Advanced Temperature Measurement and Control
Second Edition

Gregory K. McMillan

1
Temperature Measurement

Learning Objectives

A. **Appreciate the importance of temperature measurements.**

B. **Understand the relative performance of thermocouples and resistance temperature detectors.**

C. **Gain an overview of optical pyrometer performance.**

D. **Learn about the latest technological advances in transmitters and sensors.**

E. **Find out how to select specific sensor and thermowell designs.**

F. **Understand important aspects of extension wire effects.**

G. **Gain some insight into best transmitter and communication options.**

H. **Learn the basic thermowell location and installation requirements.**

I. **Learn terminology and issues to intelligently discuss industrial applications.**

1-1. Introduction and Overview

Temperature is a measure of a material's internal molecular activity. As the level of molecular activity rises, the temperature of the material increases. *Hot* and *cold* are subjective, qualitative descriptions of a change in molecular activity.

Temperature is often the most important of the common measurements because it is an indicator of process stream composition and product quality. It would be nice if we had online analyzers throughout the process but the fact of the matter is that most plants have infrequent, offline lab analysis at best. In the chemical industry, nearly all loops that are controlling the composition of a unit operation use temperature as the primary controlled variable. Even when online or at-line analyzers exist, these are usually relegated to monitoring and the manual trim or optimization of temperature set points by supervisory or model predictive control. Temperature measurements are also essential for equipment protection and performance monitoring. Some examples of common unit operations that have a critical dependence upon tight (minimum variability) temperature control are:

- Bioreactors and fermentors
- Calciners and kilns
- Chemical reactors
- Columns (e.g., absorber, distillation, stripper)
- Condensers
- Crystallizers
- Dryers
- Evaporators
- Extruders
- Furnaces
- Superheaters and desuperheaters
- Vaporizers

Over the years, the need in the process industry for more consistent and accurate ways to describe temperature led to the invention of temperature-measuring devices, or *sensors*. Sensors use standard, universally recognized temperature scales. Because these scales rely on fixed points in nature (e.g., freezing point of water), they provide a way to describe temperature that is both objective and quantitative. The four temperature scales in use today are Fahrenheit, Celsius (also called Centigrade), Kelvin, and Rankine. In commercial applications, Fahrenheit and Celsius are the most commonly used scales.

In industrial environments, high process temperatures, pressures, and vibration make it necessary to have a robust temperature sensor. Fast response time, accuracy, and stability are also needed. While several types of temperature sensors are available, such as thermistors, infrared pyrometers, fiber optic, and others, the two most commonly used in the process measurement industry are resistance temperature detectors (RTDs) and thermocouples (TCs).

Comparison of Thermocouples and Resistance Temperature Detectors

In the process industry as a whole, 99% or more of the temperature loops use thermocouples (TCs) or resistance temperature detectors (RTD). The RTD provides sensitivity (minimum detectable change in temperature), repeatability, and drift that are an order of magnitude better than the thermocouple, as shown in Table 1-1 [1, 2]. Sensitivity and repeatability are 2 of the 3 most important components of accuracy. The other most important component, resolution, is set by the transmitter. Drift is important for extending the time between calibrations. The data in this table dates back to the 1970s and consequently doesn't include the improvements made in thermocouple sensing element technology and premium versus standard grades. However, the differences are so dramatic that the message is still the same.

A Resistance Temperature Detector (RTD) has a much better sensitivity and repeatability, a lower and more predictable drift, and a higher signal level than a thermocouple (TC).

Table 1-1 includes data on thermistors, which have seen limited use in the process industry despite their extreme sensitivity and fast (millisecond) response, primarily because of their lack of chemical and electrical stability. Thermistors are also highly nonlinear but this can be addressed by smart instrumentation.

For bare sensing elements, thermistors are much faster-responding than thermocouples, which are slightly faster than RTDs. This point rarely comes into play because for most industrial processes a 1 or 2 second additional lag time in a temperature loop is well within the uncertainty of the loop's dynamics. The secondary process time lags can easily change by 10 to 20 seconds for slight changes in operating conditions. Also, once these sensing elements are put inside a thermowell or protection tube (a closed-end metal tube that encapsulates and protects a temperature sensor from process flow, pressure, vibration, and corrosion), the fit, fill, material, and construction of the thermowell have the biggest impact on temperature measurement time lags, as noted in Tables 1-2a and 1-2b [1][3, 4]. Protection tubes like thermowells provide isolation of the element from the process but unlike thermowells, protection tubes do not necessarily provide a pressure tight attachment to a vessel, a tapered or stepped wall, or a tight fit of the element. Protection tubes may be ceramic for high temperature applications. The measurement lags from protection tubes are generally larger than for thermowells.

Table 1-1. Accuracy, range, and size of temperature sensing elements [1, 2]

Criteria	Thermocouple	Platinum RTD	Thermistor
Repeatability (°C)	1 - 8	0.02 - 0.5	0.1 - 1
Drift (°C)	1 - 20	0.01 - 0.1	0.01 - 0.1
Sensitivity (°C)	0.05	0.001	0.0001
Temperature Range (°C)	–200 - 2000	–200 - 850	–100 - 300
Signal Output (volts)	0 - 0.06	1 - 6	1 - 3
Power (watts at 100 ohm)	1.6×10^{-7}	4×10^{-2}	8×10^{-1}
Minimum Diameter (mm)	0.4	2	0.4

Table 1-2a. Dynamics of bare sensing elements [1][3, 4]

Bare Sensing Element Type	Time Constant (seconds)
Thermocouple 1/8-inch sheathed and grounded	0.3
Thermocouple 1/4-inch sheathed and grounded	1.7
Thermocouple 1/4-inch sheathed and insulated	4.5
Single Element RTD 1/8 inch	1.2
Single Element RTD 1/4 inch	5.5
Dual Element RTD 1/4 inch	8.0

The thermowell and protection tube design and material, the process heat transfer coefficient, and the fit of the sensor determine the temperature measurement speed of response more than the sensor type.

Table 1-2b. Dynamics of thermowells [1][3, 4]

Process Fluid Type	Fluid Velocity (feet per second)	Annular Clearance (inches)	Annular Fill Type	Time Constants (seconds)
Gas	5	0.04	Air	107 and 49
Gas	50	0.04	Air	93 and 14
Gas	150	0.04	Air	92 and 8
Gas	150	0.04	Oil	22 and 7
Gas	150	0.02	Air	52 and 9
Gas	150	0.005	Air	17 and 8
Liquid	0.01	0.01	Air	62 and 17
Liquid	0.1	0.01	Air	32 and 10
Liquid	1	0.01	Air	26 and 4
Liquid	10	0.01	Air	25 and 2
Liquid	10	0.01	Oil	7 and 2
Liquid	10	0.055	Air	228 and 1
Liquid	10	0.005	Air	4 and 1

There are many stated advantages for thermocouples, but if you examine them more closely you realize they are not as important as perceived for industrial processes. Thermocouples are more rugged than RTDs. However, the use of good thermowell or protection tube design and installation methods makes an RTD sturdy enough for even high-velocity stream and nuclear applications [5, 6]. Thermocouples appear to be less expensive until you start to include the cost of extension lead wire and the cost of additional process variability from less sensor sensitivity and repeatability.

Thermocouple extension wire and the consequences of drift in terms of process offsets and the need for more frequent calibration make the life cycle costs of a thermocouple (TC) larger than a Resistance Temperature Detector (RTD).

The minimum size of a thermocouple is much smaller. While a tiny sensor size is important for biomedical applications, miniature sensors are rarely useful for industrial processes.

The main reason to go to a thermocouple is if the temperature range is beyond what is reasonable for an RTD or you don't need the accuracy of an RTD. Thus, for temperatures above 850°C (1500°F), the clear choice is a thermocouple for a contacting temperature measurement. For temperatures within the range of the RTD the decision often comes down to whether the temperature is used for process control or just the monitoring of trends. If you have lots of temperatures for trending where errors of several degrees are unimportant, you could save money by going to thermocouples with transmitters mounted on the thermowell (integral mount) or nearby. If you are using temperature for process control, data analytics, statistical or neural network predictions, process modeling, or in safety systems, a properly protected and installed RTD is frequently the best choice for temperatures lower than 500°C (900°F). At temperatures above 500°C, changes in sensor sheath insulation resistance have caused errors of 10°C or more.

Optical Pyrometers

While thermocouples can be used at high temperatures in furnaces and wireless transmitters have expanded their use in rotating equipment, such as kilns and calciners, there is still a significant niche market for optical pyrometers in the process industry.

Non-contacting temperature measurements are needed for solid products that are moving, such as plastic webs, fiber spin lines, and paper sheets. Non-contacting temperature measurements are also useful for furnaces where the installation integrity and reliability of thermocouples is questionable.

