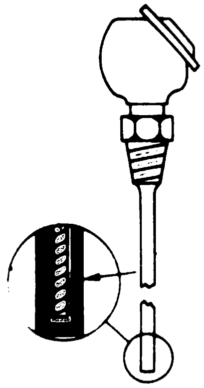
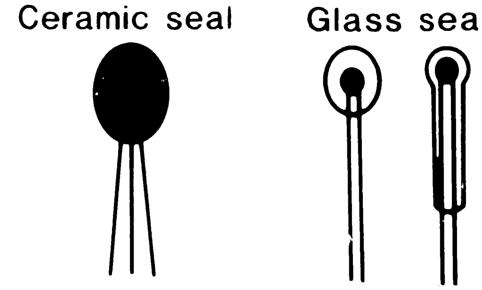
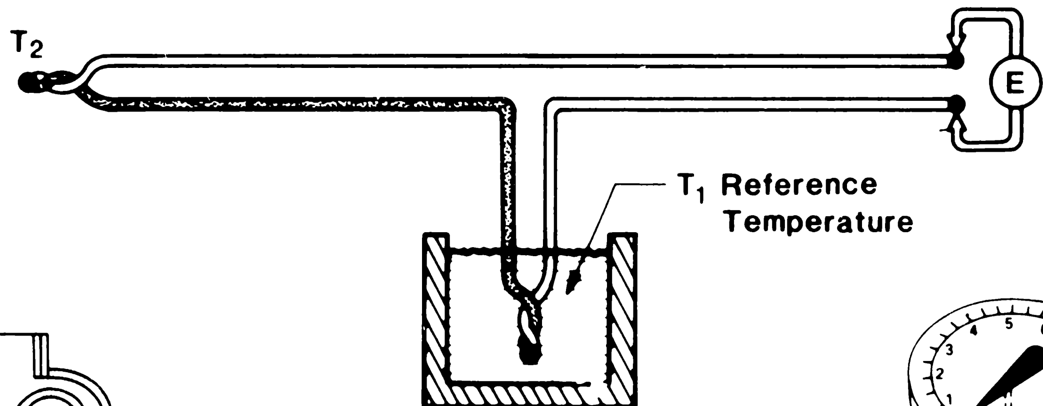


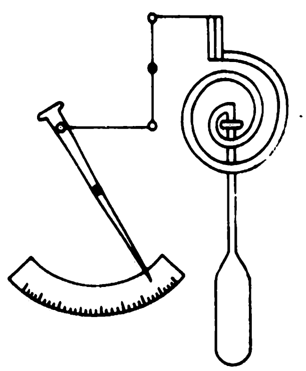
Resistance Thermometer



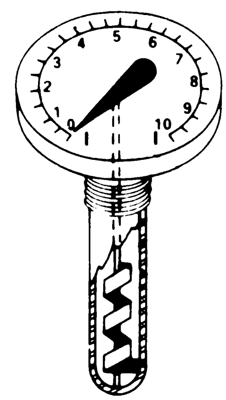
Hermetically Sealed Thermistors



Thermocouple



Pressure Type Thermometer



Bimetallic Thermometer

NBS BUILDING SCIENCE SERIES 153

Calibration of Temperature Measurement Systems Installed in Buildings

U.S. DEPARTMENT OF COMMERCE • NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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NBS BUILDING SCIENCE SERIES 153

Calibration of Temperature Measurement Systems Installed in Buildings

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ABSTRACT

Energy Management Control Systems (EMCS) cannot function properly or efficiently without accurate temperature measurements since temperature is one of the fundamental measurements of any EMCS. This report was written for the purpose of describing various methods of on-site calibration of temperature sensing devices used in EMCS and to review the characteristics of these devices that are directly related to calibration. The significance of recording the results of each calibration is emphasized and the possible effects of systematic errors in temperature monitoring systems is discussed. Illustrative examples of the calibration of temperature monitoring systems are given.

Liquid-in-glass thermometers, pressure thermometers, resistance temperature detectors (RTD), thermistors, integrated circuit temperature sensors, thermocouples, and bimetallic thermometers are discussed in detail with respect to their characteristics related to calibration.

Key Words

Averaging thermocouples; bimetallic thermometers; calibration techniques; integrated circuit sensors; liquid-in-glass thermometers; pressure thermometers; resistance temperature detectors (RTD); systematic errors; thermistors; thermocouples; thermopiles.

SI CONVERSIONS

The contents of this report are directed toward assisting field personnel in the calibration of instrumentation monitoring the temperature of air, water, and steam supplied by mechanical equipment in buildings. In view of the presently accepted practice of the building industry in the United States and the reference material readily accessible to field personnel managing and operating the mechanical equipment in buildings, common U.S. units of measurement have been used in this report. In recognition of the fact that the United States is a signatory to the General Conference of Weights and Measures, which gave official status to the SI system of units in 1960, appropriate conversion factors have been provided in the table below. The reader interested in making further use of the coherent system of SI units is referred to NBS SP 330, 1972 Edition, "The International System of Units,"; E380-72, ASTM Metric Practice Guide (American National Standard Z210.1); or ASHRAE "SI Metric Guide for Heating, Refrigerating, Ventilating, and Air-Conditioning," 1976.

Metric Conversion Factors

To convert from	To	Multiply by*
Area		
ft^2	$metre^2$ (m^2)	9.290304E-02
$in.^2$	$metre^2$ (m^2)	6.451600E-04
Energy		
Btu (Int'l Steam Table)	joule (J)	1.055056E+03
calorie (Int'l Steam Table)	joule (J)	4.186800E+00
erg	joule (J)	1.000000E-07
Force		
pound-force (lb_f)	newton (N)	4.448222E+00
kilogram-force	newton (N)	9.806650E+00
Length		
ft	metre (m)	3.048000E-01
in.	metre (m)	2.540000E-02
Mass		
gram	kilogram (kg)	1.000000E-03
lb	kilogram (kg)	4.5359237E-01

*The notation "xE±y," where x and y are numbers, is a standard form for indicating multiplication of the number x by the number 10 raised to the power ± y.

Metric Conversion Factors (cont.)

To convert from	To	Multiply by*
Mass per unit vol.		
g/cm^3	kg per m^3	1.000000E+03
lb/ft^3	kg per m^3	1.601846E+01
$lb/in.^3$	kg per m^3	2.767991E+04
Pressure (force per unit area)		
atmosphere	pascal (Pa)	1.013250E+05
in. of mercury (60 °F)	pascal (Pa)	3.376850E+03
mm of mercury (32 °F)	pascal (Pa)	1.333224E+02
in. of water (60 °F)	pascal (Pa)	2.488400E+02
in. of water (39.2 °F)	pascal (Pa)	2.490820E+02
Temperature		
degree Fahrenheit	degree Celsius (°C)	subtract 32 and divide by 1.8
degree Celsius	degree Fahrenheit (°F)	multiply by 1.8 and add 32
degree Fahrenheit	kelvin (K)	add 459.67 and divide by 1.8
degree Celsius	kelvin (K)	add 273.15
degree Rankine	kelvin (K)	divide by 1.8
Velocity		
ft/min	metre per second (m/s)	5.080000E-03
ft/s	metre per second (m/s)	3.048000E-01
in./s	metre per second (m/s)	2.540000E-02
Volume		
ft^3	$metre^3$ (m^3)	2.831685E-02
$in.^3$	$metre^3$ (m^3)	1.638706E-05
Volume per unit time		
ft^3/min	$metre^3$ per second (m^3/s)	4.719474E-04
ft^3/s	$metre^3$ per second (m^3/s)	2.831685E-02

*(see preceding page)

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1. INTRODUCTION

The measurement and control of the temperatures of various components and fluids in the mechanical systems serving a building and of the air within the various areas of that building are often considered to be simple tasks. As a result, accurate temperature measurements are often neglected in an Energy Management and Control System (EMCS). However, the laws of thermodynamics demand careful control of the temperatures in both heating and cooling systems if the equipment is expected to operate at optimum efficiencies. Also, human nature demands that the temperature of the air in areas where people are working be maintained within a comfortable range to allow them to function with optimum effficiency. Therefore, one of the primary objectives of an EMCS of a heating, ventilation, air-conditioning (HVAC) system in a building is to accurately measure and control temperatures.

To accurately measure and control temperatures, each temperature sensing device in an EMCS must be properly calibrated and maintained in calibration during the entire operation of the equipment. The number and various types of devices used to monitor temperature in an EMCS will depend upon the size of the building, the number of heating zones, and the design and complexity of the control system. Since many different types of temperature monitoring devices may be used in a single EMCS, the personnel responsible for the operation and calibration of the monitoring components of the system must be familiar with a variety of temperature measurement techniques and the equipment required for calibration.

This report provides fundamental information pertaining to the on-site calibration of temperature sensing devices such as the definitions of terms used in the monitoring of temperatures, on-site calibration techniques used in maintaining the accuracy of EMCS temperature monitoring systems, a description of various temperature sensing devices used in EMCS and their characteristics related to calibration, and procedures for logging the results of calibrations for determining the scheduling of future calibrations. The possible effects of systematic errors in temperature sensing systems and illustrative examples of calibrating temperature sensing systems installed in buildings are also included.

2. DEFINITIONS OF TERMS USED IN TEMPERATURE MONITORING

This section contains a brief list of the major terms used in this report. Other useful terms are defined in appendix A. Since this report is intended for EMCS operators and managers, several of the defined terms list a second definition of the term, as commonly used in the field of EMCS, which may deviate slightly from the formal definition. The reader is encouraged to review the definitions in this section and in appendix A whenever there is doubt about the meaning of a particular term or instruction.

Inaccuracy and Accuracy - The lowest level at which the measurement of a particular parameter by a particular instrument agrees with the measurement made by correct procedures with a calibrated instrument is properly called "the inaccuracy"; however, the word "accuracy" is often used to express the same idea.

Measurement - The act of using an instrument to obtain a value of a particular parameter. Also, the value of the parameter thus obtained.

Resolution - The ability of an instrument to discriminate between one reading and another. For example, "The liquid-in-glass thermometer No. 81-465 has a resolution of $\pm 0.05\ ^{\circ}C$ when read with a 10x telescope."

Imprecision, Precision, Irreproducibility, and Reproducibility - The lowest level of measurement to which a given instrument repeats its reading when used with a particular system at a given time by a particular observer is properly called "the imprecision" or "the irreproducibility". The words "precision" and "reproducibility" are also used to express the same idea. For example, "The temperature of the ice-point bath was measured ten times by operator No. 243, using a liquid-in-glass thermometer in conjunction with a 10x telescope. The average imprecision (or precision) was $\pm 0.04\ ^{\circ}C$."

Thermometer - The true definition of a thermometer is a device used to obtain the temperature of an object or system. However, in EMCS applications, a device to measure temperatures often consists of several components such as a sensor or transducer, transmission means and a receiver or readout device. Since each of these components will be discussed separately for the various types of temperature monitoring methods in this report, the term thermometer will be limited to liquid-in-glass thermometers, bimetallic thermometers, and pressure-type thermometers.

Temperature - The "hotness" of an object, usually expressed as a numerical value on an agreed scale. It is important to remember that heat flows from an object whose temperature is higher to any contacting object whose temperature is lower until they are separated or until their temperatures become equal as a result of the energy exchange.

Heat, Heat Energy, and Thermal Energy - The capability of an object to perform work as a result of its temperature is called its "heat energy" or its "thermal energy". Stored thermal energy is known as "internal energy". The transfer of this energy from one object to another is referred to as "heat" or "the flow of heat". Heat flows as the internal energy of a hotter object is dissipated in order to raise the temperature of a colder object in thermal contact with it.

Thermal Contact - The capability of carrying heat from one object to another. The three ways of establishing thermal contact in temperature monitoring systems are by conduction, by convection, and by radiation.

Thermal Equilibrium - The state in which two or more objects have the same temperature, or in which a single object has the same temperature throughout all of its parts. This state is commonly achieved by bringing the objects into physical contact or contact through a convective gas and allowing sufficient time to pass for the required amount of heat energy to flow from the hotter objects to the colder ones until their temperatures are the same.

Temperature Scale - A reference or standard used to assign a number to an object to indicate its temperature. There are several temperature scales in use today. These include:

a) the basic scientific scale, the "Kelvin Thermodynamic Temperature Scale", which runs from absolute zero to positive infinity in units of the kelvin (K);

b) the scale endorsed by the General Conferences on Weights and Measures and called the "International Practical Temperature Scale of 1968", which has two sets of numerical values, one running from absolute zero to positive infinity in units of kelvins (K) and the other running from negative 273.15 through zero at the melting point of ice and then onward to positive infinity in units of degrees Celsius (^{o}C).

c) the "Fahrenheit Scale" (used commonly in the United States but not elsewhere), running from negative 459.67 through zero and on to positive infinity. Zero on the Fahrenheit Scale does not occur at a common fixed point. The melting point of ice is generally used to reference the positive value of 32 ^{o}F. The Fahrenheit and Celsius temperature scales are commonly used in EMCS. The conversion factors are listed in the "SI Conversions" given in the front of this report.

d) the "Rankine Scale" (the analog of the International Practical Temperature Scale of 1968 in kelvin units), running from absolute zero through 491.67 at the melting point of ice to positive infinity.

Thermal Gradient - The existence of different temperatures in different parts of an object or system. An example of thermal gradient is the difference between the temperatures of the inner and outer surfaces of the wall of a boiler.

Sensor/Transducer - A sensor is defined as a device that receives and responds to a signal or stimulus. A transducer is defined as a device which converts one form of input energy into another form of output energy. In temperature monitoring for EMCS and for the purposes of this report, these terms are used interchangeably.

3. CALIBRATION TECHNIQUES

Many different types of temperature monitoring systems are used in EMCS. In addition, many combinations of temperature sensors and transducers, methods of transmitting the output of the transducer to the point of termination, and methods of reading and translating the received signal into an engineering term exist. For these reasons, a single method of calibrating various systems is seldom sufficient.

Throughout this report (especially in this section) the text may appear to deviate from the direct subject of "calibration". However, in each case the reader will be made aware of typical conditions that are found in EMCS and reflect the results of the calibration of EMCS equipment. The fundamental characteristics of the various temperature sensing devices found in EMCS will be described in section 4. Special emphasis is placed on those characteristics pertaining to calibration.

In this section, two fundamental terms are defined and several general calibration techniques are described. The technique or techniques used in the calibration of the EMCS temperature sensing device or system will depend upon characteristics such as the complexity of the system utilized to obtain the response of the sensor at a remote readout or control station, the type of sensor, the method used in mounting the sensor in the medium it is monitoring, etc. Since the majority of temperature sensing devices are mounted in EMCS equipment for remote monitoring, this area is covered in more detail than the simpler techniques. However, in many remote systems, the temperature sensing device itself often can be calibrated by one of the simpler techniques described. Therefore, all of the material presented is pertinent.

3.1 Definitions of Calibration and Standard

The term "calibration" as used throughout this report refers to the comparison of an indicated value of a temperature monitoring system or any part thereof, to the value indicated by a "standard" device or a standard method of generating a reference temperature. The calibration must also account for all parameters which affect the final indication.

A "standard" is understood to be an instrument whose indications and accuracies within the ranges it is being used have been determined and recorded by a qualified laboratory. A standard may also be a technique which produces a particular temperature within known error bounds when certain transitions occur in pure materials. An example would be the melting point of ice or boiling point of water of known purity.

For the purpose of this report, it must be emphasized at this point that there is an important difference between maintenance of equipment and calibration of equipment. Maintenance of equipment involves the tasks of keeping the equipment running, while calibration of the same equipment involves determining how well the equipment is doing its job.

3.2 Calibration of Temperature Sensors In-Place

If the system is designed to allow a standard such as a laboratory-calibrated liquid-in-glass thermometer, thermistor, thermocouple, or other suitable standard to be placed in the system adjacent to the temperature sensing component and if the temperature of the system can be varied over its normal operating range, then calibration can be performed by comparing the temperatures indicated by the standard and those indicated by the sensing device. The values indicated by the device being calibrated must be those used by the EMCS for monitoring and/or control.

In calibrating any sensing component while it is in place in a monitoring system, extreme care must be used to avoid disturbing the natural environment of the sensor being calibrated by positioning the standard being used for calibration. Likewise, the environment of the standard in position in the system must be the same as that of the sensing component. The characteristics of the device being used as a standard as described in section 4 of this report should be reviewed prior to use in any calibration method to avoid exceeding the constraints of the sensor or the standard.

In many cases, it may be found advisable to install a removable section in the system to allow a standard to be utilized as shown in figure 3.1. Using this technique, the medium being monitored by the sensor being calibrated can be monitored by a standard inserted in a second removable section similar to that previously installed. The sections can be interchanged after the calibration is completed. Care must be taken to avoid disturbing the normal operation of the system while interchanging the removable sections. Figure 3.1 (b) shows one method (the use of valves) of utilizing the technique in installed water and steam lines.

Often, mixing devices are required in systems to assure that the temperature at the sensing device is representative of the average temperature of the medium being monitored. Mixing is often required in air and in water distribution systems upstream of the temperature sensor. The term "mixing" refers to baffles or other means installed in the transporting enclosure (as shown in figure 3.2) to generate turbulence in the medium and reduce any thermal gradient that may be present. A temperature sensor or standard placed in a medium where thermal gradients are present will show significant errors in the indication of the true mean temperature of the medium. These errors often will vary as the velocity and/or the temperature of the medium are varied and introduce additional problems for those attempting to calibrate the sensor.

It must be pointed out, however, that the installation of mixing devices in a system must be done with care since induced turbulence in a stream of air, water, or steam may generate problems in the system monitoring the velocity of the medium. Therefore, the location of the velocity-monitoring sensor should be studied and given careful attention before arbitrarily installing mixing devices to reduce thermal gradients. If a conflict in the two sensors arises, it is generally wise to relocate the temperature sensor or to install a temperature sensor such as an averaging thermocouple which will reduce the error caused by thermal gradients to an acceptable level. Averaging thermocouples are discussed in section 4.6.2. of this report.

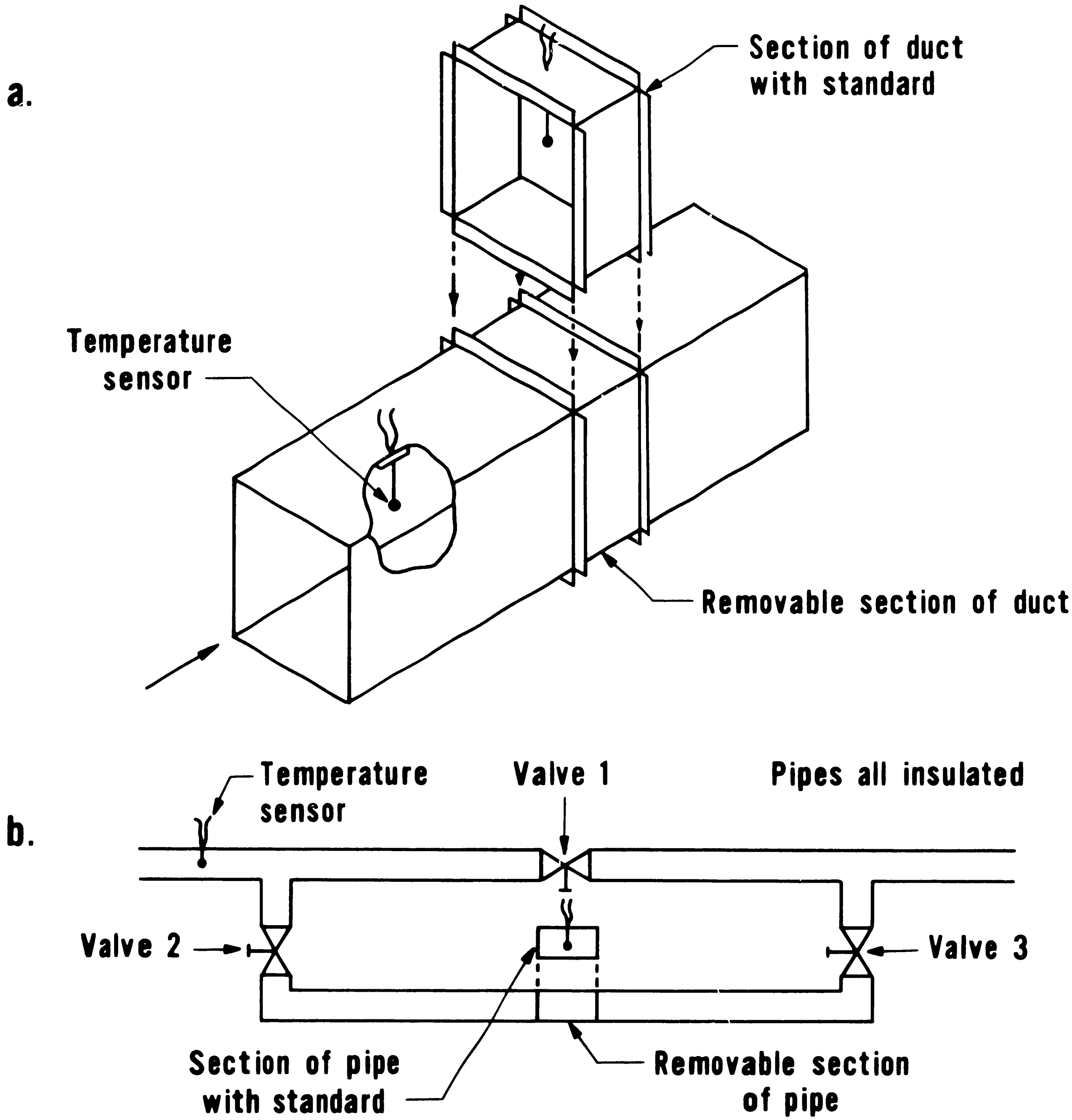

Figure 3.1 Examples of the in-place calibration technique using removable standards for calibrating temperature sensors

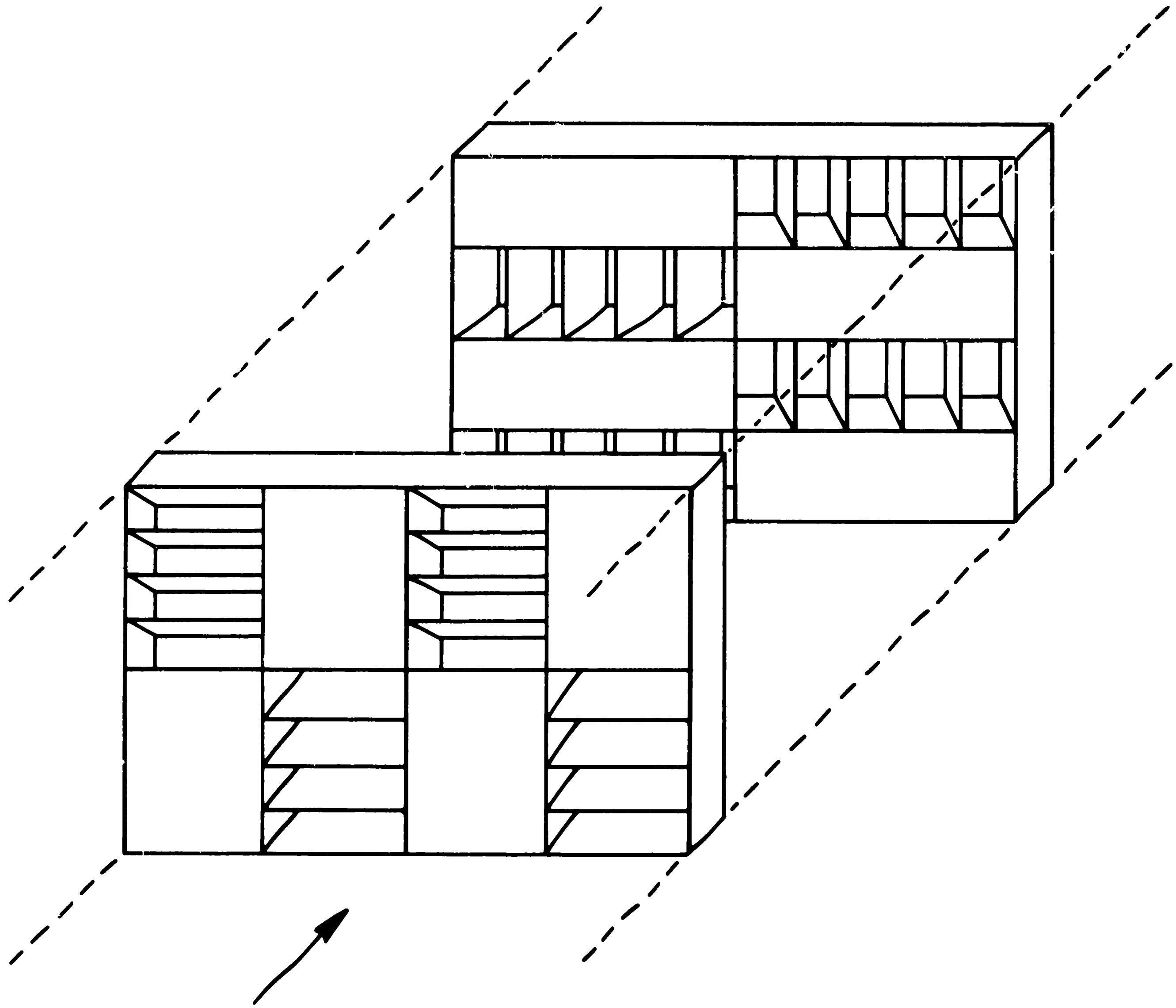

Figure 3.2. An example of a mixing device mounted in a rectangular duct to reduce thermal gradients and allow the media to be monitored by a single sensing device

3.3 Calibration of Temperature Sensors Removed From The HVAC System

When the complete working monitoring system can be removed from the building system and calibrated directly at a primary calibration facility, or at a qualified calibration facility established at the site of the EMCS, this is usually the most desirable method of calibration and should be utilized. An example of this calibration technique would be the removal of the sensor and its related components from the mechanical system and transferring it to a qualified laboratory utilizing a variable-temperature calibration bath with appropriate standards to calibrate the system over its full operating range. This technique avoids disturbing the operation of the mechanical system during calibration.

