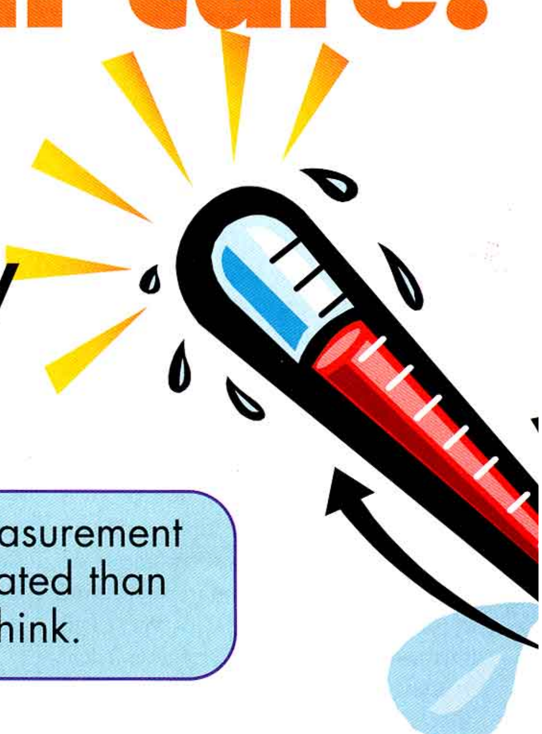
Handle with care:
Temperature sensors need know-how



By Bud Adler

This common measurement is more complicated than you might think.

Hundreds of interviews with plant personnel have made it clear to me that most users believe they are making a better temperature measurement than they actually are and that this common measurement is among the most misunderstood. With improved technologies and better performing products, however, it is important that designers, engineers, and users understand the latest advances in order to make the best choices for their applications. Most importantly, analysts must consider the accuracy and drift characteristics of both the sensor and the transmitter when determining measurement precision.

The basic question is: What is the best way to relate sensor and transmitter performance considerations to real-world temperature measurement systems?

Though the sophistication of electronics has improved dramatically over the years, it remains the case that measurement is only as good as its weakest component. Almost always, that's the sensor. And while I/O subsystems, distributed control systems (DCSs), or programmable logic controller (PLC) cards have reasonable specifications, they don't match the performance of today's quality temperature transmitters.

Selecting sensors for reliability

For temperatures ranging from cryogenic to about 800°F (427°C), a resistance temperature detector (RTD) is better than a thermocouple. Though RTDs were once more expensive, today the cost difference between the two is negligible, and an RTD provides greater accuracy, stability, and life span. Over its useable range, a standard-grade RTD provides more than twice the accuracy of a thermocouple.

To understand why, consider the materials of construction. A thermocouple is comprised of two dissimilar metals welded together; the resulting junction begins to deteriorate immediately. The deterioration is faster at higher temperatures and can result in drift of several degrees per year. On the other hand, an RTD consists of stable, highly purified platinum.

RTDs drift just fractions of a degree per year and are accurate for many years when used at temperatures below 800°F (427°C). Thermocouples, however, are not and require frequent replacement. This tips the scale for installation costs in favor of the RTD.

Spring-loaded sensor assemblies provide the fastest response by keeping the sensor pressed against the bottom of the well, dramatically reducing the time constant. A sensor installed into a well with temperature-conductive grease improves the response even further. The assembly's thermowell governs thermal inertia. The metal well adds mass around the sensor, slowing overall response to temperature changes. A stepped well helps reduce the effect, and a finned well provides more surface area exposed to the process fluid, offering the best possible system response. A common industrial grade sensor is within 0.06% of the temperature vs. resistance curve. Low-cost manufacturers usually provide 0.1% sensors, while quality manufacturers provide 0.04% or even 0.01% sensors.

Thin film technology–based RTDs are gaining on wire-wound construction in popularity. Their low mass contributes to low susceptibility to vibration damage. They are less expensive than wire-wound models, and their low mass improves time response. They cannot, however, withstand temperature extremes or cycling applications. Wire-wound RTDs are usually the best choice for cyclic applications, for cryogenic applications below –200°F (–100°C), and for temperatures above 1,000°F (600°C) but use lead extension wires for high temperatures. Thermocouples are often a good choice for high-temperature applications where high accuracy is not required.

