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      Average Temperatures and Temperature Differences 685

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4.1 Application and Selection


Partial List of Suppliers:
- ABB (www.abb.com)
- Foxboro/Invensys (www.foxboro.com/temp)
- Honeywell (www.iac.honeywell.com/ichome)
- Hukseflux (www.hukseflux.com)
- Kamstrup (www.kamstrup-process.com)
- Mathis Instruments Ltd. (www.mathis.unb.ca)
- Rosemount/Emerson (www.rosemount.com/products/temperature/)
- Siemens (www.sea.siemens.com)
- Yokogawa (www.yokogawa.com)

INTRODUCTION

Temperature is as fundamental a physical concept as the three basic quantities of mechanics: mass, length, and time. Temperature is an expression that denotes a physical condition of matter. Yet, the idea of temperature is a relative one, arrived at by a number of conflicting theories. Classic kinetic theory depicts heat as a form of energy associated with the activity of the molecules of a substance. These minute particles of all matter are assumed to be in continuous motion that is sensed as heat. Temperature is a measure of this heat.

To standardize on the temperature of objects under varying conditions, several scales have been devised. The Fahrenheit scale arbitrarily assigns the number 32 to the freezing point of water and the number 212 to the boiling point of water. The interval is divided into 180 equal parts. The Centigrade or Celsius scale defines the freezing point of the water to be 0, and its boiling point to be 100.

In line with the classic theory, some relation to the point where molecular motion is at a minimum had to be established, and the Kelvin scale, using Centigrade divisions, was drawn. Zero Kelvin was determined to be 273.19°C. The Rankine scale places its zero at 459.6°F and uses Fahrenheit divisions in the same arbitrary way in which Lord Kelvin used the Celsius scale.

Orientation Tables

The range in temperature within the universe varies 18 orders of magnitude. It ranges from the near absolute zero of black space to the billions of degrees in the nuclear fusion process deep within the stars. But the practical range on earth can be considered as extending from 1°F upward about 5 decades to around 20,000°F. This is still a tremendous range, and no single sensor could possibly cover it.

Table 4.1a provides the reader of this handbook with an orientation table containing information on the ranges and other features of the various temperature sensors. Table 4.1b is a conversion table, which is convenient when one has to go from Fahrenheit to Centigrade units and back. Therefore, one of the restrictions on the temperature sensor concerns the temperature range over which it can stay reasonably accurate. Table 4.1c provides the approximate temperature ranges of each sensor type. The many types of sensors are listed on the left, while some of their characteristics are shown horizontally across the top. If it is not known what general type of sensor will do a specific job, the table can help point the way to the right selection.

Once the class of sensors has been found, the data in the table will give a rough idea of the applicability of that design. When the possible choices of selection have been narrowed down to a few instrument types, the reader should turn to the corresponding sections of this chapter. In the front of each section there is a listing of range, accuracy, cost, and vendors. Inspecting these briefly, one can determine if the instrument generally meets the requirements or not. If it does, one should read the section for a description of the design and its available variations in detail. If some of the features are unacceptable, one should proceed to the next choice noted in the orientation table (Table 4.1a).

Temperature sensors should be selected to meet the requirements of specific applications. Sensor Selection Table 4.1d can assist the reader in this task. If the application engineer determines the required temperature range, the nature of the information required (point or average temperature), and the nature of the process environment, this table can be used to determine
### TABLE 4.1a
Orientation Table for Temperature Sensors

<table>
<thead>
<tr>
<th>Type</th>
<th>Available Span</th>
<th>Accuracy</th>
<th>Cost ($)</th>
<th>Sensor Size</th>
<th>Available With</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature Range</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>°F</td>
<td>°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-250 - -100</td>
<td>0</td>
<td>100</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>-100 - 100</td>
<td>200</td>
<td>500</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>100 - 1000</td>
<td>1000</td>
<td>2000</td>
<td>5000</td>
<td>10000</td>
</tr>
<tr>
<td></td>
<td>1000 - 10000</td>
<td>10000</td>
<td>20000</td>
<td>50000</td>
<td>100000</td>
</tr>
<tr>
<td>Bimetallic Elements</td>
<td>✓</td>
<td>✓</td>
<td>1-2</td>
<td>1</td>
<td>✓</td>
</tr>
<tr>
<td>Color Indicators</td>
<td>✓</td>
<td></td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber-Optic</td>
<td>✓</td>
<td>✓</td>
<td>0.2</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Filled Elements Liquid</td>
<td>✓</td>
<td>✓</td>
<td>0.5-2</td>
<td>0.1</td>
<td>✓</td>
</tr>
<tr>
<td>Vapor</td>
<td>✓</td>
<td>✓</td>
<td>0.5-2</td>
<td>0.6</td>
<td>✓</td>
</tr>
<tr>
<td>Gas</td>
<td>✓</td>
<td>✓</td>
<td>0.5-2</td>
<td>1.2</td>
<td>✓</td>
</tr>
<tr>
<td>Mercury</td>
<td>✓</td>
<td>✓</td>
<td>0.5-2</td>
<td>0.25</td>
<td>✓</td>
</tr>
<tr>
<td>Glass-Stem Therm.</td>
<td>✓</td>
<td>✓</td>
<td>0.1-2</td>
<td>0.01</td>
<td>✓</td>
</tr>
<tr>
<td>Integrated Circuit Diodes</td>
<td>✓</td>
<td>✓</td>
<td>0.2-2</td>
<td>0.2</td>
<td>✓</td>
</tr>
<tr>
<td>Transistors</td>
<td>✓</td>
<td>✓</td>
<td>2</td>
<td>1</td>
<td>✓</td>
</tr>
<tr>
<td>Misc.—</td>
<td>✓</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Resistors</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluidic Sensors</td>
<td>✓</td>
<td>✓</td>
<td>2</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Liquid Crystals</td>
<td>✓</td>
<td></td>
<td>1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Paramagnetic Salts</td>
<td>✓</td>
<td></td>
<td>1</td>
<td>0.005</td>
<td>✓</td>
</tr>
<tr>
<td>Spectroscopy</td>
<td>✓</td>
<td>✓</td>
<td>1</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Thermography</td>
<td>✓</td>
<td></td>
<td>1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pyrometers—Suction</td>
<td>✓</td>
<td>✓</td>
<td>2</td>
<td>20</td>
<td>✓</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>✓</td>
<td>✓</td>
<td>2</td>
<td>25</td>
<td>✓</td>
</tr>
<tr>
<td>Pyrometric Cones</td>
<td>✓</td>
<td>✓</td>
<td>5</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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| Radiation Pyrometers—Optical & Ratio | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | F | F | G | G | N | ✓ | 100 |
| Narrow & Wide Band | ✓ | ✓ | 0.5–2 | 5 | ✓ | ✓ | ✓ | ✓ | F | F | E | G | N | ✓ | 100 |
| Quartz Crystals | ✓ | ✓ | 0.1 | 0.2 | ✓ | ✓ | ✓ | ✓ | E | G | G | E | ✓ | ✓ | N | 1000 |
| Resistance Bulbs—Nickel | ✓ | ✓ | 0.25 | 0.3 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | G, E | G | E | ✓ | N | N | 1000 |
| Platinum | ✓ | ✓ | 0.15 | 0.2 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | E | E | G | G, E | ✓ | ✓ | N | 3000 |
| Thermistors | ✓ | ✓ | 0.2 | 0.02 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | F | G | E | E | ✓ | N | N | 3000 |
| Thermocouples—Type T | ✓ | ✓ | 0.1 | 1.5 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | G | G | G | G | ✓ | N | N | 3000 |
| Type J | ✓ | ✓ | 0.1 | 2.5 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | G | G | G | G | ✓ | N | N | 3000 |
| Type K | ✓ | ✓ | 0.1 | 2.5 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | G | G | G | G | ✓ | ✓ | N | 3000 |
| Types R & S | ✓ | ✓ | 0.1 | 4 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | G | G | E | E | ✓ | N | N | 3000 |
| Ultrasonic | ✓ | ✓ | 5 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | G | F, G | E, E, G | N | N | |

**Terminology**
- N—No or None
- E—Excellent
- G—Good
- F—Fair

1. Interchangeable sensor, without recalibration of entire system.
2. System is complete when sensor and readout is sold as a single unit. When several readouts can be used with the same sensor, system is not considered to be complete.
3. Without special compensation.
### Temperature Conversion Table

(When converting any temperature, find the boldface value of the temperature to be converted and look to the left for its °C equivalent or to right for its °F equivalent. Temperatures not listed can be converted using °F = \(9°\text{C}/5 + 32\) or °C = \(5°\text{F} - 32)/9.)