At first glance, this may seem to be an unnecessary task, especially for the more complex systems. However, the more complex the monitoring system, the more susceptible it becomes to error. In addition, the more complex the monitoring system, the more difficult the debugging of any internal electronic problems that may be present in one or more of the components of the system. A primary calibration facility or a qualified on-site calibration facility should be equipped with the necessary test equipment to locate and correct the majority of any internal problems in the system.

Manufacturers' representatives selling some of the more-complex temperature systems are equipped with mobile equipment for testing and calibrating temperature systems and their components without removing the complete system from the EMCS. When such methods are used, it is advisable to recheck the calibration and operation of the system by direct comparison with a standard device before the mobile equipment leaves the site. The majority of the personnel working with mobile equipment of this type will have access to qualified standards for checking the components of a system. However, it is not uncommon for a person who has been heavily involved in the debugging of multiple problems in a complex system to neglect checking the calibration of an operating monitoring system that has just been repaired.

3.4 Calibration Of Remote Temperature Monitoring Systems

The majority of EMCS temperature monitoring systems fall within this more complex area since the sensors are located throughout the mechanical system of a building or group of buildings and the central control unit for the system can be located in any convenient place. The media being monitored, the size of the ducts or pipes, the temperature ranges, etc. usually vary throughout the system. In general, this is the primary reason calibration by removing the sensor from the system is often not practical for medium and large-size systems. Therefore, methods of calibration of the system and its components with a standard are required.

As shown in figure 3.3, each channel of a remote temperature monitoring system consists of a temperature sensitive device usually referred to as the sensor or transducer, a signal conditioning means for receiving the signal from the transducer and "conditioning" the output signal of the transducer (by amplifying, attenuating, impedance matching, etc.) to an acceptable level to be received by the transmitting means for generating and transmitting the output from the transducer to the multiplexer. Often the output of the

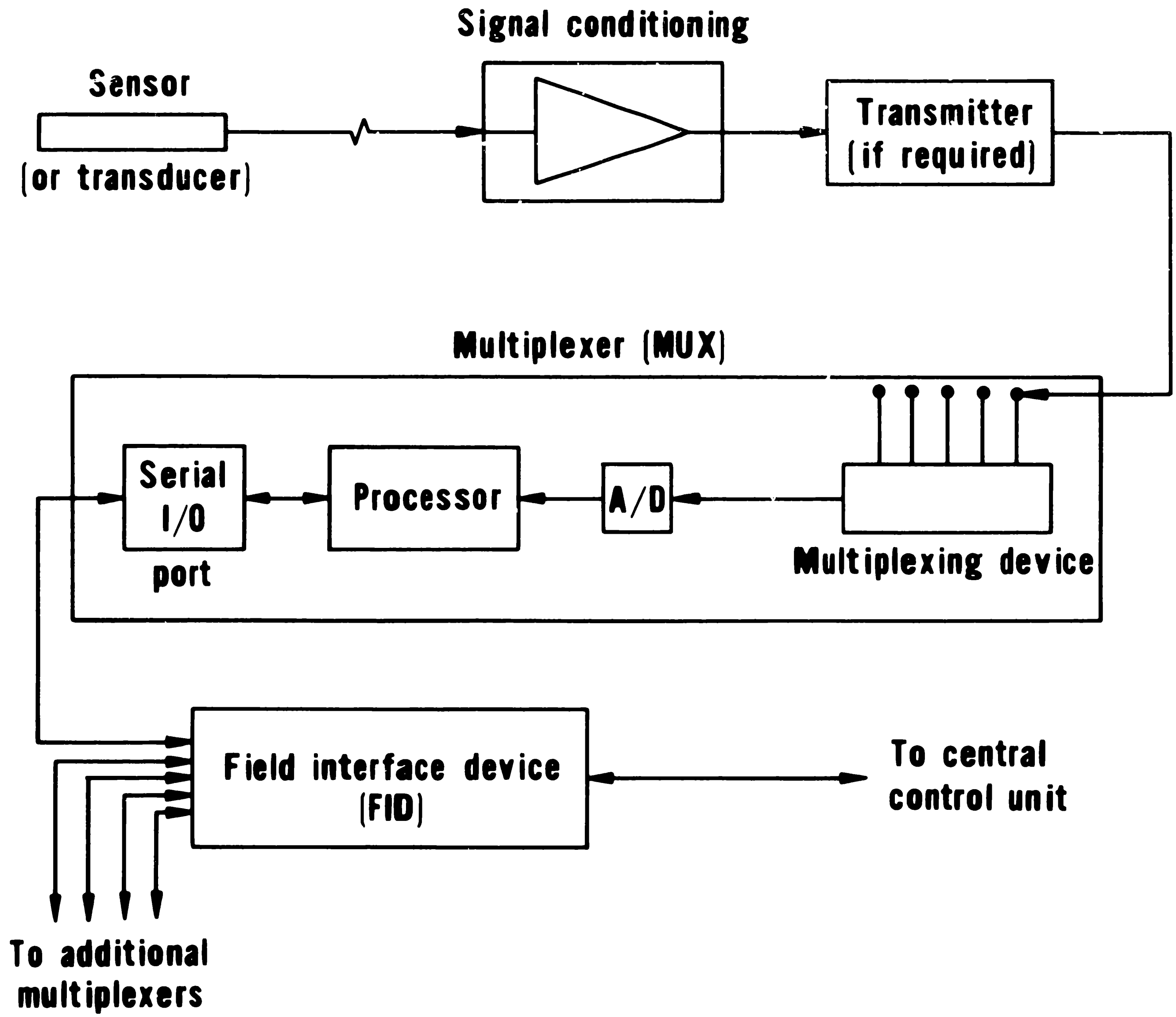

Figure 3.3. Simplified sketch of a remote temperature monitoring system

signal conditioning device is adequate to be connected directly to the multiplexer without the use of a "transmitter".

The multiplexer ("MUX"), as shown in figure 3.3, is a device usually mounted at each primary piece of mechanical equipment in the HVAC system. The multiplexer contains a "multiplexing" device which continually scans the inputs from each remote sensing station. The voltage (or current) received by the multiplexer is transmitted to an A/D (analog to digital) converter to translate the amplitude of the signal received from the individual remote lines into a corresponding digital signal. The digitizing of the analog signal allows the signal to be processed by microprocessors and retains the signal until changed by the input from the sensor or the command for a readout by the central control unit. The output signals from the "MUX" as shown in the figure, are usually transmitted over a serial (two or three conductor) cable to the central control unit. The frequency and the mode of transmission will depend upon the basic design and programming of the "MUX" and central control unit.

Since <u>each component</u> of a remote temperature monitoring system must function properly to allow a signal analogous to the temperatures of the medium being monitored by each sensing element to be received by the central control unit, the calibration of a remote sensing system requires the calibration and testing of <u>each component</u> for accuracy and proper operation throughout the full range of temperatures and environmental conditions that will exist in the actual operation. In addition, all the components as a system must be calibrated.

3.4.1 Calibration of the Sensor

The calibration of the sensing element or transducer can be made by either of the methods described above, whichever is the more suitable for the type of sensor. One important point must be emphasized in this section on calibration techniques: <u>regardless of the available facilities for calibrating, the manufacturers' instructions for calibration must be referred to and followed.</u> This applies to the calibration and the actual use of the sensor. Numerous sensors and systems have been destroyed or improperly calibrated by the people designing, installing, calibrating, etc. failing to spend a few minutes to read the manufacturers' specifications! Still more temperature sensing elements have been found to be malfunctioning for the same reason! Subjecting a temperature sensing element to environments beyond its specified limits can result in costly replacements and, more often, in lengthy periods of down time of an EMCS.

3.4.2 Calibration of the Transmitting Means

The transmitter can consist of something as simple as a serial cable (as described above) or a capillary tube to a complex electronic system, depending on the type of transducer. However, the calibration of the transmitter is usually very straightfoward if the proper calibrating equipment is available. In general, if the output of the transducer can be simulated and entered at the transducer end of the transmitting means, the output at the receiving end must be identical. Unfortunately, the input signal from the temperature sensing unit is not always simple to reproduce. This signal must be reproduced under the same conditions (impedance, voltage, current, etc.) as produced by the transducer.

For the purpose of calibrating the transmitting means, consider the output of a simple thermistor which requires a pair of lead wires for transmitting a voltaic signal. Since thermistors used in EMCS are used in a voltaic mode, the manufacturers' specifications may typically state that the output impedance of the thermistor is in the order of 10 megohms. This high impedance requires the leads to be shielded and that both ends of the leads as well as the main body of the leads be free from excessive electromagnetic interference. Using care in routing the lead wires away from power lines, electrically powered equipment, etc. will help to eliminate the excessive interference from the main body of the leads. However, the ends of the lead wires must be close together to minimize the electromagnetic fields between them.

The example given above for transmitting the output of a simple thermistor to the multiplexer emphasizes the need for the calibration of the transmitting means in any remote temperature sensing system. Other examples of possible problems in the transmission of remote signals from temperature transducers will be given in section 4 as they apply to the types of tranducers described.

3.4.3 Calibration of the Receiving Unit

The calibration procedure for the receiver or interpreting means of the remote temperature monitoring system will vary depending upon the type of receiver installed in the system. The typical receiver in a remote temperature monitoring system will consist of a MUX, a FID (field interface device), and a central control unit as shown in figure 3.3. Although numerous combinations can be assembled to perform the tasks as they are shown in the figure, the complexity will vary from system to system. However, each receiver of this type will have the capability of converting an analog signal into a digital one which is then converted into a decimal value which represents the temperature of the medium the sensor is monitoring.

This conversion starts at the A/D converter previously described. As the magnitude of the analog signal changes, the A/D converter changes it into a digital value in the base in which the computer is designed to function. In general, the input to the A/D converter is presented in a magnitude (voltage) directly proportional to the temperature of the sensor. In some cases, the signal is transmitted in the form of electrical current which is translated using a resistor of known value to voltage and is directly proportional to the input. The electrical current method of transmission is often preferred if line losses become significant. In some cases the response of the sensor/transducer is non-linear, and the necessary manipulations to produce the representative data are made by the central control unit. Thermocouples are an example of a non-linear temperature sensing device.

Although the input signal to the A/D converter may be presented in an infinite number of increments, the A/D converter will divide the range of the converter into an integral number of increments depending upon its capability. For example, an eight bit A/D will divide the full scale input range of the converter into 256 parts while a twelve bit A/D will divide the full scale input range into 4096 parts. If the person performing the calibration has the option, the input range of the incoming signals should be "conditioned" (amplified and/or offset) to cover most of the input range of the A/D converter. This will reduce the error introduced by the conversion of an analog signal into a fixed number of increments as required to process the data by a digital computer.

The method of transforming analog data into digital data is being described to allow the person performing the actual calibration of the equipment to understand why the temperature being measured by the sensing device, or an analog signal being applied to the input end of a transmission line, may not be exactly analogous to the signal displayed by the receiving device. However, the increments described above indicate the level of discrepancy that can be caused by this conversion. When the A/D portion of the receiving component is being calibrated, it should be calibrated over its full range, applying input signals in both ascending and descending directions.

The actual calibration of the receiving unit is best accomplished by utilizing the in-place comparison technique at the sensor and comparing the sensor output with the output displayed at the central control unit for the temperature of the sensor being calibrated. If a discrepancy is noted, the next step is finding the cause for the difference. This is often a difficult task. However, by following some of the techniques noted above, the area of the problem will soon surface. If the signals at all points in the remote sensing system are found to be within an acceptable range yet the temperatures displayed at the central control unit are not acceptable, the person responsible for the software of the central control unit should be presented all of the facts found in checking out the various parts of the system. Although errors in the software for an operating system seldom exist, the electronic components of the MUXs, FIDs, and the central control unit do not have a lifetime warranty. The facts found in tracing the source of the problem through the system will often lead the people responsible for the operation of the MUXs, FIDs, and central control unit directly to the solution.

Factors that affect the calibration of other types of receiving components such as mechanical, pneumatic, and direct readouts will be discussed in conjunction with the applicable descriptions of the various temperature sensors.

3.5 Additional Factors To Be Considered During Calibration

Many additional factors reflecting on the calibration of temperature monitoring equipment could be added to this section. However, this sub-section will list a few items that are often overlooked by personnel performing the task of "determining how well the equipment is doing its job"; i.e. calibration.

Many Energy Management Control Systems are installed in existing mechanical systems of buildings. Some of these mechanical systems may have been in service for many years. The person designing the EMCS will often be working from drawings of the mechanical system as it was originally designed, or was installed, or was intended to be installed. Unfortunately, very few mechanical systems are installed exactly as originally designed. Obstacles are frequently generated during the constuction phase of a building which require revisions of the original design. Even if the working drawings were revised to reflect the changes in the original design, the majority of drawings available will not reflect the modifications that have been made in the mechanical system since its original installation.

This unfortunate (but typical) fact must be considered by those performing the calibration of the EMCS. Unless all sensors are properly placed in the mechanical system, the EMCS cannot function as designed. Checking the location and method of installation of temperature sensors is part of the task of calibration. If additional branch lines or ducts have been added to an air system upstream of the temperature sensor and the sensor is assumed to reflect the temperature of the supply air stream, the person responsible for the calibration should record the modification and compare the temperature at the sensor with the actual temperature of the supply air. If a discrepancy is noted, action should be taken to move the sensor to a more appropriate place.

This same example can be used to point out another typical error made in the installation of sensors. If the sensor is intended to monitor the temperature of the air flowing in the duct, does the cold (or hot) surface of the duct on which the sensor is mounted affect the output of the sensor? In section 4, the reader will be reminded of the possible effects of the thermal conductivity of the lead wires on several types of sensors. This example points out the possible temperature effects of the surface on which the sensor is mounted. In general, the person responsible for the calibration of the system is not responsible for the original design of the system. However, if the calibration is to determine how well the system is functioning, the person performing the calibration must take responsibility for recording and reporting any sensor found to be incorrectly monitoring a function of an EMCS.

Another item that is frequently overlooked in the mounting of sensors and the use of standards for calibration is the thermal conductivity of the materials used. For example, heat can be either carried to or from the bulb by the stem of a liquid-in-glass thermometer being used as a standard for calibration faster than the air flow in the duct can remove heat or add it. The stem correction factor described in section 4 for liquid-in-glass thermometers will further address this problem.

A further responsibility of the person performing the calibration is monitoring the performance of the signal conditioning and transmitting means of the temperature sensor. If the sensor is functioning properly and the central control unit is not receiving the appropriate signal, the calibration of the sensor is of little, if any, value. The signal for the temperature measured by the standard at the location of the sensor must be the same as that received at the central controlling unit. Often relatively high-impedance instrumentation amplifiers are required to amplify the signal from the sensor to a level acceptable by the central control unit. Such amplifying circuits are subject to drift and possible loss of linearity. In performing calibration of temperature sensors in systems with signal conditioning circuits, verification of the proper functioning of all related circuits is considered to be part of the job of calibration of the temperature sensor; otherwise the task of calibration is incomplete.

One of the most important factors that is always present in calibration and in the use of a standard is the possible effect of direct radiation from another source of thermal energy. It is the responsibility of the person performing the calibration to determine whether direct radiation to or from a component in the system is influencing the output of the sensor or the standard being used in the calibration. Such effects usually can be avoided adequately by shielding the sensor or moving the sensor and/or the standard to a position where it does not receive direct radiation. Components such as intermittent-acting electrical heating elements or pre-heat steam coils often are overlooked during the installation of the sensor and during calibration. When a heating element or other high temperature source is activated, the direct radiation from the source can heat the sensor and/or the standard. Radiation pyrometers use such radiation effects to measure temperatures. However, they are best suited for temperature ranges higher than those used in EMCS. Therefore, they are not discussed in detail in this report. For further information see reference 1.

4. DESCRIPTION OF VARIOUS TEMPERATURE SENSORS AND SUGGESTED CALIBRATION TECHNIQUES

In this section typical temperature sensing devices used in EMCS temperature monitoring systems will be described. The fundamentals of operation, typical ranges, expected accuracy, precision, time constants, recommended areas of application, advantages, disadvantages, etc. are listed for each type described. Particular attention is given to those characteristics which pertain directly to calibration.

4.1 Liquid-In-Glass Thermometers

The liquid-in-glass thermometer is a well-known temperature measuring device with a wide range of applications. The physical principle upon which these thermometers operate is that of thermal expansion. It should be noted that the reading of a liquid-in-glass thermometer depends upon the difference in the thermal expansion between the glass envelope and the liquid enclosed within it as shown in figure 4.1. Mercury is the most common liquid used at intermediate and high temperatures, although its freezing point is -38 ^{o}F (-38.9 ^{o}C) which limits its lower range. The upper limit for mercury is in the region of 1000 ^{o}F (537.8 ^{o}C) and requires the use of special glass and an inert-gas fill (usually dried nitrogen) in the capillary space above the mercury. The compression of the gas, which is inserted under pressure, helps to prevent the separation of the mercury column and raises the normal boiling point of the liquid metal. For lower temperatures, alcohol is usable to -80 ^{o}F (-62.2 ^{o}C), toluol (a commercial grade of toluene) to -130 ^{o}F (-90 ^{o}C) and a mixture of propane and propylene giving the lower limit of -360 ^{o}F (-218 ^{o}C). These lower temperatures may not be directly applicable to EMCS; they are presented to emphasize the broad range of temperatures that can be measured by the liquid-in-glass thermometer.

For the mercury in a bulb made of borosilicate or other type of glass, the bulb volume is approximately 6,222 times the volume of a one-degree length of the capillary on the scale for Celsius thermometers and 11,200 times the volume of a one degree length of capillary on the scale for Fahrenheit thermometers. These relatively high ratios produce the high sensitivities offered by liquid-in-glass thermometers. They will be discussed subsequently.

Liquid-in-glass thermometers normally are available in two types: total immersion and partial immersion. The total immersion type is initially calibrated with the liquid column completely immersed in the measured fluid. Since this may obscure the reading, a small portion of the column may be allowed to protrude, thereby inducing negligible error. Partial immersion thermometers are calibrated initially to read correctly when immersed to a given depth (immersion line, see figure 4.1) and the exposed portion is held at a definite temperature.

Corrections for total- and partial-immersion thermometers when used under conditions other than those intended are shown in figure 4.2. The temperature of the exposed portion of the stem is measured by a second thermometer and the general correction may be calculated from the equation:

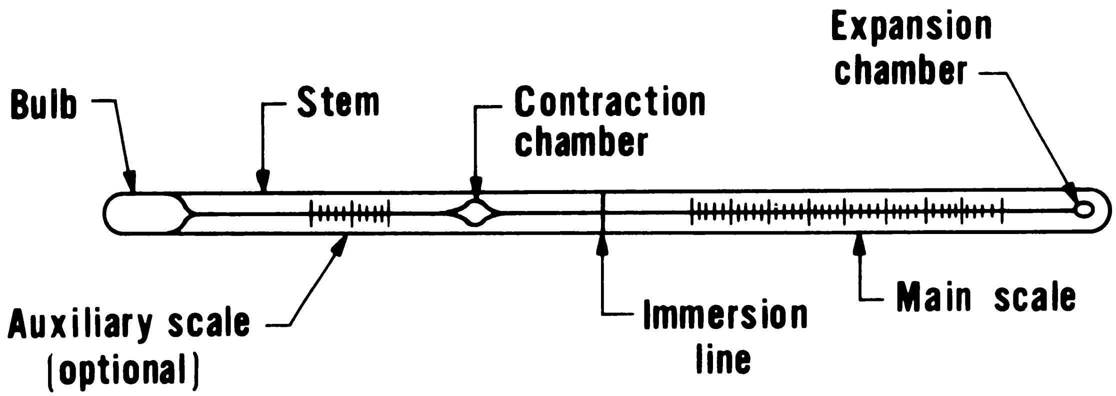

Figure 4.1. The "partial-immersion" liquid-in-glass thermometer

$$\text{Correction} = 0.00009\ n(t_{cal} - t_{act})\ ^{o}F$$

where n = number of scale degrees equivalent to the portion of the stem not immersed

t_{cal} = air temperature (^{o}F) at calibration

t_{act} = air temperature (^{o}F) during measurement.

The bulb of the auxiliary thermometer should be located at the midpoint of the exposed column of mercury. Note from figure 4.2 that when a total-immersion thermometer is used at partial immersion, $(t_{cal} - t_{act})$ in the correction equation is replaced by the temperature indicated by the main thermometer minus the temperature indicated by the auxiliary thermometer. For Celsius thermometers the constant 0.00009 becomes 0.00016. In the example shown in figure 4.2, the significance of the corrections should be noted and compared. The bulb of the auxiliary thermometer should be located at the midpoint of the exposed column of mercury.

The expansion chamber noted in figure 4.1 is provided to prevent the buildup of excessive pressures in gas-filled thermometers as the liquid advances to the top of the scale. The contraction chamber, which is frequently located just above the bulb, is an enlargement of the capillary column. It serves to reduce a long length of capillary above the auxiliary scale.

Liquid-in-glass thermometers are relatively inexpensive. They serve as good standards when properly used and their calibration is easily checked by a qualified laboratory facility. They are dependable, with a relatively long life. More elaborate types are available for higher accuracy over smaller temperature ranges.

The accuracies of the total immersion types are:

0.5 ^{o}F (0.28 ^{o}C) for the -68.8 ^{o}F (-56 ^{o}C) to 32 ^{o}F (0 ^{o}C) range,

0.05 ^{o}F (0.03 ^{o}C) for the 32 ^{o}F (0 ^{o}C) to 212 ^{o}F (100 ^{o}C) range,

0.4 ^{o}F (0.22 ^{o}C) for the 212 ^{o}F (100 ^{o}C) to 600 ^{o}F (315 ^{o}C) range, and

0.8 ^{o}F (0.44 ^{o}C) for the 600 ^{o}F (315 ^{o}C) to 950 ^{o}F (510 ^{o}C) range.

Errors in the partial-immersion type may be several times larger even after corrections for air temperature have been made. The uncertainties in precision are slightly less than those listed for accuracy. The response time of the liquid-in-glass thermometer varies with the size of the instrument and the medium being monitored--usually 5 to 20 seconds.

