It's HOT! Darn HOT! Real HOT!

A move to lights-out plant management requires highly reliable sensor data as companies squeeze out people.

Thermocouples are extremely important to the operation of turbine engines. Although they are the most rugged and reliable temperature sensors available, thermocouples experience decalibration or drift while in service.

There is no reliable way to tell when thermocouple drift begins to occur or to determine its magnitude or direction. Decalibration is not only a problem for turbine engine operators.

The uncertainties resulting from thermocouple “drift” cost industry millions of dollars each year in off-quality product, less-than-optimum yields, underutilized capacity, unnecessary emergency shutdowns, reduced equipment life, and safety and emissions problems.

Two major improvements to thermocouple technology have developed. A new mineral insulated metal-sheathed (MIMS) cable has developed that is superior to the one commonly used to make the thermocouples used in turbine engines.

Tests show that thermocouples made with this new cable have greater signal stability and three to four times the life of standard thermocouples.

Building on this technology, dynamically self-validating sensors that eliminate unreliable readings altogether and warn before the onset of drift are now available.

**Sheathed Thermocouple Complex**

Temperature is one of the most important variables measured in industry. Often temperature measurements are critical to the safe operation of a device or process. Frequently they are crucial to the output of the process—the throughput or capacity, quality, yield, energy efficiency, or emissions often depend on reliable temperature measurements.

Thermocouples and resistance temperature detectors (RTDs) cover a wide range of temperatures and provide different degrees of reliability and accuracy. Good correlation exists between temperature and voltage output or resistance change of several standard thermocouple and RTD designs.

Using carefully formulated standard materials and sophisticated polynomial relationships embedded in electronic signal conditioners, quite accurate estimates of temperature are possible.

However, the sensors themselves are subject to change or decalibration when placed in service—drift. Although some causes of drift are identifiable and are somewhat predictable, such as the positive shift of type-K (or E) thermocouples between 700°F and 1000°F, most are not.

Attempts to predict the onset, magnitude, and even direction of decalibration in thermocouples have been largely unsuccessful.

Dr. Richard Anderson and co-workers at Oak Ridge National Labs conducted landmark experiments that demonstrated that different types of materials could interact with each other to produce drift.

He also demonstrated that different kinds of drift errors contribute to the overall errors in thermocouple signals.

Commonly reported thermocouple drift performance data reflects only errors of the first kind, where tests took place with the thermocouple in a fixed position. Drift measured in this way gives a much too optimistic view of thermocouple stability.

Thermocouple errors of the second kind, where the thermocouple may move with respect to the temperature gradient, can...
produce large errors even when the thermocouple junction is at a constant temperature.

Basically Dr. Anderson concluded that the sheathed thermocouple is a complex system at elevated temperatures. It can begin drifting anytime after beginning service, and the direction and magnitude of the drift depends on many factors that one cannot quantify or predict.

There are many examples where sensors have provided misleading information that led to costly misfortunes—explosions, fires, or releases. Misleading sensors don't always result in catastrophes. But inaccurate sensor data causes process inefficiencies costing industry millions of dollars every year in less-than-optimum performance.

Engineers have employed several techniques to try to detect failing or incorrect sensors to improve the effectiveness of automated process controls. Further advancements in sophisticated model-based controls and a move to lights-out plant management will require highly reliable sensor data as companies try to squeeze the most out of their investment with the fewest people and operate as close to equipment constraints as possible.

**DRIFT IS NOT DETECTABLE**

Current thermocouple technology has a well-promoted set of strengths. Thermocouples are rugged, have a wide range of configurations, cover wide temperature ranges, and are relatively inexpensive.

Developers have made significant advancements in electronic signal conditioners used to process the measurements into the estimate of the temperature.

However, current thermocouple technology has a not so well understood set of problems. One problem is installation errors. If one isn't careful with hookups, connections, insertion depths, and eliminating outside interference, one can unknowingly introduce significant errors into the system.

Even diligent users, who check and recheck calibrations, can incur inconsistencies and the effects of insertion depths.

