The Engineer's Guide to Industrial Temperature Measurement

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EMERSON™

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The Engineer's Guide to Industrial Temperature Measurement

PREFACE

This handbook provides a thorough discussion of the considerations for selecting the proper measurement system for a wide variety of applications and conditions. The engineered system selection guidelines are suitable for almost every industrial application.

INTRODUCTION

Temperature is the most widely measured variable in the process industries. Temperature is often a critical factor in industrial processing. If a temperature measurement is not accurate or reliable for any reason, it can have a detrimental effect on such things as process efficiency, energy consumption, and product quality.

Even a small measurement error can be disruptive or very costly in some processes, so it's extremely important to be certain your temperature measurements are accurate and reliable. Pharmaceutical processing is an example where an inaccurate temperature measurement might ruin a batch of product worth hundreds of thousands of dollars. For this reason, each measurement system needs to be evaluated and carefully engineered to satisfy the requirements of the process.

In a Safety Instrumented Function in a SIS, poor performance could be deadly, costly or both and an error of 2 % is considered a dangerous non-diagnosed fault. An example might be a process that can go exothermic and possibly explode if temperature is not measured and controlled accurately.

Another example of where an accurate measurement has enormous cost consequences is custody transfer where the amount of material that is bought and sold (referred to as custody transfer) is based on a measurement of the volumetric flow rate of gas. The amount of material contained in a specific volume of gas decreases with rising temperatures and increases with falling temperatures. Therefore, it is extremely important to know the exact temperature of the gas when determining volumetric flow rate. Inaccurate temperature measurements during custody transfer applications result in over- or undercharging of customers. This can directly impact a customer's financial performance. A natural gas custody transfer application is one example of where accurate temperature measurements are required.

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 4-20mA current 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 ±11 °C (±20 °F) of the actual measurement, some look for trends and accuracy is not as important, while others call for extremely tight measurements of up to ±0.01 °C (±0.025 °F). Long-term measurement stability varies from 5.5 °C to 11 °C (10 to 20 °F) of span per year for non-critical measurements, to those providing better than 0.044 °C (0.08 °F) of span per year for the most critical applications. In all cases, the degree of precision of the measurement is limited by the sensor choice.

This handbook 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.

Examples of operations where accurate and reliable temperature measurement are important include:

- Pharmaceutical bioreactors
- Various chemical reactors
- Distillation columns
- Absorbers
- Crystallizers
- Solid state component manufacturing
- Custody transfer

2 – Frequently Asked Questions

1 – **How to choose the right sensor technology (RTD or T/C)** *(See 4.3.3.1)*

2 – **What is the recommended insertion length for a thermowell?** *(See 4.3.2.2.5)*

3 – **What is the best way to calculate the accuracy of the entire temperature measurement system?** *(See 3.1.4.2)*

4 – **How to choose the correct thermowell** *(See 4.4.2.4.1)*

5 – **What are the recommended grounding best practices?** *(See 4.2.5.2.4.1)*

6 – **What are the sensor lead wire color standards that should be followed?** *(See 3.2.3.10 and 3.2.4.5)*

7 – **How to choose the proper transmitter** *(See 3.1.2.4.1)*

8 – **What benefits can be gained by using transmitter diagnostics?** *(See of 5.11.1)*

9 – **Why should long sensor wires be avoided and what are the alternatives?** *(See 4.5.3.2)*

10 – **What is the benefit of transmitter-sensor matching?** *(See 4.4.3.1.7)*

11 – **What are the thermocouple temperature ranges?** *(See 3.2.4.4)*

12 – **What are the recommendations for high accuracy measurements?** *(See 3.1.1)*

13 – **How to protect the measurement from noise interference** *(See 3.1.2.4.1)*

14 – **What are Best Practices for Calibration?** *(See 5.7.2)*

3

Temperature Measurement Basics

TOPIC PAGE

3.1 Transmitters

3.1.1 Overview

For the purpose of this handbook, we will confine our discussion to industry standard Intelligent or Smart transmitters as are manufactured by virtually every leading manufacturer. These are microprocessor-based instruments with enormous capabilities for signal processing as compared to the analog transmitters that were the mainstay for many years. In the days of pure analog devices, functions such as calibration, ranging, zeroing, and damping were set using potentiometers. A screwdriver and multi-meter were the tools used to communicate with the transmitter. These devices required frequent maintenance and were limited to communicating only one piece of information via a signal that could drift and suffer offset from electrical interference. This often created an "on-scale" failure, where the process variable appears to be valid, but is in fact false.

These analog transmitters evolved over the years from using discreet components like transistors and diodes into using "chips" or "chip sets" and finally what we now refer to as microprocessors. While analog models are still available from some manufacturers, they have a declining position in the industrial process market.

A variety of devices are used to measure temperature. These devices, referred to as sensors, are discussed in detail in the Sensors chapter in this handbook. Smart temperature transmitters accept signals from all industry standard sensor types of Resistance Temperature Detectors (RTDs) and Thermocouples (T/C). Transmitters also can accept millivolt and resistance signals.

The transmitter converts the measurement input signal to a high level robust 4-20 mA output signal. Some models have a digital signal output for connection to a remote device or system.

Transmitters are available in a variety of housing styles and enclosures, and are available in many different materials of construction. Refer to Figure 3-1. They may be mounted integrally with a sensor/thermowell assembly at the process measurement point and transmit either a hard-wired or wireless signal. Alternatively, they can be mounted remotely from the sensor assembly in any of several types of enclosures. They can be configured locally or remotely and can provide local indication. They have an array of standard and optional performance features to provide remarkable functionality. Systems may be provided to meet virtually any agency approval requirement.

Figure 3-1 – Transmitter Styles

WHAT ARE THE RECOMMENDATIONS FOR HIGH ACCURACY MEASUREMENTS?

As discussed in Chapter 3.1, selection of a high end microprocessor based transmitter will afford superior performance and a wide array of optional features that can greatly enhance measurement integrity, performance and accuracy.

Proper selection, calibration and installation of the sensor assembly are additional critical components of measurement system accuracy.

A more precise compensation for RTD inaccuracies is provided by Transmitter-Sensor Matching using the transmitter's factory programmed Callendar-Van Dusen equation. While this matching is typically not required for all process measurements, it is the clear choice for those measurements requiring the best possible accuracy.

Refer to:

4.4.3.5 – Guidance Review for Ensuring Optimal System Performance and Accuracy

3.1.4.3 – Sensor Related Accuracy Factors

3.2.3.11 – RTD Accuracy/Interchangeability

3.1.4.3.3 – Transmitter-Sensor Matching

3.1.2 Transmitter Anatomy

Transmitters accept a variety of measurement signals (RTD and T/C for example), process them, and provide a robust output signal. Not all are designed and perform equally. Each major manufacturer incorporates their own engineering expertise gained from months or even years of research and development. This Intellectual Property (IP) sets the higher quality transmitters apart from the others in their ability to process the measurement signal to provide an accurate and stable output signal. The following sections provide a high level overview of common functions of a high quality transmitter.

Transmitters incorporate three subsystems; the input subsystem converts the sensor measurement signal into a digital signal (called Analog-to-Digital conversion or A/D); the signal conditioning subsystem accepts this digital signal and performs various conditioning and mathematical manipulations to produce a digital representation of the temperature measurement; and the output subsystem that converts this digital signal to a robust analog output signal (D/A). Refer to Figure 3-2. The following discussion provides further insight.

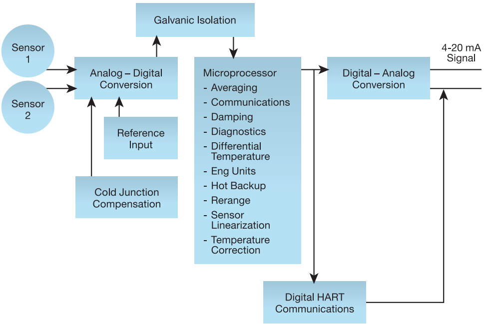


Figure 3-2 – Transmitter Functional Block Diagram

3.1.2.1 Inputs

The real world analog signals from measurement sensors are converted to digital signals using a sampling technique with a precisely known internal reference voltage. The more bits of resolution that the A/D uses the more precise will be this conversion.

The most common sensor inputs for temperature measurement are Resistance Temperature Detectors (RTDs) and thermocouples (T/Cs). Additional inputs are millivolt (mV), ohm, and potentiometer. Refer to Figure 3-3. A discussion of each type follows.