Cushioned sensor construction provides longer life in high-vibration applications. The fill adds significantly to the response time of the sensor, however, and designers should avoid cushioning when fast response is important. Where temperatures above 600°F (315°C) are involved or where speed of response is important, a wire-wound sensor or a precision thermocouple are the choices.

Use of extension wire increases the susceptibility to electrical noise and radio frequency interference (RFI) for both thermocouples and RTDs. A transmitter with an RFI immunity specification of about 20 volts/meter will adequately filter out these effects. I/O subsystems are typically far less RFI tolerant. Further, long runs of extension wire invite failure from physical damage and corrosion, as well as shorts or open circuits.

For an RTD, a quality signal conditioner will detect shorts or open leads and drive the output to an extreme (upscale or downscale) to alert the receiver to the condition. For a thermocouple, a short becomes a second measurement junction in parallel with the original thermocouple. This type of fault is termed a nondiagnosed dangerous failure. In safety-instrumented functions, a dangerous failure is a measurement error in excess of 2% and is undetectable by diagnostics. Thermocouple extension wire degrades over time, with an unpredictable contribution to measurement drift. Yearly drift of 10°F (5.5°C) or more is common.

Can you trust your signal conditioning?

A transmitter using a three-wire measuring circuit assumes that the resistance in the two outer legs of a three-wire RTD is the same. While the extension wires may have nearly equal resistance, terminal corrosion may cause a resistance differential of several ohms. These circuits introduce additional error at each sensor termination point before reaching the transmitter. The imbalance in a three-wire circuit manifests itself as an error of 4.7°F (2.6°C) for each ohm of imbalance between leads one and three.

Exacerbating the situation, the error will fluctuate in response to changing ambient temperature and humidity conditions. Four-wire RTDs, used with transmitters that incorporate four-wire measurement circuits, are immune to the effects of terminal corrosion. The fourth wire provides a path for a high-impedance voltage measurement across the sensing element, independent of the resistance of the outer leads.

Direct wiring to a DCS or PLC introduces several reliability issues:

- Many I/O cards do not support "true" four-wire RTD inputs.
- Long wiring runs subject the signal to electromagnetic interference (EMI), RFI, potential damage to the cable, and errors due to degradation of the cable.
- Most systems measure the entire range of the chosen sensor, not just the span of interest. For example, an RTD has a published range of –328° to +1562°F (–200° to +850°C), while the span of interest may be only 50° to 150°F (10° to 66°C). The result is greatly reduced resolution.

A transmitter, however, differentiates between an "out of range" condition and a "sensor failure" condition by driving the 4–20 mA signal upscale or downscale. For safety-related systems, this feature allows the safety PLC to trigger a "failed sensor" alarm instead of a "shutdown" command, thus eliminating a false trip.

A transmitter with a Failure Mode Effects and Diagnostic Analysis (FMEDA) report, as calculated by an independent agency, offers a far higher expectation of reliable performance than a generic model. This report provides the safety failure fraction (SFF) and probability of failure on demand numbers that analysts use to determine the safety integrity level (SIL) of a measurement function.

Calibration

Remember to include all possible sources of error when determining total calibrated accuracy. Top-of-the-line transmitters have an input accuracy with an RTD of ±0.18°F (±0.1°C) and an output accuracy of 0.015% of span. For a Type K thermocouple, the input accuracy is ±0.54°F (±0.3°C). These specifications, combined with drift, ambient temperature, and power supply effects, provide measurements well within the parameters of most applications.

When plant policy demands calibration certification by an outside agency—for example, the National Institute of Standards and Technology (NIST)—a vendor-provided calibration is usually required. Matching the sensor to the transmitter usually yields the best performance.

Capture two points on the curve by connecting the sensor to the transmitter and then using a precision temperature bath. For high-temperature systems using a thermocouple, the temperature standard is a precision-controlled oven. Optimally, these points should bracket the operating point. Accuracies of ±0.025°F (±0.014°C) for RTD systems and ±2°F (±1.1°C) for thermocouples are typical.

Savings begin with design

Specifying a single temperature assembly to meet a given performance goal puts all of the responsibility on a single vendor and saves multiple specification sheets, quotation requests, and bid reviews. The I/O subsystem of the host requires only high-level input cards. There is no need for different card types for different input signals. System cost will be lower.

