Sensor Integrity Ensures Temperature Measurement Accuracy

Whether measuring or controlling temperature, it begins with the sensor. Better sensors make better process measurements.

By Gary Prentice, Moore Industries

Although not every temperature application is a high-accuracy mea¬surement, best practices can be applied to eliminate sensor drift at the start of an installation. This helps users achieve optimal results while avoiding downtime or troubleshooting that might result from future drift during operation.

Several factors influence temperature system accuracy: individual sensor accuracy, extension wire, and measuring devices. When embarking on a project involving temperature measurement or control, consider these basic rules of thumb:

- The same techniques used to achieve accuracy also result in curbing measure¬ment drift.
- Specifying the appropriate sensor will keep drift to a minimum.
- Selecting the appropriate transmitter will keep drift from occurring.
- Using 4-wire RTDs will eliminate the possibility of measurement drift. (Even if using direct-wired 3-wire RTDs, solutions exist to minimize lead wire drift.)

- Reduction in drift means fewer calibrations/verifications, which translates to lowered operating expense.
- Thermocouple extension wire decays over time, causing measurement error, in the form of drift, and requiring replacement.
- Many of the considerations above have trivial impact on the initial purchase price and offer very significant impact on cost of ownership.

The most common temperature sensors acceptable for temperature measurement and control include thermocouples, resistance temperature detectors (RTDs), thermistors, and semiconductor-based sensors. Only T/Cs, RTDs, and remote input/output (I/O) are discussed here.

Thermocouples

Thermocouples (T/Cs) are the most common temperature measurement sensors used in the U.S. for process control. T/C use is a proven technology in industry. They are rugged, relatively inexpensive, and easy to use.

When metals of different composition come into contact, they form a junction that produces a voltage in the millivolt range. If the temperature to which this junction of dissimilar metals is exposed changes, there will be a corresponding change in the millivoltage produced by the junction.

Figure 1. Solid sheath RTD or thermocouple temperature sensors.

Thermocouple types

Theoretically, any two different types of conductive material could be used to make a thermocouple. However, only a few combinations are used. The criteria for the material combinations chosen for use in thermocouples include the magnitude of their relative Seebeck coefficient, chemical stability, metallurgical stability, strength, ductility, and cost.

There are eight standard thermocouple types established in the U.S. The American National Standards Institute (ANSI) assigned letter designations to these eight types: T, J, K, E, N, S, R, and B (Table 1). The designations are based on the voltage versus temperature relationship for these thermocouples. The designations are not based on their compositions. T/Cs built to the ASTM E230 standard are more accurate. The ASTM E320 standard governs thermocouple accuracy.

Type	Composition	Color Code (U.S. only)	Polarity	Magnetic?	Temperature Range
T	Copper	Blue	+	No	-270°C to 400°C (-454°F to 752°F)
	Constantan	Red	-	No	
J	Iron	White	+	Yes	-210°C to 1,200°C (-346°F to 2,192°F)
	Constantan	Red	-	No	
K	Chromel	Yellow	+	No	-270°C to 1,372°C (-454°F to 2,500°F)
	Alumel	Red	-	Yes	
E	Chromel	Violet	+	No	-270°C to 1,000°C (-454°F to 1,832°F)
	Constantan	Red	-	No	
N	Nicrosil	Orange	+	No	-270°C to 1,300°C (-454°F to 2,372°F)
	Nisil	Red	-	No	
S	Platinum-rhodium (90%-10%)	Black	+	No	-50°C to 1,768°C (-58°F to 3,214°F)
	Platinum	Red	-	No	
R	Platinum-rhodium (87%-13%)	Black	+	No	-50°C to 1,768°C (-58°F to 3,214°F)
	Platinum	Red	-	No	
B	Platinum-rhodium (70%-30%)	Gray	+	No	0°C to 1,820 °C (32°F to 3,308°F)
	Platinum-rhodium (94%-6%)	Red	-	No	

Table 1. ANSI standard thermocouple types along with their compositions, color coding, polarity, magnetic properties, and temperature ranges.