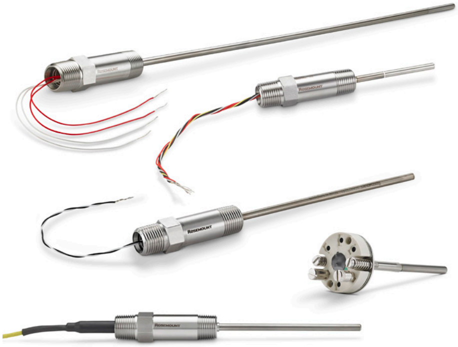


Figure 3-3 – Typical Sensors

3.1.2.1.1 RTD Inputs

Resistance temperature detectors (RTDs) are based on the principle that the electrical resistance of a metal increases as temperature increases – a phenomenon known as thermal resistivity. Thus, a temperature measurement can be inferred by measuring the resistance of the RTD element.

RTDs are constructed of a resistive material with wire leads attached and usually placed into a protective sheath. The resistive material may be platinum, copper or nickel with the most common by far being platinum. Platinum sensors range from 100 Ω (Ohm) to 1000 Ω and are available as two, three, or four wire constructions.

Refer to section 3.2.3 for a detailed discussion of RTDs.

3.1.2.1.2 Thermocouple Inputs

A thermocouple (T/C) is a closed-circuit thermoelectric temperature sensing device consisting of two wires of dissimilar metals joined at both ends. A current is created when the temperature applied to one end or junction differs from the other end. This phenomenon is known as the Seebeck effect, which is the basis for thermocouple temperature measurements.

One end is referred to as the hot junction whereas the other end is referred to as the cold junction. The hot junction measuring element is placed inside a sensor sheath and exposed to the process. The cold junction, or the reference junction, is the termination point outside of the process where the temperature is known and where the voltage is being measured. This cold junction is typically in a transmitter, control system input card or in a signal conditioner.

Transmitters accept inputs from most common industry standard T/C types including types J, K, E, T, R, and S. Many models can also accept the types B and C and Type N, which commonly serves as an alternative to Types R and S.

Refer to section 3.2.4 for a detailed discussion of T/Cs.

3.1.2.1.3 Millivolt Inputs

Millivolt signals are prone to voltage drop losses and noise pickup and need to be converted in the field to robust 4-20 mA current signals for transmission to receiving instrumentation. Millivolt output signals are very common in analysis instrumentation. Additionally most strain-gauge based transducers and load cells are assigned units of measure for weight, force, tension, pressure, torque, and deflection with a full-scale value measured in mV/V of excitation. For example, a load cell with a 10-V excitation supply and a 2-mV/V-gain factor generates an output of 20 mV at full load, whether the load cell was designed to handle 10, 100, or 1,000 lbs. Another example of mV output is a Hall Effect transducers, which are typically used in tachometers, contactless switches, magnetizers and compasses and in devices for position, tilt/level, pressure, and thickness measurements.

3.1.2.1.4 Potentiometer Inputs

Potentiometers are basically a variable resistance device where a pickup or “wiper” slides along the resistance in accordance with some external physical movement, thus developing a variable resistance output to the transmitter. They are used in a variety of devices to provide position feedback. There are rotary, linear, helical, and string styles. They can be found in speed controls, conveyer controls and in some processing and laboratory equipment.

3.1.2.1.5 Resistance Inputs

Pure Resistance change signals are found in some strain gauges and other bridge circuits.

3.1.2.2 Isolation

An installed measurement loop will very often have two ground level potentials. One is at the point of measurement where the sensor is in contact with the process, which in turn is connected to the local ground. The other ground is usually the signal ground, which is most often at the receiving instrument in the control room. These grounds will rarely, if ever, be at the same potential. If there is a galvanic path between the two grounds, a current will flow dependent on the difference between the two ground voltage potentials. This is referred to as a ground loop and will have a varying and unknown effect on the output signal, causing potentially significant error. Most transmitter designs incorporate a means of galvanic isolation, using either optic or transformer isolation stages to eliminate this problem.

An isolated transmitter also has provision to block both normal mode and common mode voltages that may inadvertently come in contact with the measurement circuit. Faults in field equipment can inject ac voltages of 120 V, 240 V or even higher into the process equipment and grounded thermocouples, shorted RTDs and cable shields can carry this voltage to the transmitter. High voltage can also be induced by welders, motor starters, lightning strikes and other switchgear. The isolation provided in the transmitter front end will block these voltages preventing them from travelling to the control room ground system, causing potentially lethal conditions.

With this isolation being applied, a safe digital signal is presented to the signal conditioning stage.

3.1.2.3 Single, Dual and Multipoint Transmitters

All transmitters allow for at least one sensor input. However, some temperature transmitters have a dual-input capability, allowing them to accept inputs from two sensors simultaneously. Dual sensors provide a more reliable measurement through sensor redundancy and by detecting sensor drift and they can also provide a measurement of differential or average temperature of the two sensors. See Figure 3-4.

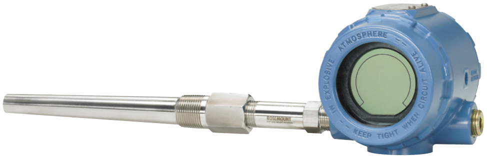


Figure 3-4 – Transmitter with Single or Dual Inputs

Multi-input temperature transmitters accept up to eight sensor inputs and are useful in applications where many temperature measurement points are concentrated in one area, known as high density transmitters. See Figure 3-5.

Figure 3-5 – Multichannel Transmitter

High density transmitters minimize installation costs in applications such as heat exchangers, boilers, chemical reactors, and distillation columns. They are also often used for temperature profiling of furnaces and reactors. See Figure 3-6.

For more information on multipoint sensors, refer to section 3.1.11.1.

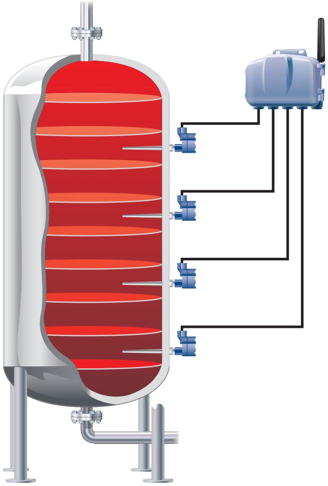


Figure 3-6 – Temperature Profiling a Reactor

3.1.2.4 Signal Conversion and Conditioning

In this stage, the digitized raw temperature measurement signal is filtered, linearized and otherwise mathematically manipulated to yield an accurate representation of the measured temperature.

These processes will be discussed in detail in the following sections.

3.1.2.4.1 Noise filtering

Virtually every plant environment contains electrical interference sources, such as pumps, motors, Variable Frequency Drives (VFDs) and radios, as

HOW TO CHOOSE THE PROPER TRANSMITTER

Transmitters accept a variety of measurement signals (RTD and T/C for example), process them, and provide a robust output signal. Not all are designed and perform equally. Each major manufacturer incorporates their own engineering expertise gained from months or even years of research and development. This Intellectual Property (IP) sets the higher quality transmitters apart from the others in their ability to process the measurement signal to provide an accurate and stable output signal.

A smart transmitter generally provides a more accurate and robust temperature measurement than is provided by direct wired I/O systems. A smart transmitter provides signal isolation, filtering, linearization and sensor type or sensor specific compensation to the measurement before sending the value to the host system.

Transmitters are available in a variety of housing styles that may be mounted into any of a wide selection of enclosures that are available in many different materials of construction. They may be mounted integrally with a sensor/thermowell assembly at the process measurement point and transmit either a hard-wired or wireless signal. Alternatively, they can be mounted remotely from the sensor assembly in any of several types of enclosures. They can be configured locally or remotely and can provide local indication. They have an array of standard and optional performance features to provide remarkable functionality. Systems may be provided to meet virtually any agency approval requirement.

Refer to:

3.1.2.3 – Single, Dual and Multipoint Transmitters

3.1.3 – Output Options

3.1.4 – Transmitter Performance

3.1.5 – Stability

3.1.6 – Intelligent Filtering Features and Options

3.1.8 – Diagnostics

3.1.10 – Transmitter Styles; Housings and Mounting Options

3.1.11 – Transmitter Options

3.1.12 – Safety Certified Transmitters

4.5.4 – Advantages of Using Transmitters vs. Direct Wiring well as sources of electrostatic discharge and other electrical transients. A transmitter is designed to reject common mode and normal mode interference as well as provide a high degree of immunity to Electromagnetic Interference (EMI), Electrostatic Discharge (ESD), and Radio Frequency Interference (RFI).

3.1.2.4.2 Linearization

All T/Cs and RTDs have a nonlinear output vs. temperature relationship. If this relationship was ignored, significant errors would result, especially for wider ranges. The transmitter applies a linearization technique that greatly reduces the errors caused by the nonlinearities of sensors, thus providing a much more accurate measurement.