The major problem, however, is the gradual decalibration of the sensor elements causing signals to drift at unknown time, rate, and direction. The uncertainties surrounding decalibration are not always quantifiable or removable by even the most sophisticated electronic signal conditioning units and smart transmitters.

RTDs have very high accuracy in the ranges in which they function, but they are also subject to decalibration. Although the causes of decalibration of RTDs are different, they too are unpredictable and not detectable.

**DECALIBRATE WITHOUT DETECTION**

Over the years a number of improvements to thermocouple and RTD technology have taken place.

The materials have improved, and professionals have developed industry standards (ASTM, DIN) for performance of materials and also for the construction of sensors. Advances in electronics have led to better signal conditioners that can check themselves to be sure they are operating properly.

Despite these refinements, we have not been able to reliably predict or monitor the performance of these sensors when in service—especially when they perform under conditions that stress the materials.

The challenge then is how to construct a sensor so that the performance and health of its internal components continuously relay to monitors outside the device. Self-validation, then, is the ability to measure the process variable, in this case temperature, with a high degree of confidence and at the same time determine whether the materials producing the signal representing that variable are stable or showing signs of impairment.

This is sometimes called self-calibrating, self-correcting, self-diagnosing, dynamically self-validating, or simply an SVS.
Now there are temperature sensors that are capable of self-validation. This technology evolved from combining a set of known technologies in a new way and has resulted in a uniquely designed thermocouple-like probe. Externally the probe looks and feels like a normal thermocouple or RTD and can be a direct replacement in most processes. One constructs it using similar techniques. It is rugged and robust; it bends, welds, and configures just like a typical metal-sheathed thermocouple.

However, imbedded in the tip of this new probe is a combination of thermally sensitive materials—a calibration reference matrix (CRM). A CRM provides all the information needed to develop a far more accurate temperature estimate than a thermocouple and also continuously monitor the health of the probe and its components while it is in service.

An electronic signal conditioner multiplexes several measurements taken from the probe and monitors the health of each individual element in the probe. In addition to the temperature, the signal conditioner provides sensor health status to the operator or control system and notifies of impending loss of measurement validation before it occurs.

No element in the sensor can decalibrate without detection. This is a major breakthrough in contact temperature measurement technology.

To build such a probe and achieve satisfactory life and stability, developers required better materials than are currently used for thermocouples and RTDs. A mineral insulation superior to magnesium oxide (used in 90+% of MIMS sensors) and aluminum oxide (the other 10%) was required. This led to the development of a new mineral insulation material called MI-Dry.

**INSULATING PROPERTIES DIMINISH**
To discuss the advantages of MI-Dry, one requires some grounding in the causes of thermocouple sensor decalibration. The temperature measurement in a thermocouple is derived from the now-famous observation by Tom Seebeck in 1821 that when two dissimilar electrically conductive materials are joined at one end, and that end is maintained at a different temperature than the open end, a voltage or electromotive force (EMF) is generated across the open end.

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**Harsh turbine engine test**

An accelerated comparison stress test of sensors made with the new mineral insulation material and those made with MgO took place at 1200°C.

The test was conducted using a Lindberg box furnace with an upper temperature limit of 1371°C. A 22-inch long ceramic tube was inserted through a hole in the furnace door, with the tip of the tube located 5 inches from the back interior wall of the furnace.

Sensors were bundled together and wrapped with platinum wire to keep them in thermal equilibrium. The sensor bundle inserted into the ceramic tube to a point where the tip of the bundle was one-half inch from the end of the ceramic tube.

The ceramic tube was held in place with two ring stands and appropriate clamps to keep the ceramic tube at a fixed location during the test.

Five type-K sensors were bundled together with a type-S working reference standard and held in a constant temperature zone of the furnace at 1200°C until all had failed.

Analysts registered sensor outputs daily and compared them to the type-S working reference standard. The working standard had previously been calibrated versus a NIST-traceable primary reference type-S sensor. The test samples were type-K sensors in Inconel 600 sheaths. Three well-known companies manufactured the sensors using MgO mineral insulation and sold them as within special limits of error tolerances.