Optical pyrometers are required when contact with the process is not possible or extreme process temperatures and conditions cause chemical attack, physical damage, or an excessive decalibration, dynamic, velocity, or radiation error of a TC or RTD (see Chapter 2).

While the market is small for optical pyrometers, an overview of the technology is merited to better understand some of the limitations and difficulties not commonly discussed in product catalogs. Equations are used to clarify the assumptions and quantify the effects of a non-ideal target, installation, intervening space, and viewing window.

For details on selection, configuration, installation, and calibration, the user should use information and application specialists from the manufacturer.

Pyrometers infer temperature from the optical radiation intensity at one or more wavelengths from a target. The most prevalent non-contacting temperature measurements devices in industry are single-color and ratio (2-color) pyrometers [1][7, 8, 9, 10]. The concept of blackbodies, graybodies, and non-graybodies is necessary to understand how the radiation seen by the pyrometer for a particular temperature varies with target and process conditions.

Blackbodies

A blackbody is a theoretical surface that absorbs all energy (does not reflect or transmit energy). A blackbody is also a perfect radiating body. The total net energy radiated by a blackbody is proportional to the difference between the target temperature (T_t) and the sensor temperature (T_s) each raised to the 4^{th} power as detailed in Equation 1-1a (Stephan-Boltzmann Equation). The total energy radiated is the area under the curve in Figure 1-1 at the given temperature. The parameter K takes into account the areas of the target and sensor and the distance between them. For high temperatures, the sensor temperature is considered negligible so this temperature is dropped in Equation 1-1b but the K factor remains to take into account the characteristics of the sensor [1][7, 8, 9, 10].

Emissivity and Emittance

Process temperature targets do not behave as blackbodies. In Equation 1-1b, the total emissivity term is introduced as a multiplier to take into account the non-ideal radiating behavior of materials (e.g., aluminum, carbon, Monel, steel, titanium, zirconium, plastic, paper). The total emissivity is the ratio of the total energy radiated by a material to the total energy radiated by a blackbody. The total emissivities of most materials encountered in process applications at various temperatures can be found in tables in books with chapters on pyrometers.

The emissivity is a physical property of the material and is specified for a sample with a highly polished surface. The targets in industrial equipment (e.g., furnaces, calciners, and kilns) have different roughness, geometry, and sizes and are often covered with oxides and corrosion products. To take into account the effects of installation and operating conditions, a factor called *emittance* is used instead of emissivity. The total emittance is the ratio of total radiation for the physical and operating conditions of the target to the total radiation from a blackbody at a given temperature. In Equation 1-1c total emissivity is replaced with total emittance. Tables are available to give some typical values of total emittance but the actual emit-

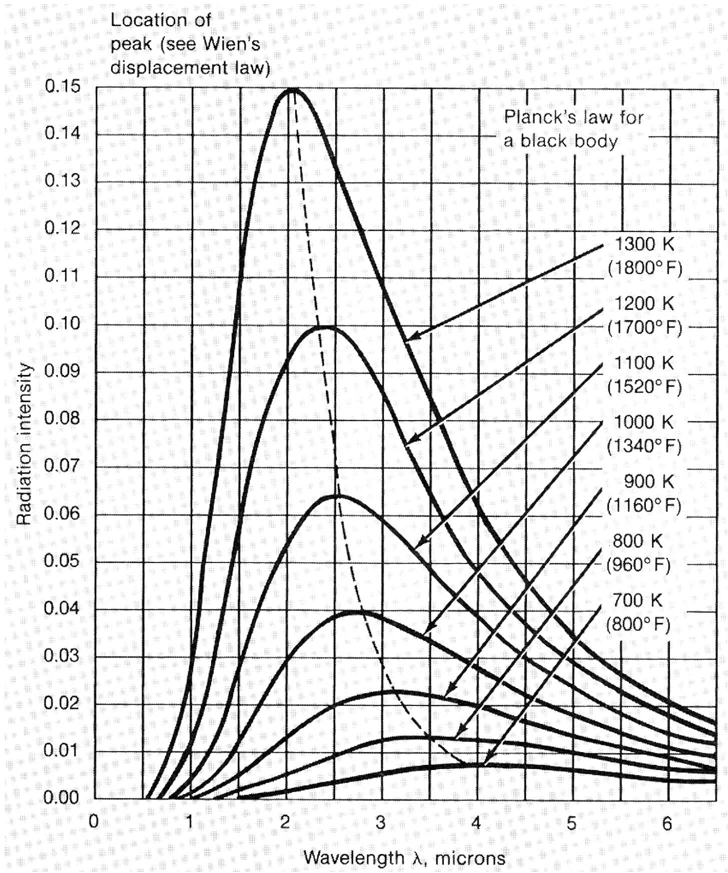

Figure 1-1. Blackbody radiation intensity as a function of wavelength and temperature *(Source: Figure 8-3. Temperature Measurement in Industry [ISA, 1990])*

tance depends upon application conditions and changes to the surface from coatings, corrosion, oxidation, and erosion during a production run.

Sensitivity

In Figure 1-1 for blackbodies the peak in the curve for each temperature shifts to the left as the temperature increases. The maximum change in radiation intensity for a change in temperature occurs near the peaks. To the left of the peak, the radiation intensity drops off suddenly. The change in intensity with temperature is appreciable until the intensity becomes close to zero. To the right of the peak, the radiation intensity tails off and the curves start to converge. The change in intensity with temperature becomes smaller and the pyrometer loses sensitivity. Figure 1-1 is for a blackbody [1][7, 8, 9, 10].

Graybodies

For graybodies, a fraction (e.g., 0.65 to 0.95) of the radiation intensity radiated by a blackbody is emitted. The fraction is fixed for all wavelengths for a given set of operating conditions. The shape of the graybody curve is similar to the blackbody curve and the peak would occur at the same wavelength but the graybody curve would be shifted below the blackbody curve as illustrated in Figure 1-2 by an amount that corresponds to the emittance of the graybody. The emittance can be a function of temperature and can vary with time but these changes are the same for all wavelengths. The graybody curve is simply the blackbody curve's values multiplied by the same emittance factor for all wavelengths. Equation 1-1c gives the total energy radiated for a graybody [1][7, 8, 9, 10].

Non-Graybodies

For non-graybodies, the fraction of the radiation emitted is variability and generally lower. The variation in emittance with wavelength and can result in multiple peaks as shown in Figure 1-2. The area under each of the peaks must be integrated to get the total radiation. We can get back to a simple general equation if we compute the spectral radiation (radiation at a specific wavelength) rather than the total radiation from all wavelengths. Equation 1-1d shows that a further modification of the Stephan-Boltzmann equation (that simply consists of raising the target temperature to the power N as a function of wavelength and temperature as defined by Equation 1-1e) provides a prediction of the spectral radiation for graybodies. If we make the emittance a function of wavelength besides temperature, we end up with Equation 1-1f, which provides a prediction of spectral radiation for non-graybodies.

Single and Two-color Pyrometers

In single-color and two-color pyrometers, wavelengths are chosen to provide a maximum change in radiation intensity with temperature but with minimum absorption by anything in the space between the target and the sensor. There is a peak in the absorption for the various gases, vapors, particles, and steam in the process equipment and the condition and material of the window into the process equipment. There is also a peak in the detector output. Ideally, the peak in radiation intensity and detector output coincide and are sufficiently separated from the peaks in absorption. As the maximum temperature increases, smaller wavelengths are desired because of the shift of the peak to the left in Figure 1-1 but this corresponds to peaks in absorption by gases, notably carbon dioxide.

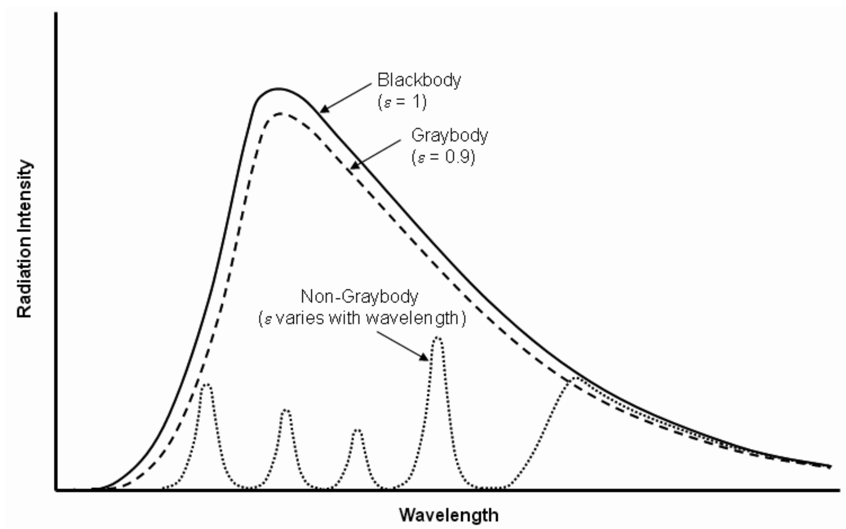

Figure 1-2. Radiation intensity for blackbody, graybody, and non-graybody [10]

Single-color or narrow band pyrometers use filters to narrow the view to a particular wavelength. In general a single-color pyrometer is more accurate than total radiation or broadband pyrometers (e.g., hand-held pyrometers) because smart instrumentation can take into account the known effects at a particular wavelength and a color can be chosen that is a better match for the application. However, there are often many unknown and time-varying effects, such as changes in the surface, the intervening vapors, and the viewing window, that introduce errors into the readings from a single-color pyrometer [1][7, 8, 9, 10].