<table>
<thead>
<tr>
<th>°C</th>
<th>°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>-273.1</td>
<td>-459.4</td>
</tr>
<tr>
<td>-268</td>
<td>-450</td>
</tr>
<tr>
<td>-262</td>
<td>-440</td>
</tr>
<tr>
<td>-257</td>
<td>-430</td>
</tr>
<tr>
<td>-251</td>
<td>-420</td>
</tr>
<tr>
<td>-246</td>
<td>-410</td>
</tr>
<tr>
<td>-240</td>
<td>-400</td>
</tr>
<tr>
<td>-234</td>
<td>-390</td>
</tr>
<tr>
<td>-229</td>
<td>-380</td>
</tr>
<tr>
<td>-223</td>
<td>-370</td>
</tr>
<tr>
<td>-218</td>
<td>-360</td>
</tr>
<tr>
<td>-212</td>
<td>-350</td>
</tr>
<tr>
<td>-207</td>
<td>-340</td>
</tr>
<tr>
<td>-201</td>
<td>-330</td>
</tr>
<tr>
<td>-196</td>
<td>-320</td>
</tr>
<tr>
<td>-190</td>
<td>-310</td>
</tr>
<tr>
<td>-184</td>
<td>-300</td>
</tr>
<tr>
<td>-179</td>
<td>-290</td>
</tr>
<tr>
<td>-173</td>
<td>-280</td>
</tr>
<tr>
<td>-169</td>
<td>-273</td>
</tr>
<tr>
<td>-168</td>
<td>-270</td>
</tr>
<tr>
<td>-162</td>
<td>-260</td>
</tr>
<tr>
<td>-157</td>
<td>-250</td>
</tr>
<tr>
<td>-151</td>
<td>-240</td>
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<td>-146</td>
<td>-230</td>
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<tr>
<td>-140</td>
<td>-220</td>
</tr>
<tr>
<td>-134</td>
<td>-210</td>
</tr>
<tr>
<td>-129</td>
<td>-200</td>
</tr>
<tr>
<td>-123</td>
<td>-190</td>
</tr>
<tr>
<td>-118</td>
<td>-180</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>4.1 Application and Selection</th>
</tr>
</thead>
</table>

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the suitability of various sensors to that application. The suitability for the application may range from using a bimetallic dial thermometer for a water tank with an accuracy of ±2° to 5°F (1 to 3°C) to a temperature transmitter assembly with a resistance temperature detector (RTD) that can measure within ±0.02°F (0.01°C).

**International Practical Temperature Scale**

The International Practical Temperature Scale is the basis of most present-day temperature measurements. The scale was established by an international commission in 1948 with a text revision in 1960. A revision of the scale was formally
### TABLE 4.1d

**Temperature Sensor Selection Table**

<table>
<thead>
<tr>
<th>Measured Temperature</th>
<th>Under 500°C</th>
<th>Above 500°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reading</strong>'</td>
<td>Point</td>
<td>Average</td>
</tr>
<tr>
<td><strong>Hostile Environment</strong>'</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Interference</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Sensors' Color Indicators</td>
<td>G(L)</td>
<td>G(L)</td>
</tr>
<tr>
<td>Bimetallic Units</td>
<td>G</td>
<td>F</td>
</tr>
<tr>
<td>Filled Elements</td>
<td>G</td>
<td>F</td>
</tr>
<tr>
<td>Thermocouples</td>
<td>G</td>
<td>F</td>
</tr>
<tr>
<td>Spectroscopic (Fraunhofer) Sensors</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Thermopile</td>
<td>G(A)</td>
<td>F(A)</td>
</tr>
<tr>
<td>Acoustic Time Domain Reflectometry (TDR)</td>
<td>D</td>
<td>D</td>
</tr>
</tbody>
</table>

**CODE LETTERS:**

D - in development
L - limited
F - fair
G - good
E - excellent
P - protective well reduces speed of response
A - detects the average temperature of an area

**EXAMPLE:** G(D)—This combination of code letters refers to a device which is a good selection for the particular service, but is not yet commercially available.

1 This device either detects a point or the average temperature of some section of the process or of the refractory.
2 The term “hostile environment” here is used to mean processes such as fluid beds, where the sensor is likely to experience the mechanical impact of high velocity solid particles.
3 “Interference” refers to need to overcome temperature interferences due to hot refractories or to temperature differences between the carrier gas and the solid particles in it.
4 For considerations of measurement error, span, cost stability, response time, linearity, materials of construction, etc., refer to the text.
Temperature Measurement

adopted in 1990 and is reproduced in Tables 4.1e and 4.3a. Reproducible temperature points established by physical constants of readily available materials define the scale. Interpolation between these fixed points is made by platinum resistance thermometers when the temperature is below 1832°F (1000°C), and by platinum-platinum and 10% rhodium thermocouples (TCs) when it is higher. The National Institutes of Standards and Technology (NIST—formerly the National Bureau of Standards) has capability for calibrating temperature-measuring devices against these primary temperature points. These devices are secondary standards that are then used by manufacturers and users to calibrate other equipment.

NIST’s capability for calibrating temperature-measuring devices is illustrated in Figure 4.1f. This figure also shows the error (uncertainty) of other thermometers at different temperatures.

**TEMPERATURE SENSORS**

It is believed that Galileo invented the liquid-in-glass thermometer around 1592. Thomas Seebeck discovered the principle behind the TC—the existence of the thermoelectric current—in 1821. The same year Sir Humphry Davy noted the temperature dependence of metals, but C.H. Meyers did not build the RTD until 1932. The development of temperature sensors was a slow process until the middle of the 20th century. Today the application engineer can select from among over 20 different types of thermometers. In addition, the old practice of using only filled system thermometers, RTDs, or TCs throughout a particular industrial plant is giving way to the practice of selecting each temperature sensor for a particular application, just as each level or flow meter is individually selected. This requires a better understanding of the features and capabilities of the many thermometers on the market.

**Nonelectric Temperature Sensors**

**Liquid-in-Glass Thermometers** Most versions have used mercury or alcohol as the liquid. The element mercury is liquid in the temperature range of about −40 to 700°F (−38.9 to 356.7°C). As a liquid, mercury expands as it gets warmer; its expansion rate is linear and can be accurately calibrated.

![FIG 4.1f](image)

Uncertainties in calibrating different temperature sensors at various temperatures. (From NBS Technical Note No. 262.)
Because of mercury’s toxicity and the strict governing laws, the use of the mercury-in-glass thermometer has declined. One manufacturer has recently introduced a line of thermometers with a proprietary fill liquid offering the performance of mercury with none of the toxicity concerns.\textsuperscript{8} For high accuracy applications, laboratory grade and reference standard models are available with calibration certification to NIST standards.

**Bimetallic Thermometers** Bonding two dissimilar metals with different coefficients of expansion produces a bimetallic element. These are used in bimetallic thermometers, temperature switches, and thermostats having a range of 100 to 1000°F (−73 to 537°C). When manufactured as a helix or coil, its movement with a change in temperature can move a pointer over a dial scale to indicate temperature. Dial thermometers ranging from pocket size to 5 in. dials are offered with a variety of local and remote mounting configurations.

