Measuring Temperature by Direct Contact

Gary Freemer
ABB Measurement Products

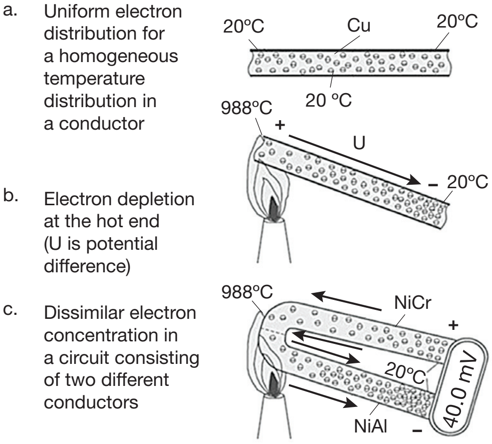
Thermocouples and resistance temperature detectors are the most common contacting temperature sensors. Understand the techniques and apply them correctly to increase your temperature measurement accuracy.

In most industrial applications, temperatures are typically recorded directly, from within a process medium. Because measurements are taken in a wide variety of media, techniques and devices appropriate for the specific process must be employed. This article on contacting temperature-measurement techniques describes the operating principles of thermocouples (TCs) and resistance temperature detectors (RTDs), and provides practical tips on their use. (A subsequent article will discuss noncontacting infrared detection techniques for measuring temperature.)

Temperature is a measure of the average kinetic energy of the molecules within a system, which is directly related to heat energy content. An object will have no heat content when its molecules have lost all of their kinetic energy and are completely at rest. This occurs at a temperature of absolute zero, which is defined as 0 on the Kelvin scale (0 K). Observing and measuring molecular motion is impractical and unrealistic, however, so more-practical techniques have been developed to determine temperature based on the effects of heat energy on system properties, such as geometric expansion and electrical phenomena.

A temperature scale should cover the entire range of temperatures expected within the system. The International Temperature Scale of 1990 (ITS-90) defines a range from 0.65 K to far above 3,000 K. This scale is based on fixed points that correspond to phase equilibrium of extremely pure substances — the triple point of water (0.01°C), the triple point of hydrogen (−259.3467°C), and the melting point of aluminum (660.323°C). Temperatures between points are obtained through interpolation.

In industrial practice, contacting electrical temperature sensors — primarily TCs and RTDs — dominate in measurement and control applications. TCs and RTDs function by transforming a measured temperature difference into a raw electrical signal, which a field transmitter then converts to a standard value, such as a 4–20-mA analog signal or a corresponding digital output. Thermocouples are more rugged than RTDs and are typically less expensive. Resistance temperature detectors, on the other hand, are more accurate and can be equipped with better protective shielding.



▲ **Figure 1.** As electrons accumulate at the cold end of a dissimilar-metal circuit, a voltage develops in proportion to the difference in the temperatures of the hot and cold ends.

Thermocouples

In an electrical circuit consisting of two dissimilar metal conductors, a current develops when the contact points of the conductors are at different temperatures. This thermal current results from a small voltage that is proportional to the temperature difference between the hot and cold ends, and its magnitude is a function of the particular metals.

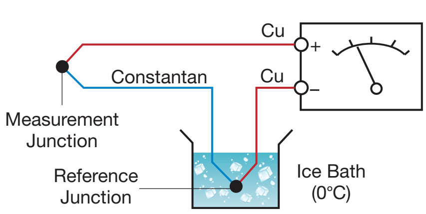
Figure 1 illustrates this phenomenon. Electrons are distributed uniformly throughout a conductor at a single temperature (a). When one end of the material is at a higher temperature, electrons migrate from the hot end to the cold end (b), with the number of moving electrons a function of the specific metals. When two dissimilar conductors are connected in a circuit, the difference in the number of electrons at the cold ends generates a voltage (c).

The signal produced by a thermocouple is proportional to the difference in temperature between the junction of the two metals (measurement junction) and the open ends of the wires. To compensate for the ambient temperature and obtain an absolute reading of temperature (rather than a temperature difference), the temperature at the open ends must either be held constant (Figure 2), which is impractical, or be measured by an extremely accurate temperature device, such as a platinum resistance thermometer. This latter reading then becomes the reference junction of the measurement. The signal developed by the thermocouple is proportional only to the difference in temperature between the measurement junction and the reference junction. Variations in temperature over the length of the thermocouple have no effect on the output.