Two-color or ratio pyrometers measure the radiation at two wavelengths. If the change in emittance at each wavelength with temperature is identical (graybodies), the effect of emittance can be cancelled out by ratio calculations. In reality, the change in emittance with temperature varies with wavelength (non-graybodies). Additionally, the change in emittance with changes in surface, operating conditions, and the composition of the intervening space may vary with wavelength.

In one comparison test on a blackbody, single-color and two-color pyrometers exhibited errors of 2 and 30°C (3.6 and 54°F), respectively [10]. Equal changes in emittance due to surface and operating conditions and intervening gases, particles, and vapors may make a two-color ratio pyrometer more accurate than a single-color pyrometer but it puts into question any accuracy statements for two-color pyrometers that are much better than

30°C. As a surface becomes closer to a blackbody and the absorption of radiation in the intervening space decreases, a single-color pyrometer may be best. The proper selection of the pyrometer type and wavelengths requires application experience or field trials.

The accuracy of a ratio two-color optical pyrometer may be less than a single color pyrometer because of the variation of emittance and radiation intensity with wavelength.

Equations for Total and Spectral Radiation

Total radiation intensity from a ***blackbody*** target can be expressed by the Stephan-Boltzmann Equation with the factor K to account for differences in target and sensor area and the distance between them:

$$E(T_t) = K * \sigma * (T_t^4 - T_s^4) \quad \text{(1-1a)}$$

For a negligible sensor temperature and a ***graybody*** with a target material emissivity that is a function of temperature, the equation for total radiation becomes:

$$E(T_t) = \varepsilon(T_t) * K * \sigma * (T_t^4) \quad \text{(1-1b)}$$

The substitution of target emittance for material emissivity takes into account installation and application effects on a ***graybody*** target on the total radiation:

$$E(T_t) = \kappa(T_t) * K * \sigma * (T_t^4) \quad \text{(1-1c)}$$

The substitution of N for the exponent of the ***graybody*** target temperature, gives the radiation intensity at a particular wavelength (spectral radiation):

$$E(\lambda_i, T_s) = \kappa(T_t) * K * \sigma * (T_t^N) \quad \text{(1-1d)}$$

$$N = \frac{14388}{\lambda_i * T_t} \quad \text{(1-1e)}$$

The spectral radiation intensities of ***non-graybodies*** have emittances that depend upon both wavelength and temperature:

$$E(\lambda_i, T_s) = \kappa(\lambda_i, T_t) * K * \sigma * (T_t^N) \tag{1-1f}$$

where:

$E(T_t)$ = total radiation at a given temperature (Watts/cm^2)

$E(\lambda_l, T_t)$ = spectral radiation at a given wavelength and temperature (Watts/cm^2)

$\varepsilon(T_s)$ = emissivity of a surface at a given temperature

$\kappa(T_s)$ = emittance of a surface at a given temperature

$\kappa(\lambda_l, T_t)$ = emittance of a surface for a given wavelength and temperature

K = factor for distance and size of target and type of detector

σ = Stephan-Boltzmann constant (5.669x10^{-12} W/cm^2°K^4)

T_t = target temperature (°K)

T_s = sensor temperature (°K)

λ_l = wavelength i (cm)

1-2. Thermocouples and RTDs

Sensing Element

The sensing element, which is constructed of metal, responds to the process temperature by generating a measurable resistance (RTDs) or voltage (TCs) signal.

Sensor Sheath

Most temperature sensors used in the process industry today have a sheath to prevent damage during handling and installation and from debris and solids. Furthermore, they are usually installed in a thermowell for additional protection and to meet the various material of construction requirements.

The sensor sheath, or cable housing, is constructed of metal and holds most of the component parts of the temperature sensor as shown in Figures 1-3a and 1-3b for an RTD. Typically magnesium oxide (MgO) sensor packing (also known as minerally insulated [MI]) surrounds the sensing element and is contained within the sensor sheath. The sensor packing decreases the impact of process vibration on the sensing element and thus ensures a more accurate measurement over time. The end of the sensor sheath is sealed with a fill (e.g., epoxy) that keeps moisture out of the sheath and away from the sensing element.

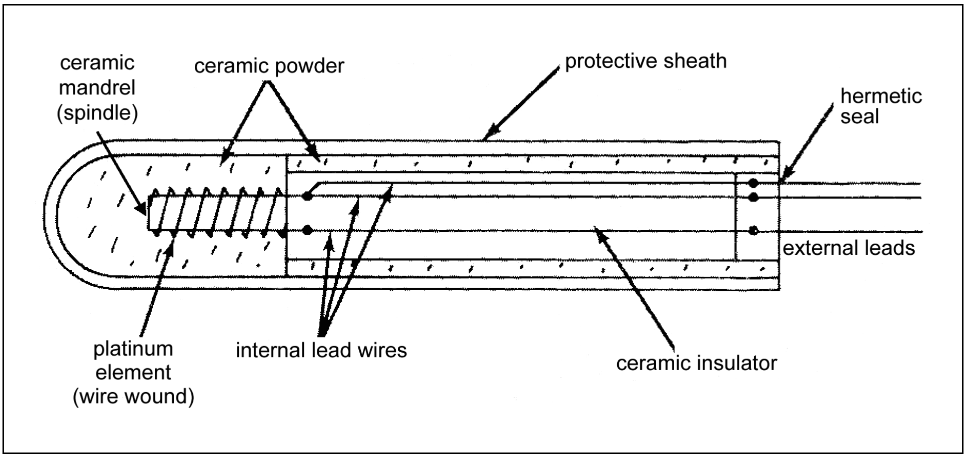

Figure 1-3a. Sheathed wire wound RTD sensor with 3 lead wires [8] (*Source: Figure 6-1. Temperature Measurement In Industry – [ISA, 1990]*)

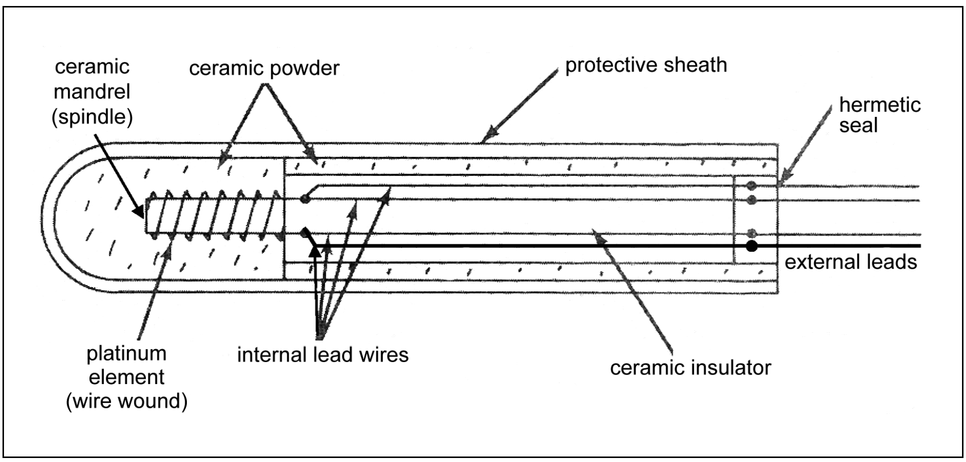

Figure 1-3b. Sheathed wire wound RTD sensor with 4 lead wires [8] (*Source: Figure 6-1. Temperature Measurement In Industry – [ISA, 1990]*)

Resistance Temperature Detectors (RTD)

RTDs operate on the principle that the electrical resistance of a metal increases as temperature increases, a phenomenon known as *thermoresistivity*. A temperature measurement can be inferred by measuring the resistance of the RTD element. The thermoresistive characteristics of RTD sensing elements vary depending on the metal or alloy from which they are made.

Platinum

Platinum RTD elements are the most common type used in process industries. Platinum elements have high accuracy, high repeatability, and a high resistance change per degree of temperature change. In addition, the output of platinum RTD elements is highly linear throughout their temperature range.