T/C sensor accuracy

Thermocouple sensors built to the ASTM E230 standard are more accurate. The ASTM E320 standard governs thermocouple accuracy, as shown below in Table 2.

Sensor	Accuracy spec, greater of:	149°C/300°F	316°C/600°F	482°C/900°F	649°C/1,200°F
Type E	0°C to 870°C: ±1.7°C or ±0.005 * | t |	±1.7°C/3.0°F	±1.7°C/3.0°F	± 2.4°C/4.3°F	± 3.2°C/5.8°F
Type J	0°C to 760°C: ±2.2°C or ±0.0075 * | t |	± 2.2°C/4.0°F	± 2.4°C/4.3°F	± 3.6°C/6.5°F	± 4.9°C/8.8°F
Type K	0°C to 1260°C: ±2.2°C or ±0.0075 * | t |	± 2.2°C/4.0°F	± 2.4°C/4.3°F	± 3.6°C/6.5°F	± 4.9°C/8.8°F
Type T	0°C to 370°C: ±1.0°C or ±0.0075 * | t |	± 1.1°C/2.0°F	± 2.4°C/4.3°F		

Table 2. Temperature sensor accuracy.

Premium/special grade thermocouple wire

Thermocouples can be constructed with premium- or special-grade wire that cuts uncertainty in half. The premium/special designation indi¬cates that this wire has a higher purity alloy mix. Even with premium/special grade T/C, Moore Industries recommends using RTDs instead of T/Cs whenever possible, as their accuracy, repeatability, and stability are superior to those of T/Cs.

Sensor special tolerance	Accuracy spec, greater of:	482°C/900°F
Type E	0°C to 870°C: ±1.0°C or ±0.004 * | t |	± 1.9°C/3.5°F
Type J	0°C to 760°C: ±1.1°C or ±0.004 * | t |	± 1.9°C/3.5°F
Type K	0°C to 1260°C: ±1.1°C or ±0.004 * | t |	± 1.9°C/3.5°F
Type T	0°C to 370°C: ±0.5°C or ±0.004 * | t |	

Table 3. Uncertainty is cut in half by using premium-grade sensors.

In comparing the accuracy data between Table 3 and Table 2, notice that the uncertainty is cut in half by using premium-grade sensors. If T/Cs must be used, premium grade offers greater stability at a negligible cost difference. The problem consistently seen in thermocouples is wire contami¬nation. As contamination occurs, error gradually increases to a point necessitating sensor replacement.

T/C extension wire characteristics

Anytime T/C extension wire is connected to a T/C, it introduces more un¬certainty to the measurement (Table 4). If T/C extension wire will be exposed to temperatures outside the specified ranges, consider using actual thermocouple wire instead.

Extension wire	Temperature range	Standard error
EX	0 to 200°C, 32 to 400°F	±1.7°C/±3.0°F
JX	0 to 200°C, 32 to 400°F	±2.2°C/±4.0°F
KX	0 to 200°C, 32 to 400°F	±2.2°C/±4.0°F
TX	-60 to 100°C, -75 to 200°F	±1.0°C/±1.8°F

Table 4. When T/C extension wire is connected to a T/C, it introduces uncertainty into the measurement.

In addition to uncertainty, T/C extension wire is susceptible to radio-frequency interference (RFI) and electromagnetic interference (EMI). Extension wire for J and K thermocouple types adds another ±2.2°C (±4.0°F) uncertainty when wire is clean and uncontaminated. Also, T/C extension wire tends to behave as an antenna for RFI and EMI. Use best practices to keep disruptive noise out of these low-level mV signals. T/C extension wire will degrade to the point of replacement; replacing it with more extension wire perpetuates the T/C extension wire replacement loop. However, premium-grade T/C extension wire cuts the potential error in half and should be selected.

If extension wire is stressed by being exposed to temperatures outside the limits shown in Table 3, uncertainty will grow. Premium-grade extension wire still allows the possibility of error once metals become contaminated by airborne influences. It is recommended that T/C extension wire be eliminated as close to the T/C as possible by installing either temperature transmitters or remote I/O.