Many process applications require use of a thermal well to allow for the removal or replacement of the thermometer while the process is pressurized.\textsuperscript{9} Other designs include switches for on-off control that range from the simple wall thermostat to more rugged industrial models for simple process control or over-temperature protection. Other configurations include snap disk switches often used for over-temperature alarm and control. Low-end models are used in home furnaces, clothes dryers, and coffee makers. More rugged units find application in automobiles, trucks, and industrial machinery as over-temperature limits.

**Filled System Thermometers** Filled system thermometers have been used for decades. They have a useful range of 320 to 1200°F (200 to 650°C). Applications vary in sophistication from those for commercial appliances like cooking ovens and those used in heating, ventilation, and air conditioning (HVAC), to rugged industrial units suitable for a variety of applications. The filled system element can operate switch mechanisms as in ovens or for industrial shutdown controls. Some models have an analog output that may be connected to remote locations. Thermal systems filled with solid materials or mercury have all but disappeared. Most countries mandate the removal of any mercury-filled devices due to its extreme toxicity.

There are some models that use a vapor fill, but these suffer in applications where the temperature crosses the vapor/liquid point and causes liquidization and loss of performance (typical is 0.25% per 25°F/14°C). Liquid filled units are the most popular, but consideration must be given to offsets due to the weight of the liquid head and compensation for capillary length. Thermocouples and RTDs are replacing filled systems in industrial process control applications. The low cost of electronic devices to read the output of TCs and RTDs and to indicate or control, together with the ability to locate the sensor independently of the receiving device, has made electronic means more attractive.\textsuperscript{9}

**Bistate/Phase Change Sensors** These low cost nonelectric sensors are made from heat-sensitive fusible crystalline solids that change decisively from a solid to a liquid with a different color at a fixed temperature depending on the blend of ingredients. They are available as crayons, lacquers, pellets, or labels over a wide range of temperatures from 100 to 3000°F (38 to 1650°C). They offer a very inexpensive method for surface temperature visual verification within about 1°F. Monitoring minimum and maximum temperatures during shipment of perishable goods is a common application.

**Electronic Thermometers/Sensors**

**Thermocouples** A TC is an assembly of two wires of unlike metals joined at one end designated the hot end. At the other end, referred to as the cold juncton, the open circuit voltage is measured. Called the Seebeck voltage, this voltage (electromotive force) depends on the difference in temperature between the hot and the cold junction and the Seebeck coefficient of the two metals. For a plot of the relationship between temperature and output signal refer to Figure 4.1g. For most industrial applications, the TC has been the popular choice over the years for a variety of reasons. Thermocouples are relatively inexpensive and can be produced in a variety of sizes. They can be of rugged construction, can cover a wide temperature range from 440 to 5000°F (262 to 2760°C), and are available in both standard and premium grade models.\textsuperscript{9,15,16} Refer to Figure 4.1h for the error limits of a Type J premium sensor.

Every credible temperature transmitter, indicator, controller, or data logger will accept a direct TC input. For many applications, this is a viable solution. However, TCs produce a very small microvolt output per degree change in temperature that is very sensitive to environmental influences. Electromagnetic interference (EMI) from motors and electrical

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\textsuperscript{8} This alternative fill liquid has capability of very high accuracy, significant linearity, and high purity.

\textsuperscript{9} The characteristics of electronic thermometers.

\textsuperscript{10} The characteristics of electronic thermometers.
distribution and especially radio frequency interference (RFI) from walkie-talkies can produce dramatic errors in measuring circuits in these instruments. The user should insist on a noise reduction spec and an RFI immunity spec that will minimize these effects. A top quality instrument will offer Common mode noise rejection of 100 db, Normal mode rejection of about 70 db, and RFI immunity of 10 to 30 V/m.

There are some applications where a bare TC with an exposed junction may be used either by itself or inserted into a protective well. For most process applications, the TC is manufactured with a protective outer sheath that uses an insulating material to electrically separate the TC from the sheath and provide mechanical and environmental protection. In some cases, the TC junction is placed in direct contact with the tip of the sheath to increase speed of response. These sensors demand the use of an electrically isolated measurement circuit. Even insulated TCs will eventually suffer from a breakdown of the insulation and the TC tip will contact the sheath and associated well. It is virtually assured that a ground loop will be present that will cause measurement errors. These errors are usually insidious in that they usually vary over time and may go unnoticed. Recommended practice is to always use an instrument with full isolation to eliminate this concern.9,10,12

Another consideration for applying TCs is that their low output (about 40 µV/°C) limits the minimum span of even the best transmitters to about 60°F (35°C). RTDs are the usual choice for narrow span applications.

The most misunderstood drawback of using TCs is their inherent drift. The junction of the two dissimilar metals begins to degrade to some degree immediately after manufacture. For some types, used at low temperatures, this may only be a few degrees per year and may be calibrated out of the system. Other types used at higher temperatures degrade much more quickly. Consideration must also be given to any TC extension wire that is used for long wiring runs from the field location to the measurement instrument. Not only is its accuracy only about half as good as a TC, but also it is often subjected to harsh environmental conditions as it passes through the plant that will cause significant degradation and drift. Some plants replace their extension wire on a regular basis to minimize this effect.

Installing a top quality transmitter in the connection head of the TC will minimize many of the problems and concerns described above. Refer to Intelligent Temperature Transmitters in a later paragraph of this section.

**Resistance Temperature Detectors**

RTDs are constructed of a resistive material with leads attached and usually placed into a protective sheath. The resistive material may be platinum, nickel, or copper with the most common by far being platinum. The relationship between the resistance change of an RTD vs. temperature is referred to as its alpha curve (see Figure 4.1g). The instrument used with the RTD must be configured to use the same alpha curve as the RTD or significant errors will occur.

As with TCs, there are some applications where an exposed sensor is suitable for the purpose. More commonly they are manufactured with a protective sheath that provides a hermetic seal to protect the sensor from moisture and/or contamination.14 These protective sheaths are offered in a variety of lengths to provide the proper insertion into the process to obtain a representative measurement. The sheathed elements are often installed into a protective well to isolate the sensor from the process. One manufacturer offers a universal model that has only a 1 in. long sheath, but has long leads encased in a spiraled spring. The unit may be cut in the field to fit in any length of thermal well. This greatly reduces the requirements for stocking sensors in varying lengths.7,11 Figure 4.1i shows this flexible sensor mounted with a transmitter.

There are very few applications for a 2-wire RTD since the error introduced by the leads can cause significant error. Measurement circuits that accept 3-wire inputs include a method of minimizing the effects of lead wire resistance as long as the outer legs are equal. However, factors such as terminal corrosion and loose connections can create significant differences between the lead resistances seen by the measurement circuit. A single ohm of difference between the legs is reflected as a 4.7°F (2.6°C) error.13 Using a 4-wire measuring circuit eliminates this problem. The design engineer should consider any of the leading brands of temperature transmitters that accept 4-wire RTD inputs as a standard feature. Direct connection to remote devices with 3-wire extension cable will often produce errors that can be significant and will vary with environmental conditions. Refer to intelligent temperature transmitters later in this section for more detail.

Copper RTDs are most commonly used to sense the winding temperature of motors, generators, and turbines. Connecting them to an alarm trip provides an over-temperature shut-down function. Historically, 10-Ω copper RTDs were the norm, and accurate measurements of the small change in resistance change with temperature limited the accuracy to about ±1 to 2°F (1.6°C). Many users have now opted for 100 Ω or even 1000 Ω units to get higher resolution. They have

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**FIG. 4.1h**

*The error limits of an iron-constantan thermocouple manufactured to meet the “special” limits of ISA.*

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4.1 Application and Selection

A useful range of −58 to 482°F (−50 to 250°C). Nickel RTDs have declined in use over the years primarily due to their limited range vs. the more popular platinum RTDs. The usable range is −112 to 608°F (−80 to 320°C). Most transmitters and alarm trips still offer the capability to accept nickel RTD inputs.