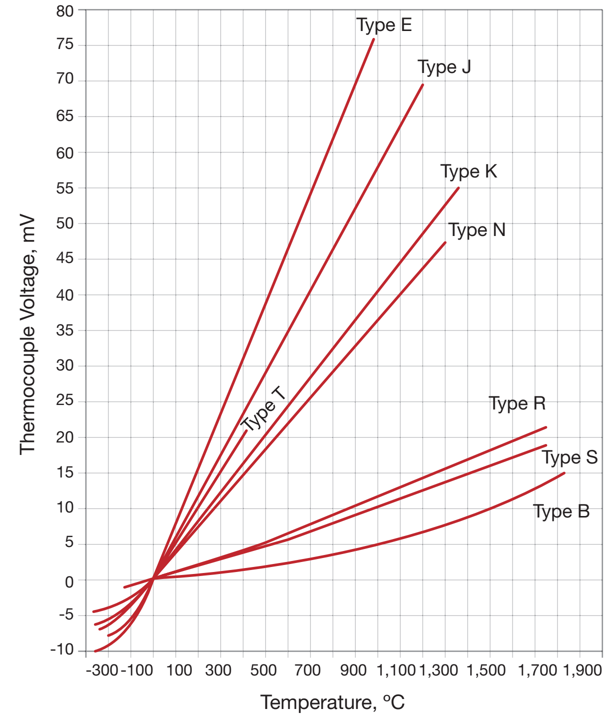
The simplest thermocouple designs consist of insulated metal wires. Typical insulation materials are glass fibers, mineral fibers, polyvinyl chloride (PVC), silicone rubber, polytetrafluoroethylene (PTFE), and ceramic. Standard thermocouples are categorized into two groups: precious-metal thermocouples (Types S, R, and B), and base-metal thermocouples (Types E, J, K, N, and T). Each type has unique thermal voltage characteristics, as indicated in Figure 3.

Precious metal thermocouples

Type S. The positive conductor of a Type S thermocouple is platinum alloyed with 10% rhodium, and the negative conductor is platinum. Although the Type S thermocouple can measure temperatures ranging from –50°C (–58°F) to nearly the melting point of platinum (1,769°C, 3,216°F), the output voltages during continuous operation are stable only to about 1,300°C (2,372°F). At the higher temperatures, the loss of crystallite boundaries within the metal conductors (known as grain growth) limits the thermocouple's lifespan and reduces mechanical strength. Impurities can also diffuse into the wires to change the thermal voltage, which results in inaccurate temperature measurements. The Type S thermocouple is most stable when operated in a clean, oxidizing environment such as air, although short-term use in inert, gaseous atmospheres or in a vacuum is possible. Without suitable protection, such as a thermowell, it should not be used in reducing environments. Metallic thermowells can be used at temperatures below 1,200°C (2,192°F); above that, ceramics — particularly very pure aluminum oxide — are most suitable.



▲ **Figure 2.** The reference junction of a standard thermocouple is held constant. This reference junction is held at 0°C.



▲ **Figure 3.** Each type of thermocouple has unique thermal voltage characteristics. The voltage response is a function of temperature.

Type R. This thermocouple has a defined range of 0–1,450°C (32–2,642°F). One conductor is platinum alloyed with 13% rhodium, and the other is pure platinum. For most of its temperature range, a Type R thermocouple has an output per unit temperature change (temperature gradient) approximately 12% higher than the Type S, making it more sensitive with a higher signal-to-noise ratio. The remaining material properties are identical to those of the Type S.

Type B. Type B thermocouples satisfy requirements for temperature measurements in the range of 1,200–1,800°C (2,192–3,272°F). The positive conductor contains platinum alloyed with 30% rhodium, while the negative conductor is platinum alloyed with 6% rhodium. Near the high end of the temperature range, it may take hours for an appreciable change in the output thermal voltage to occur. Compared to Types S and R, Type B thermocouples offer improved stability, increased mechanical strength, and higher temperature capabilities.