The draftsperson has only one type of symbol to use for the field device and only one type of wire type to show in the piping and instrumentation diagram and bill of material. There is no need to differentiate between several thermocouple or RTD types. There is only one kind of extension wire, and purchasing it in large quantity lots reduces costs. Copper wire is far less expensive than thermocouple or RTD extension cable.

The universal transmitter is the same for all measurements and all ranges, minimizing spares. I/O cards are high-level (4–20 mA) and discrete. There is no need to periodically replace thermocouple extension wire. There is less maintenance because high-level signals are more tolerant of corrosion and interference from EMI or RFI.

Operators calibrate a single assembly as a system, for maximum performance. Remote sensors usually preclude this option.

Design of safety-related systems

The design team will usually select loop components offering the highest reliability. Though long-term failure data from applications within a plant are the best indication of an instrument's reliability, few facilities maintain proper proven-in-use (PIU) records. The next best solution is to select instruments that have had a detailed FMEDA report compiled by a reputable third-party firm. This probabilistic analysis provides confidence that the instrument will operate reliably and provides the data for SIL calculations. If the vendor can provide long-term PIU data, the confidence increases.

Selection of a transmitter without FMEDA data forces the analyst to use generic average data in his calculations. This generic data is usually conservative, forcing a redundant architecture. Because SIL calculations must account for each component of a loop, a temperature subsystem must include both the sensor and the signal conditioning device. Direct wiring of a sensor to the I/O subsystem of a safety PLC should be avoided for several reasons:

- Direct wiring requires long runs of extension cable, with the corresponding burden of higher susceptibility to EMI, RFI, ground loops, and physical damage than 4–20 mA cable.
- Four-wire RTD systems provide immunity to the lead wire resistance imbalance typically caused by terminal corrosion in three-wire systems. No safety PLC currently offers I/O cards that accept four-wire RTD inputs. Recall that lead imbalance in three-wire circuits causes an error of 4.7°F (2.6°C) per ohm and that 2% of span error is a nondiagnosed dangerous failure.
- A PLC measurement reflects the entire range of the sensor, regardless of the span of interest. A dramatic loss of resolution results.
- I/O card resolution is typically 14 to 16 bits of precision, while quality transmitters provide 18- to 20-bit resolution. Isolation and EMI/RFI rejection specifications on transmitters are far superior to most I/O subsystems. For precision measurements, a sensor must be calibrated/matched to the transmitter—an almost impossible feat with remote sensors.

The standards for safety-instrumented systems suggest periodic proof testing of all loop components. A single bench test of a close-coupled temperature assembly is quick and conclusive. Verification and calibration of a remote sensor, its connecting cabling, and a single channel of the I/O subsystem is a huge task. A temperature assembly is the only reasonable choice if NIST certification is necessary.

The safety PLC should be programmed to differentiate between an overrange condition and a sensor failure. Nuisance shutdowns for sensor failure are costly and potentially dangerous. For high-reliability SIL 2 applications, a dual architecture is best unless a temperature subsystem can demonstrate an SFF greater than 90%.

Continuous improvement

Temperature measurement technology continues to improve. Filled system pneumatic transmitters have given way to electronic models. Sensor performance and reliability have increased dramatically. Electronic measurement circuits have progressed from the 8-bit designs of the 1960s to the 22-bit designs of 2001. Transmitted signals have evolved from the 3–15 pounds per square inch, gauge, pneumatic signals to 4–20 mA analog signals and now to digital signals. Fieldbus technology is emerging as a viable method to distribute functionality, increase diagnostic coverage, and reduce maintenance. There are even products that have rugged industrial configurations that communicate over an Ethernet link directly to a Web page.

It is critical to select the proper sensor for each application. Direct-connected sensors are fine for some applications—those where trends instead of absolute values are monitored—but for most other applications, there is no benefit, and inferior performance is certain. Most often, there is also a greater cost of ownership.

With technology improving rapidly, it is important that designers, engineers, and users understand the latest technological advances so they make the best choices for their applications. The leading vendors have a wealth of application guidance. It is not appropriate to trust the "we've always done it that way" mentality. Better performance, higher reliability, and longer life await those who have the knowledge. As mundane as temperature measurement may appear, its associated technology is among the most sophisticated. **ST**

Behind the byline

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