ASME PTC 19.3-2024

[Revision of ASME PTC 19.3-1974 (R2004)]

Temperature Measurement

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Two Park Avenue • New York, NY • 10016 USA

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NOTICE

All ASME Performance Test Codes (PTCs) shall adhere to the requirements of ASME PTC 1, General Instructions. It is expected that the Code user is fully cognizant of the requirements of ASME PTC 1 and has read them before applying ASME PTCs.

ASME PTCs provide unbiased test methods for both the equipment supplier and the users of the equipment or systems. The Codes are developed by balanced committees representing all concerned interests and specify procedures, instrumentation, equipment-operating requirements, calculation methods, and uncertainty analysis. Parties to the test can reference an ASME PTC confident that it represents the highest level of accuracy consistent with the best engineering knowledge and standard practice available, taking into account test costs and the value of information obtained from testing. Precision and reliability of test results shall also underlie all considerations in the development of an ASME PTC, consistent with economic considerations as judged appropriate by each technical committee under the jurisdiction of the ASME Board on Standardization and Testing.

When tests are run in accordance with a Code, the test results, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. Parties to the test shall ensure that the test is objective and transparent. All parties to the test shall be aware of the goals of the test, technical limitations, challenges, and compromises that shall be considered when designing, executing, and reporting a test under the ASME PTC guidelines.

ASME PTCs do not specify means to compare test results to contractual guarantees. Therefore, the parties to a commercial test should agree before starting the test, and preferably before signing the contract, on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any ASME PTC to determine or interpret how such comparisons shall be made.

FOREWORD

In 1974, thermowell calculations were first added to ASME PTC 19.3 to establish a consistent and reliable methodology to evaluate whether a given design of such product would be likely to withstand flow-induced forces, especially in steam lines.

In 2004, this Committee identified gaps in the thermowell calculation set out in ASME PTC 19.3 and determined that the subject matter was sufficiently involved to justify the creation of a separate standard dealing specifically with that issue.

In 2010, that independent thermowell calculation standard was first published as ASME PTC 19.3 TW. ASME PTC 19.3 TW was amended and reapproved in 2016.

Since 1974, no significant changes had been made to this Code. However, following publication of ASME PTC 19.3 TW in 2010, it was plain that this Code could not be approved without removing the now obsolete calculation language.

Moreover, in the years following 1974, technology in temperature measurement has experienced significant change. Although foundational principles for the described technology remain much the same, the former ASME PTC 19.3 code was last revised when the IPTS-68 Temperature scale was new. We now live in a world where ITS-90 is very mature. Many sensors that were once commonplace in the world of temperature measurement, such as mercury-in-glass thermometers, are common no more. Other sensors that were less common, such as swaged mineral insulated thermocouples and noncontact temperature-measuring devices, are now quite common. With these technological shifts in mind, the ASME PTC 19.3 Committee set out to update the 1974 edition.

ASME PTC 19.3-2024 includes many changes while preserving the excellent work of the previous edition. The thermocouple, resistance temperature detectors, and calibration sections were updated significantly to reflect modern construction techniques and technological advancements. Thermowell calculations contained in ASME PTC 19.3-1974 (R2004) have been removed as they were made obsolete by the publication of ASME PTC 19.3 TW.

ASME PTC 19.3-2024 was approved by the ASME PTC Standards Committee on May 9, 2023, and was approved as an American National Standard by the American National Standard Institute Board of Standards Review on March 29, 2024.

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Performance Test Codes

(The following is the roster of the committee at the time of approval of this Code.)

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Revisions and Errata. The committee processes revisions to this Code on a periodic basis to incorporate changes that appear necessary or desirable as demonstrated by the experience gained from the application of the Code. Approved revisions will be published in the next edition of the Code.

In addition, the committee may post errata on the committee web page. Errata become effective on the date posted. Users can register on the committee web page to receive e-mail notifications of posted errata.

This Code is always open for comment, and the committee welcomes proposals for revisions. Such proposals should be as specific as possible, citing the paragraph number, the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent background information and supporting documentation.

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(a) The most common applications for cases are

(1) to permit early implementation of a revision based on an urgent need

(2) to provide alternative requirements

(3) to allow users to gain experience with alternative or potential additional requirements prior to incorporation directly into the Code

(4) to permit the use of a new material or process

(b) Users are cautioned that not all jurisdictions or owners automatically accept cases. Cases are not to be considered as approving, recommending, certifying, or endorsing any proprietary or specific design, or as limiting in any way the freedom of manufacturers, constructors, or owners to choose any method of design or any form of construction that conforms to the Code.

(c) A proposed case shall be written as a question and reply in the same format as existing cases. The proposal shall also include the following information:

(1) a statement of need and background information

(2) the urgency of the case (e.g., the case concerns a project that is underway or imminent)

(3) the Code and the paragraph, figure, or table number

(4) the editions of the Code to which the proposed case applies

(d) A case is effective for use when the public review process has been completed and it is approved by the cognizant supervisory board. Approved cases are posted on the committee web page.

Interpretations. Upon request, the committee will issue an interpretation of any requirement of this Code. An interpretation can be issued only in response to a request submitted through the online Inquiry Submittal Form at https://go.asme.org/InterpretationRequest. Upon submitting the form, the inquirer will receive an automatic e-mail confirming receipt.

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Interpretations are published in the ASME Interpretations Database at https://go.asme.org/Interpretations as they are issued.

Committee Meetings. The PTC Standards Committee regularly holds meetings that are open to the public. Persons wishing to attend any meeting should contact the secretary of the committee. Information on future committee meetings can be found on the committee web page at https://go.asme.org/PTCcommittee.

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Section 1 General

1-1 OBJECT

The purpose of this ASME Performance Test Code (PTC) is to give instructions and guidance for the accurate determination of temperature values in support of the ASME Performance Test Codes. The choice of method, instruments, required calculations, and corrections to be applied depends on the purpose of the measurement, allowable uncertainty, and characteristics of the equipment being tested.

Measurement of temperature is generally considered to be one of the simplest and most accurate measurements performed in engineering. While true when compared to other measured parameters, there are many challenges. Accurate measurement of temperature can be obtained only by observance of suitable precautions in the selection, installation, and use of temperature-measuring instruments and in the proper interpretation of the results obtained with them. In some cases, an arbitrarily standardized method is prescribed in the Performance Test Codes that is to be followed in making temperature measurements under such conditions.

Some of the instruments available for temperature measurement can indicate temperature to a closer degree of accuracy than is required in some of the tests considered in the Performance Test Codes. The difficulty in obtaining accurate temperature measurements with such instruments is encountered in installation or use of the temperature-measuring instruments. Specific directions and precautions in usage of the instruments are given in subsequent sections for each of the various types of temperature-measuring instruments.

1-2 SCOPE

The methods for temperature measurement and the protocols used for data transmission are provided in this Code. Guidance is given for setting up the instrumentation and determining measurement uncertainties. Information regarding the instrument type, design, applicable temperature range, accuracy, output, and relative cost is provided.

Information on temperature-measuring devices that are not normally used in field environments is given in Mandatory Appendices I, II, and III.

1-3 DEFINITIONS

Where special terms are used, they are specifically defined in the body of this Code at the point at which they are introduced. Otherwise, this Code is meant to be a straightforward text capable of interpretation without the need to resort to unusual definitions. To the extent that clarification of the intended meaning of a word is desired and the dictionary does not provide an acceptable explanation, users of this Code are directed to the definitions sections contained in the most recent edition of ASTM E344.

1-4 TEMPERATURE SCALES

Temperature is a measure of thermal potential. Two bodies are at the same temperature when there is no thermal (heat) flow from one to the other. If one body loses heat to another, the first is at a higher temperature.

To measure temperature, it is necessary to have a scale with appropriate units, just as it is necessary in measuring length to have the meter with its subdivisions of centimeter and millimeter or the yard with its subdivisions, the foot and the inch.

1-4.1 Thermodynamic Temperature Scale

The ideal temperature scale is known as the Thermodynamic Temperature Scale. Temperature measured on such a scale will obey all the laws of thermodynamics, which relate such physically measurable quantities as energy, specific heat, latent heat, pressure, and other quantities to temperature. The temperature scale defined in this manner is independent of the physical properties of any specific substance.

Any physical system that has properties that depend on temperature in a theoretically well-understood manner can be the basis for a laboratory realization of the Thermodynamic Temperature Scale.

A simple example of such a system is a constant volume gas thermometer. A constant volume gas thermometer is composed of a bulb filled with a fixed amount of a dilute gas that is attached to a mercury manometer. An ideal gas obeys the equation of state.

$$PV = nRT \tag{1-4-1}$$

where

n = number of moles of gas
P = absolute pressure
R = gas constant
T = absolute temperature on the Thermodynamic Temperature Scale
V = volume in which the gas is contained

If the volume and number of moles of gas are fixed, the ratio of temperature at an unknown point to the temperature at a reference point can be determined by measuring the ratio of pressures at these two points:

$$T/T_{\text{ref}} = P(T)/P(T_{\text{ref}}) \tag{1-4-2}$$

In practice, the triple point of water 32.018°F (0.01°C) is commonly used as T_{ref}.

By placing laboratory thermometers in the wall of the vessel containing the gas, the readings of the laboratory thermometers as a function of the thermodynamic temperature, T, can be determined.

Reversible heat engines are impossible to construct, and gas thermometers are difficult to construct and use under ideal laboratory conditions, let alone under industrial test conditions, and are therefore not suitable for general everyday use.

1-4.2 Units of Measurement for Temperature

The International Temperature Scale of 1990 (ITS-90) is defined in terms of either the kelvin (K) or the degree Celsius (°C). The relation between temperatures expressed in kelvin, T, to those expressed in degrees Celsius, t_C, is given by:

$$T/\text{K} = (t_{\text{C}}/^{\circ}\text{C} + 273.15\ \text{K}) \tag{1-4-3}$$

In some countries, Fahrenheit (F) and Rankine (R) scales are also defined. The relation between temperatures in degrees Fahrenheit, t_F, and degrees Celsius, t_C, is

$$t_{\text{F}}/^{\circ}\text{F} = 32^{\circ}\text{F} + 1.8(t_{\text{C}}/^{\circ}\text{C}) \tag{1-4-4}$$

The relation between temperatures in degrees Rankine, T_{R}, and degrees Fahrenheit, t_{F}, is

$$t_{\text{R}}/^{\circ}\text{R} = t_{\text{F}}/^{\circ}\text{F} + 459.67^{\circ}\text{R} \tag{1-4-5}$$

Temperatures expressed in either kelvin or degrees Rankine have the property that at absolute zero, the temperature is 0 K or 0°R. These temperatures are said to be on an "absolute" scale and are written with a capital T. Temperatures in degrees Celsius or Fahrenheit are written with a lowercase t.

Note that the unit of kelvin does not carry a "degree" symbol, e.g., 100°C, 373.15 K, 212°F, 491.67°R.

1-5 SENSOR AND GAUGE TYPES

The following types of sensors and gauges are available for use under appropriate conditions. The section and appendix numbers refer to sections and appendices in this Code.

(a) Thermocouple Thermometer. A thermocouple thermometer (see Section 2) is a temperature-measuring system comprising a temperature-sensing element called a thermocouple, which produces an electromotive force (emf), a device for sensing emf at an established reference temperature to convert emf to equivalent temperature units and electrical conductors for operatively connecting the two (see Figure 2-1.2-1).

(b) Resistance Thermometers [Resistance Temperature Detectors (RTDs) and Platinum Resistance Thermometers (PRTs)]. Resistance thermometers (see Section 3) are temperature-measuring instruments in which electrical resistance increases as the exposure temperature increases [positive temperature coefficient (PTC)]. Temperature measurement is established as a function of resistance versus temperature. RTDs consist of a sensing element called a resistor, a resistance-measuring instrument, and electrical conductors for connecting the two. These typically operate over a smaller temperature band than a thermocouple and a larger temperature band than a thermistor thermometer.

Table 1-5-1
Typical Temperature Ranges

Temperature-Measuring Instrument	Range of Use, °F (°C)
Thermocouple (see Section 2)	−328 to +4,500 (−200 to 2 482)
Resistance thermometer (RTD) (see Section 3)	−328 to +1,200 (−200 to +650)
Filled-system thermometer (see Section 4)	−200 to +1,200 (−130 to +650)
Thermistor (see Section 5)	−58 to +300 (−50 to +150)
Radiation thermometer (see Mandatory Appendix I)	Ambient and above
Optical pyrometer (see Mandatory Appendix II)	Above +1,300 (+700)
Bimetallic thermometer (see Mandatory Appendix II)	−200 to +800 (−130 to +425)
Liquid-in-glass thermometer (see Mandatory Appendix III)	−328 to +1,110 (−200 to +600)

(c) Thermistor Thermometers. Thermistor thermometers (Section 5) are temperature-measuring instruments in which electrical resistance decreases as the temperature of exposure increases [negative temperature coefficient (NTC)]. Temperature measurement is established as a function of resistance versus temperature. Thermistors consist of a sensing element called a resistor, a resistance-measuring instrument, and electrical conductors for connecting the two. These typically operate over a narrower temperature band of allowable temperatures closer to ambient temperature as compared to a resistance thermometer.

(d) Filled-System Thermometers. Filled-system thermometers (see Section 4) are temperature-measuring instruments in which the change in volume of a liquid, the change in pressure of a gas, or the change in vapor pressure of a volatile liquid is used as a means of temperature measurement. They consist of an all-metal assembly comprised of a bulb, capillary tube, and Bourdon tube, provided with a temperature responsive fill. These are readout-only devices and have no signal transmission capabilities.

(e) Radiation Thermometers. Radiation thermometers (see Mandatory Appendix I) are temperature-measuring instruments in which the intensity of the radiation emitted from a body is used as a measure of the body temperature. They consist of an optical system, used to intercept and concentrate a definite portion of the energy radiated from a body whose temperature is being measured; a temperature-sensitive element, usually a thermocouple or a thermopile; and a measuring device, such as an emf-measuring instrument.

(f) Optical Pyrometers. Optical pyrometers (see Mandatory Appendix I) are temperature-measuring instruments in which the brightness of radiation in a very narrow band of wavelengths emitted by a source, the temperature of which is to be measured photometrically matched against the brightness of a calibrated source, is used as a means of temperature measurement. They consist of a telescope, a calibrated lamp, a filter to provide for viewing nearly monochromatic radiation, a readout device, and usually an absorption glass filter.

(g) Bimetallic Thermometers. Bimetallic thermometers (see Mandatory Appendix II) are temperature-measuring instruments in which the differential expansion of two metals is used as a means of temperature measurement. They consist of an indicating device, a sensing element called a bimetallic thermometer bulb, and a means for operatively connecting the two. These are readout-only devices.

(h) Liquid-in-Glass Thermometers. Liquid-in-glass thermometers (see Mandatory Appendix III) are temperature-measuring instruments in which the differential expansion of a liquid in a closed glass system is used as a means of temperature measurement. They consist of a thin-walled glass bulb attached to a glass capillary stem closed at the opposite end, with the bulb and a portion of the stem filled with an expansive liquid. These readout-only devices were historically filled with mercury and have been generally replaced by digital thermometers capable of providing local temperature readout as well as signal out, enabling remote monitoring.

The above instruments are recommended for ASME PTC work for the measurement of temperature when used under appropriate conditions.

The recommended ranges of use for these temperature-measuring instruments when properly installed are indicated in Table 1-5-1.

1-6 THERMOWELLS AND PROTECTION TUBES

Thermowells and protection tubes are pressure-tight receptacles adapted to receive a temperature-sensing element and provided with means for pressure-tight attachment to a vessel, pipe, or other process containing structure. In most temperature measurements for PTC work, the temperature sensor cannot be placed directly into the medium. The need may exist to be able to remove and replace the sensor without losing process containment. In such cases, a thermowell or

Table 1-6-1
Factors That Influence Strength and Measurement

Factor	Ideal for Measurement	Ideal for Strength
Length	*Long*: Reduced conductivity errors Enables location of active portion of thermometer in flow stream	*Short*: Reduced impingement force Higher natural frequency
Thickness	*Thin:* Reduced conductivity losses Faster response due to better heat transfer to installed temperature sensor	*Thick*: Better resistance to fluid-induced stresses
Mass velocity	*High*: Enhanced heat transfer	*Low*: Less stress caused by process flow

protection tube is used to encase the element, protect it from mechanical forces, and allow removal and replacement without opening up the process (ASME B40.200).

Attachment to the vessel may be made in any manner approved by the ASME Boiler and Pressure Vessel Code (BPVC), ASME B31.1, ASME B31.3, ASME B31.4, ASME B31.5, ASME B31.8, or ASME B31.9. This includes designs using branch fittings that accommodate threaded or socket-welded wells. It also includes flanged wells and full penetration welds, where the well is welded directly into the piping system. The ASME piping codes should be consulted for specific requirements regarding attachment of thermowells into piping system, including size limits, requirements for seal welding, and other necessary design and installation aspects.

Any material approved by these Codes for the intended service may be used. Note that where materials are specified for the purposes of illustrating the example, no inference is intended that these materials are preferred. Thermowells and protection tubes are typically fabricated of stainless steel (304 or 316), carbon steel, alloy steel, or other more exotic materials as required by the process. Note that thermowells or protection tubes for use in molten metals, furnace atmospheres, salt baths, and chemical processes must be selected to withstand the particular conditions and hazards prevailing in the installation. In such cases, protection tubes can be coated or constructed from ceramic as well as metallic materials.

Detailed design and strength analysis requirements for thermowells as well as specific manufacturing tolerances are provided in ASME PTC 19.3 TW. Recommendations for typical thermowell geometries and other tolerances are provided in ASME B40.200. Protection tubes are not governed by any ASME standard and are typically constructed from pipe with a welded tip, ceramic materials, or ceramic composite materials (ASTM MNL 12, chap. 4; BS EN 50446). Metal protection tubes are often provided with external support to reduce or eliminate process-induced stress or vibration.

Factors required to produce adequate thermowell strength tend to reduce the accuracy and response of the temperature measurement, as shown in Table 1-6-1.

Table 1-6-1 is not all inclusive but indicates that thermowell design methods must carefully balance these factors so that accuracy is compromised to a minimum when using a well of adequate strength. Excessive length can increase the possibility of thermowell resonance and breakage at high fluid velocities. When balancing the need for temperature measurement versus mechanical integrity, mechanical integrity requirements should always control the ultimate design decision (ASME PTC 19.3 TW).

1-7 OTHER ACCESSORIES

When it is necessary to place a temperature-sensing element in a gas or a vapor at a location where it can "see" surfaces at materially higher or lower temperatures than that of the medium in which it is immersed, accessories may be used to minimize errors arising from radiation under such conditions. Several schemes may be employed by

(a) surrounding the sensing element with one or more coaxial tubes mounted and axially aligned in the direction of gas flow (King, 1943; Moffatt, 1952; Rohsenow and Hunsaker, 1947). This arrangement screens the sensor from radiation exchange with the surrounding surfaces.

(b) increasing the convective heat transfer rate from the gas to the sensor, thereby minimizing the effect of radiation losses. This may be accomplished by using a suction or aspirating type pyrometer (ASME PTC 19.3 TW; ASTM MNL 12, chap. 4). A special case of this principle is employed in the sonic-flow thermocouple pyrometer in which the gas flow over the sensor is maintained at sonic velocity (BS EN 50446).

(c) covering the sensing element with a low emissivity radiation shield mounted directly onto the element (King, 1943). This arrangement has been found effective in minimizing radiation losses where space limitations prevent the use of the coaxial type screens.

For a more complete discussion of this subject, see Rohsenow and Hunsaker (1947).

1-8 INSTALLATION AND PROCESS EFFECTS

Any contact temperature-sensing element or gauge indicates its own temperature. However, even under steady-state conditions, the temperature of the element may not be that of the fluid or solid with which it is in contact.

In general, temperature errors are more pronounced when dealing with the gaseous phase as compared with the liquid or solid phase. However, errors can also be a factor when measuring temperatures in liquids or solids. If a fluid is at rest or moving with relatively low velocity, the temperature indicated by the temperature-sensing element for steady-state conditions is a result of a balance of convective heat transfer between the element and fluid, and heat transfer by conduction and radiation between the element and its surroundings. For a gas stream moving at high velocity (above Mach 0.3), however, the temperature determination becomes more difficult because of the aerodynamic heating effect.

Paragraphs 1-8.1 through 1-8.8 describe some (though not all) generic sources of static and dynamic error associated with installation and general means by which errors can be determined or reduced.

1-8.1 Placement Recommendations

Improper or inappropriate placement of sensors can lead to a variety of error conditions presented here, particularly stratification. In general, sensors shall be

(a) located in the area requiring measurement
(b) located in nonstratified flow streams, where possible
(c) sufficiently long to minimize the effects of conduction error
(d) of appropriate materials and shielded from radiative sources (where radiation sources are not the target of the measurement)
(e) located sufficiently apart from nearby sensors or sensing ports to avoid shadowing or other issues

1-8.2 Conduction Error

Conduction error, also called immersion error, may be present whenever a temperature difference exists in the temperature sensor (e.g., in the wires of a thermocouple between its measuring junction and point of attachment).

Recommended installation practice for thermometer wells is described in Sections 1 through 6 and para. 1-8.1. If followed, these practices will reduce the conduction error. The following simplified relation may be used with acceptable accuracy for determining the extent of the conduction error if this is the only error of significance (Moffatt, 1952):

$$T_{sg} = T_i - \left[\frac{T_w - T_{sg}}{\text{Cosh}\,(mL)}\right] \tag{1-8-1}$$

where
a = conduction cross-sectional area of temperature sensor, ft^2
h = convective coefficient of heat transfer, Btu/hr ft^2 °F
k = thermal conductivity of temperature sensor, Btu/hr ft °F
L = immersion length of temperature sensor, ft
m = $(hp/ka)^{1/2}$, ft^{-1}
p = perimeter of temperature sensor, ft
T_i = temperature indicated by temperature sensor, °F
T_{sg} = static temperature of the fluid, °F
T_w = temperature at point of attachment (e.g., vessel wall), °F

Since the hyperbolic cosine of the mL product increases as the product itself increases, it follows that the larger mL becomes, the closer the indicated temperature, T_i, approaches the static temperature of the fluid, T_{sg} (i.e., the conduction error is reduced). As a consequence, any means of increasing the mL product will result in a decreased conduction error. Although the calculation above is generally acceptable for establishing a conduction error value, a more refined approach taking into account the influence from each cross-sectional area of each component of the assembly using finite element analysis (FEA) may be helpful in some applications in identifying the most accurate estimate.

From a practical viewpoint, increasing the length is typically the best way to decrease conduction error. Determination of an appropriate immersion length should take into account the impact on accuracy as well as structural integrity and the purpose for which the measurement is being made (Liptak, 2017, pp. 1108–1124).

1-8.3 Radiation Error

If the temperature sensor can "see" surfaces that are at either higher or lower temperatures than the sensor itself (e.g., a sensor is exposed to adjacent surfaces that are maintained at either higher or lower temperatures than the sensor itself), net radiant heat transfer will occur. The sensor will experience a net gain or loss of heat by radiation with a possibly significant measurement error. The net radiant heat transfer may be determined by means of the following relation (Brown and Marco, 1958, p. 63):

$$q_r = 0.1714\, F_\epsilon F_A A_s \left[\left(\frac{T_i}{100} \right)^4 - \left(\frac{T_r}{100} \right)^4 \right] \quad (1\text{-}8\text{-}2)$$

where

A_S = surface area of temperature sensor, ft^2
F_A = configuration factor, dimensionless
F_ε = effective emissivity, dimensionless
q_r = net rate of radiant interchange, Btu/hr
T_i = temperature indicated by temperature sensor, °R
T_r = mean temperature of surrounding surfaces, °R

If the sensor surface area is small compared with the area of the surrounding surfaces (as is typical), the effective emissivity (F_E) is equal to the normal total emissivity (e_s) of the sensor. Also, since all the energy radiated by the sensor is intercepted by the surrounding surfaces, the configuration factor (F_A) from the sensor to its surroundings is equal to unity. As a result, eq. (1-8-2) may be simplified as follows:

$$q_r = 0.1714\ \in_s\ A_s \left[\left(\frac{T_i}{100} \right)^4 - \left(\frac{T_r}{100} \right)^4 \right] \quad (1\text{-}8\text{-}3)$$

For most industrial measurement applications, the first step in reducing radiation error comes down to decreasing the emissivity. This is frequently done by using lower emissivity materials, such as polished stainless steel in the sensor sheathing. Reduction of the offending source of radiation error is often further addressed by shielding the sensitive element of the temperature measurement device behind a larger metallic structure so that it can intervene between the sensor and source of radiation while allowing the process contents of interest to continue to flow in proximity through the shield and in contact with the sensitive portion of the sensing element. Section 1-7 also describes some methods for effectively reducing heat transfer error.

NOTE: Equations (1-8-3), (1-8-6), and (1-8-7) are valid only for the case where there are no radiation-absorbing gases present. For the case where absorbing gases such as water vapor or carbon dioxide are present, see Rohsenow and Choi (1961).

1-8.4 Aerodynamic Heating Effect

Aerodynamic heating is caused by localized stagnation of the moving gas stream in the immediate vicinity of the temperature sensor. As a result, the temperature as indicated by the sensor tends to be higher than the static temperature of the gas stream.

static temperature: the temperature of the gas stream as indicated by a temperature-sensing element moving with the same velocity as the gas and with isentropic conditions existing at the temperature-sensing element.

In the case where radiation, conduction, and aerodynamic heating occur simultaneously, the temperature indicated by the temperature sensor will be dependent on the corresponding magnitudes of these three heat transfer effects. If the moving gas stream is brought to rest isentropically at the temperature sensor, the resulting localized temperature of the gas stream is called total, or stagnation, temperature, T_t. The total temperature would be higher than the static temperature because of the conversion of kinetic energy to internal energy. These two temperatures are related in the following manner (Woodfield and Bloomfield, 1958):

$$T_t - T_{sg} = V^2/2J\, g_c c_p \quad (1\text{-}8\text{-}4)$$

where

c_p = specific heat at constant pressure, Btu/lb, °F
g_c = dimensional constant = 32.1740 (lb·ft)/(lbf·s^2)

J = mechanical equivalent of heat = 778 ft·lbf
V = gas velocity, ft/sec

Whenever the kinetic energy of the gas stream is reduced, the conversion of kinetic energy to internal energy is manifested by a localized rise in gas temperature at the temperature sensor. This temperature rise results in heat transfer from the localized region to the surrounding gas stream, as well as to the sensor. If the sensor experiences no heat transfer, an adiabatic condition, the temperature that the sensor then assumes is defined as the "adiabatic temperature," T_a. For convenience, the ability of a temperature sensor to "recover" the converted kinetic energy of the gas stream is defined in terms of a "recovery factor," r, as follows (Woodfield and Bloomfield, 1958):

$$r = \frac{(T_a - T_{sg})}{(T_t - T_{sg})} \tag{1-8-5}$$

The rise in temperature, $(T_t - T_{sg})$, of the stagnated portion of the gas stream during isentropic slowing of the gas stream may be calculated by means of eq. (1-8-4). The recovery factor is primarily dependent on geometric configuration, orientation, and Mach number. For a more complete discussion of this subject, see Benedict (1959), Benedict and Murdock (1963), Roughton (1966), and Stickney (1955).

1-8.5 Heat Transfer at Low Velocity

Consider the case of a temperature sensor exposed to a lower than 0.3 Mach velocity (i.e., no aerodynamic heating) gas stream with the sensor experiencing both radiation and conduction effects. For the steady-state condition between the flowing gas and sensor, heat transfer by convection must equal the rate of heat transfer by radiation and conduction. This equilibrium condition may be written as follows:

$$hA_s(T_{sg} - T_i) = 0.1714 \in_s A_s \left[\left(\frac{T_i}{100}\right)^4 - \left(\frac{T_r}{100}\right)^4\right] + ka\frac{(T_i - T_w)}{L} \tag{1-8-6}$$

It can be seen from the above expression that as the radiation and conduction effects are reduced, the temperature of the sensor, T_i, will approach the static temperature of the gas, T_{sg}. Means of reducing the radiation effect are described in subsection 1-7. There is also a more complete discussion of radiation and related factors in Mandatory Appendix I.

1-8.6 Heat Transfer at High Velocity

In the case where aerodynamic heating occurs and the temperature sensor has conduction and radiation effects, the temperature, T_i, indicated by the sensor may differ from the adiabatic temperature. In other words, all four temperatures, T_i, T_{sg}, T_t, and T_a, generally have different values. For this case, the applicable steady-state relation is as follows:

$$h_eA_s(T_a - T_w) = 0.01714 \in_s A_s\left[\left(\frac{T_i}{100}\right)^4 - \left(\frac{T_r}{100}\right)^4\right] + ka\frac{(T_i - T_w)}{L} \tag{1-8-7}$$

where
h_e = effective convective heat transfer coefficient, Btu/hr ft^2 °F

The effective coefficient, h_e, which is primarily dependent on flow regime, geometric configuration, and orientation, may be calculated through use of appropriate convection correlations. Further information may be obtained from Benedict and Murdock (1963) and Scadron and Warshawsky (1952). When calculating the temperature error for the above case, the adiabatic temperature, being the unknown quantity, is determined through use of eq. (1-8-7). Equations (1-8-4) and (1-8-5) may then be used for determining the static temperature of the gas.

At the relatively low velocity of 300 ft/sec, the difference between the total and static temperatures is only 7°F, but at a velocity of 1,100 ft/sec, approximately Mach 1 at 40°F, the difference in temperature increases to 40°F. At a velocity of 2,200 ft/sec, approximately Mach 2 at 40°F, the difference is 400°F, thus emphasizing the significance of aerodynamic heating at high velocities.

At velocities of 300 ft/sec or less, a recovery factor for air of 0.65 should be used for thermowells dimensioned in accordance with the latest version of ASME PTC 19.3 TW.

1-8.7 Gradients and Stratifications

In temperature measurements in a system where there are velocity, density, or temperature gradients, such gradients must be accounted for to reduce temperature measurement errors.

Typically, value of the bulk temperature is desired. This bulk temperature is that which would be realized if the flow could be interrupted and the material thoroughly mixed without gain or loss in energy (i.e., an adiabatic situation). In practice, the desired result can be obtained by taking multiple measurements and numerically integrating against the appropriate profile (velocity or density).

A number of measuring stations and sensing elements is typically selected depending on the relative magnitude of the gradients and the accuracy desired. For each station, the local temperature, density, velocity, and flow area are evaluated. The value of the bulk temperature is related to the local quantities though the following equation:

$$T_b\left(C_p\right)_b = \frac{\sum \left(C_p T V_A\right)}{\sum \left(\rho V_A\right)} \tag{1-8-8}$$

where

A = local area represented by measuring station, ft^2
C_p = specific heat at constant pressure, evaluated at the local stagnation temperature, Btu/lbm °F
$(C_p)_b$ = specific heat at constant pressure, evaluated at the bulk temperature, Btu/lbm °F
T = local stagnation temperature, °F
T_b = bulk stagnation temperature, °F
V = local stream velocity, ft/sec
ρ = local stream density, lbm/ft^3

Practical considerations to minimize stratification can also be used, including avoidance of upstream obstacles (e.g., other temperature sensors, elbows, tees, flow restrictions) where natural flow disturbances are introduced. For the impact on mechanical integrity of a thermowell installation in a flowing line, refer to the most current iteration of ASME PTC 19.3 TW.

Several of the equipment-specific performance codes include recommendations on measurement array geometries and measurement quantities to reduce stratification errors. Where provided, these may be adopted to reduce the impact of stratifications and gradients, which are then reflected as measurement errors.

1-8.8 Speed of Response Contributing to Dynamic Error

It is critical that PTC measurements be taken under steady-state conditions. However, the mere failure of a temperature sensor to indicate a change in temperature is not sufficient to prove that no change in temperature has taken place. The sensor and its associated measuring equipment may be so slow in responding that the actual conditions at the time of measurement are obscured.

It is impossible for any temperature sensor to instantaneously undergo a step-change in temperature due to the response restriction imposed by thermal capacity of the individual sensor. A finite time interval is required for the sensor to absorb, or dissipate, heat during a transient. Because of this, the temperature of the sensor, in general, will be out of phase with the temperature of the medium being measured during a transient condition. In addition to being out of phase, it will also be of different magnitude.

The ability of a temperature-sensing element to respond to a change in temperature is typically given in terms of its "time constant."

time constant: the time required for the element to change in temperature an amount equal to 63.2% of the imposed step-change.

A temperature-sensing element having a short time constant will respond more rapidly to a change in temperature than if it had a long time constant. As a result, temperature error due to dynamic response becomes more significant for elements having long time constants.

The response of a temperature measurement system depends on the following major parameters:

(a) Ratio of Sensor Surface Area to Sensor Mass. As the ratio increases, the time constant decreases.
(b) Convective Heat Transfer Coefficient. As the heat transfer coefficient increases, the time constant decreases.
(c) Thermal Conductivity of the Sensor Material. As the thermal conductivity increases, the time constant decreases.
(d) Specific Heat of the Sensor Material. As the specific heat increases, the time constant also increases.

(e) Mechanical and Electrical Characteristics of the Accessory-Measuring Equipment. Limitations applicable to the meters and other instrumentation used to receive the input from the sensor will necessarily impact the speed of response of that temperature measurement system.

The time response of a thermocouple to a temperature change is a function of the mass and geometry of the sensing element, as well as the probe in which it is encased and the mode or modes of heat transfer between the junction and its surroundings.

In general, the smaller the probe, the shorter its time constant will be. The greater the surface area to the mass ratio of the junction, the greater the speed of response will be for a given heat transfer condition.

When a contact temperature measurement element is encased in a well or protecting sheath, the response indicated by the probe will be governed by the combined effects of heat transfer from the medium to the well and that of the well to the enclosed junction. For this reason, grounded thermocouple sensors will respond more quickly than ungrounded sensors due to the fact that they are in direct contact with the surface of the probe and not physically or electrically isolated from the probe surface.

However, grounded sensors may present other challenges for installation as discussed in Section 2 of this Code, which is dedicated to thermocouples.

Further information is given in Linaham (1956), Scadron and Warshawsky (1952), and Stickney (1955), and specific features are considered in the individual chapters dealing with various temperature-measuring instruments.

1-9 UNCERTAINTY

The precision and accuracy of the installed instrumentation should be considered in designing a test. The components of installed temperature measurement systems should be calibrated separately. These characteristics will be reflected in the ultimate uncertainty calculation.

The methods provided in this Code are designed to assist in the evaluation of measurement uncertainty based on current technology and engineering knowledge, taking into account published instrumentation specifications, and measurement and application techniques. Numerous sources already exist to provide methods of calculating uncertainty, including ASME PTC 19.1 and ASTM E2593. This subsection addresses the subject matter only to provide guidance particular to the methods useful for establishing measurement uncertainty in the context of temperature measurement.

Precision is reflected in the random error of the system and is a measure of the repeatability of the readings. In other words, random error is the extent of "scatter" in the data during a test period. Low scatter means a low value of random error.

Accuracy is reflected in the systematic error of the system, and these errors are constant and not evident in the data collected during the test period. Systematic error could be due to calibration methods, mounting effects, spatial variations, etc.

The total uncertainty, U_x, is two times the square root of sum-of-squares of the systematic standard uncertainty, b_x, and the random standard uncertainty, s_x:

$$U_x = 2\sqrt{(b_x)^2 + (s_x)^2} \tag{1-9-1}$$

The multiple of 2 is the Student's *t* value for 95% confidence interval. As a consequence, the sample mean value, X, plus U_x provides the interval containing the true value with a 95% confidence level, assuming a large sample size ($N \geq 29$).

The value of systematic standard uncertainty, b_x, and random standard uncertainty, s_x, can both be calculated using the elemental error sources as described in ASME PTC 19.1. However, the systematic standard uncertainty can usually be taken from published data.

1-9.1 Uncertainty Due to Random Error

The uncertainty due to the random error of the average temperature measurement is evaluated as follows:

(a) The sample mean, or average value, of the temperature measurements is determined using equation as follows:

$$\overline{X} = \frac{1}{N}\sum_{j=1}^{N} X_j \tag{1-9-2}$$

(b) The sample standard deviation is determined as follows:

$$S_X = \sqrt{\frac{\sum_{j=1}^{N}\left(X_j - \overline{X}\right)^2}{N - 1}} \tag{1-9-3}$$

(c) The standard deviation of the sample mean is determined as follows and is used as an estimate of random uncertainty of the mean:

$$S_{\overline{X}} = \frac{S_X}{\sqrt{N}} \tag{1-9-4}$$

1-9.2 Uncertainty Due to Systematic Error

The uncertainty due to the systematic error of the average circulating water-bath temperature measurement is evaluated by

(a) identifying all elemental sources of systematic error for the measurement

(b) evaluating elemental systematic standard uncertainties as the standard deviations of the possible systematic standard error distributions

(c) combining the elemental systematic standard uncertainties into an estimate of the total systematic standard uncertainty for the measurement

The systematic standard uncertainty of the temperature is calculated as follows:

$$b_{\overline{X}} = \left[\sum_{k=1}^{K}\left(b_{\overline{X}_k}\right)^2\right]^{1/2} \tag{1-9-5}$$

where K is the total number of systematic error sources, and each is an estimate of the standard deviation of the k^{th} elemental error source. Prepublished values of systematic error, b_x, are generally used.

There can be many sources of systematic error in measurement, such as the calibration process, instrument systematic errors, transducer errors, and fixed errors of method. Also, environmental effects, such as radiation effects in a temperature measurement, can cause systematic errors of method. There usually will be some elemental systematic standard uncertainties that will be dominant.