Base metal thermocouples

Type J. A steep temperature gradient and low material cost have made Type J one of the most commonly used industrial thermocouples. The positive conductor is iron and the negative conductor is a copper-nickel alloy called constantan. Although the Type J has a nominal temperature range from –210°C to 1,200°C (–346°F to 2,192°F), it is suitable for continuous operation only from 0°C to 750°C (32°F to 1,382°F). At higher temperatures, the oxidation rate of both conductors increases rapidly. The Type J thermocouple can be used in vacuum, oxidizing, reducing, or inert atmospheres. In sulfur environments, a thermowell should be employed at temperatures above 500°C (932°F).

Type E. This thermocouple, which consists of a nickel-chromium conductor paired with a copper-nickel alloy conductor, is the most common for low-temperature measurements. At temperatures above 750°C (1,382°F), the oxidation rate of both conductors in air is high, so it is essentially insensitive to oxidizing or inert atmospheres. A thermowell is necessary in reducing and sulfur-containing environments.

Type K. This thermocouple is used for mid-range temperatures and better resists oxidation than Types J and E. It is used in many applications at temperatures over 500°C (932°F). Although its basic temperature range is –270°C to 1,372°C (–454°F to 2,501°F), at temperatures above 750°C (1,382°F), the oxidation rate of both conductors in air increases sharply. Suitable protection such as a thermowell is necessary at higher temperatures for installations in sulfur and reducing atmospheres.

Type N. The newest standard thermocouple, the Type N offers better thermoelectric stability above 870°C (1,598°F) and is less likely to oxidize than thermocouple Types J, K, and E. Type N normally consists of a nickel-chromium-silicon alloy paired with a nickel-silicon alloy conductor. Of all the base metal thermocouples, Type N best suits applications with oxidizing, damp, or inert atmospheres. At higher temperatures, suitable protection is still necessary in reducing and sulfur-containing atmospheres.

Type T. Type T is one of the oldest thermocouples for low-temperature measurements. It is commonly used from the triple point of neon (–248.6°C, 415.5°F) to 370°C (698°F). Type T contains a copper conductor paired with a copper-nickel alloy conductor. It exhibits good thermoelectric homogeneity. The Type T can serve in vacuum, oxidizing, reducing, or inert atmospheres. It is not recommended for use in environments containing hydrogen above 370°C (698°F) without a thermowell.

The TC reference junction may be far from the measurement site for many reasons. Precious metal thermocouples are costly to route over long distances, so the thermocouple can be connected by a special cable to the reference junction. The cable must have the same thermoelectrical properties as

T/C Type	Cable Code	Conductor +	Conductor –	T/C Junction Continuous Range, °C	International IEC 584-3	Former British BS 1843-1952	French NFE-18001	German DIN-43714	Japanese JIS C 1610-1981	United States ANSI MC 96.1
K	KX	Ni-Cr	Ni-Ai	0 to +1100						
J	JX	Fe	Cu-Ni Constantan	+20 to +700						
T	TX	Cu	Cu-Ni Constantan	–185 to +300						
N	NX NC	Ni-Cr-Si	Ni-Si-Mg	0 to +1300						
E	EX	Ni-Cr	Cu-Ni Constantan	0 to +800						
B	BX	PT-30Rh	PT-6Rh	0 to +1800						
R	RCA	PT-13Rh	Pt	0 to +1600						
S	SCA	PT-10Rh	Pt	0 to +1550						
V_x	KCB	Cu	Cu-Ni	Compensating Cable for Type K (0 to +80)						

▲ **Figure 4.** International color coding for insulation of thermocouple conductors is based on type.

the corresponding thermocouple over a limited temperature range — usually –25°C to 200°C (–13°F to 392°F), depending on the temperature resistance of the insulation material. Thermal cables have the same nominal composition as the corresponding thermocouple; compensating cables, on the other hand, may be made of different alloys that have the same thermoelectrical properties over a limited temperature range. Standard colors for conductor insulation (Figure 4) identify these interconnection cables to help technicians and engineers match them to a particular thermocouple.

