TEMPERATURE MEASUREMENT

Physical principles underlie the four common methods.

BY ERNEST MAGISON

In a scientific laboratory, the objective of measurement may be accuracy, regardless of cost and time. This might be the case, for example, when determining the melting point of a new material.

In industry, however, the usual objective is to find a way to measure temperature that yields the following:

- The accuracy and speed of response required by the application
- Acceptable initial investment
- Low maintenance cost, which implies long life and stability of calibration

For instance, several types of thermocouples may have similar accuracy and initial cost. The objective is to select the type with the greatest stability and longest life. The selection may depend on whether the atmosphere will corrode or poison the thermocouple.

Or in glass forming, such as molding bottles, viscosity changes require readjustment of the bottle-making machine. Viscosity closely correlates with temperature, so the accuracy of the temperature measurement is critical. Because glass melts at temperatures too high for most metals to operate and because most materials would contaminate the glass, it is economically justifiable to specify platinum thermocouples in platinum-protecting tubes or sophisticated radiation thermometers.

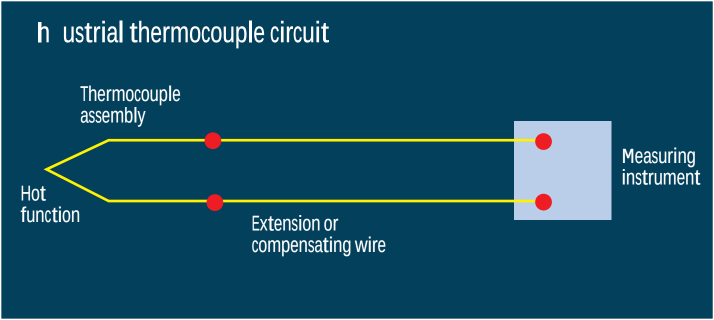
Most applications cannot justify such an investment.

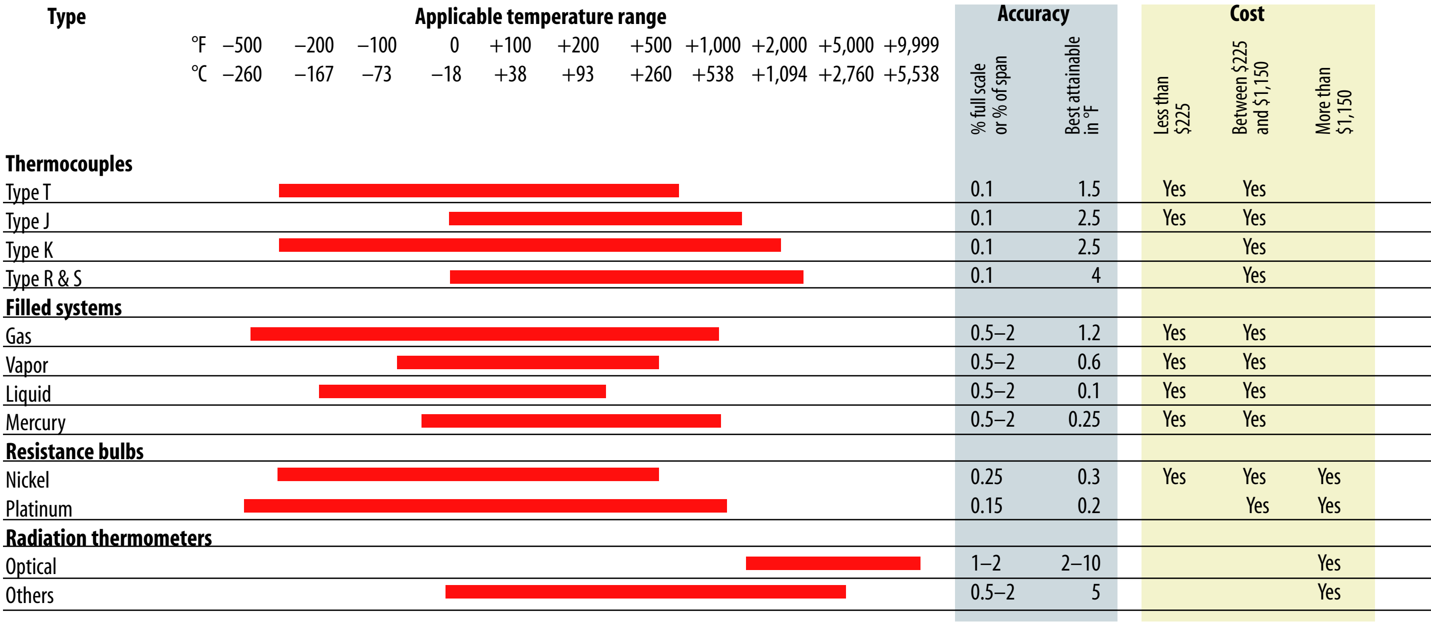
TOUCH IT OR FEEL IT INDIRECTLY

All temperature measurements are indirect. That is to say, the measurement is the measurement of volumetric expansion (liquid-filled thermometer), dimensional change (bimetallic thermometer), electromotive force (thermocouple), resistance (resistance temperature detector, or RTD), radiated energy (radiation thermometer), or some other characteristic of a material that varies predictably and reproducibly with temperature.