Once the systematic standard uncertainty and the random standard uncertainty have been established, they can be combined to give the value of the total uncertainty, U_x. The interval ($X + U_x$) is then expected to contain the true value of the measurand with a 95% confidence level.

After ascertaining the total uncertainty of the measurand, the error needs to be propagated to assess the impact on the final parameter involved in the testing. For instance, if temperature measurements are taken to compute the flowrate (result) of a gas or vapor, then the sensitivity of the temperature error on the final flowrate value must be established. See ASME PTC 19.1 for details.

1-10 CONCLUSIONS

In the measurement of temperature, it is important that the instrument be selected that is best suited to the particular problem. The choice will be governed by required accuracy, accessibility to the material to be measured, types of available equipment, and economic factors. When the proper selection of measurement equipment has been made, calibration shall be conducted as described in Section 6. However, temperature test data obtained from calibrated instruments should not be taken for granted as necessarily being accurate. The possibility of temperature errors occurring as a result of the factors described herein should be investigated and, if significant, evaluated.

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1-11.2 Additional References

In addition to the cited references, the ASME PTC 19.3 Committee recommends the following publications:

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Gibson, C. E., Tsai, B. K., and Parr, A. C. (1998). Radiance Temperature Calibrations (NIST Special Publication 250-43). U.S. Department of Commerce, National Institute of Standards and Technology.

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Section 2
Thermocouple Temperature Measurements

2-1 THERMOCOUPLES

2-1.1 Scope

The purpose of this Section is to guide the user in the selection, installation, and use of thermocouple thermometers and related instrumentation and accessories.

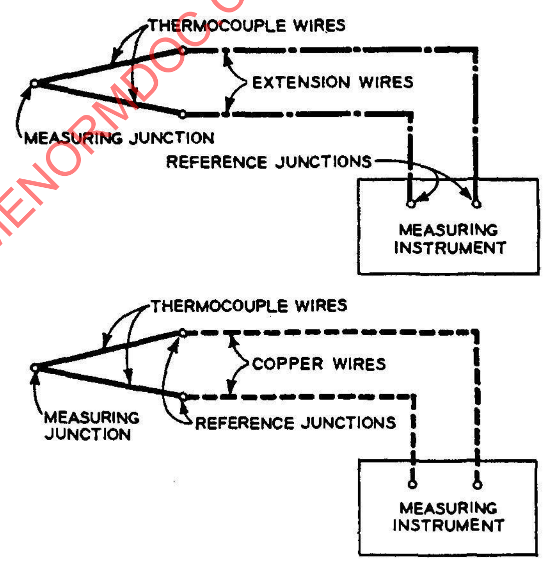
2-1.2 Definition

thermocouple thermometer: a temperature measurement system comprising a temperature-sensing element called a thermocouple that produces an electromotive force (emf), a device for measuring the emf, and electrical conductors for operatively connecting the two. The value of emf may be converted to an equivalent temperature reading by the measuring device or by subsequent manipulations of the data (see Figure 2-1.2-1).

A thermocouple is the temperature-sensing element of a thermocouple thermometer comprised of two dissimilar electrical conductors called thermoelements, electrically insulated from each other except where joined together to form junctions.

There are necessarily two types of junctions to each thermocouple corresponding to the two extremities of the thermoelements. The measuring junction is that which is subjected to the temperature to be measured. The reference junction is that which is at a known temperature.

Figure 2-1.2-1
Thermocouple Thermometer Systems



2-1.3 Principles of Operation

Thomas Johann Seebeck discovered in 1821 that an electric current will flow in a closed circuit of two dissimilar metals when the junctions of the metals are at dissimilar temperatures. The voltage that causes the current flow is termed the Seebeck voltage. The simplest thermocouple circuits have a measuring junction, at some unknown temperature, and two reference junctions at a known temperature, often 32°F (0°C). The Seebeck voltage created by the thermocouple can be related to the unknown temperature for a given reference junction temperature. There are two other thermoelectric phenomena that are of less practical concern for thermometry. The Peltier effect is the transfer of heat at thermocouple junctions when a current is passed through the thermocouple. The Thomson heat is an additional transfer of heat in a single conductor proportional to the current flowing through the conductor and proportional to the thermal gradient along the length of the conductor. In typical thermocouple circuits, the use of high impedance measuring devices ensures that very little current flows through the thermocouple, and the Peltier effect and Thomson heat are negligible. Thus, the thermoelectric motive force, or emf, of a thermocouple circuit is equal to the sum of the Seebeck voltages for the circuit, for all practical purposes.

The emf of a thermocouple is not produced at the junctions of dissimilar metals. Rather, each individual conductor, or thermoelement, in the thermocouple generates a voltage drop along its length. The voltage created along a short section of a thermoelement is proportional to the thermal gradient along that section of the thermoelement and proportional to the Seebeck coefficient. The total voltage across the thermoelement is the integral of the voltage produced by all the segments of wire between the two ends. When two thermoelements are combined into a thermocouple, the total emf produced by the thermocouple is equal to the difference in the emfs produced by the individual thermoelements. It can be shown mathematically that the emf of a thermocouple depends only on the temperatures of the measuring and reference junctions. Nonetheless, it is the section of the thermoelement that is passing through a large thermal gradient that produces most of the emf.

The emf generated by a single thermoelement with ends at two different temperatures is termed the absolute emf. Because measurement of the absolute emf is difficult, it is common practice to measure the emf of single thermoelements with respect to the emf generated by very high purity platinum.

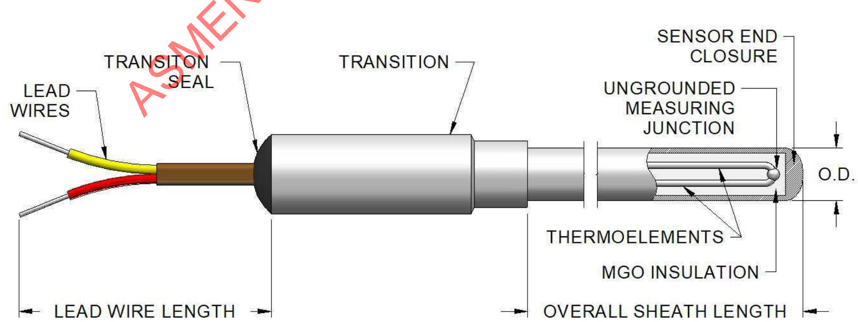
2-1.4 Thermocouple Construction and Terminology

Common thermocouple constructions are shown as Figures 2-1.4-1 through 2-1.4-3. Recommended upper temperature limits and specification information are set forth in Tables 2-1.4-1 and 2-1.4-2.

2-1.4.1 Measuring Junction. The measuring junction is the junction of a thermocouple that is subjected to the temperature to be measured (ASTM E344).

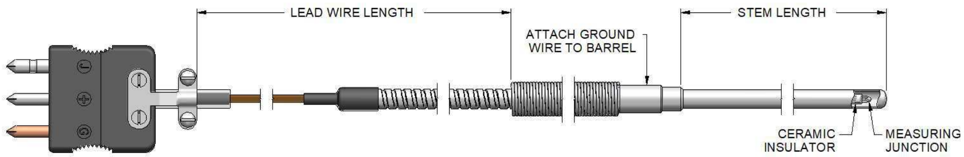
The method employed for making the junction between the thermoelements has no influence on the emf developed, provided that good electrical contact is attained. The most widely used method for making the junction is autogenous welding, in which the thermoelements are fused together by a torch or by electrical means without using any other material to form the junction. Various electrical welding methods are commonly used to fabricate thermocouple junctions, including capacitive discharge welding and tungsten-inert gas welding. Any method that gives good mechanical and electrical integrity of the junction is allowable. Welding methods using inert gas to purge the junction during joining do not require the use of flux, and this has the advantage that there is no possibility of contamination of the thermocouple by flux residues left after incomplete cleaning. Noble metals are commonly welded using a gas-oxygen torch and no flux. For torch

Figure 2-1.4-1
Typical Industrial Sheathed Thermocouple With Transition to Lead Wires



GENERAL NOTE: The figure supplied courtesy of JMS Southeast, Inc. (www.JMS-SE.com).

Figure 2-1.4-2
Hollow Tube Construction Thermocouple With Continuous Leads and Ground Wire



GENERAL NOTE: The figure supplied courtesy of JMS Southeast, Inc. (www.JMS-SE.com).

welding base metals, it is advantageous to use a flux, such as borax powder, to minimize oxidation. Care should be exercised in the application of heat to the ends of the thermoelements to avoid overheating, and all traces of flux should be removed after the welding process.

The thermocouple-measuring junction may be formed by twisting, soldering, or brazing with a material that is compatible with the thermoelements at the temperatures to be encountered in service. However, the best way to form a measuring junction is to weld the thermoelements together in an autogenous process that fuses the thermoelements without the addition of a third material. If solder or braze is used, care should be taken to prevent the solder or brazing material from running back from the junction. Traces of flux shall be removed as far as possible. Welding the measuring junction wires is recommended. Forming a measuring junction by soldering or brazing the wires together is not recommended.

Twisted junctions are usually found on older style beaded type thermocouples. The mechanical strength of the junction for a beaded thermocouple may be increased by twisting the wires together for a few turns at the junction end. The twist should be omitted whenever the thermocouple is to be used where a temperature gradient exists at the junction, because the thermocouple signal will average the temperature gradient over the length of the twist, weighted toward the end closest to the reference junction. A twisted wire may be thought of as a thermocouple with many parallel measuring junctions. The temperature measured by such a composite junction is an average of the temperatures of all points of electrical contact between the thermocouples, with appropriate weighting factors to account for differences in electrical resistance through different paths.

In measuring the temperature of a metal surface, it is often advantageous to attach the thermoelements separately to the metal so that the surface of the metal itself becomes the measuring junction. This may be done by spot welding or peening the wires to the metal. The points of attachment should be close enough together that there will be no significant difference in temperature between them.

2-1.4.2 Reference Junction. Modern instrumentation now routinely provides for reference junction compensation without the need to create a stable point of temperature reference, such as an ice bath. The use of ice baths in thermocouple measurements is now almost exclusively confined to troubleshooting and very high-accuracy test quality applications and laboratory calibrations (see Figure 2-1.4.2-1). The use and construction of an ice bath is discussed in Section 6 and set out in great detail in ASTM E563.

When it is inconvenient to use an ice bath but a reference junction external to the instrumentation remains desirable, a thermally insulated block of copper, aluminum, or silver or a stirred liquid bath may be substituted. In such cases, the temperature of the reference junctions must be measured with an auxiliary instrument and taken into proper account.

Frequently, some accuracy is sacrificed for convenience by eliminating the constant temperature reference junction in favor of automatic reference junction compensation built into an instrument used to measure the emf developed by the thermocouple. Automatic reference junction controls, external from the emf-measuring instrument are readily available. These provide either the ice point temperature or various elevated temperatures, usually within 0.5°F (0.28°C).

2-1.4.3 Lead Wires. Lead wires are any pairs of electrical conductors that connect the thermocouple to the emf-measuring device, such as a meter, transmitter, controller, or thermocouple card.

When the reference junction is maintained external to the measuring device, then the lead wires must be homogenous and of identical composition. Copper is most commonly used as lead wire material when the reference junctions of the thermocouple are maintained at some fixed temperature, such as an ice bath, 32°F (0°C) (see Figure 2-1.4.2-1).

When the reference junction is maintained internal to the measuring device, then the lead wires must be homogenous and match the material of the thermocouple thermoelements.

Thermocouple lead wires and extension wire that are supplied in insulated form are generally color coded, according to various standards. International color codes differ substantially from the standard in the United States.

Figure 2-1.4-3
Ungrounded Thermocouple With No Housing or Transition

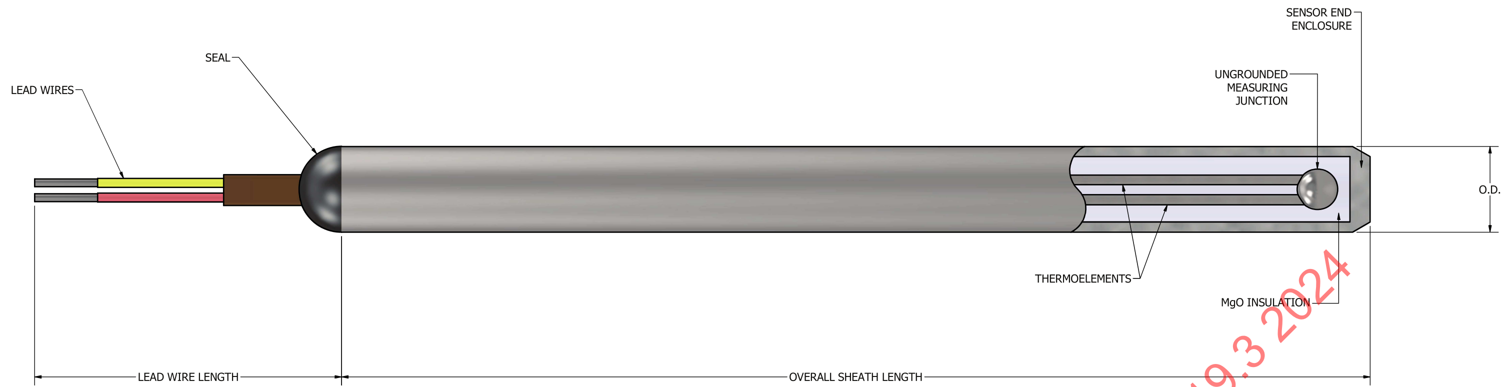


Table 2-1.4-1
Specification Information by Thermocouple Calibration Type

ANSI CODE & Ext Grade Jacket Color	CONDUCTOR COMBINATION		COLOR CODING		MAXIMUM USEFUL TEMPERATURE RANGE *		MAXIMUM THERMOCOUPLE GRADE TEMPERATURE	EMF (mV) OVER MAXIMUM TEMP RANGE	STANDARD LIMITS OF ERROR (ABOVE 0°C)	SPECIAL LIMITS OF ERROR (ABOVE 0°C)	INTERNATIONAL CODE IEC 584-3	IEC CODE
	+ LEAD	- LEAD	THERMOCOUPLE GRADE	EXTENSION GRADE	THERMOCOUPLE GRADE	EXTENSION GRADE						
J	IRON Fe (magnetic)	CONSTANTAN COPPER-NICKEL Cu-Ni	White + red -	White + red -	32 to 1400°F 0 to 760°C	32 to 400°F 0 to 200°C	-346 to 2192°F -210 to 1200°C	-8.095 to 69.553	greater of 2.2°C or 0.75%	greater of 1.1°C or 0.4%	black + white -	J
K	CHROMEL NICKEL-CHROMIUM Ni-Cr	ALUMEL NICKEL-ALUMINUM Ni-Al (magnetic)	Yellow + red -	Yellow + red -	32 to 2300°F 0 to 1260°C	32 to 400°F 0 to 200°C	-454 to 2500°F -270 to 1372°C	-6.458 to 54.886	greater of 2.2°C or 0.75%	greater of 1.1°C or 0.4%	green + white -	K
T	COPPER Cu	CONSTANTAN COPPER-NICKEL Cu-Ni	blue + red -	blue + red -	32 to 700°F 0 to 370°C	-75 to 200°F -60 to 100°C	-454 to 752°F -270 to 400°C	-6.258 to 20.872	greater of 1.0°C or 0.75%	greater of 0.5°C or 0.4%	brown + white -	T
E	CHROMEL NICKEL-CHROMIUM Ni-Cr	CONSTANTAN COPPER-NICKEL Cu-Ni	purple + red -	purple + red -	32 to 1600°F 0 to 870°C	32 to 400°F 0 to 200°C	-454 to 1832°F -270 to 1000°C	-9.835 to 76.373	greater of 1.7°C or 0.5%	greater of 1.0°C or 0.4%	violet + white -	E
N	NICROSIL Ni-Cr-Si	NISIL Ni-Si-Mg	Orange + red -	Orange + red -	32 to 2300°F 0 to 1260°C	32 to 400°F 0 to 200°C	-454 to 2372°F -270 to 1300°C	-4.345 to 47.513	greater of 2.2°C or 0.75%	greater of 1.1°C or 0.4%	pink + white -	N
R	PLATINUM- 13% RHODIUM Pt-13% Rh	PLATINUM Pt	NONE ESTABLISHED	black + red -	32 to 2700°F 0 to 1480°C	32 to 400°F 0 to 200°C	-58 to 3214°F -50 to 1768°C	-0.226 to 21.101	greater of 1.5°C or 0.25%	greater of 0.6°C or 0.1%	Orange + white -	R
S	PLATINUM- 10% RHODIUM Pt-10% Rh	PLATINUM Pt	NONE ESTABLISHED	black + red -	32 to 2700°F 0 to 1480°C	32 to 400°F 0 to 200°C	-58 to 3214°F -50 to 1768°C	-0.236 to 18.693	greater of 1.5°C or 0.25%	greater of 0.6°C or 0.1%	Orange + white -	S
B	PLATINUM- 30% RHODIUM Pt-30% Rh	PLATINUM- 6% RHODIUM Pt-6% Rh	NONE ESTABLISHED	gray + red -	1600 to 3100°F 870 to 1700°C	32 to 200°F 0 to 100°C	32 to 3308°F 0 to 1820°C	0.000 to 13.820	0.50%	0.25%	gray + white -	B
C	TUNGSTEN- 5% RHENIUM W-5% Re	TUNGSTEN- 26% RHENIUM W-26% Re	NONE ESTABLISHED	White + red -	32 to 4200°F 0 to 2315°C	32 to 400°F 0 to 200°C	32 to 4200°F 0 to 2315°C	0.000 to 37.070	greater of 4.4°C or 1.0%	N/A	red + white -	C

*EXCEPT AS RESTRICTED BY CONDUCTOR SIZE AND INSULATION PER ASTM VOLUME 14.03 AND OTHER APPLICABLE STANDARDS

GENERAL NOTE: The table supplied courtesy of JMS Southeast, Inc. (www.JMS-SE.com).

Table 2-1.4-2
Recommended Upper Temperature Limits for Protected Thermocouples by Wire Size

	Recommended Upper Temperature Limits, °F (°C)					
Thermocouple Type	8 AWG	14 AWG	20 AWG	24 AWG	28 AWG	30 AWG
T	N/A	700 (300)	500 (260)	400 (200)	400 (200)	300 (150)
J	1,400 (760)	1,100 (590)	900 (480)	700 (370)	700 (370)	600 (320)
E	1,600 (870)	1,200 (650)	1,000 (540)	800 (430)	800 (430)	700 (370)
K, N	2,300 (1 260)	2,000 (1 090)	1,800 (980)	1,600 (870)	1,600 (870)	1,400 (760)
R, S	N/A	N/A	N/A	2,700 (1 480)	N/A	N/A
B	N/A	N/A	N/A	3,100 (1 700)	N/A	N/A
C	N/A	N/A	N/A	4,200 (2 315)	N/A	N/A

Figure 2-1.4.2-1
Laboratory Thermocouple With "T" Stem Reference Junction

GENERAL NOTE: The figure supplied courtesy of JMS Southeast, Inc. (www.JMS-SE.com).

2-1.4.4 Thermocouple Transition. Thermocouple transition is the point in a sheathed thermocouple where the magnesium oxide (MgO)-insulated wires are connected and secured to lead wires of like material (see Figure 2-1.4-1). Hollow tube constructions are not typically as rugged as MgO constructions but can be constructed so that the lead wire is one and the same as the wire inside the stem (see Figure 2-1.4-2). Sheathed constructions can also be constructed so that the thermoelements extend continuously for a short distance. This is typically the manner of construction for a thermocouple with a weather head (see Figure 2-1.4-3).

2-1.4.5 Transition Seal. Transition seal serves the function of keeping moisture out of the MgO insulation, which will cause the thermocouple to short circuit and lose accuracy if allowed ingress into the sheath material.

2-1.4.6 Insulation. Insulation must electrically isolate the thermocouple wires at all points other than the measuring junction. Various refractory materials, such as porcelain, alumina, and magnesia in the form of beads, tubes, and powder encased in metallic sheaths, serve as a means of insulating and supporting the thermoelements internal to the thermocouple stem.

The preferred insulation internal to sheathed base metal thermocouples is mineral material such as MgO and aluminum oxide (Al_2O_3) conforming to ASTM E585/E585M, ASTM E1652, and ASTM E2181/E2181M.

Mineral insulated metal sheathed (MIMS) thermocouples are thermocouples that have been swaged inside an outer metal sheath with crushable mineral insulation separating the two thermoelements from each other and the sheath. This construction protects thermoelements from the environment outside the sheath, allowing the use of thermocouples in highly corrosive or oxidizing environments. MIMS thermocouples are available in very small diameters. Because the compaction of the crushable insulator (usually MgO) prevents the transport of alloy components of the thermocouples and the sheath prevents the intrusion of oxygen, MIMS thermocouples of small diameter can often be used at temperatures greatly in excess of the recommended upper temperature limits for similarly sized bare wire thermocouples. At high temperatures, the choice of sheath material is an important factor in the lifetime and thermoelectric stability of the thermocouple. Special care is taken to prevent the intrusion of moisture into the cold end of the thermocouple.

MIMS thermocouples may be fabricated with the following:

(a) exposed junctions in which the sheath and insulator are removed around the vicinity of the measuring junction

(b) grounded junctions, in which the measuring junction is integral with the tip of the sheath

(c) ungrounded junctions, in which the junction is inside the sheath and also insulated from the sheath

Exposed junctions have the quickest time response but are susceptible to adsorption of water by the crushed insulation. Grounded junctions are not susceptible to water intrusion and have the second quickest time response, but grounding of the junction may complicate the electrical measurement of the thermocouple emf. Ungrounded junctions have the slowest time response but are most flexible from an instrumentation standpoint.

MIMS thermocouples may incorporate bends in their construction. Swaged MIMS material have been observed to work successfully in service with bend radii that do not exceed two times the sheath outside diameter.

Fiberglass, rubber, fabrics, enamels, vitreous silica, ceramic fibers, and various plastics are commonly used to insulate the lead wires, and the insulation is selected based on the anticipated environment to which these insulation materials will be exposed. In lower temperature applications, these materials may also be used as thermocouple insulations internal to the probe stem, although they are not as rugged or durable as thermocouples manufactured from sheath material. The thermocouple, extension, and connecting wires should be maintained dry over their entire length as moisture can create shorts in the thermocouple circuit.

2-1.4.7 Thermocouple Extension Wires. Thermocouple extension wires are used when the thermocouple sensor is located too far from the measuring device to be directly connected. Thermocouple extension wire extends the thermocouple from the weather head or sensor connector to the instrument receiving the signal. For this reason, it is necessary to match thermocouple extension wires to the type of thermocouple and make sure to match positive and negative legs properly. Thermocouple extension wire accuracies are governed by ASTM E230/E230, Table 2, and IEC 60584-3.

For the purposes of each standard, these extension wire tolerance classifications match the underlying thermocouple tolerances (special limits and standard for ASTM; Classes 1 and 2 for IEC). However, extension wire tolerances are held over a narrower temperature range than the thermocouple itself. For example, extension wire ASTM tolerances for thermocouple Types J, K, N, and E extend from 32°F to 400°F (0°C to 200°C) and −75°F to 200°F (−60°C to 100°C) for Type T. Where operation outside these temperature ranges at specific accuracies must be met, the purchase order shall so state (see Table 2-1.4-1).

Because of the high cost of platinum and platinum rhodium alloys, substitute materials are generally used as compensating extension wire for thermocouples made from these metals. A specially matched pair of conductors, consisting of a copper wire and a nickel copper alloy wire, has found general use as compensating extension wires for the platinum versus platinum rhodium thermocouples (Types R and S) over the temperature range 32°F to +400°F (0°C to +200°C). The copper wire is joined to the platinum rhodium thermoelement and the copper-nickel alloy wire to the platinum thermoelement. These wires do not match the individual thermoelements, but when used together, they compensate reasonably well over the range specified above. For Types R and S thermocouples, the junction between the platinum thermoelement and negative extension wire must be maintained at the same temperature as the junction between the platinum-rhodium thermoelement and positive extension wire.

Special compensating extension wire is often not necessary for Type B thermocouples. Due to the very low emf of Type B thermoelements at low temperatures, copper wire may be used as compensating extension wire over a range from 32°F to +120°F (0°C to +50°C) without introduction of any significant error. Over the range 32°F to +212°F (0°C to +100°C), the error associated with the use of copper as compensating extension wire will not exceed the tolerance of the thermocouple itself when used above 1,800°F (1 000°C).

When using thermocouple extension wires, the electrical environment in which the wire is installed should also be considered, as electrical noise can cause the thermocouple signal to experience error. For guidance regarding best practices as to electrical shielding, please refer to para. 2-5.4.

2-1.4.8 Thermowells and Protection Tubes. Thermowells and protection tubes protect the temperature sensor and enable its removal and replacement without need to open the process. Thermowells are made of metal and turned and drilled from bar stock or forged material (see ASME PTC 19.3 TW, subsection 1-2). By contrast, protection tubes are fabricated from metal pipe, ceramic tubing, or other materials and are outside the scope of ASME PTC 19.3 TW.

Thermowells and metal protection tubes are usually fabricated of austentic stainless steel, a high nickel material for temperature or corrosion resistance, or the material of the pipe if the thermowell is to be installed by welding. Thermocouple protection tubes for use in molten metals, furnace atmospheres, salt baths, and chemical processes are often constructed from high-performance silicon carbides or silicon nitride material to better withstand the particular conditions and hazards prevailing in those installations.

Although most of the metals and alloys used as thermoelements exhibit a relatively high degree of mechanical stability, most of them are subject to change in calibration when exposed to contaminating and corrosive conditions. Protection tubes that are impervious to such conditions are therefore required if high accuracy and long life are required. Platinum versus platinum-rhodium thermocouples are particularly susceptible to contamination and should be protected by high-purity alumina protection tubes that are impervious to gases and vapors at temperatures within the working range. To provide additional mechanical strength, a refractory metal tube is often placed over the ceramic tube (ASTM MNL 12).

2-1.4.9 Switches and Terminal Blocks. All switches used with thermocouples should be designed so that both wires are switched when switching from one thermocouple to the next, such that thermocouples not in use are entirely disconnected from the measuring instrument. The switches should be located so as not to be subjected to temperature fluctuations due to air currents or radiation from hot sources. Terminal blocks and panels should be protected similarly from rapid or large temperature fluctuations. It is recommended that wherever practical, all plugs, connectors, terminal studs, and jacks be of thermocouple materials matching the wires connected to such connectors. Electrical relays may contribute stray thermal emf that can cause a significant error for high-accuracy thermometry.

2-1.5 Thermocouple Element Materials

Common thermocouple materials are available for use within the approximate limits of −300°F to 4,200°F (−184°C to 2 315°C). Of the vast number of possible combinations of metals and alloys, only a limited number are in actual use in thermocouple thermometry. These few thermocouple element materials have been chosen on the basis of such factors as mechanical and chemical properties, melting point, thermoelectric properties, reproducibility, and cost. No single thermocouple meets all requirements, but each possesses characteristics desirable for selected applications.

There are nine thermocouples that have official ASTM- and IEC-accepted letter designations: types B, C, E, J, K, N, R, S, and T (ASTM E230/E230M, IEC-60584-1). In addition to those nine types, the IEC also recognizes the Type A thermocouple (ASTM E230/E230M, IEC-60584-1).

Other thermocouples may have colloquial letter designations, but these designations may not be defined by an accepted standard. Each type of thermocouple is defined by its emf versus temperature relationship with reference to a nominal material composition. Such an emf versus temperature relationship is termed a reference function. For the letter-designated types listed above, the reference functions are identical throughout the world. Manufacturers may alter the composition of the thermoelements slightly either to improve such properties as the oxidation resistance or thermoelectric stability, or to better match the reference function. Provided that a thermocouple matches a reference function within a stated tolerance for a particular thermocouple type, that thermocouple is that type, by definition. Reference functions are also published for a variety of thermocouples that do not have letter designations.

Thermocouples are provided by manufacturers to meet certain specified tolerances. Tolerances for the matching of thermocouples to reference functions are equal to the maximum allowable deviation of the emf of a particular thermocouple from the reference function emf, at a particular temperature, at the time of first heating. This tolerance includes no allowance for aging or drift of the thermocouple. Furthermore, the existence of a reference function and a tolerance up to a certain high temperature do not guarantee that a thermocouple will provide adequate performance at that temperature.

Thermocouple thermoelement materials are often separated into three categories: base metal, noble metal, and refractory metal.

2-1.5.1 Base Metal Thermocouples. The following describe various base metal thermocouple types.

(a) Type E (90% Nickel–10% Chromium/Constantan; Constantan Is an Alloy of Approximately 55% Copper and 45% Nickel). This combination of thermoelements develops the highest thermoelectric output of any of the conventional thermocouples, namely, about 34 μV/°F at normal ambient temperature and increasing to about 45 μV/°F at 1,000°F. This high output has led to the use of Type E thermoelements as sensing elements in thermopiles for radiation detection and in differential thermocouple systems. The thermocouple has also found general application for temperature measurements up to about 1,400°F (760°C). The EP thermoelement, of the same nominal composition as the KP thermoelement, is subject to the same short-range ordering effect. At temperatures below 850°F (455°C), Type E thermocouples have good long-term stability. The high sensitivity, low thermal conductivity, and resistance to corrosion make Type E thermocouples a good choice for many low-temperature applications.

(b) Type J (Iron/Constantan). This thermocouple is widely used in industrial thermometry, partly because of its low cost. Above 1,400°F (760°C), Type J thermocouples may deviate significantly from the reference function because of variations in magnetic properties. The iron thermoelement is subject to both oxidation and corrosion. It is generally limited to the temperature range 32°F to 1,400°F (0°C to 760°C) but may be used up to 1,800°F (980°C) at a sacrifice of life. For the higher temperatures, wire sizes of number 8 gauge or larger are generally employed. For temperatures up to 1,400°F (760°C), Type J thermocouples show good calibration stability in nonoxidizing atmospheres. Above 1,400°F (760°C), Type J thermocouples may deviate significantly from the reference function because of variations in magnetic properties. The iron thermoelement is subject to both oxidation and corrosion.

(c) Type K (90% Nickel–10% Chromium/94% Nickel–3% Manganese-2% Aluminum–1% Silicon). This thermocouple, usable over the temperature range 32°F to 2,300°F (0°C to 1 260°C), and higher for short time intervals, is resistant to oxidation to high temperatures. An ordering transition in the molecular structure of the KP thermoelement limits the accuracy of this type of thermocouple at temperatures above 392°F (200°C), unless special annealing procedures are used in wire manufacturing or preparation. In standard wire, exposure to temperatures above approximately 750°F (400°C) will cause an upwards shift in the thermocouple emf over a short period of use equivalent to as much as 7.2°F (4°C), as a consequence of the ordering effect. It must be protected against reducing atmosphere. Alternate oxidizing and reducing atmospheres are particularly destructive. Both thermoelements are mechanically strong and often directly exposed to the temperature environment.

(d) Type N (84% Nickel–14% Chromium–1.5% Silicon/95% Nickel–4.5% Silicon–1% Magnesium). Type N thermocouples are similar to Type K thermocouples but with changes in alloy composition to reduce the effects of ordering transitions and increase the oxidation resistance of bare wire thermocouples, relative to the performance of Type K thermocouples. The ordering effect in Type N thermocouples occurs at a higher temperature than in Type K thermocouples and has a magnitude approximately half as large. In reducing or vacuum environments, Type N thermocouples are superior in performance to Type K thermocouples.

(e) Type T (Copper/Constantan). The Type T thermocouple is widely used in industrial and laboratory applications over the temperature range −328°F to +700°F (−200°C to 370°C). Type T thermocouples are subject to oxidation at temperatures above approximately 392°F (200°C) and corrosion of the copper leg in low-temperature use if water can condense on the wires. The homogeneity of the thermoelements makes this type especially useful for precision measurements near room temperature. Thermocouple materials are normally supplied to meet temperatures above 32°F (0°C). The same materials may not fall within tolerances below 32°F (0°C). If materials are required to meet tolerances stated for temperatures below 32°F (0°C), the purchase order shall so state, as selection of materials will usually be required.

Practically all base metal thermocouple wire and base metal thermocouple sheath material are annealed or given a "stabilizing heat treatment" by the manufacturer. Such treatment is generally considered sufficient, and seldom is it advisable to further anneal the wire before testing. If a specific annealing process is required, it should be agreed on and specifically stated in the purchase order.

For example, special limits of error Type K sheathed thermocouple [standard wall thickness $\frac{1}{4}$ in. (6 mm) diameter] may be annealed at 1,700°F to 1,875°F (925°C to 1 025°C) for a minimum soak time of 30 min per inch with a minimum of 1.5 hr. These figures are estimated, and sheath/conductor metallurgies/gauge/thickness should all be considered to achieve ideal temperatures and soak times.

General requirements may be found in, but are not limited to, those in ASME BPVC, Section II; ASTM A312/A312M and ASTM A484/A484M contain annealing temperatures by material for stainless steel pipe, bars, billets, and forgings. Since thermocouples and RTDs can be customized to suit the application, it is recommended to consider all materials in an assembly (sheath, wire, etc.) to ensure that the chosen temperature is not damaging any component. The portion of the thermocouple that is annealed should include all areas of the thermocouple probe that are exposed to any temperature gradient.

2-1.5.2 Noble Metal Thermocouples

(a) Type S (Platinum–10% Rhodium Versus Platinum). This thermocouple is commonly used for high-accuracy measurements from 32°F to 2,700°F (0°C to 1 480°C) and characterized by a high degree of chemical inertness and stability at high temperatures in oxidizing atmospheres. Both thermoelement materials are ductile and can be drawn into fine wires. The thermocouple is widely used in industrial laboratories as a standard for the calibration of base metal thermocouples and other temperature-sensing instruments.

(b) Type R (Platinum–13% Rhodium Versus Platinum). This thermocouple is similar in general characteristics to the Type S thermocouple. It produces a slightly greater emf for a given temperature.

(c) Type B (Platinum–30% Rhodium Versus Platinum–6% Rhodium). This combination of platinum–rhodium alloys is commonly used over the temperature range 1,600°F to 3,100°F (870°C to 1 700°C). This thermocouple is affected by chemical contamination somewhat less than the conventional platinum versus platinum–rhodium alloy thermocouples,

and it possesses slightly greater mechanical strength. Type B thermocouples are more vulnerable to reversible effects of preferential rhodium oxidation than either Type S or Type R thermocouples, especially at temperatures between approximately 1,200°F to 1,750°F (650°C to 950°C). The Seebeck coefficient of Type B thermocouples goes to zero at 70°F (21°C), which allows the use of pure copper wires as extension wires but which severely limits the accuracy of temperature measurements below approximately 1,600°F (870°C).

2-1.5.3 Refractory Metal Thermocouples

(a) Type C (Tungsten–5% Rhenium/Tungsten–26% Rhenium). Having a range from 32°F to 4,200°F (0°C to 2 315°C), Type C thermocouples maintain a tolerance of the greater of ±7.92°F (±4.4°C) or 1%, whichever is greater. These thermocouples should be used in a vacuum, in inert atmosphere, or in dry hydrogen.

(b) Type A (Tungsten–5% Rhenium/Tungsten–26% Rhenium). Having a range from 1,832°F to 4,532°F (1 000°C to 2 500°C), Type A thermocouples maintain a tolerance of 1%. These thermocouples should be used in a vacuum, in inert atmosphere, or in dry hydrogen.

2-1.5.4 Miscellaneous Special Purpose Thermocouples. Combinations of metals other than those listed above are sometimes used for special purposes. These include nickel–chromium versus stainless steel, nickel versus nickel–molybdenum, and platinum–rhodium versus gold–palladium. Each has advantages for particular applications.

Pure element thermocouples (gold versus platinum or platinum versus palladium) have excellent homogeneity and stability compared to platinum-rhodium alloy thermocouples. With appropriate care in fabrication and in emf measurement, gold versus platinum thermocouples can have uncertainties less than 0.018°F (0.01°C) for temperatures below 1,769°F (965°C). Such thermocouples should be considered for applications requiring the highest accuracy attainable.

2-1.6 Thermocouple Characteristics

Proper use and selection of a thermocouple require understanding some basic thermocouple characteristics, such as range, accuracy, sources of drift, precision, sensitivity, and responsiveness.

2-1.6.1 Range. The upper temperature limits for the various thermocouples depend on the wire sizes, environment in which the thermocouples are used, and way they are constructed or protected from the environment. Table 2-1.4-2 lists the recommended upper temperature limits for beaded thermocouples protected from corrosive or contaminating atmospheres. The ranges of applicability and limits of error for thermocouples and extension wires of standard sizes are given in Table 2-1.4-1. The corresponding values of temperature and emf for the various types of thermocouples are given in Table 2-1.6.1-1. See ASTM E230/E230M for expanded reference tables of these thermocouples, emf versus temperature, and temperature versus emf in both degrees Celsius and degrees Fahrenheit.

2-1.6.2 Accuracy. The accuracy of a temperature measurement with a thermocouple is limited by

(a) the initial manufacturing tolerance or the uncertainty of calibration of the thermocouple wire

(b) the accuracy of emf measurements

(c) changes in the thermoelectric properties of the thermocouple with use

Tolerances are shown in Table 2-1.4-1 (ASTM E230/E230M). As a rule of thumb, thermocouple wires can be calibrated to uncertainties of approximately one-fourth of the standard manufacturing tolerances. At temperatures below 392°F (200°C), the calibration uncertainty is limited only by the inhomogeneity of the thermoelements, and substantially better accuracy is possible in demanding applications. The uncertainty of emf measurements need not be a major component in the overall uncertainty of temperature measurements; voltmeters and indicators are available with sufficient accuracy for virtually all applications. At temperatures much above 392°F (200°C), changes in the thermoelectric properties of the thermocouple with use are often the most important factor in the long-term accuracy of thermocouple temperature measurements.

