RELIABILITY ASPECTS OF TEMPERATURE MEASUREMENT

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ABSTRACT

Temperature is the most widely measured variable in the process industries. Measurements are typically made using a sensor (usually a thermocouple or an RTD) and a signal conditioning circuit (either a transmitter or a channel of an input card to a DCS or PLC) to amplify the sensor's low level (ohm or mV) signal to a more robust current (such as 4-20mA) or voltage (1-5V) signal.

Combined with a field connection head and thermowell components, the sensor and the signal conditioner are called a temperature system or assembly. Systems are available to meet a variety of measurement accuracy and stability requirements. Some applications need only be within a rather loose ±20 °F (±11°C) of the actual measurement, while others call for extremely tight measurements of up to ±0.025 °F (±0.01°C). Long-term measurement stability varies from 10 to 20 °F (5.5 to 11°C) of span per year, to those providing better than 0.08 °F (0.044°C) of span per year.

This paper will explore the recommendations, the pitfalls, and the trade-offs for various temperature measurement systems. Guidelines will be presented for selecting the proper sensor and signal conditioner to meet a variety of applications. Design of high reliability systems for use in Safety Instrumented Functions (SIF) within Safety Instrumented Systems (SIS) will also be covered.

INTRODUCTION

Even though it is such a common process variable, temperature is one with the most misunderstood as to how to make a reliable measurement. Based on hundreds of interviews with plant personnel about how they make temperature measurements, it is clear that most users believe they are making a better measurement than they are in reality. When determining measurement precision, accuracy and drift characteristics must be considered for both the sensor and the transmitter.

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

While the sophistication of electronics has improved dramatically over the years, the basic fact that measurement is only as good as its weakest link has (and will) endure forever. The sensor is almost always the weakest link in modern temperature systems. And while I/O subsystems (DCS or PLC cards) have reasonable specifications, they are no match for the performance of today's quality temperature transmitters.

Most still get confused on when to use a Resistance Temperature Detector (RTD) vs. a Thermocouple (T/C). The cost/performance trade-offs of using transmitters vs. direct wiring to a receiver is also widely misunderstood.

For Safety Instrumented Systems (SIS), the guidance provided by the standards suggests a thorough understanding of the reliability aspects of making a stable and dependable measurement.

RELIABILTY ASPECTS OF SELECTING A SENSOR:

- For temperatures ranging from cryogenic to about 800 °F (427°C), an RTD is preferred over a T/C. While RTD's where once more expensive, today the cost difference between the two is negligible. There are those who still make their own thermocouples and cram them into a well with the expectation that it is "good enough". However, where accuracy, drift and long life are concerned, the wise user buys a quality sensor from a reputable manufacturer.
- An RTD provides greater accuracy, stability, and lifespan. Over its useable range, a standard grade RTD provides more than twice the accuracy of a T/C. To better understand this concept, consider the materials of construction. A T/C is constructed from two dissimilar metals welded together. The resultant junction begins to deteriorate immediately. The effect is faster at higher temperatures and can result in an unpredictable drift of several degrees per year. An RTD is constructed from highly purified platinum that has extraordinary stability. RTD's drift just fractions of a degree per year. An RTD used under 800 °F (427°C) will last many years, while a T/C is often replaced much more often when accuracy is a concern. This definitely tips the scale for installation costs in favor of the RTD.
- Spring-loaded sensor assemblies provide faster response. T/C's and many RTD's are tip sensitive, with the active element being in the bottom ¼- inch of the sensor. Forcing this tip against the bottom of the well decreases the time constant of the measurement. There is a

new sensor design now on the market that has a sensor sheath length of just 1 inch instead of the traditional designs where the sheath runs the length of the well. It is spring-loaded to keep it pressed against the bottom of the well, which dramatically reduces the time constant. A sensor installed into a well with temperature conductive grease improves the response even further. These considerations of construction and installation greatly minimize the time response difference between a T/C and an RTD, while also providing increased vibration resistance. The assembly's thermowell is the dominant factor in thermal inertia. The metal well adds mass surrounding the actual sensor, thus 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. The fastest response is obtained by using an exposed sensor. However, these are typically only used in low-risk or "dry" applications, like air ducts, where there is no danger of process fluid leakage.