The relationship between the resistance change of an RTD vs. temperature is called its Temperature Coefficient of Resistance (TCR) and is often referred to as the RTD's alpha curve. (Refer to section 3.2.3 for more detail.) The transmitter is configured to provide a linear output to compensate for the difference between the alpha curve of a sensor and an ideal straight-line relationship. How closely a sensor's alpha curve matches this ideal straight-line relationship is referred to as its class. For example, a Class A sensor has a closer tolerance than a Class B sensor and will provide a more accurate measurement. See also sensor matching below and in section 3.1.4.3.3 and see Figure 3-7.

HOW TO PROTECT THE MEASUREMENT FROM NOISE INTERFERENCE

Virtually every plant environment contains electrical interference sources, such as pumps, motors, Variable Frequency Drives (VFDs) and radios, as well as sources of electrostatic discharge and other electrical transients. Low level sensor signals from RTDs and T/Cs are very susceptible to Electromagnetic Interference (EMI), Electrostatic Discharge (ESD), and Radio Frequency Interference (RFI).

Sensor leads act like an antenna for noise interference, causing potentially very large errors in the measurement. The longer the leads (the antenna), the greater will be the noise pickup. A transmitter is designed to reject common mode and normal mode interference as well as provide a high degree of immunity to EMI, ESD and RFI. Where possible and practical, transmitters should be mounted close to the measurement point to minimize potential noise pickup by the sensor leads. This is especially important for low level T/C signals which are especially susceptible to noise.

3.1.2.4.1 – Noise filtering

4.5.4 – Advantages of Using Transmitters vs. Direct Wiring

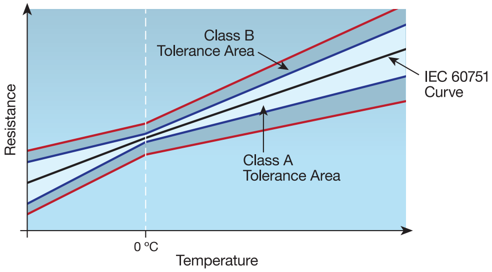


Figure 3-7 – IEC 751 Ideal vs. Class A vs. Class B Tolerance Graph

For each type of T/C, there is a corresponding curve of the relationship between the emf generated by the T/C hot junction and temperature. The transmitter is configured to linearize this relationship. See Figure 3-8.

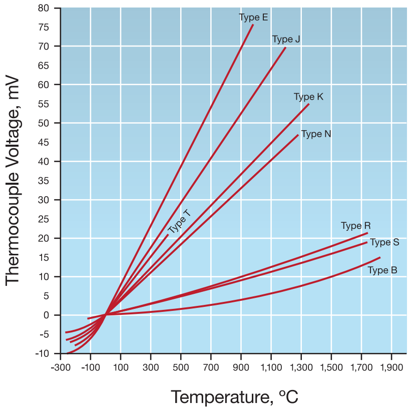


Figure 3-8 – T/C emf vs. Temperature Curves for Popular T/C Types

3.1.2.4.3 Cold Junction Compensation (CJC)

The voltage measured at the cold junction correlates to the temperature difference between the hot and cold junctions; therefore, the temperature at the cold junction must be known for the hot junction temperature to be calculated. This process is known as "cold junction compensation" (CJC).

CJC is performed by the temperature transmitter, T/C input cards for a control system, alarm trips, or other signal conditioner. Ideally, the CJC measurement is performed as close to the measurement point as possible because long T/C wires are susceptible to electrical noise and signal degradation.

Performing an accurate CJC is crucial to the accuracy of the temperature measurement. The accuracy of the CJC is dependent on two things: the accuracy of the reference temperature measurement and the proximity of the reference measurement to the cold junction. Many transmitters use an isothermal terminal block (often made of copper) with an imbedded precision thermistor, an RTD or an integrated circuit transistor to measure the temperature of the block. Refer to Figure 3-9.

TIP: Refer to section 4.5.4 for a detailed discussion of why it is preferable to use field transmitters vs. direct wiring the sensors over long distances to a control room.

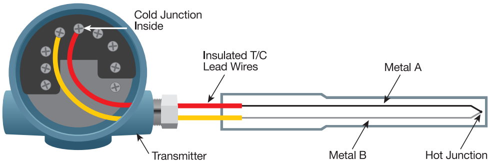


Figure 3-9 – Cold Junction Compensation

Summary of Transmitter Anatomy

A smart or microprocessor-based transmitter performs a succession of operations upon the measurement signal to condition it to provide an accurate and stable digital signal to the output stage. The operations that are performed are quite sophisticated and are often proprietary to the specific manufacturer.

3.1.3 Output Options

After the signal conditioning functions as described above are completed, the isolated, filtered, linearized and compensated digital signal reaches the final transmitter stage of conversion to a robust analog signal for transmission over potentially very long distances to the control room. This analog-to-digital conversion provides a highly accurate signal with excellent noise immunity as compared to the weaker and noise susceptible signals coming directly from the sensor. Further insight is provided in section 4.5.

For many years, an analog output signal had been the industry standard approach for communicating signals to a control system, individual controllers or recorders. As digital circuit technology matured, industry began to adopt the concept of using digital communication from field devices in addition to the analog signal or as an alternative to the analog signal.

In the 1980s, the HART® protocol was introduced that enhanced the analog signal functionality by providing access to more field device data and the ability to manipulate certain parameters. It also offered a rudimentary digital networking capability.

In the late 1980s and into the 1990s, several different digital fieldbus technologies were launched globally with the intent of distributing the control architecture to the bus and the field devices.

In the new millennium, wireless technology has evolved to serve as a viable protocol for transmitters. It complements the existing HART protocol by providing access to more data in those hard-to-reach locations.

3.1.3.1 Analog Current

Industry standard 4-20 mA analog signals are used globally to communicate with field mounted devices over long distances. These robust signals are highly resistant to electrical interference. Typically 4 mA represents 0% of the measured value and 20 mA represents 100%. Signals outside of this range indicate a system abnormality or failure condition. Current from the 0 mA to 4 mA portion of the signal range is used to provide operating power to the loop device. This is commonly referred to as a loop-powered device. In a current loop, the signal is not affected by the voltage drop of long cable runs or junction boxes.

HART®
COMMUNICATION PROTOCOL

3.1.3.2 HART

The HART (Highway Addressable Remote Transducer) protocol is a digital protocol that provides for the superimposing of a digital signal onto the 4-20 mA signal wires. This superimposed digital signal allows two-way communications for configuration and for extracting operational and alarm data from

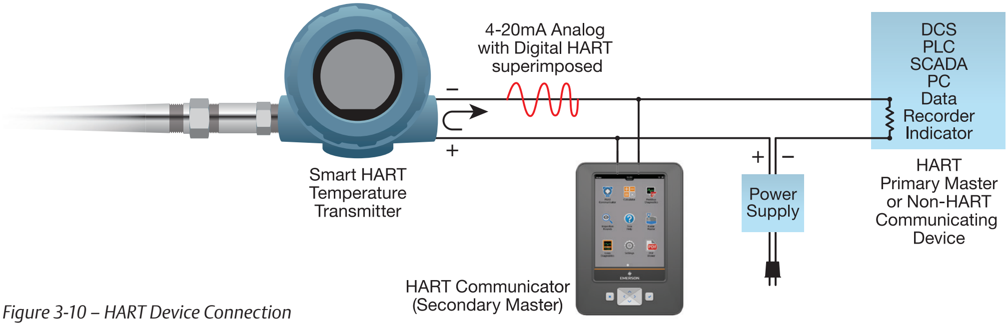


Figure 3-10 – HART Device Connection

the transmitter. Refer to Figure 3-10. HART protocol is widely accepted and utilized throughout the world. Using HART, along with the 4-20 mA signal, offers enhanced diagnostics options including status and alarm data that can be useful for maintenance or process analysis.

On a very basic level, field configuration tools can access any of this information by request one instrument at a time. An alternative solution to accessing this information exists on a higher level where this data can be accessed continuously from all field devices simultaneously using fieldbus or HART-enabled multiplexors interfaced with the DCS and/or an asset management system.

3.1.3.3 FOUNDATION™ Fieldbus

FOUNDATION Fieldbus is an all-digital, serial, two-way communications system that can serve as the base-level network in a plant or factory automation environment. It is an open architecture, developed and administered by the Fieldbus Foundation.

It's targeted for applications using basic and advanced regulatory control, and for much of discrete control associated with those functions. FOUNDATION Fieldbus technology has been widely used globally in the process industries.

Fieldbus installations may use any or a combination of field topologies where measurement and control devices are distributed throughout the plant to best meet the needs of the application. These topologies connect to an I/O rack and then to the plant control highway using a network of high speed ethernet cables, junction boxes, device couplers and power supplies. Refer to vendor documentation for additional detail.

