full compensation.
  - IB. Compensation of the detecting element only.
- Class II. Vapor-pressure systems:
  - IIA. Designed to operate with the bulb temperature above the temperature of the remainder of the system.
  - IIB. Designed to operate with the bulb temperature below the temperature of the system.
  - IIC. Designed to operate with the bulb temperature above or below the temperature of the remainder of the system.
  - IID. Designed to operate with the bulb temperature above, below, or at the temperature of the remainder of the system.
- Class III. Gas-filled systems:
  - IIIA. Full Compensation.
  - IIIB. Compensation of the detecting element only.
- Class V. Mercury-filled systems:
  - VA. Full compensation.
  - VB. Compensation of the detecting element only.

Although the physical principles upon which these sensors work are relatively simple, there are a number of causes which do affect their accuracy. In order to discuss these interferences, it is convenient to keep the above classification in mind.

Because the capillaries, detecting elements, and bulbs of all Class I, III, and V sensors are filled with actuating fluid or gas, all parts are sensitive to differences in ambient temperature. Therefore, serious system errors can result from ambient-temperature variations between components unless compensating means are employed. Classes IA, IIIA, and VA are fully compensated for such temperature variations by means of an auxiliary system which duplicates the primary system except for the bulb. Such an arrangement provides that an ambient-caused response is opposed by an equal and opposite response, thus compensating fully for ambient-temperature effects. Because of simplicity of construction, compensation of the detecting element only (Classes IB, IIIB, and VB) is frequently employed. In this type of compensation, the capillary bore is reduced in size to a point where system response to ambient-temperature variations is not seriously affected, in order to minimize the capillary-temperature error. The detecting element is then compensated by means of a bimetallic strip which provides a response opposing any ambient response of the element. Since the error caused by the capillary has only been reduced and not eliminated and since the longer the capillary the greater the error, sensors with this type of compensation are generally limited to relatively short capillary-tube lengths.

The only ambient temperature error in the vapor-filled system (Class II) is caused by the change in elastic modulus of the pressure detecting element with changing temperature. This error is very small and can usually be ignored.

A difference in elevation between the bulb and the detecting element can cause an appreciable error in all filled-system temperature sensors except the gas-filled type (Class III). Vapor-filled systems (Class II) and gas-filled systems (Class III) use pressure-sensitive detectors; consequently, they are affected by changes in barometric pressure.

The filled-system temperature sensor has the advantage that the bulb and detecting element can be separated by some distance. It is, however, like the bimetallic sensor, sensitive to severe shock, vibration, or other forms of mechanical abuse.

Thermocouple

The basis of one of the most commonly used temperature-sensing devices is the principle of thermoelectricity. Seebeck discovered in 1821 that when two dissimilar metals are welded together at one end and this junction is heated, a voltage is developed on the free ends.

There are two thermoelectric effects which combine to produce the electromotive force (emf) developed; one is known as the Peltier effect and the other as the Thomson effect. The Peltier effect dominates—the emf resulting solely from the contact of two dissimilar metals. Its magnitude varies with the temperature at the point of contact. The emf resulting from the less predominant Thomson effect is that produced by a temperature gradient along a single wire.

Considering the above effects, three thermoelectric laws have been formulated which characterize the behavior of thermocouples. They are as follows:

1. *Law of homogeneous circuit.*—An electric current cannot be sustained in a circuit of a single homogeneous metal, however varying in section, by the application of heat alone.
2. *Law of intermediate metals.*—If in a circuit of solid conductors, the temperature is uniform from any point P through all the conducting matter to a point Q, the algebraic sum of the thermoelectromotive forces in the entire circuit is totally independent of this intermediate matter and is the same as if P and Q were put in contact.
3. *Law of successive or intermediate temperatures.*—The thermal emf developed by any thermocouple of homogeneous metals with its junctions at any two temperatures T_1 and T_3, is the algebraic sum of the emf of the thermocouple with one junction at T_1 and the other at any other temperature T_2 and the emf of the same thermocouple with its junctions at T_2 and T_3.

By combining these laws, it is apparent that leads of homogeneous metals connecting the thermocouple with the measuring instrument to not affect the emf developed by the thermocouple, provided that junctions of dissimilar conductors which are added to the circuit are all at the same temperature or that one junction of each pair of junctions between dissimilar metals is at the same temperature as the other junction of the pair.

The composition of thermocouples may be of any two dissimilar metals. However, there are several combinations of pure metals and alloys which are frequently used because they produce a reasonably linear temperature-emf relationship, and they develop an emf per degree of temperature change that is detectable with standard measuring instruments. Among these are copper-constantan, iron-constantan, chromel-alumel, and platinum rhodium-platinum.

Thermocouple sensors have an advantage in that they can be separated a considerable distance from the measuring instruments. However, great care must be taken in observing the laws previsously mentioned or errors will be caused by extraneous voltages produced by insertion of the electrical leads of different metals between the thermocouple and the measuring instrument. Although they have an extremely rapid time response, when used in water they must be sealed in a case, and this increases their thermal mass and, consequently, their time response. Thermocouples themselves are relatively inexpensive, but the measuring instrument used with them can be fairly expensive.