- High grade RTD's more closely match the published curve for temperature vs. resistance, and deliver a better long-term drift specification. RTD manufacturers perform a sorting process after manufacture, and grade their sensors into categories of precision. They are categorized as to how closely they match the established curve of resistance vs. temperature. A common industrial grade sensor is within 0.06 % of the actual curve. Low cost manufacturers usually provide 0.1% sensors, while a quality manufacturer can provide 0.04% or even 0.01% sensors. Whatever this offset may be, the more advanced temperature transmitters have the ability to trim or match the sensor to their transmitter. This sensor-to-transmitter matching advantage allows a precise measurement without the added cost of a premium sensor.
- The welds that join the RTD sensing element to the lead wires are considered the weak links. A quality manufacturer uses the finest precision welding equipment to create a secure and durable joint. As with most products, it what's inside that counts.
- RTD's manufactured using Thin Film Technology are gaining in popularity vs. the more common wire-wound construction. They are manufactured with a platinum film deposited on a substrate that is then precision trimmed using a laser to an exact resistance of 100 ohms or 1000 ohms. Their lower mass contributes to a lower susceptibility to vibration damage to lead/sensor welds. They are less expensive than wire-wound models and their lower mass improves time response. They cannot, however, withstand temperature extremes or cycling applications. It is important to specify the process operating range of the sensor since a quality manufacturer will condition the sensor over that range by subjecting it to repeat cycles in a temperature bath to stabilize its performance. Operation outside of this range will cause an offset. Reconditioning is then required to restore the sensor's performance specifications.
- Wire-wound RTD's are usually a better choice for widely cyclic applications, for cryogenic applications below -200°F (-100°C) and for high temperatures above 1000°F (600 °C). Special lead extension wires are required for high temperatures, and thermocouples are often selected for high temperature applications where high accuracy is not required.
- Cushioned sensor construction provides longer life in high vibration applications. The cushioning is provided by a special polymer fill in the sensor sheath instead of the typical magnesium oxide filler. This polymer fill adds significantly to the time response characteristic of the sensor and is therefore not a wise choice where fast response is

important. Polymer fill is limited to about 600°F (315°C). Where high temperatures are involved or where speed of response is important, a wire-wound sensor or a precision T/C are the choices.

- Use of extension wire increases the susceptibility to electrical noise and RFI (Radio Frequency Interference) for both T/C's and RTD's. Leads act as antennas, gathering in stray signals. While shielding will help with EMI (Electro-Magnetic Interference), it provides minimal protection to the short wavelengths of RFI. A transmitter with an RFI immunity specification of about 20 volts/meter will adequately filter out these effects. I/O subsystems typically are far less RFI tolerant.
- Long runs of extension wire invite failure from physical damage and corrosion, and shorts or open circuits. For an RTD, shorts or open leads will be sensed by a quality signal conditioner that will drive the output to an extreme (upscale or downscale) to alert the receiver of the condition. For a T/C, a short becomes a second measurement junction in parallel with the original T/C. The measurement may appear to be within range when, in reality, the actual temperature of the process could be anywhere. This type of fault is termed a non-diagnosed dangerous failure and should be avoided in safety critical applications. In Safety Instrumented Functions, a measurement error in excess of 2% is considered a dangerous failure and is typically undetectable by diagnostics.
- The accuracy specification for T/C extension wires is typically twice as low as the T/C itself, resulting in lower overall accuracy of the system. Four-wire RTD extension wires have no effect on the accuracy of the measurement. Three-wire systems are susceptible to the effects of terminal corrosion as previously described and should be avoided. It would not be uncommon to discover 5 to 10 ohms of corrosion difference between the leads, resulting in an error of about 23 to 47 °F (13 to 26°C) in 3-wire systems.
- T/C extension wire degrades over time and therefore has an unpredictable contribution to measurement drift. Yearly drift of 10 °F (5.5°C) or more is common. Knowledgeable users know that T/C extension wire has a finite life and should be replaced. Some do this on five-year schedules while others disregard replacement tolerating the errors.