Copper

Copper RTD elements are highly linear throughout their temperature range, but have limited accuracy and a narrower temperature range than platinum elements. Copper elements, which are less expensive, are most often used for measuring temperature in bearings and motor windings—applications in which accuracy is not critical.

Wire-Wound RTD

Wire-wound RTD sensing elements are constructed by coiling a platinum (or other resistance metal) wire inside (internally wound) or around (externally wound) a ceramic *mandrel* (spindle). Most RTD sensors for the process industry are internally wound and sheathed for protection as shown in Figures 1-3a and 1-3b.

A dual-element wire-wound RTD can be created by coiling a second set of wires inside or outside the ceramic mandrel. If connected to a second transmitter, a transmitter with dual-sensor capabilities, or to another distributed control system (DCS) card, a *dual-element sensor* increases the reliability of the temperature measurement.

Wire-wound RTD elements are very sturdy and reliable. Compared to thin-film RTD elements, their accuracy tends to be higher, and their time response (how quickly the output reflects the temperature change) is several seconds faster than thin-film RTD elements. Wire-wound RTD elements work well for a wide variety of applications, although they may fail in high-vibration applications. The single element has a lower gauge sensing element and smaller time constant than the dual element. The use of redundant sensors helps eliminate common mode failures and enables a better cross check of sensor drift than dual elements. Three sensors and middle signal selection reduces noise and drift and provides inherent automatic protection against a single failure of any type.

Two single-element RTD sensors, instead of a dual-element sensor, provide a faster response with better diagnostics (such as drift) and less susceptibility to vibration and common mode failures.

Thin-Film RTD

Thin-film RTD sensing elements are constructed by depositing a thin film of resistance metal onto a ceramic substrate (base piece) and trimming the metal to specifications. Sensing elements of thin-film construction are typically less expensive than those of wire-wound construction because less resistance metal is required for construction. However, thin-film RTDs tend to be less stable over time, typically have a more limited temperature range, and may be more susceptible to damage from rough handling.

Extension Lead Wires

To get an accurate temperature reading from an RTD, the resistance of the RTD sensing element must be measured. Each copper lead wire that connects the RTD sensing element to the resistance measuring device adds a small amount of resistance to the measurement. If this added resistance is ignored, an error is introduced and an inaccurate temperature measurement results. The error is referred to as the *lead wire effect*. The longer the wire run, the greater the error, or lead wire effect, reflected in the temperature measurement. To compensate for lead wire effect, three-wire and four-wire RTDs are used instead of two-wire RTDs. Three-wire RTDs are created by connecting one additional copper wire to one of the lead wires. Four-wire RTDs are created by connecting one additional copper lead wire to each of the existing lead wires. These additional wires are used by the transmitter to compensate for lead wire resistances.

The third wire compensates for the resistance of the lead wires based on the assumption that each wire has exactly the same resistance. In fact, there is a tolerance of 10% in the resistance of standard wires. The fourth wire compensates for the uncertainty in the resistance of wires. For example, 500 feet of 20 gauge cable would add 10 ohms which would cause a measurement error of 26°C (47°F) for a two-wire RTD. The 10% tolerance of the cable could create an error as large as 2.6°C (4.7°F) for a three-wire RTD [11]. For high accuracy applications or long extension wire runs, a four-wire RTD or a transmitter mounted on the thermowell (integral mount) should be used. The increased accuracy, stability, and reliability of microprocessor based transmitters and the advent of secure and reliable wireless networks makes integral mounted transmitters an attractive option. Accessibility is less of an issue because maintenance requirements are drastically reduced. The transmitters rarely need removal, wiring problems are gone, and calibration checks and integrity interrogation can be done remotely.

A four-lead wire RTD is advisable for tight measurement accuracy requirements or long distances because the fourth wire can compensate for the differences in lead wire resistance not compensated by a three-lead wire RTD.

Once the resistance value is determined, it is converted to a temperature measurement. One of two conversion methods may be used by the transmitter:

- RTD standard (i.e., IEC 751 standard)
- Callendar-Van Dusen equation

IEC 751 standard

The IEC 751 standard describes an ideal relationship between the resistance of a platinum RTD and the temperature to which the RTD is subjected. For example, at 100°C (212°F), the IEC 751 standard shows that an ideal platinum RTD (one that exactly matches the IEC 751 standard) would have a resistance value of 138.5 ohms.

When a transmitter or control system accepts a resistance signal from a platinum RTD, the IEC 751 standard curve is often used to translate that resistance signal into a temperature reading. However, since actual RTDs are never ideal, they do not match the resistance versus temperature relationship as described in the IEC 751 standard. The difference between the actual RTD curve and the ideal RTD curve results in a measurement error, which is referred to as a *sensor interchangeability error.*

The maximum allowable sensor interchangeability error at a given process temperature is defined by two IEC 751 standard classifications—Class A and Class B. These classifications are used to identify platinum RTDs. Figure 1-4 compares these two classes to the IEC 751 standard ideal.

Callendar-Van Dusen Equation

The Callendar-Van Dusen equation offers an alternative to the IEC 751 standard. The equation, used in "Transmitter-Sensor Matching," can cre-

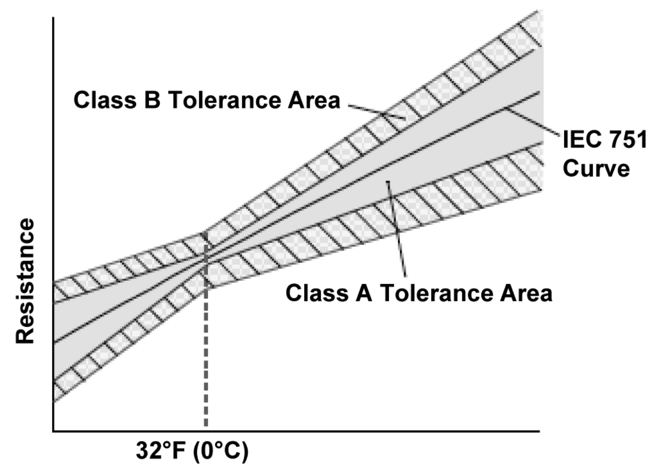

Figure 1-4. IEC 751 standard

ate a curve that approximates an RTD's resistance-temperature relationship. The Callendar-Van Dusen equation is:

$$R_t = R_O + R_O\alpha[(t-\delta)(0.01t-1)(0.01t) - \beta(0.01t-1)(0.01t)^3]$$

where:

t = Temperature in °C

R_t = Resistance of the RTD at t

R_O = Resistance of the RTD at t = 0°C (a Callendar-Van Dusen constant)

α, β and δ = Callendar-Van Dusen constants

The Callendar-Van Dusen equation can be programmed into a transmitter so that the transmitter can use the actual RTD curve rather than an ideal curve (e.g., IEC 751 standard) to translate the sensor's resistance signal into a temperature value. The Callendar-Van Dusen equation provides a significant improvement in measurement accuracy, even when compared to Class A RTDs.

The Callendar Van Dusen equation can eliminate most of the RTD sensor interchangeability error.

Thermocouples (TC)

A thermocouple (TC) consists of two wires of dissimilar metals (e.g., iron and constantan) that are joined at one end to form a *hot junction* (or sensing element). The temperature measurement is made at the hot junction, which is in contact with the process. The other end of the TC lead wires, when attached to a transmitter or volt meter, forms a *cold* or *reference* junction.

Thermocouple Types

Several types of TCs are available, each differing by the metals used to construct the element. While accuracies are better for type T and E compared to J, the type selected in industry often comes down to the plant standards and the application temperature range. Figure 1-5 shows the milliVolts generated over the approximately linear range of the following types of thermocouples:

- Type E—Chromel and constantan
- Type J—Iron and constantan
- Type K—Chromel and alumel
- Types R and S—Platinum and rhodium (differing in the % of platinum)
- Type T—Copper and constantan

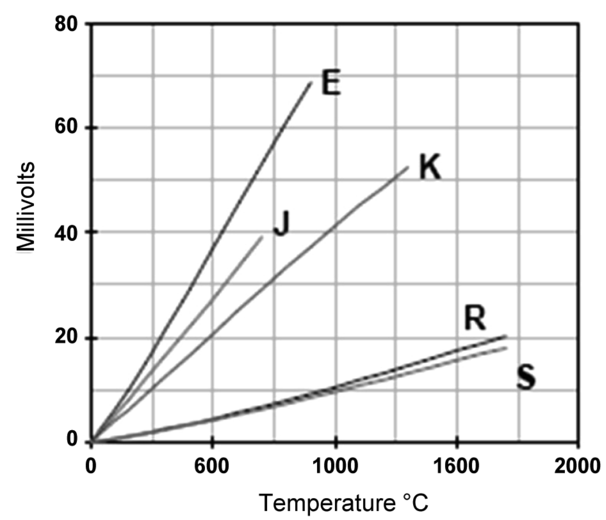

Figure 1-5. MilliVolts generated by various thermocouple types

Hot Junction Configurations

Junctions can be grounded or ungrounded to the sensor sheath. With dual-element TCs (two TCs in one sheath), the elements can be isolated or connected (unisolated). Each configuration offers benefits and limitations:

- *Grounded*—Grounding creates improved thermal conductivity, which in turn gives the quickest response time. However, grounding also makes TC circuits more susceptible to electrical noise (which can corrupt the TC voltage signal) and may cause more susceptibility to poisoning (contamination) over time.
- *Ungrounded*—Ungrounded junctions have a slightly slower response time than grounded junctions, but are not susceptible to electrical noise.
- *Unisolated*—Unisolated junctions are at the same temperature, but both junctions will typically fail at the same time.
- *Isolated*—Isolated junctions may or may not be at the same temperature. The reliability of each junction is increased, because failure of one junction does not necessarily cause a failure in the second junction.