Resistance bulb

Resistance-temperature sensors are based upon the principle that metals (metallic) and semiconducting materials (thermistors) change in electrical resistance when they undergo a change in temperature. The change in electrical resistance of a material with a change in temperature is termed "temperature coefficient of the resistance" for the material. This coefficient is positive for most metals, and for pure metals the change in resistance with temperature is practically linear. The temperature coefficient for semiconductor material is negative, and the change in resistance with temperature is exponential.

Metallic.—As stated above, the resistance-temperature sensor, called the resistance bulb, depends on the inherent characteristics of metals to change in electrical resistance when they undergo a change in temperature. Resistance bulbs are manufactured in a number of shapes, the most common of which is a tubular-shaped stainless steel stem with the lower end sealed and the electrical leads protruding from the upper end. The resistance winding is located in the lower end of the stem, electrically insulated, but in good thermal contact with the stem.

The material from which the resistance element is wound must possess certain characteristics. It should have a high temperature coefficient of resistance, because the greater the resistance change per degree for a given value of resistance the greater the sensitivity of the element. It should have a high value of resistivity, for the higher the resistivity of the material, the more resistance for a given length of wire and, consequently, for a given size. It should remain stable, not changing its electrical characteristics over a long period of time. It should possess a linear resistance-temperature relationship, which greatly simplifies its calibration. It should be ductile and strong so that it can readily be drawn into fine wire and still possess strength for ruggedness in winding and adjusting.

Several metals meet the above criteria and are used in the manufacture of resistance bulbs. The three most commonly used are platinum, nickel, and copper, with platinum—except for its cost—being the most suitable of all metals.

After selection of the material, proper design and careful manufacture play important roles in the functional performance of a resistance sensor. As much of the metal as practical must be wound in as compact a configuration as possible. The winding must be encased in a protective housing or shield, usually a stainless steel tube that has one end closed for mechanical protection and has electrical insulation. The winding must also be insulated from the metal housing but must have good thermal coupling in order to respond rapidly to changes in surrounding temperatures and in order to dissipate what is referred to as self-developed heat caused by the flow of electrical current used in measuring its resistance value. In a well-designed resistor bulb, this self-developed heat will be properly dissipated into the medium being measured. The electrical leads from the winding itself to the measuring instrument should be low-resistance wire so that any change in their resistance plays an insignificant role in the total resistance of the sensor. In the best bulbs, a four lead arrangement is used such that the resistance value of the leads can be eliminated. In connecting the leads to the winding, usually a junction of two dissimilar metals, there exists a thermal junction and an emf is produced which would affect its reading. In a properly designed bulb the junctions will be located close to each other to eliminate any difference in temperature, and with no difference the algebraic sum of the developed emf's will equal zero.

Resistance bulbs have all the advantages of thermocouples, except that they are usually larger and have a slightly longer time constant. A resistance bulb basically measures temperature directly in that the resistance of the coil of wire is a direct function of its temperature, and the accuracy of this measurement is entirely unaffected by the temperature to which the measuring instrument is exposed. Resistance bulbs also have the advantage of greater sensitivity because the change of resistance per degree change in temperature is relatively large; hence, it is more easily measured than the microscopic change in voltage per degree change in a thermocouple.

Thermistors.—A thermistor is an electrical device made of a solid semiconductor with a high temperature coefficient of resistivity, which would exhibit a linear voltage current characteristic if its temperature were held constant. It changes electrical resistance markedly with temperature, the relationship usually being exponential.

Thermistors are made from a variety of metal oxides and their mixtures, including the oxides of cobalt, copper, iron, magnesium, manganese, nickel, tin, titanium, uranium, and zinc. The oxides, usually compressed into the desired shape from powders, are heat treated to recrystallize them, resulting in a dense ceramic body. Electrical contact is made by attaching wires by various means to opposite sides of the material. Thermistors are generally shaped as beads, rods, or disks.

Thermistors have many of the same advantages as metallic resistance sensors, and they are less costly. In addition, they are even more sensitive because of their high coefficient of resistivity, but for the same reason, self-developed heat is of greater significance in causing errors. They are not manufactured to the same degree of uniformity as metallic elements, and their resistance temperature is nonlinear; therefore, they must be calibrated at many points to achieve reasonable accuracy. They also have a tendency to age—that is, shift calibration with time—but developments in this are constantly improving their reliability.

Others

There are several other physical and chemical principles which are sometimes employed in measuring temperature. Most do not provide sufficient accuracy to be considered here; however, there is one temperature sensor, the quartz crystal, which will be discussed briefly. This sensor is based upon the sensitivity of the resonant frequency of a quartz crystal to temperature change. This change of resonant frequency is linear with respect to temperature. The quartz crystal is driven by an oscillator, the frequency of which is controlled by the crystal; therefore, a frequency that is linearly proportional to temperature is produced.

The quartz-crystal sensor has a number of advantages over other sensors. Its sensitivity is excellent, its linearity is excellent, and it provides a signal suitable for direct digital readout. However, in its present stage of development and manufacture, it is very expensive in comparison with other sensors and does not warrant this high cost for most field applications.