Options for eliminating T/C extension wire

Options exist that allow the elimination of T/C extension wire, thereby taking a step in ensuring reliable measurements. Among the options are temperature trans¬mitters, which can pose cost considerations, and remote I/O.

Temperature transmitters, remote I/O, and temperature concentrator modules eliminate expensive T/C and RTD extension wire and other point-to-point wires by sending temperature measurements, process monitoring, and control signals between the field and control room on one digital communication link. Related technologies, such as temperature concentrator modules (TCMs) and temperature transmitter/signal converters, have programmable inputs configurable for RTD, T/C, Ohms, mV or potentiometer, and current or voltage, depending on the specific module type. Outputs would often support HART, PROFIBUS PA, FOUNDATION Fieldbus, MODBUS RTU, etc.

Typical characteristics of state-of-the-art remote I/O include:

- Minimum hazardous area certification of Class 1, Div. 2/Zone 2
- Ambient temperature specs -40 to 85°C (-40 to 185°F)
- Each input configured, calibrated, and custom-trimmed individually, as with temperature transmitters
- A 20-bit input resolution and input accuracy equivalent to that of temperature transmitters
- 500 Vrms isolation in all directions
- Sensor and I/O diagnostics
- Serial, Ethernet, or wireless communication capability supporting open protocols such as MODBUS RTU, MODBUS/TCP, PROFINET, and EtherNet IP

Figure 2: Complete temperature assemblies using the WORM flexible sensor and an infinite combination of materials and components.

Resistance temperature detectors

RTD wire is a pure material, typically platinum, nickel, or copper. The material has an accurate resistance/temperature relationship, which is used to provide an indication of temperature. RTD elements are normally housed in stainless steel protective probes insulated and isolated from protective sheath with magnesium oxide.

Common RTD sensing elements constructed of platinum, copper, or nickel have a repeatable resistance versus temperature relationship (R versus T) and operating temperature range. The R versus T relationship is defined as the amount of resistance change of the sensor per degree of temperature change. The relative change in resistance (temperature coefficient of resistance) varies only slightly over the useful range of the sensor.

Premium- and special-grade RTD sensors

Moore Industries thermally ages all of its RTDs to minimize drift once they get into the field. The RTDs are temperature cycled for 1,000 hours at 0° and 600°C, and will maintain accuracy for more than five years. Typically, only Class A sensors are thermally aged. Just as it is recommended that you use premium-grade T/C wire for thermo¬couple measurements, it is also suggested that you upgrade to Class A RTD sensors, which cuts uncertainty in half.

Sensor trimming for high accuracy

When a particular application demands the highest accuracy possible, Moore recommends ordering a temperature measurement system with bath calibration. A Class A RTD sensor is calibrated in a bath to calibrate it to the transmitter or remote I/O measuring device. This process eliminates the final "as-built" offset error that exists in every sensor. You then receive a NIST-traceable calibration report that indicates the combined sensor and temperature transmitter uncertainty, which is typically better than ±0.01°F.