The required manual reading of the liquid-in-glass thermometer often induces errors far beyond those caused by the instrument itself. This type of thermometer in EMCS applications is usually graduated in one degree increments. Should the person using the instrument record the integer value of the graduation which appears to be the closest to the top of the column, the value of the accuracies previously listed are far exceeded by "human error." This is often the case, and the effectiveness of the functioning EMCS

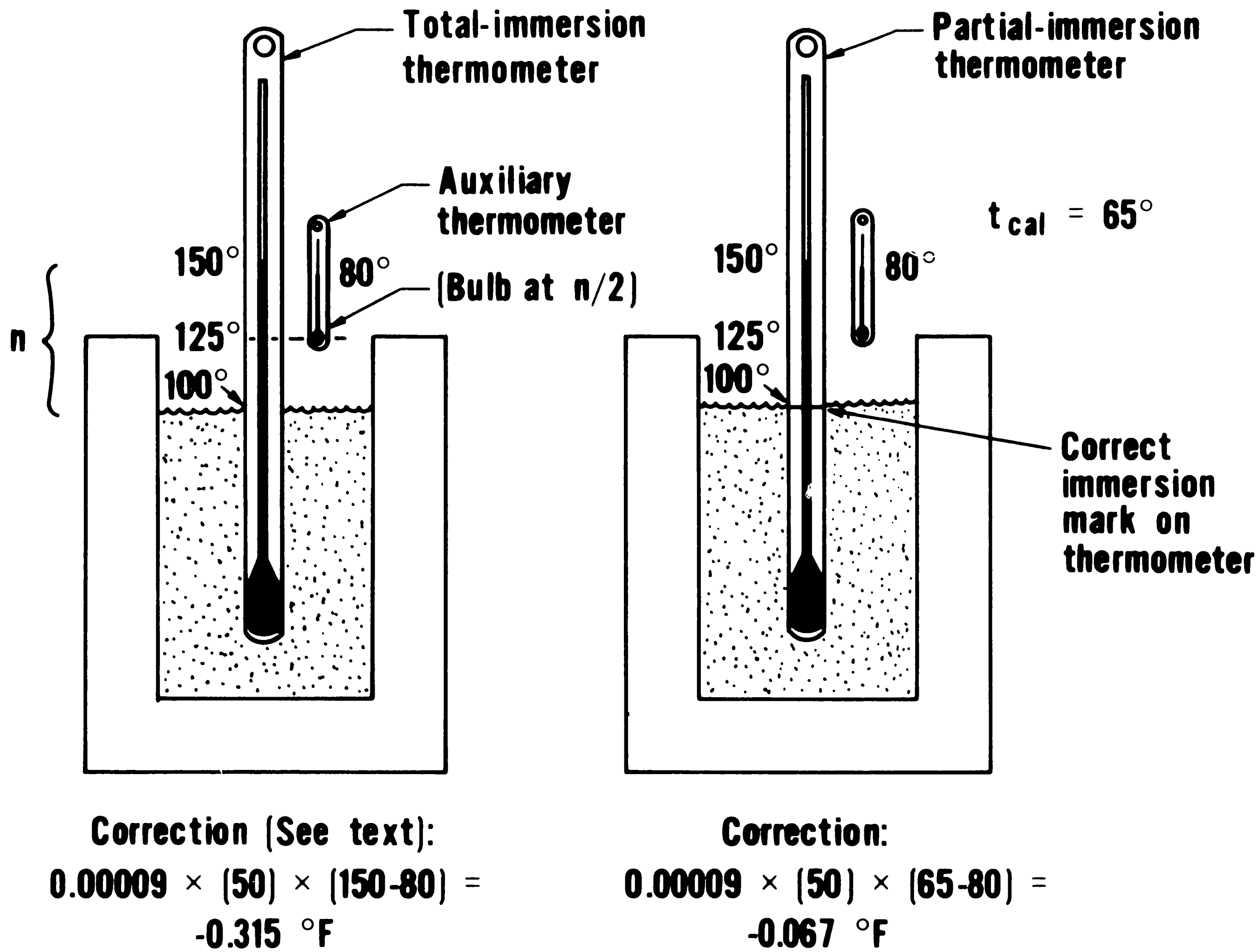

Figure 4.2 Examples of stem corrections in using total and partial immersion liquid-in-glass thermometers

will suffer from this fact. Carefully reading the scale with a magnifying glass will allow most typical liquid-in-glass thermometers to be read to within ±0.15 degrees.

Liquid-in-glass thermometers, although not especially fragile, are frequently dropped and broken. Proper precautions should be used in collecting the scattered mercury as soon as possible for safety reasons. An experienced EMCS person using a liquid-in-glass thermometer will carry the instrument from point to point in a protective tube that is supplied with each instrument. The experienced person will also place the instrument in the tube while it is not actually in use. Such action prevents many unnecessary accidents.

Liquid-in-glass thermometers installed in pipe lines are used for manually monitoring the functioning of a supply system rather than specifically for EMCS. Such units are assumed to have been calibrated prior to installation. However, it is not unusual to observe an instrument of this type in a working mechanical equipment system which is obviously indicating an incorrect temperature or which has a cracked stem. When a thermometer is observed in this condition, it should be noted in the calibration notebook and reported to those responsible.

The calibration of liquid-in-glass thermometers to be used as standards in EMCS work should begin by examining the instruments, using a 15-20X microscope, for errors, chips, or irregular coatings in the graduations; glass chips or debris in the capillary; non-uniform capillary; and cracks in the glass. The actual calibration of the instrument then is best accomplished by the technique described in section 3.2. In checking the calibration of the instrument over its full range, it is easiest to check the performance at the ice point, 32 ^{o}F (0 ^{o}C). If the range of the thermometer is above this temperature and the instrument has an auxiliary scale as shown in figure 4.1, most often the auxiliary scale will include the ice point.

If the ice point is to be used as a calibration point, the thermometer should be immersed to the proper level in shaved or crushed ice. The ice should be made from distilled water or obtained from the clear portion of block ice. The ice should be contained in a Dewar flask to retard heat flow from the room. Distilled water should be added to the ice, but only enough to fill the spaces between the ice particles. As the ice melts, more ice should be added so that the thermometer bulb is never sitting only in water. A carefully prepared ice bath will provide a 32 ^{o}F (0 ^{o}C) reference within ±.02 ^{o}F (.01 ^{o}C).

A variable temperature calibration bath using another liquid-in-glass thermometer or an RTD as a standard is best suited for checking the calibration of the full range of the thermometer. In such baths, adequate agitation is usually provided to maintain the homogeneity of the temperature in the bath. However, it is advisable to keep the instrument being calibrated and the standard far enough away from the heating or cooling coils in the bath to avoid possible errors. The proper immersion for the type of thermometer being calibrated must be observed.

Determining the corrections to be applied to the readings of a liquid-in-glass thermometer is accomplished by comparing its readings with those of the standard. The number of calibration points depends upon the accuracy required and the behavior of the thermometer. If the corrections are similar in magnitude throughout the thermometer range, or if the corrections vary slowly with the temperature, only a few points are needed to characterize a given thermometer.

The bulb is the thinnest and therefore the weakest part of the thermometer. When the thermometer is heated to high temperatures, the resulting pressure causes the bulb to expand; subsequently, the thermometer will read low. With time, glass tends to relax to its former condition, but until it does, all of the readings of that thermometer will tend to be in error by the same amount. Keep in mind the vast ratio of the volume of the bulb to that of the capillary. Reference 2 fully describes the methods to be used in arriving at corrections for emergent-stem temperatures.

During the calibration of a liquid-in-glass thermometer and when using it as a standard, care must be used in several areas. First, make sure that the bulb is in the medium to be measured; e.g., if the temperature of the air flowing in an air duct is to be determined, the bulb should project inside the duct far enough to avoid the gradients in the medium caused by the hot or cold surface of the duct wall. Second, avoid touching the stem of the thermometer to the wall enclosing the fluid whose temperature is to be measured. Third, the medium being measured must be "mixed" as described in section 3.2 to avoid "hot" or "cold" areas of flow. Fourth, determine whether heat is being either carried to or taken from the thermometer bulb faster than the flowing medium can remove or add it. This last area presents a very general problem that applies to all types of thermal sensing units. In the case of the liquid-in-glass thermometer, the stem correction factor can generally be used as a solution.

Recertification by a qualified laboratory is recommended for all standards. The frequency of recertification will be discussed further in section 5 of this report.

4.2 Pressure-Type Thermometers

Pressure-type thermometers consist of a sensing bulb, an interconnecting capillary tube, and a pressure measuring device such as a diaphragm, bellows, or Bourdon tube as shown in figure 4.3. The typical system of this type is completely filled with a liquid (mercury and xylene are common choices) or with gas under an initial pressure.

A less-popular vapor-pressure thermometer of this type utilizes a nonvolatile liquid to fill the lower portion of the sensing bulb, the capillary tube, and the pressure measuring device. A volatile liquid is used to fill the center portion of the sensing bulb and the vapor from the volatile liquid fills the upper portion of the sensing bulb as shown in figure 4.4. The end of the capillary tube is always protruding into the nonvolatile liquid in the sensing bulb.

For the liquid-filled system, the compressibility of the liquid usually is small enough that the measurement is essentially one of determining the changes in the volume caused by the expansion and contraction of the liquid. Compensation is required for the expansion and contraction of the bulb itself together with changes in the capillary and pressure measuring device volumes caused by changes in the temperature in their respective environments. The reverse is true for the gas-filled systems. Here, the basic effect is one of change in the gas pressure at a constant volume. If a pure gas is used, the indicating pressure generally follows the ideal gas law:

$$PV=nRT.$$

See reference 4 for further details. Minimal compensation may be needed for the expansion and contraction of the enclosing components.

The capillary tubes on liquid and gas filled systems can be as long as 200 ft (61m) for remote measurement. However, at these capillary lengths, temperature variations along the capillary and at the pressure measuring device usually make compensation mandatory. The systems using a volatile liquid generally will not require compensation since the pressure depends only upon the temperature at the liquid's free surface located in the bulb. Again, the capillary may be as long as 200 ft (61m) for the volatile-liquid type if the end of the capillary is retained in the nonvolatile liquid in the bulb.

A common method used for compensation of the liquid-filled thermometer is the attachment of an auxiliary pressure sensing device and capillary. The movements of the auxiliary system are caused by the interfering effect only. These components are mechanically attached to the primary measuring device to subtract (or add) to the output normally indicated by the primary system as shown in figure 4.5. Bimetal elements sometimes are used to obtain compensation for the temperature differences of the case enclosing the measuring device and of a portion of the capillary tube. See reference 2 for further details.

Systems filled with xylene, or a similar liquid, have a range of -150 ^{o}F (-101 ^{o}C) to 750 ^{o}F (399 ^{o}C). Systems filled with mercury have a range of -38 ^{o}F

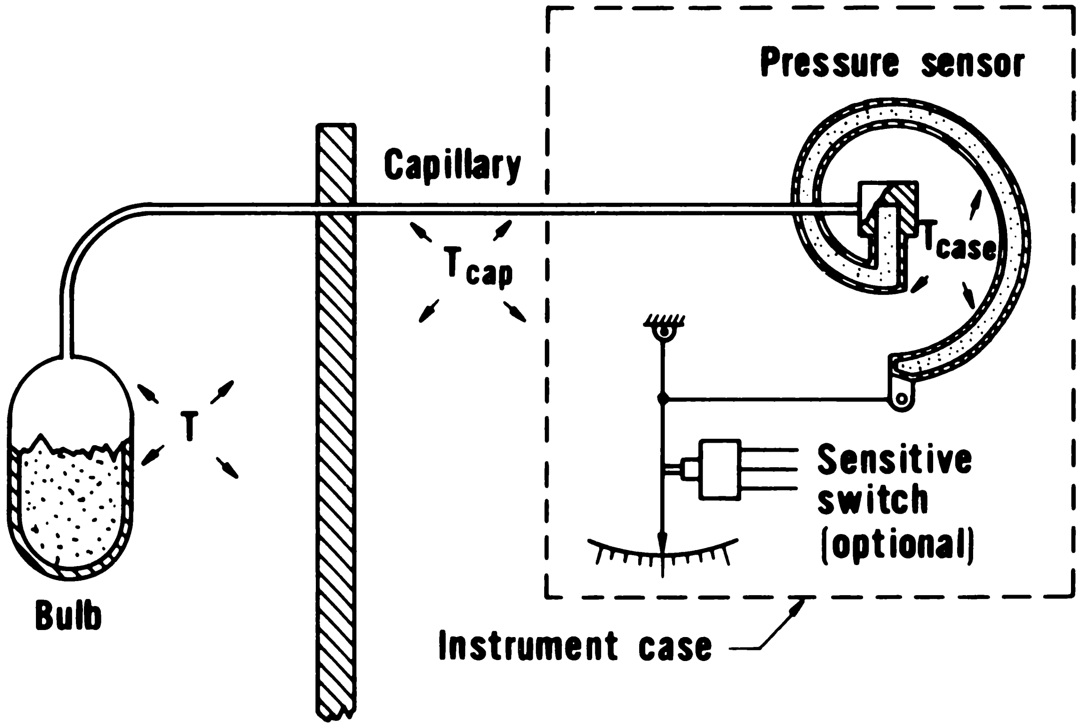

Figure 4.3 Schematic diagram of a typical pressure-type thermometer

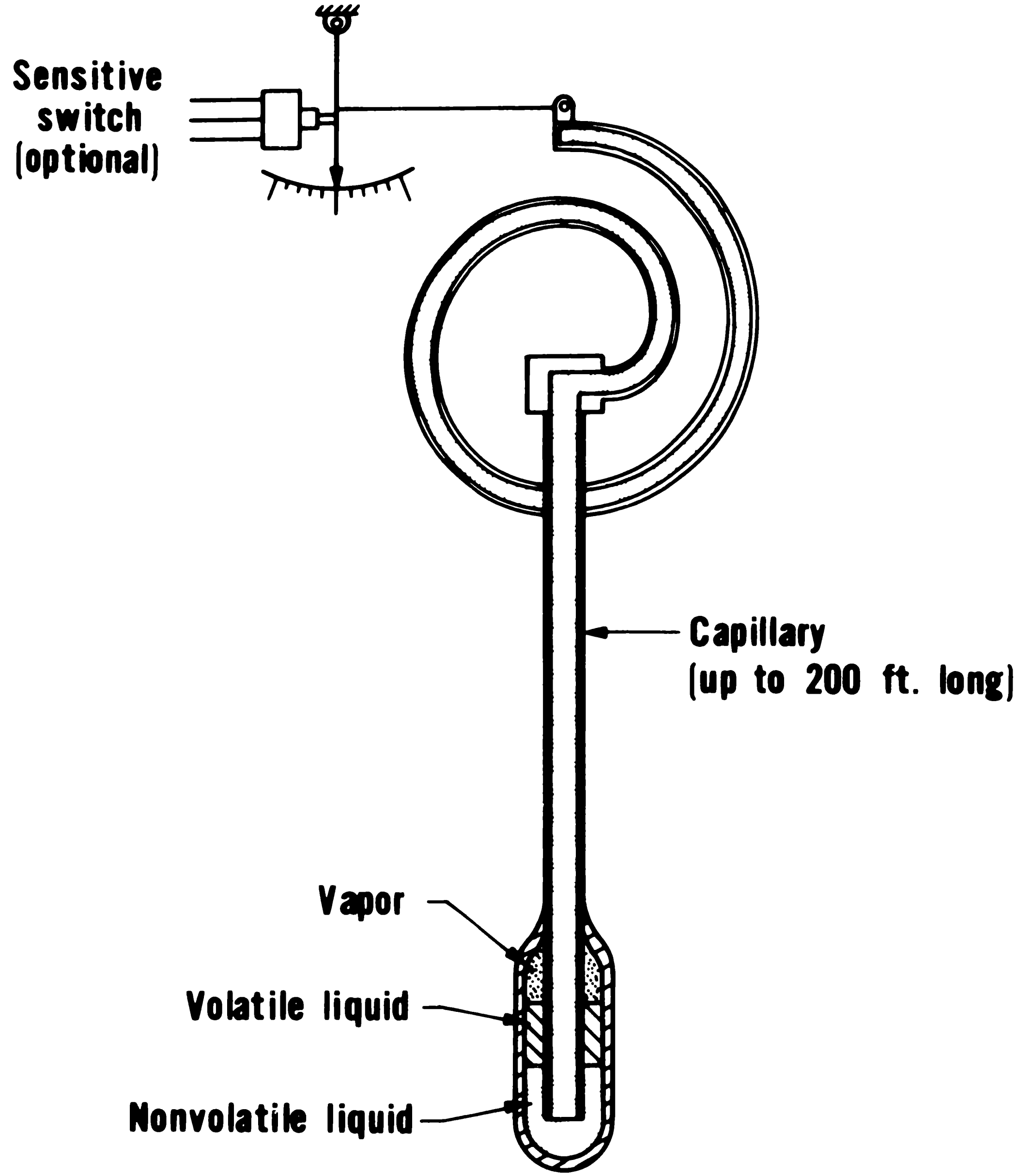

Figure 4.4 Schematic diagram of a vapor-pressure thermometer

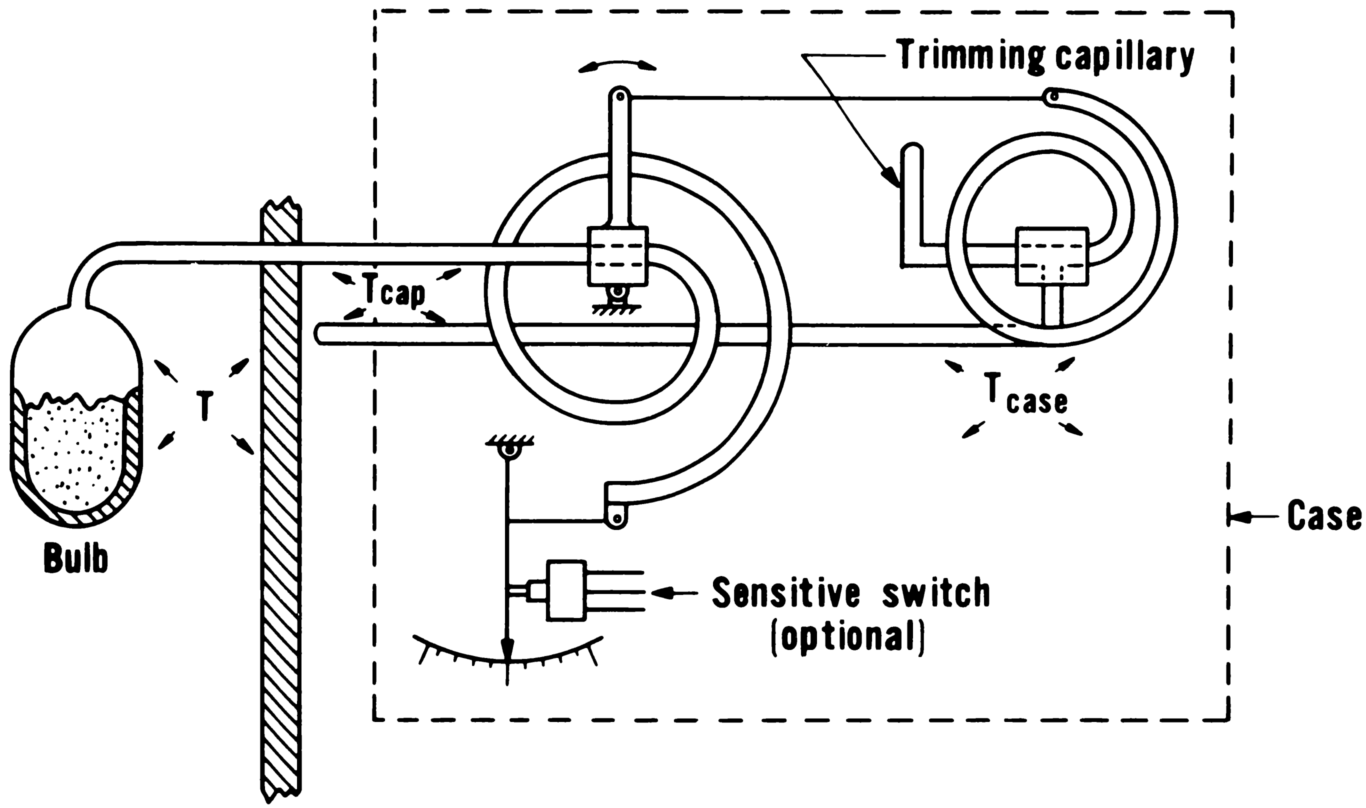

Figure 4.5 Schematic diagram of one method of automatically compensating for changes in case and capillary temperatures on pressure-type thermometers

(-56 ^{o}C) to 1100 ^{o}F (593 ^{o}C). The response is essentially linear over ranges up to 300 ^{o}F (149 ^{o}C) for xylene and 1000 ^{o}F (538 ^{o}C) for mercury. Gas-filled systems generally operate over a range of -400 ^{o}F (-240 ^{o}C) to 1200 ^{o}F (649 ^{o}C). The response for the gas-filled systems is essentially linear up to 1000 ^{o}F (538 ^{o}C). The vapor-pressure systems are generally usable in the range of -40 ^{o}F (-40 ^{o}C) to 600 ^{o}F (315 ^{o}C). However, the calibration of the vapor-pressure thermometers is non-linear to such an extent that special linearizing mechanical linkages are needed if a linear output is required.

Additional characteristics of pressure thermometers that may affect the calibration include:

1. In the liquid-filled types, differences in the elevation of the bulb with respect to the pressure sensor will cause slight errors in the calibration.

2. In the gas-filled types, errors caused by capillary temperature variations are usually small. However, compensation for variations in the temperature of the pressure sensor is required and generally is accomplished by bimetal elements.

3. The response time of a pressure thermometer will depend upon the medium it is monitoring. For example, relatively long periods (1 to 3 min) may be required for the massive bulb and its contents to respond to a small change in the temperature of an air stream it is monitoring.

4. The accuracy of pressure thermometers under ideal conditions is about 0.5 percent of the scale range. Adverse environmental conditions in the area of the capillary or pressure sensing device will increase this error considerably.

5. Capillary tubes without the typical bulb are also used as temperature sensing devices in EMCS. The characteristics of the capillary discussed in this section are utilized and the capillary is mounted in the fluid stream in a manner to produce a pressure that is representative of the average temperature of the fluid. Sensors of this type are normally found in pneumatically-controlled systems. Although sensors of this type are often "factory-calibrated", provisions generally are provided for on-site calibration. The manufacturers' instructions must be consulted before any adjustments are made.

Pressure thermometers often are installed for manual inspection of the operation of the mechanical equipment system in a building. However, they also are used for activating and deactivating controls in an EMCS. Therefore, they are included in this report.

The calibration of the pressure thermometers while they are in place is most likely to provide satisfactory results. Such calibrations can be performed using a suitable standard. The level of accuracy of the pressure thermometer is not likely to require unusual calibration techniques. Regardless of the level of accuracy provided, a pressure thermometer used for direct control in an EMCS requires special attention in its operating ranges.

If the thermometer must be removed for calibration, the problem of temperature gradients within the medium or along the capillary or the pressure sensor must be considered. It is the responsibility of the person performing the calibration to determine the magnitude of these effects. In remote systems with long capillaries, it may be found advisable to temporarily dismount only the sensing bulb and a small portion of the capillary from the mechanical system to allow a variable-temperature bath to be used for calibration at the location of the bulb. This will allow the majority of the capillary and the pressure sensor to remain in their typical environments while the calibrator varies the temperature of the bulb within its operating range and checks for the response of the device that the pressure sensor is actuating.

Although many negative features have been pointed out concerning pressure thermometers, they have been installed and have functioned properly in many buildings for many years. If a contractor prefers to use these types of actuators and they meet the general requirements of the mechanical equipment system for the building, they are likely to be found. Therefore, it is the responsibility of the person performing the calibration of the EMCS to calibrate and test each such instrument for proper operation.

4.3 Resistance Temperature Detectors (RTDs)

A resistance temperature detector (RTD) operates on the principle of a change in its electrical resistance as a function of temperature. In general, the resistivity of all metals increases with an increase in temperature and yields a positive resistance-temperature coefficient [2,4]. Platinum, copper, and nickel are the typical metals used for RTDs. The resistance/temperature curves for these three metals are shown in figure 4.6. Platinum is the most desirable for use as a sensor in EMCS because of the linearity of the resistance/temperature coefficient. However, copper and nickel are used for RTDs where the linearity is not important, and in installations in EMCS when the signal from the sensor is not being conditioned.

Platinum is linear within $\pm$0.3 percent from 0 ^{o}F (-17.8 ^{o}C) to 300 ^{o}F (149 ^{o}C) and improves to $\pm$0.2 percent from 0 ^{o}F (-17.8 ^{o}C) to 200 ^{o}F (93.3 ^{o}C). At the higher temperatures, 500 ^{o}F (260 ^{o}C) to 1500 ^{o}F (815.5 ^{o}C), platinum is linear within $\pm$1.2 percent. The ranges of sensitivity and linearity of copper and nickel relative to platinum can be observed from figure 4.6.

RTDs acceptable as sensors for EMCS installation and standards are made by winding very pure (usually 99.99 percent), annealed platinum wire about a strain-free core usually made from ceramic or glass. This assembly is then hermetically sealed in a ceramic or glass capsule. RTDs are made with two, three or four leads, depending upon the desire for temperature measurements independent of changes in the electrical resistance of the leads. The encapsulated assembly is often mounted in a stainless steel sheath to provide protection against moisture, shock, and the medium being monitored.

Open-type RTDs expose the resistance winding directly to the fluid being monitored and give a faster response. However, the fluid must be noncorrosive; a fluid that seldom exists in EMCS.