Resistance temperature detectors

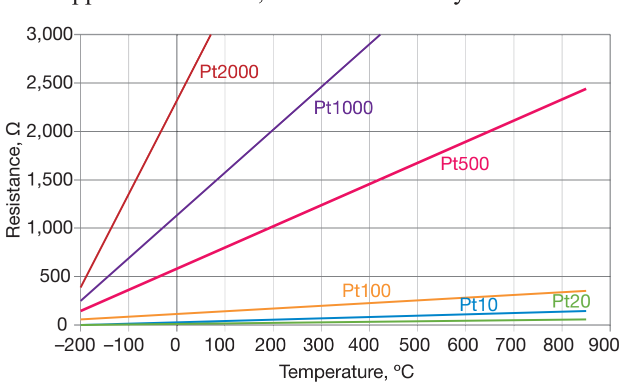
The electrical resistance of metal conductors increases with increasing temperature, and depends on the movement of the surface electrons of the metal's atoms. The atoms of the metal form a dense ion lattice structure, and both the atoms and the lattice oscillate. As the temperature increases, the oscillation amplitude also increases, which impedes the motion of the surface electrons (and thereby inhibits conduction). As a result, the metal's electrical resistance depends on temperature (Figure 5). Because of flaws in the metal's crystalline structure, the relationship between temperature and electrical resistance is slightly nonlinear, but it can be approximated by a simple polynomial.

Metals suitable for use as resistance thermometers should be:

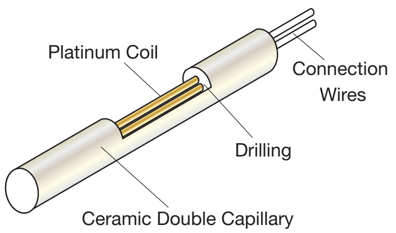
- highly resistant to chemical exposure
- easily shaped
- available in a very pure state
- unaffected by hysteresis
- insensitive to pressure and pressure changes.

In addition, the material should have reproducible electrical properties, and its physical and chemical properties should not vary in the temperature range of interest.

Platinum satisfies these requirements, and in spite of its high price, has become the material of choice for industrial RTDs. Alternative materials such as nickel, molybdenum, and copper are also used, but less commonly.



▲ **Figure 5.** The resistance of an RTD increases with temperature and is a function of the metal.



▲ **Figure 6.** In one type of RTD, platinum wires are wound around a mandrel and encased in ceramic.

RTDs that have a resistance of 100 ohms (Ω) at 0°C have become standard in recent years — particularly the Pt100 RTD that is made from platinum. In addition to the features listed above, platinum has a wide application range of –250°C to 850°C (–418°F to 1,562°F).

The temperature coefficient of the electrical resistance defines the change in electrical resistance between two temperatures, usually between 0°C and 100°C (32°F and 212°F). The International Electrotechnical Commission Standard IEC 20751, "Industrial Platinum Resistance Thermometer Sensors," specifies the temperature-resistance relationship, the nominal value of the temperature coefficient of resistance, the allowable deviation limits, and the temperature range. For example, in the range of 0–100°C (32–212°F), platinum has a temperature coefficient of 0.00385 K^{-1}. This means that a Pt100 measurement resistor has a resistance of 100 Ω at 0°C (32°F) and 138.5 Ω at 100°C (212°F). Outside this temperature range, polynomials are used as correction factors. For small temperature ranges, a linear relationship can be assumed.

Platinum measurement resistors fall into two categories: thin-film and wire-wound resistors. Ceramic, glass, or plastic serves as a carrier material. Thin film layers can be placed on carriers via vacuum vapor deposition, sputtering, or sintering a thick platinum paste. In wire-wound RTD sensing elements (Figure 6), a platinum wire is coiled around a mandrel and sheathed in a ceramic.

The lead wires from the RTD sensor to the measuring transmitter (especially if they are long) can add a small amount of resistance, which affects accuracy. To compensate, three-wire and four-wire RTDs have been developed. The temperature transmitter uses these extra wires to offset the lead-wire error. An alternative is to mount the transmitter directly on the thermowell containing the RTD.

Protecting temperature sensors

Few applications in a chemical plant would permit the direct installation of sensors. Thus, temperature sensors are typically placed within protective thermowells. This increases the life of the sensor under adverse conditions and facilitates a fast sensor exchange without interrupting the process. Thermowells must:

• position the temperature-sensitive sensor tip in the process
• protect the sensor
• seal the process areas from the environment to prevent leakage.