However, in industrial process measurement and control, the concept of direct and indirect temperature measurement has a different meaning. A direct measurement is a measurement of the temperature of the product itself. An indirect measurement is a measurement of some other temperature from which one can infer the product temperature.

An example of direct temperature measurement occurs when, as in roasting meat or making candy, it is possible to insert a thermometer directly into the product; insertion or immersion thermometers are often used.


h ustrial thermocouple circuit



Type	Accuracy: % full scale or % of span	Accuracy: Best attainable in °F	Cost: Less than $225	Cost: Between $225 and $1,150	Cost: More than $1,150
Thermocouples					
Type T	0.1	1.5	Yes	Yes	
Type J	0.1	2.5	Yes	Yes	
Type K	0.1	2.5		Yes	
Type R & S	0.1	4		Yes	
Filled systems					
Gas	0.5–2	1.2	Yes	Yes	
Vapor	0.5–2	0.6	Yes	Yes	
Liquid	0.5–2	0.1	Yes	Yes	
Mercury	0.5–2	0.25	Yes	Yes	
Resistance bulbs					
Nickel	0.25	0.3	Yes	Yes	Yes
Platinum	0.15	0.2		Yes	Yes
Radiation thermometers					
Optical	1–2	2–10			Yes
Others	0.5–2	5			Yes

One uses an indirect measurement in baking bread because one controls the oven air temperature. It is not practical to insert a thermometer into the bread because the action adversely affects the quality of the bread.

The nature of the process influences the selection of a temperature measurement technique. Is it necessary to measure product temperature, and is it possible to measure it? It is essential to understand the process and its characteristics before trying to determine which temperature measuring method to use.

INDUSTRY LEANS TOWARD BIG FOUR

Thermocouples, resistance thermometers, filled systems, and radiation pyrometers are the most commonly used temperature-measuring elements in industrial applications.

A thermocouple is an assembly of two wires of unlike metals joined at one end, the hot end. At the other end, the *cold* junction, the open circuit voltage is measured. This voltage (electromotive force, or EMF), the Seebeck voltage, depends on the difference in temperature between the hot and the cold junction and the Seebeck coefficient of the two metals.

The Seebeck EMF develops when there are differences in temperature between junctions of dissimilar metals in the same circuit. Also known as the *thermoelectric effect*, German physicist J. T. Seebeck discovered the phenomenon in 1821.

The Seebeck EMF depends on the characteristic of the thermocouple metals and the temperature difference between the measuring and cold junctions. A measurement indicates the temperature of the hot junction when one knows the cold junction temperature or when measuring circuitry compensates for cold junction temperature.

The procedure for determining the temperature boils down to this procedure:

- Measure the EMF at cold junction.
- Measure temperature at cold junction T_{cj}.
- Determine the EMF at T_{cj} from a table. This is the EMF the thermocouple would read if its hot junction were in an ice bath.
- Add this EMF to the EMF measured in the first step. This EMF would be developed by the thermocouple if the cold junction were in an ice bath and the hot junction at the unknown temperature.
- Find this EMF in the table and read the corresponding temperature. This is the hot junction temperature and the information about the process that we seek.

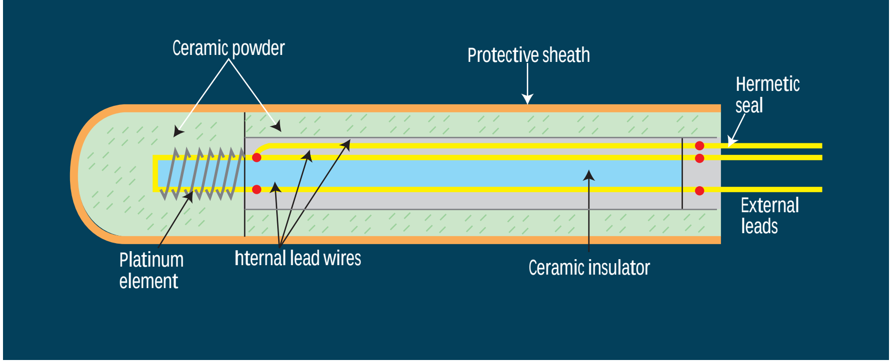
RESISTANCE GOES OHMS

A resistance thermometer, to be a useful means to measure temperature, must have a predictable and stable relationship between resistance and temperature. For detectors to be as small as practicable, the specific resistance of the wire or the film must be relatively high so that measuring the resistance is easy.

The change in resistance with temperature should also be high. The wire must be mechanically strong, and its resistance temperature characteristic should suffer from the strains that occur when winding the temperature-sensitive element.