3.1.3.4 PROFIBUS®

Profibus is an international fieldbus communications standard for linking process control and plant automation modules. Instead of running individual cables from a main controller to each sensor and actuator, a single multi-drop cable is used to connect all devices, with high speed, bi-directional, serial messaging used for transfers of information. Profibus DP is used for discrete signals and has had extensive use in factory automation applications. Profibus PA is used for analog process control signals and has gained widespread use in the process control industry. Both protocols may be connected together using a coupling device. Similar to FOUNDATION Fieldbus, Profibus networks use a distributed system of measurement and control devices connected to a plant control highway. Refer to vendor documentation for additional detail.

3.1.3.5 *Wireless*HART®

*Wireless*HART is an open-standard wireless networking technology developed to complement the existing HART standard. The protocol was defined specifically for the requirements of process field device networks and utilizes a time synchronized, self-organizing, and self-healing mesh architecture. Refer to Figure 3-11. The protocol currently operates in the 2.4 GHz ISM Band using IEEE 802.15.4 standard radios. It is backward compatible with existing HART systems and configuration tools allowing for easy adoption with minimal training. As with the HART devices described above, the information embedded in the HART signal may be accessed by field devices or HART-enabled I/O systems and processed by the DCS and/or an asset management system.

Figure 3-11 – WirelessHART Network

It is especially useful in remote and hard-to-reach locations throughout a plant (remote storage tanks or pipelines, for example) where installing wiring over long distances, under/over roadways and railroad tracks etc. would be very expensive. See Figure 3-12.

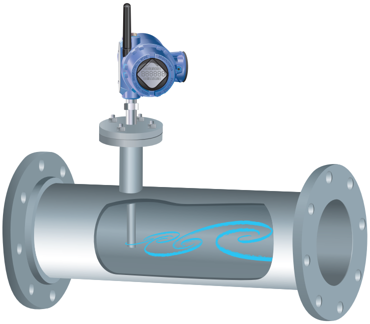


Figure 3-12 – Wireless Remote Mount Pipeline Installation

Output Options Summary

In summary, transmitters have three primary stages. The input stage provides the A/D conversion of the analog sensor signal to a digital signal that is passed to the second stage for signal conditioning and mathematical manipulation. The third stage converts the digitally processed signal back into an analog signal in the D/A converter for output to the receiving device. High quality transmitters incorporate years of expertise into their designs. This Intellectual Property is what sets them apart from lesser quality products.

3.1.4 Transmitter Performance

3.1.4.1 Temperature Measurement Performance Factors

Temperature measurement system performance is influenced by a number of factors in reporting process temperature measurements, including accuracy, stability, internal conditions, intelligent filtering, response time and diagnostics.

3.1.4.1.1 Accuracy

Accuracy of a temperature measurement system is the degree of closeness of the measurement of a temperature to that temperature's actual (true) value.

3.1.4.1.2 Repeatability

The repeatability of a measurement system, also called precision, is the degree to which repeated measurements under unchanged conditions show the same results.

As an example, an instrument could present the same value for temperature every time (under the same measurement conditions), but the value is offset from the correct value. This is repeatable, but not accurate. The ideal measurement therefore would be both accurate and repeatable.

For those familiar with target shooting, a marksman could tightly cluster his shots on the target (repeatable), but the cluster may not be in the bull's-eye. (Accuracy) The ideal situation is to have all the shots closely clustered in the bull's-eye. (This result is both accurate and repeatable). See Figure 3-13.

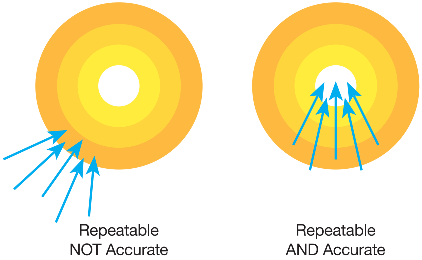


Figure 3-13 – Accuracy vs. Repeatability

WHAT IS THE BEST WAY TO CALCULATE THE ACCURACY OF THE ENTIRE TEMPERATURE MEASUREMENT SYSTEM?

Refer to:

3.1.4.2 – Error Calculations

Worst Case Error (WCE) is the largest possible error expected under the anticipated conditions. These calculations are a summation of the raw values of reference accuracy, digital temperature effect, and ambient temperature effects on the input and output.

Total Probable Error (TPE) is a calculation that reflects the probable error of the transmitter and sensor system, based on anticipated installation conditions. The components of this calculation include the root sum square of the multiple transmitter and sensor accuracy effects.

See also:

3.1.4.2.1 – Example Error Calculations

3.1.4.3 – Sensor Related Accuracy Factors

3.1.4.3.3 – Transmitter-Sensor Matching

4.3.4.1 – System Error Analysis

3.1.4.1.3 Input Accuracy

The input accuracy (also called digital accuracy) is unique for each sensor input. For example, the input accuracy of an RTD is about ±0.1 °C (0.18 °F) for a high quality transmitter. The input accuracy of a T/C varies by T/C type from about ±0.2 °C (0.36 °F) up to ±0.8 °C (1.44 °F).

There are many factors that affect the accuracy of a transmitter, including ambient temperature compensation, CJC and sensor selection.

3.1.4.1.4 Output Accuracy

This is a statement of the accuracy of the D/A converter stage given as a % of span. (Typical is 0.02% of span.)

3.1.4.1.5 Ambient Temperature Compensation

Both input and output accuracy will vary with fluctuations in the ambient temperature of the transmitter. This is referred to as the ambient temperature effect. Typical errors for a 100Ω platinum RTD (α =0.000385) for each °C change in ambient temperature are 0.0015 °C (0.0027 °F) for the input and 0.001% of span for the output. These errors are as compared to a reference ambient temperature (specified by the manufacturer) of 20 °C (68 °F). T/Cs have similar data.

Transmitters are characterized during manufacturing over their specified operating range to compensate for these fluctuations to maintain measurement accuracy and stability. Typical transmitter ambient temperature range is -40 to 85 °C (-40 to 185 °F).

3.1.4.2 Error Calculations

Worst Case Error (WCE) is the largest possible error expected under the anticipated conditions. These calculations are a summation of the raw values of reference accuracy, digital temperature effect, and ambient temperature effects on the input and output.

Total Probable Error (TPE) is a root sum of the squares of multiple error producing factors affecting the accuracy. It is based on anticipated installation conditions.

3.1.4.2.1 Example Error Calculations

For a 4-20mA HART transmitter when using a Pt 100 (α =0.000385) sensor input with a 0-100 °C span operating at an ambient temperature of 30 °C (86 °F), the following statements would be true: (Using the typical error data listed above in 3.1.4.1.4 and 3.1.4.1.5 and as found in a product data sheet)

3.1.4.2.1.1 Digital Temperature Ambient Change Effects (Input Error)

Input Error = (Ambient temperature effect) x (Change in ambient)
= (0.0015 °C/ °C) x (30°- 20°)
= 0.015 °C (0.027 °F)

3.1.4.2.1.2 D/A Ambient Change Effects (Output Error)

D/A Effects = (Transmitter D/A Spec from data sheet) x (Temp span) x (Change in Ambient Temp)
= 0.001%/ °C x Temp Span x (Amb Temp – Cal Temp) °C
= 0.001%/ °C x 100 °C x (30-20) °C
= 0.001%/ °C x 100 °C x 10 °C
= 0.01 °C (0.018 °F)

3.1.4.2.1.3 Worst Case Error (WCE)

WCE = Digital (Input) Accuracy + D/A (Output) Accuracy + Ambient Change Digital Temp Effects + Ambient Change D/A Effects
= Input error + Output error + Ambient change effect on input + Ambient change effect on output
= 0.1 °C + (0.02 %span/ °C) (100 °C) + 0.015 + 0.01
= 0.1 °C + 0.02 °C + 0.015 °C + 0.01 °C
= 0.145 °C (0.261 °F)

3.1.4.2.1.4 Total Probable Error (TPE)

(For 100 °C span and using specifications from a typical product data sheet)

TPE = √ (Transmitter specified digital input accuracy)^2 +(Output (D/A) error spec)^2 + (Ambient change effect on Input)^2 + (Ambient change effect on output)^2
= √ (Digital)^2 + (D/A)^2 + (Dig Temp Effects)^2 + (D/A Effects)^2 °C
= √ (0.1)^2 + (0.02)^2 + (0.015)^2 + (0.01)^2 °C
= 0.1 °C (0.18 °F)

3.1.4.3 Sensor Related Accuracy Factors

3.1.4.3.1 – Cold Junction Compensation (CJC) is crucial to the accuracy of the temperature measurement when a thermocouple is used. Since the accuracy of the CJC depends primarily on the accuracy of the reference temperature measurement, a precision thermistor or platinum RTD is commonly used to determine this temperature.