2-1.6.3 Sources of Thermocouple Inhomogeneity and Drift. Because it is the portion of the thermoelement that is located in a thermal gradient that produces the emf of the thermocouple, the value of emf will depend primarily on the thermoelectric properties of the wire in the region where the thermocouples are exposed to large thermal gradients. Often the length of this region is quite short relative to the overall length of the thermocouple. If the thermocouple is inhomogeneous, the emf produced by the thermocouple will depend not only on the temperature of the measuring junction but also on the details of the thermal profile along the length of the thermocouple. Consequently, an inhomogeneous thermocouple cannot be removed from one apparatus and reliably calibrated in another apparatus.

Thermocouple wire now being produced is usually sufficiently homogeneous in chemical composition for most purposes. Occasionally, inhomogeneity in a thermocouple may be traced to the manufacturer, but such cases are rare. More often it is introduced in the wires during test or use. It usually is not necessary, therefore, to examine new thermocouples for inhomogeneity, but thermocouples that have been used for some time should be examined

Table 2-1.6.1-1
Temperature emf Relationship for Base Metal and Noble Metal Thermocouples

Temperature, °F	S (Pt–10Rh vs. Pt), emf-mV	R (Pt–13Rh vs. Pt), emf-mV	B (Pt–30Rh vs. Pt), emf-mV	K (Cr vs. Alomel), emf-mV	J (Iron vs. Constantan), emf-mV	E (Cr vs. Constantan), emf-mV	T (Cu vs. Constantan), emf-mV
32	0.000	0.000	0.00	0.00	0.00	0.00	0.000
200	0.595	0.596	0.02	3.82	4.91	5.87	3.967
400	1.474	1.504	0.018	8.31	11.03	13.75	9.525
600	2.458	2.547	0.47	12.86	17.18	22.25	15.773
700	...	...	...	...	...	...	19.100
800	3.506	3.677	0.89	17.53	23.32	31.09	...
1,000	4.596	4.868	1.43	22.26	29.52	40.06	...
1,200	5.726	6.125	2.09	26.98	36.01	49.04	...
1,400	6.897	7.436	2.85	31.65	42.96	57.92	...
1,600	8.110	8.809	3.72	36.19	...	...	...
1,800	9.365	10.237	4.68	40.62	...	...	...
2,000	10.662	11.726	5.72	44.91	...	...	...
2,200	11.989	13.255	6.84	49.05	...	...	...
2,400	13.325	14.798	8.03	53.01	...	...	...
2,600	14.656	16.340	9.28	...	...	...	...
2,800	15.979	17.875	10.56	...	...	...	...
3,000	17.292	19.394	11.85	...	...	...	...
3,300	...	...	13.84	...	...	...	...

for signs of contamination before an accurate calibration is attempted. Thermoelements exposed to high temperatures will undergo various physical or chemical changes that will alter the thermoelectric properties in the portion of the wire that has been heated. As a result, the thermoelements become inhomogeneous, with the heated portion having different thermoelectric properties than the portion of the wire that has not been heated.

There are unavoidable variations in thermoelectric properties caused either by compositional variations in the wire alloy along its length or by variations in the annealing state along its length. In the best circumstances, the fractional uncertainty of measuring a temperature interval is approximately the following:

Temperature Interval	Fractional Uncertainty
Base metal	10^{-3}
Pt–Rh alloy	10^{-4}
Au/Pt or the best Pt/Pd	10^{-5}

This level of performance requires careful manufacture of the thermocouple wires and careful use.

Preferential oxidation describes the process in which an alloy is exposed to oxygen and one component of the alloy oxidizes more rapidly than the other components. The net result is to shift the composition of the alloy and alter the thermoelectric properties of the thermocouple. The magnitude of this effect can be many degrees. This effect is only important if the thermocouple is exposed to temperatures sufficiently high to cause oxidation.

Preferential sublimation describes the process in which one component of an alloy sublimates from the thermoelement surface more rapidly than the other components. This effect is most important for bare thermocouple wires in a vacuum environment at high temperatures. Mounting the wire in continuous lengths of insulator tubing inhibits mass transport away from the thermoelement and slows this effect.

Chemical contamination can cause substantial shifts in thermocouple homogeneity. Pure element thermoelements are especially sensitive to contamination. This is one reason why Type B thermocouples (Pt-30% Rh versus Pt-6% Rh) give less drift at high temperatures above 2,372°F (1 300°C) than Type S or Type R thermocouples. All thermocouples will give the best performance when the thermoelements are mounted in single lengths of high purity insulators, especially in the regions of maximum thermal gradient.

Certain alloys may have temperature-dependent variations in the magnetic or molecular structure of the alloy. This effect is reversible, depending on the thermal history of the thermocouple. The magnitude of this effect can be as high as approximately 0.36°F (0.2°C) for noble metal thermocouples or approximately 7.2°F (4°C) for base metal thermocouples (especially Type K). This effect can be substantially reduced in base metal thermocouples and nearly eliminated in noble metal thermocouples with suitable annealing. Thermocouples used below approximately 392°F (200°C) have minimal structural change with use.

While rather simple methods are available for detecting thermoelectric inhomogeneity, no satisfactory method has been devised for quantitatively determining it or the resulting errors in the measurement of temperatures. Abrupt changes in the thermoelectric power may be detected by connecting the two ends of the wire to a sensitive voltmeter and slowly moving a source of heat, such as a hot air gun or a small electric furnace, along the wire. This method is not satisfactory for detecting gradual changes in the Seebeck coefficient along the length of the wire. Inhomogeneity of this nature may be detected by calibrating samples of wire taken from a longer length of wire or by doubling the wire and inserting it into a Dewar filled with liquid nitrogen.

All thermocouples show a gradual drift in calibration with operating service, as a consequence of the effects described above. Drift is a function of the exposure time to high temperatures. Drift can be calculated as set forth in ASTM E601 and tested as set out in ASTM E839. A calibration of a thermocouple is valid indefinitely as long as it is stored in a laboratory environment at room temperature. Small diameter thermoelements [less than 0.010 in. (0.254 mm) diameter] are particularly susceptible to change in calibration when used near their upper temperature limit.

2-1.6.4 Sensitivity. The sensitivity of a thermocouple, i.e., dE/dT, varies somewhat with temperature. Table 2-1.6.1-1 lists the average thermoelectric power for the conventional thermocouples.

2-1.6.5 Precision. The precision of measurement attainable with thermocouples depends on the equipment used to measure the emf and the experimental techniques employed. With moderate care and good quality laboratory equipment, emf measurements may be made with a precision and repeatability of 1 μV. With high-quality equipment and attention to all sources of stray thermal emf, precision and short-term repeatability of a measurement of 0.1 μV is possible. At high temperatures, drift of most types of thermocouples will result in accuracies substantially poorer than the precision of the measurements.

2-1.6.6 Response. The time response of a thermocouple to a temperature change is a function of the mass and geometry of the sensing junction and the mode or modes of heat transfer between the junction and its surroundings. The greater the surface area to mass ratio of the junction, the greater will be the speed of response for a given heat transfer condition. When a thermocouple is encased in a thermowell or protecting sheath, the response indicated by the probe will be slower than when directly immersed into the process, as the response is governed by the combined effects of heat transfer from the medium to the well and that of the well to the enclosed junction. A response for purposes of thermocouple thermometry is typically considered to have occurred when the sensor indicates a change equal to 63.2% of the step induced.

2-2 THERMOCOUPLE ACCESSORIES

The minor accessories used in conjunction with thermocouples, such as protection tubes, extension wires, switches, and terminal blocks, have been discussed earlier in this Section.

A detailed discussion covering instrumentation employed to measure and record the emf signals from thermocouples is given in subsection 2-5.

2-3 APPLICATION AND INSTALLATION

2-3.1 Sources of Error

The emf generated by a thermocouple depends on the temperature of both the measuring and reference junctions. Consequently, the temperature of the reference junctions must be known. Temperature emf tables for thermocouples are usually based on a reference junction temperature of 32°F (0°C) (ice point). It is not necessary to maintain the reference junction temperature, during use, the same as during calibration, provided that the necessary mathematical corrections are made to the data.

The elements of a thermocouple must be electrically insulated from each other, from ground and conductors on which they may be mounted, except at the measuring junction. When a thermocouple is mounted along a conductor, such as a pipe or a metal structure, special care should be exercised to ensure good electrical insulation between the thermocouple wires and conductor to prevent stray currents in the conductor from entering the thermocouple circuit and vitiating the readings.

Junctions in thermocouple wires or the use of extension wires is an extreme case of variations in wire composition. The mismatch of extension wire to thermocouple wire is particularly poor for Type S and Type R thermocouples and for W-Re alloy thermocouples. An extension wire will only generate emf if its two ends are at different temperatures; any extension wire whose ends are at the same temperature will not introduce any error in the measurement. Most applications do, at a minimum, see a temperature variance intermittently between the point of connection to the thermocouple and the point at which the extension wires are connected to the instrument receiving the thermocouple signal. For this reason, users of this Standard should always run matching thermocouple grade or extension grade wire from the thermocouple to the instrument receiving the signal.

Inasmuch as the curves giving the relation between emf and temperature are not, in general, linear, equal increments of temperature do not correspond to equal increments of emf. This should be particularly observed in applying reference junction corrections. Many commercial instruments used in conjunction with thermocouples are provided with either manual or automatic means for compensating for deviations of the reference junction temperature from that on which standard calibrations are based.

In the event the emf-measuring instrument has automatic reference junction compensation, the thermocouple itself or thermocouple extension wires should extend directly to the instrument, and an ice point should not be used.

2-3.2 Essential Considerations

Regardless of the type of thermocouple or the techniques employed in carrying out the measurements, there are certain basic factors that must be considered. The primary consideration is that the temperature indicated by a thermocouple is that of the measuring junction. The accuracy obtained in measuring the temperature of any object or space usually depends on how closely the measuring junction of the thermocouple can be brought to the temperature of the object or space, or to some temperature that is related to that of the object or space.

A small size thermocouple-measuring junction suitably imbedded in a solid or immersed in a liquid will attain equality in temperature with the substance and will, therefore, indicate the true temperature of the solid or liquid to within the calibration accuracy of the instrument. However, in many applications, this may not be the case. If under steady conditions there is a net exchange of heat between the thermocouple junction and substance, then a difference in temperature will exist between the two. The magnitude of this difference in temperature depends on the rate of heat transfer and the thermal resistance between the junction and substance. As an illustration, suppose it is desired to measure the temperature of a metal plate that is heated from within by some means. The bare thermocouple-measuring junction is brought into contact with the metal plate. The junction will receive some heat from the plate by thermal conduction. The junction will lose heat by conduction along the thermocouple wires and by convection, conduction, and radiation to the surrounding environment. Obviously, the junction will be at a lower temperature than the plate. This difference in temperature can be reduced by

(a) improving the thermal contact by

(1) flattening the junction to obtain a larger area of contact

(2) soldering, brazing, or welding the junction to the plate

(b) reducing the heat loss from the junction by

(1) using thermocouple wire of the smallest practical diameter

(2) keeping the wires close to the plate for some distance to reduce the temperature gradient in the wires near the junction

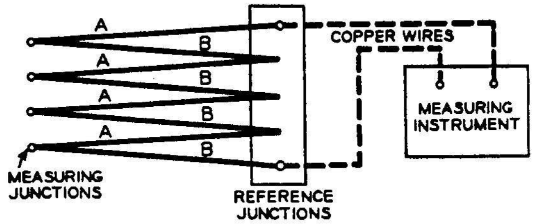
(3) raising the temperature of the space surrounding the junction by use of insulation or an auxiliary source of heat

Methods and practices for optimizing temperature measurements with use of thermowells are set forth in Section 1 of this Code and ASME PTC 19.3 TW.

Various procedures and special type thermocouple assemblies have been employed in making gas temperature measurements. Each has certain advantages for particular applications and operating conditions. The following is a list of the most widely used methods and references where detailed information on each may be found:

– coaxial–tube radiation-shielded thermocouple (Moffat, 1952; Rohsenow and Hunsaker, 1947)
– aspirating or high-velocity thermocouple (Land and Barber, 1974)
– thermocouple with low emissivity radiation shield (Dahl and Fiock, 1949)
– sonic flow thermocouple pyrometer (Allen and Hamm, 1950; Lalos, 1951)
– radiation-compensated thermocouple pyrometer (Severinghaus, 1937)
– thermocouples for steam temperature measurements (Murdock and Fiock, 1950)
– thermocouples for gas measurements in two-phase flow (Benedict, 1963)

Figure 2-3.2-1
Thermocouples Connected in Series



Thermocouples may be joined in series. A series-connected thermocouple assembly is generally referred to as a thermopile and is used primarily in measuring small temperature differences, e.g., as a sensor of optical radiation or as the sensing element in AC/DC thermal converters. The series connection, in which the output is the arithmetic sum of the emfs of the individual thermocouples, may be used to obtain greater measurement sensitivity. A schematic diagram of a series thermocouple is shown in Figure 2-3.2-1.

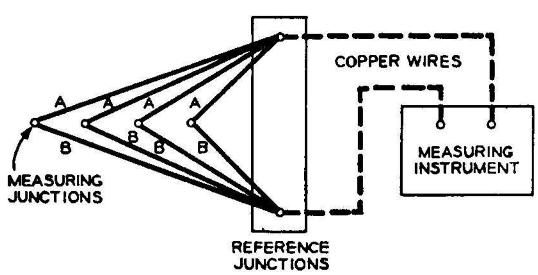
In a parallel-connected thermocouple circuit, a mean value of the individual thermocouples is indicated, and it will be the true arithmetic average if all thermocouple circuits are of equal resistance. Should one or more of the thermocouples become open-circuited, the indicated reading will be the mean of the remaining thermocouples. A schematic diagram of a parallel thermocouple circuit is shown in Figure 2-3.2-2.

2-3.3 Treatment of Data

The conversion of thermocouple emf readings to temperature may be based on the emf-temperature reference functions in those cases when the desired measurement uncertainty is greater than the manufacturing tolerances of the thermocouples. In circumstances demanding higher accuracy, corrections must be made for the deviation of the emf of a thermocouple at a particular temperature from the emf of the reference function. The deviations may be determined by calibration of individual thermocouples or by calibration of a set of spools of wire. To calibrate a set of spools, sample cuts of wire are taken from the beginning, the end, and possibly the middle of the spools. These samples are calibrated, and averages of the calibrations are taken as the calibration of other thermocouples cut from the spools. Calibration of a base metal thermocouple at high temperatures is a use of the thermocouple. Users should be aware that certain characteristics of thermocouples, including the emf-temperature relationship, will change with usage. Since lot calibrations do not expose the thermocouple to use prior to shipment, calibrations by lot can provide an excellent means of verifying the accuracy of a thermocouple to its limits without exposing the supplied sensors to risk of damage or drift. Methods for performing lot calibrations are set forth in SAE AMS 2750G. Offsets applied should be made on the side of the instrument receiving the signal, such as a transmitter, controller, DCS, or PLC.

2-3.3.1 Sample Calculation of Determining Temperature From emf. An emf of 21.085 mV is measured on a Type N thermocouple whose measuring junction is at an unknown temperature, *t*, and whose reference junctions are maintained at 109.4°F (43°C). The measuring instrument has no automatic ice point compensation.

Figure 2-3.2-2
Thermocouples Connected in Parallel



The thermocouple wire deviates from the reference function by 0.020 mV at 212°F (100°C), 0.120 mV at 1,112°F (600°C), and 0.80 mV at 1,292°F (700°C). The deviation at 32°F (0°C) is assumed to be 0. What is the temperature, t? (For clarity of the calculations, the number of significant digits is extended beyond the accuracy of a Type N thermocouple.)

2-3.3.1.1 Lowest Level of Accuracy. Because emf-temperature relationships for thermocouples commonly assume a reference junction temperature of 32°F (0°C), it is common to first express the measured emf, E_m, in terms of an emf-temperature relationship that assumes a reference junction temperature of 32°F (0°C).

$$E_c(t) = E_m + E_c(43°\text{C})$$

where

$E_c(t)$ = emf of the calibrated Type N thermocouple with a measuring junction at temperature, t, and reference junctions at 32°F (0°C)

If the deviation of the wire from the reference function is small compared to the desired measurement uncertainty, the temperature may be determined by approximating $E_c(t)$ by $E_r(t)$ = the reference function for Type N thermocouples.

$$E_r(t) = E_m + E_r(43°\text{C})$$

Using the approximate inverse functions from Burns et al. (1993) or using temperature-emf tables for the inverse function $t_0 = f^1(E_r)$,

$$t_0 = f^1[E_r(t_0)] = f^1[E_m + E_r(43°\text{C})] = f^1(21.085\text{ mV} + 1.147\text{ mV}) = 641.461°\text{C}$$

2-3.3.1.2 Improved Accuracy. The deviation ΔE of the thermocouple calibration from the reference function can be determined once the approximate temperature t_0 is known. Determining ΔE by linear interpolation for both the reference and measuring junctions,

$$\begin{aligned} \Delta E(43°\text{C}) &= (0.020\text{ mV})(43°\text{C}/100°\text{C}) = 0.009\text{ mV} \\ \Delta E(641°\text{C}) &= 0.120\text{ mV} + (0.080\text{ mV} - 0.120\text{ mV})(641°\text{C} - 600°\text{C})/(700°\text{C} - 600°\text{C}) \\ &= 0.104\text{ mV} \end{aligned}$$

and using

$$\begin{aligned} E_c(t) &= E_r(t) + \Delta E(t),\ E_r(t_1) + \Delta E(641°\text{C}) \\ &= E_m + [E_r(43°\text{C}) + \Delta E(43°\text{C})] \\ E_r(t_1) &= E_m + [E_r(43°\text{C}) + \Delta E(43°\text{C}) - \Delta E(641°\text{C})] \\ &= 21.085\text{ mV} + 1.147\text{ mV} + 0.009\text{ mV} - 0.104\text{ mV} = 22.137\text{ mV} \end{aligned}$$

The approximate inverse function can then be used to find a better approximation, t_1, to the temperature

$$t_1 = f^1[E_r(t_1)] = f^1(22.137\text{ mV}) = 639.032°\text{C}$$

2-3.3.1.3 Highest Accuracy. The approximate inverse function, f^1, is not exact, and linear interpolation introduces small errors. For the highest accuracy, the calibration relationship, $E_c(t)$, must be known in some mathematical form, and Newton's Method is used to numerically iterate from the initial, approximate value, t_0, to more accurate values for t. To do this calculation, define the function $F(t)$.

$$\begin{aligned} F(t) &= E_m - [E_c(t) - E_c(43°\text{C})] \\ dF/dt &= -dE_c/dt = -S_c \end{aligned}$$

where S_c is the Seebeck coefficient of the calibrated Type N thermocouple to find $E_c(t)$ and $S_c(t)$, ΔE was assumed to be linear between 32°F (0°C) and 212°F (100°C) and between 1,112°F (600°C) and 1,292°F (700°C). Newton's Method finds the value of t that gives $F(t) = 0$. The first iteration of Newton's Method gives an improved value of $t = t_1$.

$$t_1 = t_0 + F(t_0)/S_c(t_0) = 639.030°\text{C}$$

A second iteration gives a slight additional improvement in accuracy.

$$t_2 = t_1 - F(t_1)/S_c(t_1) = 639.005°\text{C}$$

Further iterations give changes in t less than 0.001°C.

2-3.3.2 A Sample Calculation of Adjusting for an Offset of a Readout Device. A Type S thermocouple is connected directly to a readout instrument with ice point compensation and software to convert to temperature. Assume that the coefficients of the thermocouple may be entered into the unit or that the deviation of the thermocouple from the reference function is negligible. When the Type S thermocouple is immersed into an ice point, the unit reads 31.2°F. During a test, the unit reads 1,460.0°F. What is the reading after correction for the ice point offset?

Assume that the instrument has stray offset voltage ΔE, such that the instrument indicates the voltage corresponding to a temperature of 31.2°F when the actual thermocouple is producing an emf corresponding to 32°F.

$$\Delta E = E_c(32.0°\text{F}) - E_c(31.2°\text{F}) = S_c(32°\text{F})(32.0°\text{F} - 31.2°\text{F})$$

The corrected temperature is

$$\begin{aligned} t &= 1{,}460.0°\text{F} + \Delta E/S_c(1{,}460°\text{F}) = 1{,}460.0°\text{F} + (32.0°\text{F} - 31.2°\text{F})[S_c(1{,}460°\text{F})/S_c(32°\text{F})] \\ &= 1{,}460.0°\text{F} + (0.8°\text{F})(6.03\ \mu\text{V}/°\text{C})/(3.00\ \mu\text{V}/°\text{C}) \\ &= 1{,}460.0°\text{F} + 1.6°\text{F} = 1{,}461.6°\text{F} \end{aligned}$$

For data analysis on a computer, the thermocouple reference and inverse functions, together with Newton's Method when appropriate, are straightforward to implement. In small instruments with limited processing speed, it may be desirable to use alternative numerical methods, such as look-up tables with an interpolation algorithm.

2-4 ADVANTAGES AND DISADVANTAGES

The advantages and disadvantages of thermocouples are found in paras. 2-4.1 and 2-4.2.

2-4.1 Advantages

(a) Thermocouples are simple in basic design and operation.
(b) Thermocouples are small in size, flexible, and capable of installation in relatively inaccessible spaces.
(c) Thermocouples are suitable for remote indication; their signal may be used to indicate, record, or control temperature.
(d) Primary elements are relatively low in cost.
(e) All components of their measuring system are individually replaceable.
(f) Thermocouples are suitable for a wide range of temperature applications.
(g) High accuracy is attainable.
(h) Thermocouples are rugged and extremely well suited to industrial handling and use.

2-4.2 Disadvantages

(a) Thermocouples produce a small signal output, requiring sensitive measuring equipment.
(b) Knowledge of compensation for reference junction temperature is required.
(c) Thermocouples are subject to calibration changes with use, known as drift.
(d) Thermocouple wires must extend from the point of unknown temperature to the location of the reference junctions.
(e) Thermocouples that become inhomogeneous with use may be impossible to recalibrate.

2-5 THERMOCOUPLE INSTRUMENTATION

2-5.1 General

The basic principle of thermoelectric thermometry is that a thermocouple develops an emf that is a function of the difference in temperature of its measuring and reference junctions. If the temperature of the reference junctions is known, the temperature of the measuring junction can be determined by measuring the emf generated in the circuit. The use of a thermocouple in temperature measurements therefore requires the use of an instrument capable of measuring emf.

The relationship between an input voltage, V, and the indication of an emf-measuring device, D, can be expressed as $D = gV + V_o + \Delta V$, where g and V_0 are constants equal to the device gain and offset, respectively, and ΔV is a measure of the deviation of D from the simple linear form $D = gV + V_0$. Specifications that are relevant to the performance of emf-measuring devices are

(a) *Gain Accuracy*. Gain accuracy is a measure of how close to unity the factor g is known.
(b) *Offset Voltage*. Offset voltage is a measure of how large V_0 is and how much it will change with time and temperature.

(c) Linearity. Linearity is a measure of how large ΔV is, the deviation from a linear response of D to V.

(d) Common-Mode Rejection Ratio. Common-mode rejection ration is a measure of the immunity of an emf measurement to a noise voltage appearing on both the positive and negative leads connected to the measuring device.

(e) Normal-Mode Rejection Ratio. Normal-mode rejection ratio is a measure of the immunity of an emf measurement to a noise voltage appearing across the positive and negative leads.

Instruments used to measure emf include digital voltmeters, analog-to-digital converters, and specialized readout or control instruments that contain ice point compensation circuits and software or hardware that converts the emf reading to an equivalent temperature. Although there are some purely analog circuits used with thermocouples for temperature indication and control, most circuits used in PTC work use analog-to-digital circuits to convert the thermoelectric emf to a digital signal.

For most applications, thermocouples should be calibrated separately from the measuring instrument. In cases where a single thermocouple is always used with a single measuring system, it may be advantageous to calibrate the system as a whole. However, it may be difficult to determine if subsequent drift in the system calibration is due to drift in the thermocouple itself or to the measuring system.

If extension wire is used for high-accuracy thermometry work, corrections can be applied to the readings if the temperatures of the two ends of the extension wire can be independently measured and if the deviation of the extension wire emf versus temperature relationship from that of the thermocouple itself is known.

Electrically, thermocouples can be thought of as DC signal sources generating less than 40 mV, typically. They have low source impedances, typically less than 100 Ω, except for special applications or long lengths, and this impedance is predominantly resistive.

2-5.2 emf-Measuring Devices

Digital voltmeters read the thermocouple emf directly by first amplifying the emf through analog circuitry and then converting the resulting analog signal to a digital signal with an analog-to-digital converter. Various filtering procedures, either analog or digital, may be applied to the signal either before or after the conversion to a digital signal. Various methods may also be used to compensate for stray thermal emfs inside the instrument. Because the internal circuitry relies on copper interconnects through wires and printed circuit boards, it is proper practice to use pure copper wires to connect the voltmeter terminals to the thermocouple reference junctions.

Temperature transmitters and other instruments designed for temperature indication and control can be thought of as consisting of special ice point compensation circuitry, a digital voltmeter, and appropriate mathematical processing circuits to convert the indicated emf reading into a temperature reading. These instruments are often convenient to use because the user need not supply an ice point nor convert voltage readings into temperature. The accuracy of the reading can be impacted significantly by the selection of sensor type, as well as the temperature range of operation. Users should confirm that the accuracy specifications of the particular instrument being used meet their needs prior to implementation.

Analog-to-digital conversion cards (“thermocouple cards”) that mount directly into computers are also available. As with transmitters, users should confirm that the resolution and offset voltages of such cards are acceptable for their application. Additional errors of nonlinearity, resolution, and stability exist. The low level of thermocouple signals requires special attention to system resolution and filtering of both common and normal mode noise. A typical example of thermocouple card accuracy is stated in Table 2-5.2-1.

2-5.3 Scanners/Multiplexers

The terms “scanners” and “multiplexers” are interchangeable. Scanners are instruments that enable one readout device to be connected sequentially to a large number of thermocouples via a set of relays that are either controlled through a computer or through the instrument front panel. Often, the relays are mounted on cards that are inserted into a scanner chassis. Special cards are available that minimize stray thermal emfs. High-quality scanner relays will introduce typical thermal emfs of 0.05 μV to 2 μV. If electromechanical relays that require continuous coil current for contact closure are used in the scanner, these stray thermal emfs will often increase in magnitude with time as the relay coil heats up the relay environment. This effect can be minimized by not keeping the relay channel used for measurements closed for long periods (greater than a minute or so). It is good practice to periodically measure these stray thermal emfs by shorting out each scanner channel and then reading all of the scanner channels with a high-accuracy voltmeter. Some digital voltmeter or temperature-measuring systems have integrated scanner capabilities.

In addition to providing a means of measuring multiple thermocouple channels, scanners can be used to correct for drifts in the stray thermal emfs of digital voltmeters. One channel of the scanner is dedicated to use as a “zero” channel. The inputs of this channel are shorted with a bare copper wire. Periodically during data acquisition, the voltmeter reads the

Table 2-5.2-1
Typical Thermocouple Card Accuracy and Drift

Input Type	Accuracy at 77°F (25°C)	Temperature Drift at 32°F–140°F (0°C–60°C)
B	±6.66°F (±3.70°C)	±0.710°F/°F (±0.710°C/°C)
E	±0.92°F (±0.51°C)	±0.104°F/°F (±0.104°C/°C)
J	±1.22°F (±0.68°C)	±0.130°F/°F (±0.130°C/°C)
K	±1.80°F (±1.00°C)	±0.186°F/°F (±0.186°C/°C)
R	±5.69°F (±3.16°C)	±0.601°F/°F (±0.601°C/°C)
S	±6.67°F (±3.70°C)	±0.651°F/°F (±0.651°C/°C)
T	±1.21°F (±0.67°C)	±0.174°F/°F (±0.174°C/°C)
N	±1.93°F (±1.07°C)	±0.223°F/°F (±0.223°C/°C)
C	±6.12°F (±3.40°C)	±0.434°F/°F (±0.434°C/°C)
L	±1.35°F (±0.58°C)	±0.119°F/°F (±0.119°C/°C)
mV	±39 μV (±39 μV)	±14.06 μV/°F (±7.812 μV/°C)

voltage on this zero channel, and all other voltage readings are corrected by subtracting off the reading on the zero channel.

2-5.4 Accuracy of the emf Measurement and Noise

For most applications, the uncertainty of the emf measurements can be estimated from the manufacturer's specifications for the accuracy of DC voltage readings. Careful correction of the stray thermal emf of the voltmeter can substantially improve the uncertainty of low level DC voltage measurements. A quantitative determination of the system uncertainty using correction for the voltmeter zero requires careful calibration of the scanner and voltmeter system.

Electrical noise on thermocouple circuits can consist of inductive pickup of electromagnetic fields produced by AC currents in the vicinity of the thermocouple, by capacitive pickup of variations in the voltage of adjacent signal lines, or electrical leakage effects. Capacitive pickup can be minimized by routing thermocouple cabling through shielding or conduit maintained at earth ground. Capacitive pickup is most often a problem in the presence of high-frequency noise caused by high-speed digital signals or by certain furnace control circuits. Because thermocouples have relatively low impedance and are often used in environments where low frequency noise from AC power supplies dominates the total noise, inductive pickup is usually greater than capacitive pickup. Inductive pickup can be minimized by using a twisted pair of lead wires or by minimizing the enclosed area of the loop formed by the thermocouple wires. Physically separating thermocouple wires from wires carrying currents is also effective. Electrical leakage is primarily a problem at high temperatures where ceramic insulators may have degraded electrical resistance. Placing a grounded shield around the thermocouples is an effective means of preventing noise or DC voltage shifts from electrical leakage effects. Including a ground wire electrically connected to the thermocouple sheath material has proven to be an effective means of avoiding electrical interference.

High-frequency, common-mode noise may be reduced by placing capacitors from the input terminals of the emf-measuring device to earth ground. The product of the thermocouple resistance and capacitance defines a response time for the low-pass filter consisting of the thermocouple resistance and capacitor. The response time must be short enough that the emf at the input terminals settles sufficiently prior to initiation of readings by the measuring instrument.

Rejection of normal mode noise is primarily a function of the properties of the measuring instrument. Because much of the normal mode noise is at the power line frequency or harmonics of this frequency, good noise rejection usually requires integration of the emf signal for at least one power cycle.

Temperature transmitter signals are much less sensitive to environmental effects, such as electromagnetic interference, resulting in a more stable measurement in comparison to direct wired sensors. A measurement of 4 mA to 20 mA or a digital signal from the transmitter has a greater signal-to-noise output than directly wired sensors (~40X greater than RTD and ~400X greater than TC). Most transmitters also have the capability for 50 Hz or 60 Hz AC filtering and may have additional processing to reduce measurement issues arising from short duration transient spikes in the signal.

2-5.5 Reference Junction Apparatus

Since the emf generated by a thermocouple is a function of the difference in temperature between its measuring and reference junctions, the temperature of the reference junction must be known in order to determine the temperature of the measuring junction. The one exception is a Type B thermocouple with reference junctions in the range of 32°F to 122°F (0°C to 50°C) does not require ice point compensation for most applications because of the extremely low sensitivity of the thermocouple in this range.

Most thermocouple thermometers for industrial applications are furnished with means for automatically compensating the reading of the instrument for the actual reference junction temperature. The reference junctions are normally located in the instrument and vary in temperature with ambient conditions. Such compensated instruments usually have their readout calibrated in terms of the temperature of the measuring junction.

Automatic reference junction compensation requires specification of the type of thermocouple connected to the isothermal block in the instrument. The accuracy of the automatic reference junction compensation is limited, but the accuracy may be improved by connecting to the instrument the same thermocouple to be used in the measurement, placing the measuring junction in a glass tube inserted into an ice point bath, and reading the resulting emf or temperature when the measuring junction comes to thermal equilibrium. Deviations of this reading from 32°F (0°C) or 0 V are an indication of an error or offset in the ice point compensation. This offset may be removed either by software correction or by a hardware adjustment.

2-5.5.1 Limitations of Ice Point Compensation. Inexpensive compensation circuits have typical uncertainties of 0.9°F (0.5°C), far inferior to that of a standard ice bath, which has an uncertainty of 0.0036°F (0.002°C). Compensation circuits may be limited by

(a) temperature gradients on isothermal blocks or within nominally isothermal zones
(b) the accuracy of thermometers used to measure the temperature of isothermal blocks or zones
(c) stray thermal emfs in electrical compensation circuits

There is another effect related to the properties of the thermocouple connected to the compensation circuit. Most compensation circuits assume that the connected thermocouple has the same thermoelectric response as the standard reference function for that type of thermocouple. If the thermocouple deviates from the reference function at the temperature of the reference junctions by a given quantity, the compensation of the thermocouple will be in error by the amount of the deviation. This effect is often important for reference junction compensation with uncertainties of 0.36°F (0.2°C) or better.

In PTC work, there are two basic methods for providing suitable reference junctions. Either the junction is maintained at a fixed temperature or the temperature of the junctions is allowed to vary, and a compensating emf is introduced into the circuit or accounted for by calculation.

Under fixed temperature, reference junctions can be listed as triple point of water cells, ice baths, automatic ice baths, and constant temperature ovens.

2-5.5.2 Triple Point of Water. A cell can be constructed in which there is equilibrium between ice, water, and water vapor. The temperature of this triple point is 0.018°F (0.01°C) exactly, and it is reproducible to ~0.00018°F (0.0001°C).

2-5.5.3 Single Ice Bath (Mangum, 1995). The following describes a method for maintaining reference junctions at the temperature of an ice bath, which is 32.000°F (0.000°C).

A wide-mouth Dewar flask is partially filled with shaved ice and water. The Dewar should be packed to its full depth with shaved ice that has been saturated with water, and water should fill all spaces between the ice particles. A properly prepared ice bath and ice made from distilled water have an uncertainty of 0.0036°F (0.002°C). Baths made from deionized water will have similar uncertainties. If the ice bath and ice are made from tap water, the uncertainties may be as high as approximately 0.054°F (0.03°C), although this will vary greatly with the locality and perhaps even the day.

The lid of the Dewar is bored to accommodate two glass tubes, closed at one end, for each thermocouple to be used. The tubes are most readily inserted into the ice-water mixture if the lid is first in place and the ice is not packed too firmly. A copper lead wire is joined to a thermoelement at the bottom of each glass tube by one of a variety of methods. The copper wires may be attached to the thermoelements by

(a) welding or soldering the wires together
(b) using a connector that secures the wire by crimping, by spring pressure, or by screw pressure

The wires may be placed into tubes that are dry or that have a small amount of mineral oil at the bottom of the tube to promote heat transfer. For high accuracy work with dry tubes, as much as 8 in. (203.2 mm) of tube should extend into the ice-water mixture.

It is important that enough ice be maintained in the bath so that the level of water does not come closer than 1 in. (25.4 mm) to the bottom of the test tubes. When setting up the bath, periodic observations should be made to determine the time required for the water level to reach this point. Thereafter, the ice point should be renewed by adding shaved ice and draining excess water within this time limit (ASTM E563; Mangum, 1995).

2-5.5.4 Multiple Ice Bath With Master Ice Bath. When the number of thermocouples used on an installation is large enough to require a number of ice baths, it is recommended that a reference junction master ice bath be used to enable the operator to readily determine whether all the baths are maintaining a temperature of 32°F (0°C). A checking thermocouple is installed in each of the ice baths and runs to the master ice bath, where its wires are joined to copper wires, and the copper wires are run to a switch or scanner. When this thermocouple is selected on the scanner, the emf reading is a measure of the temperature difference between the master ice bath and auxiliary ice bath.

2-5.5.5 Automatic Ice Bath. Practical thermoelectric refrigerator devices are available in which thermal equilibrium between ice and water is constantly maintained. The change of volume of water in freezing is used to control the removal of heat from the volume containing the ice and water. Some commercially available devices provide wells into which the user may insert reference junctions formed from his own calibrated wire. Others are provided with many reference junction pairs brought out to terminals, which the user may connect into his system. The error introduced into a system by these devices may be as small as 0.09°F (0.05°C).