RELIABILITY ASPECTS OF SIGNAL CONDITIONING:

- A transmitter using a 3-wire measuring circuit assumes that the resistance in the two outer legs of a 3-wire RTD is the same. While the extension wires may be quite close in resistance, the effects of terminal corrosion may develop a resistance differential of several ohms. These circuits introduce additional error at each sensor termination point before reaching the signal conditioner (temperature transmitter). The imbalance in a 3-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.
- 4-Wire RTD's, used with transmitters that incorporate 4-wire measurement circuits, are immune to the effects of terminal corrosion. The forth wire provides a path for a high impedance voltage measurement across the sensing element, independent of the resistance of the outer leads. They, in fact, may be different by several thousand ohms with no negative effects. Moving up to 4-wire RTD's is no longer a concern since they are now about the

same price as 3-wire models. In fact, high volume manufacturers produce only 4-wire sensors and, if the user insists on using a 3-wire RTD, either clip off or tie back the 4th lead.

- Direct wiring to a DCS or PLC introduces several reliability issues:
    - Many I/O cards do not support "true" 4-wire RTD inputs (refer to negative aspects of using 3-wire circuits described above).
    - Long wiring runs subject the signal to EMI, RFI, potential for 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 addresses all of the issues above to provide a superior measurement.
- A transmitter differentiates between an "out-of-range" condition and a "sensor failure" drive condition by driving the 4-20mA signal upscale or downscale. For example, the transmitter will drive to 21.4mA for an over-range condition and over 23.6mA for a sensor failure (3.8mA and 3.6mA respectively for downscale drive). For safety related systems, this feature allows the safety PLC to trigger a "failed sensor" alarm instead of a "shut-down" command, thus eliminating a false trip. A false trip always has severe implications of danger and/or economic impact.
- A transmitter with a Failure Mode Effects and Diagnostic Analysis (FMEDA), as calculated by an independent agency, offers a far higher expectation of reliable performance than a generic model. This report provides Safety Failure Fraction (SFF) and Probability of Failure on Demand (PFD) numbers that may be used in calculations to determine the Safety Integrity Level (SIL) of a measurement function. (For additional information, reference Moore Industries' FMEDA Report for their model TRY PC-Programmable Temperature Transmitter)
- A temperature assembly, where the sensor is close-coupled to the transmitter, provides the least potential for introduction of error. The copper extension wire used to carry the 4-20mA signal is rugged enough to last the life of the installation, and the 4-20mA signal is far more immune to EMI and RFI. Purchasing a complete assembly provides single-source responsibility for a quality measurement. A single purchase order is always less expensive than two or three when buying separate components.
- A temperature assembly includes the spring-loaded sensor, the well, associated fittings, the housing and the transmitter itself. It may also include factory calibration and/or sensor-transmitter trimming.
- There are many considerations that come under the heading of "calibration".
    - Off-the-shelf components from reputable suppliers will meet the accuracy needs of many applications. To determine total calibrated accuracy, remember to include all of the possible sources of error. 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 T/C, 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.
    - Where plant policy demands calibration certification by an outside agency such as NIST, a vendor provided calibration is usually required. The vendor will properly