3.1.4.3.2 – Proper selection, calibration and installation of the sensor assembly is another critical component of measurement system accuracy. All sensors have inherent inaccuracies or offsets from an ideal theoretical performance curve referred to as sensor interchangeability. Transmitters can compensate for this offset by allowing the user to make adjustments to the factory defined sensor curves stored in the transmitter memory by digitally altering the transmitters interpretation of the sensor input. Factory calibrations can also be performed using either three or five-point data. Refer to Chapter 5 for more information.

3.1.4.3.3 – Transmitter-Sensor Matching – A more precise compensation for RTD inaccuracies is provided by Transmitter-Sensor Matching using the transmitter's factory programmed Callendar-Van Dusen (CVD) equation. This equation describes the relationship between resistance and temperature of platinum resistance thermometers (RTDs). The matching process allows the user to enter the four sensor specific Callendar-Van Dusen (CVD) constants into the transmitter. The transmitter uses these sensor-specific constants in solving the CVD equation to match the transmitter to that specific sensor thus providing outstanding accuracy. Accuracy improvement for sensor matching is typically 7:1. Refer to Figure 3-14 and section 3.2 for a more complete discussion.

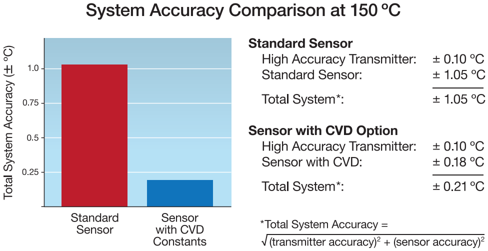


Figure 3-14 – Sensor - Transmitter Matching Comparison

3.1.5 Stability

Stability refers to the ability of the transmitter to avoid drift in order to maintain accuracy over time. It is related to the sensor's measurement signal, which can be influenced by humidity and prolonged exposure to elevated temperatures. Stability is maintained by using reference elements in the transmitter, against which the sensor input is compared. At superior transmitter manufacturers, in order to improve accuracy and stability, every transmitter is fully temperature characterized to compensate for the temperature-dependency of the D/A and A/D in order to improve accuracy and stability.

Stability is often stated in terms of percent of the reading or the expected maximum change in measured temperature in °C or °F over a specified amount of time for each sensor type. Data is typically given for 1 year, 2 years or 5 years. For example: 0.25% of reading or 0.25 °C (0.45 °F) for 5 years (Whichever is greater) is typical for RTDs and 0.5% of reading or 0.5 °C (0.9 °F) for 5 years (Whichever is greater) for T/Cs. Transmitter calibration cycles for high quality smart transmitters can be extended accordingly. See Figure 3-15.

Tip: The stability specification above refers to the transmitter performance and does not include the sensor itself. A well-made RTD is generally considered to be highly stable and will not degrade significantly over time. However, even a well-made T/C will degrade measurably over time and much more quickly at high temperatures. Refer to section 3.2.3 for more information.

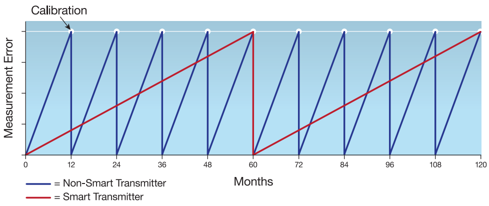


Figure 3-15 – Comparing Smart vs. Non-Smart Transmitter Stability

3.1.6 Intelligent Filtering Features and Options

In most plant environments, surges from lightning or other static discharge are common as are electrical power surges and dips. There can be other hostile conditions caused by vibration, high humidity, high or low ambient temperature, and corrosive atmosphere etc. that can adversely affect transmitter performance as well. Fortunately, many manufacturers have design features and configuration options that address these issues and help to provide a reliable temperature measurement. Many of these are discussed below.

3.1.6.1 Damping

Damping is the amount of time required, in addition to the update time, for the output to reach 63.2% of its final value after a step change has been applied to the input. See Figure 3-16. It is adjustable from 1 to 32 seconds. Damping reduces the effects of electrical noise and any other insignificant transient noise that may influence the transmitter output signal. It is often used to stabilize control loops and prevent false trips. In the absence of electrical or transient noise, damping may not be required since temperature changes in most processes are slow and have inherent lag time in influencing the sensor due to thermowell inertia, etc. Additionally, for fast changing process conditions or to identify runaway conditions as early as possible, damping should be minimized.

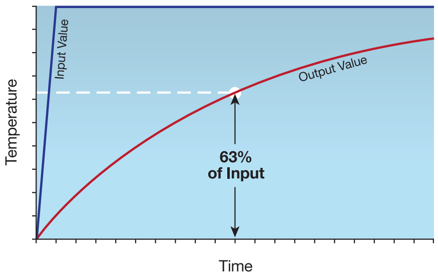


Figure 3-16 – Damping Response Curve

3.1.6.2 Open Sensor Holdoff

The Open Sensor Holdoff option detects a false open sensor condition and performs calculations to determine when the transmitter should send an indication to the control system. For example, the transmitter determines if an open sensor event has actually occurred or a high voltage transient event, such as lightning or electrostatic discharge, has caused a false open sensor condition. To avoid an unnecessary alarm and possible process control disruption, the established temperature value continues to be sent until the transmitter identifies the true source of the condition and takes the appropriate failure action only upon a verified sensor failure. See Figure 3-17.

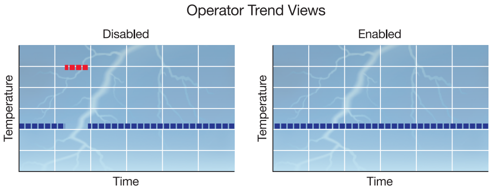


Figure 3-17 – Open Sensor Holdoff

3.1.6.3 Transient Filter

The Transient Filter feature recognizes conditions like high vibration or a noisy environment that may cause incorrect intermittent temperature readings and rejects them. By disregarding these temperature spikes, sensor signal interruption is prevented and the last known reliable temperature continues to be transmitted, thus saving a potential process upset or trip condition. See Figure 3-18.

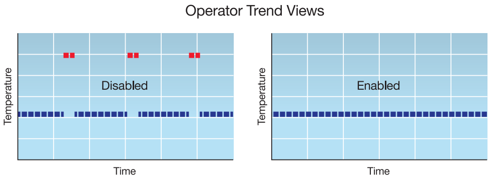


Figure 3-18 – Transient Filter

3.1.6.4 EMF Compensation

In temperature measurement loops using RTDs, small voltages, called thermal EMFs, can be induced on the sensor wires, increasing the effective resistance and causing false temperature readings. Rosemount™ transmitters feature Emerson's patented EMF Compensation, which monitors RTD sensor loops and compensates for the unwanted thermal EMF voltages. As a result, these transmitters deliver more accurate and reliable temperature values.

3.1.6.5 Line Voltage Filter

Noise from nearby 50 or 60 Hz AC voltage sources, such as pumps, variable frequency drives, or power lines, is easily detected by low-amplitude sensor signals. If not recognized and removed, this noise can compromise the transmitter's output signal. A transmitter's Line Voltage Filter can be customized at 50 or 60 Hz to protect temperature measurements from AC voltage interference and to filter out this noise, enabling the delivery of accurate temperature readings. Verify the voltage to be used in the country of installation. See Figure 3-19.

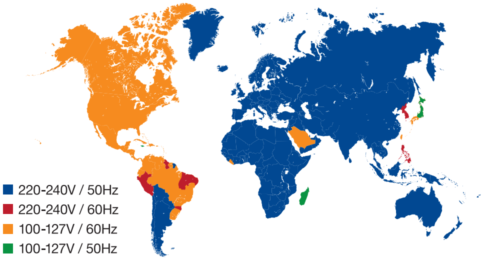


Figure 3-19 – Global Voltage Usage

3.1.6.6 The Hot Backup™ Feature

The Hot Backup Feature is the ability of the transmitter to automatically switch the transmitter input from the primary sensor to the secondary sensor should the primary sensor fail. This prevents a process disruption due to the failure of the primary sensor. A maintenance alert is also generated to notify operators that a sensor has failed and the Hot Backup feature is active. In this way, a critical temperature measurement is not lost, and control is not disrupted. See Figure 3-20.

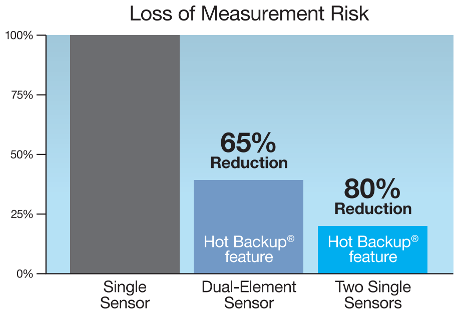


Figure 3-20 – The Hot Backup Feature Prevents Primary Sensor Failure from Disrupting Process Control

3.1.6.7 Sensor Drift Alert

Sensor Drift Alert notifies the control system of the degradation of a sensor that is causing its measurement signal to drift away from the actual value, thus decreasing the measurement integrity. By using two sensor inputs, the difference between the two sensors is monitored. When the difference becomes greater than a value entered by the user, the transmitter sends an alert to indicate a sensor drift condition. See Figure 3-21.