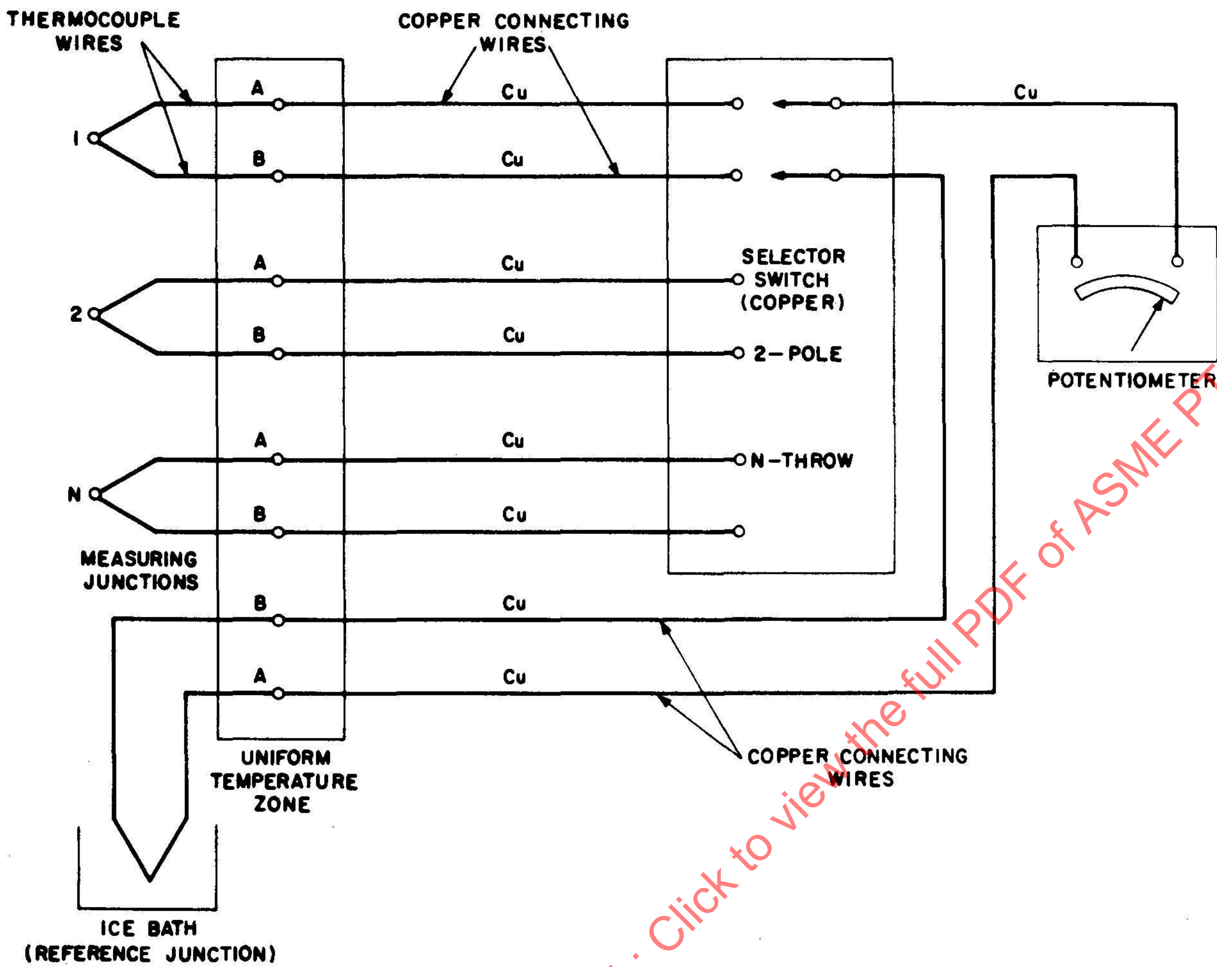
2-5.5.6 Constant Temperature Ovens. A thermostatically controlled oven provides a means of holding a reference junction at an approximately constant temperature. To use reference junctions held at elevated temperature with tables based on 32°F (0°C) reference junction temperature, a constant amount must be added to the thermal emf.

2-5.5.7 Electrical Compensation. A compensating circuit consisting of a source of current and a combination of fixed resistors and a temperature-sensitive resistor (thermistor) are available that will have a variation of emf with a temperature of the reference junctions similar to the emf that would be produced by a thermocouple with junctions at 32°F (0°C) and at the reference junction temperature.

2-5.5.8 Zone Box. An alternative method of dealing with many thermocouples makes use of a single reference junction. All the thermocouples are routed to a zone of uniform temperature. A single reference thermocouple with a junction maintained at 32°F (0°C) is also routed to the same zone box. Through copper wires, the emf of the reference junctions is added to each of the measuring junctions in turn as they are switched to the emf-measuring instrument (see Figure 2-5.5.8-1).

2-5.5.9 Software Compensation. In many modern instruments, multiple thermocouples are connected to copper wires at an isothermal block, whose temperature is monitored by a thermistor or another type of thermometer that is readily integrated into an electronic instrument and that is accurate near ambient temperatures. Often, the copper traces of a printed circuit board serve as the copper wires leading to the emf-measuring device. The emf in these instruments is read without any compensation voltage being added to the circuit. The deviation of the temperature of the isothermal block from 32°F (0°C) is instead accounted for in the conversion of this emf to a temperature reading, using appropriate mathematical techniques.

Figure 2-5.5.8-1
A Zone-Box Circuit Involving Only One Reference Junction



Section 3
Resistance Temperature Detectors (RTDs)

3-1 SCOPE

The purpose of this Section is to present information that will guide the user in the selection, installation, and use of resistance temperature detectors (RTDs) for industrial use. RTDs used for calibration are discussed in Section 6.

3-2 DEFINITIONS

error: the difference between a measured value and the true value. Error can be broken up into two categories: random error and systematic error.

random error: the closeness of agreement between a group of measured values. Random error is characterized by scatter or variance in readings from one instance to another.

systematic error: error that remains consistent, typically associated with measuring equipment and its attachments. In the case of a sensor, accuracy class and installation effects are important components of systematic error. General sources of systematic error can be found in ASTM E2593 and ASME PTC 19.1.

pad- or ribbon-style element: a type of resistance element comprised of a winding encapsulated in a ribbon usually made from Kapton, Silicone, or fiberglass.

Figure 3-2-1 shows a pad-style RTD typically epoxied or glued to a surface for surface temperature measurement.

Stator-winding RTD elements are of similar appearance but are longer to fit in slots between stator windings to monitor motor temperature rise and prevent overheating. The longer length of stator-winding ribbon elements allows them to provide an average temperature, avoiding the potential to miss a hot spot by use of a tip-sensitive RTD. In addition to the 100-Ω platinum style common to point-sensitive industrial RTDs, stator-winding RTDs are often manufactured in 10-Ω copper construction, as well as 120-Ω nickel construction.

precision and accuracy: the precision and accuracy of the installed instrumentation should be considered in designing a test. Installed temperature measurement systems should be calibrated separately. These characteristics will be reflected in the ultimate uncertainty.

(a) Precision is reflected in the random error of the system and is a measure of the repeatability of the readings. In other words, random error is the extent of the "scatter" in the data during a test period. Low scatter means a low value of random error.

(b) Accuracy is reflected in the systematic error of the system, and these errors are constant and not evident in the data collected during the test period. Systematic error could be due to calibration methods, mounting effects, spatial variations, and other characteristics that impact the test results uniformly.

See Section 1 for a more detailed discussion of uncertainty.

resistance element: a wire-wound or thin-film resistor with a known, reproducible, and stable temperature coefficient of resistance. The most common material of construction is platinum. Resistance elements can also be manufactured from other materials, such as copper or nickel.

averaging RTD: a resistance temperature detector that incorporates a long flexible element capable of providing an average temperature indication. Averaging RTDs are common in duct temperature monitoring applications where an average temperature across the duct is desired (see Figure 3-2-2). Not all RTD assemblies are capable of being bent without damage to the assembly, so where the user intends to bend a probe, they should confirm minimum permissible bend radii with the manufacturer.

multipoint RTD: a resistance temperature detector that incorporates individual elements spaced within an assembly so that either an average temperature or multiple discrete temperatures can be determined. See also *averaging RTD.*

One set of methods for properly mapping and accounting for duct temperatures is set forth in ASME PTC 4.3.

resistance temperature detector (RTD): a sensor assembly comprised of a resistance-sensing element, connecting wires, with or without means for mounting. Resistance temperature detectors are also called *resistance thermometers*. Because resistance temperature detectors often have resistance elements made of platinum, the term is typically used interchangeably with *industrial platinum resistance thermometer (IPRT)*.

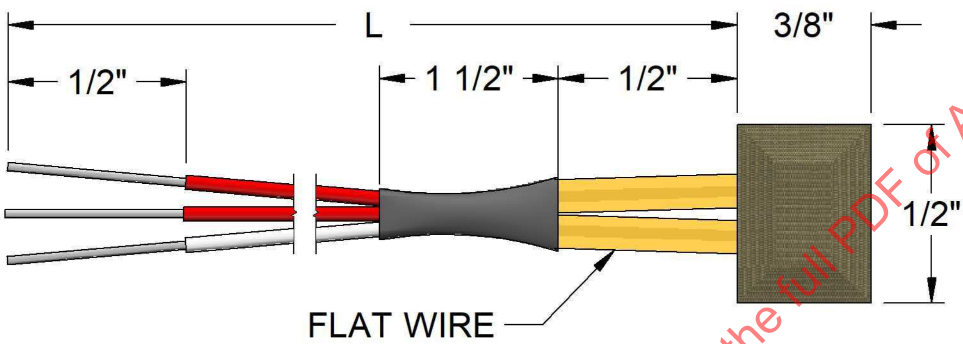
self-heating: the term used to describe the Joule heating of an RTD sensor due to the excitation current necessary to measure the RTD element's resistance at a given temperature.

thin-film element: a type of resistance element embodied by a thin platinum film applied to a ceramic carrier plate and attached to leads. Thin-film elements are usually sealed against external effects by a layer of glass. See Figure 3-2-3.

tolerance: permitted variation of a measured value from the correct value.

wire-wound element: a type of resistance element comprised of thin platinum wire encased within a round protective body of ceramic connected to leads.

Figure 3-2-1
Pad-Style RTD Element



GENERAL NOTE: The figure supplied courtesy of JMS Southeast, Inc. (www.JMS-SE.com).

Figure 3-2-2
Averaging RTD in a Duct

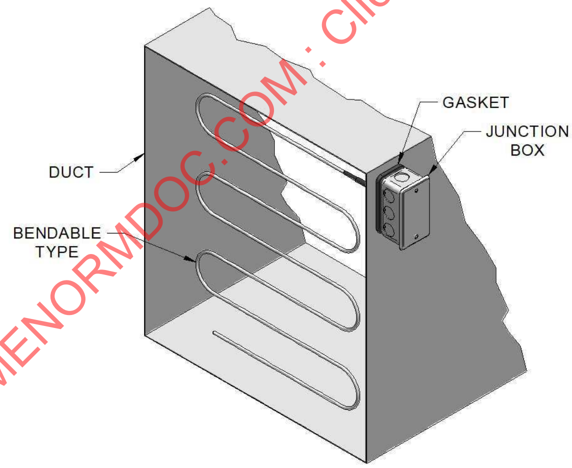


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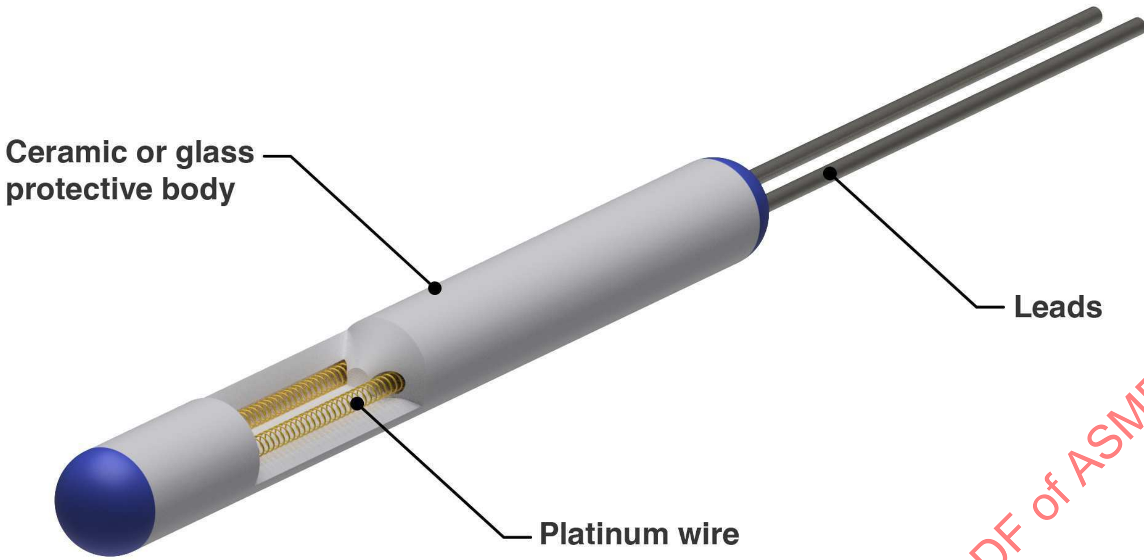
Figure 3-2-3
Thin-Film Element



GENERAL NOTE: The figure is reprinted courtesy of WIKA Instruments LTD (www.wika.com).

Figure 3-2-4
Wire-Wound Element

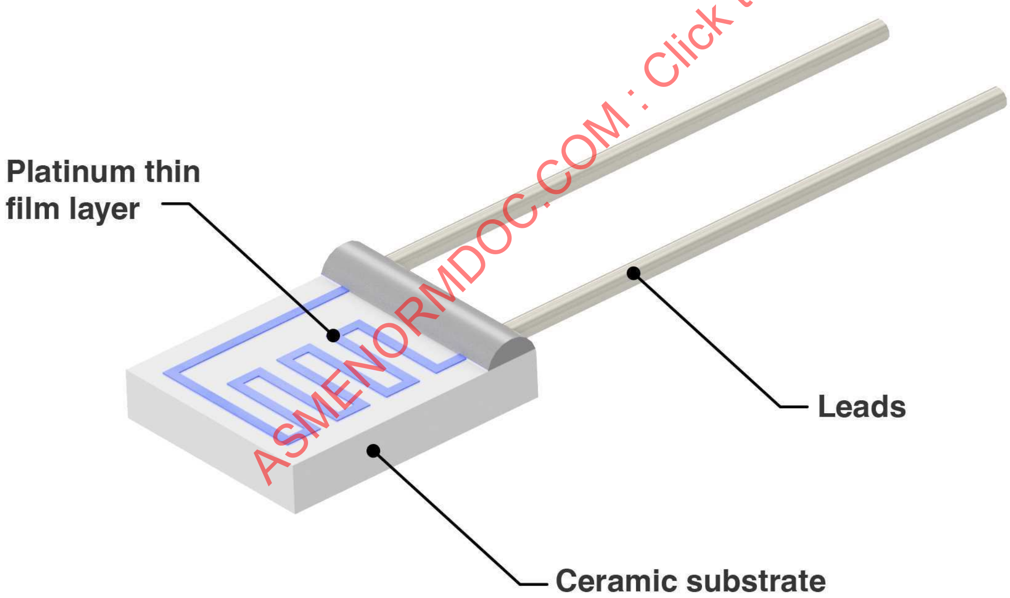


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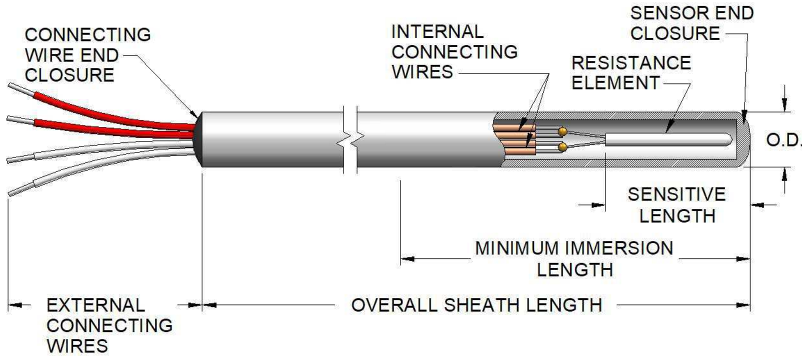
Figure 3-3-1
Typical Industrial Platinum Resistance Thermometer



GENERAL NOTES:
(a) Figure supplied courtesy of JMS Southeast, Inc. (www.JMS-SE.com).
(b) Transition at the wire end closure: Environmental seal commonly made with potting. The cold end of the sensor may not have the same temperature rating as the sensor tip.
(c) Industrial RTDs have an approximate range of −328°F to 1,562°F (−200°C to 850°C), but typically, one sensor only covers a part of that range. Around 842°F (450°C) industrial RTDs typically become less accurate than similarly constructed thermocouples.
(d) Resistance element may be thin film or wire wound, typically platinum construction.
(e) Sensor and wire end closures must be sealed from the environment. The protective sheath can be manufactured out of a variety of materials, including stainless steel and nickel-based alloys.
(f) Internal connecting wires must be insulated with a jacket or mineral insulation to electrically isolate them from each other and avoid shorts in the resistance loop.
(g) External connecting wires may not have the same insulation or be the same size as the wires inside the overall sheath length.

3-3 PRINCIPLES OF OPERATION AND SPECIFICATION CHARACTERISTICS

RTDs are the most commonly used resistance thermometer in industry. They are found in laboratory and nonlaboratory settings, measuring a variety of applications, including duct temperatures in the HVAC industries, refrigeration cabinets, stators in motors/generators, bearing temperature monitoring, surface mounting measurements, oil temperatures, steam temperatures, and many others below approximately 842°F (450°C). See Figure 3-3-1 for RTD construction elements.

An RTD consists of a resistance element connected to two, three, or four wires. In application, the wires are connected to a resistance measurement device so that the resistance measured can be related to a temperature. As the temperature of the resistance element increases, its electrical resistance also increases in a known and reproducible manner that can be expressed in terms of a simple mathematical formula. The shape of that line is nominally characterized by the temperature coefficient of resistance known as its alpha ("α").

Along with characteristics common to other sensor specifications, RTD specifications require a reference to the resistance element material (e.g., platinum), the resistance of that element at a reference temperature [e.g., 100 Ω at 32°F (0°C)], the alpha specific to that element (e.g., $\alpha = 0.00385$), the number of wires to be connected to the instrument (e.g., three wires), the number of elements in the sensor (e.g., single or dual), and an accuracy specification for the element or sensor (e.g., "Class A per IEC 60751").

Since platinum element RTDs constitute the great majority of RTDs used in industrial and laboratory environments, this Section will focus primarily on platinum elements.

3-3.1 RTD Accuracy Specifications

Accuracy specifications are called out differently depending on whether the intended use is industrial or laboratory and should include expected temperature range of use.

Accuracy specification for industrial use RTDs are commonly stated by reference to an IEC or ASTM Accuracy Class. The most common industrial reference is the IEC standard. See Table 3-3.1-1 (Table 3-3.1-1M) for industrial RTD tolerance specifications.

Which standard is selected as the reference holds particular significance because an RTD does not always maintain the same accuracy or suitable temperature range despite having the same "class" designation.

Table 3-3.1-1
Industrial RTD Tolerance Specification Table (U.S. Customary)

Industrial RTD Tolerance Comparisons by Standard and Construction					Tolerance, ±°F			
		Element	Temperature, °F				Temperature	
Class	Standard	Type	Min.	Max.	32°F	Equation	Min.	Max.
AA	IEC 60751	WW	−58	482	0.18	±(0.18 + 0.00306 |t|)	0.357	1.655
AA	IEC 60751	TF	32	302	0.18	±(0.18 + 0.00306 |t|)	0.278	1.104
A	IEC 60751	WW	−148	842	0.27	±(0.27 + 0.0036 |t|)	0.803	3.301
A	IEC 60751	TF	−22	572	0.27	±(0.27 + 0.0036 |t|)	0.349	2.329
A	ASTM E1137	All	−328	1,202	0.234	±(0.234 + 0.00306 |t|)	1.238	3.912
B	IEC 60751	WW	−320.8	1,112	0.54	±(0.54 + 0.009 |t|)	3.427	10.548
B	IEC 60751	TF	−58	932	0.54	±(0.54 + 0.009 |t|)	1.062	8.928
B	ASTM E1137	All	−328	1,202	0.45	±(0.45 + 0.00756 |t|)	2.930	9.537
C	IEC 60751	WW	−320.8	1,112	1.08	±(1.08 + 0.018 |t|)	6.854	21.096
C	IEC 60751	TF	−58	1,112	1.08	±(1.08 + 0.018 |t|)	2.124	21.096

Legend:
t = temperature
TF = thin film
WW = wire wound

Table 3-3.1-1M
Industrial RTD Tolerance Specification Table (SI)

Industrial RTD Tolerance Comparisons by Standard and Construction					Tolerance, ±°C			
		Element	Temperature, °C				Temperature	
Class	Standard	Type	Min.	Max.	0°C	Equation	Min.	Max.
AA	IEC 60751	WW	−50	250	0.10	±(0.1 + 0.0017 |t|)	0.185	0.525
AA	IEC 60751	TF	0	150	0.10	±(0.1 + 0.0017 |t|)	0.100	0.355
A	IEC 60751	WW	−100	450	0.15	±(0.15 + 0.002 |t|)	0.350	1.050
A	IEC 60751	TF	−30	300	0.15	±(0.15 + 0.002 |t|)	0.210	0.750
A	ASTM E1137	All	−200	650	0.13	±(0.13 + 0.0017 |t|)	0.470	1.240
B	IEC 60751	WW	−196	600	0.30	±(0.3 + 0.005 |t|)	1.280	3.300
B	IEC 60751	TF	−50	500	0.30	±(0.3 + 0.005 |t|)	0.250	2.800
B	ASTM E1137	All	−200	650	0.25	±(0.25 + 0.0042 |t|)	1.100	3.000
C	IEC 60751	WW	−196	600	0.60	±(0.6 + 0.01 |t|)	2.560	6.600
C	IEC 60751	TF	−50	600	0.60	±(0.6 + 0.01 |t|)	1.100	6.600

Legend:
t = temperature
TF = thin film
WW = wire wound

Table 3-3.1-2
Thin Film Versus Wire Wound Elements

Characteristics	Pt 100 Elements	
	Thin Film	Wire Wound
Accuracy	Good	Best
Resistance to vibration	Good	Fair
Response time	Better	Good
Tip sensitivity	Better	Good
Cost	Better	Good
Size	Small	Larger
Stability	Good	Good
Self-heating	Good	Better
Temperature range	Good	Better

For example, the tolerance for a "Class A" RTD at −32°F (0°C) is

$$\pm 0.27°\text{F}\ (\pm 0.15°\text{C})\ \text{if ordered per the IEC standard}$$
$$\pm 0.23°\text{F}\ (\pm 0.13°\text{C})\ \text{if ordered per the ASTM standard}$$

Moreover, the temperature range over which "Class A" tolerance must be achieved differs by standard and element construction.

$$-22°\text{F to } 572°\text{F}\ (-30°\text{C to } 300°\text{C})\ \text{if thin film per the IEC standard}$$
$$-148°\text{F to } 842°\text{F}\ (-100°\text{C to } 450°\text{C})\ \text{if wire wound per the IEC standard}$$
$$-328°\text{F to } 1{,}202°\text{F}\ (-200°\text{C to } 650°\text{C})\ \text{per the ASTM standard}$$

While the ASTM standard is more stringent, thin film elements are not generally available in specifications that meet the full Class A temperature range. Thin film elements maintain some advantages over wire wound elements (e.g., resistance to vibration and smaller size enabling greater tip sensitivity).

Regardless of which tolerance standard is selected, it is important to specify a sensor's range of operation as it is often not necessary that one sensor cover the entire temperature range. Advantages of quality, cost, and availability can be obtained by communicating the actual temperature range the needed sensor is expected to "see" once installed.

Typically, the sensor manufacturer will make the selection of thin film or wire wound based on the design requirements of the user. Sufficient resistance to thermal and mechanical shock, vibration, high pressure, and other hostile environments found in industrial applications will need to be considered. Quality is influenced by the actual fabrication. Which type of element is used is not often called out in the part number or specification. Table 3-3.1-2 sets forth a comparison of thin film and wire wound elements.

At present, developments in thin film technology are taking place at a higher rate than wire wound elements for industrial RTDs.

3-3.2 Specification of RTD Lead Wires

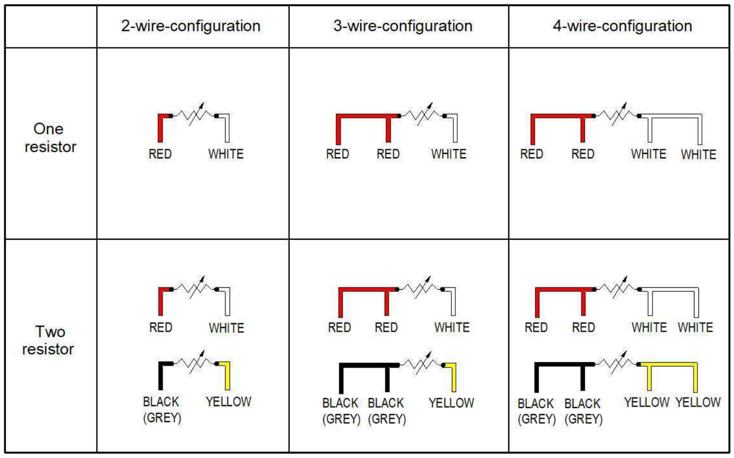
Lead wires contribute considerably to the accuracy of a given RTD sensor. As the measured signal is the loop resistance, any failure to properly account for resistance in the lead wires is reflected as an error. For this reason, RTDs are typically specified as being of four-, three-, or two-wire construction.

The most accurate construction is a four-wire RTD where modern instrumentation is capable of directly measuring and eliminating the lead wire resistance from the RTD circuit, entirely removing lead wire resistance as a potential source of measurement error.

The most common industrial lead wire specification is three-wire construction. A three-wire construction incorporates a common wire loop that the receiving instrument will use to compensate for the lead wire resistance in the measuring loop. This method yields acceptable accuracies in all but extremely long RTD constructions.

Two-wire constructions are reserved for applications where accuracy is not a critical component and those incorporating high-resistance elements (1,000 Ω and higher) where the impact of lead wire resistance makes a much smaller contribution to the overall resistance measurement.

Figure 3-3.2-1
RTD Wire Color Code by Standard



GENERAL NOTE: The figure supplied courtesy of JMS Southeast, Inc. (www.JMS-SE.com).

RTDs are often made in single or dual construction. Dual construction specification indicates the presence of two RTD elements located at the same point in the probe. These are often specified to provide a spare or to provide a means of monitoring the probe for potential drift indicating a need for replacement. Accordingly, a four-wire dual RTD will have eight wires in the housing, a three-wire dual will have six wires in the housing, and a two-wire dual will have four wires in the housing.

RTD lead wires are color coded by standard to enable quick field identification of function and character. See Figure 3-3.2-1 for RTD wire color coding examples.

3-3.3 Temperature Coefficient of Resistance or Alpha, α

For RTDs, the ratio of the change in electrical resistance of a material to a corresponding change in temperature of that material is defined by the following equation:

$$\alpha = \frac{(R_T - R_{T\,\mathrm{ref}})}{R_{T\,\mathrm{ref}}(T - T_{\mathrm{ref}})} \tag{3-3-1}$$

where

R_T = Ω at a given temperature, °C
$R_{T,\mathrm{ref}}$ = resistance (Ω) at 32°F (0°C)
T = temperature correlating to R_T, °C
T_{ref} = 32°F (0°C)

For RTD specification, the Fundamental Interval (FI) of −32°F to 212°F (0°C to 100°C) is used to establish the alpha where $R_{T,\mathrm{ref}}$ equals the resistance at 0°C, and R_T equals the resistance at 100°C. Accordingly, where

$$R_T = 38.51\ \Omega \text{ at } 212°\text{F } (100°\text{C})$$
$$R_{T\,\mathrm{ref}} = 100\ \Omega \text{ at } 32°\text{F } (0°\text{C})$$

Alpha is derived in the following manner:

$$\begin{aligned}\alpha &= (138.51\,\Omega - 100\,\Omega)/[100\,\Omega \times (100°\text{C} - 0°\text{C})] \\ &= 38.51\,\Omega/10{,}000\,\Omega℃ \\ &= 0.003851\,\Omega/\Omega℃ \\ &= 0.003851°\text{C}^{-1} \\ &= 3.851 \times 10^{-3}°\text{C}^{-1}\end{aligned}$$

Alpha is sometimes conventionally written in units of Ω/Ω/°C as in 0.00385 Ω/Ω/°C. An Industrial RTD's alpha is typically between 0.00385°C^{-1} and 0.003925°C^{-1}.

3-3.4 Platinum Resistance Element Temperature-Resistance Relationships

If the resistance to temperature relationship was perfectly linear, the resistance change per degree of temperature change could be established by

$$R_T = R_{T\,\text{ref}}[1 + \alpha(T - T_{\text{ref}})] \tag{3-3-2}$$

However, because the temperature to resistance relationship is not perfectly linear, the temperature-resistance relationship is better defined by a polynomial where the coefficient values are either supplied by a standard or, where greater accuracy is required, derived from a calibration such as a Callendar-Van Dusen (CVD) calibration that characterizes these coefficients on a sensor-by-sensor basis.

The CVD polynomial from 32°F to 1,562°F (0°C to 850°C) incorporates two temperature coefficients: A and B.

$$R_T = R_{T\,\text{ref}}[1 + AT + BT^2] \tag{3-3-3}$$

The CVD polynomial below 0°C to −200°C incorporates three temperature coefficients: A, B, and C.

$$R_T = R_{T\,\text{ref}}[1 + AT + BT^2 + C(T - 100)T^3] \tag{3-3-4}$$

where

R_T = resistance in Ω of an RTD at a given temperature, T

$R_{T,\text{ref}}$ = resistance in Ω of an RTD at 32°F (0°C)

For the most common industrial RTD elements, namely platinum RTDs where $\alpha = 3.851 \times 10^{-3}$ °C^{-1}, the ASTM E1137 and IEC 60751 standards agree as to the following temperature coefficients:

$$\begin{aligned}\text{A} &= 3.9083 \times 10^{-3}°\text{C}^{-1} \\ \text{B} &= -5.775 \times 10^{-7}°\text{C}^{-2} \\ \text{C} &= -4.183 \times 10^{-12}°\text{C}^{-4}\end{aligned}$$

Accuracy classes established by ASTM E1137 and IEC 60751 describe the extent to which the temperature to resistance relationship can vary from the above stated fixed values of A, B, and C. RTDs with different alpha values will have different A, B, and C values.

Of note, historically, the above equations were written in an alternative but equivalent form with different coefficients, namely α, δ, and β. These are not the same as A, B, and C values. For the standard ASTM E1137 or IEC 60751 RTD element, those values are the following:

$$\begin{aligned}\alpha &= 3.851 \times 10^{-3}°\text{C}^{-1} \\ \delta &= 1.500°\text{C} \\ \beta &= 0.1086\end{aligned}$$

3-3.5 Measurement Considerations Particular to RTDs

3-3.5.1 Self-Heating. Measuring the resistance of the RTD loop requires an excitation current. The current that flows through the loop must be small enough to avoid Joule heating of the sensor. The greater the resistance, the greater the potential for self-heating error. For this reason, higher resistance elements have a greater susceptibility to self-heating error.

Table 3-3.5.1-1
Maximum Applied Current for RTDs by Nominal Resistance

RTD Nominal Resistance (ohm at 0°C)	Maximum Applied Current to Avoid Self-Heating (Platinum Elements)
100 Ω	1 mA
500 Ω	0.5 mA
1,000 Ω	0.3 mA
2,000 Ω	0.2 mA
10,000 Ω	0.1 mA

This process has been described by the following formula:

$$\Delta T = (R \times I^2)/E \tag{3-3-5}$$

where

E = self-heating coefficient, mW/K
I = measuring current, mA
R = resistance, KΩ
ΔT = change in temperature, K

In the case of a typical 100-Ω platinum industrial RTD, a sensing current of 1 mA or less is sufficient to avoid self-heating having a significant impact on measurement accuracy (Kerlin and Shepherd, 1982; see Table 3-3.5.1-1).

3-3.5.2 Response Time. Response time is the time required for a thermometer to reach a certain percentage of initial and final temperature values when subject to a step change in temperature. Time response is typically specified by time in seconds for 63.2% or 50% with details of the test medium and flow conditions. Due to the need for an RTD to be electrically isolated from the stem of the probe, it is typically going to respond to a change in temperature at a similar rate as an ungrounded thermocouple when directly exposed to the step change in temperature. The response time of resistance thermometers varies considerably depending on their construction.

Care should be taken to ensure proper immersion of the element sensing length into the process.

RTDs meeting ASTM E1137 or IEC 60751 will report type tests for response time in air or water (or possibly another fluid). The outcome of the test relies heavily on the heat transfer conditions, so it is important to understand the fluid type and velocity.

Slower response time will occur when used with a thermowell. It is recommended that the RTD diameter be close in size to the thermowell bore diameter (within 0.01 in./1 mm) and there is spring-loaded contact at the tip for applications where response time is critical.

3-3.5.3 Stability. The following considerations can lead to change in an RTD element that can impact stability:

(a) Strain in the platinum wire contained in a resistance element can cause a change in electrical resistance.
(b) A change in impurity concentration (such as oxidation) can affect the thermometric properties.
(c) IPRTs exhibit hysteresis on thermal cycling. Hysteresis is caused by
  (1) reversible changes in resistance from annealed to strained conditions in the platinum
  (2) moisture inside the encapsulation, which acts as a shunting resistance on the platinum wire

PRTs should be tested for stability with time on thermal cycling between extreme temperatures in the expected range of operation. There is some information that thin-film elements are less susceptible to hysteresis than wire-wound elements.

3-4 LESS COMMONLY USED RESISTANCE ELEMENTS

Platinum has been chosen as the resistor material for high-accuracy thermometers for the following reasons:

(a) The relation between resistance and temperature is linear over a wide temperature range.
(b) Its resistance is higher than other types of resistance thermometers.
(c) It maintains a stable output resulting in minimal drift over time.
(d) It is resistant to corrosion.
(e) It can be stress relieved (annealed) by heating to high temperature in air.
(f) It can be drawn to very fine wires.

Despite the prevalence of platinum, it is not the only resistor material used in industry. Copper, nickel, and iron resistors, among others, can be found in the field, especially in legacy applications.

3-4.1 Copper Resistance Thermometer

Copper has been used satisfactorily as a material for use in resistance thermometry. Its temperature coefficient is slightly greater than that of platinum. It can be secured commercially in a pure state, so that it is not difficult to match an established temperature-resistivity table. It is often encountered in stator-winding RTD measurements.

The resistivity–temperature curve is straight within narrow limits from about −60°F to 400°F (−51°C to 204°C), i.e., for copper, the curve becomes $R_t = R_0\,(1 + AT)$. Because of this linear characteristic, two copper resistance thermometers can be used for temperature–difference measurements where a compensator is used to match the resistances of the two thermometers, so that accurate measurements to within ±0.1°F (±0.05°C) can be made for temperature difference work.

3-4.1.1 Other features of copper resistance thermometers are as follows:

(a) They have a higher cost, primarily used in legacy noncritical applications.

(b) They do not perform well in oxidizing atmospheres.

(c) Their temperature is limited to −60°F to 500°F (−51°C to 260°C).

(d) Because of the low electrical resistivity of copper, the resistance ohm value is normally limited to 10 Ω.

(e) The 10-Ω element has an accuracy of ±0.2% at 77°F (25°C).

(f) The temperature coefficient of resistance (TCR) is 0.00427 Ω/Ω/°C.

3-4.1.2 The disadvantages of copper resistance thermometers are as follows:

(a) They tend to oxidize at higher temperatures.

(b) They have low resistance value compared to platinum or nickel.

(c) Their low commercial usage drives up cost per probe.

3-4.2 Nickel Resistance Thermometer

Nickel has also been used satisfactorily as a resistance thermometer material. Prior to the widespread adoption of platinum elements, nickel's lower material cost as compared with platinum provided it with a cost advantage in industrial measurements in its range of temperatures about −148°F to 572°F (−100°C to 300°C). Due to the much greater scale of platinum resistance element, manufacturing the nickel resistance element is no longer advantageous from a cost perspective.

A nickel resistor's upper limit is typically imposed by the materials used in insulating the nickel wire-enamel, silk, or cotton. The limit of error is dependent on the measuring circuit used and on the range. With a balanced bridge method of measurement, it is of the order of ±0.5°F (±0.28°C).

3-4.2.1 Other features of nickel resistance thermometers are as follows:

(a) They have similar characteristics to the copper element.

(b) They have higher cost legacy systems, used in noncritical applications.

(c) The common resistance values are 100 Ω and 120 Ω, with an accuracy of ±0.5% at 32°F (0°C).

(d) The TCR for the 100-Ω resistance is 0.00617 Ω/Ω/°C.

(e) The TCR for the 120-Ω resistance is 0.00672 Ω/Ω/°C.

(f) Nickel elements can be manufactured with resistance values in excess of 2KΩ. This allows the RTD to be used in a two-wire configuration as lead wire resistance has a significantly reduced impact on the overall accuracy.

3-4.2.2 The disadvantages of nickel resistance thermometers are as follows:

(a) They are less stable in their characteristics than platinum.

(b) They have a higher cost.

(c) Compatible instrumentation is less widely available.

3-4.3 Nickel–Iron Resistance Thermometer

Nickel–iron RTD is a legacy element, lower in cost than the pure nickel element but typically more expensive than a platinum element due to low demand. It is typically used in noncritical applications. Some of the features of nickel–iron RTD are as follows:

(a) Its temperature rating is limited to −148°F to 399°F (−100°C to 204°C).

(b) The most common resistance value is 604 Ω, with an accuracy of ±0.5% at 32°F (0°C). Other resistance values are available.

(c) The TCR is 0.00518 Ω/Ω/°C to 0.00527 Ω/Ω/°C.

Section 4
Principles of Operation for Filled-System Thermometers

4-1 SCOPE

The purpose of this Section is to present information that will guide the user in the selection, installation, and use of filled-system thermometers.

4-2 DEFINITIONS

Bourdon tube: a closed and flattened tube formed into a spiral, helix, or arc that changes in shape when internal pressure or volume changes are applied (Vander Pyl, 1953).