Various flat types of RTDs are also available for measuring surface temperatures. Surface temperatures of bodies being monitored with RTDs consisting of grid windings and thin deposited films of platinum may produce erratic outputs because of interfering mechanical strains in the sensor caused by differential thermal expansion stresses in the bodies. If the surface temperature is relatively high and/or the temperature measurement is critical, the thermal radiation from the surface of the body being monitored is obstructed by the flat RTD and the temperature indicated by the RTD may exceed that of the temperature of the surface without the obstruction. Open, flat grid, and thin-film types of RTDs are not recommended for general use in EMCS for these reasons.

The most sensitive areas in the installation and calibration of the RTD are changes in the resistance of the lead wires caused by temperature variations and variations in contact resistance. In operation, the RTD is generally electrically mounted as one leg of an electrical resistance bridge. The bridge circuit can be operated in either a null or deflection mode. For EMCS measurements, the deflection mode is generally used. However, when the RTD is being used as a standard, the null mode is often preferred. If the null method

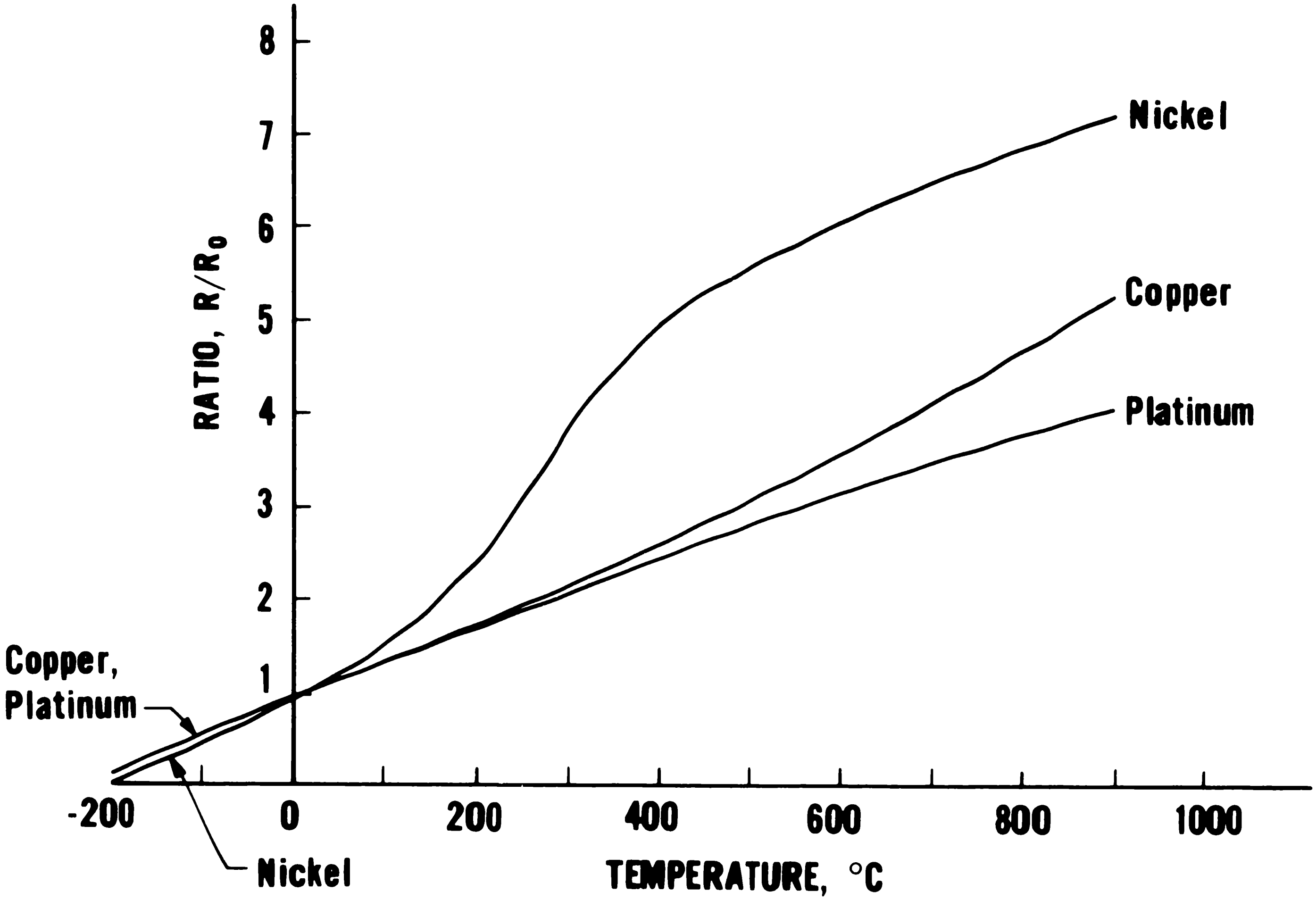

Figure 4.6 Resistance/temperature curves for nickel, copper and platinum. The ordinate R/R_o, represents the ratio of the resistances of the three metals at various temperatures to the resistances at 32°F (0°C)

is used in a simple bridge circuit such as that shown in figure 4.7(a), the resistor R_4 is varied until the bridge is balanced. The value of R_4 is the same as that of R_3 excluding all errors. The bridge circuit shown in figure 4.7(b) is useful for measurements of high accuracy since the contact resistance of the variable resistor does not influence the resistance of the bridge legs. If the leads from the RTD are long and are subjected to varying temperatures, the bridge circuit shown in figure 4.7(c) is recommended. Errors caused by the resistance changes in the legs will cancel since one of these leads is in each of the bridge legs R_2 and R_3. The effect of a resistance change in the third lead is negligible if the indicating instrument requires minimal current for operation. After proper calibration, the circuits shown in figures 4.7(b) and (c) can be used in the deflection mode. These circuits are useful in the null mode when being used as a standard for detecting a given temperature (as opposed to detecting a range of temperatures).

The circuit in figure 4.7(d) is shown to emphasize that when $R_1 = R_2 > 10R_3$, good linearity of the RTD can be obtained if the bridge is balanced with R_4 at the middle of the temperature range. A typical platinum RTD with a 100 ohm nominal resistance, will vary approximately 20 ohms over its operating range in an EMCS. If the legs of the bridge were of equal value, severe nonlinearity would occur. The higher values of R_1 and R_2 greatly reduce this problem area and offer a bridge circuit with good performance.

When properly designed, the RTD will make an excellent standard. The use of a four lead Mueller bridge such as that shown in figure 4.8 is recommended [6]. The resistances of the leads are compensated in a large measure by placing the resistance of one lead in each of the measuring legs of the bridge, then reversing the connections before making a new balance. Using the resistance terms shown in figure 4.8, the balance equations are:

Normal connections $R_{d1} + R_c = R_x + R_t$

Reverse connections $R_{d2} + R_t = R_x + R_c$

By adding these equations, the value of R_x can be determined from the resulting equation:

$$2R_x = R_{d1} + R_{d2}.$$

The unknown resistance of the RTD (R_x) is simply the arithmetic average of the normal and reverse readings.

AC bridges are seldom available with <u>AC resistance standards</u> for EMCS calibration standards. However, if such bridges are available, they offer a fast and extremely sensitive method for calibration in comparison with the Mueller bridge shown in figure 4.8 or the bridges shown in figure 4.7. The accuracy level of AC bridges can be determined by the use of <u>AC resistance standards</u>.

Measurements made by the RTD sensor or standard using different currents will show the presence of the self-heating error. Off-on measurements will give an indication of the time response. Other ambient conditions to consider include the presence of electromagnetic fields from inductors, high-current power

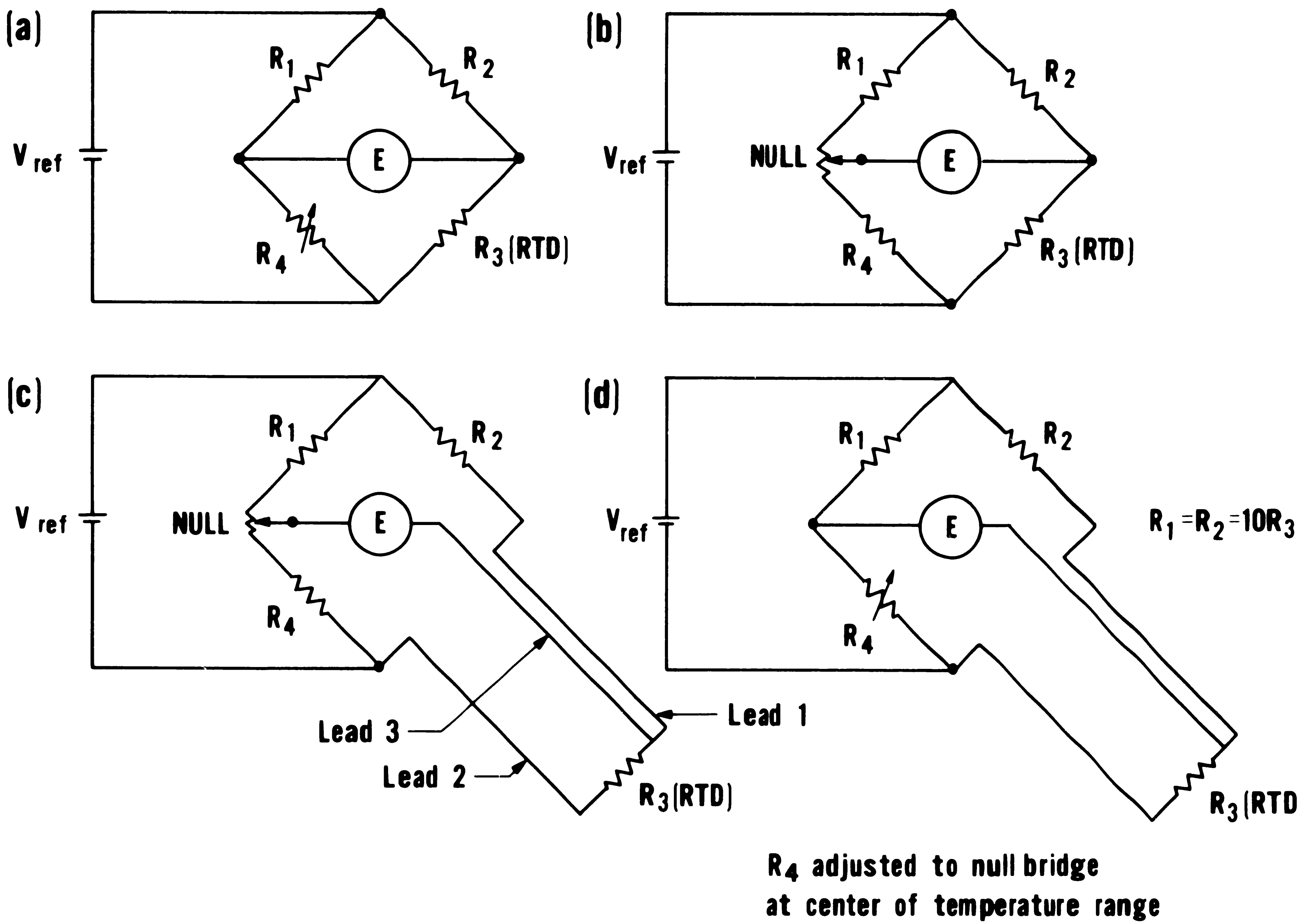

Figure 4.7 Various bridge circuits used for resistance temperature detectors (RTDs)

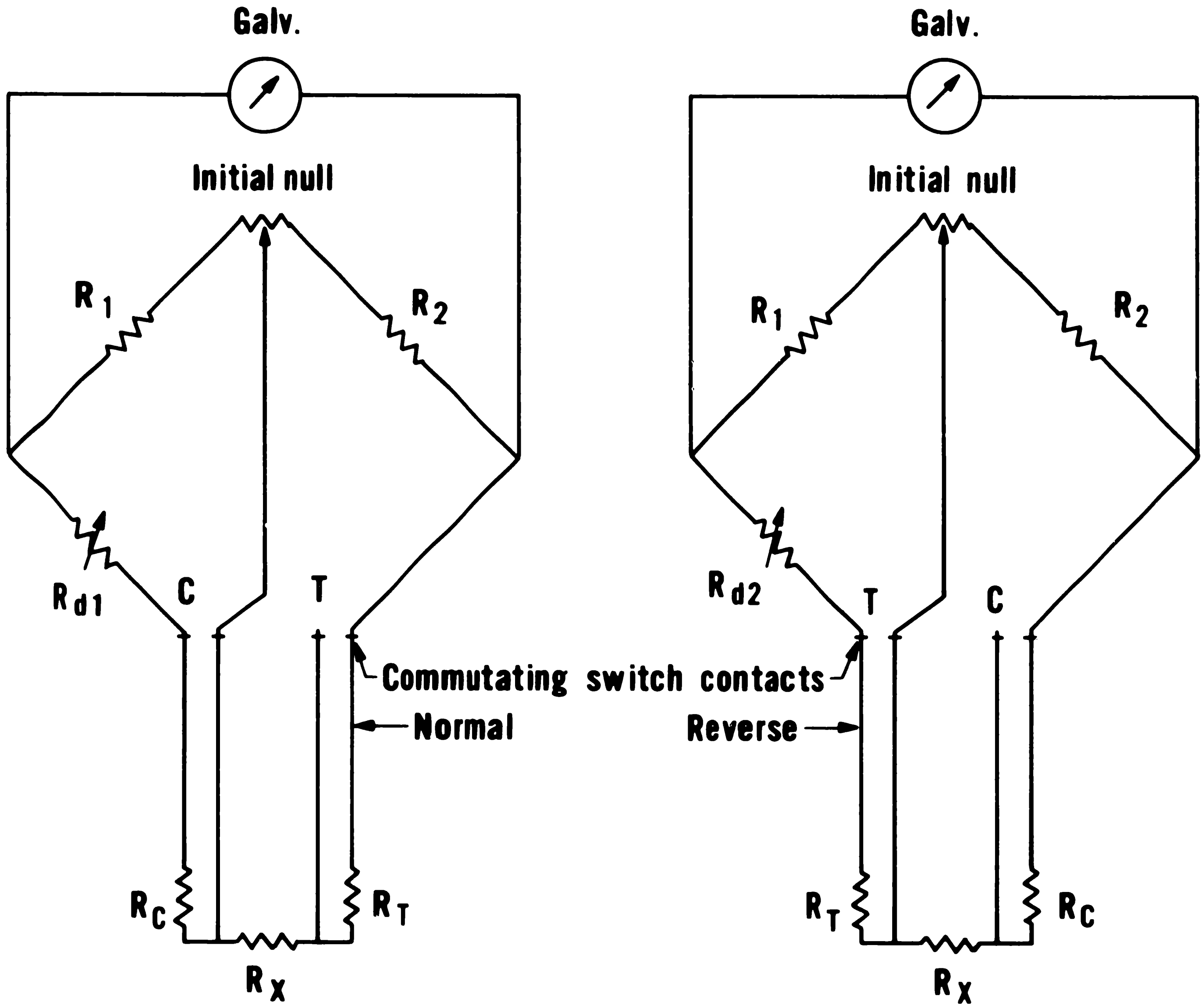

Figure 4.8 The use of a Mueller bridge for the calibration of a four lead RTD

NOTE: R_T and R_C are the resistances of leads t and c respectively; the initial null potentiometer should not be disturbed while taking measurements lines or rectifiers; unwanted sources of heat near the installation; frayed insulation on the leads; and internal inhomogeneities in the medium being monitored as mentioned in section 3 of this report.

In general, RTDs are best calibrated using the in-place comparison technique and a standard. Assuming the RTD in the EMCS has a stainless steel sheath, a variable temperature bath may be well suited when properly used. In all cases, the thermal energy gains or losses via the sheath and leads must be considered and compared with such gains or losses when the RTD is mounted in the system.

The response time of a RTD which has been hermetically sealed (without sheath) is approximately one second in flowing water and two seconds in moving air. These are 90 percent response times. The addition of the stainless steel sheath will, of course, increase these response times depending upon the design of the sheath and the medium being monitored. The self-heating error in the hermetically sealed RTD is less than 0.1 ^{o}C/mW in moving air (v=1 m/s), and less than 0.25 ^{o}C/mW in still air.

The name of the precious metal, platinum, has a tendency to frighten designers, engineers, and EMCS management personnel away from considering the RTD as a sensor or a standard. However, the price of a platinum RTD hermetically sealed in ceramic or glass is generally less than that of a certified liquid-in-glass thermometer. The cost of a platinum RTD mounted in a stainless steel sheath is in the same price range as that of a certified liquid-in-glass thermometer.

4.4 Thermistors

Commercially available thermistors usually are fabricated in forms of beads, discs, rods or flakes. With the exception of the bead type, they are generally composed of sintered particles of metal oxides bound between two conductive surfaces with lead wires attached. In the bead type, the lead wires are embedded in the oxide. The oxides of nickel, manganese, iron, cobalt, copper, magnesium, titanium, and other metals are used. Thermistors differ from RTDs in several fundamental ways. First, a thermistor usually has a high initial resistance (1,000 - 10,000 ohms) relative to the low resistance of the RTD. Because of the higher initial resistance, the resistance of the lead wires is usually negligible. Second, thermistors generally possess a relatively large negative resistance/temperature coefficient. Some thermistors possess a positive resistance/temperature coefficient and are generally used for switching, not temperature measurement (this type will be discussed later in this text). A third difference is that the resistance-temperature relationship of a single thermistor is very non-linear as shown in figure 4.9. There are techniques, however, for linearizing the resistance-temperature relationship of thermistors. These types are commonly found in EMCS. The fourth major difference is that the thermistor resistance varies inversely with the applied voltage since the resistance is decreasing with temperature instead of increasing as it does with the RTD.

Recent research [7] has helped to develop thermistors that are quite stable with time. Off-the-shelf bead-in-glass and glass-coated disc thermistors which drift no more than a few thousandths of a degree Celsius per year are available at relatively low cost.

There are several recommendations for thermistors which are to be used in EMCS. First, the thermistor must be hermetically sealed to prevent the deterioration of the oxides from the typical environments of EMCS. Thermistors encapsulated in ceramic materials are not recommended for direct immersion in liquids, especially water found in EMCS environments. Glass encapsulated thermistors generally are suitable for direct immersion if specified by the manufacturer. Second, two or more oxides separately encapsulated within an outer seal and utilizing specified related components to complete the bridge circuit should be used to produce a linear output within an acceptable range for EMCS. Figure 4.10 displays some typical circuits used for linearized thermistors. Figure 4.10 (a) represents a dual-element thermistor from which a positive or negative temperature/voltage output can be obtained. Figure 4.10 (b) represents a more practical circuit for EMCS using the same thermistor. The leads shown in the figure can be as long as 300 ft (91 m) for temperature ranges from 32 ^{o}F (0 ^{o}C) to 100 ^{o}F (37.8 ^{o}C). By extending the upper end of the range to 212 ^{o}F (100 ^{o}C), the length of the leads must be limited to 100 ft (30.5 m) to retain the specified linearity. One restriction in using a typical dual-element thermistor in this fashion is that the resistor R_2 must remain close to the environment of the thermistor. The linear deviation of available dual units such as shown in figure 4.10 is approximately $\pm$0.4 ^{o}F (0.2 ^{o}C) over the specified range. The error introduced by interchanging the components (R_1, R_2, and the thermistor) which are supplied by the manufacturer is approximately $\pm$0.27 ^{o}F (0.15 ^{o}C). Currently-available thermistors made from three elements and using their

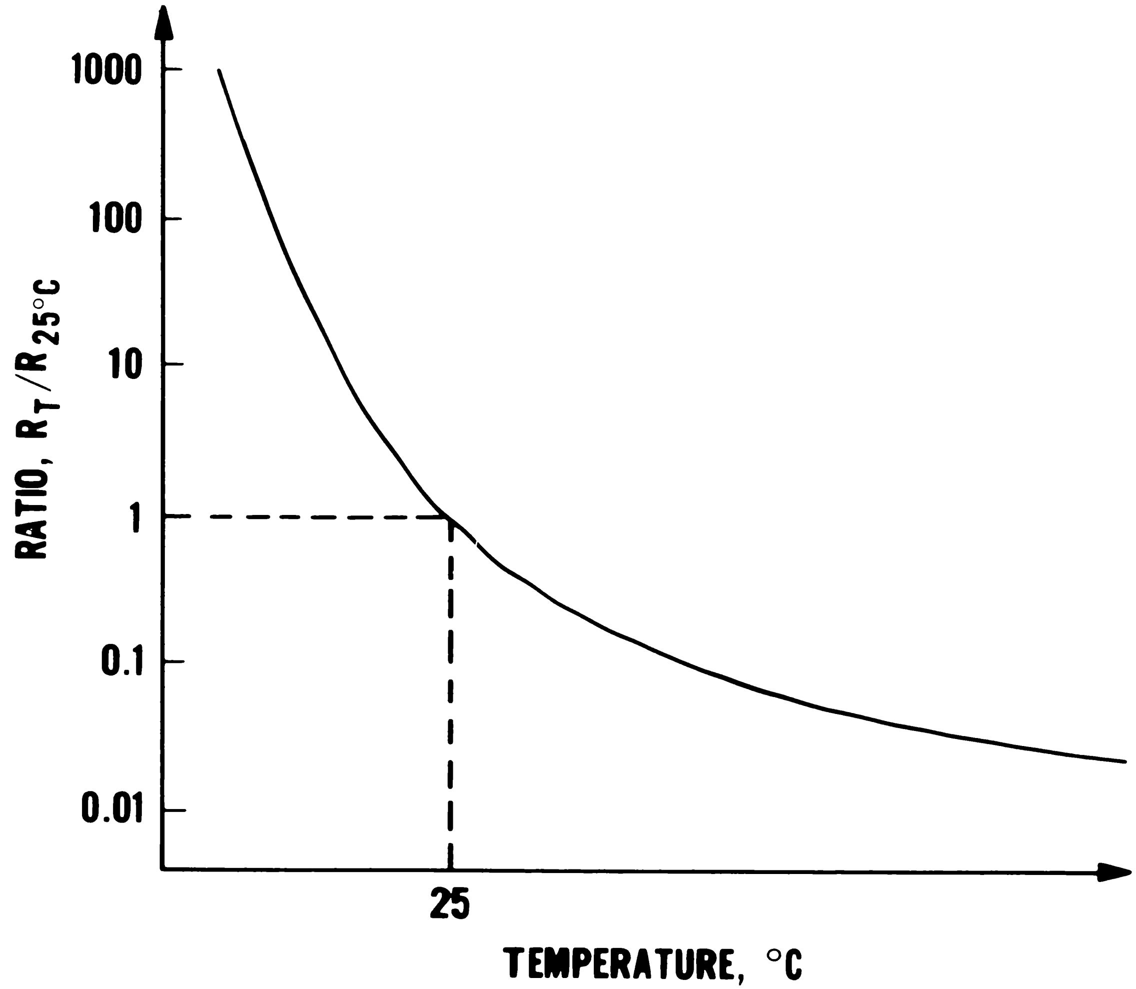

Figure 4.9 Example of the non-linearity of the ratio of a single element thermistor resistance at temperature T to that at 25°C

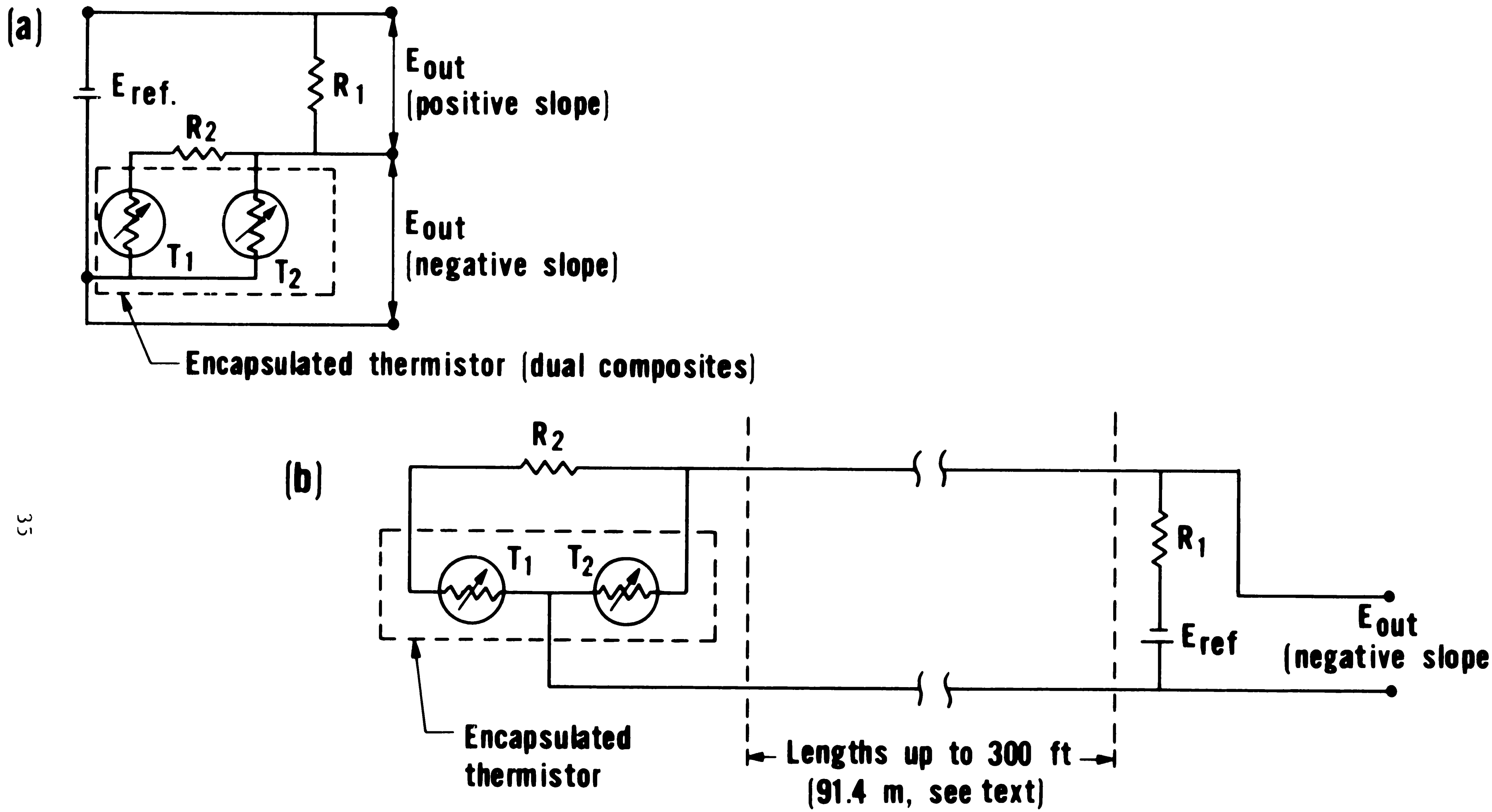

Figure 4.10 Typical bridge circuits for linearized thermistors. a) a circuit for obtaining positive or negative coefficients at local sensor stations. b) a typical circuit for EMCS where the output is desired at distant stations.