Grounded thermocouples provide the fastest and most accurate response by minimizing dynamic error and the temperature difference from the process by minimizing the thermal resistance between the sensor and the process. Ungrounded thermocouples are less susceptible noise and contamination (see Chapter 2 for more details).

Voltage Measurement and the Seebeck Effect

TCs use a phenomenon known as the Seebeck effect to determine process temperature. According to the Seebeck effect, a voltage measured at the cold junction of a TC is proportional to the difference in temperature between the hot junction and the cold junction. The voltage measured at the cold junction is commonly referred to as the Seebeck voltage, the thermoelectric voltage, or the thermoelectric EMF. As the temperature of the hot junction (or process fluid) increases, the observed voltage at the cold junction also increases by an amount nearly linear to the temperature increase.

If the hot junction temperature is held constant, an increasing cold junction temperature will produce a decreasing voltage, because the temperature difference between the hot and cold junction is decreasing. When the cold and hot junctions reach the same temperature, the observed voltage will be 0 V. The magnitude of the voltage signal produced at the cold junction also depends on the type of metals used to form the TC. Different combinations of metals, or different TC types, have different thermoelectric voltages at the same temperatures.

Cold Junction Compensation

As with RTDs, each type of TC has a standard curve. The standard curve describes a TC's voltage versus temperature relationship when the cold junction temperature is 0°C (32°F). As mentioned, the cold junction is where the TC lead wires attach to a transmitter or volt meter. Because the voltage measured at the cold junction is proportional to the difference in temperature between the hot and cold junctions, the cold junction temperature must be known before the voltage signal can be translated into a temperature reading. The process of factoring in the actual cold junction temperature (rather than assuming it is at 0°C [32°F]) is referred to as cold junction compensation (CJC).

1-3. Selection of a Temperature Sensor

Why Use an RTD Rather Than a TC?

The main reasons for selecting RTDs rather than TCs are as follows:

- RTDs have better sensitivity, repeatability, and stability.
- RTD signals are less susceptible to noise (higher signal-to-noise ratio).
- RTDs have better linearity over temperature ranges.
- RTDs can use the Callendar-Van Dusen equation to eliminate sensor interchangeability error.
- Cold junction compensation and related errors are not associated with RTDs.
- RTD drift is predictable, while TC drift is erratic and unpredictable. In addition, TC drift errors can be large as a result of element poisoning and element oxidation at high temperatures.
- The changes that affect the output of an RTD or TC occur over time due to mechanical shock, poisoning, and temperature

cycling. These changes can be eliminated by an in-line RTD calibration, an option not available for a TC.

- RTDs do not need special extension wire.

Why Use a TC Rather Than an RTD?

In summary, the main reasons for selecting TCs rather than RTDs are as follows:

- TCs function at higher temperatures than RTDs (above 850°C [1500°F]).
- TCs are typically less expensive than RTDs and more resistant to vibration damage but the life cycle costs are higher.
- TCs have a faster response time than RTDs but this is only a consideration for bare elements (direct immersion of the element without a thermowell) in very fast temperature change processes (process time lag < 10 seconds). Bare elements are not used in industrial chemicals or elevated temperatures due to safety concerns.

The main reasons to use a TC instead of a RTD are high temperatures and high vibration.

1-4. Specifications

The accuracy of a temperature measurement is based on the combination of the sensor used and the performance specifications of the transmitter. The accuracy ranges shown in Table 1-3 are what can be expected for various sensor/transmitter combinations.

If supported by the transmitter, sensor matching using the Callendar-van Dusen constants for an RTD sensor will improve the accuracy by 75%. Ambient temperature effect: 0.001% of span or < 0.007°C per 1°C (0.0013°F per 1°F) of temperature change for most sensor types. Stability will range from ±0.25% of reading for 5 years for RTDs to ± 0.5% of reading for 1 year for thermocouples.

Table 1-3. Range and accuracy specifications

RTD Sensor Type	RTD Sensor Reference	Sensor Range		Accuracy over Range	
		°C	°F	°C	°F
Pt 100 (_ = 0.00385)	IEC 751; _ = 0.00385, 1995	–200 to 850	–328 to 1562	± 0.10 to ± 0.30	± 0.18 to ± 0.54
Pt 100 (_ = 0.003916)	JIS 1604, 1981	–200 to 645	–328 to 1193	± 0.10 to ± 0.30	± 0.18 to ± 0.54
Pt 200	IEC 751; _ = 0.00385, 1995	–200 to 850	–328 to 1562	± 0.22 to ± 0.54	± 0.40 to ± 0.98
Pt 500	IEC 751; _ = 0.00385, 1995	–200 to 850	–328 to 1562	± 0.14 to ± 0.38	± 0.25 to ± 0.68
Pt 1000	IEC 751; _ = 0.00385, 1995	–200 to 300	–328 to 572	± 0.10 to ± 0.40	± 0.18 to ± 0.72
Ni 120	Edison Curve No. 7	–70 to 300	–94 to 572	± 0.10 to ± 0.30	± 0.18 to ± 0.54
Cu 10	Edison Copper Winding No. 15	–50 to 250	–58 to 482	± 1.00 to ± 3.20	± 1.80 to ± 5.76
Cu 100 (a=428)	GOST 6651-94	–185 to 200	–365 to 392	± 0.48	± 0.86
Cu 50 (a=428)	GOST 6651-94	–185 to 200	–365 to 392	± 0.96	± 1.73
Cu 100 (a=426)	GOST 6651-94	–50 to 200	–122 to 392	± 0.48	± 0.86
Cu 50 (a=426)	GOST 6651-94	–50 to 200	–122 to 392	± 0.96	± 1.73

TC Sensor Type	TC Sensor Reference	Sensor Range		Accuracy over Range	
		°C	°F	°C	°F
NIST Type B	NIST Monograph 175	100 to 300	212 to 572	± 3.00 to ± 6.00	± 5.40 ±10.80
(varies by input range)		301 to 1820	573 to 3308	± 0.75 to ± 1.54	± 1.35 to ± 2.78
NIST Type E	NIST Monograph 175	–50 to 1000	–58 to 1832	± 0.20 to ± 0.40	± 0.36 to ± 0.72
NIST Type J	NIST Monograph 175	–180 to 760	–292 to 1400	± 0.25 to ± 0.70	± 0.45 to ± 1.26
NIST Type K	NIST Monograph 175	–180 to 1372	–292 to 2502	± 0.25 to ± 1.00	± 0.45 to ± 1.80
NIST Type N	NIST Monograph 175	–200 to 1300	–328 to 2372	± 0.40 to ± 1.00	± 0.72 to ± 1.80
NIST Type R	NIST Monograph 175	0 to 1768	32 to 3214	± 0.60 to ± 1.50	± 1.08 to ± 2.70
NIST Type S	NIST Monograph 175	0 to 1768	32 to 3214	± 0.50 to ± 1.40	± 0.90 to ± 2.52
NIST Type T	NIST Monograph 175	–200 to 400	–328 to 752	± 0.25 to ± 0.70	± 0.45 to ± 1.26
DIN L	DIN 43710	–200 to 900	–328 to 1652	± 0.35 to ± 0.70	± 0.63 to ± 1.26
DIN U	DIN 43710	–200 to 600	–328 to 1112	± 0.35 to ± 0.70	± 0.63 to ± 1.26
w5Re26	ASTME 988-96	0 to 2000	32 to 3632	± 0.70 to ± 1.60	± 1.26 to ± 2.88
GOST Type L	GOST R 8.585-2001	–200 to 800	–392 to 1472	± 0.71	±1.28

1-5. Setup and Calibration

Calibration is a means to verify the proper operation of the sensor and the electronics receiving the sensor signal.