A concern common to all RTDs is that of error produced by self-heating. RTD measurement circuits measure the voltage across an RTD produced by passing a precise current flow through the RTD. A current flowing through a resistance produces heat that will appear as a positive offset to the actual process temperature at the RTD. The lower the measuring current, the less is this heating effect. It will be minimized by good thermal contact to the process fluid and is less of a concern at higher temperatures. A measure of the quality of an RTD measuring circuit is the amount of measuring current used. Circuits in better transmitters use about 250 µA. This current is typically higher for nickel and copper RTDs.

Thermistors

Like the RTD, the thermistor is also a resistive device that changes its resistance predictably with temperature. Its benefit is a very large change in resistance per degree change in temperature, allowing very sensitive measurements over narrow spans. Due to its very large resistance, lead wire errors are not significant. However, there are several disadvantages to the thermistor:

1. It is a very nonlinear device and reasonable accuracy is obtained only over narrow spans (see Figure 4.1g).
2. It is quite small and will exhibit errors due to self-heating.
3. Exposure to high temperature will cause a dramatic and permanent shift in its output characteristics.

Most applications of the thermistor are in commercial and laboratory applications. Few are used in industrial process control. Thermistors are designated by their resistance at 25°C with the most common value being 2252 Ω.

Radiation Pyrometers

An infrared (IR) thermometer is a noncontact radiant energy detector. Every object in the world radiates IR energy. The amount of radiant energy emitted is proportional to the temperature of an object. Noncontact thermometers measure the intensity of the radiant energy and produce a signal proportional to the target temperature. The physics behind this broadcasting of energy is called Planck’s Law of Thermal Radiation. This radiated energy covers a wide spectrum of frequencies, but the IR spectrum is most commonly used for temperature measurement. IR thermometers capture the invisible infrared energy that is naturally emitted from all objects warmer than absolute zero (0 K).

Infrared radiation is part of the electromagnetic spectrum that includes gamma rays, x-rays, microwaves, ultraviolet, visible light, and radio waves. IR falls between the visible light of the spectrum and radio waves. IR wavelengths are usually expressed in microns with the infrared spectrum extending from 0.65 to 1000 µm.

In practice, the 0.65- to 14-µm band is used for IR temperature measurement over a range from −50 to 6500°F (−46 to 3000°C). IR technology has become a viable and cost effective alternative to TC and RTD measurements in hostile environments like furnaces and in ovens where food, textiles, plastic, or glass are heated. The TC or RTD can only measure the temperature of its immediate surroundings and therefore cannot measure the actual product temperature. The actual temperature of the product will change due to variations such as line speed, thickness of the product, color, or roughness. The TC or RTD will not respond to these temperature changes quickly enough to permit close control. The IR thermometer will instantly measure the actual product temperature, not the environment surrounding the product.

IR thermometers are ideal for moving targets such as glass, plastic, and steel. They do not interfere with the process. They are also ideal for measuring products with very high temperatures or hostile environments. They can see through windows to measure products in a vacuum furnace or a semiconductor reactor. IR thermometers can measure targets as small as 0.025 in. in diameter and can respond in
Temperature Measurement

10 ms to a temperature change. IR instruments operate at various wavelengths and Figure 4.1j shows the standard wavelengths that are available from most manufacturers. Each bar represents a series of instruments. The shortest wavelength band utilized is 0.65 µm and the longest is 8 to 14 µm. An instrument using a 0.65-µm wavelength can measure the higher range temperatures from 1400 to 6500°F (700 to 3600°C). Instruments with sensitivity to the 8- to 14-µm range can measure down to −50°F (−45°C).

Here are some guidelines for applications for the various wavelengths:

1. Wavelength bands centered on 0.65 and 2.6 µm are used for metals and can see through quartz windows. Fiber-optic systems for remote sensor applications are optional. Two color systems in these bands use slightly differing wavelengths to make their measurement.
2. The 3.4-µm band (±0.05 µm) and the 7.9-µm band (±0.15 µm) are used to measure thin plastic films. At these wavelengths, films as thin as 0.001 in. are opaque and only the surface temperature is measured.
3. The 5-µm band (±0.2 µm) is used to measure glass windows and containers.
4. The 7.9-µm band is also utilized for ceramics and very thin glass.
5. The 8- to 14-µm wavelength is probably most commonly used for low temperature applications for textiles, paper, and food. It also is a very common wavelength for portable infrared thermometers.

Distance does not affect the measurement. Models are available that can measure from 1 to 300 ft (0.3 to 91 m). However, IR sensors measure the energy from a circular spot on the target, and the size of that spot is a function of the distance between the sensor and target. The farther away from the target the sensor is, the larger the spot (Figure 4.1k). Consequently, distance is limited by the size of the object you want to measure. Some models offer a low power laser that facilitates proper aiming. Where a direct line of sight to the target is not possible, models with a fiber-optic connected sensor system often can solve the problem. Fiber optics allows installations into difficult locations up to 30 ft from the instrument. They can withstand ambient up to 400°F (200°C) without cooling. The lowest target temperature for these systems is about 1300°F (705°C). At least one manufacturer offers an instrument with an optical aiming system that may be viewed on a TV monitor to ensure proper aim at the target.

There are many applications for wire drawing, annealing, and vacuum furnaces where the sighting must be made through dirty windows. Other applications have small windows, obstructions in the sight path, or dusty atmospheres like those found in steel mills. For all these applications, the Two-Color or Ratio Thermometer provides an excellent solution. This instrument utilizes two detectors operating at two wavelengths to measure one hot target. They can measure temperatures from 500°F (250°C) up to 6500°F (3500°C) and, by using sensors with two different wavelengths, can eliminate the interference problems. In addition, they can measure targets that do not completely fill the optical spot size of the instrument.

The installation of an IR thermometer requires attention to detail to ensure successful operation. Figures 4.1l and 4.1m...
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explain some of the problems with installation of IR thermometers. Ideally, a clear unobstructed line of sight is required and the target has to be large enough to fill the cone of vision. The spot size required is related to the distance to the sensor, and the user should consult the manual for details. Solid obstructions have to be removed or eliminated from the field of view by possibly aiming the instrument at a different angle or by using a fiber optic remote sensor system. For applications with sighting windows, the instrument must be selected to use a wavelength that will pass through the window material unchanged. The window also must be large enough so as not to obstruct the cone of vision. It also has to be kept clean by possibly using an air purge. Smoke, steam, and dust all cause temperature fluctuations.

Most IR thermometers have an electrical feature called a Peak Picker. This is a simple circuit that picks the peak temperature and does not allow the signal to decay when dust obstructs the field of view. Flames are also a consideration. Clean gas flames are transparent to most thermometers while coal, oil, or garbage flames are opaque and no thermometer can see through them. The actual temperature of oil, coal, or garbage flames can usually be measured with the two-color instrument. Most sensors can operate in environments up to 145°F (65°C). For hotter ambient environments, water or air-cooling is required (Figure 4.1n). IR instruments should be calibrated once a year using a certified blackbody.

There is a growing market for line scanners that can produce a two-dimensional thermal image. This type of IR thermometer is used to measure wide webs such as hot strip steel, glass, plastic, and paper. This instrument utilizes one detector and two 45-degree mirrors with one mirror rotating and scanning over a 90° angle as shown in Figure 4.1o. For moving targets, the instrument uses a software technique to create two-dimensional thermal images of the moving web. The software provides temperatures at any location on the web and can provide output signals that can be used for closed loop control or stored for future review.

Thermal imagery is a rapidly growing application of IR technology that is used on some automobiles and by military and law enforcement in night vision applications. Architectural analysis of building insulation, surveillance, and quality control are other uses. This imaging system is an IR thermometer that uses a detector called a focal plane array instead of a single sensor. Its functionality is similar to a digital camera, except that, instead of capturing photographic images, each pixel measures temperature. A two-dimensional image is created using software resident within the system. The detector can have as many as 76,000 pixels. The image of the temperature profile can be used for closed loop control of processes, such as detecting defective personal computer (PC) boards, or stored away for future analysis.
Most manufacturers of IR instruments continue to refine existing products and offer enhanced capability with newer models. One new model offers bidirectional digital networking communications. Multiple sensors can connect to host systems for monitoring, control, and diagnostics. The design engineer is strongly urged to consult with multiple vendors to get recommendations for selecting the proper instrument for each application.