NOTE: In both cases, the resistor R_2 must be connected directly to the leads of the thermistor.

respective resistors are linear within ±0.09 °F (0.05 °C) over an operating range of 0 °C to 100 °C.

Several additional factors should be noted in the application and calibration of thermistors. One of the most important factors is the power dissipation constant (i.e. power in mW required to raise a thermistor 1 °C above the surrounding temperature). A typical thermistor suspended by its leads in a stirred oil bath has a dissipation constant of 8 mW/°C, or 1 mW/°C in still air. The time constant (i.e. the time required for a thermistor to indicate 63 percent of a change in temperature) is approximately 2.5 seconds in stirred oil and 25 seconds in still air. These factors must be kept in mind during the calibration of any thermistor. Long-term operation at temperatures above those specified for the thermistor will cause the unit to exceed the specified tolerances.

Linearized thermistors operating in a self-heated mode can be a problem in calibration. If the applied voltage is not adequate, the medium being monitored will dissipate the thermal energy faster than it is supplied. In this case, the thermistor will not produce an output meeting the manufacturers' specifications. In each case, the reference potential should be computed as recommended by the manufacturer for the medium being monitored.

Simple, hermetically-sealed, single-element thermistors may also be found in EMCS. Such components follow the general non-linearity shown in figure 4.9. However, by adding a resistor in parallel with the thermistor of a value approximately that of the thermistor at the center of the range in which it is to operate, the extremities of the non-linearity will be greatly reduced. If the range is relatively small (e.g. 20 °C) the thermistor will tend to function in a linear fashion as shown in figure 4.11. This figure points out another factor concerning the calibration of thermistors used in EMCS. Thermistors are often used in the "resistive" mode instead of the voltage mode. When thermistors are used in the resistive mode, the thermistor and its related components are generally used as a leg in a bridge circuit where the output of the bridge is amplified and used to transmit the signal to the receiving unit of the EMCS. Figure 4.12 (a) shows the linearized thermistor shown in figure 4.10 being used in a resistive mode. Figure 4.12 (b) is a schematic diagram of a linearized composite unit utilizing three different thermistors being used in the resistive mode. The resistors R_1, R_2, and R_3 are generally supplied with the encapsulated thermistors.

The details of the circuitry in figures 4.10, 4.11, and 4.12 are presented to emphasize one major item related to the calibration of any thermistor. This item is impedance. The impedance of the device being used to measure the resistance or voltage of the sensor during calibration, or, the input impedance of the amplifier used to amplify and/or condition the signal suitable for EMCS is critical. Although the exact value for this impedance may vary from one manufacturer to another, in general, it will be in the range of ten megohms. By observing the nature of the circuits shown for thermistors, it will become obvious that any significant load placed across the thermistor will reflect upon its reading. Therefore, the proper instrumentation must be used to obtain the proper calibration signals. The impedance of any additional load placed in parallel across the thermistor,

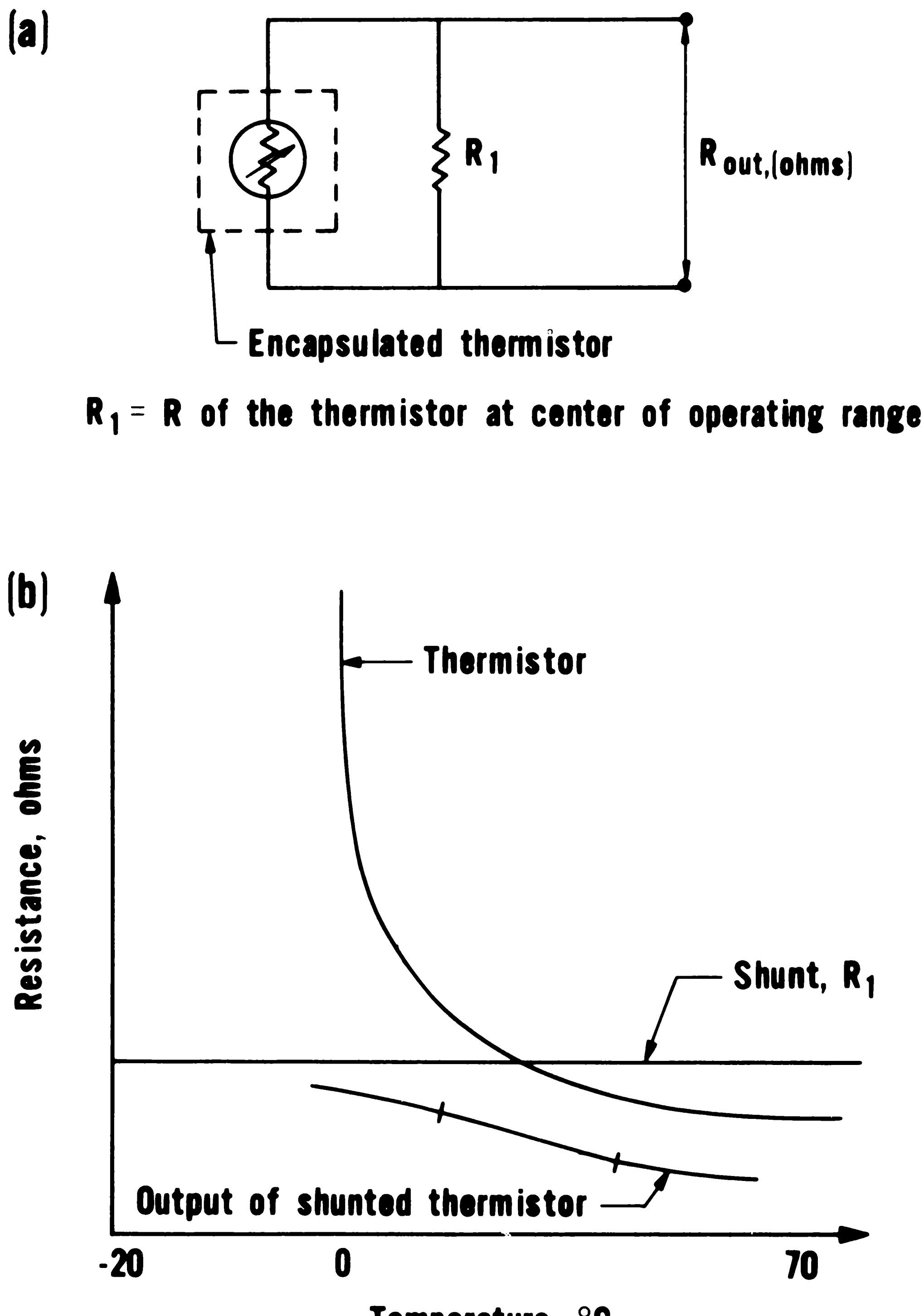

Figure 4.11 a) Schematic diagram of a single element thermistor shunted by resistor R_1. b) Resistance versus temperature diagram

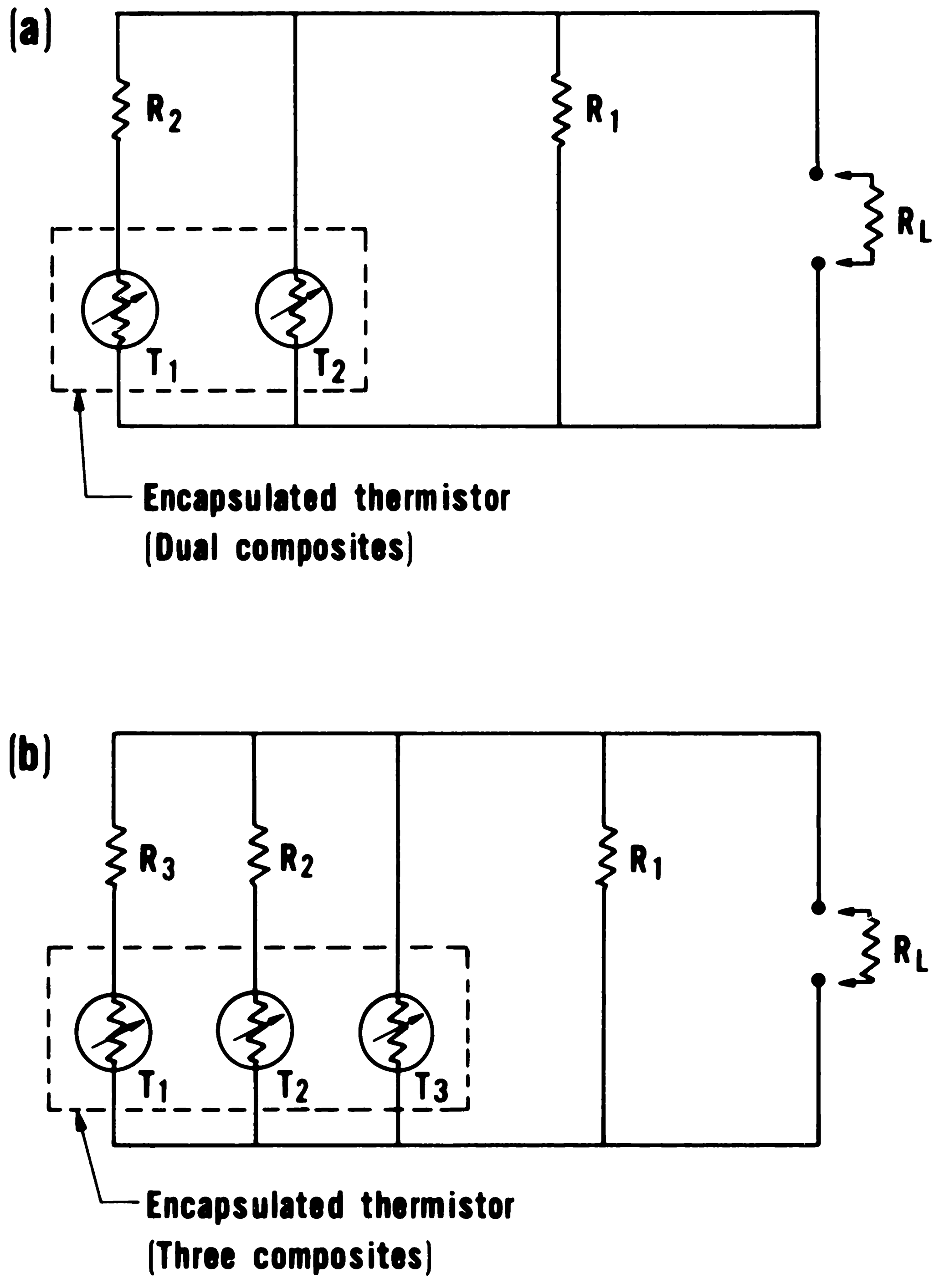

Figure 4.12 Schematic diagrams of: a) a linearized two thermistor circuit used in a resistive mode, and b) a linearized three thermistor circuit used in a resistive mode

such as an amplifier, must also be considered if the thermistor is being calibrated in-situ.

Other related items of importance include the selection of the values for the other legs of the bridge when the thermistor is being used in the resistive mode. The values of the resistors used must be high enough to prevent unwanted self-heating and to minimize calibration errors caused by excessive current in the thermistor. In simple bridge circuits, the values of the other legs of the bridge will depend upon the reference voltage applied, the values of the resistance of the thermistor, and, most important, the manufacturers' specifications.

Another typical problem in the calibration of thermistors is broken lead wires in the immediate area of the sensor. The thermal expansion and contraction of the encapsulating material and other materials that form the thermistor package often break the leads within the hermetically sealed package. A simple continuity test using a digital volt/ohm meter will locate this problem during calibration.

Positive resistance/temperature coefficient thermistors are often found in EMCS. However, such thermistors are generally used for switching. Resistance/temperature curves for three such thermistors are shown in figure 4.13. If a thermistor is being used in a switching circuit in the system being calibrated, it is the responsibility of the person performing the calibration to test each thermistor switching circuit for its proper switching range.

The various details of the thermistors and their related circuitry have been presented in this report because they are known to be responsible for problems that develop during calibration. If an error is found in the design of a circuit which reflects in the calibration of the sensor, it is the responsibility of the person performing the calibration to report the problem and be sure it is corrected. The typical design "errors" that have been discussed should assist the person performing the calibration in determining if the problem is one of design, installation, or calibration.

A thermistor is best calibrated in-situ by direct comparison using a standard. This technique will allow the thermistor to be calibrated in the medium it is monitoring and will test the circuitry being utilized for amplifying and transmitting the signal. If the thermistor must be removed for calibration, the necessary precautions mentioned throughout this section must be taken; especially if the thermistor must be disconnected from its original circuitry.

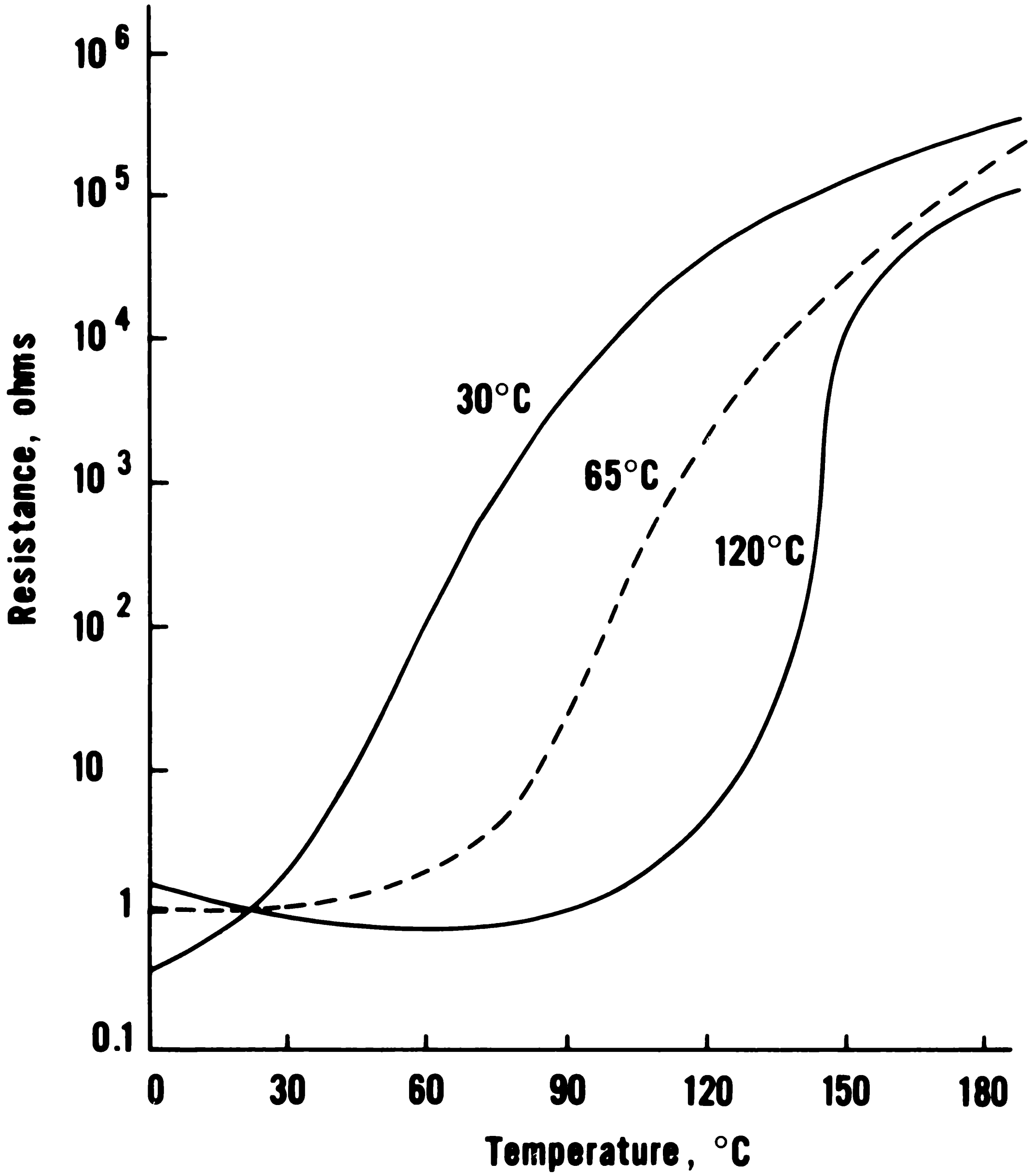

Figure 4.13 Positive resistance/temperature coefficient switching thermistors. Three switching values are shown.

4.5 Integrated Circuit Temperature Sensors

Integrated circuit (IC) temperature sensors are available from many manufacturers in different forms. Many of these sensors resemble an integrated circuit chip in the form of a dual-in-line package (usually 8 pins) or a metal can-package resembling a transistor. This type of temperature sensor uses the fundamental properties of the silicon transistor. Reference 8 is included for the reader who is interested in the details of the designs.

Several manufacturers produce integrated circuits that are designed to yield approximately 10 mv/^{o}C. These IC can be biased in one of several ways to function within a desired temperature range from -67 ^{o}F (-55 ^{o}C) to 302 ^{o}F (150 ^{o}C). The self-heating effect of the excitation current can reduce the specified accuracy significantly. Therefore, the manufacturers' specifications must be followed to apply the lowest current suitable for the application. Manufacturers of these sensors generally recommend from one to 25 typical application circuits including features which make the self-heating error proportional to the absolute temperature. Several IC temperature sensors are available with a reference voltage stablizer and an operational amplifier. Such units are more expensive. However, the temperature rise of the sensor is only approximately 2 ^{o}F (1.2 ^{o}C) in still air from the effects of self-heating. Heat sinks are often used to reduce self-heating effects in moving air.

Still other types are available for yielding an output current proportional to the temperature. These sensors also function over the range of -67 ^{o}F (-55 ^{o}C) to 302 ^{o}F (150 ^{o}C) with specified accuracies of $\pm$1 ^{o}C. However, the factory calibration error for the less elaborate models has been found to be in the area of $\pm$5 ^{o}C at 25 ^{o}C.

In general, integrated circuit temperature sensors are satisfactory for a limited number of EMCS applications only if they are properly installed and have been calibrated as specified by the manufacturer. Care must be taken in applying and calibrating such circuits in many EMCS where the environment often changes from a temporary power outage, causing the unit to fall well below the minimum requirements for any EMCS. The particulate matter found in typical EMCS environments is also a negative factor in this type of sensor and the effects of accumulation of this matter must be carefully examined by the person responsible for the calibration.

The time constant of sensors of these types is approximately 5 seconds in moving air with no heat sink. Although these units are relatively inexpensive and easily mounted, their application is usually limited to monitoring the temperature of well filtered moving air. The self-heating effect and limited accuracy and precision of these types of sensors often make them inadequate for EMCS use.

Because of the numerous types, manufacturers, and installation techniques, the methods of calibration are not noted in detail in this report. The reader is encouraged to contact the manufacturer for calibration details.

4.6 Thermoelectric Sensors (Thermocouples)

Advancements in solid state electronics and the demand for more accurate temperature measurements have made thermoelectric sensors more popular in EMCS. Before getting into the calibration techniques of the various applications of thermoelectric sensors (commonly known as thermocouples), a brief review of the fundamentals of the thermocouple itself will be given.

When two wires of different materials, A and B, are connected in a circuit as shown in figure 4.14, with one junction at temperature T_1, and the other junction at T_2, a relatively high-impedance voltmeter will register an electromotive force (volts) E. If a galvanometer is used to indicate current, a current I is measured. If current is allowed to flow, electric power is developed. In EMCS measurements, this thermoelectric effect is used as a temperature sensor known as a thermocouple. The electromotive force, E, is generally used as the temperature-dependent parameter [2,5]. The overall relationship between the voltage E, and the temperatures T_1 and T_2 is the basis of thermoelectric temperature measurement and is known as the Seebeck effect.

The Peltier effect occurs when an external current is passed through the junctions between dissimilar metals. One junction will be heated and one junction will be cooled. These heating and cooling effects are proportional to the current and, fortunately, are completely negligible when the current that is produced by the thermocouple itself is only that required by a high-impedance instrumentation amplifier or a digital voltmeter.

The Thomson effect influences the temperature of the conductor between the junctions rather than that of the junctions themselves. When current flows through a conductor having a thermal gradient along its length, heat is liberated at any point where the current flow is in the same direction as the heat flow, while heat is absorbed at any point where these flows are opposite. Since the Thomson effect also depends on current flow, this effect is also negligible if the current required to drive the potentiometer or amplifier is negligible. Again, this is the case in proper EMCS installation and calibration of the thermocouple.

The fundamental effects described above are mentioned to emphasize the need for proper instrumentation and the possible side effects of junctions of dissimilar metals inadvertently placed in the lead wires of a thermocouple (T/C). The term "dissimilar metals" includes sections of the T/C wire that have been cold-worked to change the homogeneity of the material as well as a junction at the terminating ends of T/C leads. Both of these conditions inadvertently create another T/C junction.