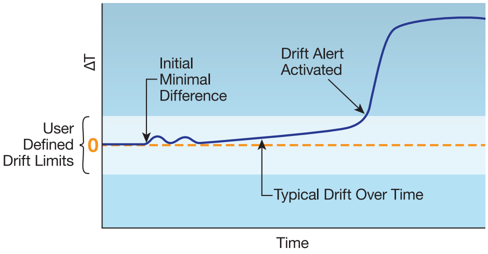


Figure 3-21 – Sensor Drift Alert Detects a Degrading Sensor

3.1.6.8 Thermocouple Degradation

The Thermocouple Degradation feature continually monitors the resistance of the thermocouple loop. If the resistance goes above a certain designated trigger level, an alert is sent suggesting sensor replacement. The degrading thermocouple can be caused by wire thinning, sensor breakdown, moisture intrusion or corrosion and can be an indication of an eventual sensor failure. Identifying this degraded condition prior to a complete T/C failure could prevent an unscheduled process trip and save an expensive unscheduled shutdown.

3.1.6.9 Minimum-Maximum Tracking

Use Minimum-Maximum Tracking to verify installation temperature or to troubleshoot quality issues. This feature keeps records of both the process and ambient temperature values. This enables a user to verify that the internal transmitter temperature has not exceeded recommended limits in areas where the ambient temperature around the transmitter fluctuates substantially. Operating a transmitter above its published maximum operating temperature may cause premature failure and/or invalid outputs. Operating it below its rated ambient temperature may lead to degradation of the accuracy. Also, this Minimum-Maximum Tracking feature records the minimum and maximum temperatures reached by the sensors and their differentials, which can be helpful when troubleshooting product quality issues by indicating whether or not optimal temperatures have been maintained.

TIP: This feature could be very useful for documenting the performance of a transmitter used in a Safety Instrumented loop.

3.1.7 EMI Compliance

Transmitters are designed to withstand and reduce the effects of electromagnetic interference (EMI). This includes the use of shielded circuit cards, shielded housings, proper circuit design, and appropriate parts selection.

Compliance with national or international standards is often required by laws passed by individual nations. Different nations can require compliance with different standards.

For example, by European law, manufacturers of electronic devices are advised to run EMC tests in order to comply with compulsory CE-labeling.

3.1.8 Diagnostics

Transmitters often have diagnostics. There are internal diagnostics that monitor transmitter memory and output validity. Also, there are external diagnostics that check the sensor.

Transmitters initiate either Alerts or Alarms based on these diagnostic processes.

Alerts cover diagnostics that are determined not to affect the transmitter's ability to output the correct measurement signal and therefore will not interrupt the 4-20 mA output. An example is "Process Variable Out-of-Range". See Figure 3-22.

Alarms cover diagnostics that are determined to affect the transmitter's ability to output a correct value of the measurement. Detected alarms will drive the transmitter output either high or low depending on user's choice.

Alerts and alarms can be read on a local indicator (if so specified), on a field communicator or on a HART-compliant monitoring system like an asset management system.

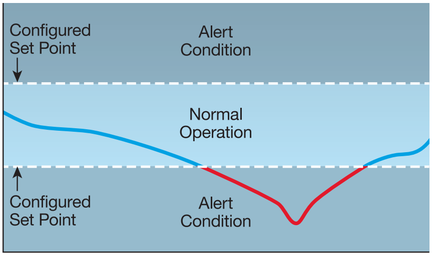


Figure 3-22 – Configurable Process Alerts

3.1.8.1 Internal Diagnostics

Internal diagnostics perform internal checks for corrupted memory. Also, diagnostics check for erroneous fixed outputs due to transmitter processing being stuck in infinite loops. Many of the internal diagnostics are proprietary to the transmitter manufacturers.

3.1.8.2 External Diagnostics

External diagnostics monitor measurement validity due to external sources, such as the sensor wiring connections, noise on the sensor, and sensor failure.

3.1.8.3 Open/Short Sensor Diagnostics

Open/Short Sensor Diagnostics identifies an open sensor connection or a short in the sensor connection and generates an alarm. Open sensors can be caused by shock, vibration, corrosion, wire thinning or fraying. Shorted sensors could be the result of vibration, bent wiring, or contamination. Open or short sensors are the most common sensor failure conditions. This diagnostic is helpful in determining why a measurement point failed.

TIP: This option could be very useful for high vibration applications where sensor failure is more common.

3.1.8.4 Measurement Validation Diagnostic

3.1.8.4.1 Deviation Alarming

Before a sensor fails, it will exhibit signs of degradation such as increased signal noise which will often result in inaccurate on-scale readings. Measurement Validation is a diagnostic that can provide validation of temperature measurement data, ensuring visibility of measurement and process abnormalities before a sensor failure occurs. Measurement Validation monitors the signal noise and uses it to calculate a deviation value indicating the magnitude of the noise which is compared to a user selected alert limit. When this limit is exceeded, the user is notified, allowing action to be taken. Measurement Validation can also detect on-scale failures associated with loose or corroded connections, high vibration and electronic interference, which can contribute to a signal noise increase.

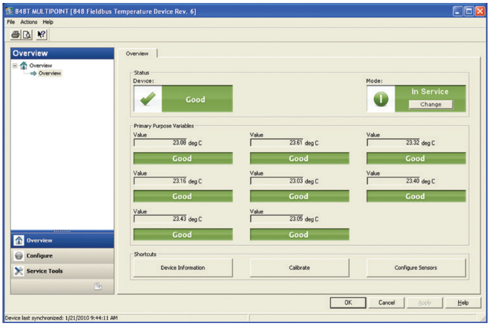
3.1.8.4.2 Rate-of-Change Alarming

In addition to detecting on-scale failures and validating measurement values, Measurement Validation also performs a rate of change calculation, which can be used to identify abnormally fast temperature changes that could indicate a runaway reaction condition even before alarm conditions are met.

3.1.8.5 Diagnostics Log

The Transmitter Diagnostics Logging feature stores advanced diagnostic information between device resets, such as what caused the transmitter to go into alarm, even if that event has disappeared. For example, if the transmitter detects an open sensor from a loose terminal connection, the transmitter will go into alarm. If wire vibration causes that wire to begin making a good connection, the transmitter will come out of alarm. This jumping in and out of alarm is frustrating when trying to determine what is causing the problem.

However, the Diagnostics Logging feature keeps track of what caused the transmitter to go into alarm and saves valuable debugging time. This information is available from the field communicator and/or from an asset management system. See Figure 3-23.



848T MULTIPOINT [848 Fieldbus Temperature Device Rev. 6]

Status

Device: Good

Mode: In Service

Primary Purpose Variables

Value 23.08 deg C Good

Value 23.61 deg C Good

Value 23.32 deg C Good

Value 23.16 deg C Good

Value 23.03 deg C Good

Value 23.40 deg C Good

Value 23.43 deg C Good

Value 23.05 deg C Good

Device last synchronized: 1/21/2010 9:44:11 AM

Figure 3-23 – Typical Diagnostics Log

3.1.9 Response Time Considerations

There are several considerations when analyzing the response time of a temperature measurement system. In most cases, the sensor/thermowell response is by far the limiting factor of any system. There are lag times associated with the sensor itself and for the thermowell into which it is inserted that are usually significant. Refer to section 3.2.3.8 for more detail on sensor response time. The transmitter response to noise and transient filter situations is addressed by the damping adjustment which is adjustable from 1 to 32 seconds and the functionality and adjustment of the transient filter monitoring algorithm. Process temperature changes less than the threshold setting of the algorithm will be reported without delay.

For applications in Safety Instrumented Systems (SIS), the transmitter response is considered to be 5 seconds.

Typical transmitter update time is 0.5 seconds.

Consideration must also be given to the control loop response requirements. For fast changing processes, the control algorithm requires more frequent updates than it does for a slow changing process. Transmitter response plus the damping time must be within the allowable window.

3.1.10 Transmitter Styles, Housing and Mounting Options

There are a variety of choices for mounting a transmitter that are driven by process conditions at the point of measurement, plant standards and policies, and user preference. See Figure 3-24.

Figure 3-24 – Transmitter Family

A methodical approach of reviewing all related factors will very likely present the best choice. Here are some examples of questions that must be answered to drive the selection process.