And, of course, there must be no change of phase or state over the desired range of temperature. Lastly, the material must be commercially available with a consistent temperature resistance relationship so that detector calibration is uniform from unit to unit.

Resistance temperature detector



Type	Stability	Repeatability	Response time	Sensitivity	Interchangeable sensor w/o system recalibration	Linear	Maximum distance to readout (feet)
Thermocouples							
Type T	Good	Good	Good	Good	Yes	No	
Type J	Good	Good	Good	Good	Yes	No	3,000
Type K	Good	Good	Good	Good	Yes	Yes	3,000
Type R & S	Good	Good	Excellent	Excellent	Yes	No	3,000
Filled systems							3,000
Gas	Excellent	Fair	Good	Fair		Yes	
Vapor	Excellent	Fair	Good	Fair		No	150
Liquid	Excellent	Fair	Fair	Good		Yes	200
Mercury	Excellent	Fair	Fair	Good		Yes	40
Resistance bulbs							50
Nickel	Good, Excellent	Excellent	Good	Excellent	Yes	No	
Platinum	Excellent	Excellent	Good	Good, Excellent	Yes	Yes	1,000
Radiation therm.							3,000
Optical	Fair	Fair	Good	Good		No	
Others	Fair	Fair	Excellent	Good		No	100

Compiled by Nicholas Sheble, nsheble@isa.org, from sources including *Instrument Engineers Handbook* and *Temperature Measurement in Industry*

Resistance elements for industrial use are manufactured of small diameter wire, with 0.001 inches in diameter being typical. They may be wound in a coil and inserted in a hole in a ceramic insulator, or the coil may be wound on a ceramic or glass bobbin.

A sheath, usually stainless steel or some other temperature- and corrosion-resistant material, always protects the resistance element from moisture and the environment. If a temperature measurement is to be made in a vessel with high internal pressure, in a pipe with high fluid velocity, or in the presence of corrosive liquids, the temperature probe may be further protected by insertion in a well or protecting tube of a design similar to those used for thermocouples.

A circuit such as a Wheatstone bridge attaches to and measures the resistance of the detector. The resistance translates to a temperature.

LEGACY-FILLED SYSTEMS DECLINE

A filled-system thermometer consists of four parts. A capillary tube connects a bulb containing a fluid that is sensitive to temperature changes to an element that is sensitive to pressure or volume changes. The pressure-sensitive or volume-sensitive element may be a Bourdon tube, a helix, a diaphragm, or bellows.

The motion of the temperature- or volume-sensitive element couples mechanically to the indicating, recording, or controlling device.

Thermocouples and RTDs are replacing filled systems in industrial process control applications. The low cost of electronic devices to read the output of thermocouples 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.

However, filled systems are still common for temperature measurement and control in appliances and similar applications.

In liquid-filled systems, the bulb, the capillary, and the Bourdon are completely full of liquid. A Class I system contains liquids other than mercury, and a Class V system contains mercury. Organic liquids in filled systems have volumetric coefficients of expansion about eight times that of mercury. Mercury-filled systems operate at much higher temperatures.

Vapor-filled systems, Class II, contain a volatile liquid. Temperature change at the bulb changes the vapor pressure in the system, translating to motion by the Bourdon tube.

Gas-filled systems operate on the principle of Charles' Law:

(Pressure) x (volume) = (temperature) x (the system's constant)

whereby the temperature and temperature change cause a mechanical movement that translates to an indicator, recorder, or controller.

Radiation thermometers/pyrometers measure the energy radiated from an object. The radiation thermometer can measure this radiation from a distance. There need be no contact between the thermometer and the object because, unlike thermocouples, RTDs, and filled-system bulbs, the radiation thermometer need not be at the same temperature as the object of interest.

Every body radiates energy to its surroundings proportional to its absolute temperature. Although the emitted radiation of a body includes all wavelengths, the region in which the amount of radiation is significant to industrial temperature measurement extends from 0.3 micrometers (μm) to about 20 μm. From 0.4 μm to 0.7 μm is the visible region. Radiation at wavelengths longer than 0.7 μm is in the infrared region, which humans cannot see.

The radiation wavelength is sensed using a variety of detectors: simple optics, thermopile detectors, silicon cell detectors, tungsten filament, and others using varied radiation thermometer classes that are roughly categorized as broadband, band pass, narrowband, ratio, optical, and fiber optics.

Radiation thermometers are suited especially to the measurement of moving objects or objects inside vacuum or pressure vessels. They are rugged and may be in service for decades but they require routine maintenance to keep the sighting path clear and optical elements clean. Unlike thermocouples and resistance thermometer, radiation thermometers have no industrywide calibration curves. IT

Behind the byline

Ernest Magison is a registered P.E. in Pennsylvania who worked for Honeywell for 48 years. He joined ISA in 1950. He also served as U.S. delegate to IEC SC 31G, Electrical Apparatus for Explosive Atmospheres.