Before looking closer at T/C applications and their related calibration techniques, five fundamental laws of behavior of the T/C will also be reviewed [2]. Each of these laws apply to the calibration of the T/C and must be understood to avoid typical erroneous conclusions that are often reached during the process of calibration. Referring to figure 4.15:

1. The thermal electromotive force of a T/C with the <u>junctions</u> at

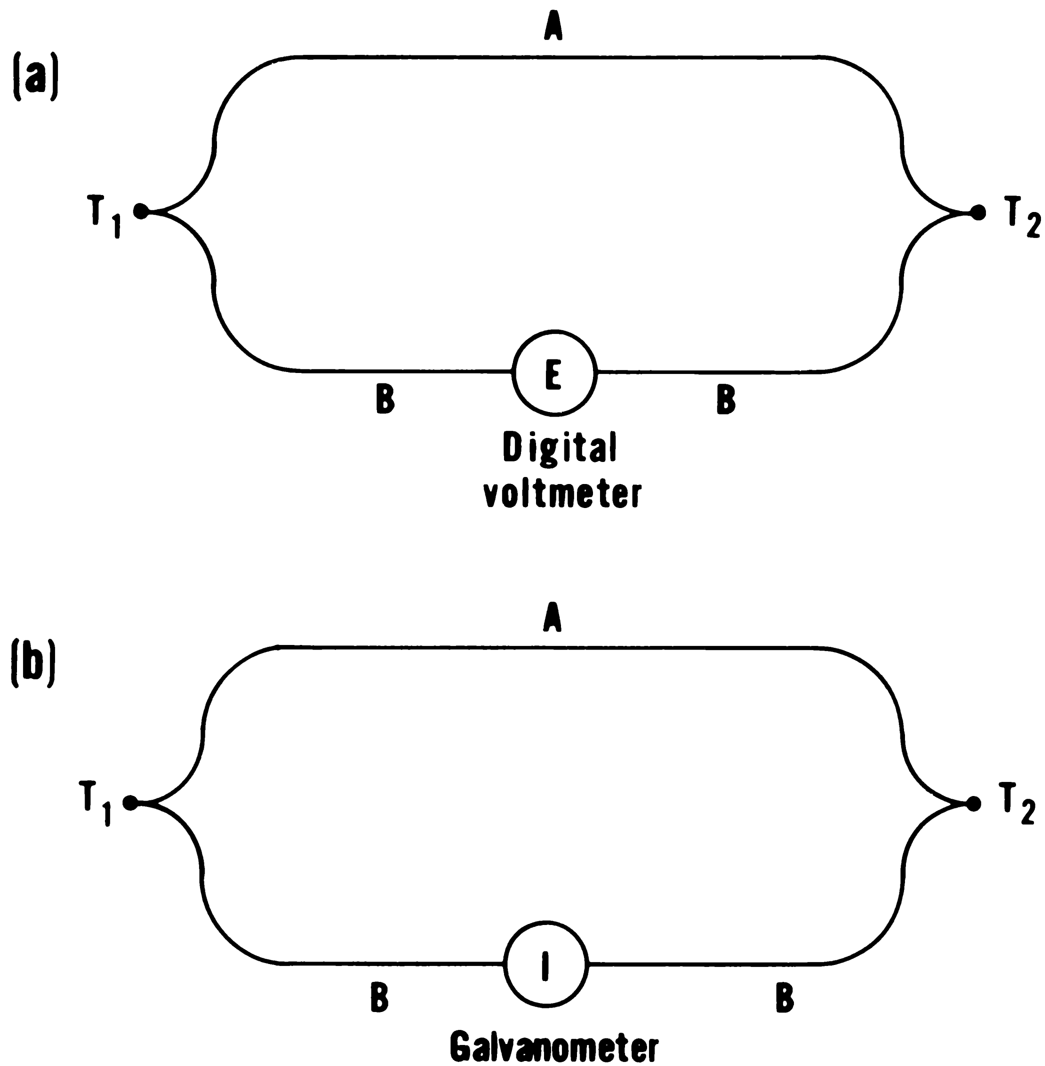

Figure 4.14 The basic thermocouple circuit. a) The resulting potential E is being monitored. This circuit is used for sensing temperatures. b) The current is being monitored.

temperatures of T_1 and T_2 is totally unaffected by temperatures elsewhere in the circuit assuming the two metals are homogeneous, figure 4.15 (a). (Note that all of these laws refer to the junction temperature and assume adequate care has been taken to maintain the temperature of the junctions at the temperatures of interest.)

2. A third homogeneous metal, C, can be inserted into either A or B as shown in figure 4.15 (b) if the two new thermojunctions are at equal temperatures. The net electromotive force (emf) arising from the temperatures of the thermojunctions of A and B is not changed regardless of the temperature of C.

3. A third metal C, can be added between the legs of one junction and the temperature distribution of wire C is immaterial at any point away from the junctions of interest AC and BC. If the junctions AC and BC are at the same temperature T_1, the net emf is the same as if the third metal C were not in the circuit. This law permits junctions to be soldered or brazed without affecting the readings. See figure 4.15 (c).

4. The emf produced by the difference in the temperature of the junctions in figure 4.15 (d) (left), using metals A and C is E_{ac}. The emf produced by the same junction temperatures using metals B and C is E_{cb}. The emf produced by metals A and B is $E_{ac} + E_{cb}$, again at the same junction temperatures. This law shows that all possible pairs of metals need not be calibrated since the individual metals can be paired with one standard (platinum is generally used) and calibrated. Any other combinations can then be calculated; calibration is not necessary. This technique is often used in producing a standard for the higher temperatures in EMCS.

5. If a T/C produces an emf of E_1 when its junctions are at T_1 and T_2, and E_2 when its junctions are at T_2 and T_3, it will produce an emf of $E_1 + E_2$ when the junctions are at T_1 and T_3 as shown in figure 4.15 (e).

The fifth law allows a thermocouple to measure an unknown temperature if the temperature of one of the thermojunctions (called the reference junction) is known. A voltage measurement allows the temperature of the second junction to be determined by a voltage measurement and calibration tables. Most calibration tables are obtained by maintaining the reference junction at 32 °F (0 °C) and varying the temperature of the measured junction over the desired range [9].

The fifth law also allows temperatures to be measured when the reference junction is at temperatures other than "ice point". A calibration table may be used providing the temperature of the reference junction is known. For example, the fifth law allows the use of standard reference tables as follows: suppose the reference junction is known to be 80 °F (26.7 °C) and the voltage reading is 1.24 mv. From figure 4.15 (e), T_1 = 32 °F (0 °C), T_2 = 80 °F (26.7 °C), and T_3 is the temperature being measured. Assuming the T/C is of type T (copper-constantan), E_1 is 1.06 mv found by using the tables. Since the measured voltage E_2 is 1.24 mv, $E_1 + E_2$ = 2.30 mv. The unknown

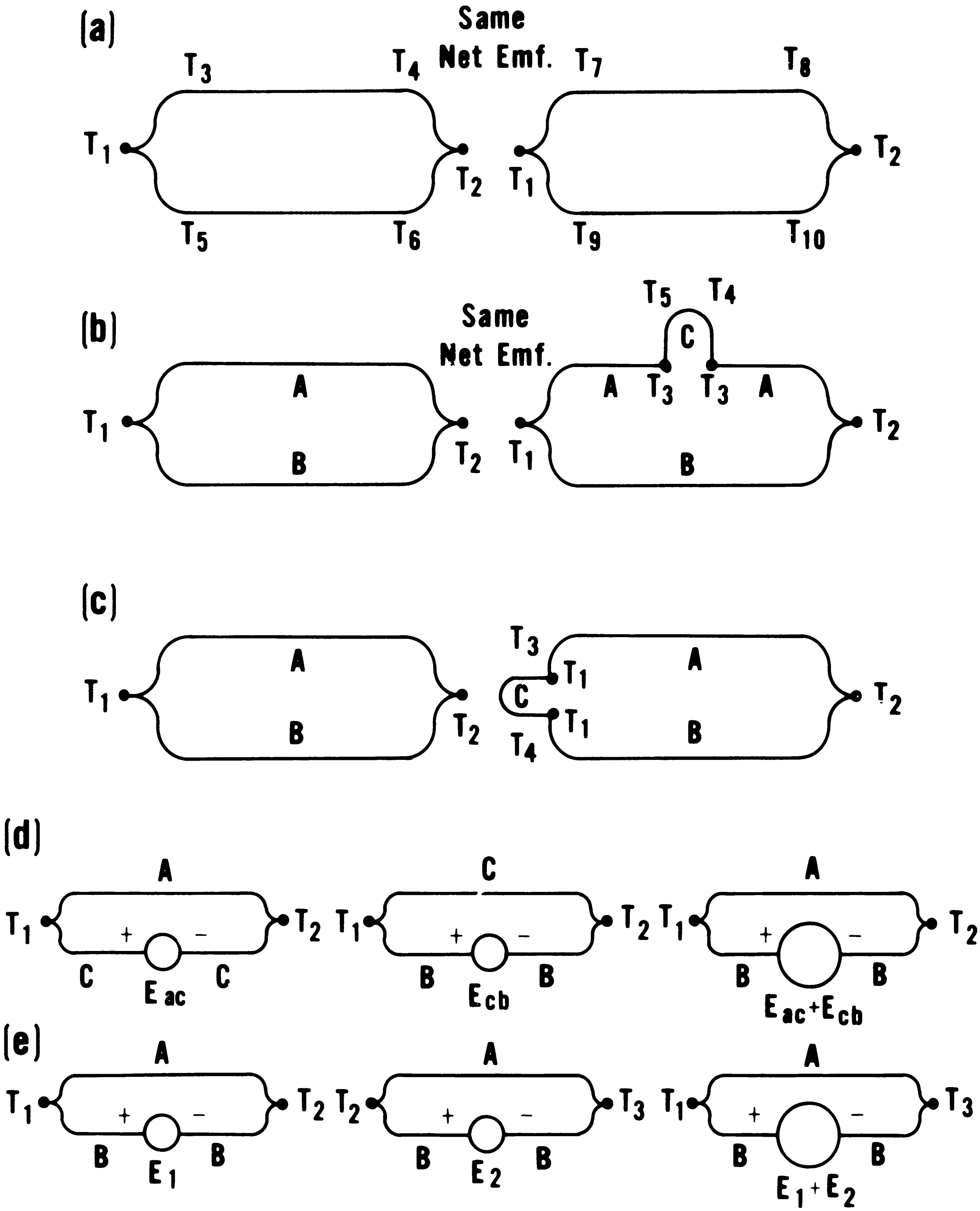

Figure 4.15 The fundamental laws of thermocouples

temperature T_3 is found by looking for the temperature value corresponding to 2.30 mv in the standard T/C tables. In this case, T_3 = 133 ^{o}F (56 ^{o}C).

4.6.1 Thermocouples

Common thermocouples (T/C) are formed by welding, soldering, or pressing two materials together. If the same type (combination of materials) is used, identical voltages will be produced by the same junction temperatures T_1 and T_2. The type of T/C to be used in EMCS is determined by several factors. Figure 4.16 shows the temperature/voltage curves for several of the typical combinations of materials used. Type T (copper-constantan) are used for typical EMCS measurements. Types J and K (iron-constantan and chromel-alumel, respectively) may be found in monitoring systems for higher temperatures such as stack temperatures.

A common T/C is normally applied as shown in figure 4.17. The reference temperature may be produced by an ice bath or a commercially available ice point reference junction system. Such systems are available with one to fifty or more reference junctions and allow both leads going to the voltmeter or instrumentation amplifier to be of the same material, reducing the possibility of introducing unwanted T/Cs within the leads. Because of the high output impedance of the T/C signal and the relatively low level of the signal, the two leads of each T/C must be maintained in close proximity to avoid the unwanted effects of electromagnetic fields; especially those of 60 Hz power lines and inductive sources. The leads, if separated, will act as an antenna and amplify the noise source. When the leads are maintained in close proximity (electrically insulated from each other), each lead will pick up the same noise signal and the net result will approach zero. This factor is very important during calibration since the leads of a digital voltmeter attached to the T/C junction at the amplifier can produce erroneous results if they are not twisted or bound together to avoid excessive electromagnetic fields from passing between them.

The accuracy of common thermocouples is generally determined in two different ways. If standard thermocouple wire is used which has not been calibrated by the manufacturer, the manufacturers' quality control is the basis for deviations from the published tables. These tables give the average characteristics; not those of a selected batch. In the type T thermocouple, this error is ±0.5 % or ±1.5 ^{o}F (0.8 ^{o}C), whichever is the larger. Greater accuracies are achievable when the individual thermocouples are calibrated. Also thermocouple wire which has been factory calibrated yields a higher degree of accuracy. In general, a maximum deviation of ±1 ^{o}F (0.5 ^{o}C) at temperatures up to 300 ^{o}F (149 ^{o}C) can be obtained.

If automatic ice point control references are used, the accuracy of these units must be considered also. Such reference junctions that use the Peltier cooling effect as a refrigerator are available with an accuracy of ±0.05 ^{o} C [10]. However, the accuracy of typical commercially-available multijunction ice point reference units is better than ±0.25 ^{o}C.

In-line cold junction reference units which operate from a small "button" battery are less accurate and require additional compensation for ambient temperatures. Such devices are not recommended for EMCS since the battery

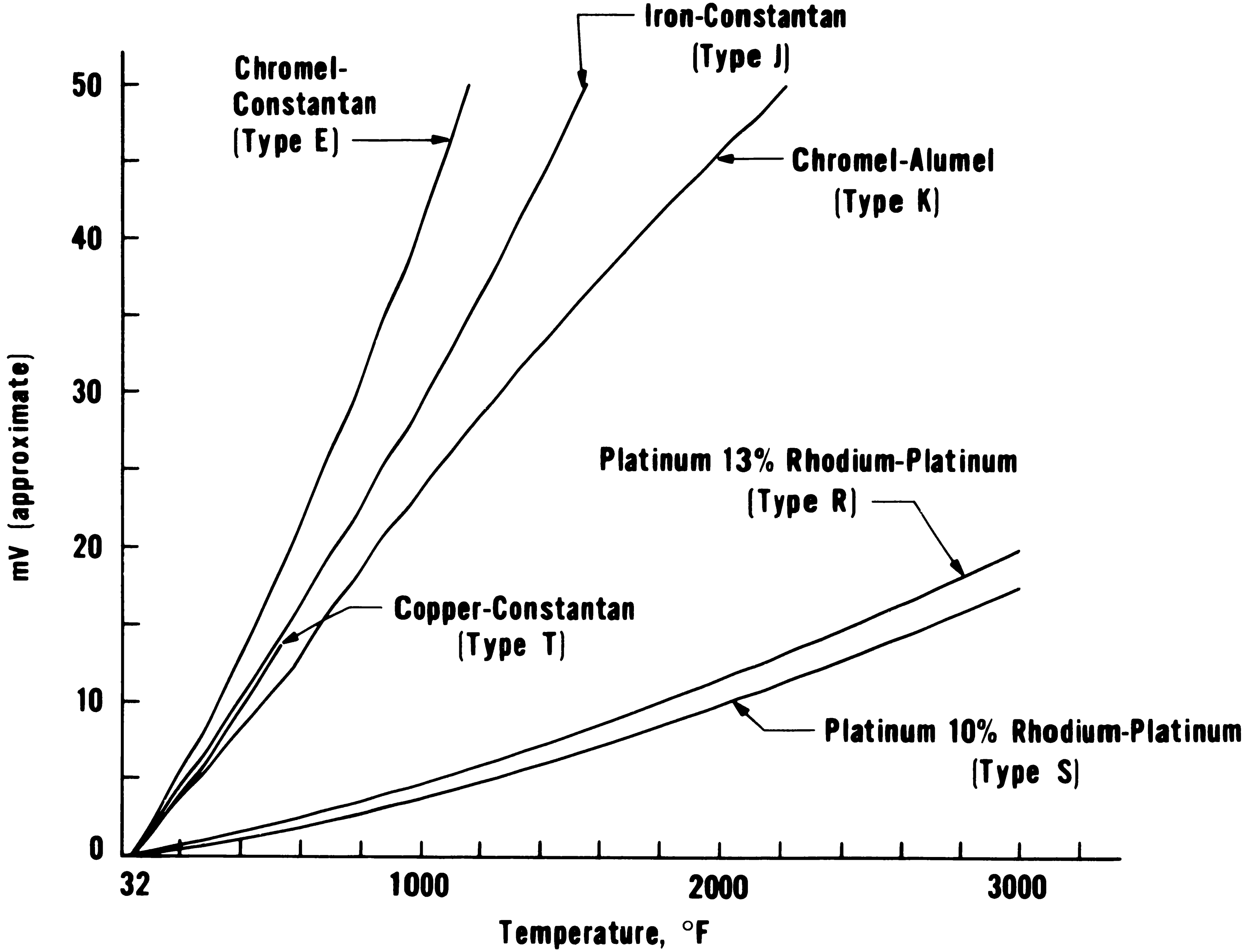

Figure 4.16 Thermocouple temperature/voltage curves

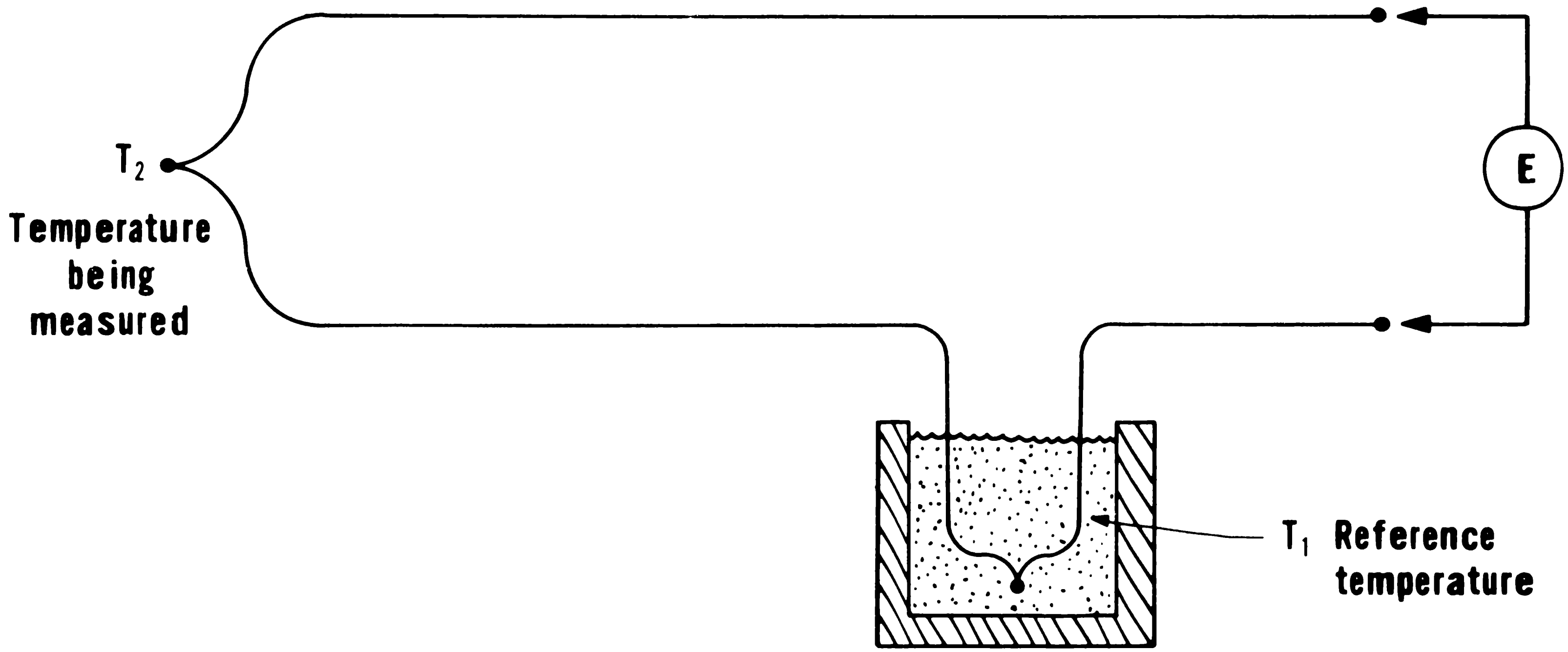

Figure 4.17 Schematic diagram of a typical single thermocouple circuit with reference junction

adds to the task of calibration and the accumulated cost exceeds that of multijunction ice point reference units.

A simple dual-junction thermocouple such as that shown in figure 4.17 using ice as previously described for a reference bath will make an excellent standard after calibration with a certified standard. Several multijunction, digital-readout units are also available with built-in references. Such units are often used for determining the stratification in a duct of air across a heating or cooling coil. However, units of this type must be carefully calibrated under typical ambient conditions prior to their use as a standard.

The use of a digital voltmeter can induce further errors if the clip-on devices used at the ends of the leads are of different materials and are still further amplified if their temperatures vary. The clip-on devices can be made from any <u>one</u> metal. Although two new thermocouples are added to the circuit, if the temperatures are equal, the net effect will be zero.

The time constants for thermocouples vary from several microseconds to several seconds depending upon the gauge of the wire used to make the thermocouple and the media being monitored. For example, <u>in still air</u> the time constant for 0.001-inch-diameter wire is 0.05 seconds, while for 0.032-inch-diameter wire the time constant is approximately 40 seconds. In air moving at approximately 18 m/s, the time constant is one order of magnitude smaller. In general, the response time is very fast for thermocouples used in EMCS applications.

4.6.2 Averaging Thermocouples

A parallel arrangement of thermocouples as shown in figure 4.18 is used to determine the average temperature of the medium in which the junctions are mounted. An arrangement of this type is commonly found in an air duct where the mixing devices described in section 3 are not practical. It must be noted that figure 4.18 is only a simplified schematic diagram and does not show several items of importance. First, the leads of the individual thermocouples are shown separated in the schematic diagram. As previously emphasized, the leads must remain in close proximity to avoid noise from electromagnetic fields ever present in EMCS work. Next, when using a group of thermocouples as shown in figure 4.18, all thermocouple leads must be of equal length to avoid unequal IR drops in producing the average emf of all thermocouples in the parallel circuit. In addition, equal lengths of the thermocouple leads should be exposed to the medium being monitored to avoid unequal thermal conductivity from the various junctions by the thermocouple leads to the air or mounting means outside the pipe or duct in which the averaging thermocouples are mounted.

An averaging thermocouple requires a reference junction as shown in figure 4.18 to allow standard T/C tables to be used to translate the voltage measured by the digital voltmeter or amplifier to the average temperature of the medium.

In general, the individual thermocouple junctions are mounted at the center of each of N equal areas of the duct or pipe in which the grid of averaging thermocouples is mounted. The number N depends upon the size and shape of the pipe or duct in which the medium is flowing. References 11 and 12 give further details.

Averaging thermocouples open unique areas for the person performing the calibration of a system. For example, each thermocouple can be removed or connected in any desired order and allow the performance of each thermocouple in the grid to be tested for proper operation. This is an important factor since the malfunctioning of any one thermocouple will affect the output of the group. Also, by obtaining the outputs of the individual thermocouples, the variations in the temperature across the section of duct or pipe in which the grid is mounted can be determined directly from the outputs.

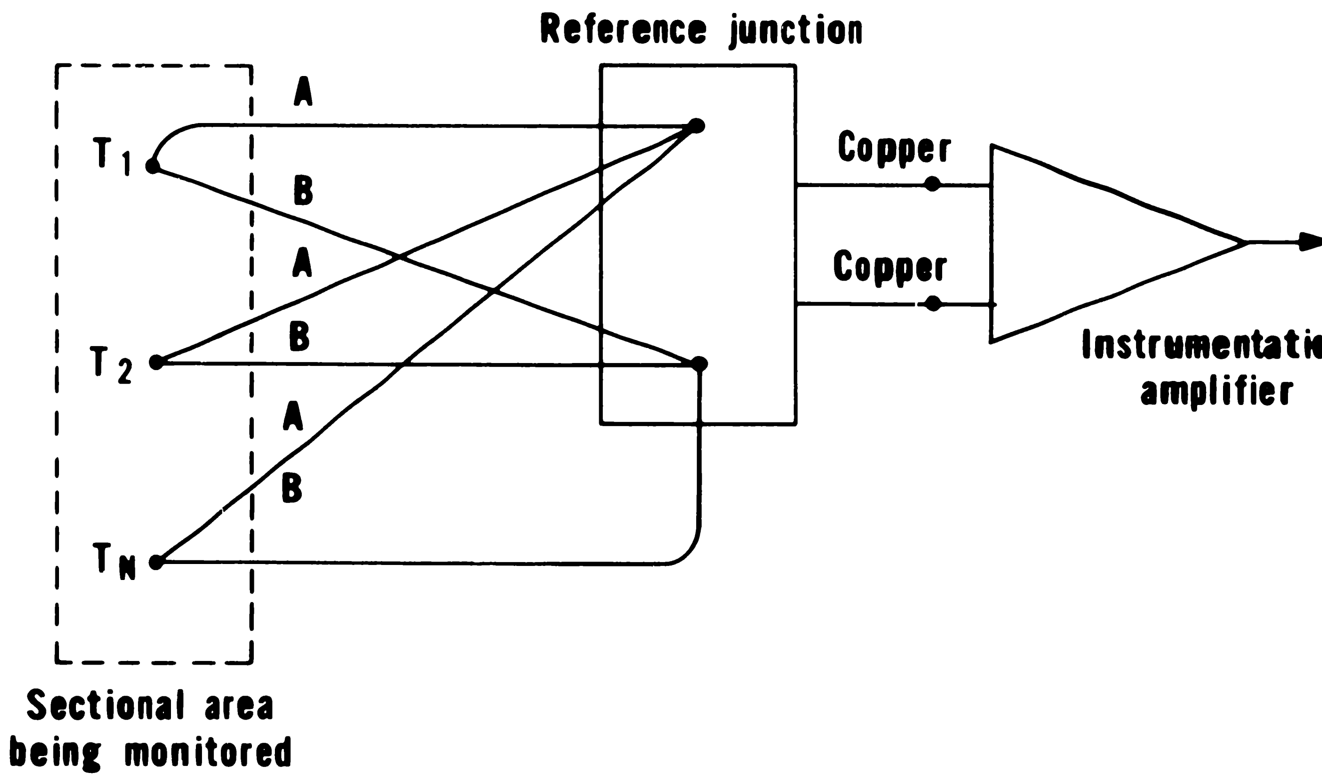

Figure 4.18 Averaging thermocouples. The thermocouples T_1--T_N are mounted in the center of equal areas of the section being monitored. The output voltage measured is the average of the individual thermocouple voltages. The thermocouples must have the same lead resistance.