Sensors can be calibrated by exposing them to one or more known temperatures and measuring the sensor output. The output is then compared to that of a certified sensor probe to determine the calibration error. It is also possible to calibrate the combined measurement system by measuring the resulting reading of the transmitter or other measurement electronics.

Transmitters and other electronics measurement equipment such as system I/O cards can be calibrated by applying an electronically generated signal to simulate the voltage or resistance of a sensor. A wide variety of calibrators are available for this purpose.

Most suppliers of temperature sensors and transmitters will provide factory calibration for their products with associated documentation of the results.

1-6. Installation

The best practice for making a temperature measurement is to keep the length of the sensor wiring as short as possible to minimize the effect of electromagnetic interference (EMI) and other interference on the low level sensor signal. The temperature transmitter should be mounted as close to the process connection as possible.

To minimize conduction error (error from heat loss along the sensor sheath or thermowell wall from tip to flange or coupling), the immersion length should be at least 10 times the diameter of the thermowell or sensor sheath for a bare element. Thus, for a thermowell with a 1 inch (2.54 cm) outside diameter, the immersion length should be 10 inches (25.4 cm). For a bare element with a ¼ inch (6.35 mm) outside diameter sensor sheath, the immersion length should be at least 2.5 inches (63.5 mm). This is just a rule of thumb. Computer programs can compute the error and do a fatigue analysis for various immersion lengths and process conditions.

For high velocity stream and bare element installations, it is important to do a fatigue analysis because the potential for failure from vibration increases with immersion length.

The process temperature will vary with process fluid location in a vessel or pipe due to imperfect mixing and wall effects. For highly viscous fluids such as polymers and melts flowing in pipes and extruders, the fluid temperature near the wall can be significantly different than at the centerline (e.g., 10 to 30°C; 50 to 86°F) [12]. Often the pipelines for specialty polymers are less than 4 inches (101.6 mm) in diameter, presenting a problem for getting sufficient immersion length and a centerline temperature measurement. The best way to get a representative centerline measurement is by inserting the thermowell in an elbow facing into the flow (position 1 in Figure 1-6). If the thermowell is facing away from the flow, swirling and separation from the elbow as can create a noisier and less representative measurement (position 2 in Figure 1-6). An angled insertion (position 3 in Figure 1-6) can increase the immersion length over a perpendicular insertion (position 4 in Figure 1-6) but the insertion lengths shown for both are too short unless the tip extends past the centerline. A swaged or stepped thermowell can reduce the immersion length requirement by reducing the diameter near the tip.

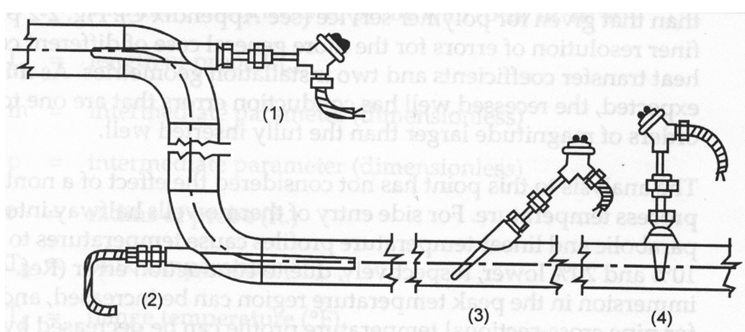

Figure 1-6. Ranking of installations to reduce heat conduction and profile errors
(*Source: 614. Advanced Control Unleashed [ISA, 2003]*)

Swaged and tapered thermowells in elbows reduce the thermowell length requirement and the pipe temperature profile error.

The distance of the thermowell in a pipeline from a heat exchanger, static mixer, or desuperheater outlet should be optimized to reduce the transportation delay but minimize noise from poor mixing or two phase flow. As shown in Figure 1-7, generally 25 pipe diameters is sufficient to ensure sufficient mixing after the recombination of divided flows from heat exchanger tubes or static mixer elements.

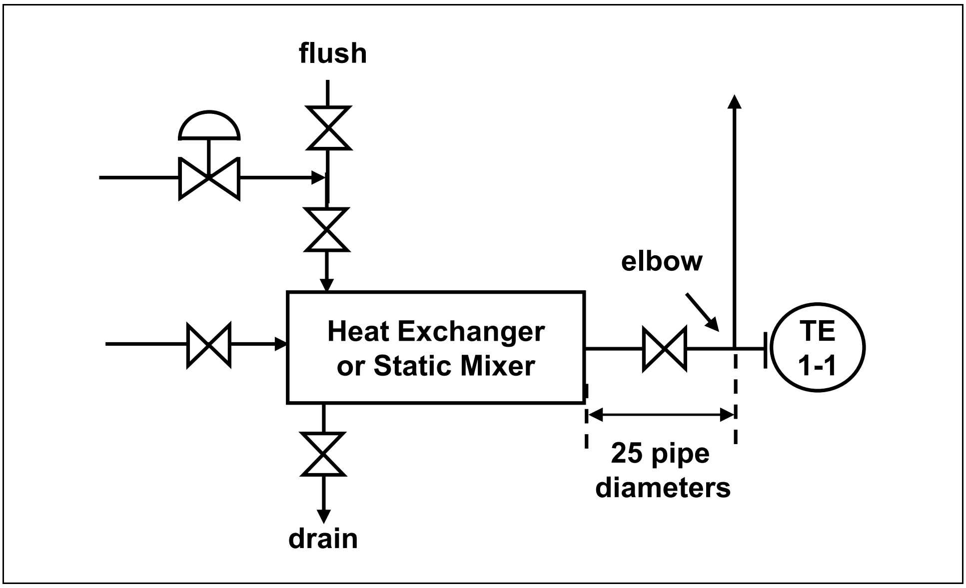

Figure 1-7. Minimum distance from outlet of heat exchanger and static mixer

For desuperheaters, the distance from the outlet to the thermowell depends upon the performance of the desuperheater, process conditions, and the steam velocity. To give a feel for the situation there are some simple rules of thumb for the straight piping length (SPL) to the first elbow and the total sensor length (TSL). Actual SPL and TSL values depend on the quantity of water required with respect to the steam flow rate, the temperature differential between water and steam, the water temperature, pipe diameter, steam velocity, model, type, etc. and are computed by software programs [13].

SPL (feet) = Inlet steam velocity (ft/s) * 0.1 (seconds residence time)
SPL (m) = Inlet steam velocity (m/s) * 0.1 (seconds residence time)

TSL (feet) = Inlet steam velocity (ft/s) * 0.2 (seconds residence time)
TSL (m) = Inlet steam velocity (m/s) * 0.2 (seconds residence time)

Typical values for the inlet steam velocity, upstream of the desuperheater range from 25–350 ft/s (7.6 to 107 m/sec). Below 25 ft/s there is not enough motive force to keep the water suspended in the steam flow. Water tends to fall out and run down the pipe to a drain. When this happens the water no longer cools the steam and the system thinks it needs to add more water, which compounds the problem. Problems can also include pipe wall erosion and high thermal stress gradients in the pipe wall (i.e., a hot top and cold bottom, which can crack welds or warp the pipe to an egg-shaped cross-section). Current technology has an inlet velocity limitation of 350 ft/s (107 m/sec). Velocities higher than 350 ft/s cause the desuperheater to vibrate and damage the unit to the point where it breaks apart [13].

For desuperheaters, the straight pipe length to the first elbow and the total length to the sensor from the desuperheater outlet must provide a residence time of 0.1 and 0.2 seconds, respectively, to prevent water droplets from hitting sensor.

Thermowells

As mentioned, a *thermowell* is a closed-end metal tube that encapsulates and protects a sensor from process flow, pressure, vibration, and corrosion. Thermowells allow for the installation and removal of sensors without having to shut down the process. They are mounted in various ways to a process pipe or vessel.

Thermowells are available in several different materials, mounting methods, and stem types. The variety of design features renders thermowells suitable for various applications and environmental conditions. Three factors affect the choice of material:

- Type of corrosive environment the thermowell will be exposed to
- Temperature and pressure limits of the material
- Compatibility with the process piping or vessel material to ensure solid, non-corroding welds and junctions

Mounting Methods

Thermowells and sensing elements can be assembled and mounted as shown in Figures 1-8 through 1-9. Thermowells can be threaded, welded, or bolted (flanged style) onto the process pipe or vessel wall process connection.

Thermowells are threaded onto the process piping or vessel, which enables them to be easily installed and removed. Threaded thermowells are the weakest type of thermowell.

Welded thermowells are permanently welded onto the process pipe or vessel. Thus, removal is very difficult and requires cutting the thermowell out of the system. Welded thermowells are the strongest type of thermowell and are used with fluids of high velocity, high temperature, or high pressure. Welded thermowells are necessary for applications that require a leak-proof seal.