- Is the ambient temperature expectation at the measurement site within the limits of the transmitter specification?
- Is the measurement site easily accessible?
- Is local temperature indication required? Where can operator see display?
- Is there high vibration at the measurement point?
- What is the area classification? What is the approval agency?
- Does the plant site require Intrinsically Safe (IS) installation?
- Are there sources of EMI, RFI or electrical transients near the measurement point?
- Is this measurement associated with a SIS?
- Is there a sanitary consideration?
- Is there a corrosive environment?

> *TIP: Many times a site inspection and consultation with process engineering and operations will greatly facilitate the choice.*

The most common mounting styles are:

- Head mount
- Field mount or Dual-compartment
- Rail mount

3.1.10.1 Head Mount

Head mount transmitters are compact disc shaped transmitters most often mounted within a connection head which can be field mounted. Most common styles are DIN A and DIN B, which differ slightly in dimensions and mounting method. However, the distance between the mounting screws is identical. See Figure 3-25.

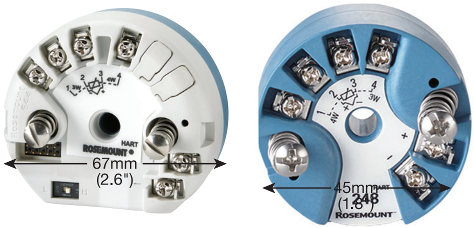


Figure 3-25 – DIN A and DIN B Head-mount Housing Styles

These are commonly mounted in single compartment housings, such as sensor connection heads or junction boxes. See Figure 3-26 and Figure 3-27. They can be mounted integrally with the sensor or remotely from the sensor. For integral mounting, the transmitter housing is threaded directly onto the sensor/thermowell assembly. With the remote mount, the transmitter is installed within a housing on a pipe stand or other support in the vicinity of the sensor assembly.

Figure 3-26 – Head Mount Transmitter Assembly

Figure 3-27 – Head Mount Exploded View

It must be noted that single compartment housings may allow moisture or other contaminants egress through improperly sealed conduit connections. Exposure of the terminal strip and the electronics assembly to these contaminants could potentially cause damage to the transmitter.

3.1.10.2 Dual-Compartment

Dual-compartment transmitter housings, often known as field mount, are a two part housing that isolates the transmitter electronics module from the terminal strip compartment to protect it from exposure to harsh plant environments. The terminal compartment contains the terminal and test connections for the sensor and signal wires and provides access to the terminal block for wiring and maintenance while isolating the transmitter electronics.

The electronic module with an optional display is in the second compartment. Any moisture/humidity or other contaminants that might find ingress into the housing through the conduit connections will be contained in the terminal section and not come in contact with the electronics, thereby greatly reducing the risk of damage from environmental effects. Another benefit is the increased immunity of the electronics from EMI and RFI that may be conducted by the wiring. See Figure 3-28.

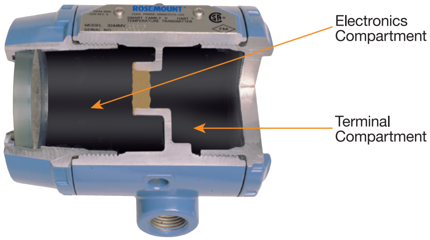


Figure 3-28 – Dual-Compartment Housing

Dual-compartment transmitters can be mounted directly on the sensor assembly or remotely on a pipe stand or other support in the vicinity of the sensor. Remote mounting may be necessary when the measurement point is inaccessible or when the process environment prevents the transmitter from being installed integrally with the sensor. See Figure 3-29.

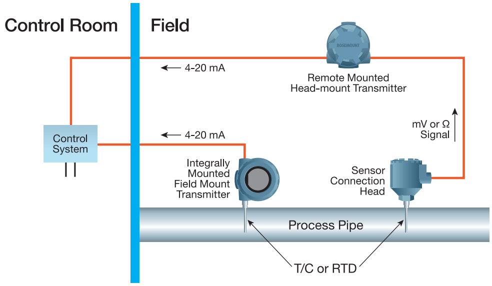


Figure 3-29 – Integral Mount vs Remote Mount Configurations

The transmitter will operate within specifications for ambient temperatures between -40 and 85 °C (-40 and 185 °F). Since heat from the process is transferred from the thermowell to the transmitter housing, if the expected process temperature is near or beyond specification limits, consider using additional thermowell lagging, a nipple union extension, or a remote mounting configuration to isolate the transmitter from the process. See Figure 3-30.

TIP: Because sensor lead wire extensions are comprised of low-grade wiring, which are more susceptible to plant noise, it is best practice to install the temperature transmitter as close as possible to the sensor. The instrument wiring from the transmitter to the PLC or DCS is more robust than the sensor wiring, allowing for temperature measurement and diagnostic information to be transferred across greater distances. In cases where the sensor is installed in inaccessible, high temperature, or corrosive environments, remote mounting of the transmitter is recommended. Remote mounting can provide operators easier access to perform calibration, maintenance, and observe visual readings from the device.

Figure 3-30 – Remote Mount Installation

3.1.10.3 Rail Mount

Rail mount transmitters are thin rectangular transmitters that are typically attached to a DIN-rail (G-rail or top-hat rail) or fastened directly onto a surface. This provides a compact high-density installation where a number of rail mount transmitters can be placed very closely together on the same DIN-rail. Unlike the field mount transmitters, the DIN rail style are not designed for harsh environments nor can they be used in areas designated as explosion-proof. See Figure 3-31.

Figure 3-31 – Rail Mount Transmitters

These rail mount transmitters are usually located in a mild or controlled environment in or near a control room where they are convenient for maintenance and away from harsh process plant conditions. However, when rail mount transmitters are installed near a control system, the sensor lead wires generally run long distances, making these installations much more susceptible to electromagnetic noise (EMI) and RFI.

Another alternative rail mounted option is a Multichannel Rail Mount Transmitter. One or more of these instruments can be mounted into a field enclosure. See Figure 3-32.

Figure 3-32 – Multichannel Rail Mount Transmitters

TIP: While there may be an advantage to using the Rail mount transmitters from a transmitter cost point-of-view, the extra expense of long lead wires (4 conductor for RTDs and T/C extension wire for T/Cs), potentially degraded performance due to EMI and RFI, and for lead-wire deterioration induced drift of T/C extension wires may easily justify using the much more robust field-mount transmitter models. This is especially valid for high accuracy/high stability measurements and for installations in electrically harsh/noisy environments.

3.1.10.4 Sanitary Housings

Applications in the biotech, food, beverage, and pharmaceutical industries often require sanitary housings and enclosures. These are typically manufactured from stainless steel and are sealed and are suitable for the wash-down and sterilization processes demanded by these industries. The surface finish is typically polished to 32 RMA.

The housings may be either head mount or remote mount styles and offer indicating and field configuration options. See Figure 3-33.

Figure 3-33 – Sanitary Housing Transmitter

Housing and Mounting Option Summary

In summary, there are many factors to be considered in the selection of the optimum mounting style and housing. Since any length of connection cable for the sensor input or the output serves an antenna for EMI and RFI, a transmitter directly mounted to the sensor is almost always the better choice. However, as was discussed above, overriding factors of environment and viewability of indicators etc. may suggest remote mount options. Some projects lend themselves to high density rail mount options. For harsh field environments, a dual-compartment housing is far superior to the single compartment housing in protecting the electronics from exposure to humidity, moisture, or other contaminants. Refer to Chapter 4 for additional guidance.

3.1.11 Transmitter Options

There are a variety of additional options and features for a transmitter that may make it easier to use, install, calibrate and maintain. Some of the more popular and recommended options are described below.

3.1.11.1 Dual and Multipoint Options

As discussed in section 3.1.2.3, many transmitters have an option of dual inputs that can be used for redundancy with the Hot Backup feature switching, drift monitoring, differential temperature measurements or T/C degradation monitoring.

Other models are designed to accept up to 4 or 8 individual sensor inputs, each with their own output signal. These may be used for high density measurements such as profiling applications.

3.1.11.2 Local Display

Many models offer a liquid crystal display (LCD) that attaches to the face of the transmitter. There are two types: standard and local operator interface.

3.1.11.2.1 Standard LCD display

The standard LCD displays show the measured temperature, range, engineering units, device status, error messages and diagnostic messages. See Figure 3-34.

Figure 3-34 – Dual-Compartment Transmitter with LCD Display

3.1.11.2.2 Local Operator Interface (LOI) Display

The LOI interface provides the ability for local configuration of the device to make changes in real-time without having to attach a laptop or field communicator. The buttons on the LOI are used to perform the configuration tasks by following a menu of configuration information. When the LOI is not being used for configuration, the display will show the same information as the Standard LCD. See Figure 3-35.