Thermometers

A thermometer is an instrument for measuring temperature, consisting of a temperature sensor and some type of calibrated scale or readout device. The comparative performance of temperature-measuring systems, both recording and nonrecording, are discussed in the following sections in order to provide a better understanding of the relative advantage and limitations of the various kinds of thermometers available. The material for this section on thermometers was obtained from Considine (1957) and Kallen (1961).

Nonrecording thermometers

All the temperature-sensing systems discussed in the preceding section can be and are used in nonrecording thermometers. When there are no additional requirements to consider, such as recording or fixed installation of instruments, simpler designs and lower costs are possible.

The liquid-in-glass sensor requires only the addition of a calibrated scale, usually etched on or enclosed within the stem to become a nonrecording thermometer. (See fig. 9*A*.) Those having an attached or removable scale generally are not considered suitable for scientific work. Liquid-in-glass thermometers are divided into two types—partial immersion and total immersion. This classification is used because the liquid in the column is a part of the total thermally responsive system and is affected by the temperature along its entire length. Partial-immersion thermometers have a line etched around the stem to indicate the exact immersion depth for maximum accuracy. Total immersion does not mean that all of the thermometer must be immersed, but that the bulb and all or nearly all of the liquid column should be immersed for maximum accuracy. In addition to the typical laboratory all-glass thermometer, there are several variations or special purpose liquid-in-glass thermometers available, the most common of which is the maximum-registering thermometer. The lower part of the capillary bore has a constriction, usually a wide slitlike opening, through which the liquid can easily be forced when heated, but when the bulb is cooled, the column breaks at the point of constriction. After a reading, the liquid can be forced back into the bulb by shaking. The clinical thermometer is of this type.

The liquid-in-glass thermometer is by far the most commonly used of all portable thermometers because of its low cost and relatively high degree of accuracy. Of course, accuracy depends upon the care with which the scale is etched and the length of the stem,

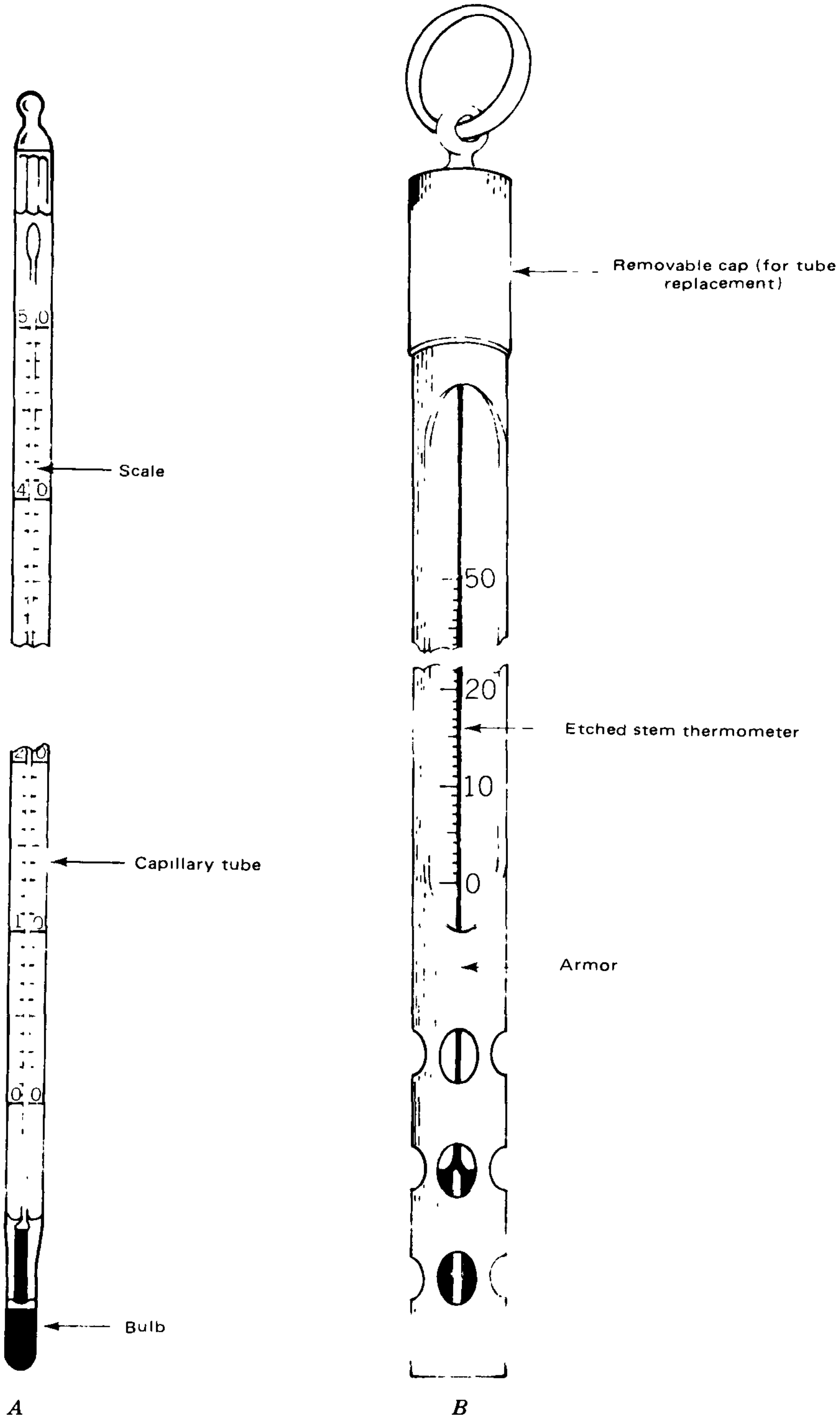


Figure 9.—Sketches showing various components of (*A*) an enclosed thermometer and (*B*) an armored thermometer.