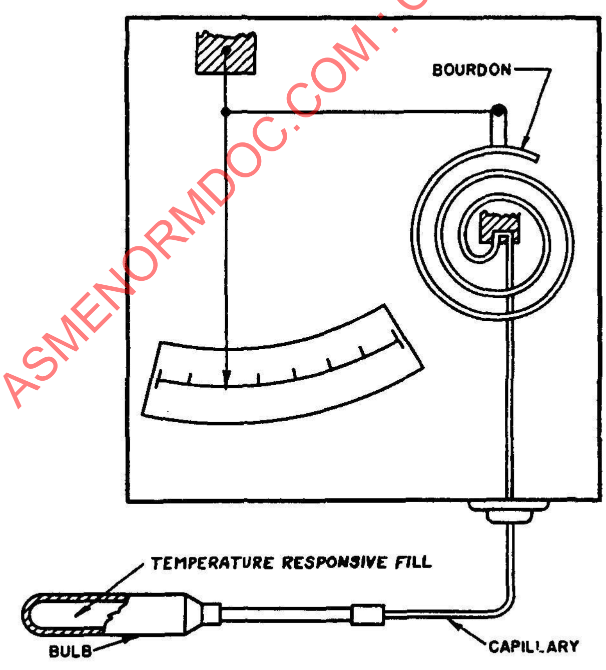
NOTE: In the interest of brevity, "Bourdon tube" is referred to hereafter as "Bourdon."

filled-system thermometer: an all-metal assembly consisting of a bulb, capillary tube, and Bourdon tube, containing a temperature-responsive fill. A mechanical device associated with the Bourdon tube is designed to provide an indication or record of temperature (see Figure 4-2-1).

4-3 PRINCIPLES OF OPERATION

The sensing element (bulb) contains a fluid or gas that changes in physical characteristics with temperature. This change is communicated to the Bourdon through a capillary tube. The Bourdon movement provides an essentially linear pointer motion through mechanical linkages in some instruments. Bourdon tube motion is directly related to

Figure 4-2-1
Filled-System Thermometer



(a) volume change of a liquid within the bulb
(b) pressure change of a gas within the bulb
(c) vapor pressure change of a volatile liquid within the bulb

4-4 CLASSIFICATION

4-4.1 General Classification

Filled-system thermometers may be separated into two fundamental types: those in which the Bourdon tube responds to volume changes and those which respond to pressure changes. The systems that respond to volume changes are completely filled with liquid. The liquid in the bulb expands with temperature to a greater degree than does the bulb metal, thereby producing a net volume change that is transferred to the Bourdon tube. The temperature span is dependent on the bulb volume. An internal system pressure change is always associated with the Bourdon tube volume change, but this effect is not of primary importance.

The system that responds to pressure changes is either filled with a gas or is partially filled with a volatile liquid. Changes in gas or vapor pressure with changes in bulb temperature are transferred to the Bourdon tube. The Bourdon tube will increase in volume with an increase in pressure, but this effect is not of primary importance.

Based on these two fundamental principles of operation, filled-system thermometers have been classified as follows (SAMA Standard PMC 6-10-1963):

(a) *Volumetric Principle:*
Class I, Liquid-Filled System

(b) *Pressure Principle:*
Class II, Vapor-Filled System
Class III, Gas-Filled System

4-4.2 Subclassification

4-4.2.1 Liquid-Filled Thermal System (Class I). Class I is a thermal system completely filled with a liquid and operating on the principle of liquid expansion.

The system is usually compensated for ambient temperature effects either

(a) with full compensation (Class IA), the compensation means being a second thermal system minus the bulb, or equivalent means of compensation (see Figure 4-4.2.1-1)

(b) with compensating means within the case only in the form of a bimetal compensator usually sized for compensation at mid-range (Class IB) (see Figure 4-4.2.1-2)

4-4.2.2 Vapor Pressure Thermal System (Class II). Class II is a thermal system partially filled with a volatile liquid and operating on the principle of vapor pressure. The following four types are employed:

(a) Class IIA is designed to operate with the measured temperature above the temperature of the rest of the thermal system, above ambient temperature (see Figure 4-4.2.2-1).

(b) Class IIB is designed to operate with the measured temperature below the temperature of the rest of the thermal system, below ambient temperature (see Figure 4-4.2.2-2).

(c) Class IIC is designed to operate with the measured temperature above and below the temperature of the rest of the thermal system, cross ambient. This type normally requires a larger sensitive portion than Class IIA or Class IIB (see Figure 4-4.2.2-3).

(d) Class IID is designed to operate with the bulb temperature above, below, and at the temperature of the rest of the thermal system, ambient and cross ambient (see Figure 4-4.2.2-4). In this type, the volatile liquid is confined to the sensitive portion, and a second relatively nonvolatile liquid is used to transmit the vapor pressure to the expansible device.

4-4.2.3 Gas-Filled Thermal System (Class III). Class III is a thermal system filled with gas and operating on the principle of pressure change with temperature change. The system is either compensated for ambient temperature effects or is designed to have low effect due to changes in ambient temperature. Compensating means include the following:

(a) with a second thermal system minus the bulb, or equivalent means of compensation (Class IIIA; see Figure 4-4.2.1-1).

Figure 4-4.2.1-1
Fully Compensated Liquid, Mercury, or Gas-Filled Thermal System — Class IA, Class IIIA, or Class VA

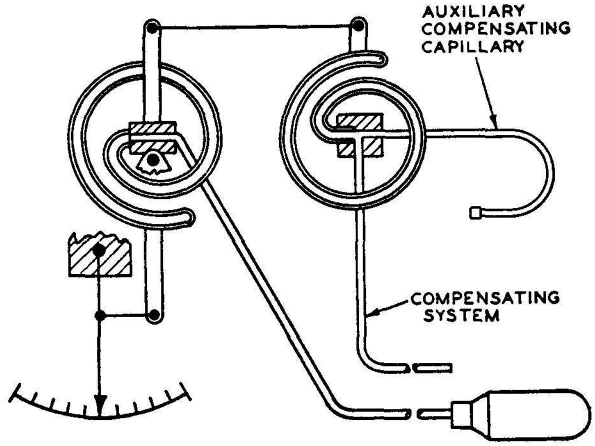


Figure 4-4.2.1-2
Fully Compensated Liquid, Mercury, or Gas-Filled Thermal System — Class IB, Class IIIB, or Class VB

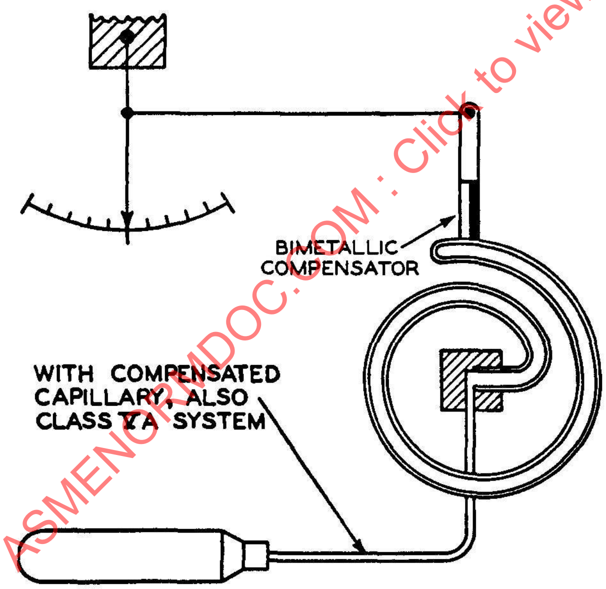


Figure 4-4.2.2-1
Vapor Pressure Thermal System — Class IIA

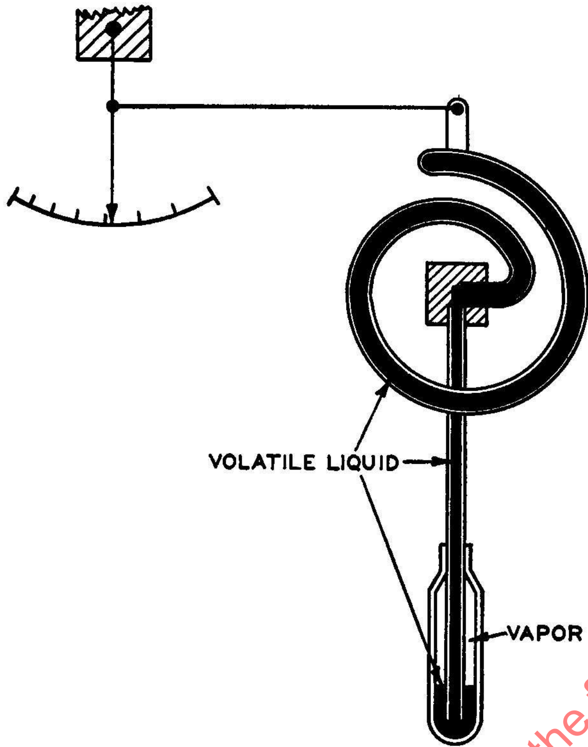


Figure 4-4.2.2-2
Vapor Pressure Thermal System — Class IIB

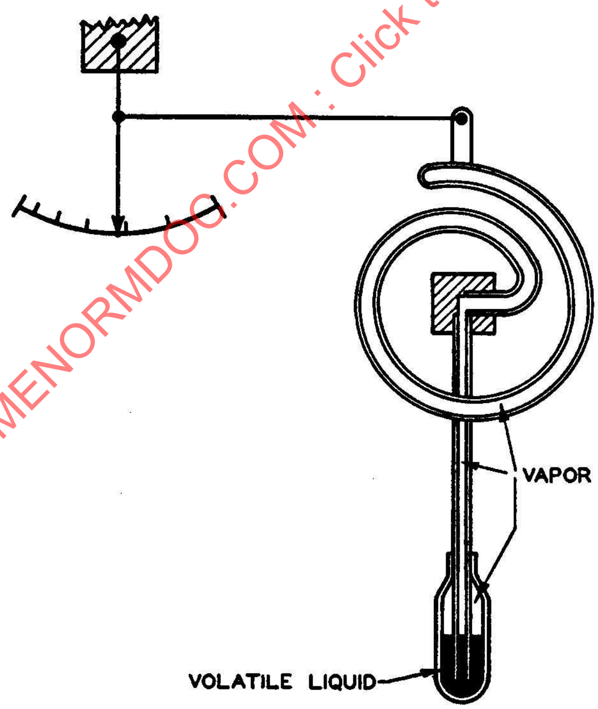


Figure 4-4.2.2-3
Vapor Pressure Thermal System — Class IIC

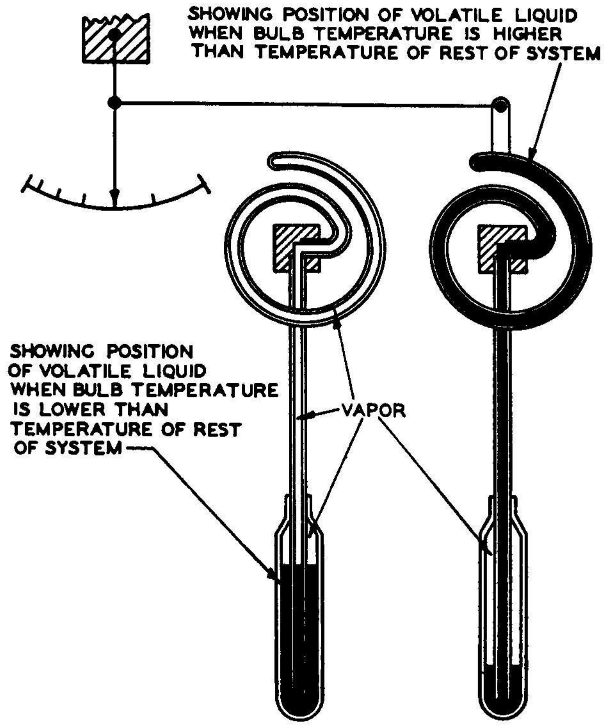
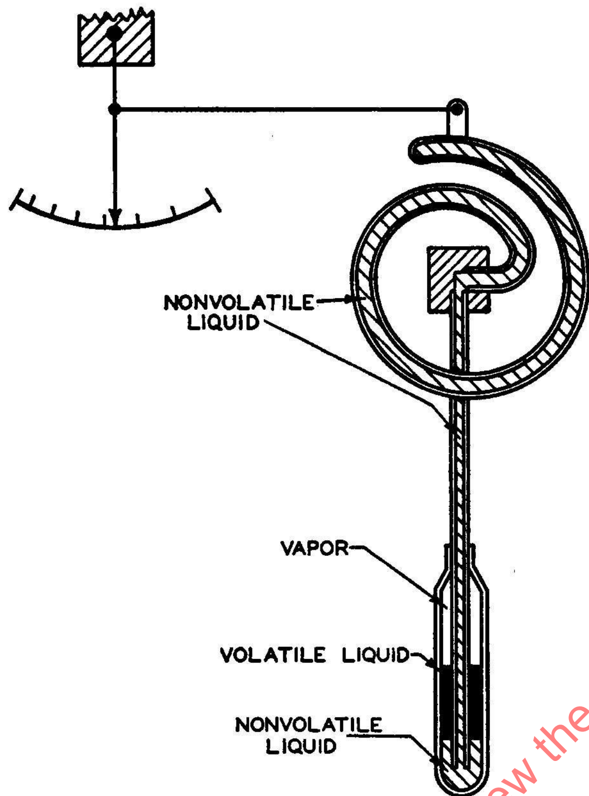


Figure 4-4.2.2-4
Vapor Pressure Thermal System — Class IID



(b) with compensating means within the case only (Class IIIB; see Figure 4-4.2.1-2). Low ambient temperature construction consists of the following:

(1) very low volume in the capillary and Bourdon compared to the bulb volume

(2) a Bourdon material that has a low change in the elastic properties with temperature

(3) including activated carbon in the bulb to adsorb the gas and effect a greater pressure change than otherwise due to the gas laws

4-5 DESCRIPTION

4-5.1 Bulb Size

The bulb size of the various thermal systems varies greatly (approximately 100 to 1) depending on system class, temperature span, and capillary length. Table 4-5.1-1 provides a guide in determining the size of the bulb. Considerable variation in bulb size exists among the various manufacturers. The basic reasons for the variations in bulb size are briefly described in Table 4-5.1-1.

Liquid-filled systems (Class I), which operate on the principle of liquid expansion in the bulb, have a bulb internal volume that is inversely proportional to temperature span. Therefore, larger temperature spans will require smaller bulbs. Since the temperature span of a liquid-filled system (Class I or a Class V) may vary by 25 to 1, the bulb size will vary accordingly.

The bulb size for all types of vapor systems (Class II) also varies greatly but for different reasons. The pressure within the system to which the Bourdon tube responds is the vapor pressure at the interface of the liquid and vapor. The interface must always be located in the bulb. The fill will always be in a liquid state at the coolest parts of the system. The system must be filled so that the liquid in the bulb will not completely vaporize nor completely fill the bulb under any conditions of bulb or ambient temperature.

Table 4-5.1-1
Approximate Bulb-Sensitive Dimensions

System Class	Fill	Outside Diameter, in.	Length, in.	Remarks
IA and IB	Liquid	$^{9}/_{16}$	3	50°F span
	Liquid	$^{3}/_{8}$	$2^{1}/_{2}$	275°F or greater span
IIA	Vapor	$^{9}/_{16}$	4	...
IIB	Vapor	$^{3}/_{8}$	2	...
IIC	Vapor	$^{9}/_{16}$	6	...
IID	Vapor	$^{9}/_{16}$	4	...
IIIA and IIIB	Gas	$^{7}/_{8}$	10	Based on 75-ft capillary
VA and VB	Mercury	$^{9}/_{16}$	$2^{1}/_{2}$	50°F span or greater span
	Mercury	$^{11}/_{16}$	4	100°F span

For Class IIB, a bulb always below ambient temperature, the system requires that liquid exists only in the bulb. Since the vapor density in the capillary and Bourdon tube is affected only slightly by ambient temperatures, the bulb may be very small, as indicated by the dimensions in Table 4-5.1-1. Whereas the bulb may be as small as illustrated, it is frequently supplied in a large size in order to reduce the number of bulb sizes.

For Class IIA, the bulb always above ambient temperature, the system bulb must be slightly larger in order to accommodate the liquid expansion within the capillary and Bourdon tube, resulting from ambient temperature variations. The standard bulbs of a particular manufacturer may be larger or smaller than specified in Table 4-5.1-1.

A Class IIC system bulb needs to accommodate the entire capillary and Bourdon tube volume when the bulb temperature becomes equal to the temperature of the capillary and Bourdon tube (see Figure 4-4.2.2-3). Therefore, the bulb size is generally larger than that of the Class IIA system; it is also dependent on the capillary length. The bulb size can be minimized by having a small amount of liquid in the bulb at the top of the range; this technique is called limit filling.

A Class IID system bulb must have an internal trap of such dimensions that the volatile liquid will not enter the capillary under all values of ambient temperature (i.e., the trap must accommodate the nonvolatile liquid expansion under all values of ambient temperature). The capillary and Bourdon tube are filled with a liquid having a low vapor pressure at ambient temperature, and the bulb is filled with the volatile liquid-vapor. This technique is called dual filling (see Figure 4-4.2.2-4).

The gas-filled system (Class III) generally requires a large bulb in order to minimize errors caused by ambient variations on the capillary and Bourdon tube. This error is also increased as the span is reduced and as the bulb temperature is raised due to increased pressure in the capillary and Bourdon tube. Approximate bulb sizes for various temperature spans and capillary lengths are specified in Table 4-5.1-1. A further restriction based on the bulb temperature may be obtained from the manufacturer. Several manufacturers have been able to design very small bulb gas thermometers. Bulb size in these designs is 3 in. to $3^{1}/_{2}$ in. long and $^{3}/_{8}$ in. in diameter. Temperature ranges vary from −320°F (−196°C) to 100°F (212°C), to 400°F (204°C) to 1,200°F (649°C).

Over-range protection is defined as the maximum temperature to which the bulb of a filled system may be exposed indefinitely without damage to the system. It is usually expressed in percent of temperature span above the upper limit of the range. A summary of the extent of over-range protection for filled-system thermometers of the various types is specified in Table 4-5.1-2.

The over-range protection of liquid systems (Class IA) varies with capillary length. Generally, it is in the region of 100% to 200% of the temperature span for short systems. For long systems, because the capillary volume generally approaches the bulb volume, the capillary volume change with ambient temperature change neutralizes the over-range possibilities of the Bourdon tube, thus reducing the over-range protection to essentially zero for systems 200 ft (60.96 m) long.

Liquid systems (Class IB) are generally provided with over-range protection of 100% of temperature span. Some thermometers are provided with greater over-range protection, depending on the manufacturer.

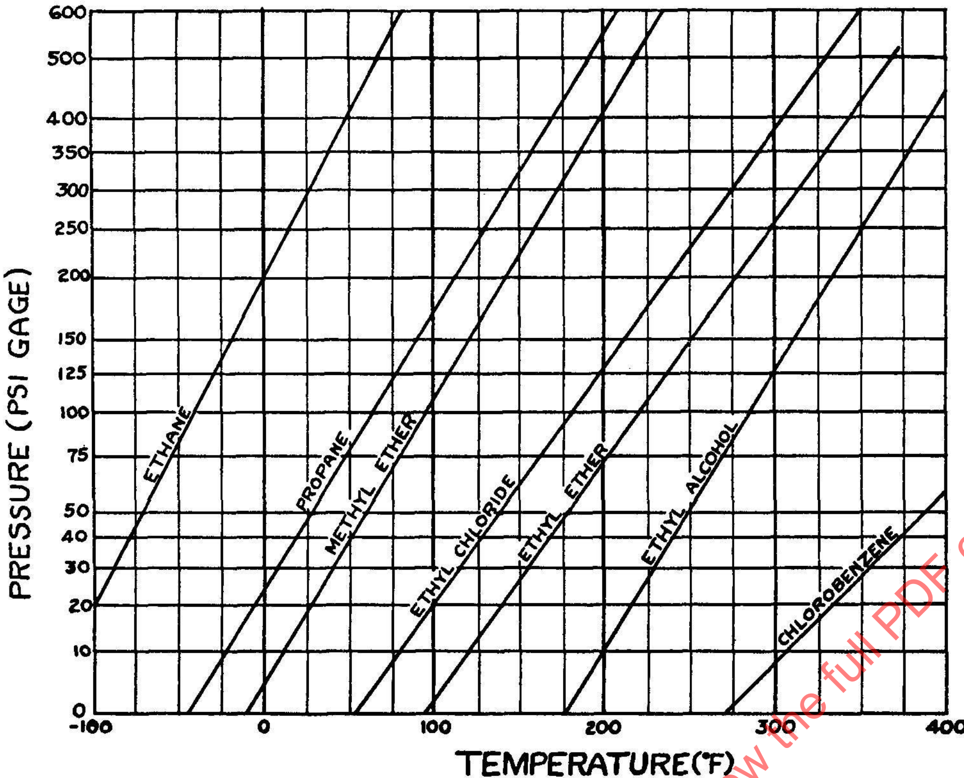
In vapor pressure thermal systems (Class II), over-range protection is generally more limited than in other systems because of the increasing rate of vapor pressure rise with temperature rise. Typical vapor pressure temperature relationships are shown in Figure 4-5.1-1. A specific over-range temperature for each range offered is usually specified by the manufacturer. This is generally appreciably less than 100% of temperature span. If the upper limit of range is near the critical point of the fluid fill, the over-range protection may be extended because of the fill being a vapor above the critical point. When limit filling is used as described above, it is possible to fill the system so that all of the liquid will be exhausted

Table 4-5.1-2
Comparison of Thermal Systems

Operating Principle	Liquid Expansion				Pressure Change	
Type	**Liquid Filled**		**Mercury Filled**		**Vapor Pressure**	**Gas Filled**
Class	**Class IA**	**Class IB**	**Class VA**	**Class VB**	**Class IIA, IIB, IIC, and IID**	**Class IIIA and IIIB**
Low-temp limit	−300°F (−148.9°C)	−300°F (−148.9°C)	−38°F (−3.3°C), −65°F (−18.3°C)	Hg–Th eutectic	−40°F (4.4°C)	−400°F (−240°C)
High-temp limit	600°F (315.6°C)	600°F (315.6°C)	1,200°F (648.9°C)	600°F (315.6°C)	600°F (315.6°C)	1,500°F (815.6°C)
Longest span	600°F (315.6°C)	600°F (315.6°C)	1,000°F (537.8°C)	600°F (315.6°C)	300°F (148.9°C)	1,000°F (537.8°C)
Shortest span	25°F (−3.9°C)	25°F (−3.9°C)	40°F (4.4°C)	40°F (4.4°C)	40°F (4.4°C)	100°F (212°C)
Bulb size						
— Long span	Smallest	Smallest	Intermediate	Intermediate	Intermediate	Large
— Short span	Intermediate	Intermediate	Large	Large	Intermediate	Large
Dial or chart divisions	Equal	Equal	Equal	Equal	Larger at range top (also equal with separate linkage)	Equal
Maximum standard capillary length (approximate)	200 ft (60.96 m)	15 ft (4.57 m)	200 ft (60.96 m)	25 ft (7.62 m)	200 ft (60.96 m)	200 ft (60.96 m)
Capillary temperature compensation	Dual capillary and Bourdons	None	Compensated capillary or dual capillary and Bourdons	None	None necessary	Generally none, rarely, dual capillary and Bourdons
Case temperature compensation	Second Bourdon	Bimetal strip	Second Bourdon	Bimetal strip	None necessary	Bimetal strip; rarely a second Bourdon
Bulb elevation error	Negligible	Negligible	Generally small	Negligible	Frequently large	Negligible
Over-range capacity	Varies with length 200% to 0% range	100% of range	100% of range	100% of range	Generally small	Varies with range, up to 300% of range
Speed of response	Slowest in water; intermediate in air	Slowest in water; intermediate in air	Intermediate in water; slowest in air	Intermediate in water; slowest in air	Fastest to intermediate	Varies widely with bulb diameter
Barometric errors	Negligible	Negligible	Negligible	Negligible	Usually small	Usually small

GENERAL NOTE: Dimensions are to be used as a guide only and will vary in O.D. and length with manufacturer. Functional values also vary with manufacturer. For more detail, see Table 4-5.1-1.

Figure 4-5.1-1
Vapor Pressure–Temperature Curves



from a bulb at a bulb temperature above the instrument range, in which case the safe over-range temperature can be increased.

The nonlinear vapor pressure–temperature relationship is an advantage where the user desires more reading sensitivity toward the top of range.

The over-range protection of a gas system (Class III) will be reduced for short range temperature spans because of the higher internal pressures of these systems. Since the protection offered varies considerably for various system ranges and manufacturers, the over-range protection should be obtained from the manufacturer. Generally, 25% to 50% over-range capability is offered.

The Bourdon tube motion is normally amplified by a mechanical linkage or gear system to drive a pointer for temperature indication or to drive a pen for recording the temperature signal. A direct drive Bourdon tube may be used without amplification in indicating instruments. Bourdon tubes are generally used in industrial filled-system thermometers. Other devices such as bellows and diaphragms are frequently used; however, the large volumetric change in these devices is limiting. In the previously mentioned small bulb gas designs, the Bourdon tube is in the form of a coil. The conventional links and gears used in most designs to transmit Bourdon tube motion to the pointer are eliminated. Pointer drive is either direct or accomplished through magnetic coupling. In conventional designs, the Bourdon is in the case. Thus, any failure of the indicating mechanism requires the entire instrument to be replaced, since the thermal system cannot be severed without destroying it.

4-6 MATERIALS OF CONSTRUCTION

4-6.1 Bulb Materials

Among standard bulb materials listed in most manufacturers' catalogs are bronze, copper, steel, SAE alloy steels, and Types 304, 347, and 316 stainless steel. Optional materials, such as nickel, Monel, Inconel, Hastelloy, and silver, are available. Some manufacturers supply bulbs made of externally finned tubing designed to increase the response to temperature changes; similarly, bulbs having a high surface-to-volume ratio, such as small diameter long length, increase the temperature response time.

4-6.2 Thermowell Materials

Standard bushing and well materials are generally confined to brass, steel, and Types 304 and 316 stainless steel. Optional materials, such as aluminum, cast iron, nickel, Monel, Inconel, Hastelloy, and silver, are also available.

4-6.3 Capillary Materials

The capillary is commonly of a small outside diameter [approximately $^1/_{16}$ in. (1.5875 mm)] protected by a flexible armor of bronze, plated steel, or stainless steel or an armor covered with a plastic, such as polyethylene, for corrosion resistance. Capillary materials normally consist of copper or stainless steel. Stainless steel (Type 304 or Type 316) and Inconel capillaries of $^1/_8$ in. (3.175 mm) O.D. and copper capillaries of $^3/_{16}$ in. (4.76 mm) O.D. are frequently employed without armor protection.

4-7 CHARACTERISTICS

4-7.1 Maximum and Minimum Temperatures

The minimum temperature of liquid-filled systems (Classes I and V) is limited by the freezing point of the fluid fill. The maximum temperature of liquid-filled systems is limited by the vapor pressure if higher than the internal pressure. See Table 4-5.1-2.

The organic liquids employed in Class I systems freeze between −100°F (−73°C) and −300°F (−184°C), depending on the liquid used. The maximum temperature of the organic liquid system (Class I) is limited by the upper temperature at which the organic liquid remains chemically stable and does not vaporize, which is approximately 600°F (315.56°C).

The minimum temperature of the vapor pressure system (Class II) is limited by the filling materials. Materials are available for temperatures as low as −430°F (−257°C). The maximum temperature is limited by chemical instability of organic liquids to approximately 600°F (316°C) and also by the critical temperature above which pressure no longer expands logarithmically.

The minimum temperature of the (Class III) must be above the boiling point of the gas employed, which for commonly used helium is −451°F (−268°C). The upper temperature is usually limited to 1,000°F (538°C), but gas systems have been made to operate successfully up to 1,500°F (816°C).

4-7.2 Range

The minimum range of the organic liquid system (Class I) is limited by maximum bulb size to approximately 25°F (−4°C). Because of nonlinearity of expansivity and compressibility of the organic liquids employed, the maximum range is frequently limited to 200°F (93°C) to 400°F (204°C), because of differences in manufacture, so that a specified accuracy may be met with linear dials or charts.

The range of a vapor system (Class II) is limited by low and high temperatures of 40°F (4°C) and 600°F (316°C), respectively, for the reasons discussed in para. 4-7.1. However, the nonlinear vapor pressure–temperature relationship is accentuated by greater ranges, and the range is therefore normally limited to approximately 350°F (177°C).

Because the pressure within a gas system (Class III) essentially follows Charles' Law, (i.e., absolute pressure is proportional to absolute temperature), it is characteristic of this system that the shorter the range, the higher will be the internal system operating pressure. This condition limits the minimum range to approximately 120°F (49°C). When activated carbon is used in the bulb, a span as low as 60°F (16°C) is achievable. The maximum range is limited only by the upper temperature, usually 1,000°F (538°C) to 1,200°F (649°C), although longer ranges generally require larger bulbs to provide an adequate linear output. Small bulb and large bulb gas thermometers capable of operating up to 1,200°F (649°C) are available. A nonlinear scale is used in some designs to eliminate the nonlinear output effect.

4-7.3 Sensitivity

The Bourdon tube of a filled system will respond to the smallest measurable change in bulb temperature. Therefore, the output for small temperature changes is affected only by friction or loose fits in the mechanical apparatus, which transforms Bourdon tube motion into pointer or pen motion. The backlash in mechanical gearing and links usually is greater than 0.1%; thus, the sensitivity may be on the order of 0.25% of range span. In the designs where mechanical linkages are reduced or eliminated, sensitivity may be affected by highly viscous oil that is put on the Bourdon tube coil to damp shock and vibration effects. Sensitivity in these designs is no better than above.

4-7.4 Accuracy

Filled-system thermometers are normally regarded as 1.0% instruments. This means that under most environmental conditions of case or capillary ambients, the error will not exceed 1% of temperature span. However, many instruments are calibrated to higher accuracy, and in indoor applications, the maximum error is frequently specified as 0.5% of temperature span. Accuracy may be only 2% or 3% when thermometers are used in environments where the case and capillary temperature vary considerably from usual room temperature, e.g., case or capillary temperature can be as low as 60°F (16°C) and as high as 160°F (71°C) in some power plant applications. The reduction of accuracy is caused by the inability of the compensation devices to completely compensate for ambient temperature changes. Direct mount thermometer cases, which are attached directly to the bulb, are exposed to heat conducted along the thermometer stem and also to heat radiated by nearby pipes. Capillaries wound around boiler casings are also subjected to high ambient temperatures. Thermometers used outdoors could be subjected to very low ambient temperatures. Accuracy is also affected by mechanical backlash and mechanical and fluid friction. For vapor-type-filled systems, the scale is nonlinear, and it is recommended to use in the upper half of the range; accuracy is stated as one scale division as the divisions change over the entire range.

4-7.5 Temperature Compensation

Since the capillaries and Bourdons as well as the bulbs of thermal systems are filled with actuating fluid, these portions of the system are sensitive to ambient temperature. Therefore, system errors will result because of ambient temperature variations, unless compensation means are employed.

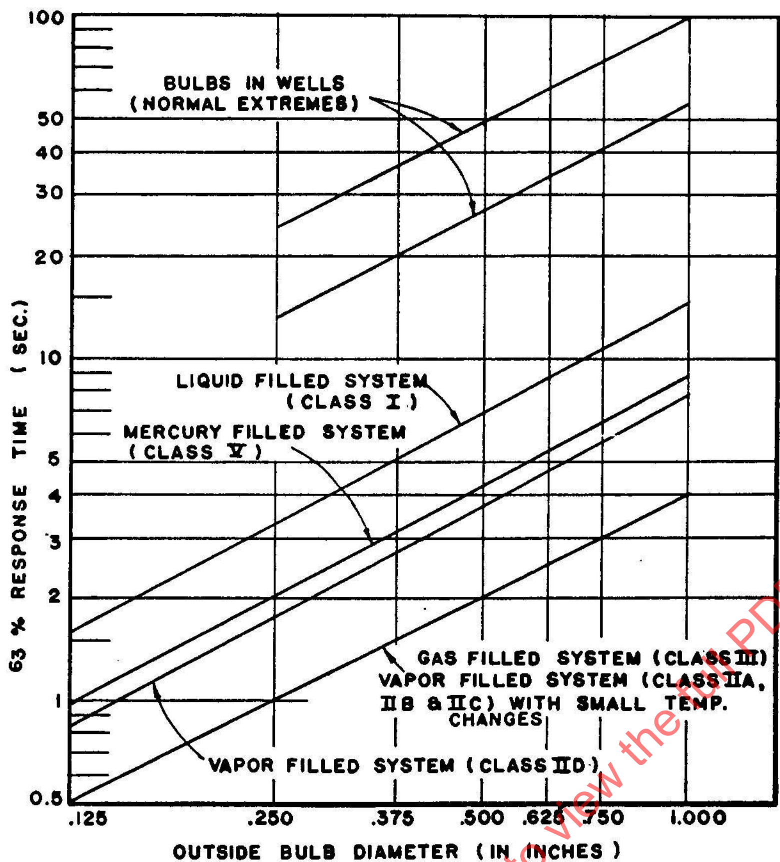
The vapor-filled system (Class II), as an exception, is not subject to errors from the fluid fill. The only temperature error observed in this system is of small magnitude; it is caused by change of Modulus of Elasticity of the Bourdon material with temperature and is usually ignored.

The liquid- and gas-filled systems (Classes I and III) are provided with full compensation (the capillary and Bourdon compensated) by means of an auxiliary system less the bulb (see Figure 4-4.2.1-1). The capillary and Bourdon tube volumes of the auxiliary system are essentially equal to the corresponding volumes of the primary system. This arrangement permits the erroneous response to be opposed by an equal erroneous response, thus providing full temperature compensation. These systems with full compensation are classified by SAMA standards as IA, IIIA, and VA systems, respectively (see Sections 8, 10, and 11). The error tolerance of these systems is specified by the manufacturer and usually equal to or less than ±l% of range for an ambient temperature change of ±50°F (±10°C) and for a capillary length of 100 ft (30.5 m), i.e., 0.0002% of range per foot per degree Fahrenheit). Other methods of compensation, as discussed previously, are also used and probably more common. The error tolerance of these systems should be equal to or less than 1% of range span for an ambient temperature change of ±50°F (±10°C) and for a capillary length of 100 ft (30.5 m) or less. Uncompensated gas-filled systems using a low-volume capillary and Bourdon and a Bourdon material having a low-temperature coefficient of elasticity should have the same ambient error 0.5% per 50°F (10°C).

Because the capillary error of a gas system (Class III) is reduced as the bulb size is increased, the Class IIIA system that has full compensation is rarely built. Gas-filled systems are therefore generally limited to the Class IIIB type, where only the case is compensated.

The liquid and gas systems with case compensation only (Classes IB, IIIB, and VB) are frequently employed because of the simplicity of construction. The capillary bore size is reduced to a point where system response is not seriously affected in order to minimize the capillary temperature error. The Bourdon of these systems is compensated by means of a bimetallic strip (see Figure 4-4.2.1-2). These systems are employed when the capillary length may be sufficiently short or when the ambient temperature range is sufficiently small that the capillary error may be ignored. In practice, the capillary error of a liquid-filled system (Class IB) is in the range of 0.003% to 0.005% range per foot per degree Fahrenheit, depending on the manufacturer. The length of these systems is normally limited to 20 ft (6.1 m). The capillary temperature error of the gas system (Class IIIB) varies with length, range, and bulb size. It is therefore recommended that this information be obtained from the manufacturer.

Figure 4-7.6-1
Bulb Response Versus Bulb O.D. in Water (Velocity of 2.5 fps)



4-7.6 Response

The response of a thermal system is usually determined by the response of the bulb because the lag in the capillary is generally equal to or less than 1 sec; the 63% response time for the bulbs of the various types of thermal systems in water, with a velocity of 2.5 ft/sec (0.762 m/s), is approximated by the curves of Figure 4-7.6-1. The 63% response time in air at various velocities for typical bulb sizes is given by the nomograph of Figure 4-7.6-2. See Section 1 for installation procedures to obtain optimum response.

A bulb will respond faster if the following fundamental design factors are employed:

(a) Increase the external area relative to the internal volume.

(b) Lower the heat capacity.

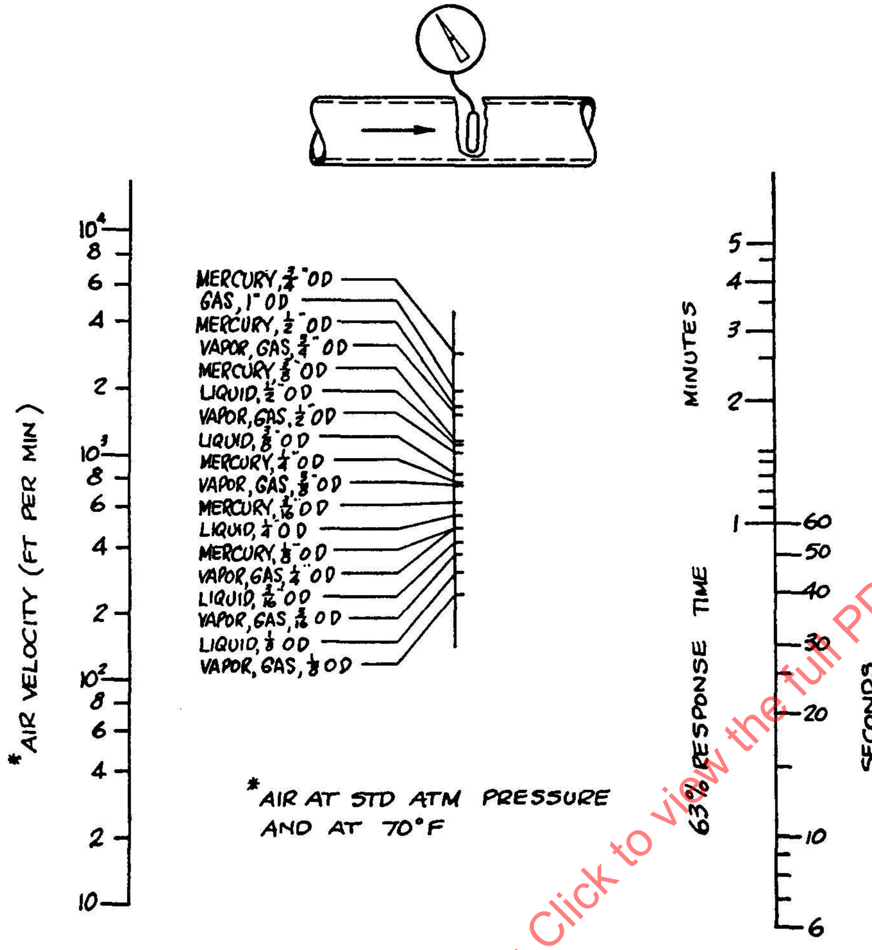
(c) Increase the thermal conductivity of the bulb walls and internal fill.