Thermowell selection depends on process characteristics and on the required measurement parameters. Engineers tend to prefer metal thermowells, since they assure an absolute seal against the process medium and the process pressure. However, their use is limited to temperatures below about 1,200°C (2,192°F). Above this, the metal's lower mechanical strength and oxidation resistance can shorten operating life.

Ceramic thermowells may be needed for very high temperatures or when operating conditions exclude metal. Because of their brittle nature, thermowells require delicate handling — a single impact could lead to their sudden and complete destruction. In critical installations, a second barrier may be necessary to prevent the escape of hazardous material via a damaged ceramic thermowell.

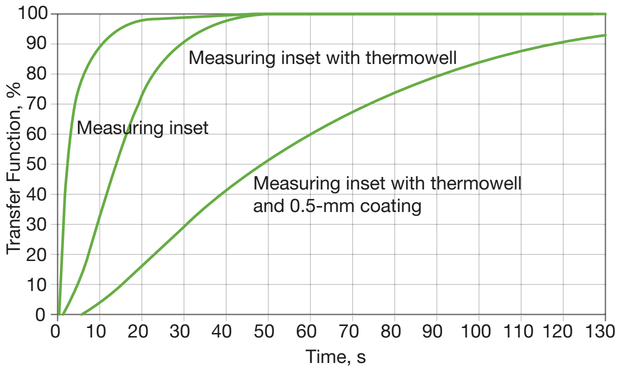
Thermowells are available in standardized forms with a variety of different process connections. For selection of standardized thermowells, manufacturers publish load diagrams that specify the maximum allowable pressure in air/steam or water at a specific temperature and a specific maximum flow velocity. For processes with less-demanding conditions, manufacturers can supply economical thermowells made from tubing material with a welded plug at the outer end. Specific thermowell designs have been developed for such applications as:

• hot gas measurements in a furnace
• reactors operating at high pressures and temperatures
• pipes carrying gases with high particle loads
• fluegas channels
• multipoint sensors in large tanks
• metal melting and salt baths
• plastic extruders
• food and pharmaceutical manufacturing
• surface temperatures
• housing and wall temperatures
• pump bearings.

Dynamic response of temperature sensors

When the temperature of the measured medium changes, the sensor reacts, and its output signal approaches the new temperature. When the output signal no longer indicates any measurable changes, the sensor has reached equilibrium with the medium's new temperature. Understanding the sensor's dynamic response, or time constant, is important when measuring processes with rapidly changing temperatures and for sensors operating in control loops.

Dynamic response depends on: the design of the temperature sensor (size, weight, material, and internal construction); the medium undergoing measurement (heat capacity, heat-transfer coefficient, and flow velocity, which are known); and installation parameters. A thermowell or protection tube will increase the overall response time, as will any protective coating (Figure 7).



▲ **Figure 7.** Thermocouples and RTDs installed in thermowells have longer response times than bare sensors. Coated thermowells have even longer response times.

Smaller sensors and thermowells provide faster response times, but size must be balanced against the conditions that the sensor and thermowell must withstand. The chemical medium acts mechanically on the installation through pressure, flow velocity, eddy formation, and vibration. Fatigue failure due to vibration is a challenge when measuring high-velocity streams and when using bare (unprotected) elements. In addition, without a thermowell, the temperature element cannot be changed while the process is operating.

Wrapping up

When deciding between thermocouples and resistance temperature detectors, keep in mind the following general considerations. Thermocouples as a class have a wider operating range. Most wire-wound RTDs are used to measure temperatures below 500°C (932°F); thin-film models, below 200°C. Thermocouples, on the other hand, can be used up to 1,800°C (3,272°F). Base metal thermocouples are considerably less expensive than RTDs; precious metal thermocouples are not, especially when long distances are involved, since RTDs use inexpensive copper lead wire to transmit the signal for display or control. RTDs tend to be more accurate, precise, and stable than TCs.

GARY FREEMER has worked at the ABB Group for 10 years, currently as the product manager for recording, control and temperature products and previously technical and application support (Phone: (215) 205-1689; Email: gary.freemer@us.abb.com). Prior to joining ABB, he worked at Eurotherm Chessell Recorders (now part of Invensys), in R&D, manufacturing engineering, and applications and factory support. He has a BS in mechanical engineering from Pennsylvania State Univ.