which is, in turn, dependent upon the bore of the capillary. Being all glass, it is fragile, but protective metal sleeves or armor cases can be obtained for thermometers that are subjected to rough handling. (See fig. 9*B*.)

The maximum-minimum thermometer is a U-shaped liquid-in-glass thermomter in which the mercury column positions metal markers to indicate the two temperature extremes. The device indicates the temperature extremes but not their time of occurrence. A small magnet is used to reset the metal markers on the mercury columns. Possible errors when using the maximum-minimum thermometer are (1) the thermometer's response to the air temperature can reposition one of the metal markers if readings are not made quickly, (2) the scale for minimum temperature, which increases in a downward direction, can be misread, and (3) air temperature can affect registration, after it has been reset, if the thermometer is not quickly replaced in position in the water.

The bimetallic sensor, when wound into a spiral or helix, produces a rotary motion with changes in temperature. (See fig. 10.) This motion is transmitted to a pointer by a shaft mounted on precision-made bearings and guides which center the shaft with minimum friction. A scale graduated in degrees is fixed to the case.

Bimetal thermometers are rugged in construction and retain their calibration indefinitely unless they are subjected to abuse. Their accuracy, however, is not as good as that for the liquid-in-glass thermometer, being approximately one-half percent of full scale in the better grades. They are also generally more costly than liquid-in-glass thermometers.

Filled-system sensors, like the bimetallic, usually transmit a rotary motion for changes in temperature. (See fig. 11.) Although the angular movement for a given temperature change is smaller, it provides more force; therefore, a lever arrangement is normally used to magnify the movement of a pointer.

Although fundamental simplicity allows rugged construction, minimizing the possibility of damage during use, filled-system thermometers are not frequently used as portable instruments because the capillary tube is not highly flexible or convenient to handle.

The emf produced by a thermocouple may be read on a millivolt meter, potentiometer, or any other device for detecting and indicating small d.c. emf's. The simple millivolt meter is the least costly, and, for many applications, sensitivity and accuracy are adequate. However, for the best accuracy a potentiometer must be used. The potentiometer draws no current at balance and thus balances as if it had no resistance, whereas even the best millivolt meter still has enough resistance to cause some loading of the thermocouple.

The thermocouple has the advantage that the sensors can be separated from the indicator unit for some distance by a highly flexible electrical cable. There are, however, problems associated with the various junctions of different metals. Because of these problems, thermocouples are not frequently used as portable thermometers in water-temperature measurement unless a very rapid time response is required.

The equivalent temperature value of resistance sensors, either metallic bulbs or thermistors, can be read on a common bridge or other resistance measuring circuit. The conventional Wheatstone is most frequently used. For best accuracy, a null-balanced bridge circuit is used, and the adjusting mechanism of the slidewire is calibrated for temperature. Where less accuracy at a lower cost is an application requisite, deflectional-type circuits can be used. These simply consist of a circuit similar to the d.c. Wheatstone bridge and a meter indicating the amount of imbalance of the bridge. The readout is calibrated in temperature units.

The resistance-type thermometer also has the advantage that the indicator unit can be separated by some distance from the sensor by an electrical lead, but it must be remembered that resistance of the lead is measured by the instrument, and lead length cannot be changed without affecting calibration. Unlike the thermocouple, the accuracy of the resistance thermometer is unaffected by the ambient temperature to which the leads and junctions are exposed, and it is, in general, easier to operate and maintain.