The gas system (Class III) is frequently the most favorable because the bulb can usually be made with a relatively thin wall, and the heat capacity of the internal gas is almost negligible. However, the large bulb size frequently required tends to offset this natural advantage. The small bulb gas thermometers are somewhat faster in response than conventional larger bulb gas thermometers.

The vapor systems (Classes IIA, IIB, and IIC) have almost equally favorable response because the heat capacity of the volatile fluids employed is low, and the thermal conductivity is high. This is particularly true for small temperature changes because under these conditions, condensation and evaporation of the fill will take place on the internal bulb walls. The Class IID vapor system has a somewhat slower response because of the presence of the internal bulb trap and, in some cases, because of the increased viscosity of the nonvolatile liquid fill.

The liquid systems (Class I) have the slowest response because of the increased mass and poorer conductivity of the fluid fill. Some manufacturers incorporated fin-like copper disks on liquid-filled bulbs to enhance heat transfer.

Figure 4-7.6-2
Bulb Response Rate in Air at Various Velocities



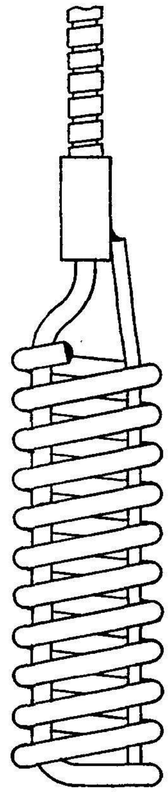
Capillary bulbs with outside diameters of $^1\!/_{16}$ in. (1.5 mm) to $^3\!/_{16}$ in. (4.8 mm) are sometimes employed to provide rapid response. Response is nearly directly proportional to the bulb's outside diameter. These bulbs are frequently coiled by the manufacturer (preformed capillary bulb), providing compactness for installation. A typical bulb form is shown in Figure 4-7.6-3. A long capillary bulb [up to 200 ft (61 m) in length] is sometimes left uncoiled to measure average temperature along its installed length. Class I, III, and V systems may be employed in this manner. In the case where the coil is adjusted as with uncoiling to wrap around a pipe or extend across an air duct, vapor systems are employed, as the change in the volume of the bulb has little effect on the output.

4-8 ACCESSORIES

The Bourdon tube motion of filled-system thermometers is usually amplified by a simple linkage, as shown in Figure 4-2-1, to drive the pointer of an indicator or the pen of a recorder. In dial thermometers, greater angular motion of the pointer, usually 270-deg angular displacement, is achieved by a "movement." The most common movement employs a geared sector to drive a pinion to achieve angular amplification.

In temperature transmitters, the temperature signal is converted to a pneumatic or electrical signal, and this signal in turn is communicated to a recorder or other readout device. Transmitters provide the means of transmitting temperature information over long distances. In the case of the pneumatic transmitter, the Bourdon tube is usually replaced by a diaphragm that will exert a force responsive to bulb temperature. This force in turn is balanced by a feedback force of a pneumatic servo, the feedback force being generated by the transmitter pressure. Similarly, in an electrical transmitter,

Figure 4-7.6-3
Preformed Capillary Bulb



the filled-system force is balanced by a force that is generated by an electrical current. In other electrical transmitters, the Bourdon tube motion directly operates the core of a differential transformer for A-C output, or the force from a Bourdon tube actuates a strain gage for DC output.

4-9 APPLICATION AND INSTALLATION

4-9.1 Sources of Error

4-9.1.1 Zero Shift Error. Filled-system thermometers are subject to mechanical abuse during shipment, which may cause an error in the calibration. The user, therefore, should check the instrument calibration and make corrections. A calibration error associated with shipment is usually confined to a "zero" shift, in which the entire range is shifted up or down, which may be corrected by a simple screw adjustment or with an adjustable pointer. However, a severe shock could cause a permanent shift in the Bourdon tube or misalignment of the linkage. In this case, the change in calibration would not necessarily be uniform over the entire range.

4-9.1.2 Conduction and Immersion Error. The bulb of a filled-system thermometer must be completely immersed in the medium in which the temperature is being measured. If this is not done, a significant portion of the filling medium volume can be at a different temperature than that which is being measured. Errors due to improper immersion can be extremely large. The bulb should be immersed so that not only the filling fluid reservoir is immersed but also a sufficient amount of the bulb extension, to prevent heat conduction to or from the sensitive portion. The amount of extra immersion varies as the heat transfer and temperature environment varies, e.g., a thermometer with a 3-in. (76-mm) sensitive portion length and being used to measure temperature as high as 1,000°F (538°C), the bulb should be immersed about 5 in. (127 mm). Heat transfer from un-immersed portions of the thermometer should be reduced when measurements are being made in a medium having low heat transfer capabilities. The entire sensitive portion should be immersed in the flowing fluid when thermometers are used in forced convection applications.

4-9.1.3 Capillary Immersion Error. The capillary of all system types except vapor systems (Class II) is temperature sensitive. Dual capillary systems are frequently used in liquid systems (Class IA), and compensated capillary is used in mercury systems (Class VA). These compensating means are imperfect, and the instrument output reading will vary with length of capillary immersion. If the immersion length is greater than 8 in. (203.2 mm), the immersion length should be specified to the manufacturer, or the instrument should be adjusted by the user under the conditions of the application. Small bulb, liquid-filled thermometers are more affected by capillary immersion than larger bulb designs, e.g., on a liquid-filled thermometer with a 3 in. × $^3/_8$ in. (76 mm × 9.5 mm) bulb and a range of 400°F (204°C) to 1,200°F (649°C), no more than 2 in. (50.8 mm) of capillary should be immersed.

4-9.1.4 Bulb Elevation Error. When the Bourdon elevation of a liquid- or vapor-filled system is changed relative to the bulb, a pressure head caused by the column of the fluid fill is generated within the system. This pressure redistribution causes a small volume change of the fluid and of the bulb and capillary, thereby causing a system error. If the bulb is to be elevated more than 25 ft (7.6 m) above the case, it is desirable for the manufacturer to know the above elevation to increase the pressure of the system so that the bulb pressure will not drop to zero after installation.

The elevation error is nonexistent in a gas system (Class III).

If the Bourdon is above the bulb in a vapor system (Class IIA or Class IID), the pressure within the Bourdon equals the vapor pressure in the bulb minus the liquid pressure head in the capillary. This means that the bulb elevation error is equal to the ratio of the liquid head to the internal vapor pressure change across the temperature span. This further confirms that it is advantageous for the manufacturer to provide systems having a relatively large internal pressure. If the bulb elevation relative to the case is 20 ft (6 m), it is advisable for the user to specify this elevation or depression to the manufacturer so that he will calibrate the instrument accordingly. The vapor system (Class IIC) will have liquid within the capillary only over part of the range span and is, therefore, not recommended when the bulb and case are at appreciably different elevations. The instrument cannot read correctly for bulb temperatures both above and below the capillary case temperature.

4-9.1.5 Barometric Error. This error is essentially nonexistent for systems operating on the volumetric principle, i.e., for the liquid-filled system (Class I). Vapor systems (Class II) and gas systems (Class III) operating on the pressure principles are sensitive to barometric pressure changes by the ratio of barometric pressure change to the internal pressure corresponding to the range. Therefore, these systems are designed to have a minimum pressure change of 100 psi (7 bar) for the range of the thermometer. Since the maximum barometric pressure change is approximately ±0.4 psi (±0.03 bar), this error will be equal to or less than 0.4% of range.

4-10 ESSENTIAL CONSIDERATIONS

A thermal system is generally installed in a vessel by means of a union connection, a flange, or a combination of union connection and flange. A thermowell is recommended for high-pressure pipe or tanks and also it is convenient to use thermowells if replacement or recertification is expected. See Figure 4-10.1-1.

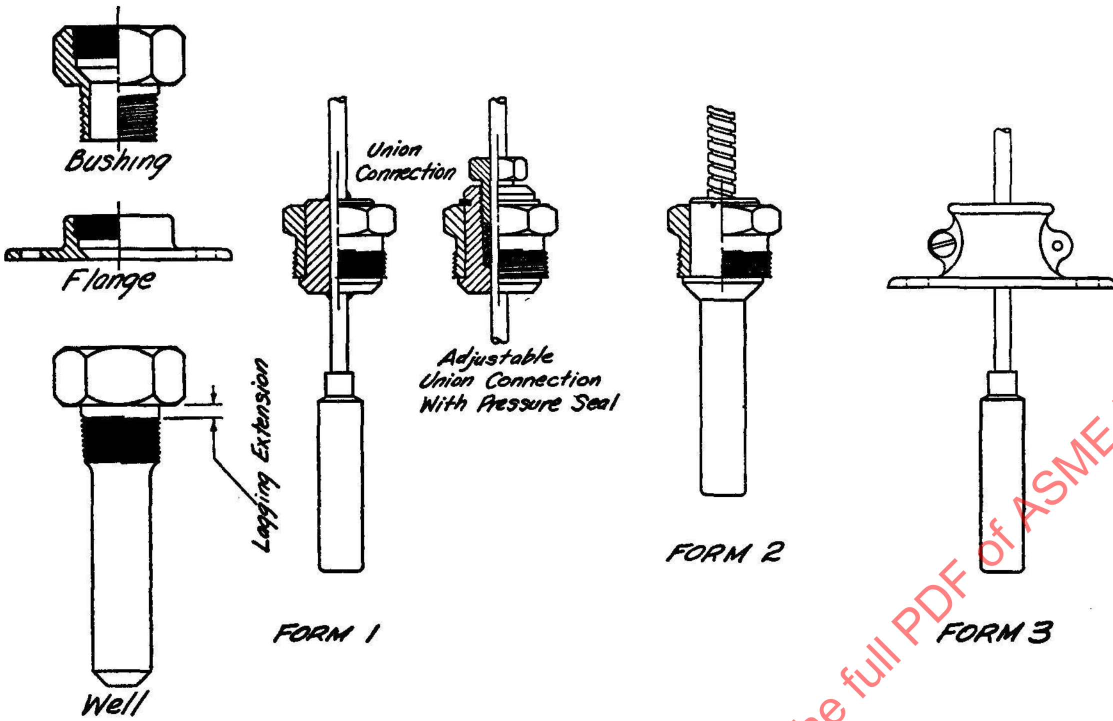
Form 1 in Figure 4-10.1-1 is employed when it is desired to attach to the equipment by means of a bushing or flange (in which case the bulb is exposed) or when it is desired that the bulb be protected by insertion into a well. If it is not necessary to have the union connection adjustable along the extension, the union is attached to the extension by soldering, brazing, or welding to provide a pressure-tight joint. However, when it is necessary to have the union adjustable along the extension, particularly when mounting in a bushing to provide a pressure-tight seal, the union connection is provided with an additional pressure seal as shown in Figure 4-10.1-1.

Extension stems may be provided between the bulb-sensitive portion and the union in Form 2 in Figure 4-10.1-1 or between the external threads of the bushing or well and the hex nut. The external threads of bushings and wells have been standardized as $^1/_2$ NPT, $^1/_4$ NPT, and 1 NPT.

A relatively inexpensive mounting into equipment where pressure tightness is not important is illustrated by Form 3 in Figure 4-10.1-1. The flange is generally split so that it may be attached to or removed from the completely fabricated thermal system.

The pressure rating of the fittings is specified by the manufacturer and generally 100 psig (7 barg). If higher ratings are necessary, special fittings or thermowells must be supplied. The well ratings follow no established code. The manufacturer's well ratings will vary from 1,000 psi (70 barg) to 5,000 psi (345 barg), depending on material and design.

Figure 4-10.1-1
Attachment of Thermal Systems to Vessels



4-11 ADVANTAGES AND DISADVANTAGES

4-11.1 Advantages

(a) System construction is rugged. The amount of upkeep is generally minor.
(b) There is a low initial cost.
(c) Instrument can be located up to 125 ft (38 m) from the point of measurement.
(d) Instrument needs no auxiliary power supply unless an electric chart drive is used.

4-11.2 Disadvantages

(a) Bulb size may be too large for some applications.
(b) Minimum ranges are limited.
(c) Maximum temperature is limited.

Section 5
Thermistor Thermometry

5-1 SCOPE

The purpose of this Section is to guide the user in the selection, installation, and use of thermistor thermometers.

5-2 DEFINITIONS

thermistor: a resistor specially fabricated to have a high thermal coefficient of resistance (Hyde, 1971; Sachse, 1975). Thermistors are available with either a negative temperature coefficient (NTC) or positive thermal coefficient (PTC). With a negative thermal coefficient, the thermistor resistance decreases as the temperature increases. NTC thermistors are most often used for thermometry applications.

thermistor thermometer: a temperature-measuring system comprising a temperature-sensing element called a thermistor, a device for sensing the resistance of the thermistor and converting this resistance to a temperature value, and the electrical conductors connecting the thermistor and sensing device.

5-3 PRINCIPLES OF OPERATION

NTC thermistors are resistors fabricated from specially selected semiconductor materials. The electrical resistance of a resistor formed from an ideal semiconductor can be written as

$$R(T) = A\exp(\beta/T) \tag{5-3-1}$$

where
A = constant dependent on the geometry and materials properties of the resistor
T = temperature in absolute units, K or °R
β = constant dependent only on the materials properties of the resistor

The value of resistance at a temperature can be adjusted over a broad range by choosing a semiconductor material with different properties, and to a lesser extent by altering the geometry of the resistor. The temperature coefficient of resistance is given by

$$\alpha = (1/R)dR/dT = -\beta/T^2 \tag{5-3-2}$$

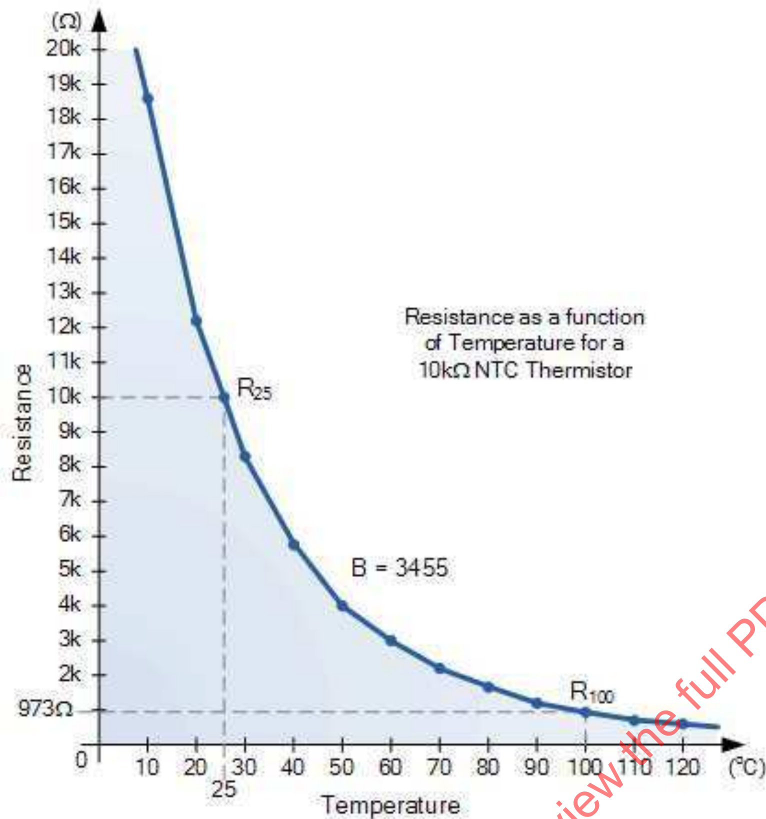
Figure 5-3-1 illustrates some typical resistivity versus temperature curves for some commercial NTC thermistor materials.

5-4 CLASSIFICATION

5-4.1 Description

NTC thermistors are described by their shape, resistance characteristics, the method of lead attachment, and the type of conformal coating covering the sensing element. Thermistor shapes are divided in the categories of bead, disk, rod, or chip thermistors. Bead thermistors are the smallest and can be readily mounted in a variety of metal sheaths or in a hole bored into an apparatus. Disk, rod, and chip thermistors have a cylindrical or rectangular shape, respectively, and have tighter dimensional tolerances than bead thermistors. Resistance properties are classified into the two broad NTC and PTC categories, and a manufacturer may further subdivide thermistors according to the type of ceramic semiconductor that was used in the fabrication of the thermistor. Conformal coatings hermetically seal the ceramic sensing element of the thermistor. The two standard coatings are epoxy and glass. Some bead thermistors are encased in fused lengths of glass tubing to form what are termed bead-in-glass probe thermistors.

Figure 5-3-1
Resistance Versus Temperature for 10-kΩ NTC Thermistor



GENERAL NOTE: The figure, "NTC Thermistor Characteristics Curve" (Thermistors, n.d.), is reprinted courtesy of Basic Electronics Tutorials (www.electronics-tutorials.ws).

5-5 MATERIALS OF CONSTRUCTION

Thermistors are fabricated from ceramic semiconductors specially chosen to have the desired thermal coefficients of resistance.

Transition metal oxides, such as $(Ni_{0.2}Mn_{0.8})3O_4$, are very common. The ceramic is initially a granular powder that is then sintered at high temperature [2,012°F to 2,372°F (1 100°C to 1 300°C)] to form a bead, disk, chip, or rod. In the sintering process, various complex compounds are formed from the initial mixture of ceramic powders.

Bead thermistors are directly sintered onto two lead wires. Disk, rod, or chip thermistors have a metallization coating applied on two faces of the thermistor following the ceramic sintering, and lead wires are attached to this metallization. Following lead attachment, the thermistors are generally coated either with epoxy or glass to prevent the intrusion of water into the ceramic and to provide strain relief for the electrical connections between the ceramic and the leads or metallization contacts.

5-6 CHARACTERISTICS

5-6.1 Temperature-Resistance Relationship

Resistors formed from impure semiconductors, such as thermistors, obey eq. (5-3-1) only approximately. A more accurate equation, determined empirically, is the Steinhart-Hart equation (Steinhart and Hart, 1968).

$$1/T = a + b(\ln R) + c(\ln R)^3 \quad (5\text{-}3\text{-}3)$$

The coefficients a, b, and c are derived for a specific device by fitting eq. (5-3-3) to three or more resistance temperature data pairs, spaced relatively uniformly across the temperature range of interest.

5-6.2 Interchangeability

Bead thermistors are generally not interchangeable, unless the thermistors are specially selected or fabricated by the manufacturer. Variations in resistance for a given model of bead thermistor are as large as the equivalent of tens of degrees Celsius. Therefore, each bead thermistor must be calibrated individually. Disk, rod, and chip thermistors, however, are often stated to be in conformance with a standard resistance versus temperature curve, to within some stated tolerance. The tightest tolerance band is typically ±0.1% or 0.2%, ±32°F over the range 32°F to 158°F (±0.05°C over the range 0°C to 70°C).

5-6.3 Range and Accuracy

Because the resistance of NTC thermistors varies rapidly with temperature and because they are susceptible to drift at temperatures much above 212°F (100°C), thermistors are most often used for high-accuracy measurements of temperatures over the approximate range 32°F (0°C) to 212°F (100°C) (Siwek et al., 1992).

The accuracy attainable with a thermistor thermometer is limited by the quality of the initial calibration of the thermistor, the interpolation errors of the Steinhart-Hart equation, and any drift in the thermistor. Complete systems with uncertainties of 32.02°F (0.01°C) over the temperature range 32°F (0°C) to 158°F (70°C) are readily attainable.

5-6.4 Precision and Sensitivity

The precision of a thermistor is 2°F (1.1°C) or better with high-quality digital voltmeters or digital ohmmeters. Typical sensitivity of an NTC thermistor is $\alpha = 32.072$°F ($\alpha = 0.04°C^{-1}$). A resistance measurement with a fractional uncertainty of 10^{-4} would have a corresponding temperature uncertainty of $10^{-4}/0.04°C^{-1} = 0.0025°C$.

5-6.5 Response

Small bead thermistors are available with widths as small as 0.002 in. (0.0508 mm). The response time of such a thermistor is less than 16 fps (5 ms) in moving air or liquid (Berger et al., 1992). The response time of larger thermistor probes is correspondingly longer.

5-7 APPLICATION AND INSTALLATION

5-7.1 Sources of Error

5-7.1.1 Self-Heating. As the current used for sensing a thermistor resistance is increased, the thermistor will heat to a temperature greater than the temperature of the surroundings by an amount $\Delta t = I^2R/C$, where C is the thermal resistance between the thermistor-sensing element and its environment, I is the current through the thermistor, and R is the thermistor resistance. Typical values of C are 0.5 mW/°F to 2 mW/°F (1 mW/°C to 4 mW/°C) for a disk thermistor in still air and 5 mW/°F (10 mW/°C) for disk thermistors in stirred oil or a bead thermistor in still oil. In choosing a sensing instrument, either the value of I should be small enough to make Δt a negligible error, or the thermistor resistance should be measured at two values of I, to enable direct measurement of the thermal resistance factor, C. For high-accuracy measurements, it is common to use measurement currents of 10 μA or less.

5-7.1.2 Drift. The resistance versus temperature relation of a thermistor may change with time due to a variety of effects, including contamination with water, migration of metallization atoms into the ceramic, degradation of the metallization, microcracks caused by thermal strains, and structural changes of the ceramic materials. For accurate thermometry, thermistors coated or sealed with glass are superior to those sealed in epoxy. Measurements over extended periods of time demonstrated that bead and disk thermistors sealed in glass have drift rates of 32.018°F (0.01°C) or less per year when used in the temperature range 32.018°F to 140°F (0°C to 60°C) (Wise, 1992; Wood et al., 1978). At higher temperatures, higher drift rates can be expected. Tests on bead-in-glass probe thermistors showed drift rates of up to 32.072°F (0.04°C) per year for thermistors that were continuously baked at 212°F (100°C). Drift rates of thermistors encapsulated in epoxy can be an order of magnitude higher than the drift rates reported above.

5-8 INTEGRATION INTO AUTOMATED MEASUREMENT SYSTEMS

The high sensitivity of thermistors and convenient range of their resistance values allows accurate temperature measurements to be made with relatively simple electronic circuits. Standard digital ohmmeters are capable of measurement uncertainties of better than 32.0018°F (0.001°C), provided that the sensing current does not cause appreciable self-heating. A four-wire resistance measurement is necessary for the highest accuracy, but in many circumstances requiring less accuracy, the high sensitivity and relatively high resistance of thermistors allow sufficiently accurate measurements with a two-wire resistance measurement.

A method that allows more flexibility in the choice of sensing current is to use an external current source that passes a current through the thermistor and a reference resistor in series with the thermistor. A voltmeter is then used to measure the voltage across the thermistor and across the reference resistor. The thermistor resistance is calculated from the ratio of measured voltages and the calibration value of the reference resistor. In circumstances demanding the highest accuracy, the current may be reversed and the measurements repeated. Averaging results for the two directions of current flow will cancel the effects of any stray thermal emf.

Standard shielding methods are appropriate to reduce the measurement noise. Lead wires should be twisted paired with an outer shield tied to ground.

5-9 TREATMENT OF DATA

Because thermistors are highly nonlinear, the use of analog circuitry to provide voltage or current signals that are linear in temperature is complex and difficult. Such circuits exist, but the preferred solution is to use a microprocessor to convert a measured resistance value into a temperature, using the Steinhart-Hart equation either as a mathematical formula or in the form of a lookup table with interpolation between entries.

Over the temperature range 32°F to 158°F (0°C to 70°C), calculation of the Steinhart-Hart parameters from data at three temperatures will usually lead to interpolation errors of less than 32.009°F (0.005°C). As an example, Mangum (1983) shows the difference for two thermistors between the interpolated temperature using the three-parameter Steinhart-Hart equation and the temperature as determined by comparison to a standard platinum resistance thermometer. The thermistors were calibrated at the triple point of water [32.018°F (0.01°C)], the melting point of gallium [85.5763°F (29.7646°C)], and the triple point of succinonitrile [136.5156°F (58.0642°C)].

Additional terms of the form $c_i (\ln R)^i$, where i is a positive integer greater than or equal to two and c_i is a constant, may be added to the right-hand side of eq. (5-3-3) to obtain an interpolation equation with reduced interpolation error or that is applicable over a broader temperature range.

5-10 ADVANTAGES AND DISADVANTAGES

The advantages and disadvantages of thermistor thermometers are found in paras. 5-10.1 and 5-10.2.

5-10.1 Advantages

(a) Thermistor thermometers are low cost.
(b) Thermistor thermometers are small and have a correspondingly fast response.
(c) Thermistor thermometers provide high sensitivity, at 32.018°F (0.001°C) or better with modestly priced equipment.
(d) Thermistor thermometers are resistant to shock and vibration relative to standard platinum resistance thermometers.

5-10.2 Disadvantages

(a) Thermistor thermometers have nonlinear resistance versus temperature relation.
(b) Thermistor thermometers have a narrow temperature range for a single device <212°F (<100°C temperature span).
(c) Thermistor thermometers have a large drift at elevated temperatures.
(d) Thermistor thermometers are not suited for use at high temperatures.

Section 6
Calibration of Temperature Sensors

6-1 SCOPE

The purpose of this Section is to present information that will guide the user in achieving calibration uncertainties required to satisfy the ASME PTC 19.1 overall performance test uncertainty. A brief description of common calibration methods is provided, but it is assumed the user is a consumer of commercial calibration services. As used here, calibration means a comparison between the temperature output indicated by the sensor under test as compared to the corresponding value of temperature realized by the standard. Calibration does not refer to an adjustment made to bring the accuracy of a sensor under test into a specific accuracy over a given temperature range. Most of the temperature sensors described in this Code (e.g., thermocouples, RTDs, thermistors) are not capable of any internal adjustment for accuracy. Compensation for the difference between the sensor under test and the reference value must be made on an instrument connected to but external to the sensor itself (e.g., transmitter, controller, PLC, "smart" connector).

6-2 SELECTION OF CALIBRATION VENDORS

(a) When selecting a calibration service provider, it is important to understand the distinction between claims of "traceable calibration" and claims of "accredited calibration." "Traceability" is a provider's self-proclaimed property of the calibration data back to a national calibration laboratory, such as the National Institute of Standards and Technology (NIST). When a provider claims traceability, the responsibility to verify the claim rests solely on the consumer. If the provider wishes to relieve the consumer from that responsibility, a third party is contracted to audit and accredit the claim of traceability in accordance with a recognized standard for competence in calibration. The presence of a valid accrediting body logo on a calibration certificate generally is all the evidence needed to verify traceability. A commonly accepted calibration accreditation is accreditation of a calibration laboratory to ISO/IEC 17025.

(b) ASME PTC 19.1 addresses instrument calibration uncertainty as a contributor to the overall test uncertainty. A pretest analysis of uncertainty can determine a target uncertainty required for a given instrument. Using the pretest uncertainty analysis as a starting point allows the performance engineer to selectively compare calibration service providers or determine an acceptable calibration method.

(c) Accredited calibration providers are required to list a Calibration and Measurement Capability ("CMC") for work done within their accredited scope of calibration. Equipped with the ASME PTC 19.1 target calibration uncertainty and a provider's Scope of Accreditation, an appropriate and cost-effective calibration service can be selected.

6-3 TEMPERATURE SCALES

(a) Temperature is a measure of thermal potential. Two bodies are at the same temperature when there is no thermal (heat) flow from one to the other. If one body loses heat to another, the first is at a higher temperature.

(b) In order to measure temperature, it is necessary to have a scale with appropriate units, just as it is necessary in measuring length to have the meter with its subdivisions of centimeter and millimeter or the yard with its subdivisions of foot and inch.

6-4 THERMODYNAMIC TEMPERATURE SCALE

The ideal temperature scale is known as the thermodynamic scale. Kelvin has designed this scale to be such that "the absolute values of two temperatures are to one another in the proportion of the heat taken in to the heat rejected in a reversible thermodynamic engine working with a source and refrigerator at the higher and lower temperature, respectively."

The temperature scale defined in this manner is independent of the physical properties of any specific substance.

Table 6-6-1
Relations for Realizing the ITS-90

Temperature Range, K	Relation Defining Temperature Over Range
0.65 to 5	Vapor pressure temperature relationships of helium isotopes (^{3}HE and ^{4}HE)
3 to 24.5561	Constant volume helium gas thermometer calibrated at three points, including the triple point of neon and the triple point of equilibrium hydrogen
13.0833 to 1 234.93	Platinum resistance thermometry
1 234.93 and above	Planck radiation law

6-5 IDEAL GAS SCALE

Theory shows that the thermodynamic scale is identical with that defined by the ideal gas equation of state.

$$PV = RT \tag{6-5-1}$$

where
P = absolute pressure
R = gas constant
T = absolute temperature, K or R
V = specific volume

Reversible heat engines are impossible to construct, and gas thermometers are difficult to construct and use under ideal laboratory conditions, let alone under industrial test conditions, and are therefore not suitable for general everyday use.

6-6 INTERNATIONAL TEMPERATURE SCALE

In 1927, the International Committee to the Seventh General Conference on Weights and Measures adopted what was then known as the International Temperature Scale establishing the first authoritative basis for temperature measurement on a global basis. In 1948, the Ninth General Conference on Weights and Measures first revised that scale.

In October 1968, the International Committee on Weights and Measures, as empowered by the Thirteenth General Conference, adopted eight major changes in the international empirical temperature scale, which then became published as the International Practical Temperature Scale, also known as IPTS-68.

IPTS-68 was amended in 1975, and a provisional 0.5 K to 30 K temperature scale was added to IPTS-68 in 1976 (EPT-76).

In 1989, the International Temperature Scale known as ITS-90 was published, superseding the foregoing temperature scales. ITS-90 remains the current standard.

The key elements of ITS-90 are defined by the relationships set forth in Table 6-6-1 (Mangum and Furukawa, 1990). Temperatures encountered in industrial performance testing will normally fall within and above the range defined by the relationship between temperature and platinum resistance thermometry. This Code will address calibrations in those ranges. Multiple platinum resistance thermometers would be necessary to realize the ITS-90 scale, as no single platinum resistance thermometer exists that is capable of covering the entire temperature range. As a practical matter, most calibrations performed at and above the higher end of the range where temperature is authoritatively defined by the relationship with platinum resistance thermometry will be established by reference to platinum–rhodium thermocouples (Type S per IPTS-68 and Types R and B).

6-7 PLATINUM RESISTANCE THERMOMETRY

6-7.1 General

Between 13.8033 K (triple point of equilibrium hydrogen) and 1 234.93 K (freezing point of Ag), the ITS-90 is defined in terms of specified fixed points whose temperature values have been assigned by resistance ratios of platinum resistance thermometers obtained by calibration at specified sets of fixed points and by reference functions and deviation functions of resistance ratios that relate to T_{90} between the fixed points. Platinum resistance probes that meet the ITS-90 standards are generally referred to as standard platinum resistance thermometers (SPRTs).

Table 6-7.1-1
Subranges of ITS-90 for Platinum Resistance Thermometers

Temperature Range, K	Natural Standards Used in Calibration of Platinum Resistance Thermometer for ITS-90 Realization
13.8033 to 273.16	Triple point of equilibrium hydrogen, triple points of neon, oxygen, argon [Note (1)], mercury, and water, plus two other temperatures close to 17.0 K and 20.3 K
24.5561 to 273.16	Triple point of equilibrium hydrogen, triple points of neon, oxygen, argon [Note (1)], mercury, and water
54.3584 to 273.16	Triple points of oxygen, argon [Note (1)], mercury, and water
83.8058 to 273.16	Triple points of argon [Note (1)], mercury, and water
273.15 to 1 234.93	Triple point of water, freezing points of tin, zinc, aluminum, and silver
273.15 to 933.473	Triple point of water, freezing points of tin, zinc, and aluminum
273.15 to 692.677	Triple point of water, freezing points of tin and zinc
273.15 to 505.078	Triple point of water, freezing points of indium and tin
273.15 to 429.7485	Triple point of water, freezing point of indium
273.15 to 302.9146	Triple point of water, melting point of gallium
234.3156 to 302.9146	Triple points of mercury and water, melting point of gallium

NOTE: (1) Nearly all laboratories use the boiling point of liquid nitrogen in combination with a reference thermometer traceable to a national standard at the triple point of argon, avoiding the expense and complexity of realizing the triple point of argon.

The ratio of resistance, w, of the SPRT at T_{90} to the resistance at the triple point of water (TPW) is referred to as the resistance ratio. Calibration coefficients for an SPRT are provided in terms of deviation from the nominal resistance ratio across a given subrange of interest.

6-7.2 ITS-90 SPRT Specifications

(a) The SPRT-sensing element must be made of pure platinum, Pt, and strain-free.

$$w(302.9146\text{ K}) \geq 1.11807 \text{or } w(234.3156\text{ K}) \leq 0.844235$$

This is a slope that is ≥3.986e-3 K-1 at the TPW.

(b) An SPRT for use at the freezing point of Ag must meet the following additional criteria:

$$w(1\,234.93\text{ K}) \geq 4.2844$$

(c) Subranges of the ITS-90 are defined as a set of fixed points. Deviation functions differ slightly from subrange to subrange. When requesting calibration for an SPRT, the subrange of interest must be specified, and calibration coefficients are generated for that subrange only. Calibration in multiple subranges can be requested. Subranges are shown in Table 6-7.1-1.

6-8 METHODS OF CALIBRATION

Calibration of temperature sensors fundamentally consists of exposing the temperature sensor to be calibrated (the unit under test) or in some cases exposing that sensor's materials of construction to a known temperature or temperatures and then quantifying the output of the unit under test on reaching thermal equilibrium with the known temperature. Calibrations are performed by reference to certain thermometric fixed points established by ITS-90, a comparison with a SPRT thermocouple in a stable and uniform comparator (heat or cold source).

6-8.1 Calibration by Fixed Points

A precise method of calibration is that of determining the reading of an instrument at one or more of the defining fixed points that are listed in Table 6-8.1-1.

Calibration at fixed points requires specialized equipment and painstaking techniques. Standard resistance thermometers and standard platinum–platinum–rhodium thermocouples are calibrated at fixed points for use as primary standards. These are then used for the calibration of other instruments and working standards used to calibrate sensors for use in monitoring and control applications that call for calibration. It is good practice to have primary standard devices calibrated by a National Metrology Institute, such as NIST, or a laboratory qualified, equipped, and accredited to

Table 6-8.1-1
Fixed Points of ITS-90

Fixed Point	Temperature, °F (°C)
Boiling point of liquid nitrogen (BPLN2)	−320.8 (−196)
Triple point of mercury (TPHg)	−37.90192 (−38.8344)
Triple point of water (TPW)	32.018 (0.01)
Melting point of gallium (MPGa)	85.57628 (29.7646)
Freezing point of indium (FPIn)	313.8773 (156.5985)
Freezing point of tin (FPSn)	449.4704 (231.928)
Freezing point of zinc (FPZn)	787.1486 (419.527)
Freezing point of aluminum (FPAl)	1,220.576 (660.32)
Freezing point of silver (FpAg)	1,763.204 (961.78)

ISO/IEC 17025 to perform calibrations in a manner consistent with the methods established by NIST using fixed points of reference (Strouse, 2007).

6-8.2 Calibration by Comparison to Primary and Working Standards

The most common method of calibrating a temperature sensor (sensor under test) is to bring it to thermal equilibrium with another temperature sensor having a low uncertainty as to its temperature indication (primary standard or working standard) (Burns and Scroger, 1989).

6-8.2.1 Laboratory SPRTs and Secondary Reference Grade RTDs. These RTDs are segregated into two general classes: SPRTs and secondary reference PRTs.

SPRTs are often extremely fragile and very expensive and used to calibrate secondary reference probes and other SPRTs at temperatures ranging from −463°F to 1,764°F (−260°C to 962°C). They tend to have a nominal resistance at the triple point of water 32.18°F (0.01°C) (TPW) of 25 Ω, though SPRTs operating up to the highest end of the ITS-90 range 1,763.2°F (961.78°C) tend to have a lower resistance, such as 0.25 Ω or 2.5 Ω. The stems of these probes are often quartz glass. In addition to being more fragile, quartz stems must be kept very clean, and contact with metals at temperatures above 1,112°F (600°C) should be avoided to reduce the likelihood of devitrification. Less frequently, they may be found with metal sheathing, typically Inconel. It is recommended that 25 Ω SPRTs are used below 32°F (0°C). Above 1,292°F (700°C), these sensors are susceptible to metal ion calibration, which can cause decalibration and a loss of accuracy.