**Solid-State Sensors** The small solid-state sensor converts a temperature input into a proportional current output over a range of \(-67 \text{ to } 300\, ^\circ\text{F} \) (\(-55 \text{ to } 150\, ^\circ\text{C}\)) (see Figure 4.1g). It is especially suited for PC boards or heat sink mounting for special temperature measurement and control applications where solid-state reliability, linearity, and accuracy are required. They can be used to determine minimum, average, and differential temperatures, in addition to being used for TC cold junction compensation and temperature control applications. With prices beginning under $10, these sensors are gaining popularity. Diodes are typically used in cryogenic applications over a range of \(-455 \text{ to } 396\, ^\circ\text{F} \) (\(-271 \text{ to } 202\, ^\circ\text{C}\)) and can be accurate to 0.05°C when properly calibrated.

**Heat-Flow and Thermal-Conductivity Sensors** The accurate measurements of heat flow through thermal insulators and of the thermal conductivity of construction materials are both important. Such measurements are of interest not only to architects, but also to engineers who are involved with safety and energy conservation.

A common heat flowmeter design involves the placing of a thin plate of known thermal conductivity on a heat-radiating surface. It has been found that the heat flow through these elements is directly related to the temperature difference through them. This temperature difference is often detected by thermopiles—a large and even number of TCs connected in series in such a manner that their high-temperature junctions are on the inside and their low-temperature junctions are on the outside surface of the sensing element (Figure 4.1p). The heat flows that are encountered in different processes range from about 10 k-cal/m²h through freezer walls to about 100,000 k-cal/m²h through the shells of water-cooled electric furnaces. The thickness of the sensor plates is a few millimeters, and the plates are made of rubber, organic materials, or other heat-resistant materials, sometimes contained in a thin, stainless steel disk case.

The heat-flow distribution frequently varies with the direction of heat flow. For example, Figure 4.1q shows that...
the heat loss from the top of a steam pipe was found to be much more than through the bottom surface. Such findings are usually explained by noting that heat flow from a surface is not only a function of the surface temperature, but also of the effects of coating. It has been found that if a surface is coated with bright and glistening aluminum paint, it will radiate much less heat at the same temperature as a surface where the coating has worn off. Sensor elements can measure the variations in heat flow at different points on many shells, from liquefied petroleum gas (LPG) tank walls to electric and blast furnace shells, and their readings can reveal the erosion of linings as well as other hard-to-detect phenomena.

In other processes the interest is in measuring the thermal conductivity of heat insulating substances. Thermal conductivity instruments are designed to measure thermal conductivities of solid materials in the range of 0.001 to 10 W/mK. Typical materials with conductivities in this range are foam, insulation, polymers, composites, glass, silicon, natural fibers, and rock. One vendor offers a model that is an interfacial heat reflectance device that contacts a constant current heat source to the sample. The temperature of the interface is monitored and the rate of temperature rise is related to the thermal conductivity of the unknown sample. Higher thermal conductivity samples produce a lower rate of temperature rise because the heat is being conducted away from the interface. The heating element of the probe provides a one-dimensional heat flow. The entire element must be covered during testing, establishing the minimum flat surface area of $5 \times 25$ mm. The probe calculates the value of thermal conductivity ($k$) given known values of heat capacity ($C_p$) and density ($r$). If these parameters are unavailable the results give the effusivity of $(KrC_p)^{1/2}$.

The hot wire method of thermal conductivity measurement involves the stretching of a thin heating wire through a sample and applying a constant amount of power (Figure 4.1r). The higher the thermal conductivity of the sample, the lower will be the resulting surface temperature of the heater wire. Therefore, it is possible to read the surface temperature of the heater wire and interpret from that reading the thermal conductivity of the sample.

The thermal conductivity of an unknown substance can be determined by first recording the surface temperature response curve (time vs. temperature) of the wire while the wire is surrounded by a known thermal conductivity material. After that, half of the known sample can be replaced by a material having an unknown conductivity. After repeating the test, the difference in the response curves can be correlated to the thermal conductivity of the unknown substance. In the sensor shown in Figure 4.1r, the heated wire is surrounded on the top by a material of known thermal conductivity; therefore, when it is placed on the flat surface of the unknown sample, its temperature response curve will reflect the thermal conductivity of that substance.

**FIG. 4.1r**
The design of a thermal conductivity sensor. (Courtesy of Showa Denko K.K.)

**INTELLIGENT TRANSMITTERS AND REMOTE INPUT/OUTPUT (I/O)**

This first volume of the *Instrumentation Engineers’ Handbook* is devoted to measurement. While the transmission and control related topics are covered in Volume 2 and networks and buses in Volume 3, this paragraph is included here as it relates to the general topic of temperature monitoring.

Microprocessor-based temperature transmitters have continued to evolve in sophistication and capability such that there is no credible transmitter on the market today that does not use this technology. A transmitter includes an input circuit referred to as an analog-to-digital (A/D) converter that converts the sensor input signal from its analog form into a digital representation for presentation to the microprocessor. The microprocessor performs all of the mathematical manipulations of ranging, linearization, error checking, and conversion. The output stage accepts the resultant digital representation of the current value of the measurement and converts the signal back to an analog signal (D/A) that is typically a 4- to 20-mA DC current. For some special applications, 0 to 1 Vdc or 0 to 10 Vdc signals may be used and in others the signal is transmitted digitally using either an open or proprietary protocol. Some countries have adopted 0 to 20 mA as the standard transmitted signal.

Just as microprocessors have evolved in sophistication, so have A/D converters. Eight-bit resolution devices common in
the 1960s provided a resolution of about ±0.4%. In 2000, the first 21-bit resolution A/D was used in a temperature transmitter providing a resolution of ±0.00005%. D/A converters have also evolved with resolutions increasing from 8-bit up to the 18-bit versions used in the better transmitters beginning in 2000. The result of combining these technologies is a universal transmitter that accepts inputs from any TC, RTD, mV, resistance, or potentiometer signal; checks its own calibration on every measurement cycle; has minimal drift over a wide ambient temperature range; incorporates self-diagnostics; and is configured using pushbuttons or simple PC software.

The reconfiguration process is quick and convenient, and it tends to allow for lower inventories by making the transmitters interchangeable. Some transmitters are capable of handing dual RTD elements. This allows for temperature averaging, temperature difference measurement, or automatic RTD sensor switchover if the primary sensor fails in a redundant installation. Due to terminal limitations, these models can only accept dual 3-wire RTDs. Caution must be used to minimize lead resistance differences to reduce the error.

Fieldbus Structures

In the 1980s, another level of capability was added to field devices. Rosemount developed the Highway Addressable Remote Transducer (HART) protocol to enable detailed information about the setup and operation of the device to be superimposed onto the 4- to 20-mA signal. This protocol was soon released to the public domain. The HART Communication Foundation promotes its use in industry and supports its maintenance and growth. The benefits of remote configuration and access to diagnostics have encouraged the dramatic increase in use of HART-enabled instruments.

During this same time period, a variety of proprietary protocols emerged supported by many of the larger manufacturers that provided comparable benefits of remote setup and diagnostics. Unlike the HART protocol, these products were limited to use within the manufacturer’s system. In the 1990s, a trend emerged for more open protocols to enable plug-and-play of instruments from varying manufacturers to work as part of a fieldbus structure.

Two that have emerged as leaders are Foundation Fieldbus and Profibus. Each has its proponents and support groups that have been promoting their acceptance. Temperature transmitters, as well as other field and control room devices, must incorporate the specific fieldbus technology to be used in these systems. The support tends to favor using fieldbus technology for new plant construction and major upgrades where all new instrumentation and cabling would be required. Existing plants with properly functioning legacy devices, must incorporate the specifications of the 1980s and the 1990s. It has been generally accepted that the more closely a sensor matched its ideal characteristics, the more accurate the measurement will be since transmitter measuring circuits refer to the ideal data to make the measurement.