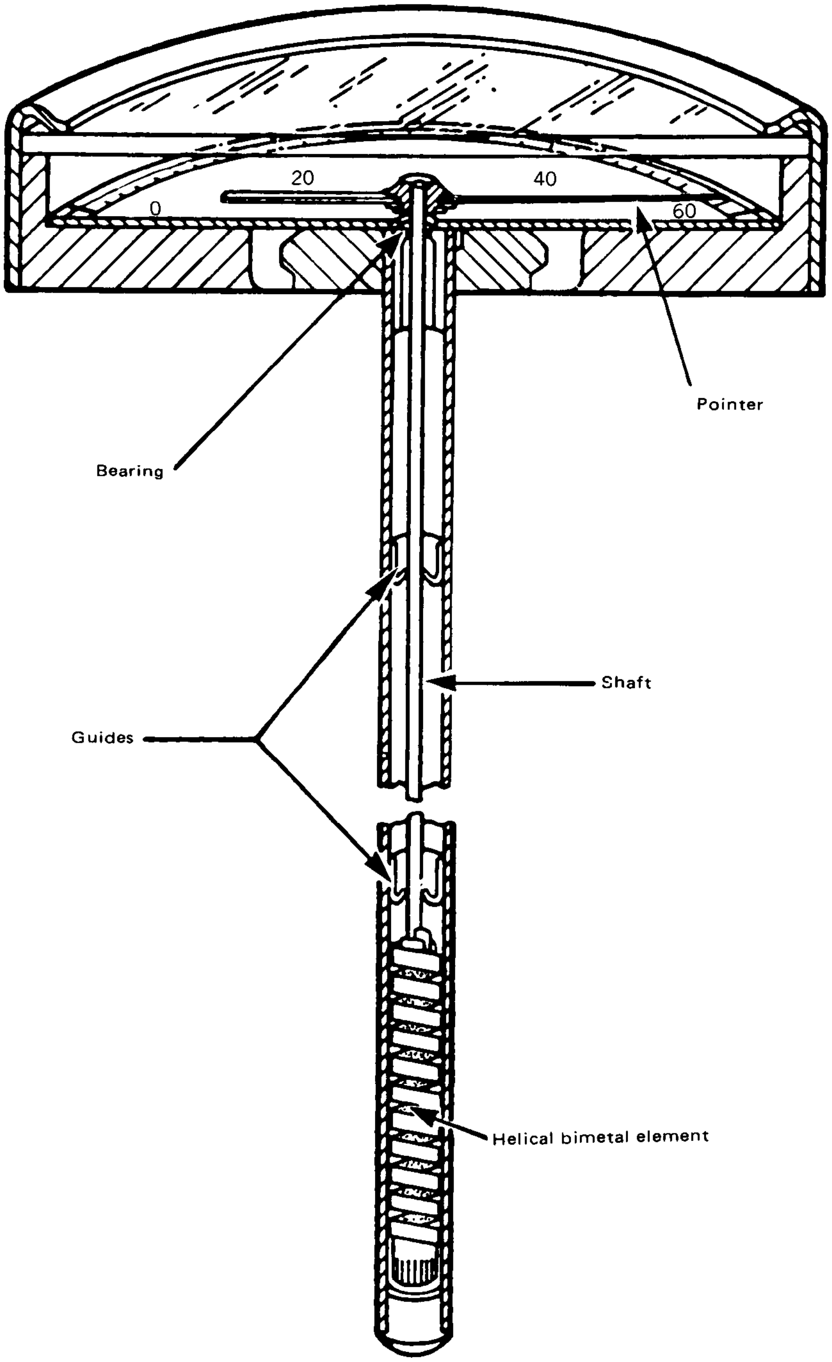


Figure 10.—Sectional view of thermometer with helical-type bimetal element.

As explained in the previous section, quartz-crystal temperature sensors, with their oscillators, generate a frequency proportional to temperature. In order to read this frequency, an electronic counter is usually employed. Readability is then within one pulse per second, which provides in the better thermometer a resolution of 0.00001°C. Accuracy is not the equivalent of resolution, but 0.01°C is easily obtained with proper calibration.

The counter of the quartz-crystal thermom-

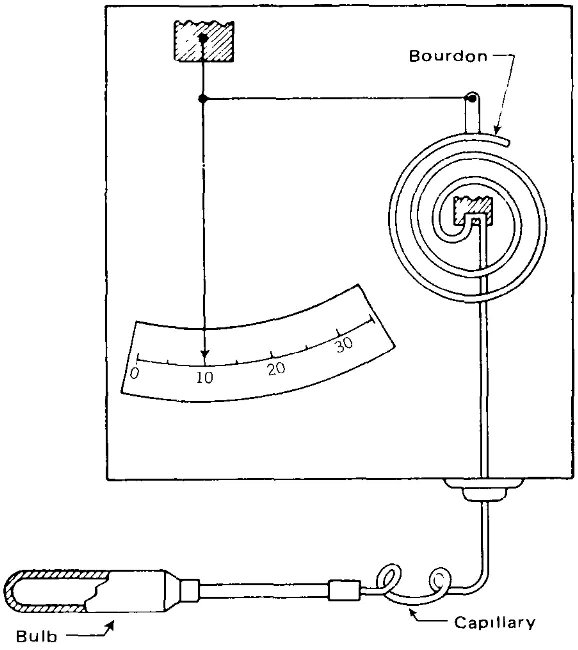


Figure 11 —Filled-system thermometer

eter also has the advantage that it can be separated from the sensor by an electrical lead without degradation of the signal. It is, however, because of its high cost, primarily useful in the laboratory where extreme accuracy is required.

In reviewing the available nonrecording thermometers, the following conclusion can be drawn concerning their application to the measurement of water temperature.

Liquid-in-glass thermometers provide good accuracy, on the order of ±0.1°C for laboratory grade, at the most economical cost. The sensor, however, cannot be separated from the scale.

Portable bimetallic thermometers are rugged and easy to read, and their costs compare with liquid-in-glass thermometers. However, their accuracy is usually on the order of from ±0.5° to ±1°C, and for this reason they generally are less desirable than liquid-in-glass thermometers for field measurement of water temperature.

Filled systems provide means of recording temperature at permanent installations with moderate cost, but, because of their bulkiness, they are not well suited to use as portable thermometers.