Secondary reference probes are generally used as working standards in calibration laboratories to calibrate industrial use temperature sensors. Their nominal resistance at TPW is commonly 25 Ω to 100 Ω. These are available with metal sheathed stems and operate over a smaller range, such as −328°F to 788°F (−200°C to 420°C) or −328°F to 1,220°F (−200°C to 660°C). The calibrated accuracy can range from ±0.012°F to >0.063°F (±0.006°C to >0.035°C). These accuracies are usually acceptable for industrial temperature sensor calibration uncertainty budgets. See Table 6-8.2.1-1 for a comparison of SPRTs secondary reference PRTs and industrial RTDs.

Table 6-8.2.1-1
Comparison of SPRTs Secondary Reference PRTs and Industrial RTDs

Properties	SPRTs	Secondary Reference PRTs	Industrial Platinum RTDs [Note (1)]
Resistance at 32.018°F (0.01°C)	Nominal 25 Ω typical	25 Ω to 100 Ω	Typical 100 Ω (range 10 Ω to 10,000 Ω)
Accuracy at 32.018°F (0.01°C)	±0.0018°F (±0.001°C)	±0.0144 to 0.036°F (±0.008°C to 0.02°C)	±0.054°F to 1.08°F (±0.03°C to 0.6°C)
Range [Note (2)]	−436°F to 1,958°F (−260°C to 1 070°C)	−328°F to 1,220°F (−200°C to 660°C)	−432°F to 1,562°F (−258°C to 850°C) [Note (3)]

NOTES:
(1) Refer to industrial RTDs in Section 3.
(2) This measurement expresses the full temperature range of the type of resistance thermometer. In most cases, no single thermometer will be capable of handling the full range expressed for SPRTs and industrial RTDs.
(3) Published resistance to temperature values are limited to −328°F to 1,562°F (−200°C to 850°C). Below that range, the standard calculations do not appropriately characterize the resistance to temperature relationship.

Table 6-8.2.2-1
Typical Reference Working Standards

Reference Standard Type	Typical Temperature Range, °F (°C)
SPRT or secondary reference RTD	−328 to 1,220 (−200 to 660)
Type S or Type R thermocouple	1,112 to 2,642 (600 to 1 450) [typical maximum 2,012 (1 100)]
Type B thermocouple	1,652 to 3,092 (900 to 1 700)

6-8.2.2 Primary and Working Standards. The primary standard is usually an SPRT. Any one of several types of thermometers, calibrated in terms of the ITS-90, may be used as a working standard for the calibration of temperature sensors by comparison. Working standards are selected to have suitable accuracy to achieve the desired uncertainty for industrial use temperature sensors. Primary and working standards are collectively referred to as "reference sensors." SPRTs and secondary reference RTDs are collectively referred to as "reference RTDs." See Table 6-8.2.2-1 for typical reference working standards.

For industrial temperature calibrations, reference RTDs are primarily used as the reference thermometer in the range from −328°F to 1,220°F (−200°C to 660°C). As reference RTDs are used, they should be checked for drift in resistance at the triple point of water. Reference RTD drift incurred due to use and calibration can often be managed or reversed through proper annealing techniques. Type R and Type S thermocouples calibrated by comparison with a PRT and at fixed points are used extensively both above and below the freezing point of silver. Accurate calibrations within 35.6°F (2°C) or 37.4°F (3°C) or better can be achieved between 1,220°F (660°C) and 2,192°F (1 200°C) by reference to a Type R or Type S thermocouple. Above that range up to a maximum of 3,100°F (1 700°C), a Type B thermocouple can be used as a reference within an accuracy of 41°F (5°C) or 42.8°F (6°C).

6-9 CALIBRATION EQUIPMENT

Equipment used for calibration consists primarily of the following:

(a) comparators used to generate the hot or cold temperature point at which the calibration will take place
(b) meters used to receive signals from the sensors involved in the calibration
(c) computer programs used to automate the process and/or generate calibration reports

6-9.1 Comparators (Heat and Cold Sources Such as Dry Wells)

6-9.1.1 Comparators — Vertical and Horizontal Metal Dry Block. Commercially available dry block comparators are widely available and simple to use. Modular inserts permit the bore of the dry block to be matched closely to the outside diameter of the reference sensor and sensors under test. Dry block comparators should be characterized to ensure axial and radial temperature gradients are factored into the reported estimate of uncertainty. Vertical dry block comparators can be used to achieve stable temperatures as low as −112°F (−80°C) and as high as 2,210°F (1 210°C) but are most commonly used in the range of 91.4°F to 1,112°F (33°C to 600°C). These units are often portable and can be taken on site to perform *in situ* or laboratory calibrations. Horizontal dry block comparators are typically used at a higher temperature in the 1,112°F to 2,192°F (600°C to 1 200°C) temperature range but are available with both lower and higher temperature limits than typical.

6-9.1.2 Tube Furnaces. Temperature calibrations above 2,192°F (1 200°C) are typically performed with a tube furnace having ceramic internals. These units are typically used to achieve stable temperatures up to 3,272°F (1 800°C), but significantly higher temperature calibrations can be achieved with an inert or vacuum environment. These furnaces are available in horizontal or vertical construction.

6-9.1.3 Bath Comparators. Stirred liquid baths provide an excellent heat source for temperature sensor calibrations at lower temperatures ranging from around −94°F to 572°F (−70°C to 300°C). These units take longer to heat and cool than dry blocks but provide excellent stability and enable more sensors to be tested at the same time. The fluids used for heating and cooling are typically alcohol or oil compounds and will differ significantly, and control settings should be used to ensure that the fluid selected will not exceed a safe operating temperature. Salt and sand bath comparators perform similarly to stirred liquid baths but typically operate over a higher temperature range than liquid baths from around 140°F to 1,022°F (60°C to 550°C).

6-9.1.4 Ice Bath. Although it is not included among the ITS-90 fixed points, a simple ice bath is easy to realize with an extremely low uncertainty in a much more rugged construction than a typical TPW cell (Mangum, 1995). A properly constructed ice bath includes ice and distilled water with the water covering the portion of the ice in which the sensor is immersed without causing that ice to float. Because of the ease of construction, this is an excellent means of performing a quick check or field test when troubleshooting the accuracy of a thermocouple or RTD. Methods for preparation and use of an ice bath are set out in ASTM E563.

6-9.1.5 Black Bodies. Black bodies are required to integrate pyrometers, infrared, and other noncontact means of temperature measurement into a calibration. These are typically fairly low temperature source devices ranging from around 5°F to 1,022°F (−15°C to 550°C), with achievable accuracies in the range of ±0.63°F (±0.35°C).

6-9.2 Meters

6-9.2.1 Meters Integrated Into the Reference Probe. Some meters are integrated into the SPRT element itself. These are sometimes called smart PRTs and can send a signal back to a computer program or provide a local indication as to temperature. Accuracies to ±0.09°F (±0.05°C) can be readily obtained using these methods. Another meter is required to obtain the reading of the sensor(s) under test.

6-9.2.2 Handheld Meters. These are field portable devices well suited to performing *in situ* and field calibrations. Accuracies exceeding ±0.8°F (±1°C) can be readily obtained for thermocouples by use of these devices. RTD and thermistor measurements can readily achieve a readout accuracy in the range of ±0.054°F (±0.03°C).

6-9.2.3 Laboratory Scanners and Data Acquisition Systems. These devices are typically designed to be used in a lab with the capability of monitoring and, in many cases, controlling comparators and recording the calibration temperatures of both sensors under test, as well as the reference sensor. Accuracies exceeding ±0.9°F (±0.5°C) for thermocouples and ±0.009°F (±0.005°C) for RTDs and thermistors are routinely achievable.

6-9.2.4 Resistance Bridges. These devices are extremely accurate laboratory devices used for resistance thermometry only. They are capable of achieving accuracies as good as ±0.00003°F (±0.000015°C) in some applications but are not useful for thermocouple calibrations. Some of these are capable of being integrated into an automated system.

6-9.3 Computer Automation Programs

Computer automation programs range in capability from collecting information to controlling comparators and generating reports. Automation of the calibration process can help to ensure rapid retrieval of calibration records and consistency in methodology from lab technician to technician.

6-10 CALIBRATION OUTPUTS

The most common type of calibration performed for temperature sensors used in the field is a comparison calibration tolerance test quantifying the error in degrees at a known temperature or over a range of temperatures. The error described in these reports is the error as compared to the reference output established by standard for a sensor of the type being calibrated. This type of calibration report allows the owner of the calibrated sensor to better understand the accuracy of the temperature indication rendered when using ordinary field instrumentation. The provided offsets can be used to ensure accuracy while enabling interchangeability. The offsets can also be incorporated into some types of field instrumentation to "tune" that instrument to the particular sensor and produce a temperature indication more accurate than the unadjusted result.

Calibrations may also take the form of a characterization calibration. Characterization calibrations are typically performed for reference probes intended to be used to calibrate other temperature sensors in a laboratory or sometimes field setting. These calibration outputs provide a set of coefficients or equations that can be applied to derive an output curve particular to the sensor under test without reference to the standard or ideal sensor output. Examples of characterization calibrations include calibrations that generate ITS-90 coefficients, Callendar-Van Dusen coefficients, polynomial coefficients, and offsets at specific temperatures. The owner of a sensor receiving a characterization calibration will require more sophisticated instrumentation capable of accepting and properly applying the characterization data to make use of the calibration results.

Unless instrumentation is incorporated into the temperature sensor assembly, most sensors are incapable of having their output at a known temperature corrected. Unlike instrumentation calibrations, temperature sensor calibrations do not include "As Found" and "As Left" data. The calibration is purely a quantification of the output of a given sensor at a known temperature. Any adjustments to be made should be performed on the instrument side.

Calibration report examples by sensor type can be found in the appendixes to ASTM E2623. For purposes of ASME PTC 19.1 compliance, the calibration report should state the accuracy with accompanying uncertainty applicable to the temperature at which the measurement is being made.

Table 6-11-1
NIST's GMP 11 Calibration Intervals for Temperature Sensors

Standards	Initial Calibration Interval, months	Source
25.5-Ω SPRT	36	NIST
100-Ω PRTs	12	Accredited lab
Standard thermistor	12	Accredited lab
Check standards	12	Accredited lab
Liquid-in-glass standards [Note (1)]	6 [Note (1)]	Accredited lab

NOTE: (1) Annual inspection must also ensure that there is no damage or separation in the liquid column. See NIST SP-1088 (2009) for additional maintenance plan requirements. New thermometers should be checked at least once a month at the ice point for a minimum of the first 6 months of use.

6-11 CALIBRATION INTERVALS

What length of time forms an appropriate basis for establishing a temperature sensor's calibration interval? There is no one-size-fits-all answer to this question, as appropriate calibration intervals will depend on accuracy requirements set by customers, contract or regulation, inherent stability of the specific sensor, and environmental factors and uses that may affect the stability of the sensor output.

NIST's GMP 11 is an excellent resource for determination of appropriate calibration intervals for temperature sensors and other calibrated equipment. GMP 11 recommends a 1-yr calibration interval for most temperature measurement standards, except the 25.5-Ω SPRT for which it assigns a 3-yr interval and a liquid-in-glass standard for which it prescribes a 6-month interval. Hours of use or numbers of uses can also form an acceptable basis for establishing a calibration interval. See Table 6-11-1 for NIST's GMP 11 calibration intervals for temperature sensors.

6-12 CALIBRATION CONSIDERATIONS SPECIFIC TO SENSOR TYPE

Subsections 6-1 through 6-11 have dealt with the broad subject of temperature calibrations for sensor types covered by this Code. This subsection discusses calibration characteristics specific to particular types of temperature sensors.

6-12.1 Thermocouples

The calibration of a thermocouple consists of the determination of its emf at a sufficient number of known temperatures so that, with some accepted means of interpolation, its emf will be known over the entire temperature range in which it is to be used. The process requires a standard thermometer to indicate temperatures on a standard scale, a means for measuring the emf of the thermocouple, and a controlled environment in which the thermocouple and the standard can be brought to the same temperature.

The emf of a thermocouple with its measuring junction at a specified temperature depends on the temperature difference between its measuring and reference junctions. Therefore, whatever method of calibration is used, the reference junction must be maintained at some known temperature.

6-12.1.1 Calibration Uncertainties. The several factors that contribute to the uncertainties in the emf versus temperature relationship for a particular thermocouple as determined by calibration may be grouped into two kinds: those influencing the observations at calibration points and those arising from any added uncertainty as a result of interpolation between the calibration points. Errors from either of these sources of uncertainty can be materially reduced, within limits, through use of well-designed equipment and careful techniques; the required accuracy should be clearly understood when choosing calibration facilities.

Estimates of the accuracies attainable in the calibration of homogeneous thermocouples by different techniques are given in Tables 6-12.1.1-1 through 6-12.1.1-5. The estimates assume that reasonable care is exercised in the work. More or less accurate results are possible using the same methods, depending on soundness of the techniques used. While excessive care is a waste when relatively crude measurements are sufficient, it should be emphasized that inadequate attention to possible sources of error is more often found to be the practice than the converse. Some of the important considerations associated with the various calibration methods are briefly emphasized in Tables 6-12.1.1-1 through 6-12.1.1-5.

Table 6-12.1.1-1
Accuracies Attainable Using Fixed Point Techniques

Type	Temperature Range, °C	Calibration Points [Note (1)]	Calibration Uncertainty, °C	
			At Observed Points	Of Interpolated Values
S	0 to 1 100	Zn, Sb [Note (2)], Ag, Au	0.2	0.3
R	0 to 1 100	Sn, Zn, Al, Cu–Ag, Cu	0.2	0.5
E	0 to 870	Sn, Zn, Al, Cu–Ag	0.2	0.5
J	0 to 760	Sn, Zn, Al	0.2	1.0
K	0 to 1 100	Sn, Zn, Al, Cu–Ag, Cu	0.2	1.0

NOTES:
(1) Metal freezing points.
(2) Temperature measured by SPRT.

Table 6-12.1.1-2
Accuracies Attainable Using Comparison Techniques in Laboratory Furnaces (Type R or Type S Standard)

Type	Temperature Range, °C	Calibration Points	Calibration Uncertainty, °C	
			At Observed Points	Of Interpolated Values
R or S	0 to 1 100	About every 100°C	0.3	0.5
E	0 to 870	About every 100°C	0.5	0.5
J	0 to 760	About every 100°C	0.5	1.0
K	0 to 1 100	About every 100°C	0.5	1.0

Table 6-12.1.1-3
Accuracies Attainable Using Comparison Techniques in Stirred Liquid Baths

Type	Temperature Range, °C	Calibration Points	Type of Standard	Calibration Uncertainty, °C	
				At Observed Points	Of Interpolated Values
E	−196 to 425	About every 100°C	PRT	0.1	0.2
	−196 to 425	About every 50°C	PRT	0.1	0.1
	−196 to 425	About every 50°C	E or T	0.2	0.2
	−56 to 200	About every 50°C	LIG	0.1	0.1
T	−196 to 250	About every 100°C	PRT	0.1	0.2
	−196 to 425	About every 50°C	PRT	0.1	0.1
	−196 to 425	About every 50°C	E or T	0.2	0.2
	−56 to 200	About every 50°C	LIG	0.1	0.1

Legend:
E or T = Type E or Type T thermocouple
LIG = liquid-in-glass thermometer
PRT = SPRT

Table 6-12.1.1-4
Tungsten–Rhenium-Type Thermocouples

Calibration Uncertainty			
At Observed Points		Of Interpolated Values [Note (1)]	
Gold (1 063°C)	±0.5°C	1 000°C to 1 435°C	±2.7°C
Nickel (1 453°C)	±3.5°C	1 453°C to 1 552°C	±4.0°C
Palladium (1 552°C)	±3.0°C	1 552°C to 1 769°C	±4.0°C
Platinum (1 769°C)	±3.0°C	1 769°C to 2 000°C	±7.0°C
Rhodium (1 960°C)	±5.0°C	...	...

NOTE: (1) These values apply only when all five observed points are taken.

Table 6-12.1.1-5
Accuracies Attainable Using Comparison Techniques in Special Furnaces (Optical Pyrometer Standard)

Type	Temperature Range, °C	Calibration Uncertainty, °C	
		At Observed Points	Of Interpolated Values [Note (1)]
IrRh versus Ir [Note (2)]	1 000 to 1 300	2	3
	1 300 to 1 600	3	4
	1 600 to 2 000	5	8
W versus WRe [Note (3)]	1 000 to 1 300	2	3
	1 300 to 1 600	3	4
	1 600 to 2 000	5	8
30 versus 6 [Note (4)]	1 000 to 1 550	2	3
	1 500 to 1 750	3	5

NOTES:
(1) Using difference curve from reference table with calibration points spaced every 200°C.
(2) 40Ir60Rh versus Ir, 50Ir50Rh versus Ir, or 60Ir40Rh versus Ir.
(3) W versus 74W26Re, 97W3Re versus 74W26Re, or 95We versus 74W26Re.
(4) 70Pt30Rh versus 94Pt6Rh.

6-12.1.2 Uncertainties Using Fixed Points. The equilibrium temperatures listed in Table 6-12.1.2-1 (except for the sublimation point of carbon dioxide) are sufficiently exact, and the materials are readily available in high enough purity that accurate work can be done using these fixed points with no significant error being introduced by accepting the temperatures listed. Good design of freezing point cells and temperature sources are important for controlling the freezes and providing sufficient immersion for the thermocouple, if the full potential of the method is to be realized.

Although uncertainties of the order of ±1.8°F (±1°C) in the temperatures are assigned to the freezing points (and, by implication, to the melting points) of palladium and platinum, these contribute in only a minor way to the overall uncertainties of calibrations using freezing-point techniques. See the current edition of ASTM E1502 for additional information.

6-12.1.3 Uncertainties Using Comparison Methods. The accuracy attained at each calibration point using the comparison method will depend on the degree to which the standard and the test thermocouple are maintained at the same temperature and the accuracy of the standard used. Comparison measurements made in stirred liquid baths usually present no special problems, provided that sufficient immersion is used. Because of the high thermal conductivity of copper, special attention should be given to the problem of immersion when calibrating Type T thermocouples.

As higher and higher temperatures are used, the difficulties of maintaining the test thermocouple and the standard at the same measured temperature are magnified, whether a tube furnace, an oven with moderating block, or whatever means is used for maintaining the desired temperature. In addition, at temperatures of about 1 500°C (2,732°F) and higher, the choice of insulating materials becomes very important. Special attention must be paid to possible errors arising from contamination from the insulators or protection tube and from electrical leakage.

When an optical pyrometer is used as the temperature-measuring standard, a good blackbody must be used, and the design must be such that the test thermocouple is at the same temperature as the blackbody.

Generally, the output of a thermocouple calibration will state offsets at specific temperatures in degrees or millivolts with a stated uncertainty. In some cases, the output of a thermocouple calibration will include a polynomial with a stated uncertainty.

The accuracies obtained in calibrating the various types of thermocouples by different methods and the uncertainty in the interpolated values by various methods are specified in Tables 6-12.1.1-2, 6-12.1.1-3, and 6-12.1.1-5.

6-12.2 RTD Calibrations and Temperature Coefficients

The most common form of calibration in an industrial setting is a comparison calibration where the resistance of an industrial RTD is determined at a temperature defined by a more accurate RTD reference, such as a primary SPRT or secondary PRT. Where greatest accuracy is required, e.g., in the case of a calibration laboratory's primary SPRT or secondary PRT, fixed point calibration is used to establish ITS-90 coefficients.

Comparison values may be used in the following ways for industrial RTDs:

Table 6-12.1.2-1
Secondary Reference Points

Secondary Reference Points	Equilibrium Temperature, °F (°C)
Boiling point of helium	−452.083 (−268.935)
Boiling point of equilibrium hydrogen	−423.189 (−252.883)
Sublimation point of carbon dioxide	−109.3 (−78.5)
Freezing point of mercury	−37.95 (−38.86)
Freezing point of water	32.00 (0.00)
Triple point of benzoic acid	252.25 (122.36)
Freezing point of indium	313.90 (156.61)
Freezing point of tin	449.44 (231.91)
Freezing point of bismuth	520.47 (271.37)
Freezing point of cadmium	609.86 (321.03)
Freezing point of lead	621.37 (327.43)
Freezing point of antimony	1,166.9 (630.5)
Freezing point of aluminum	1,220.2 (660.1)
Freezing point of copper	1,981.0 (1 083.0)
Freezing point of palladium	2,826.0 (1 552.0)
Freezing point of platinum	3,216.0 (1 769.0)

GENERAL NOTE: The pressure is 1 atm, except for the triple point of benzoic acid.

(a) The comparison values may be used to establish offsets in resistance at given temperatures for a given sensor as compared to the standard relationship. This enables a given sensor to be matched or validated as meeting a particular tolerance or accuracy class on an interchangeable basis, e.g., IEC 60751 and ASTM E1137 establish tolerance criteria in relationship to the Callendar-Van Dusen (CVD) equation using standard coefficients. The standards require minimal checks to ensure the accuracy requirements are met. Comparison at additional temperature points may be desired for higher confidence in the standard CVD relationship for a given temperature range.

More information on industrial RTD standard tolerances and the CVD equation are described in Section 3 of this Code.

(b) The established offset values may also be used as set points at the comparison temperatures. This technique does not use a curve to fit the entire range but allows a tight tolerance at specific temperature points. The offsets can be programmed into an instrument to which the sensor is connected to establish a more accurate matched temperature indication.

(c) Comparison values may also be used to create a curve for higher accuracy across a temperature range. The most common method is to use the comparison values to determine A, B, and C coefficients for the CVD equation that are unique to the given sensor. CVD coefficients require three or four calibration points, depending on the desired temperature range. Commercial programs may be helpful for calculating CVD coefficients, but it may be done by the metrologist with a math program and knowledge of the equations. IPTS-68 is a good reference for more information regarding the calculation of CVD coefficients. Some transmitters and other instruments receiving a sensor's signal permit input of the A, B, and C coefficients specific to the probe. These values can be employed to provide a more accurate matched temperature indication without the use of offsets. The uncertainty of the CVD equation yields similar results to the uncertainty of the calibration points used due to the consistent nature of platinum RTDs.

The following points are good practice for increased precision and uncertainty. Ensure settling time when switching between measurements and proper source current are used to avoid self-heating. Promote stability of the temperature source with proper placement and fit of sensors. Allow sufficient time, or use checks to ensure sensors are stable at desired temperature (a high volume of sensors may take longer). Take an average of multiple measurements at each calibration point. Ensure minimum immersion requirements are met to avoid conduction error.

Where a calibration is requested, tolerance statements should be accompanied by a suitable uncertainty statement, such as that set out in ASTM E2593.

MANDATORY APPENDIX I
NONCONTACT THERMOMETERS

I-1 SCOPE

Over the nearly 50 yr intervening between the last date of publication of this Code in 1974 and today, perhaps no technology has changed more than noncontact thermometry. Accordingly, the discussions laid out in the original standard are set out in this Appendix for historical as much as for reference purposes.

The following ASTM standards are excellent resources for comparison, validation, and calibration of noncontact thermometers: ASTM E1256, ASTM E2758, and ASTM E2847.

I-2 DEFINITIONS

absolute temperature: the temperature expressed in units, such as kelvins or degrees Rankine, so that the zero of the scale corresponds to absolute zero, the lowest temperature attainable by physical systems in thermal equilibrium.

blackbody: a source of optical radiation whose spectral radiance is described by Planck's law of thermal radiation. The term *blackbody* may refer to the theoretical ideal or to a practical approximation of the ideal. Practical blackbodies typically consist of a cavity with nearly isothermal walls and an aperture onto which the radiation thermometer may be sited. The cavity walls are often designed to be highly absorbing at the optical wavelengths of interest. A blackbody absorbs all radiation incident on it, reflecting or transmitting none.

disappearing filament optical pyrometer: device that consists of a telescope, a calibrated lamp, a filter to provide for viewing nearly monochromatic radiation, a readout device, and usually an absorption glass filter. The spectral radiance of a body whose temperature to be measured is compared to that of a standard source of radiance. Disappearing filament optical pyrometers are distinguished from other similar instruments in that two sources (images) of equal radiance are compared.

emissivity: the ratio of the radiance of a body to that of a blackbody at the same temperature. Total emissivity refers to radiation of all wavelengths, and monochromatic or spectral emissivity refers to radiation of a particular wavelength. Total emissivity is the average value of spectral emissivity weighted with respect to the blackbody distribution and summed over the entire spectrum.

monochromatic or spectral emissivity: radiation of a particular wavelength.

optical pyrometer: device that consists of a telescope, a calibrated lamp, a filter to provide for viewing nearly monochromatic radiation, a readout device, and usually an absorption glass filter. The spectral radiance of a body whose temperature to be measured is compared to that of a standard source of radiance. Optical pyrometers are distinguished from other similar instruments in that two sources (images) of equal radiance are compared.

radiance: the amount of energy radiating per unit time, per unit solid angle in a particular direction, and per unit projected area of a source. Spectral radiance is radiance per unit wavelength interval at a particular wavelength; total radiance is spectral radiance summed over all wavelengths.

radiation thermometer: a temperature-measuring instrument that is essentially a radiometer of limited spectral response that is calibrated to correctly read the temperature of a blackbody. Radiation thermometers may also be referred to as optical pyrometers or similar names.

radiometer: a device for measuring radiant power capable of transmitting an output indicating the intensity of the input power.

selective radiation thermometer: a thermometer that uses as an index of the temperature of a body the energy from only a narrow wavelength band or bands.

spectral radiance temperature of a source: the temperature of a blackbody having the same spectral radiance as the source, at a specified wavelength. It has also been commonly known in the past as the brightness temperature or currently as the luminance temperature when the eye is used as the sensor.

target: the source of radiation whose temperature is to be measured, as seen by the radiation thermometer or optical pyrometer.

total emissivity: radiation of all wavelengths.

total radiation thermometer: a thermometer that uses as an index of the temperature of a body all of the energy per unit area per unit time radiated by the body.

I-3 PRINCIPLES OF OPERATION

The calibration of a noncontact thermometer is based on the radiance of a blackbody at the temperature at which pure silver, gold, or copper freezes (or melts), and its calibration at other temperatures is in terms of blackbody radiation; the temperatures it indicates, called radiance temperatures, must be corrected for the effect of the emissivity of the target to obtain the target temperature.

Noncontact thermometers operate using principles of thermal and blackbody radiation. The total energy radiated by a blackbody is expressed by the Stefan-Boltzmann law.

$$M = \sigma T^4 \tag{I-3-1}$$

where

M = power density, total energy radiated per unit time, by a blackbody of unit area, W/m^2

T = absolute temperature, K

σ = Stefan-Boltzmann constant

Plank's radiation law expresses the distribution of energy in the spectrum of blackbody radiation. As a consequence of the Stefan-Boltzmann law, it is possible to measure the temperature of a source by measuring the intensity of the radiation it emits. This measurement is accomplished by focusing energy radiated from a source at a uniform temperature on an absorbing area, the receiver, which is heated by the incident radiation absorbed by it. The temperature of this receiver rises until its rate of heat loss to its surroundings by conduction, convection, and radiation is equal to its rate of absorption of energy from the source. In most radiation thermometers, the rate of heat loss from the receiver is such that equilibrium is reached before its temperature is much above that of its surroundings, even when the source is brightly incandescent.

I-3.1 Thermal Radiation

The operation of an optical pyrometer depends on the phenomenon that a body (most noticeably at elevated temperature) emits radiation at all wavelengths, the intensity and spectral distribution of which bear a definite relation to the absolute temperature of the body.

The temperature of a body may be determined from a measurement of its radiance. This measurement may involve the total radiance or the spectral radiance. The wavelength of radiation detected by common radiation thermometers is typically in the range 0.5 μm to 100 μm. In the case of disappearing filament optical pyrometers, radiance is measured in the visible portion of the spectrum, conventionally at a (red) wavelength of approximately 0.65 μm. In general, the radiance depends not only on the temperature of the source but also on the particular material constituting the source and on the character of its surface roughness and chemical state at the surface. For example, at a wavelength near 3 μm, the spectral emissivity of Inconel (an iron-nickel-chromium alloy) varies from 0.2 for an electropolished sample to 0.37 for a sandblasted surface to 0.9 for a sandblasted and heavily oxidized surface.

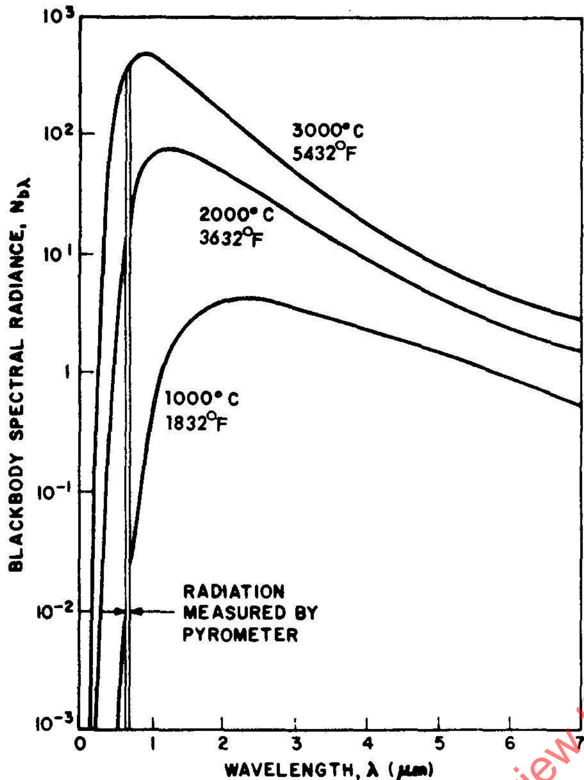
I-3.2 Blackbody Radiation

Kirchhoff's law states that the emissivity of a surface is numerically equal to its absorptivity, a condition that guarantees that the surface can exist in thermal equilibrium with its surroundings. A perfect absorber absorbs all radiation incident on it, reflecting nothing; such a surface is said to be black. A perfect absorber must also be a perfect emitter; a surface having the highest theoretically possible emissivity is therefore known as a blackbody radiator or simply as a blackbody. By definition, the emissivity of a blackbody is unity. For the unique case of a blackbody radiator, the spectral distribution of radiant energy as a function of its temperature is known exactly and is described by the Planck's radiation distribution, as follows:

$$N_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1} \tag{I-3-2}$$

where the index of refraction of the surrounding medium is assumed to be unity and

Figure I-3.2-1
Planck's Blackbody Radiation Distribution Function, Showing Spectral Band Used by an Automatic Optical Pyrometer at 0.65 µm



C_1 = a constant in the Planck radiation law
C_2 = 0.014388 m·K
e = base of the natural or Napierian logarithms
$N_{b\lambda}$ = spectral radiance of a blackbody at wavelength λ
T = absolute temperature, K
λ = wavelength of radiant energy, m

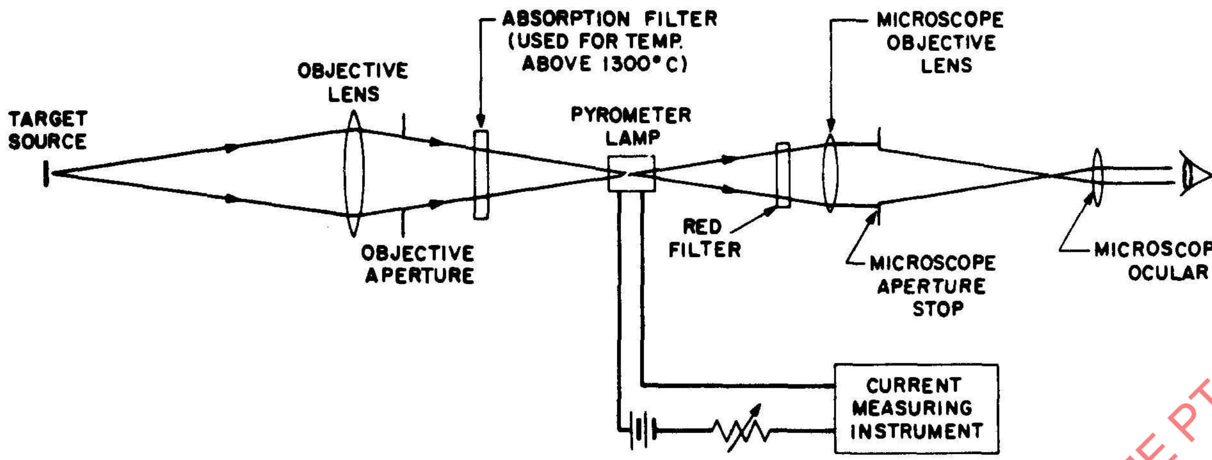
The function of the optical pyrometer is to determine the ordinate $N_{b\lambda}$ of the Planck radiation distribution. At a (nearly) constant wavelength, $N_{b\lambda}$ becomes a measure of T. The Planck's radiation distribution is illustrated in Figure I-3.2-1.

A blackbody is experimentally realized by uniformly heating a hollow enclosure and observing the radiation from a small opening in the wall of the enclosure. The intensity of the radiation emitted from this opening depends almost entirely on the temperature of the walls and almost negligibly on the material of which the walls are constructed. Design considerations are treated in para. I-7.2.

Wien's law is an approximation of Planck's radiation law; it is mathematically more convenient than the Planck function. The fractional error in radiance due to using the Wien function instead of the Planck function at 0.65 µm is less than 0.1% at temperatures below 3 200 K. The fractional error in radiance due to using the Wien function instead of the Planck function at 10 µm is less than 0.1% at temperatures below 208 K. The error rises rapidly as the temperature or the wavelength is increased. The Wien distribution of spectral radiance is the following:

$$N_{b\lambda} = C_1 \lambda^{-5} e^{-C_2/\lambda T} \quad \text{(I-3-3)}$$

Figure I-4.1-1
Schematic Diagram of an Optical Pyrometer



GENERAL NOTE: The figure adapted from Kostkowski and Lee (1962).

I-4 CLASSIFICATION

I-4.1 Detector-Based Radiation Thermometer (Dike, Gray, and Schroyer, 1966; Kostkowski and Lee, 1962)

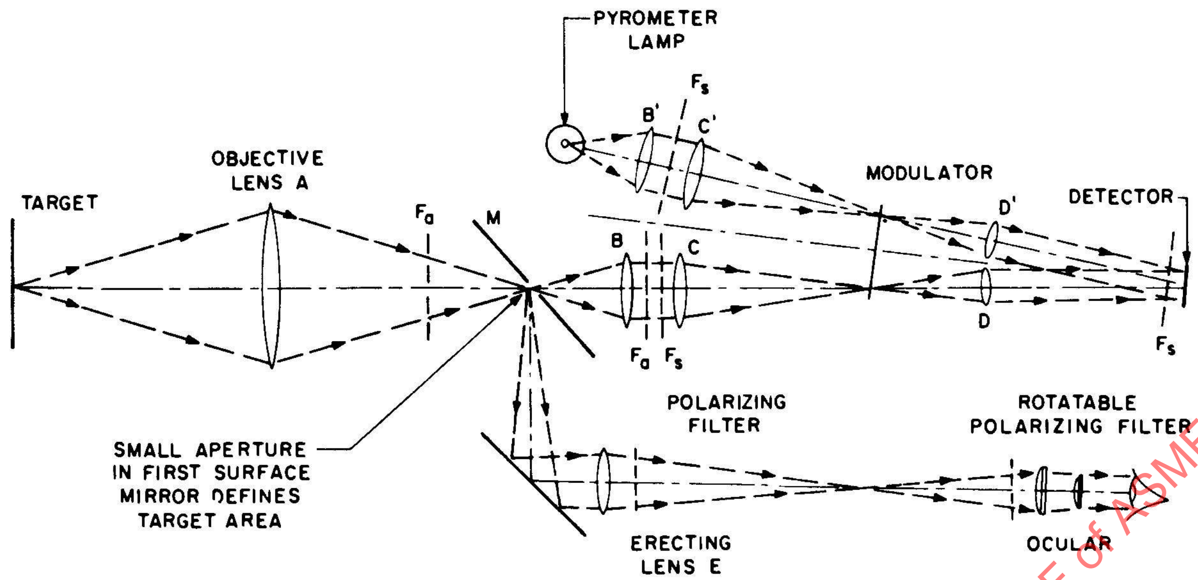
The essential elements of the instrument are typically arranged as illustrated in Figure I-4.1-1. An objective lens or mirror focuses radiation from the target onto a photodetector. A field stop located at a focal point of the optical system limits the area of the target from which the radiation thermometer detects radiation. Limit stops elsewhere in the optical system limit the solid angle of the radiation that is detected. Filters, which may consist of interference filters, colored glass, neutral absorption filters, or the optical lenses themselves, select a particular spectral band of wavelengths that are transmitted to the detector. Many types of detectors are in use. The selection of the type is governed primarily by the operating wavelength of the radiation thermometer and the desired sensitivity of the photodetector. Silicon photodiodes, operating at a wavelength near 0.9 µm, are very common for radiation thermometry above approximately 800°C. Germanium photodiodes are useful from approximately 250°C to 1 000°C, operating at a wavelength of approximately 1.6 µm. Various other semiconductor detectors, pyroelectric detectors, and thermopiles are useful at longer wavelengths and lower temperatures.

The choice of operating wavelength is critical. Instruments operating at shorter wavelengths have less sensitivity to the emissivity of the target or to window or atmospheric effects, with resulting improvements in accuracy, but the available radiance signal decreases rapidly as the wavelength is reduced. As a general rule, the shortest wavelength possible is chosen consistent with the desired signal-to-noise ratio of the radiation thermometer response at the lowest temperature to be measured.