Flanged thermowells are bolted onto a pipe or vessel and can be easily removed or installed. Flanged thermowells are used in corrosive environments, as well as in high-velocity, high-temperature, or high-pressure applications. Flanged thermowells are the most expensive type of thermowell.

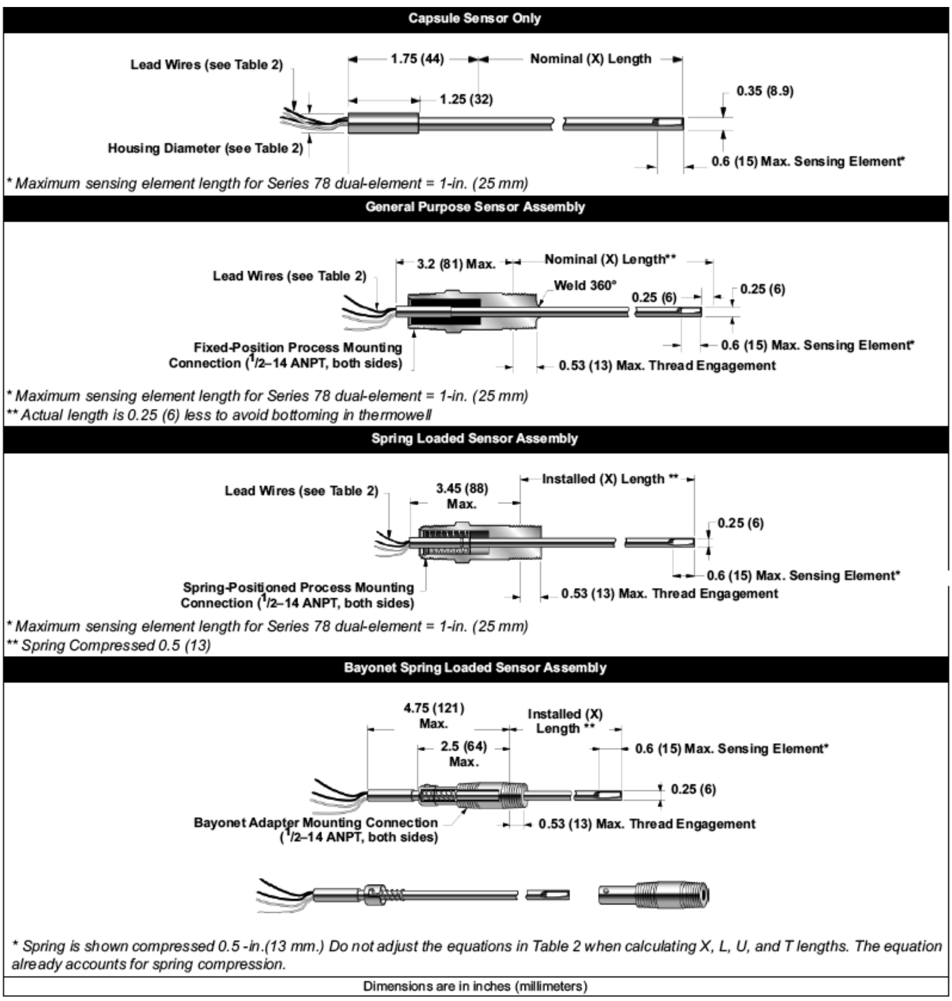

Figure 1-8. RTD sensor assembly types

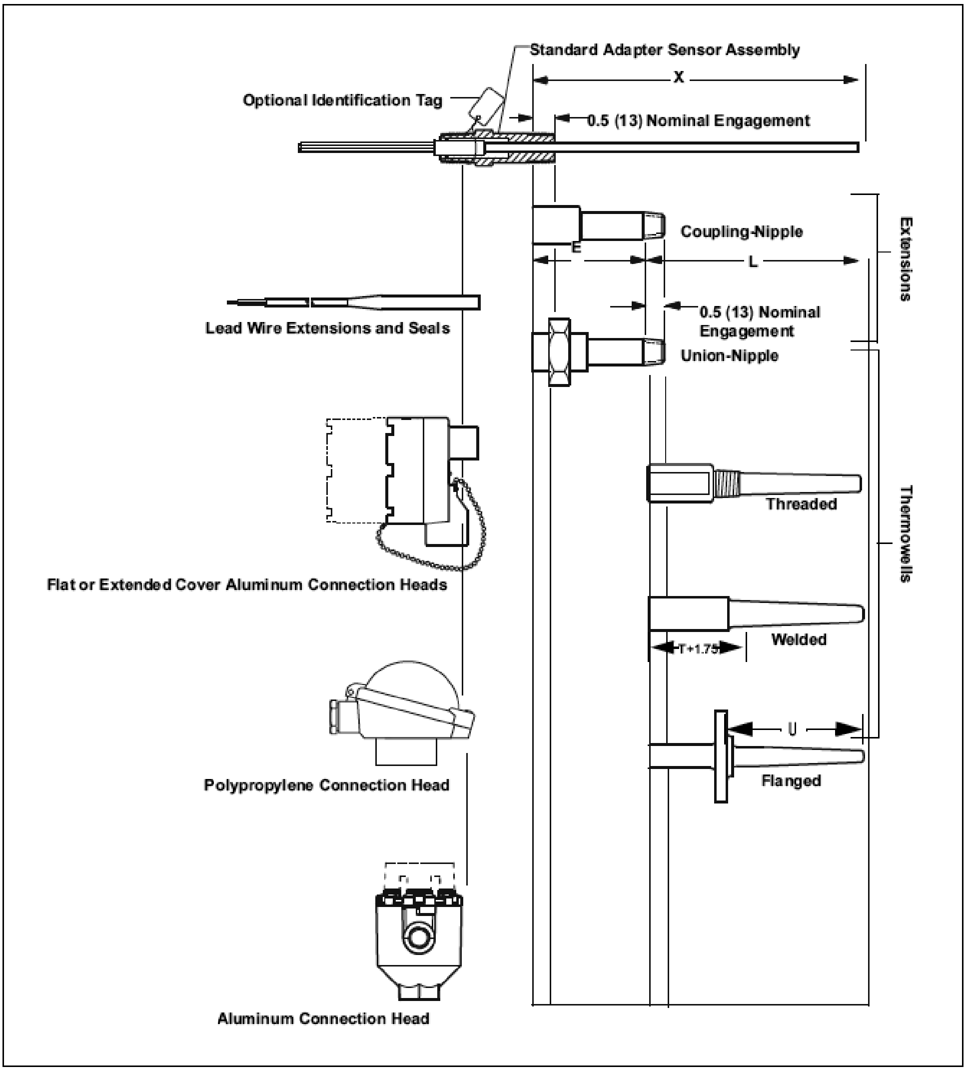

Figure 1-9. Assembly and mounting methods

Flanged thermowells are commonly used in chemical plants because of concern of the long-term integrity of threaded connections for corrosive and harsh process conditions. Hazardous chemicals and high pressures and temperatures may require welded connections.

The mounting of the transmitter on the thermowell as shown in Figure 1-10 eliminates the need for cables between the element and transmitter and offers mobility for wireless transmitters important for finding the optimum temperature measurement location.

Figure 1-10. Transmitter mounted on thermowell

Stem Designs

The *stem* of a thermowell is the part that is inserted into the process stream. Stems can be tapered, straight, or stepped. The performance of a thermowell varies with its stem design. In general, a tapered or stepped stem provides a faster response, creates less pressure drop, and is less susceptible to conduction error and vibration failure. The choice of stem design is based on:

- Process pressure
- Time response required
- Permissible conduction error
- Wake frequency—frequency of alternating side-to-side movement of a fluid; depends on properties of the fluid
- Drag force—resistance to motion of a solid shape through a body of fluid
- Price

If the thicknesses of the thermowell walls and the fit of the sensing element are identical, thermowells with straight stems have the slowest time response because they possess the most material at the tip (largest diameter). Thermowells with stepped stems have the fastest time response because they possess the least material at the tip (smallest diameter). A small diameter also results in the least amount of drag force.

Thermowells with stepped stems also provide the maximum separation between the wake frequency (vortex shedding) and the natural frequency (oscillation rate determined by the properties of the thermowell itself). If the wake frequency is 80% or more of the thermowell natural frequency, resonance and probably damage can occur. Generally, thermowells with tapered stems are slightly more expensive as a result of a more complicated manufacturing process.

Swaged, stepped, and tapered thermowells offer a faster response, lower pressure drop, and less possibility of vibration damage from resonance with wake frequencies.