Resistance thermometers provide excellent accuracy, better than ±0.1°C, and long-term stability for the metallic type with proper readout instrumentation.

The thermistor, even with the deflection-type circuit, can provide accuracies better than ±0.3°C at the most economical price of any of the resistance types. Stability is not as good as with the metallic type, so calibration must be more frequent to maintain accuracy.

On any of the resistance types, the sensor can be located remotely from the readout instrumentation.

Thermocouple thermometers have many of the same advantages as resistance types, including accuracy in order of ±0.2°C, stability, and suitability for long leads. Because of their more complex circuits and needs for standard voltage references, their costs are usually higher than the costs of resistance thermometers.

If very rapid response (1 second or less) is required, the thermocouple thermomter is the most suitable because of its low thermal mass. The thermocouple sensor can also be located remotely from the indicator unit, but extreme care must be exercised with lead junctions.

Where extreme accuracy, on the order of ±0.01°C, is required, the quartz-crystal thermometer will provide this, but the cost is very high.

Portable recording thermometers

As is true of nonrecording thermometers, all the sensors described can and have been used as recording thermometers. Several, however, do not lend themselves nicely to portable recording instruments. The liquid-in-glass is very seldom used because the only method of recording is by photographing. Although the bimetallic produces a mechanical motion, the torque produced is so low that nothing more than a lightweight pointer should be attached to it. And the filled-system thermometer makes a rather unwieldy instrument for good portability because of its somewhat inflexible capillary tube.

All the electrical-type sensors lend themselves well to use as recording thermometers. Since the signal from the sensor is electrical, it is relatively easy to condition it to drive an electrical recorder. The electronic readout section and recorder can be located remotely from the sensors. The only connection necessary between the components is a highly flexible electrical cable.

The thermocouple produces a small d.c. emf which must be conditioned before it is of significant strength to drive a recorder. The most accurate means of reading an emf is a high-quality potentiometer. Although not of the highest precision, many electrical records are, in essence, reasonably good quality potentiometers which are driven to balance by an electromechanical servo mechanism. These recorders usually have an amplifier on their input to condition the signal to a sufficiently high level to drive the servo. Many other electrical recorders are simply millivolt meters, which also have an amplifier on their input to condition the signal so it is not overloaded. While the potentiometric recorder is a null-balance-type system which gives higher accuracy than the less costly deflection-type system, such as the millivolt recorder, the state of the art is sufficiently advanced so that either will give adequate accuracy for most water-temperature-measurement requirements.

The resistance-type sensors, both the metallic bulb and the thermistor, change the value of their resistance with changes in temperature. Their resistance value can be recorded by several methods. The null-balance Wheatstone bridge is the most accurate method and has again an electromechanical servo mechanism which drives the bridge to a balanced position and, at the same time, positions the recording device. A less expensive method is to read the imbalance of a bridge and record this imbalance on a millivolt recorder. The most frequently used method is to energize the sensor with a constant-current source and, using Ohms law, $E = IR$, record the voltage drop on a millivolt recorder. All these methods provide adequate accuracy for most water-temperature-measurement requirements.

In reviewing the available portable recording thermometers, the following conclusions can be drawn concerning their application to the measurement of water temperature.

Resistance-type thermometers can provide the most accuracy at the least cost.

The metallic bulb has an essentially linear relationship with temperature and, when used in a null-balanced system, can provide excellent accuracy and long-term stability.

The thermistor used either with the deflection bridge or constant-current-type circuit will provide accuracy on the order of ±0.3°C at the most economical cost. However, stability is not as good as with the metallic bulb, and more frequent calibration is required to maintain maximum accuracy.

The thermocouple will provide the most rapid time response but does require extreme care with lead junctions.

Fixed-installation recording thermometers

Several factors in addition to accuracy and speed of response should be considered when selecting a thermometer for recording temperature at a fixed installation. Long-term stability is certainly a desirable characteristic, for the instrument usually must operate unattended and without recalibration for periods of several weeks. Also, its resistance to corrosion, vibration, and other harmful conditions, as well as its cost and expected useful life must be considered. However, because it is to be a more or less permanent type of installation, more time and care can be devoted to the initial installation.

The filled-system thermometer is an instrument which does require more time and care in its installation, and for this reason it is almost never used except as a fixed-installation thermometer. The capillary tube is not as highly flexible as the electrical leads of a thermocouple or a resistance-type thermometer. The tube length must be fixed at the factory and is not readily altered in the field as is the length of the interconnecting leads of the electrical types. As stated in the section on filled-system sensors, all of Classes I, III, and V have liquid in the bulb, capillary, and detecting elements, and all parts are therefore sensitive to ambient-temperature changes; however, if full compensation (Classes IA, IIIA, and VA) is used, errors from this source can be eliminated. A difference in elevation between the bulb and the detecting element will cause an error in all filled-system instruments except the gas-filled type (Class III). This error can be corrected by careful calibration or by full compensation. The vapor-filled and gas-filled instruments (Classes II and III) use pressure-sensitive detectors and, consequently, are affected by changes in barometric pressure. These changes can be corrected by full compensation (a duplicate opposing system except for bulb). If care and proper correcting techniques are used with filled-system thermometers, they are accurate and reliable devices for measuring water temperature. They are, however, somewhat less convenient to use than the electrical-type thermometers.