Advanced Transmitters

More advanced transmitters incorporate the ability to match the sensor to the transmitter to minimize this error. One method uses the Callander van Deusen method, which defines three experimentally determined constants that define the temperature/resistance relationship specific to an RTD. By entering these data from the RTD tag into the transmitter’s firmware, the sensor and transmitter become a calibrated system. Typical accuracies for this technique are about ±0.4°C. For higher precision, at least one vendor offers a bath calibration technique that allows the transmitter to capture actual values output by the RTD or TC at specific temperatures. This method provides system accuracies of about ±0.02°C (0.1°C) for RTDs and about ±2°F (1°C) for TC measurements. Maximum performance is gained by selecting the trim points to bracket the operating point.

Direct connection of temperature sensors to input subsystems of distributed control systems (DCSs) or programmable logic controllers (PLCs) is an alternative to using a temperature transmitter for each measurement. This may sound like a way to cut costs. In actuality, on an installed basis, it is more expensive, far less accurate, and not as robust. It may be suitable for less demanding data acquisition or control applications where wider variations in the measurement can be tolerated. The benefits of using transmitters include higher precision, sensor-transmitter systems calibrated to the range of interest, better RFI immunity and noise rejection, transmitter diagnostics, lower wiring costs, less expensive input/output (I/O) cards, faster loop checks, and shorter start-ups.
The array of intelligent temperature transmitters on the market seems almost endless. Some common features of the leading models are: universal inputs from any TC, RTD, mV, resistance or potentiometer; loop-powered with 4–20 mA output; digital outputs, and configuration with pushbuttons, PC software, or a handheld configurator. Choices must be made for which protocol is required: HART, Foundation Fieldbus, Profieldbus, vendor proprietary, Ethernet, or just 4 to 20 mA. Some field locations will benefit from local indication and this feature is optional with most manufacturers. There is a considerable cost and performance benefit afforded by purchasing the sensor and transmitter as a system. This saves cost by offering single source responsibility. For applications where it is prudent to separate the sensor from the transmitter, DIN (Deutsch Industrie Norm) rail-mounted transmitters may be grouped in a marshalling cabinet at a convenient location.

**TEMPERATURE MEASUREMENT APPLICATIONS**

**High Temperature Measurement**

There are two viable methods for measuring temperatures up to 2000°F (1100°C): special high-temperature TCs and IR pyrometers. At high temperatures TCs are installed into protective wells or protection tubes. When installed horizontally, wells tend to droop causing binding on the TC element when it must be removed for replacement and a new one inserted. The latest design of a TC incorporates a 1 in. sheath with a flexible cable that can easily be inserted into even badly drooping wells. Upper limit for this sensor is about 2000°F (1100°C). Ceramic wells do not suffer from droop but have other limitations of low surface strength, brittleness, and low erosion resistance. IR pyrometers offer a very viable noncontact method to measure temperatures all the way up to 6500°F (3600°C) and would be the best choice for most applications. Refer to the detailed description above for additional detail.

**Speed of Response**

The fundamental problem of measuring the temperature of a fluid is one of assuring strong thermal coupling. For a fluid temperature measurement to have meaning, the sensor must come to equilibrium with the temperature of the fluid. The difference between the equilibrium temperature of the sensor and the fluid temperature is a direct error. The most common process temperature measurements are made with TC and RTD sensors. Commercial and laboratory applications often use exposed TC beads or RTD elements to obtain fast response in clean environments.

Refer to Figure 4.1s for representative mounting configurations. There are very few industrial measurements where an exposed sensor would be used. This is because the process of taking the sensor out of service would release pressure or product from the pipe or vessel where the measurement is being made. Therefore, most applications use thermal wells to isolate the sensor from the process. Accordingly, the mass of the well and the piping into which it is inserted are the dominant causes of thermal lag and conduction errors. These errors can be almost insignificant for processes with stable temperatures and rapid flow. However, for dynamic temperature fluctuations or where there is little flow across the sensor, the errors can be large.

There are various designs of high speed of response sensors but most are limited by being manufactured with a protective sheath that runs the length of the well providing a long and massive path for thermal losses. A new design uses low mass RTDs or TCs in a 1 in. (2.54 cm) sheath to minimize this effect. To further increase the response, the sensor is spring loaded against the tip of the well and inserted with thermally conductive grease. One well manufacturer offers a finned thermal well providing dramatic improvement in the response. Fast response is especially valuable for gas applications. Some of the better transmitters update their output several times per second and therefore are rarely the limiting factor in the measurement.

**Surface Measurement**

Measuring the surface temperatures of moving objects like webs of paper, plastics, textiles, and metals of rotating cylinders (such as calendar rolls, rotary kilns, or drier cans) requires
special consideration. IR pyrometers offer a cost effective method as described above for many industrial applications. They offer many advantages, including high accuracy and fast response, and are especially suited to moving surfaces. However, for stationary surfaces, often a less sophisticated and less costly method is called for. The phase shift products offer a visual measurement but have no other output.

There are a variety of mounting methods where either a TC or an RTD may be affixed to the outside of a pipe or vessel and be connected to a transmitter or data logger to get continuous information. The design of the mounting hardware and its proper installation are critical in obtaining a representative surface temperature. The thermodynamics of the application are complicated by the thermal losses to the surrounding atmosphere, thermal lag of the wall of the vessel or pipe, and the rate of change of the medium. A properly designed system will use a low mass sensor with high speed of response inserted into a fixture that places the sensor tip as close as possible to the surface being measured. Refer to Figures 4.1t, 4.1u, and 4.1v for some typical examples of mounting configurations.

**Measuring the Temperature of Solids**

Determination of the allowable size and configuration of the sensor requires some knowledge of the heating or cooling conditions together with an estimate of the magnitude of the temperature gradients that are likely to exist in the region in which the measurement is to be made. A simple rule-of-thumb indicator to determine if significant gradients are likely to be present is the magnitude of the Biot modulus \( \left( \frac{hL}{K} \right) \), where \( h \) is the surface heat transfer coefficient, \( L \) is the smallest dimension of the solid, and \( K \) is the thermal conductivity of the solid. If this modulus is over 0.2, significant temperature gradients are likely to exist in the solid, and care should be exercised in choosing the size, location, and orientation of the sensor within the solid. If the Biot modulus is less than 0.2, no significant gradient is expected and a measurement anywhere on or within the solid should give identical results regardless of size or configuration of the sensor. If significant gradients are likely to exist, the maximum rate of heat transfer to the surface of the solid must be known or estimated, and the maximum gradient at the point measurement must be determined. The following relationship allows the maximum gradient at the surface of a solid to be calculated:

\[
\frac{\Delta T}{\Delta X} = \frac{q}{K}
\]

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where

\[ \frac{\Delta T}{\Delta X} = \text{temperature gradient at the surface} \]

\[ q = \text{heat transfer rate per unit area at the surface} \]

\[ K = \text{thermal conductivity of solid} \]

Under certain conditions of heating or cooling, if measurements at points other than the surface are important, it may be necessary to evaluate anticipated heat transfer conditions and resulting temperature gradients.\(^5\)

On the basis of this gradient, it is possible to establish limits on the size of the sensing device. For example, the length of any one of the three dimensions of the sensor (lead wires excluded) should not be greater than the distance between two points of the process that are different in temperature by more than the acceptable measurement error. It is assumed that the sensors are in satisfactory thermal coupling with the process material, which is not always the case. If the thermal coupling is poor, the sensor will not reflect the true temperature history that was experienced by the solid. This condition can produce dynamic errors.\(^5\)

The best thermal coupling is achieved by direct bonding of the sensor, such as welding a TC to the solid surface or into a cavity within the solid. The bond line between the sensor and the solid should be kept as thin as possible and should not fracture or fail during thermal cycling. Various epoxy and ceramic cements, with fillers to improve their

**FIG. 4.1u**
Thermocouple-type surface temperature sensor designs. (Courtesy of Syscon International Inc.)

**FIG. 4.1v**
RTD-based surface-temperature detector. (Courtesy of Wahl Instruments Inc.)
conductivity, have been successfully used for such bonding. For example, a flat RTD, which is bonded to a surface with a 0.005 in. (0.1 mm) thick epoxy bond line will produce a lag time of about 1 s. This will give a dynamic error equal to the rate of temperature rise of the surface, because a dynamic error of 25°F (14°C) corresponds to a rate of surface temperature change of 25°F/s.⁶

Methods of installing temperature sensors on or within solid bodies are shown in Figure 4.1w.