4.6.3 Thermopiles

Thermopiles are multiple-junction thermocouples electrically connected in series as shown in figure 4.19. In EMCS applications, this configuration is commonly found monitoring temperature differences in HVAC systems. The thermopile has the advantage of multiplying the output of a single thermocouple by the number of thermocouples in one of the two areas being monitored. The typical nonlinear characteristic of the thermocouple requires a direct reading of the actual temperature in one of the two areas where the temperature difference is being monitored.

The same precautions pertaining to the close proximity of the thermocouple wires, the equal lengths in the medium being monitored, and the thermal conduction of the thermocouple wire must be considered with the thermopile as it is for the averaging thermocouple and the individual thermocouple. The advantage of multiplying the signal has the side effect of also multiplying any noise induced by electromagnetic fields.

Field calibration of thermocouple-type installations of all types usually can be accomplished using a linearized thermistor as a standard in the in-place calibration approach discussed in section 3. The in-place calibration approach with a direct readout from the standard and a readout from the output of the system utilizing thermocouples in any fashion will include any errors caused by the amplification of the analog signal, noise generated in the system, improper extension wires, etc. If a digital voltmeter is used at the thermocouple-type installation, a direct comparison can be made with the thermal emf-temperature tables. In the case of the thermopile, the fundamental law number five must be followed to adjust the temperature difference in accordance with the actual temperatures measured by the standard.

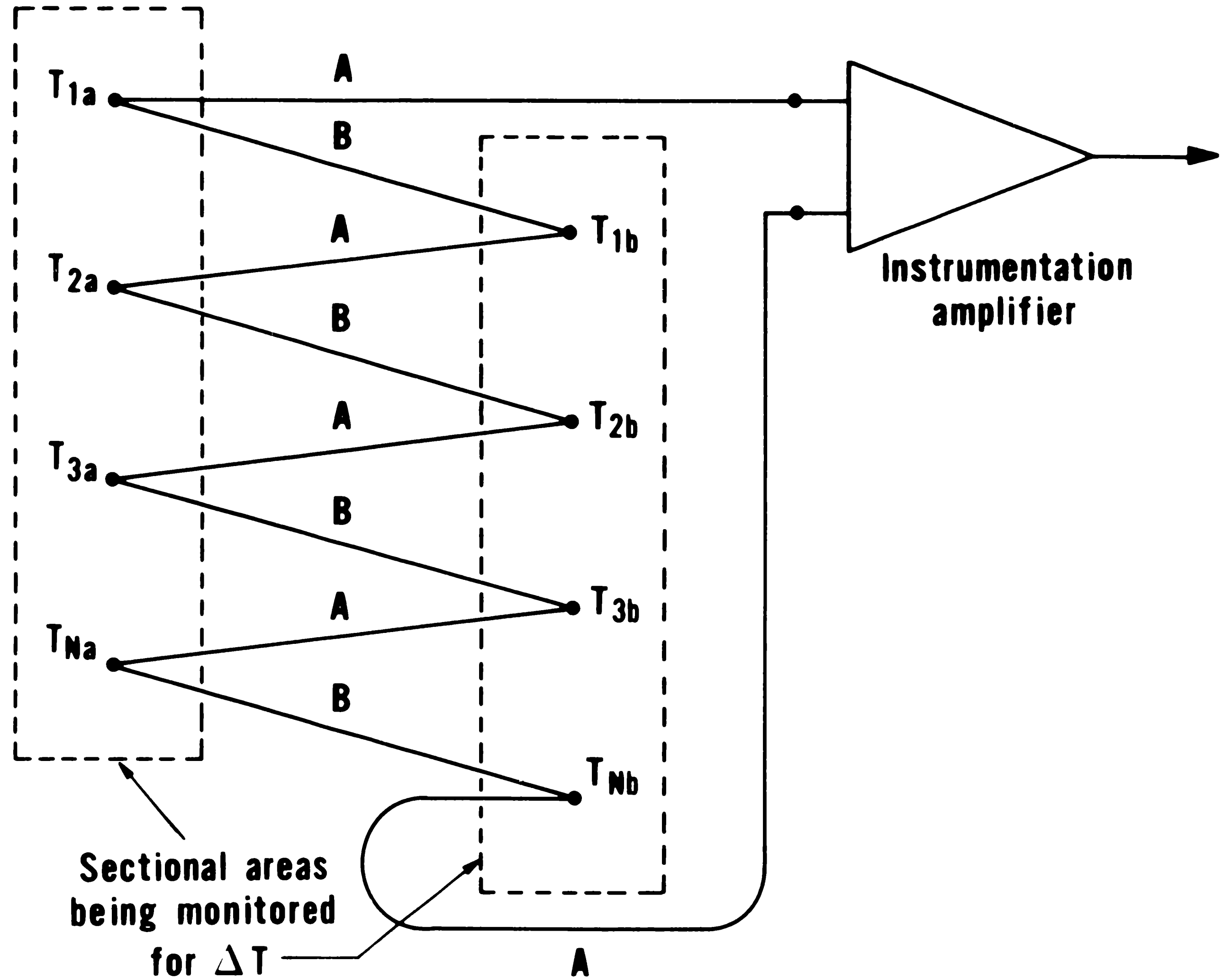

Figure 4.19 Schematic diagram of a thermopile. In the example shown, a reference temperature is required in one of the two areas to allow the computer to compensate for the non-linearity of thermocouples connected in this fashion.

4.7 Bimetallic Thermometers

Bimetallic thermometers are temperature-sensing devices that utilize the phenomenon of thermal expansion of metals. A bimetallic thermometer is made by firmly bonding two strips of metal together which have different thermal-expansion coefficients. A temperature change causes differential expansion of the bonded strip, and, depending upon the configuration of the strip, a deformation will occur if the strip is unrestrained. Figure 4.20 shows a limited number of the typical configurations used. Since there are no usable metals with a negative thermal expansion coefficient, the B element, figure 4.20(a), is generally made of Invar (a nickel-steel with an extremely low coefficient of expansion). Brass originally was used as the high-expansion strip A. However, a variety of alloys are now being used depending on the electrical and mechanical characteristics required.

Although bimetallic thermometers with dial readouts are available commercially, they are not recommended for calibration purposes because of the poor accuracy offered by those commonly found in the marketplace. High quality types are relatively expensive but offer accuracies to ± 1 % full scale. Bimetallic thermometers are rugged and have a time constant ranging from 5 to 20 minutes in still air.

In EMCS, bimetallic thermometers are generally used for on-off switching as shown in figure 4.20(b). Bimetallic-thermometer-activated switches still are commonly found in EMCS as overload cutouts in electrical equipment where excessive current flow in the bimetal causes heating and the accompanying expansion results in opening an electrical contact. These types of thermometers are also found in EMCS as temperature limit controls to avoid thermal damage to the heating system. The requirements for limit control applications are not extremely critical and lower cost units usually are satisfactory. For more critical applications such as room thermostats, the performance must be improved to that of the higher-quality types.

In EMCS calibration, each bimetallic thermometer must be tested for proper operation at the predetermined temperature limits. A room thermometer requires careful calibration of the on and off temperatures, the time constants, the switching differential, the operation of the anticipator built into the thermostat, and other items described in detail in reference 13.

The bimetal sections and linkages of those units used in EMCS for limit switching are subject to failure after long periods at elevated temperatures. Therefore, the calibration of such units is imperative to maintain a system operating with adequate safety.

Calibration using the in-place method and a standard is generally best suited for the calibration of bimetallic thermometers. Those units used for electrical overload require the assistance of a plant engineer to perform the necessary calibration safely. In general, checking the time constants for all types of bimetallic thermometers is very important in calibration.

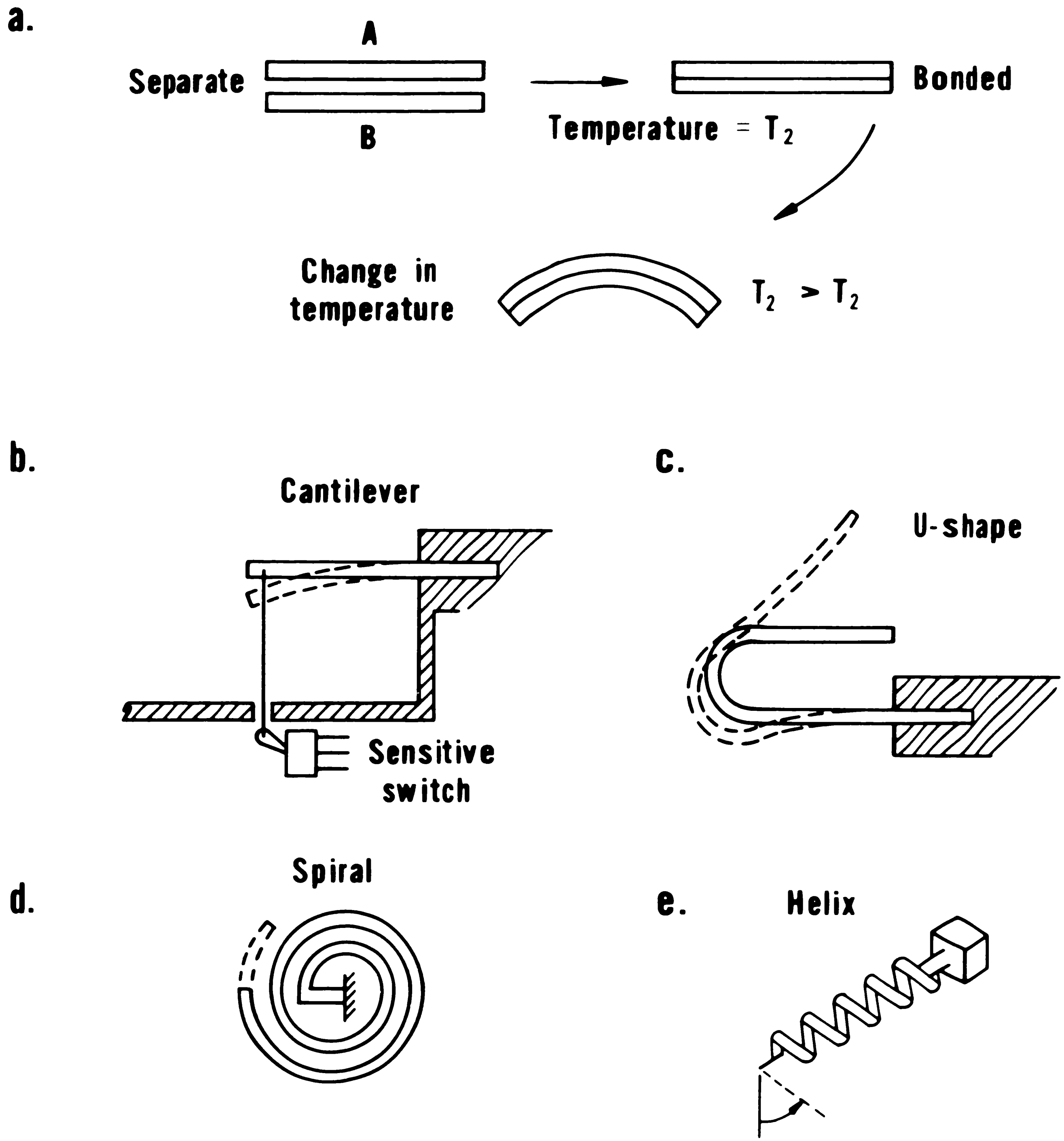

Figure 4.20 Typical configurations of bimetallic thermometers

5. CALIBRATION RECORDS OF THERMOMETERS, SENSORS, STANDARDS, AND SYSTEMS

Maintaining records of calibration has been found to be one of the most-neglected tasks of personnel who manage and perform the calibrations of thermometers, sensors, standards, and remote temperature-measuring systems in EMCS. The value of such records is never realized until an energy-balance computation is performed and found to be in error by an unacceptable amount, or until a sensor or remote-sensing system is calibrated and found to be in error to an extent that is inconsistent with the excellent performance of the equipment being controlled. In general, the value of good calibration records on each temperature-sensing device and system cannot be over emphasized.

The date and source of the calibration or recertification of all standards being used to calibrate the various temperature-sensing devices and systems in an EMCS is a good place to start such a record. The time interval for returning the standard to a qualified laboratory for recertification or recalibration can generally be determined by reviewing the dates and the status of the standard each time the calibration was checked at the on-site facilities. All calibration records of standards should be made available to the qualified laboratory performing subsequent recalibration or recertification of the standard. Complete records of the use and the calibrations of a standard often reveal factors which require particular attention in the calibration process.

Similar record-keeping is directly applicable to the on-site calibration of each instrument in an EMCS. Calibration records of temperature-monitoring instrumentation, including remote temperature-sensing methods, often reveal the source of differences in individual temperature-sensing devices that are normally very difficult to locate by mechanical means. Likewise, such records often explain the discrepancies found in the thermal computation of the heat exchange of a system or a particular portion of a system. Often, expensive components of a mechanical system are replaced only to find that the error was directly related to the method or inaccuracy of the calibration of the instrumentation.

In this report, many areas which generate errors in calibration have been called to the reader's attention. The most important items to be included in the records of EMCS temperature-sensing devices are the possible effects of the uncertainties in the temperatures being monitored by the in-situ instruments and the standards being used. Ambient conditions, temperature ranges, any questionable areas of each individual sensor, and any other factors which may affect the calibration are included in this area. Systematic errors cannot be determined without this information.

Calibration records of a specific temperature-monitoring device, remote system or standard including the response to a reference temperature such as an ice bath will generally reveal the necessity for replacement or, in the case of the standard, the need to be returned to a qualified laboratory for recertification. During the process of calibration of a temperature-sensing device, remote temperature-monitoring system, or a standard, the values indicated by the item being calibrated and the standard being used for the calibration often are recorded casually on a pad of paper while checking the response as the temperature is increased and decreased over the normal operation range. It requires only minimal effort to record these values in a bound notebook instead of the pad of paper which is usually destroyed when the calibration is completed. The value of casual records is limited, whereas the well-kept laboratory notebook can provide unlimited evidence of the measuring equipment performance.

6. POSSIBLE EFFECTS OF SYSTEMATIC ERRORS

This section is presented to emphasize the necessity of careful and frequent calibration of all components in any system being used for EMCS. Each item being calibrated and every standard used for calibration is subject to error beyond the statistical uncertainty in its measurement. The exact value of the error is very seldom known for any of the items used for the calibration or in the end product being calibrated.

For example, consider the error of a single readout from a series of components of a typical remote temperature-monitoring system. If the inaccuracy in the calibrated sensor/transducer device is ± 1 %, the inaccuracy in the transmitting device is also ± 1 %, the inaccuracy in the transmission means is ±.5 %, and the inaccuracy of the receiving device is ± 1 %, then the maximum error in the actual readout would be ±3 1/2 %.

Since the direction of the error seldom falls in the same direction for each component, the uncertainty of a measurement is often expressed using the root-sum-square (RSS) technique, also known as the statistical bounds technique (2). The RSS technique states that when a given variable, s, is determined from several measurements (say w, x, y, and z) according to the relation:

$$s=f(w,x,y,z),$$

the probable uncertainty which we may call R_s of the calculated value s, is determined by the following equation:

$$R_s = \sqrt{r_t^2 + r_m^2 + r_i^2 + r_r^2} \qquad (1)$$

where:

R_s is the uncertainty of the temperature readout with respect to the actual temperature being monitored,

r_t is the uncertainty in the calibration of the sensor/transducer,

r_m is the uncertainty in the calibration of the transmitting device,

r_i is the uncertainty in the calibration of the transmission means, and,

r_r is the uncertainty in the calibration of the receiving device.

Inserting the values given in the above example into equation (1), we have:

$$R_s = \sqrt{.01^2 + .01^2 + .005^2 + .01^2}$$

R_s = $\pm$.018 or $\pm$1.80 % is the probable uncertainty in the temperature reading.

The above example points out several items of particular interest. First, the values inserted for the uncertainty of the individual components may have at first appeared to have been somewhat "risky"; i.e. on the low side or the more accurate side. However, the maximum error in the typical example resulted in a value of 3.5 % and the uncertainty computed by the statistical bounds or RSS technique was 1.80 %. Regardless of which technique was used, one point is clear: both values are likely to be too high for the satisfactory calibration of a remote-sensing system. Therefore, the inaccuracy in the calibration of each component must be reduced.

Second, the temperature measurements in an EMCS are generally used in conjunction with other measurements such as flow to calculate the engineering values required for efficient operation of the mechanical systems of the buildings. Any uncertainty introduced at the temperature-monitoring level will always increase the uncertainty of the engineering value that is required.

Third, the calibration of temperature-monitoring systems in an EMCS are usually considered by management to be the least troublesome and, therefore, are expected to be the most accurate of all EMCS measurements. In this example, the values listed for the uncertainties for each component are too high for a typical calibration of a remote temperature-sensing system. Each component must be calibrated with greater care to improve the accuracy. The emphasis should be given to the components having larger absolute error values.

In general, the effects of the accumulation of errors in any chain of events that take place in a remote- or direct-sensing system can result in an error in the end product beyond an acceptable value. See reference 2 for further details on error analysis.

7. ILLUSTRATIVE EXAMPLES OF CALIBRATING TEMPERATURE SENSING SYSTEMS INSTALLED IN BUILDINGS

This section presents several examples of temperature-sensing-device calibration to illustrate the application of the material presented in the previous sections of this report. In each example, the type of sensor, the method used in mounting the sensor, the purpose of the sensor, and other typical features found in EMCS pertaining to calibration will be described. Details presented in the first example which are applicable to succeeding examples will not be repeated.

7.1 Thermistor Calibration

In this example, the person performing the calibration of the temperature-sensing devices of a remote monitoring system has located several linearized thermistors in the hot and chilled water supply and return lines serving the air-handlers in a large building. The thermistors are mounted in thermowells placed in the water lines to monitor the temperature of the water entering and leaving the heating and cooling coils of the air-handler. The thermowells have been filled with a synthetic oil to improve the thermal conductivity from the walls of the thermowells to the thermistors. Since the thermistors can be removed and replaced in the wells without damaging the insulation on the conductors or causing excessive mechanical fatigue to the wiring, the calibration technique with the sensor removed from the HVAC will be used for the thermistors. The balance of the system will be calibrated using the techniques for remote systems.

A schematic diagram of the system indicated that the thermistors are being used in a voltaic mode and that the signals are being amplified in a signal conditioning circuit. The output of the amplifying circuit is wired directly to the appropriate channel in the MUX near the air-handler where the water temperatures are being monitored and controlled.

The operating ranges of each thermistor are not noted in the calibration notebook. Therefore, the high and low temperatures that occur at each of the monitoring points must be obtained from drawings, specifications, or files at the plant. Often the plant engineer, the central control unit (CCU) operator, and person in charge of the software are good sources for this information if all others fail.

The characteristics of the analog-to-digital (A/D) conversion circuitry must also be known. In this case, the person in charge of the software, MUXs, FIDs, and CCU may be the best source. The characteristics of the A/D circuitry include the maximum and minimum input voltages and the temperatures these values represent in the final CCU readout device. Examples of typical voltage ranges for an A/D converter are: -10 volts to +10 volts; -2.50 volts to +2.50 volts; 0 volts to +5 volts; and 0 volts to +10 volts. It is not uncommon to find different voltage ranges at different A/D converters within the same building! The range is often set at the convenience of the person originally designing and/or installing the EMCS. In some of the more modern systems, individually-programmed sensitivities for each channel may be present in which the software is used to determine the range of inputs to produce the desired outputs. In such systems, the person responsible for the software is usually the source for the desired information for calibration.

A search for the necessary information revealed that all A/D converters were programmed to operate in the 0 volts to +10 volts range. For the cooling coils, the supply and return temperatures represented by the A/D voltage range were identical; 32 ^{o}F (0 ^{o}C) to 90 ^{o}F (32.2 ^{o}C). For the heating coils, the supply and return temperatures represented by the A/D voltage range were also identical; 60 ^{o}F (15.5 ^{o}C) to 200 ^{o}F (93.3 ^{o}C). A review of the MUX software specifications clearly indicated that the temperature change was directly proportional to the change in the input voltage to the A/D converter. In this simple example, the temperatures represented by the A/D input voltages would be found as follows:

For the cooling coils-

$\Delta T = 90 - 32 = 58\ ^{o}F$,

$\Delta V = 10 - 0 = 10$ volts,

$$\text{Scaling factor} = \frac{58}{10} = 5.8\ ^{o}F \text{ per volt},$$

Offset = 32 ^{o}F,

$T\ (^{o}F) = 32 + 5.8\ V$, where V is the digital voltmeter reading and T is the temperature of the thermistor.

For the heating coils-

$\Delta T = 200 - 60 = 140\ ^{o}F$,

$\Delta V = 10 - 0 = 10$ volts,

$$\text{Scaling factor} = \frac{140}{10} = 14\ ^{o}F \text{ per volt},$$

$T\ (^{o}F) = 60 + 14\ V$, where V is the digital voltmeter reading and T is the temperature of the thermistor.

Now that the maximum and minimum temperatures, the maximum and minimum voltages and their respective temperature indications, and any characteristics of the remote monitoring system and/or the thermistor that may affect the calibration have been found <u>and recorded in the calibration notebook,</u> the calibration task can begin.

The most important part of any calibration procedure is making sure that the necessary personnel at the plant and at the CCU have been notified in advance of the calibration, the date and time it is to take place, the limits of the calibration, the identification of the channels to be calibrated and the desired sequence, and any other information that may be requested. This important initial step has two areas of significance. First, it will allow the plant and CCU personnel to prevent the "false" signals received from the remote channel to cause the EMCS from responding directly in a normal fashion and create discomforts, hazards, etc. within the mechanical system of the building. Second, since this is a remote system that is being calibrated by removing the sensor from the HVAC, the person performing the calibration must know the temperature readout received by the CCU relative to the temperature of the bath in which the thermistor is immersed. Therefore, a close working relationship with the plant and the CCU is always necessary. For medium and large facilities, the notification of the calibration of any one or more remote channels should be made at least one week in advance in writing to avoid possible "misunderstandings".

In this example, hot and cold temperature baths are required. Since each thermistor was mounted in an oil filled thermowell, the thermistor must be calibrated in a liquid such as water, oil, ethylene glycol, etc. to avoid the self-heating effects described in section 4.4. In addition, the temperature baths must be equipped with adequate circulators to retain equal temperatures within the bath at any given time. Another thermistor, a liquid-in-glass thermometer, a thermocouple, or a RTD may be used as a standard if it has been calibrated over the range to be used. In any case, <u>the time constants for the thermistor being calibrated and the standard must be considered during the calibration.</u>

The thermistors are calibrated, one at a time, by immersing them in a circulating liquid bath adjusted to a temperature equal to that of the maximum temperature of the point in the system being monitored. The leads of a digital voltmeter are placed on the output of the signal conditioner. Care must be taken in using the proper electrical ground for the reference ground of the meter. In general, the electrical ground for the channel being calibrated is used since the voltage from the output of the signal conditioner to the electrical ground is the same as that at the A/D converter input. The input impedance of a typical A/D converter is usually very high (10-20 Megohms). Therefore, any voltage drop in a typical EMCS line is negligible.

If a sheath of any type is used on the thermistor being calibrated or on the standard being used to monitor the temperature of the bath, the time after immersion should not be less than three minutes before a calibration reading is taken. Care also must be taken to avoid situations such as the following:

1. A rapid exchange of the thermistor from one bath to another should be avoided. The thermal expansion and contraction of the leads which are hermetically sealed by glass or ceramic material will cause the leads to fracture within the seal and the electrical conductivity to be broken. In this fashion, the thermistor is "broken". Holding the thermistor in the air for one or two minutes before immersing it into the bath of the opposite extreme temperature generally will prevent this catastrophic result. Three or more immersions in each bath are recommended before the calibration is completed.

2. The thermistor and the standard should be retained in the "stream" of the circulating liquid in the bath. If either is allowed to touch or come close to the walls of the bath, the validity of the calibration is highly questionable. In a similar fashion, the standard and the thermistor must be retained at adequate depths in the bath to allow the true temperature of the bath to be monitored. The thermal conductivity of the leads or sheath of the thermistor or standard can also create incorrect calibrations by inadequate immersion.