configure the instrument and verify its operation over the specified range. A certificate of compliance is shipped with the transmitter (NIST guidelines require that this certification be renewed every 12 months). The sensor is the limiting factor to the accuracy obtainable with this method. The transmitter very closely matches the published curve for a sensor. Varying grades of sensor will deviate from the ideal curve. The system can only be as good as the sensor tolerance at best case.
    - The ultimate performance is obtained by matching the sensor to the transmitter. This is accomplished by connecting the sensor to the transmitter and then using a precision temperature bath to capture two points on the curve. For high temperature systems using a T/C, the temperature standard is a precision controlled oven. Optimally, these points are chosen to bracket the operating point. Accuracies of ±0.025°F (±0.014°C) for RTD systems and ±2°F (±1.1°C) for T/Cs are typical. NIST certificates are also supplied with this method. When using a transmitter with this feature, there is little benefit to paying extra for precision sensors since the trimming function eliminates the error. It makes no difference if the error is 1% or 10%.
- Many plants have existing temperature measurements that should be upgraded to better serve process demands or to add a measure of reliability for a Safety Instrumented System. It is rarely required to continue making the measurement using the same technology because “we have always done it that way”. There is an alternative:
    - For direct-wired sensors connected to a remote host where the poor performance has been recognized, a retrofit system using a temperature assembly may be the answer. The original sensor is replaced with a proper temperature sensor/transmitter assembly (using the same thermowell and connection head if desired). The high-level 4-20mA signal is then sent over the previously installed extension wire back to the control room. The signal is now connected to a high-level input channel instead of the previous T/C or RTD channel. Upgrades from T/C’s or 3-wire RTD’s to 4-wire RTD’s and/or calibrated systems are simple and cost effective. Extension wire does not care if it is carrying mV, µA or mA, so the same extension wire is just fine. In fact, even old degraded T/C extension wire that should be replaced is okay. It may not serve well for tiny mV signals, but is more than adequate for a high level 4-20mA signal. The cost of re-pulling new T/C extension wire could easily pay for a new temperature system.

SYSTEM DESIGN CONSIDERATIONS

The benefits of using temperature transmitters instead of DCS or PLC I/O begin at the design level and carry through as reduced cost of ownership. It is a shortsighted user/contractor who considers only purchase cost when buying equipment. The cost of ownership over the long haul is usually many times the cost difference between the high and low bids.

THE SAVINGS BEGIN AT THE DESIGN LEVEL:

- 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 draftsman has only one type of symbol to use for the field device and only one type of wire type to show in the P&ID and bill of material. There is no need for differentiating between several T/C or RTD types.
- Only one kind of extension wire need be specified, and it can be bought in larger quantity lots to reduce costs. Copper wire is far less expensive than T/C or RTD extension cable.

THE SAVINGS CONTINUE DURING INSTALLATION:

- Inventory of installation materials is reduced.
- There is only one type of extension wire to install. The common mistakes of using the wrong type of T/C extension wire are eliminated.
- Two-conductor copper cables are less expensive and easier and faster to install.
- There are fewer opportunities for error since all connections are 4-20mA using standard terminal blocks vs. T/C blocks or 3-terminal RTD blocks.
- Verification of wiring is quicker and less prone to errors than ringing out low-level signal cables.

COST OF OWNERSHIP LASTS A LIFETIME:

- Fewer spares are required. The universal transmitter is the same for all measurements and all ranges. I/O card requirements are restricted to just high-level (4-20mA) and discrete.
- There is no need to periodically replace T/C extension wire.
- Maintenance is reduced since high-level signals are more tolerant of corrosion and interference from EMI or RFI.
- Temperature system calibration is simplified. A single assembly can be calibrated as a system for maximum performance. Remote sensors usually preclude this option.

CONSIDERATIONS FOR SAFETY RELATED SYSTEMS

- A system design team will logically select loop components offering the highest reliability. While 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 a comfort factor that the instrument will operate reliably, and provide the appropriate data that can be used in SIL calculations. If the vendor can provide long-term PIU data, the confidence factor increases. Selection of a transmitter without FMEDA data forces the user to use generic average data in his calculations. This generic data is by nature quite conservative and may force a redundant architecture configuration that could have been avoided by using an instrument with good FMEDA data.