**Averaging Measurements**

There are different considerations depending on the application. The solution is different for liquids, gasses, or solids and also depends on the accuracy and speed of response required and what is to be done with the measurement results. For a temperature profile in a storage tank that is to be used for volume correction for inventory, an array of high accuracy RTDs would be the appropriate choice. There is one manufacturer that can supply a flexible array of almost any length for easy field installation. The receiving device would then average the input from the various sensors and exclude those not covered by product based on the level measurement. There are tank-gauging companies that specialize in this application.

For a high temperature reactor or furnace, the sensing array would use TCs to generate the signal that can then be averaged in software by a receiving device. For large air ducts for furnaces or clean room circulation, a highly accurate average temperature is obtained by using an RTD sensor that is constructed with a continuous resistive element so as to eliminate hot spots. This special RTD should be a 4-wire construction and be used with a 4-wire measuring circuit like what would be found in a high quality transmitter to obtain an accurate temperature measurement. For gas flow in pipes an RTD and transmitter assembly is an appropriate choice. If the application is for temperature compensation for a mass flow calculation, a 4-wire RTD trimmed to match a quality transmitter will provide the highest accuracy. Such systems are available with accuracies of ±0.02°F (0.01°C).

For stationary or moving surfaces of almost any size, the IR pyrometer is the best choice over any range.

**Narrow Span Measurements**

When the operating point of an application is stable, higher accuracy can be achieved by reducing the span of the measuring instrument. For example, when measuring temperature of a process that operates at 125°F with a variation of ±10°F, a range of 0 to 150°F would be well suited. An instrument ranged from 0 to 600°F would have 4 times less resolution. TCs are generally limited to a minimum span of about 63 to 180°F (35 to 82°C), depending on type, while spans using a 1000-Ω Platinum RTD with a high quality transmitter may be as low as 2°F (1°C). Matching a sensor to its transmitter offers the highest possible accuracy.

**INSTALLATION CONSIDERATIONS**

When making temperature measurements, two ways have traditionally been employed to get process readings from the point of measurement back to a monitoring and control system.

One method is to utilize sensor extension wires to carry the low-level signals (Ω or mV) generated by field-mounted RTD or TC sensors. Another is to install temperature transmitters at or near the measurement point. The transmitter amplifies and conditions the sensor signal and transmits it over a twisted wire pair back to the control room.

Direct wiring strategies have generally been considered less expensive and sometimes easier. Transmitter use, because of cost considerations, was often reserved for important loops and applications where signal and loop integrity was a must.

Today, highly functional, yet very affordable, microprocessor-based field-mount temperature transmitters are comparable in price to direct wiring strategies. There are additional advantages of using intelligent transmitters that will, in most applications, also save considerable time and maintenance headaches. This is especially true when the measurement point is located a long distance from the readout and control system.

**Temperature Transmitters in Place of Direct Wiring**

**Lower Wiring Costs**

Direct wiring sensors to a control system requires the use of sensor extension wires. Not only are extension wires fragile, they also cost three times more than the common shielded copper wire used for a temperature transmitter’s 4 to 20 mA signal. Using the less expensive wires, transmitters can pay for themselves in wire and conduit costs alone. The longer the wire run, the greater the potential savings.

In retrofit situations, temperature transmitters can be installed at the sensor, and the in-place RTD or TC extension wires can be used to transmit the 4 to 20 mA back to the control system. There is no need to run new copper wires to accommodate the 4 to 20 mA. No additional installation time or material costs (including conduit) are incurred, and you still get all of the advantages of using temperature transmitters.

**Protect Signals from Plant Noise**

Common in nearly every industrial environment, RFI and EMI can negatively affect process signals. Some of the common sources include mobile and stationary radio, television, and hand-held walkie-talkies; radio-controlled overhead cranes; radar; induction heating systems; static discharge; high-speed power switching elements; high AC current conductors; large solenoids and relays; transformers; AC and DC motors; welders; and even fluorescent lighting.

If there is one or more of these in your plant, RFI/EMI problems are likely. The result is sometimes just a minor inconvenience. Other times it can be as serious as a plant shutdown.
4.1 Application and Selection

Some selected methods of installing temperature sensors on or within solids.

**A-Typical Thermocouple Installation**

- **for Junction Formed through Solid by Direct Spot Welding to Surface**
- **Characteristic:**
  1. Fast Response
  2. Simple to Install
  3. May Cause Disturbance to Flow Pattern under High Speed Forced Convective, Compressible Flow

**B-Typical Resistance Thermometer Path Installation on Surface of Solid**

- **Characteristics:**
  1. Same as "A"

**C-Typical Embedded Thermocouple Installation in Solid**

- **Characteristics:**
  1. Allows Measuring Gradients within Solid
  2. No Disturbance to Fluid Flow Pattern at Heated Surface

**D-Surface Thermocouple for High Surface Heating Rates**

- **Characteristics:**
  1. Responds at Same Rate as Solid at Same Depth
  2. No Disturbance to Fluid Flow Pattern at Heated Surface
  3. Minimum Disturbance to Natural Heat Flow in Solid
  4. Applicable under Extremely High Pressure
  5. Useful up to Melting Point of Solid

**E-Typical Resistance Thermometer Embedded in Solid**

- **Characteristics:**
  1. Slow Response
  2. Inaccurate Knowledge of Location of Temperature Measured
In a direct wiring scheme, the low-level signals generated by an RTD (Ω) or TC (mV) are particularly susceptible to the signal degrading effects of RFI/EMI. Compounding the problem, sensor extension wires can behave much like an RFI/EMI antenna by actually drawing plant noise to the wires, and affecting weak, low-level signals.

Conversely, a properly designed temperature transmitter effectively negates the effects of incoming RFI noise by converting a sensor’s low-level signal to a high-level analog signal (typically 4 to 20 mA). This amplified signal is resistant to RFI/EMI and can accurately withstand long distance transmission from the field, through a noisy plant, back to the control room. When specifying a transmitter, always check for RFI/EMI protection. If there is no specification given, it is usually because the instrument is not designed to resist noise. It will probably not perform very well in a noisy plant environment. RFI immunity is specified in standard IEC 1000–4–3. A spec of 10 V/m is considered acceptable.

**Stop Ground Loops** Make sure to choose an isolated transmitter. A transmitter’s input/output/power signal isolation protects against signal inaccuracies caused by ground loops. This is important even when using ungrounded TCs because their insulation will eventually break down.

**Reduce Hardware and Stocking Costs** With direct wiring, it is necessary to match the sensor type to input-specific DCS and PLC input cards. Sensor input-specific cards usually cost a lot more per point than a 4- to 20-mA input card. And since numerous sensor types are routinely used in a plant, a large number of different cards must be ordered and kept on hand as spares. This is not only expensive, but can result in a lot of confusion when installing, maintaining, and replacing equipment. Temperature transmitters incorporate powerful microprocessors that allow them to be easily configured to accommodate nearly any sensor input type. Their 4- to 20-mA output signal is control-system ready. This allows standardization and stocking of less expensive 4- to 20-mA DCS and PLC input cards.

**Match the Best Sensor to the Application** In an intelligent temperature transmitter strategy, the user can simply change out the sensor and reconfigure the transmitter to accommodate the different sensor type. The loop’s twisted pair wiring and existing 4- to 20-mA input boards do not even have to be touched. Because it is difficult to predict what sensor you will end up with as process changes are made over the years, make sure to select a universal transmitter that configures to accept all common temperature sensor types and temperature ranges.