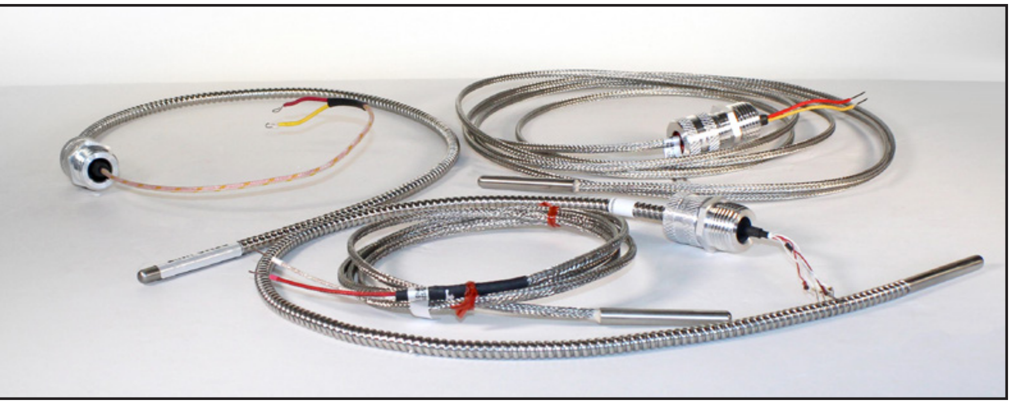
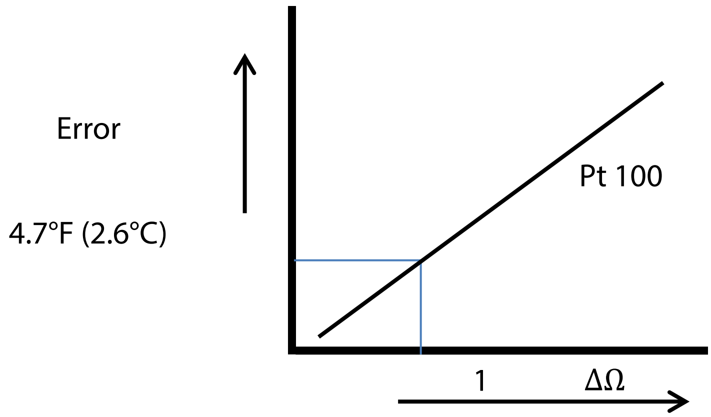


Figure 3. The WORM RTD or thermocouple temperature flexible sensors with flex armor or stainless-steel braid covering the insulating jacket.

Effects of RTD extension wire on accuracy

The 1,000 Ω platinum RTD "secret." If you must stay with 3-wire RTDs and you have long leads back to the DCS, consider replacing 100 Ω Pt RTDs with 1,000 Ω Pt RTDs. When this is done, the error caused by the resistance imbalance in the lead wire is reduced by a factor of 10.



RTD	0°F	300°F	Span	1Ω Error
100 Ω PT	93 Ω	156.9 Ω	63.9 Ω	1.565%
1,000 Ω PT	930 Ω	1,569.0 Ω	639.0 Ω	0.156%

Figure 4. By replacing 100 Ω Pt RTDs with 1,000 Ω Pt RTDs, the error caused by the resistance imbalance in the lead wire is reduced by a factor of 10

Sensor selection summary

To optimize measurement performance and minimize long-term maintenance expenses, use the following guide for sensor selection:

- Use an RTD when measuring in ranges between -40°C and 850°C (-40°F and 1562°F).
- For temperatures as low as -200°C (-328°F), use a wire-wound RTD.
- Best practice is to use 4-wire and Class A RTDs.
- Make sure sensors are temperature cycled and "aged" for long-term stability.
- When applying RTDs below 0°C and above 600°C, know the process conditions to optimize the build: temperature range, cycling, pressure, flow, media, vibration, and surrounding environmental conditions (chemicals/atmosphere).
- When highest accuracy is needed, use sensor trimming.
- If using 3-wire RTDs with long wire runs, and using 4-wire RTDs is not possible, replace the 3-wire RTDs with 1,000 Ω platinum RTDs.

- For temperatures above 850°C (1,562°F), use thermocouples.
- If using thermocouples, use premium-grade thermocouples and extension wire.
- Make sure long thermocouple extension wire is noise protected.
- Replace contaminated T/C extension wire with remote I/O.

Final thoughts

All temperature measurements, whether used for temperature indication or process control, begin with the sensor. Thermocouples and RTDs are the most common temperature sensors used in industrial applications. Temperature transmitters, remote I/O, and temperature concentrator modules eliminate expensive T/C and RTD extension wire and other point-to-point wires by sending temperature measurements, process monitoring, and control signals between the field and control room on a digital communication link.

Refer to Moore Industries Temperature Reference Guidebook for more information.

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Gary Prentice is vice president of sales at Moore Industries. He manages all of the company's sales activities and responsibilities, including direct sales management of Moore Industries' international offices located in the United Kingdom, Belgium, The Netherlands, China, and Australia.