Some of the practical variations may require extensive consideration of the sources of error discussed in para. I-7.5, especially of the transmissive properties of the medium between the radiation thermometer and target. Water vapor and carbon dioxide absorption in certain spectral regions of the infrared must be taken into account. Spectral bandwidth as well as wavelength then become important. Special advantage derives from the ability to select a spectral region in which the target emissivity is known to be high and in being able to make measurements at lower temperatures by operating in the infrared region of the spectrum.

One design concept, called the two-color ratio radiation thermometer, or simply the ratio radiation thermometer, attempts to reduce or eliminate the effect of emissivity and transmission through windows, atmosphere, etc., by measuring the ratio of the target radiance at two wavelengths. If the product of emissivity and transmittance at each of the two wavelengths has nearly the same value, the product cancels out in the ratio measurement, and the instrument reads directly in terms of temperature. However, emissivity and transmittance of materials can vary markedly with wavelength. Since this can lead to large errors if a correction is not applied, the use of a ratio radiation thermometer is advisable only when the validity of the emissivity assumption (or a suitable correction factor) has been well established for the particular application. Windows of seemingly high optical quality may introduce large errors with this type of

Figure I-4.3-1
Schematic Optical System of Automatic Optical Pyrometers — Variable Radiance Comparison-Lamp Type



radiation thermometer. The effect of a particular window on the readings of a radiation thermometer should be tested prior to actual use of the window. The low sensitivity of ratio radiation thermometers generally restricts their use to higher temperatures than is the case with "monochromatic" radiation thermometers.

I-4.2 Disappearing Filament Optical Pyrometer

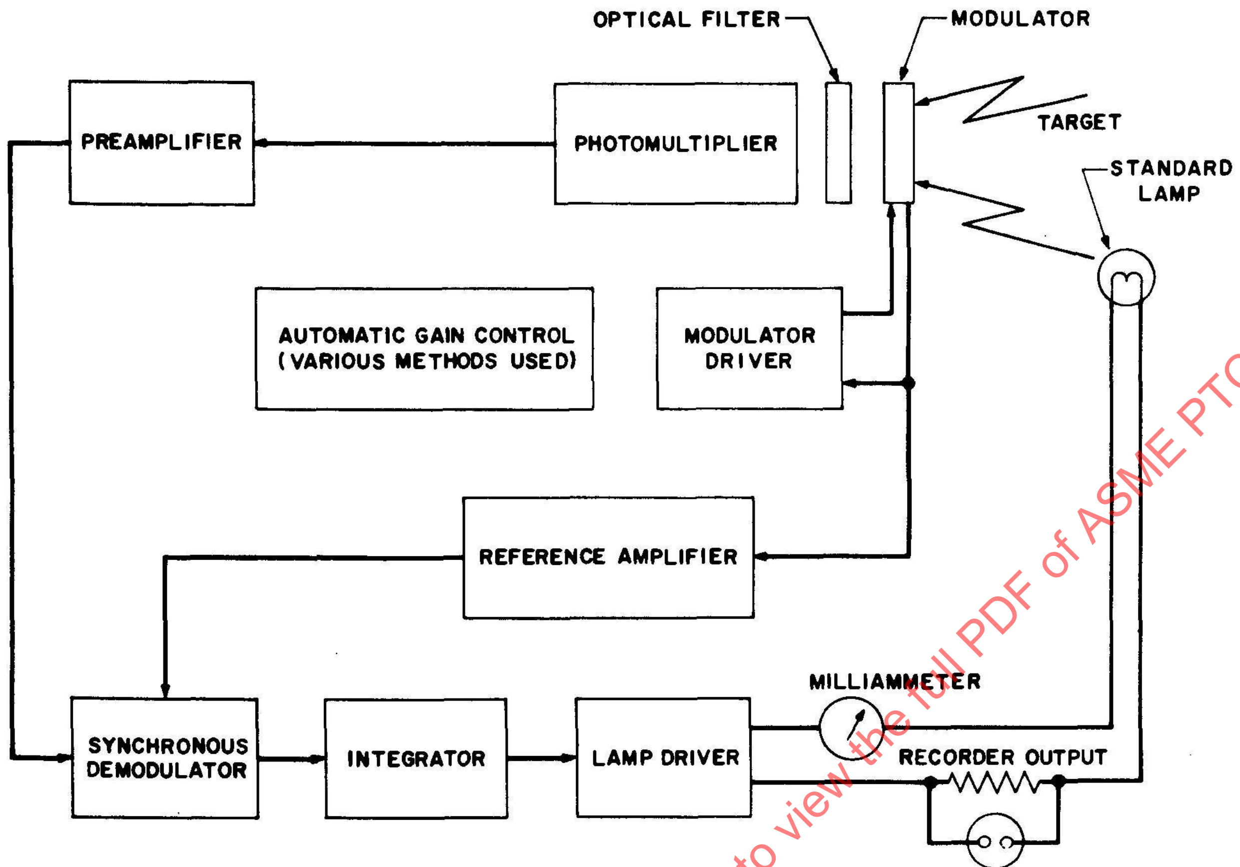
The essential elements of the instrument are typically arranged as illustrated in Figure I-4.1-1. An objective lens focuses a real image of the target in the plane of a standard lamp filament. Both image and filament are magnified for the observer by a microscope lens and an ocular lens. The eyepiece is focused first to provide a sharp image of the standard lamp filament, and then the target image is focused by adjusting the objective lens.

The red filter between the eyepiece and lamp serves to produce approximately monochromatic light to the viewer. In making an observation, the current through the lamp filament is adjusted by a rheostat until the image of the filament reference portion (opposite an index if the filament is straight or at the apex if the filament is U-shaped) is of the same luminance as the image of the target viewed. The outline or detail of the reference section of the filament is indistinguishable from the surrounding field and "disappears" when the current in the lamp is properly adjusted. The value of the current in the lamp may be measured by means of a millimeter, the scale of which is ordinarily graduated in terms of temperature, or, alternatively, a potentiometric measurement of the current may be made. In models employing a built-in potentiometer, the potentiometer scale is graduated in terms of temperature. Standardized absorption glass filters are interposed between the target and lamp, thus permitting a wide range of temperature to be measured without requiring high filament temperatures. Optical pyrometers of this type are available covering the temperature range 1,400°F to 18,000°F. However, the majority of applications are below 4,500°F, with applications above 7,000°F being rare.

I-4.3 Self-Balancing Variable Radiance Comparison-Lamp Type (Automatic Optical Pyrometer)

The essential elements of the instrument are illustrated in Figures I-4.3-1 and I-4.3-2. Operation of the instrument (Nutter, 1972) is similar in principle to that of the disappearing filament optical pyrometer. It differs in that detection of radiation is accomplished with a photodetector rather than by eye; the reference radiance source inside the instrument may be either a lamp, a light-emitting diode, or another type of source; the reference source is adjusted in radiance by an electronic null-balancing system rather than manually; and the spectral bandwidth employed is usually substantially narrower than in the disappearing filament type. A further difference is that the reference source is not mounted in the plane of the target image, resulting in the use of two separate optical trains: one for the reference source radiation and one for target radiation. The reference source is therefore not necessarily at the same radiance as the source, although the

Figure I-4.3-2
Electronic System Block Diagram for Automatic Optical Pyrometer — Variable Radiance Comparison-Lamp Type



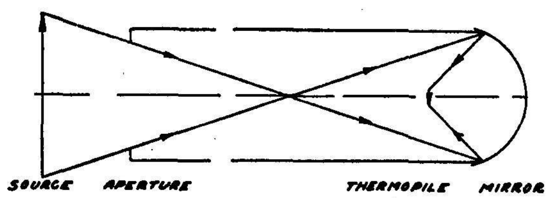
radiant flux arriving at the detector through one optical train is equal to that arriving at the detector through the other optical train.

In this type of radiation thermometer, the modulator alternately passes radiation from the target and then from the reference source at some frequency such as 90 Hz or 400 Hz. If the photodetector receives unequal amounts of radiant energy from the two sources, its response is a square wave signal, the phase of which (with respect to the modulator driver) determines whether the reference source radiance is too high or too low. This signal is synchronously demodulated and then integrated. The integrated signal controls the source radiance, driving it up or down to achieve a zero-amplitude square wave from the photodetector, at which time the reference source is said to be in null-balance. The range of this type of radiation thermometer will depend on the type of photodetector and reference radiation source. This type of radiation thermometer is calibrated by determining the driving current or voltage of the reference radiance source as a function of blackbody target temperature. Because of the null-balance operation of the electronics system, the calibration repeatability is almost totally independent of normal aging effects and other variations in the electronic components and is determined almost entirely by the stability of the reference radiance source.

I-4.4 Single Mirror Radiation Thermometer

In the single mirror type, radiation from the source enters the optical system through the aperture in the "front diaphragm." It is reflected from a concave mirror at the other end of an enclosing tube and is focused on the receiver of the temperature-sensitive element, which is placed between the diaphragm and mirror. See Figure I-4.4-1 for a depiction of radiation in a single mirror radiation thermometer.

Figure I-4.4-1
Single Mirror Radiation Thermometer



I-4.5 Double Mirror Radiation Thermometer

In this radiation thermometer, radiation enters the instrument through a window and is reflected by a concave mirror that forms an image of the source on a diaphragm in which there is a small aperture. The image of the portion of the source to be measured is made to cover the aperture, and the radiation passing through is focused by a second concave mirror on the receiver, where an image of the aperture is formed. See Figure I-4.5-1 for a depiction of radiation in a double mirror radiation thermometer.

I-4.6 Lens-Type Radiation Thermometer

A lens is used in this type of radiation thermometer to form an image of the portion of the source to be sighted on which covers an aperture in a diaphragm closely in front of the receiver, the aperture being very slightly larger in diameter than the receiver. See Figure I-4.6-1 for a depiction of radiation in a lens-type radiation thermometer.

I-5 CHARACTERISTICS

I-5.1 Range

Automatic radiation thermometers operate from temperatures near 0°C to extremely high temperatures, but any one instrument will have a more limited range depending on the choice of the operating wavelength and related choices of the detector type and materials of the optical system. Radiation thermometers operating at infrared wavelengths can be used effectively down to near 0°C, but special care must be exercised (see paras. I-7.5 through I-7.5.6), or large errors may occur.

The disappearing filament optical pyrometer has a low temperature limit of approximately 1,300°F (704.4°C) because of the low radiance of bodies below this temperature. For some observers using visual optical pyrometers, especially under unfavorable lighting conditions, readings are difficult to obtain below approximately 1,400°F (760°C).

I-5.2 Precision

Where the human eye serves as the detector in the use of an optical pyrometer, the precision of setting (repeatability) depends to a considerable extent on the experience and skill of the observer. The average observer can usually detect a "mismatch" in luminance equivalent to 0.1% or 0.2% of the temperature for values of 2,000°F (1 093.33°C) and above, depending on viewing conditions. The precision of photometric matching decreases noticeably and progressively as

Figure I-4.5-1
Double Mirror Radiation Thermometer

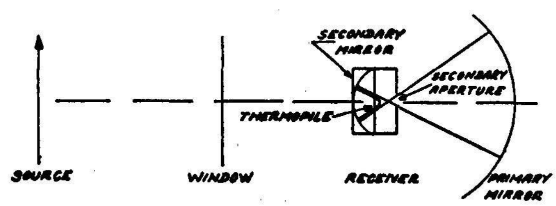
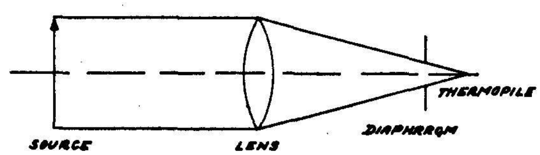


Figure I-4.6-1
Lens-Type Radiation Thermometer



temperature is reduced below 1,600°F, due to decreasing radiance coupled with decreasing visual discrimination of contrast, while the sensitivity decreases due to flattening of the lamp current-versus-temperature curve.

In the automatic radiation thermometer, the temperature resolution is generally higher than in the disappearing filament optical pyrometer by an order of magnitude or more (Lee, 1962, p. 511; Nutter, 1972) and is a function of several design parameters. The resolution is limited by noise, both in the detection system and ultimately in the randomness of the rate of emission of radiant energy from the target. The resolution of most commercial instruments is either 0.1°C or 1.0°C. Research-grade instruments are capable of resolutions of 0.01°C.

I-5.3 Accuracy

The accuracies attainable in measuring temperatures with a radiation thermometer depend primarily on the optical system of the instrument, the conditions under which observations are made, and uncertainty of the emissivity of the target. The calibration uncertainties of a high-quality detector-based radiation thermometer under favorable conditions range from 2°C at 800°C to 3°C at 2 700°C, although this may vary substantially for different instruments. For a high-grade portable disappearing filament optical pyrometer when used by an experienced observer under favorable conditions, the uncertainties range from 3°C at 800°C to approximately 8°C at 2 700°C. In industrial measurements, where errors due to fumes, reflected radiation, variations in emissivity, observer fatigue, or other unfavorable working conditions may exist, the tolerance will depend on the severity of measurement conditions.

Inaccuracies quoted in manufacturers' specifications (unless specifically stated otherwise) ordinarily apply when the radiation thermometer is used to determine the temperature of a blackbody. When the temperature of a nonblackbody is being determined, a correction should be applied to account for the target emissivity, and allowance must be made for uncertainty in the value of the emissivity and of the mean-effective wavelength (Kostkowski and Lee, 1962) of the radiation thermometer. Uncertainty in the value of the emissivity must be determined on a case-by-case basis. For high-accuracy work, the uncertainty of the emissivity may limit the overall accuracy of the temperature measurement. Many instruments incorporate software that corrects the radiation thermometer readings for a target emissivity specified by the user. If the target being sited has a geometry intermediate between a blackbody cavity and flat surface, or if nearby reflecting surfaces can create a cavity around a locally flat target, the effective emissivity of the target may be substantially larger than the emissivity of a flat target. In such cases, optical modeling, *in situ* calibrations of the radiation thermometer, or *in situ* measurements of the effective emissivity may be useful in determining the emissivity corrections.

A good lamp will not change calibration by more than a few tenths of a degree over a period of several hundred hours of use. (A poor lamp may change calibration by several degrees in that amount of time.) Most lamps drift at a rate of approximately 0.02°F/hr at the gold point but are subject to hysteresis effects of 0.2°F to 0.3°F when the filament temperature is cycled slowly. They can change by a similar amount when the lamp is turned off for a few days and then turned on again.

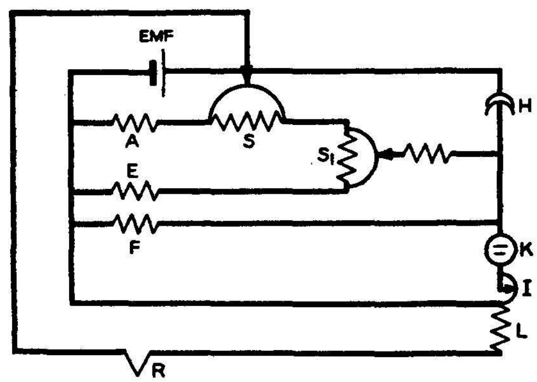
I-5.4 Sensitivity

Because radiation thermometry is based on the Stefan-Boltzmann fourth power law, the sensitivity at the low end of each range is very poor; however, over the upper third of each range, the sensitivity is excellent.

I-5.5 Response

Radiation thermometers are available having 99% response times of less than 1 sec and up to 30 sec when the receiver is lagged to reduce fluctuations that might be caused by flame radiations or reflections. Those most generally used have the lower response times.

Figure I-6-1
Potentiometer Circuit



I-6 ACCESSORIES

Optical pyrometers are generally supplied complete with optical system, lamp current-measuring device, and associated electrical or electronics system. A number of special accessories are available for certain commercially available units, including special short-focus objective lens for measuring objects of less than $^1/_{32}$-in. (0.794-mm) diameter. For some models, temperatures of targets whose diameters are as small as 0.005 in. (0.127 mm) may be measured. In general, for disappearing filament optical pyrometers, precision suffers when the target width is less than about four times the filament width, as seen through the optical pyrometer.

Potentiometric recorders are generally used in connection with radiation thermometers. They differ from those used with thermocouples in that reference junction compensation is not generally provided. As it is required for PTC purposes to make adjustment for emissivities of less than one, there are instruments available that provide this adjustment in the potentiometer circuit, so that a direct reading of temperature can be made that includes the proper emissivity correction.

A schematic circuit used in radiation thermometer potentiometric recorders is shown in Figure I-6-1. A branched circuit-type potentiometer is used, in which the ratio of the currents in the two branches is dependent on the position of the contact on the slide-wire S_1. Each adjustment of S_1 requires an adjustment of rheostat H to keep the total current constant at the value required to make the drop of potential through the standardizing resister F equal to the emf of standard cell K. The scale of slide-wire S_1 is graduated in terms of drop potential through end coil A and slide-wire S_1, with its contact set at the highest position. Slide-wire S_1 provides means for adjusting the drop in potential through the AS branch to any set of values depending on the output of the radiation pyrometer. A and E are selected to provide the proper emf at the low end of the range.

Accessories also include mounting brackets, sighting or target tubes with supporting flanges, nozzles for directing air or a nonabsorbing gas in the target or sighting tubes, and cooling jackets (either air or water).

I-7 APPLICATION AND INSTALLATION

I-7.1 General

Radiation thermometers are ordinarily calibrated to read correctly when sighted on a blackbody, and, in general, this is the preferred way in which to use them. When the temperature of a nonblackbody is to be determined, it is often possible to simulate blackbody radiation by creating a cavity in the body, such as by drilling a hole in its surface, and viewing the radiation emerging from the hole. See para. I-7.2 for information regarding design criteria and effectiveness for simulated blackbodies of this type.

Many furnaces approximate blackbody conditions very satisfactorily, although there is no convenient quantitative method for estimating their effective emissivity. In a perfect blackbody, the details of the inside of the furnace vanish, e.g., a piece of steel that is being heated cannot be distinguished from the background. If the objects in the furnace can be distinguished, but only on close observation, and if much of the detail is lost after they have been in the furnace for some time, it is not likely that the temperature measurement will be seriously in error. If in error at all, the observed temperature will be too high when the furnace walls are of higher radiance than the material being heated and too low when the walls are of a lower radiance. The latter condition is possible if the heat supply is variable or if it is shut off and the furnace is allowed to cool.

NOTE: Since the emissivity of a blackbody is unity by definition, it is a contradiction in terms to speak of a blackbody with emissivity less than unity. The most common solution to this problem, in the case of a simulated blackbody, is to speak of its "effective" emissivity.

When blackbody conditions cannot be simulated, it is necessary to account for the effect of emissivity. Where it is repeatability rather than actual temperature that is important, such as in some manufacturing processes, it is often adequate to use the radiance temperature without correction. To determine when this can be done, it is necessary to have some understanding of the factors that influence emissivity. Similar information is necessary when corrections are to be applied to convert radiance temperature to temperature (see para. I-7.4).

I-7.2 Practical Blackbodies

A completely enclosed cavity in any opaque material at a uniform temperature contains blackbody radiation characteristic of the temperature of the cavity walls but independent of the materials of their construction. A small hole, or aperture, in the enclosure will emit radiation that very closely approximates that of a blackbody at that temperature.

When the cavity is at room temperature, the aperture will appear visually to be very black. However, a small fraction of light incident on the aperture from outside will be reflected back out the aperture after a number of reflections from the cavity walls. Because the reflectance of the aperture is slightly greater than zero, its absorptance (and therefore its effective emissivity) must be slightly less than unity.

Anything that will reduce the reflectance of the aperture will increase its effective emissivity. This can be done by increasing the number of times an incident ray is reflected by the cavity walls before it emerges from the aperture (usually by making the dimensions of the aperture small compared to those of the cavity) and by constructing the cavity walls of a low reflectance material so that more radiation is absorbed at each reflection. The size-of-source effect (see para. I-7.5.1) places a practical limit on the minimum aperture size that can be used.

The number of reflections a ray will make before finally finding its way back out through the aperture will depend on the general shape of the cavity and detailed character of the surface roughness of the cavity walls. Reflection from a perfectly smooth surface is described as being specular, while the reflection from a perfectly rough surface is described as being diffuse. Real materials have surfaces that are characterized by a mixture of specular and diffuse components of reflected radiation. Effective emissivities near unity are more easily attainable in cavities with secularly reflecting than with diffusely reflecting wall materials. However, considerable care must be taken when the interior surface of the cavity is specular, because under these conditions, the effective emissivity is significantly directional, and seriously large errors may result from viewing the cavity from the wrong direction.

While there is as yet no simple formula for accurately expressing the effective emissivity of an aperture in a cavity of arbitrary shape in terms of easily determined parameters, various formulas or graphs have been devised (Bedford, 1972; De Vos, 1954; Gouffe, 1945; Peavy, 1966; Sparrow and Cess, 1966, chaps. 3 and 6) that are applicable in most special cases of practical significance. The method of DeVos (1954) is generally considered to be valid and of great generality and is commonly used as a reference against which other formulas are evaluated. However, it is mathematically very cumbersome and not recommended for routine engineering applications, unless high accuracy is mandatory. A review of the subject from the viewpoint of radiation thermometry has recently been made by Bedford (1972).

I-7.3 Gouffe's Method

Gouffe's method (1945) for computation of effective emissivity for cavities of arbitrary shape assumes perfectly diffuse reflection from the cavity walls; it is exact for spherical cavities (with diffusely reflecting walls) but yields effective emissivity values that are slightly low for cavities of other shapes. The error tends to increase the further the cavity shape departs from that of a sphere but is small enough for a wide variety of cavity shapes to justify the use of the method for many common applications. It is presented here for use as a guide in estimating effective emissivity, because it is concisely formulated for easy application. More nearly exact values of effective emissivity may be obtained from Sparrow and Cess (1966) and Peavy (1966) for certain commonly used cavity shapes and wall materials having both specular and diffuse components of reflectance.

$$\varepsilon_0 = \varepsilon_0{}'(1 + k) \qquad \text{(I-7-1)}$$

where

$$\varepsilon_0' = \frac{\varepsilon}{\varepsilon[1 - (s/S)] + (s/S)} \qquad \text{(I-7-2)}$$

and

$$k = (1 - \varepsilon)[(s/S) - (\frac{\Omega}{\pi})] \quad \text{(I-7-3)}$$

a small negative number, tending to zero as the cavity shape approaches that of a sphere.

where

S = area of interior surface of blackbody cavity, including the aperture
s = area of aperture
ε = emissivity of materials forming the blackbody interior surface
ε_0 = effective emissivity of blackbody aperture
Ω = solid angle of radiation emerging from the cavity aperture, having its apex at the intersection of the viewing axis with the back wall of the cavity

I-7.4 Radiation From the Surface of Real Materials

A body made of an actual material may be designated as a real body, to distinguish it from a blackbody. The interior of an opaque real body is totally absorbing and when at a uniform temperature must therefore radiate as a blackbody. When blackbody radiation from the interior approaches the surface, part of it is reflected back into the interior; the remainder passes through the surface and is emitted. The fraction that is emitted is defined to be the emissivity of the surface. The fraction that is reflected is defined to be the reflectance, which has the same value for radiation approaching the surface from either side.

The spectral emissivity, ε_λ, is the fraction by which blackbody radiation is reduced in the process of being emitted from the surface. A surface at absolute temperature, T_0, and having an emissivity, ε_λ, will appear to the radiation thermometer (having a narrow spectral bandwidth) to be a blackbody at a lower temperature, T_r; the relationship between T_r and T_0 is as follows (Kostkowski and Lee, 1962):

$$1/T_0 - 1/T_r = \lambda_e/c_2 \log_e \varepsilon_\lambda,\ T_0 > T_r \quad \text{(I-7-4)}$$

where

c_2 = 0.014388 m·K
T_0 = absolute temperature of the target
T_r = absolute temperature of the target as indicated by the radiation thermometer, called the spectral radiance temperature
λ_e = mean effective wavelength
ε_λ = spectral emissivity of the target surface

The blackbody radiation incident on the surface from the interior must either be emitted or internally reflected for every wavelength; this may be expressed as follows:

$$\varepsilon_\lambda + R_\lambda = 1 \quad \text{(I-7-5)}$$

where

ε_λ = spectral emissivity of the surface
R_λ = spectral reflectance of the surface

From the above expression, it can be seen that a good emitter is a poor reflector, and vice versa. Thus, carbon has a high emissivity and low reflectance, while platinum has a low emissivity and high reflectance. Anything that affects reflectance must have a corresponding effect on emissivity. Since reflectance is wavelength dependent and slightly direction and temperature dependent, so is the emissivity. A material that reflects and emits a constant fraction at all wavelengths is said to be a "graybody"; like a blackbody, a perfect graybody is an idealization that can be experimentally realized only as an approximation. Actual materials may be considered to be gray only in restricted spectral regions.

If the surface of a particular material is perfectly smooth, it will have its highest possible reflectance and will therefore have its lowest possible emissivity. If the surface is roughened, its reflectance will be reduced because of increased absorption due to multiple reflections (within the small cavities constituting the surface roughness), but its emissivity will be increased by a like amount. Emissivity is thus seen to be dependent on the state of surface roughness of the radiating body. Tables I-7.4-1 and I-7.4-2 list the spectral emissivity of the more common engineering materials. (The following references contain an exhaustive compilation and evaluation of emissivity data on a large number of materials: DeWitt and Hernicz, 1972; Thermal Radiative Properties: Coatings, 1972; Thermal Radiative Properties: Metallic Elements and Alloys, 1970; and Thermal Radiative Properties: Nonmetallic Solids, 1972.) Tables I-7.4-1 and I-7.4-2 assume that the surfaces are smooth. In practice, it is often necessary to take into account the state of surface roughness, which will tend to

Table I-7.4-1
Spectral Emissivity of Materials, Smooth Surface, Unoxidized

Wavelength = 0.65 µm (red light) (Roeser and Wensel, National Bureau of Standards) [Note (1)]		
Material	**Solid**	**Liquid**
Beryllium	0.61	0.61
Carbon	0.80 to 0.93	...
Chromium	0.34	0.39
Cobalt	0.36	0.37
Columbium	0.37	0.40
Copper	0.10	0.15
Erbium	0.55	0.38
Gold	0.14	0.22
Iridium	0.30	...
Iron	0.35	0.37
Manganese	0.59	0.59
Molybdenum	0.37	0.40
Nickel	0.36	0.37
Palladium	0.33	0.37
Platinum	0.30	0.38
Rhodium	0.24	0.30
Silver	0.07	0.07
Tantalum	0.49	...
Thorium	0.36	0.40
Titanium	0.63	0.65
Tungsten	0.43	...
Uranium	0.54	0.34
Vanadium	0.35	0.32
Yttrium	0.35	0.35
Zirconium	0.32	0.30
Steel	0.35	0.37
Cast iron	0.37	0.40
Constantan	0.35	...
Monel	0.37	...
Chromel P (90 Ni-10 Cr)	0.35	...
80 Ni-20 Cr	0.35	...
60 Ni-24 Fe-16 Cr	0.36	...
Alumel (95 Ni;Bal. Al, Mn, Si)	0.37	...
90 Pt-10 Rh	0.27	...

NOTE: (1) From the *Handbook of Chemistry and Physics*, Chemical Rubber Publishing Co.

Table I-7.4-2
Spectral Emissivity of Oxides With Smooth Surfaces

Wavelength = 0.65 µm (red light)
(Roeser and Wensel, National Bureau of Standards) [Note (1)]

Material	Range of Observed Values	Probable Value for the Oxide Formed on Smooth Metal
Aluminum oxide	0.22 to 0.40	0.30
Beryllium oxide	0.07 to 0.37	0.35
Cerium oxide	0.58 to 0.80	...
Chromium oxide	0.60 to 0.80	0.70
Cobalt oxide	...	0.75
Columbium oxide	0.55 to 0.71	0.70
Copper oxide	0.60 to 0.80	0.70
Iron oxide	0.63 to 0.98	0.70
Magnesium oxide	0.10 to 0.43	0.20
Nickel oxide	0.85 to 0.96	0.90
Thorium oxide	0.20 to 0.57	0.50
Tin oxide	0.32 to 0.60	...
Titanium oxide	...	0.50
Uranium oxide	...	0.30
Vanadium oxide	...	0.70
Yttrium oxide	...	0.60
Zirconium oxide	0.18 to 0.43	0.40
Alumel (oxidized)	...	0.87
Cast iron (oxidized)	...	0.70
Chromel P (90 Ni-10 Cr) (oxidized)	...	0.87
80 Ni-20 Cr (oxidized)	...	0.90
60 Ni-24 Fe-16 Cr (oxidized)	...	0.83
55 Fe-37.5 Cr-7.5 Al (oxidized)	...	0.78
70 Fe-23 Cr-5 Al-2 Co (oxidized)	...	0.75
Constantan (55 Cu-45 Ni) (oxidized)	...	0.84
Carbon steel (oxidized)	...	0.80
Stainless steel (18-8) (oxidized)	...	0.85
Porcelain	0.25 to 0.50	...

NOTE: (1) From the *Handbook of Chemistry and Physics*, Chemical Rubber Publishing Co.

increase the emissivity over the values listed in the table, and the extent of oxidation, which will also increase the emissivity. It may be very difficult to assign an emissivity to a heated material that exhibits surface oxidation changing with time.

When possible, a measured value of the spectral emissivity of the particular piece of material under consideration should be used, rather than published values such as those in Tables I-7.4-1 and I-7.4-2; an often used method is to drill a small hole in the surface of the material in question to provide a blackbody cavity. The hole diameter must be large enough so that the size-of-source effect is small and deep enough that the cavity approximates a blackbody. From a determination with a radiation thermometer of the radiance temperature of both the blackbody cavity and surface of the material adjacent to it in the temperature range of interest, the spectral emissivity may be calculated using eq. (I-7-4), or the A-value may be calculated using eq. (I-7-6).

I-7.5 Sources of Error

The radiation thermometer must be used with due precautions to minimize the sources of error. Some of these sources of error are beyond the control of the user of the instrument, while others can be minimized by attention to details of installation and use. The sources of error in radiation thermometry may be broadly grouped into the following categories:

(a) those associated with the radiation thermometer
(b) those associated with the media between the radiation thermometer and source
(c) those associated with the source

Sources of error of detector-base radiation thermometers include the stability of the photodetector and associated electronics, errors in the determination of the mean-effective wavelength, thermal or mechanical changes in the optical system, and the error of the instrument calibration. These errors are independent of those associated with the target and its surroundings. Stability of the detector and optical system is best evaluated by obtaining calibration results for the instrument over an extended period of time (at least several months) and then examining the results for long-term drift. Thermal effects, due to, e.g., changes of the spectral response of various optical components with temperature, may be determined by calibrating the instrument when it is held at various ambient temperatures. The error in the mean-effective wavelength is often small for instruments that use interference filters to restrict the operating wavelength to a narrow spectral band. Conversely, for instruments with large spectral bands limited only by detector response or by the spectral transmission of optical elements, the mean-effective wavelength is of limited validity because of its dependence on details of the spectral emissivity of the target or spectral transmission of windows, and complex methods may be necessary for accurate corrections for window transmission or target emissivity effects.

Sources of error associated with the disappearing filament optical pyrometer have to do primarily with the stability of calibration of the reference lamp or the photodetector, the determination of the mean-effective wavelength, the spectral transmittance characteristics of the absorption glass filter, and errors of the instrument calibration.

Radiation thermometers have a response over a finite band of wavelengths, often referred to as the passband. The response of the radiation thermometer can be expressed as an integral of various wavelength-dependent quantities, including the transmission of the optical lenses, spectral response of the detector, and the spectral emissivity of the target. These integrals are unwieldy for practical use in all but the highest accuracy applications. To simplify the use of a radiation thermometer, the mean effective wavelength is defined as that wavelength for which the response of the radiometer varies with target temperature in the same manner as Planck's distribution. For cases in which the target can be treated as a blackbody or a graybody, charts of the mean effective wavelength as a function of target temperature are available from radiation thermometer manufacturers.

The mean-effective wavelength of a disappearing filament optical pyrometer varies somewhat from one model to another, but for optical pyrometers, it is usually between 0.636 μm and 0.662 μm. For the type shown in Figure I-4.1-1, it is typically assumed to be approximately 0.65 μm. A curve of the mean-effective wavelength as a function of the target temperature is ordinarily available from the manufacturer. Variations among filters in disappearing filament optical pyrometers cause variations of as much as ±1% in the mean-effective wavelength (Lovejoy, 1962), relative to values supplied by the manufacturer, giving rise to corresponding uncertainties in computed emissivity and window transmission corrections. This will usually be the dominant uncertainty in the value of the mean-effective wavelength, since the uncertainty due to differing visual responses among observers will rarely exceed 0.2%.

I-7.5.1 Size-of-Source Effect. Radiation from outside of the target area but from the immediate neighborhood of the target is found to influence the radiation thermometer indication at least to a small extent; this is called the size-of-source effect. The effect is most noticeable for small targets. It is caused primarily by the scattering of radiation within the radiation thermometer optical system, and, in disappearing filament optical pyrometers, by heating of the pyrometer lamp filament by the incident radiation. On the upper temperature ranges of disappearing filament optical pyrometers and some models of automatic radiation thermometers, small transmission changes in the range filters can occur if the filters are heated somewhat by absorbed radiation. Scattering of radiation depends on details of aperture quality and the quality of the optic elements that may vary among instruments of the same design. Consequently, for accurate work, the magnitude of the size-of-source effect should be checked for each individual instrument. ASTM E1256 describes an appropriate method to do this.

In the automatic radiation thermometer, the location of the range filters behind the mirror aperture (one of the two possible locations of F_a in Figure I-4.3-1) reduces the filter heating effect to a negligible level (Nutter, 1972). In this configuration, an automatic radiation thermometer with clean optical surfaces has a size-of-source effect usually not greater than 0.6°F at the gold point (1,948.0°F), tending to indicate a higher temperature as the source area is increased. If the extraneous source area is at nominally the same temperature as the target, the magnitude of the effect is proportional to the square of the absolute (target) temperature and to the mean-effective wavelength; the effect is therefore inherently larger in infrared-sensing radiation thermometers.

Very few data are available on the magnitude of this error in disappearing filament optical pyrometers; the pyrometer lamp filament is heated slightly by the radiation of the target image, and no special precautions have been taken to minimize the effect of scattered radiation. The small amount of available data (Lee, 1962) suggests that the effect in a disappearing filament pyrometer is of the order of 2°F to 4°F (at the gold point) difference between viewing very small and very large targets.

The size-of-source effect can cause a very large error, especially in radiation thermometers operating in the infrared, if the area adjacent to the target is at a much higher radiance temperature than the target or if a much higher temperature source in the background (behind the target) lies near the line of sight.

The effect can be almost entirely eliminated for a particular application by calibrating the radiation thermometer against a target with similar radiance properties as the intended application. Relevant radiance properties to match include the size and shape of the target, the relative radiance of the background around the target relative to the target, and the distance between the radiometer and target.

I-7.5.2 Windows and Atmospheric Absorption. Suppose a radiation thermometer sighted on a blackbody indicates a temperature, T_0 (in absolute temperature units, such as kelvins), but indicates a lower temperature, T, when viewing the same blackbody through a window having a transmittance, τ_λ. The relationship between the temperatures indicated with and without the window in place is given to a close approximation by the following (Kostkowski and Lee, 1962):

$$1/T_0 - 1/T = \lambda_e/c_2 \log_e \tau_\lambda = -A, \ T_0 > T \tag{I-7-6}$$

Note the similarity between eqs. (I-7-4) and (I-7-6); the role of the spectral emissivity, ε_λ, is the same as that of a window of spectral transmittance, τ_λ. For any measured value of T, the value of T_0 may be obtained if the mean-effective wavelength, λ_e; the spectral transmittance, τ_λ; and the second radiation constant, c_2, are known. It is usually more practical to experimentally determine the value of A by direct measurement of T and T_0. A is very nearly constant (it varies slightly because the mean-effective wavelength varies slightly with temperature) and may thus be used to relate other values of T and T_0. The window transmittance, and thus the A-value, are dependent on the direction of the transmitted radiation. The transmittance is highest in the direction normal to the surface. For highly transparent windows used at wavelengths less than 1 μm, T is typically 1% to 2% less than T_0, with T and T_0 in absolute temperature units.

The effect of atmospheric transmission is analogous to that of window transmission. However, if atmospheric attenuation is not visually apparent, the atmosphere is sufficiently transparent that the correction is negligible for any radiation thermometer using only visible red wavelength radiation. For radiation thermometers operating in the infrared, the errors caused by atmospheric absorption may be severe at certain wavelengths and are a function of absolute humidity and the distance between the radiation thermometer and target. Where it is not negligible, atmospheric transmission is likely to be so variable as a function of time as to render computed corrections impractical. The most common practice in such cases is to sight the radiation thermometer through a tube through the offending region through which a clean transparent gas is slowly purged, creating in effect a transparent window. When a sight tube is used, precautions must be observed so as not to restrict the entrance aperture of the pyrometer, as discussed in para. I-7.5.3. See Table I-7.5.2-1 for window corrections.

I-7.5.3 Peepholes and Sight Tubes. When a radiation thermometer is used to view through a peephole, sight tube, or any other small diameter opening, care must be taken to ensure that the entrance aperture of the radiation thermometer is not obstructed. The entrance aperture of the pyrometer may be thought of as that portion of the objective lens through which radiation must pass to be measured; it is ordinarily a circular area slightly smaller in diameter than the objective lens. The truncated cone of radiation having the entrances aperture as a base and the area of the target spot (at which the measurement is made) as the apex, which may be called the entrance cone, must be free from obstructions to ensure that the entrance aperture is unobstructed. If an obstruction occurs, such as by the edge of a misaligned window or sight tube, the radiation thermometer will read low. The target spot size used in determining an appropriate entrance cone should be