As for the thermocouple and resistance-type thermometers, the same statements can be made here as appeared under the section on portable-recording thermometers. However, because the requirements for portability and, consequently, weight are not so severe, better quality circuits and recorders can be used. Of course, long-term stability is important, and, in this respect, the metallic-resistance element is the best. The advantages of greater accuracy and stability of the metallic resistance element over the thermistor more than offset its slight additional cost.

Recording systems commonly available provide a pen trace on a strip or circular chart. Recorders having 8-day circular charts may be used at frequently visited sites, but 30-day or continuous-strip-chart recorders are better suited to the normal station-visitation frequency. Because of the increasing demand for accurate current water-quality data, the U.S. Geological Survey has turned to the digital computer to eliminate the necessity of manually extracting data recorded on charts. Digital recording systems (fig. 12) have been developed that produce a punched paper tape that can be machine translated for the computer (Smoot and Blakey, 1966). Digital recorders coupled to servo-drive mechanisms are used for recording temperatures from a single sensor, and programable units are available for sequentially recording up to 10 different parameters.

Operation, maintenance and calibration

Probably the single most important contribution to the successful collection of accurate and representative water-temperature data is to have the operation of measuring systems performed by trained personnel. Observers should be familiar with methods of equipment calibration and routine maintenance.

All temperature-measuring instruments should be calibrated before use and periodically during use. Frequency at which recalibration is required will vary with instruments and must be determined by experiences of the operator. To calibrate, two waterbaths, one at 5°C, the other at 20°C, are necessary. The temperature of each waterbath should be monitored to the nearest 0.1°C with an ASTM standard or good-grade laboratory thermometer. Generally, the accuracy of all instruments should be within 0.5°C at both temperatures.

Liquid-in-glass thermometers, which require little routine maintenance, are calibrated by immersing them into each of the waterbaths. See page 22 for discussion of total-immersion and partial-immersion liquid-in-glass thermometers. The thermometers are held in the water until the mercury column no longer moves (no less than 60 seconds) and read without removing from the water. Before calibration they should be checked for possible separation of the mercury column and, when necessary, they should be cleaned but taking care not to scrub off the numbers on the glass.

Most fixed and portable temperature-measuring systems will have two calibration adjustments. These are the zero setting, which moves the temperature scale (or pen position) up or down, and the span setting, which expands or contracts the length of the temperature scale (or pen movement). For mechanical instruments, the zero setting is made by raising or lowering the pen arm, and the span setting is made by moving the position of the pen-arm pivot; for electrical instruments, the zero setting is made by changing the d.c.-voltage-bias potentiometer, and the span setting is made by changing the voltage-gain potentiometer (volts per °C).