Two were manufactured using MI-Dry as the mineral insulation and were as close in design dimensions to the three purchased sensors as possible. Special limit wires were on board the MI-Dry sensors.

The 1200°C test temperature is near the upper limits of use for the materials in a type-K sensor, but below the high-end temperature of Inconel 600 so that this did not become a sheath test.

The test protocol defined that any sensor with two consecutive daily readings outside standard limits of error would be unacceptable for industrial use and therefore disqualified. These sensors were manufactured to perform within special limits of error.

The mean-time-to-failure of the two dry sensors was four times as long as the three MgO sensors. In addition they were still indicating within special limits of error at the time of their failure. The new technology insulating material demonstrated superior performance to MgO.

Separately, a major turbine engine manufacturer has also performed cycling tests of the dry sensors. The tests simulated accelerated turbine engine operating condition temperatures and cycles.

The test covered 18,181 cycles between 300°F and 2150°F over 2,597 actual hours that simulated about 150% of the normal engine cycles and 500% of the time at maximum temperature.

There were at least 10 other type-K MIMS sensors in the test. At 18,181 cycles the test ended. All the sensors had failed except the dry sensor.

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**Utility savings**

<p>| Gas turbine—Houston-based utility (80 Mw unit, $35/Mw) |</p>
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<th><strong>Opportunity</strong></th>
<th><strong>Benefit</strong></th>
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<td>Unused capacity</td>
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<td>Maintenance S/Ds</td>
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<td>False trips</td>
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<td>Equipment life</td>
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Further, Seebeck observed that the voltage correlated with the magnitude of the difference in temperatures of the two ends. We now know that the EMF does not generate at the junction of the two materials, but rather along the length of the two materials as the temperature changes from one end to the other.

This makes it very important to have materials with consistent composition from one end to the other so that the same signal generates regardless of the positioning of the temperature profile.

It is also important that the electrical insulation surrounding the wires in a thermocouple be stable to protect them from contamination and also to avoid shorting or short-circuiting the wires.

The primary mechanism for thermocouple decalibration and impairment is inhomogeneity in the wires caused by a change in composition of the wires. This is frequently due to migration of impurities within the sensor from wire to wire or sheath to wire.

Small changes in composition cause changes in the EMF signal generated by the wire pair and can cause errors in the temperature estimate. Impurities may also come from the mineral insulation.

Magnesium oxide (MgO) is the mineral insulation used in 90% of the metal-sheathed thermocouples made today. Pure MgO is a good insulator. A problem with MgO is that it is hygroscopic—it readily takes up and retains water.

Any moisture absorbed by the MgO decreases its insulation resistance and aids in the transport of ions within the sensor from wire to wire or sheath to wire. Moisture also contributes to corrosion of some materials used in thermocouples.

Moisture can enter during the manufacturing process when the cable is open to form the thermocouple junction and to expose the lead wires. Moisture can enter if there is a leak in the sheath or thermocouple housing and the thermocouple is stored for some time before use.

Without great care in manufacturing techniques, the insulating properties of MgO can easily diminish.

**RESISTANCE TO CORROSION**

The new mineral insulation is an extremely stable high-performance ceramic made specifically for use in mineral insulated metal-sheathed cables used to make thermocouples and RTDs.

Unlike MgO, this material is nonhygroscopic. It also has higher electrical resistance properties than MgO. And manufacturers can fabricate it as cable in the same manner as MgO.

This new material not only has superior electrical resistance, but it blocks the diffusion of trace elements into thermo-element wires. Because it is nonhygroscopic, the new material reduces the ingress of moisture into the cable interior.

This significantly increases resistance to corrosion and other processes that promote thermocouple decalibration. The new ceramic itself is noncorrosive to metals up to 2000°C, whereas MgO will react with most metals above 480°C.

It exhibits negligible reaction with conducting wires or other materials up to 1300°C. The insulation resistance of thermocouples fabricated from MiDry is about 100 times higher than conventional MgO insulated thermocouples or cable, preventing virtual junction and shorting errors.

Thermocouples made with this new mineral insulation material have demonstrated greater signal stability and three to four times the life of similar sensors made with MgO. It

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**Behind the byline**

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