Communication

To be useful for control, safety, or monitoring applications, a temperature measurement signal must be communicated from the point of measurement to the control system of the process. The two most common ways are:

- *Transmitter*—the sensor is wired a short distance to the transmitter or connected directly to the transmitter, where its signal is converted to a digital, 4–20 mA, or wireless signal. The converted signal output is then communicated to the control system through transmitter wire or a wireless network.
- *Wired direct*—the sensor's lead wires are wired the entire distance to the control system. No signal conversion takes place along the route.

Three benefits of using a temperature transmitter over wiring directly to thermocouple and RTD input cards of control system are:

- *A more robust signal is delivered*—the 4–20 mA or digital signal output from the transmitter is much more robust than a sensor signal that is wired direct. Noise interference has less impact on 4–20 mA or digital signals.
- *Measurement accuracy is optimal*—Transmitters offer improved measurement accuracy over wiring direct. For example, sensors can be matched to transmitters (transmitter sensor matching), which improves the accuracy of the temperature measurement. The temperature span can be narrowed to match the process operating range (significant for older DCS with 12-bit input cards).
- *Time and money are saved*—Transmitter installation is often less expensive than wiring a sensor direct because of savings from cabling costs and installation (sensor wire, especially TC wire, is relatively expensive). Also, a robust signal and accurate mea-

surements produce time and money savings through increased functionality and diagnostic capabilities of the transmitter.

Typically, the analog signal is linear with a process temperature measurement. Most transmitters now incorporate a microprocessor, which has improved their performance compared to analog designs. These smart (also called “intelligent”) transmitters are able to compensate for ambient temperature variations and EMI, and provide cold junction compensation for thermocouples. Some also enable the transmitter to be matched to the characteristics of a specific sensor, providing very high accuracy. They are easily configured for a specific sensor type, providing an output that is linear over the temperature range. Intelligent transmitters with digital communications are also able to communicate diagnostic information about the health of the sensor and electronics.

Some transmitters provide the ability to connect more than one sensor. The most common transmitter of this type will support two sensors but has a single analog output. Coupled with dual sensor elements, this feature can be used to provide a more reliable measurement by comparing two measurements or the ability to switch to the second sensor in the event of the failure of the first.

The use of transmitters instead of TC or RTD input cards is recommended to greatly improve accuracy and maintainability, by matching the calibration and nonlinearity compensation to sensor, narrowing the span, reducing noise, and offering diagnostics.

The use of digital communications allows the additional flexibility of using a single transmitter to make more than one temperature measurement and communicate these back to the control system. There are temperature devices designed to specifically take advantage of this capability, providing the ability to measure four, or eight, or potentially more individual temperatures. The most common communication techniques are the HART® (including WirelessHART™), FOUNDATION™ Fieldbus and Profibus PA standard protocols.

The reliability, security, and ease of setup of WirelessHART (Highway Addressable Remote Transducer) networks combined with increased battery life from new communication rules and PID enhancements have made wireless communication an excellent option [14]. Since temperature changes in most processes are quite slow, the refresh time can be set longer than for other types of loops, extending battery life. Also, the noise amplitude and period in temperature loops is usually quite small compared to other loops unless there are two phases (e.g., liquid and gas) or poor mixing (e.g., poor uniformity—increased variability due to insufficient agitation), decreasing the number of exception updates triggered by noise, which also extends battery life.

Field-Mount Transmitters

Field-mount transmitters are the most rugged of all transmitter styles. Their robust housings protect against corrosion and humidity. Some field-mount transmitters house the electronics in dual-compartment housings, which completely isolates them from the effects of humidity. Dual-compartment transmitters are the best design for use in harsh environments. Field-mount transmitters can be integrally or remotely mounted.

The use of integral mounting and wireless transmitters provides portability for monitoring unit operation efficiency and finding the most representative and sensitive measurement location with the least process dead time.

- *Integral mount*—the transmitter is threaded onto the sensor directly (mounts directly to U.S. style [1/2-inch NPT] sensor or DIN plate).
- *Remote mount*—the transmitter is mounted on a pipe stand or other support near the sensor. Remote mount is preferred when the measurement point is inaccessible or when the process environment is too harsh for the transmitter to be installed directly on top of the sensor.

The integral mounting of a wireless transmitter, where permitted by accessibility and temperature, enables portability for online process and equipment performance metrics and optimization of measurement location.

Head-Mount Transmitters

Head-mount transmitters are small, puck-shaped transmitters. They are typically housed in a protective enclosure—a *connection head* for direct mounting or a *junction box* for remote mounting.

Rail-Mount Transmitters

Rail-mount transmitters are designed to be attached to a DIN-rail (G-rail or top-hat rail) or directly screwed onto a wall. Rail-mount transmitters are also designed for compact mounting, which allows for a number of transmitters to be mounted very closely together

Wiring Direct

As mentioned, *wiring direct* refers to wiring the sensor's lead wires back to the control system. Because the sensor's lead wire (and original signal) is traveling the entire distance from the point of measurement to the control system, care must be taken to avoid two key problems:

- *Noise*—TCs are especially sensitive to noise interference and extension wires must be routed around such sources as generators and motors.
- *Heat sources*—a large change in the ambient temperature can affect the sensor's signal as it travels to the control system.

Extension Wire

TC extension wires are often used to wire a TC back to a control system or to a remote transmitter, which may be anywhere from 2–2000 ft (0.61–610 m) away. TC extension wire, with a few rare exceptions, must be of the same type of metal as the TC lead wires. If the metals do not match, the cold junction will be created prematurely. TC wire is relatively costly, particularly for platinum TC Types R and S. It is often not economically feasible to make continuous runs of TC wire (perhaps hundreds of feet long) from the hot to the cold junctions. To compensate for this problem, special lead wire is used that closely approximates the thermoelectric properties of TC wire. The special wire with less expensive material allows the user to minimize cost without sacrificing performance.

1-7. Maintenance

Table 1-4 lists checks that can be made to manually track down the source of a high, erratic, or low transmitter output.

The use of intelligent transmitters can simplify the process of diagnosing problems, since they are continuously monitoring both the sensor and the electronics. Transmitter diagnostics typically include indication of an open or shorted sensor. They can also detect if the measurement is outside of the sensor range or beyond the range limits of the analog output.

As mentioned, more advanced transmitters add diagnostic capabilities such as the ability to have a second sensor input back up the first in the event of failure, and also to compare the inputs from two sensors to determine if one is drifting. Advanced diagnostics are available that can detect if a sensor's performance is deteriorating even before the condition affects the measurement, allowing the sensor to be replaced or the wiring corrected before the process is impacted.

Table 1-4. Temperature measurement troubleshooting guide example

High Output	Sensor Input	• Check for a sensor open circuit. • Check if the process variable is out of range.
	Loop Wiring	• Check for dirty or defective terminals, interconnecting pins, or receptacles.
	Power Supply	• Check the output voltage of the power supply at the transmitter terminals. It should be 12.0 to 42.4 V DC (over entire 3.5- to 23.0-mA operating range).
	Electronics Module	• Connect a Field Communicator and enter the transmitter test mode to isolate module failure. • Connect a Field Communicator and check the sensor limits to ensure calibration adjustments are within the sensor range.
Erratic Output	Loop wiring	• Check for adequate voltage to the transmitter. It should be 12.0 to 42.4 V DC at the transmitter terminals (over entire 3.5- to 23.0-mA operating range). • Check for intermittent shorts, open circuits, and multiple grounds. • Connect a 375 Field Communicator and enter the loop test mode to generate signals of 4 mA, 20 mA, and user-selected values.
	Electronics Module	• Connect a Field Communicator and enter the transmitter test mode to isolate module failure.
Low Output or No Output	Sensor Element	• Check if the process variable is out of range.
	Loop Wiring	• Check for adequate voltage to the transmitter. It should be 12.0 to 42.4 V DC (over entire 3.5- to 23.0-mA operating range). • Check for shorts and multiple grounds. • Check for proper polarity at the signal terminal. • Check the loop impedance. • Connect a Field Communicator and enter the loop test mode. • Check wire insulation to detect possible shorts to ground.
	Electronics Module	• Connect a Field Communicator and check the sensor limits to ensure calibration adjustments are within the sensor range. • Connect a Field Communicator and enter the transmitter test mode to isolate an electronics module failure.

Exercises

1-1. What are the accuracy advantages of an RTD?

1-2. What are the advantages of thermocouples?

1-3. When is a Thermistor used?

1-4. Where are non-contacting optical pyrometers used?

1-5. What affects the indication of an optical pyrometer besides target temperature?

1-6. When is a 2-color pyrometer effective?

1-7. When would a 4-wire RTD instead of a 3-wire RTD installation be advisable?

1-8. For best reliability and speed of response, what type of dual element thermocouple should be used?

1-9. What are the performance advantages of a stepped thermowell?

1-10. Why use transmitters rather than the direct wiring of sensors to DCS input cards?

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