3. Since the thermistors being calibrated in this example are mounted in oil-filled thermowells, the self-heating of the thermistor in still air must be kept in mind. If the thermistor must be removed from one of the baths for more than four minutes, it should be immersed in a container of water at room temperature while the necessary adjustments to the baths are being made.

4. If a RTD or a thermocouple is being used as a standard, the thermal conductivity of their leads becomes still more critical. Review sections 4.3 and 4.6 before using these types of sensors as standards.

5. In this example, "linearized" thermistors are being calibrated. However, the calibration of <u>any temperature sensor</u> is not completed by only checking the respective readouts with temperature baths at the two extreme limits of the operating range. A third calibration point should always be made at a temperature approximately equal to the middle of the operating range. This step is imperative to check the operation of the sensor, the signal conditioner, the transmitter (if one is used), the A/D converter, and the CCU. By observing the schematic diagrams of a "linearized" thermistor, it will be noted that one of the metal oxide elements could drastically change its characteristics and still allow the signal conditioner to be adjusted to give the proper readings at the CCU for the limits of the range of operation. The linear response could be in error at any other temperature. In the case of the linearized thermistor, the change in characteristics will usually be caused by a broken conductor.

6. The typical stability of a thermistor is supposedly accomplished by the manufacturer through proper aging of the elements prior to sale. However, experience and references 2, 5, and 7, point out that the stability of a thermistor of any type may drift significantly during the first year of operation. This factor alone indicates the necessity of calibration of a thermistor which has been recently installed or replaced at frequent intervals (e.g., once every month) until the calibration records indicate adequate stability.

If a telephone line is not available from the area of calibration to the CCU operator to obtain readouts at the various calibration points, two-way radios are helpful. Otherwise in a large building using a remote system, obtaining the readouts at the CCU becomes a major problem.

In this example, the temperature of the bath, the output of the signal-conditioning circuit, and the CCU readout should be recorded for each step until the necessary minor adjustments are made to the signal-conditioning circuit to make these parameters concur. If the bath temperatures do not concur with the relative voltage output of the signal-conditioning circuit, problems can be expected in the transmission lines to the MUX and the thermistor. Depending upon the design of the remote system, it may be feasible to connect a portable terminal at the MUX and trace the source of the error. If the output voltages at the signal conditioner concur with the respective temperatures of the baths and an error is noted at the CCU readout, the input voltage at the MUX should be checked with the digital voltmeter. If a difference is noted, transmission-line problems usually exist between the thermistor and the MUX. One test that can be made at this point is to place the digital voltmeter in an AC voltage mode. If an AC voltage is indicated, transmission interference (usually from a 60 hertz source) can be expected. The source usually becomes obvious in tracing the lines back to the thermistor.

The shield of the transmission line may be grounded to the electrical ground or to the earth ground. If ground-fault interrupters are not installed throughout a building, it may be advisable to connect the shields of the transmission lines to the <u>electrical</u> ground to reduce AC interference. This step assumes that the outside insulation on the transmission lines has been inspected and found to be in good condition. Often both ends of the shield will be connected to one ground or the other. Removing the connection of the shield at the <u>sensor</u> end will often help. If simple steps such as these fail to reduce the AC interference, it is advisable to connect an oscilloscope to the MUX end of the sensor transmission line and observe the frequency, wave form, etc. of the interference. The oscilloscope will generally give clues to the source of the interference.

Often the shielded transmission line will be found routed too close to a high-current power line. If this is the case, the frequency indicated by the oscilloscope will <u>not</u> <u>necesssarily</u> be 60 Hertz or have the form of a sine wave. High current rectifiers, electronic ignition devices, welders, etc. will usually be found if the transmission line is routed too close to a power line feeding such items.

Thermistors as well as thermocouples generate a high-frequency thermal junction noise within the metal oxides of the thermistors and at the junctions of thermocouples. This noise usually will range from 0.5 to 3 megahertz. However, the intensity of this noise is very low; amplifiers originally used for signal conditioning were not capable of responding to these higher frequencies. In this manner, the amplifier served as its own filter. The instrumentation amplifiers now available and used in EMCS respond to this noise and often cause problems for the A/D converter. By placing <u>passive filters</u> in the transmission lines ahead of the amplifier, this noise problem can be controlled even if electronic gains of over 10,000 are required to meet the range of the A/D converter. See reference 2 for further details.

When the calibration of each channel is completed, measure the temperature of the oil in the thermowell using a standard. Replace the thermistor in the well and request a last readout from the CCU. Unless the system is in a transient state, the readout from the CCU should be close or equal to that temperature measured by the standard. Always notify the plant and the CCU operator when the calibration of each channel is completed.

7.2 Thermocouple Calibration

The typical environments of HVAC systems require routine calibration of thermocouple sensors. Characteristics such as the relatively low output signal of the thermocouple, the numerous ways thermocouples are used, and the relatively high input impedance required for the signal-conditioning amplifier often make the person responsible for the calibration of the EMCS instrumentation hesitate to perform routine calibrations. However, temperature-sensing systems utilizing the thermocouple are often the simplest to calibrate in a routine manner. This example covers several different types of thermocouple sensors utilizing the fundamental information presented in section 4.6 and proven techniques applicable to EMCS.

In this example, a medium-sized building is using thermocouples in the form of single thermocouples with a multi-channel ice-point reference to monitor the temperatures of the water entering a heating coil and a cooling coil in an air-handler. The primary objective of these thermocouples is to provide a base temperature measurement for the thermopiles which are monitoring the difference in the temperatures of the water entering and leaving the coils in the air-handler. The temperature profile of the air in the supply duct leaving the air-handler is <u>not uniform</u> because a small heat exchanger has been installed in the duct upstream of the supply air monitoring point. Therefore, an averaging thermocouple grid is installed to monitor the most critical part of an air-handler; the temperature of the output or supply air. The ice-point reference for the averaging thermocouples utilizes a third channel of the unit used for the single thermocouples.

A diagram of the air-handler is shown in figure 7.1. The thermowells are designed to protrude deep into the supply and return lines. This feature allows the individual thermocouples in the supply lines and all thermocouples of the thermopiles to be at the bottom of the oil-filled wells and avoid excessive heat losses through the conductors and the walls of the thermowells. All thermocouples are Type T (copper-constantan).

The individual thermocouples are wired identically to that shown in figure 4.17 except the reference bath shown in the figure has been replaced by a commercial, multi-junction, ice-point reference. (This device provides built-in thermocouple reference junctions of the type being used and maintains these junctions at 32 ^{o}F (0 ^{o}C); the equivalent error of these references is less than 0.23 μV/^{o}C ambient temperature). The thermopiles are wired identically to that shown in figure 4.19 and the averaging thermocouples are represented in figure 4.18. An important feature present in the installation of all thermocouples is not represented in the diagrams shown in section 4. This feature is that <u>all thermocouple leads</u> of each temperature monitoring channel are retained in close proximity to avoid the unwanted effects of electromagnetic fields as explained in section 4.6.1. In addition, all thermocouples have been electrically insulated to avoid contact with each other.

Because the air-handler in this example is in a medimum-sized building, the mechanical system is controlled by a MUX, a FID, and a small CCU. The MUX is adjacent to the air-handler, the FID is in the central part of the attic

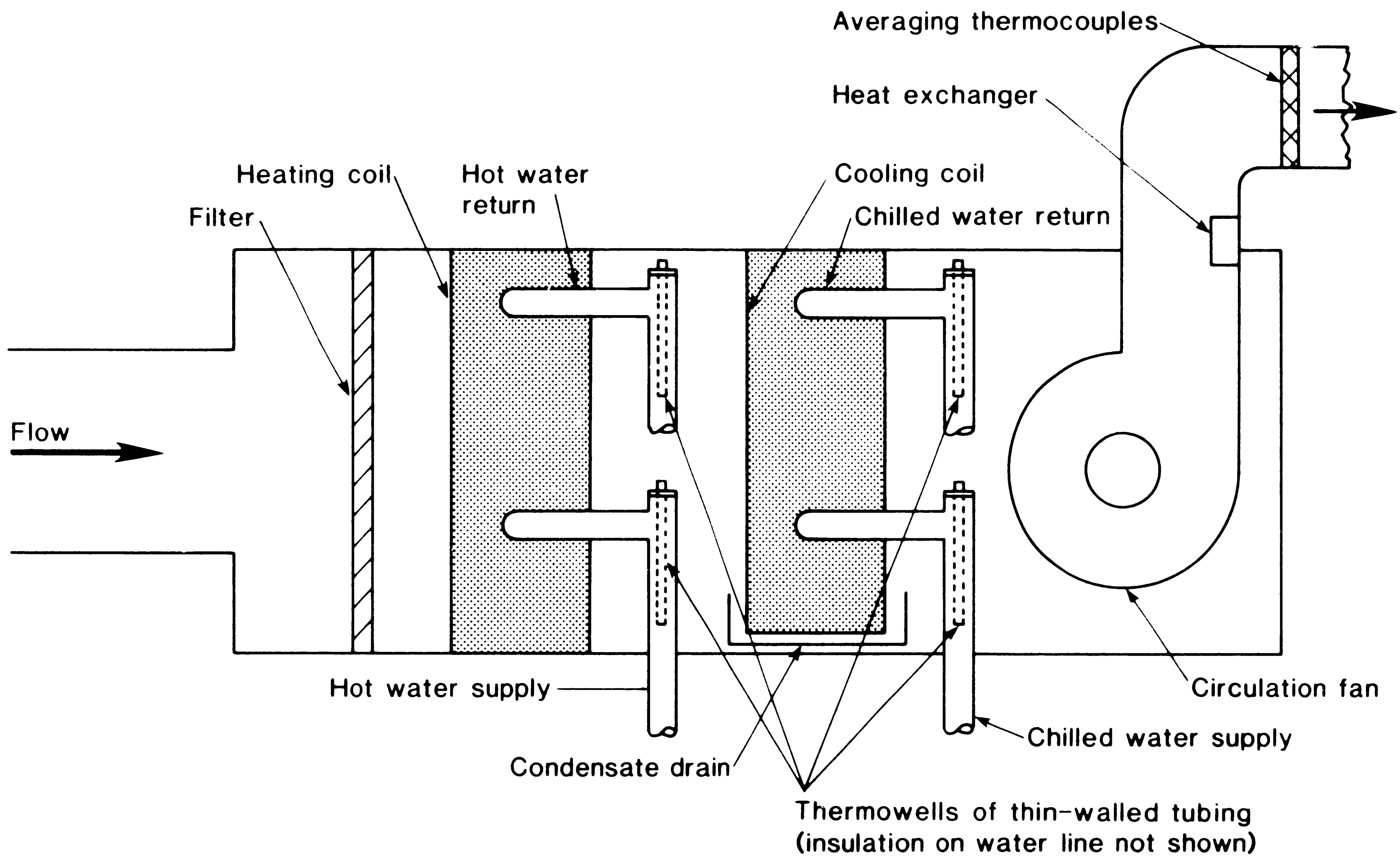

Figure 7.1 Schematic diagram of air handler used in example 7.2

serving other MUXs monitoring and controlling other air-handlers in the attic, and the CCU is located in an office adjacent to the mechanical-equipment room in the basement. Under these conditions, typical calibration techniques are not applicable because of the discomforts that would be imposed on the occupants of the building by fluctuating the temperature of the water in the coils and the supply air over the full range of operation during a routine calibration.

The thermocouple wire that was used in producing all of the thermocouples at this site was factory-calibrated wire which has a maximum deviation of ±1 °F (0.5 °C) at temperatures up to 300 °F (147 °C). Therefore, a special technique applicable to EMCS is used for the general calibration procedure. Before describing this technique, it must be emphasized that follow-up calibrations using a standard are mandatory. These follow-up calibrations are made as the seasons change requiring different temperatures in the water flowing through the coils and the supply air.

The special technique referred to above is the removal of the copper leads from the signal conditioning amplifier which originate at the ice-point reference and applying potentials from a well-calibrated source to the signal conditioner. The source of the potentials being applied must be of laboratory quality and capable of adjustment to within ±1 μV. In the case of the thermopile, the copper leads (A) that are removed from the signal conditioner are those coming directly from the thermopile as shown in figure 4.19. Except for the thermopiles, the potentials to be applied are taken from reference 9 or from the literature of one of many manufacturers who provide the same data and make direct reference to the NBS Monograph 125.

Starting with the individual thermocouples, potentials are applied to the signal-conditioning circuit starting with that potential corresponding to the lowest temperature of the water in the coil. (The various temperature ranges are found and recorded in the same manner described in the previous example.) The amplifier in the signal-conditioning circuits is connected to the various thermocouple-type temperature monitors in a differential mode. This is typical and is recommended by the majority of manufacturers of instrumentation amplifiers for thermocouples. Therefore, careful attention must be given to polarity when connecting the leads from the reference voltage source. A simple method of checking polarity is to connect a digital voltmeter (a 5 1/2 digit voltmeter capable of reading microvolt potentials is required for thermocouple calibration) across the terminals before disconnecting the leads from the thermocouple. This simple procedure serves several purposes in addition to determining the polarity. First, the potential indicated by the digital voltmeter must lie within a reasonable range of values with respect to the estimated or measured temperature of the thermocouple. If it does not, a calibration of the ice-point reference should be made using an independent thermocouple and a reference temperature bath with a standard. (All channels of the ice-point reference should be calibrated in this fashion before completing the calibration regardless of the initial readout when checking for polarity.)

Second, this simple test will immediately indicate any broken leads, leads or thermocouple junctions short-circuited to the mechanical system, thermocouples that have fractured, etc. The temperature readout at the CCU can be referenced to the type T temperature/voltage reference tables being used, and an initial check on the remote transmission and A/D converting system is also performed by this simple preliminary test.

The ice-point reference was found to be in proper working order and the polarities of the amplifiers were determined and recorded. The leads from the reference junction were removed and the reference voltage source applied and the voltages were varied up and down throughout the range of voltages produced by the temperatures of each thermocouple. It will be noted that the thermocouple does not function linearly. Therefore, tables must be used when comparing a readout at the CCU with the potential applied to the signal conditioning-amplifier. In general, thermocouples are very stable temperature-sensing devices. Therefore, only very minor adjustments, if any, should be required. If other than very minor adjustments are required, the channel should be examined for problems in the thermocouple itself, the ice-point reference, the junctions, the signal conditioner, transmission, etc. as described in the previous example.

Throughout all thermocouple calibrations including the superficial calibration described above, care must be taken to avoid establishing additional thermocouple junctions during the calibration procedure. Use like materials for the leads and connecting means on the voltmeter and the reference voltage source. Refer to the thermocouple laws given in section 4.6. Fortunately, these laws make it very easy to avoid establishing additional thermocouple junctions during the calibration procedure if they are followed.

By noting the schematic diagram shown in figure 4.18, one will observe that the averaging thermocouples in the supply air duct are identical to the individual thermocouples. The basic superficial calibration of the channel is made in the same way as that used for the individual thermocouples. However, one additional test is required assuming that the superficial tests indicated everything to be functioning in a normal manner.

The leads of the averaging thermocouples are removed from the ice-point reference and the leads of an independent type T thermocouple being used as a standard are then placed on the ice-point reference. The standard thermocouple junction is carefully inserted into the supply air stream. A small wooden dowel is used to support the standard. After placing the voltmeter on the output of the signal-conditioning circuit, the output voltage is observed and noted as the standard is moved to areas of the air stream simulating the positions of the individual averaging thermocouples. The leads of the standard are then removed from the ice-point reference and the leads of each thermocouple are then connected to the ice-point reference and independently tested. The output voltage resulting from the connection of each individual pair of leads of the averaging thermocouples to the ice-point reference is recorded. After each individual thermocouple has been tested and recorded, the values are then compared to those obtained with the standard for the various areas of the duct. If any one or more of the averaging thermocouples fall more than 5 % outside of the value established by the standard, the individual thermocouple should be checked for electrical insulation damage, dirt collected on the thermocouple junction, sharp bends in the leads, and other typical faults noted in section 4.6. Correct the fault if it is a simple one. Otherwise replace the thermocouple using the precautions given in section 4.6.1.

In the above example for the calibration of averaging thermocouples, it is assumed that the temperature of the supply air is constant and that alternative methods have been used to maintain this critical parameter.

As shown in figure 4.19, the thermopile does not use an ice-point reference. The two copper leads "A" are connected directly to the signal conditioning unit. The potential resulting from the differences of the temperatures of the water entering and leaving the cooling coils is directly applied to the amplifier. The software uses this potential and the temperature indicated by the input from the single thermocouple monitoring the water entering the coil, to compute the <u>difference</u> in the temperatures of the water entering and leaving the coil. See reference 9 for further details.

Since the potentials needed for the signal-conditioning unit cannot be determined directly from tables, the person most familiar with the software utilized by the CCU is contacted and the technique of applying reference potentials to the thermopile amplifiers is discussed. By referring to the software files and the temperature/voltage conversion tables, the CCU operator can produce the potentials to be applied to the input of the signal conditioning unit to produce 0 volt and 10 volt output signals. Since the thermopile is a multi-junction thermocouple sensor, the potentials that are applied to the signal conditioner to produce the maximum input to the A/D converter will be higher than those used for the single thermocouple. The values obtained were 0 millivolts for 0 volt output and 43.628 millivolts for a 10 volt output.

After checking polarity, the connections from the thermopile are removed and the voltages from the reference potential source are applied as previously described. The output of the signal conditioner is monitored by the voltmeter. Only very minor adjustments to the signal conditioning unit should need to be made. Otherwise problems in the thermopile, transmission lines to the signal conditioner, the signal conditioner, etc. probably exist. The techniques of detecting noise from electromagnetic fields previously described are used in addition to checking the thermopile leads for electrical contact with the thermowells and other parts of the air-handler. If problems still exist, the thermopile is checked for the proper functioning of each thermocouple in the thermopile. Broken junctions and junctions making electrical contact with other junctions or the thermowell are possible problem areas. The conductivity of an improper liquid that has been placed in a thermowell also has been known to generate problems unless each thermocouple has been hermetically sealed.

After the above calibration is completed, the actual temperatures are periodically measured at each thermowell using a standard as described for the single thermocouple. The difference in the actual temperatures must be the same as that indicated by the CCU readout. Otherwise, the same types of problems listed in the previous example may exist. In addition, the person responsible for the software and/or the CCU should be approached with the facts noted in the calibration notebook or described in the first example. In general, finding and correcting such problems in the calibration of a thermopile is a joint effort shared by the person responsible for the temperature sensing calibrations and the person operating the CCU.

7.3 Bimetallic Thermometer Calibration

In this example, a bimetallic thermometer employed in a switching device on an oil furnace used to heat a remote building requires calibration. The device functions to shut the furnace down if either of the following conditions exist:

a) The temperature of the heat exchanger being monitored has not reached 120 ^{o}F (49 ^{o}C) within 30 seconds after the furnace has been turned on. (This is to detect a possible failure of the ignition device in igniting the fuel.)

b) The temperature of the surface of the heat exchanger exceeds 300 ^{o}F (149 ^{o}C).

If the furnace is shut down by the bimetal thermometer device for either of these reasons, a manual reset is required.

Calibrating the thermometer in situ presents two problems. First, operating the furnace long enough to deliver an accurate calibration of the thermometer may cause discomfort to people working in the area, especially if the calibration is performed during the summer months. Second, allowing the temperature of the heat exchanger being monitored to rise high enough to shut the furnace down will present a safety hazard if the control unit is not functioning properly. For these reasons, the unit is removed from the HVAC for calibration.

It is necessary to remove the control unit from the furnace and replace it with a tight fitting cover. Qualified plant personnel should be assigned to manually monitor the furnace if its operation is required during the calibration period. In any case, plant personnel must be notified of the date, time and duration of the calibration period as was done in the first example.

The status of the unit is visually inspected for deposits caused by the combination of heat and particulate matter. Any deposits which are found are removed with a soft wire brush or other suitable tool to avoid damaging the bimetal thermometer. The repeated expansion and contraction of the bimetal portion of the thermometer in conjunction with various deposits often cause rapid deterioration. If either of these conditions are found during inspection, the thermometer is repaired or replaced.

Before beginning the calibration, the wiring diagram for the control unit is studied. It is necessary to power the unit in the same way as is done in the furnace. The locations of all the appropriate connections are noted. These and all other calibration information are recorded in the calibration notebook.

A suitable variable-temperature electric oven is found and its rate of increase in surface temperature is adjusted to reach 120 ^{o}F (49 ^{o}C) within 30 seconds. The thermometer portion of the unit is installed on the surface of the oven and it is confirmed that the thermometer is shielded from the direct radiation of the oven's heating elements. The appropriate power connections to the control unit are made. A suitable standard is used to monitor the temperature of the surface of the oven.

Continuity-detecting devices are connected to the appropriate switch contacts and the status of each switch is noted. The power to the control unit and the oven is turned on and the time and temperature of the surface of the oven required for the low temperature timing switch to change status is recorded. The surface temperature of the oven at which the high temperature relief switch changes status is also noted. The results of the calibration are then compared with the specified switching time and temperatures of the device. If more than a 10% deviation from the specified values is found, the bimetal control unit is repaired or replaced.

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APPENDIX A

ADDITIONAL DEFINITIONS OF TERMS USED IN TEMPERATURE MONITORING

APPENDIX A. ADDITIONAL DEFINITION OF TERMS USED IN TEMPERATURE MONITORING

TEMPERATURE FIXED POINT--A particular, precisely reproducible hotness suitable for calibrating thermometers or serving as a marker on a temperature scale. Temperature fixed points are commonly achieved by use of transitions occurring in pure materials, including boiling points, melting or freezing points, and triple points.

MELTING OR FREEZING POINT--The temperature at which the liquid and solid forms of a substance are in thermal equilibrium with the vapor of that substance and with air, usually at one atmosphere of pressure. Sometimes the temperature achieved during a warming cycle (melting) is different from the temperature achieved during a cooling cycle (freezing); this difference can arise from the presence of impurities in the substance. Sometimes also a particular substance "undercools" or "supercools" considerably before the onset of freezing; in such a case one might choose to use the melting procedure to define a fixed point of temperature.

TRIPLE POINT--The temperature at which the vapor of a particular one-component substance is in thermal equilibrium with both the liquid and the solid forms of that substance in the absence of air. According to the Gibbs Phase Rule, only one unique temperature and one unique pressure can exist in such a system.

THERMAL EXPANSION--The property, common to most materials, of becoming larger in physical dimensions as the temperature increases. All gases undergo thermal expansion, more or less in accordance with the "Ideal Gas Law", $PV=nRT$; thus their rate of expansion is about 1/273 of their room-temperature volume per ^{o}C, if they are maintained at constant pressure. Many liquids expand with increasing temperature, as, for example, liquid mercury does; their behaviors are more complex, however, as evidenced by water, which contracts in volume when its temperature is raised a few degrees above its melting point, then expands as its temperature rises above about 4 ^{o}C. Solids also show complicated thermal expansion behavior; their rates of expansion in general are lower than those of liquids or gases, however.

THERMAL CONDUCTIVITY--The ability of a substance to carry heat under the influence of a thermal gradient. Note that heat always flows from the hotter part of a system or material to the colder part. Note also that, technically speaking, it takes an infinite length of time for the two ends of a rod of thermal conductivity "K" to reach the same temperature, if they started at unequal temperatures; the heat energy per unit time, dQ/dt, carried from the hotter end to the colder end can be calculated from the relation $(dQ/dt)=K(T_1-T_2)$. As T_1 and T_2 become more and more nearly the same, the heat flows less and less rapidly. The thermal conductivities of different materials vary greatly, from less than 0.01 W/(cm. ^{o}C) for substances such as glass to more than 10 W/(cm. ^{o}C) for pure metals.

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Energy Management Control Systems (EMCS) cannot function properly or efficiently without accurate temperature measurements since temperature is one of the fundamental measurements of any EMCS. This report was written for the purpose of describing various methods of on-site calibration of temperature sensing devices used in EMCS and to review the characteristics of these devices that are directly related to calibration. The significance of recording the results of each calibration is emphasized and the possible effects of systematic errors in temperature monitoring systems is discussed. Illustrative examples of the calibration of temperature monitoring systems are given.

Liquid-in-glass thermometers, pressure thermometers, resistance temperature detectors (RTD), thermistors, integrated circuit temperature sensors, thermocouples, and bimetallic thermometers are discussed in detail with respect to their characteristics related to calibration.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

averaging thermocouples; bimetallic thermometers; calibration techniques; integrated circuit sensors; liquid-in-glass thermometers; pressure thermometers; resistance temperature detectors (RTD); systematic errors; thermistors; thermocouples; thermopiles.

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