**Enhance Accuracy and Stability** Using temperature transmitters can substantially enhance measurement accuracy. DCS and PLC systems measure readings over the entire (very wide) range of a sensor. Measuring a narrower range produces far more accurate measurements. Transmitters can be calibrated to any range within a sensor’s overall capabilities. Their measurements are more precise than is possible with most direct wiring strategies. Better transmitters deliver accuracy ratings of ±0.23°F (±0.13°C) when paired with a common Platinum 100 RTD sensor over a 200°F (111°C) span.

If better accuracy is required, transmitters can be trimmed to precisely match a particular sensor. Even though sensors are designed to have a high degree of conformance to an established curve, each one (even precision sensors) will vary to some degree from their stated specification. Transmitters without matching capability assume that the sensor matches its published curve. To properly determine the measurement accuracy, the actual sensor offset error must be combined with the transmitter error.

**Simplify Engineering and Prevent Miswiring** In place of numerous sensor lead-wire and DCS/PLC input board combinations, engineering designs and drawings will only need to show one wire type (twisted wire pair) and one input board type (4 to 20 mA). This one wire and one input board system means maintenance is greatly simplified, and the chances of loop miswiring are virtually eliminated.

**Ease Future Upgrades** Throughout the lifetime of a process, enhancements are routinely made to accommodate the manufacture of upgraded or even completely new products. Process changes may require different measurement ranges or greater temperature accuracy than was previously required. Either of these conditions may necessitate a change in the type of sensors that are used.

In a direct wired system, changing sensors generally means removing existing extension wire and pulling new wire. This is because extension wire must be matched to the sensor type. Additional costs are incurred when the control system’s costly input boards (if also sensor-type dependent) must be replaced to accommodate the new sensors.

**Lower Maintenance Time and Expense** Temperature transmitters have come a long way since the days of fixed-range, inflexible instruments. High quality transmitters are not only universal in regards to input type and range, they also incorporate powerful sensor diagnostics that save considerable time and money.

Temperature transmitters with intelligent diagnostic capabilities continuously monitor sensor operation and quickly find and diagnose sensor failures. If a wire breaks or otherwise stops sending a signal during operation, the transmitter sends the output upscale or downside to warn of sensor burnout or other unwanted conditions. Furthermore, these transmitters can tell you which wire has broken via an error message on an integral digital display, using their PC configuration software, or via HART diagnostics. Specific fault messages eliminate the work of removing the sensor or checking all of the lead wires to diagnose a problem. During start-ups, in the middle of the night or in the middle of winter, this can be a huge timesaving advantage.
Avoid Lead Wire Imbalances

Where feasible, use 4-wire RTDs, and specify a temperature transmitter that is able to accept a true 4-wire RTD input. The advantage is that the fourth wire in an RTD circuit effectively cancels out errors due to resistance imbalances between the leads. Every ohm of imbalance in an RTD sensor’s lead wires can produce as much as a 4.7°F (2.6°C) error in the measurement. Serious imbalances may be present from the very first day of commissioning without the user even being aware of them. Typical causes include manufacturing variances, lead length differences, loose connections, terminal block corrosion, and work hardening from bending and other stresses.

Intelligent temperature transmitters are capable of accepting true 4-wire RTD inputs and provide a constant current loop. There is essentially no current measured across the inner leads, which is a high impedance circuit, so voltage is directly proportional to resistance. Lead resistance is ignored. You will get a very accurate measurement providing the resistance value of the RTD plus corrosion, plus wire resistance, is less than 4000 Ω (typically). A 4-wire RTD costs about the same as a 3-wire and can be used with less expensive, smaller gauge wire without concern for added resistance.

Calibration/Certification

For many applications, using an off-the-shelf sensor with a receiving device will provide adequate measurement accuracy. The offset of the sensor from ideal published relationships may be within the acceptable variation. However, the higher the accuracy required, the more important factors like drift, sensor interchangeability, and system repeatability become.

For critical temperatures, there is often a requirement for certifying that a temperature system produces a given accuracy. In some cases, this is a plant standard and in other cases, accuracy must be traced back to NIST. Whatever the requirement, the calibration must be done as a system that includes the sensor and its measuring device. The key point to understand is that the instrument assumes that the sensor matches published relationships of temperature vs. output. If the sensor is offset from this relationship due to manufacturing tolerances or drift, then the measurement will have an error. The only way to have a true calibration is to bring the sensor to a known temperature and then verify that the instrument output agrees with that value. For field-mounted sensors connected to an I/O system in a remote control room, this is quite difficult to achieve, and errors may have to be tolerated or other methods utilized. One alternative is inserting a certified measuring device adjacent to the installed sensor and adjusting the output trim of the instrument to obtain the correct output reading. For integral sensor/transmitter systems, using a calibration bath or a precision oven offers a solution. How often a calibration is required depends on how closely a system can be verified vs. the accuracy required. For example, a TC system with an accuracy requirement of ±5° can be calibrated to about ±2°, but will have an expected drift of 1 to 5°/year. Hence calibration would have to be performed two or three times/year to calibrate out the drift. However, a premium RTD that has been matched to a transmitter using a calibration bath and capture techniques can offer an accuracy of ±0.02°F and a drift expectation of about ±0.08°F/year. If the system accuracy required were only 0.5°F, a calibration every few years would be adequate to ensure this performance.

The insight to be gained is that a proper choice of components and initial calibration may save significantly on calibration labor and potential process downtime. A wise design engineer will consider the cost of ownership, not just the cost of purchase. Should NIST calibration certification be required, there are many vendors and calibration services that can perform the calibration and provide certificates of traceability to NIST. Calibration on a 12-month interval is suggested by NIST guidelines.

Agency Approvals for Hazardous Areas

When electronic devices are mounted in an area that is, or may be, exposed to explosive vapors, very strict rules apply. Almost every plant in every country with these hazardous environments follows specific guidelines as directed by their insurance coverage. Most often, the guidelines are from one of the recognized certification agencies with jurisdiction in the country. These include FM and UL in the United States; CSA in Canada; CENELEC, LCIE, ISSeP, and ATEX in Europe; SAA in Australia; and NEPSI in China. Each of these agencies tests equipment submitted by a manufacturer and certifies it for use in specific area classifications and specifies the associated installation details. It is the design engineer’s responsibility to determine the appropriate area classification and then select equipment that has the required approvals.

Protection of field devices from moisture, dust, and corrosive contamination is yet another consideration. Solutions include watertight enclosures, powder coat painted surfaces, air-purged enclosures, and special materials of construction. Proper wiring, grounding, and installation practices are critically important for a problem-free installation. Basic considerations include separating signal and power wiring into different conduit runs and using twisted shielded wire pairs with the shield grounded at only one end. In addition, proper drip loops and conduit seals should also be provided for field instruments, which should be using lagged thermal wells and proper insulation to protect transmitters from the heat radiated from hot pipes or vessels. Lastly, close-coupling sensors with transmitters and properly sized, fused, and surge-protected power supplies should be used.

Safety-Related Applications

For safety-related applications, functional safety is another concern. Safety standards such as the American National Standards Institute/Instrumentation, Systems, and Automation
Society 84.01, IEC 61508, and IEC 61511 offer guidance for maximizing reliability and availability of devices used in safety related applications. The higher the Safety Integrity Level (SIL) required, the higher the availability of the devices in the loop must be to perform their designated task. To prevent nuisance failure situations, consideration is given to the reliability of the devices.

To verify that an instrument loop meets specific SILs, reliability data on all of the loop devices must be used in verification equations as suggested by the standards. Leading transmitter manufacturers offer these data in the form of Failure Modes, Effects, and Diagnostic Analysis reports. Failure probability data from these reports are used in the equations to verify that the loop components selected provide the required SIL. High reliability instruments do not necessarily demand a premium price. It seems a wise choice to standardize within a plant on products that offer documented reliability data from recognized third-party agencies for all applications, not just those that are safety related. It is clear that higher reliability requires less maintenance and produces less downtime of the process.

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