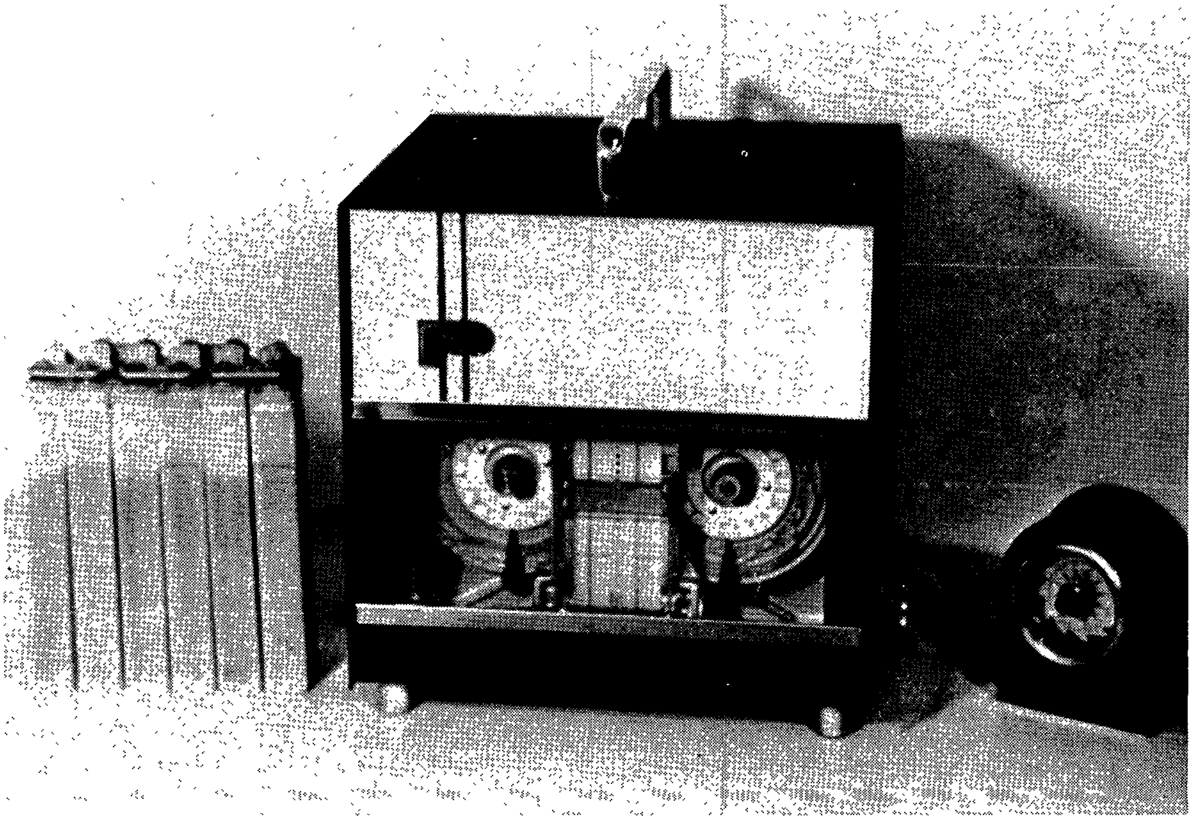


Figure 12.—Digital recorder. Photograph by L. H Ropes.

The following procedure, which may be modified to fit a particular instrument, should be used to calibrate a temperature-measuring system:

1. Place sensor in the 5°C waterbath and adjust the zero setting until the instrument indicates the temperature of this waterbath.
2. Place sensor in the 20°C waterbath and overcorrect the instrument by an amount equal to the difference between the temperature of this waterbath and the temperature indicated by the instrument (error) with the span setting.
3. Repeat steps 1 and 2 until the error is at or near zero. The instrument should now indicate the temperature of both waterbaths within 0.5°C (as closely as 0.005°C in some precision instruments).

When using calibrated portable systems in the field, batteries and electrical connections should be periodically checked and indicated water temperatures should be periodically compared with calibrated liquid-in-glass thermometer readings. These checks, which are most important when unusual temperature conditions occur, insure that the system is indicating accurate water temperatures.

Several important routine maintenance considerations for fixed sensor-recorder measuring systems are that:

1. A sensor covered by sediment or debris or one which has been physically damaged will not be responsive to temperature changes in the body of the flow.
2. Mechanical friction (or electrical malfunction) may prevent accurate recording of the signals transferred by the sensor to the recorder. and
3. The sensor-recorder system is subject to electrical-mechanical drift.

U.S. Geological Survey observers frequently read air temperature as well as water temperatures during each visit to field stations; therefore, they should obtain these temperature readings with a calibrated portable thermometer (liquid-in-glass generally preferred) using the following procedure, an example suggested by Robert Averett (written commun., 1970) for small, wadable streams:

1. Measure air temperature in the shade using a dry thermometer to minimize the risk of obtaining an erroneously low air-temperature reading due to evaporation.
2. Select a site in the stream where the water is moving and where the influence of tributaries is diminished because of mixing. Studies have shown that a temperature taken in main flow of the stream is usually representative of the entire water mass (Jones, 1965; Moore, 1967). During the summer when discharges are low, it may be necessary to wade into the center of the stream, or as far as possible in deep streams, to obtain the temperature. If sufficient mixing has not occurred, temperature observations must be obtained at several locations so that a discharge-weighted mean temperature can be computed. (See later section on field application and procedures for streams.)
3. Stand so that a shadow is cast upon the site chosen for collecting the temperature.
4. Hold the thermometer by its top and immerse it entirely in the water in the shadow area. Position the thermometer so that the scale can be read and hold the thermometer in the water until the liquid column no longer moves (no less than 60 seconds). Make certain the liquid column in the thermometer is not separated.
5. Without removing the thermometer from the water (to avoid wet-bulb cooling), read the temperature to the nearest 0.5°C, and record it in the field notes. If the water is too rough or too turbid to allow a reading in the stream, the temperature may be taken by filling a container with the water, immersing the thermometer in the container, and then reading the temperature. The container must be large enough to allow full immersion of the thermometer, and the walls of the container must be brought to the same temperature as the stream before it is filled with water for temperature determination. In addition, it must provide sufficient thermal mass to insure that the temperature of the water in the container does not change while the temperature is being recorded. A volume of at least a pint should be withdrawn for temperature measurement.

The observed water temperature is considered to be the true stream temperature and will be designated as TST. The next step is to repeat the above procedure (steps 3 through 5) in the water near the sensor. This is not the sensor temperature, but is the temperature of the water mass surrounding the sensor and will be designated as TNS (temperature near sensor). After recording this temperature the observer should check the thermograph recorder and note the indicated temperature. The recorder temperature is designated as TRC. The three temperatures should all be recorded in the field notes and also should be recorded on the temperature chart along with the date and time. Differences between TST and TNS will generally be diurnal or seasonal in nature. The recorder should, hence, be set to read TNS, and corrections should be made during the analysis of the record to account for differences between TNS and TST. This recording procedure will provide a clear record of problems at a given site and permits the recording of accurate temperatures at the higher flows, when TNS is likely to be representative of the true stream temperature (TST). Usually, changes in a recorder setting of less than 1°C should not be made unless the apparent error is verified by two or more field inspections.

After the observer has obtained and recorded the three reference temperatures, he should check and correct, if necessary, the recorder-chart time and the zero and span settings. Sensors should be checked, cleaned, and replaced if necessary. Sensor-recorder measuring systems should be recalibrated at least twice each year.