- Since each component of a loop must be included in an SIL calculation, a temperature sub-system must include both the sensor and the signal conditioning device. As presented above, the most reliable configuration is a close-coupled sensor with the transmitter. At this writing, only one manufacturer has provided FMEDA data for such complete temperature assemblies.
- Direct wiring of a sensor to the I/O sub-system of a safety PLC should be avoided for several reasons:
  - Direct wiring requires long runs of extension cable that carry the burden of higher susceptibility to EMI, RFI, ground loops and physical damage than does 4-20mA cable.
  - 4-wire RTD systems provide immunity to lead wire resistance imbalance typically caused by terminal corrosion in 3- wire systems. No safety PLC currently offers I/O cards that accept 4-wire RTD inputs. Recall that lead imbalance in 3-wire circuits causes an error of 4.7 ° F (2.6°C) per ohm and that a 2% of span error is considered to be a non-diagnosed dangerous failure.
  - A PLC measurement is made over 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 sub-systems.
  - For precision measurements, a sensor must be calibrated/matched to the transmitter. This is almost impossible with a remote sensor configuration.
  - The standards provide guidance for SIS that suggests periodic proof testing of all loop components. A single bench test of a close-coupled temperature assembly is quick and conclusive. Verification/calibration of a remote sensor, its connecting cabling and a single channel of the I/O sub-system is a momentous task. The sensor would have to be removed from service and immersed into a temperature bath in the field environment while connected to the extension wire and the remote I/O channel. Should NIST certification be required, a temperature assembly is the only reasonable choice. Some users save down time by pre-calibrating a spare assembly and just performing a quick exchange in the field on a rotational basis
- The safety PLC (or host machine) should be programmed to differentiate between an over range condition and a sensor failure. It is assumed that most systems would trigger an alarm for a failed sensor and a shutdown for an over range. Nuisance shutdowns for sensor failure are typically costly and potentially dangerous.
- For high reliability SIL 2 applications, a dual architecture is typically required unless a temperature sub-system can demonstrate a Safety Failure Fraction (SFF) greater than 90%.
- Transmitters using HART protocol offer a significant opportunity for increased diagnostic coverage when they are used in conjunction with HART loop monitors. The increased functionality and enhanced diagnostic coverage are significant considerations in safety related systems.

ADDITIONAL CONSIDERATIONS

- 4-20mA signal cables should always be twisted and shielded with the shield wire connected to a proper ground system at only one end (usually at the control room).
- All signal cable should be physically separated from power and switching circuits to avoid cross-talk interference.
- Smart HART transmitters offer the opportunity for additional Layers Of Protection (LOP's) by offering remote diagnostic capability that is over and above that of any on-board diagnostics that simply drive the 4-20mA current output to a specified value. HART transmitters have a much more complete diagnostic capability that will change the state of specified bits for various diagnosed conditions. These status changes are encoded into the HART data signal that is superimposed onto the 4-20mA signal. HART loop monitoring back in the control room can extract this information and provide alarm relay input to the PLC. A technician can then pinpoint the specific failure condition using the Hand Held Communicator (HHC).
- For loops where field shutdown contacts are preferred to save long cable runs from the control room for start-stop commands, a combination alarm/transmitter device may be used. One vendor offers a product that provides four relay outputs, local indication, sensor diagnostics and an isolated 4-20mA output to meet this need.
- Some plants are subject to electrical surges and spikes from lightning or switched electrical equipment. For susceptible cable runs, protection must be installed at both ends of the line to mitigate the destructive effects. Several vendors offer surge suppression devices that mount into the transmitter housing. Other models that snap into DIN rails in the I/O rack protect the system input cards. Having a line protected at both ends provides protection for all but the most direct hits.

CONCLUSION

Temperature measurement technology continues to improve. Filled system pneumatic transmitters have given way to electronic models. Sensor performance and reliability has increased dramatically. Electronic measurement circuits have progressed from the 8-bit designs of the 1960's, to the 22-bit designs of 2001. Transmitted signals have evolved from the 3-15 psig pneumatic signals, to 4-20mA 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 can communicate over an Ethernet link directly to a web page. (However, existing standards do not support digital transmission for SIS installations.)

It is critical to select the proper sensor for each application. It has been demonstrated that the most reliable temperature measurement is achieved by using a close-coupled temperature assembly with a 4-wire thin film RTD and a transmitter supported by FMEDA data. Direct connected sensors may be fine for some applications where trends and not absolute values are being monitored. For most other applications, there is no benefit and inferior performance is assured. Most often, there is also a cost penalty from a cost–of-ownership point of view.

With the rapid increase in technologies and higher performance products, it is important that designers, engineers and users understand the latest technological advances so that they may make the best choices for their applications. The leading vendors have a wealth of application guidance to offer. It is not appropriate to trust the “we have 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.

REFERENCES

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