Figure 3-35 – Head-mount Transmitter with LOI

Typical Configuration Menu Selections

- Sensor Type
- 4 mA Value
- 20 mA Value
- Engineering Units
- Damping
- Failure/Saturation Mode
- Line Voltage Filter Frequency

3.1.11.3 Transient Protection

Most high quality transmitters are generally protected by integral galvanic isolation from potential damage from high voltage induced by welders, motor starters, lightning strikes, switchgear and inadvertent exposure to power lines up to 500 to 700 VAC.

However, lightning strikes and other induced transient overvoltage events can cause spikes and surges at much higher voltage levels. Additional protection for receiving devices may be a wise investment for higher risk installation areas. Many transmitters offer transient suppression options that can be integrally mounted onto the terminal strip within the housing. For other transmitters an external protection device may be used. See Figure 3-36.

It is not uncommon for a lighting generated transients hitting the output signal line to propagate towards the transmitter and then be reflected back towards the receiving device. This situation may require additional external devices at the receiver.

TIP: External field mounted suppressors may not carry agency certification for explosion proof applications. A transmitter with an integral style suppressor is suggested for these applications.

TIP: For high risk plant sites, transient protection for all critical instrumentation and control devices may be worth considering.

Figure 3-36 – Terminal Block Transient Suppressor

3.1.12 Safety Certified Transmitters

A Safety Instrumented System (SIS) is defined by the IEC 61511 Safety Standard as an instrumented system used to implement one or more safety instrumented functions. An SIS is composed of any combination of sensors (transmitters), logic solvers, and final elements.

A transmitter to be used for a safety function in an SIS must meet certain design and performance criteria and be certified for use in accordance with IEC 61508.

As an example manufacturers specification: “Certification: The 3144P is certified to IEC61508 for single transmitter use in Safety Instrumented Systems up to SIL 2 and redundant transmitter use in Safety Instrumented Systems up to SIL 3. The software is suitable for SIL 3 application.”

The certification process is performed by an approved third party agency (TUV, for example). The transmitter will have a distinctive yellow tag affixed. See Figure 3-38 in section 3.1.13.

TIP: Tip: A Safety Instrumented Function (SIF) is assigned a Safety Integrity Level (SIL) during risk analysis. All of the components of the SIF are considered together in performing a SIL compliance calculation. The result is that, even though the transmitter is certified up to SIL 2 as a single device, the limitations of the sensor and the valve typically demand a redundant configuration to meet a SIL 2 requirement.

As an alternative, a device that has not been certified but that has a long record of proven-in-use safe operation may be used in a SIS at the user’s discretion. This option requires that the user have detailed failure data for a statistically valid sample of the same model device operating under similar operating conditions. Records must be provided showing the hours of operating usage, the operating environment, the type and frequency of failures. Vendor upgrades to new models may require restarting the time clock on the data.

Best practice indicates that designing your system around an IEC 61508 certified instrument avoids the laborious and expensive record keeping for proven-in-use devices. It should be noted that many vendors offer the same basic product for both process control and safety applications. There is benefit to using the same models as are used in the basic process control system (BPCS) to benefit from the history of installation and operation knowledge that already exists as well as spare parts inventory.

3.1.13 Tagging

Each instrument installed as a functional part of a control system has a unique identification number. Users frequently want a permanent corrosion resistant tag number affixed to the transmitter. See Figure 3-37.

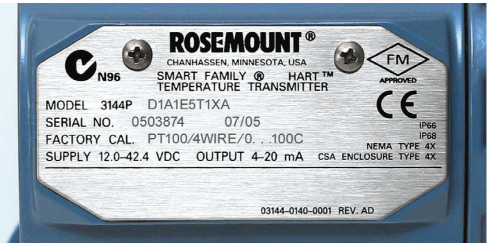


Figure 3-37 – Standard Instrument Tag

Most intelligent transmitters also provide for the tag number to be programmed into its electronics – known as a soft tag – so the transmitter is capable of responding to an inquiry sent via the control system or a communicator. This is very useful during commissioning and troubleshooting to enable easy verification of the identity and/or integrity of each control loop and the functionality of every transmitter. Safety Certified transmitters have a distinctive yellow tag affixed. See Figure 3-38.

Figure 3-38 – Safety Certified Instrument Tagging (Yellow)

3.1.14 Configuration Options

All transmitters must be configured for certain basic variables to operate properly. In many cases, these variables are pre-configured at the factory to default settings. Since these default settings may or may not match the actual loop parameters of your application, user configuration may be required to adjust these variables to the actual process requirements of the specific loop. Configuration may be accomplished in a variety of ways depending on the manufacturer’s options, plant preferences and/or system architecture. They include:

- Hand-held field configurator
- Laptop software program with interface
- Local operator interface (LOI) push-buttons
- Asset management system

TIP: For a complete discussion of transmitter configuration, installation, commissioning and maintenance, refer to chapters 4 and 5 of this handbook.

Options and Features Summary

In summary, regardless of the hostile conditions that might exist at the point of measurement, it is apparent from the descriptions above of available transmitter features and options, a properly specified and configured temperature measurement system can go a long way to ensure that a stable, accurate and reliable measurement is continually reported to the receiving system or device.

3.2 Temperature Sensors

3.2.1 Overview

High process temperature, pressure, and vibration make robust temperature measurement devices a necessity in industrial environments. Accuracy, repeatability, and stability are needed for consistent process control. While several types of temperature sensors may be used, resistance temperature detectors (RTDs) and thermocouples (T/Cs) are most common in the process industry and will be the focus of this section. Temperature measurements comprise the largest segment of all process measurements and can often have the largest impact on production efficiency, quality, and safety. The user must fully understand each application and make the best choice of a temperature measurement system.

We hope that the information and insights presented in this section will provide much of the information required to make informed sensor selections. Refer to Chapter 4 for further discussion about the implications associated with your choice and guidance in designing your complete temperature system.

3.2.2 History of Sensors

RTD sensor technology used today has its roots dating back over a century. The application of the tendency of electrical conductors to increase their electrical resistance with rising temperature was first described by Sir William Siemens at the Bakerian Lecture of 1871 before the Royal Society of Great Britain. The necessary methods of construction were established by Callendar, Griffiths, Holborn and Wein between 1885 and 1900.

T/C technology is based on the Seebeck Effect. This effect is named after the German physicist Thomas Johann Seebeck (1770–1831), who, in 1826, published the results of experiments done four years earlier that opened up the new field of thermoelectricity. He observed that an electrical current is present in a series circuit of two dissimilar metals, provided the junctions of the two metals are at different temperatures. In a T/C, we are using the emf generated by one of the junctions with respect to a reference junction to infer temperature. The Peltier effect, first exhibited by Jean Peltier in 1834, is viewed as the compliment to the Seebeck Effect and describes the ability to generate a heat variation due to a voltage difference across a two dissimilar metals at the junction. This phenomenon in one application has been applied as a cooling mechanism for solid state devices. These complimentary effects are generally known as the Peltier-Seebeck Effect.

The evolution of indicating, recording, transmitting and controlling instrumentation has been extraordinary. From the early days of vacuum tube operated electrical devices, we have progressed through solid state components to the microprocessor powered devices of today offering extraordinary performance and features not even thought of a few years ago. A technology breakthrough in the 1960s fostered the birth of the first two-wire temperature transmitter by what was then Rosemount Engineering Company.

3.2.3 Resistance Temperature Detectors (RTDs)

Resistance temperature detectors (RTDs) are based on the principle that the electrical resistance of a metal increases as temperature increases –

WHAT ARE THE SENSOR LEAD WIRE COLOR STANDARDS THAT SHOULD BE FOLLOWED?

Various standards prescribe color codes for RTD and Thermocouple lead wires and for thermocouple extension wire.

For RTDs refer to:

3.2.3.10 – Lead Wire Colors

3.2.3.14 – RTD International Standards

For Thermocouples refer to:

3.2.4.5 – T/C Lead Wire Color Standards

Figure 3-76 – International Color Coding for Thermocouple Insulation a phenomenon known as thermal resistivity. Thus, a temperature measurement can be inferred by measuring the resistance of the RTD element.

RTDs are constructed of a resistive material with leads attached and usually placed into a protective sheath. The resistive material may be platinum, copper or nickel with the most common by far being platinum because of its high accuracy, excellent repeatability, and exceptional linearity over a wide range and it exhibits a large resistance change per degree of temperature change. Refer to Figure 3-39.

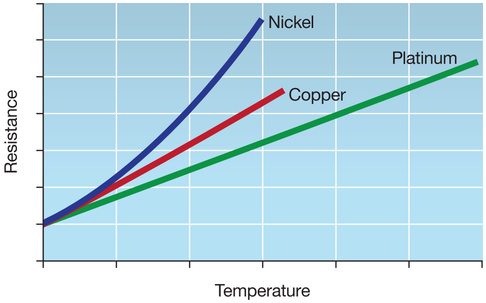


Figure 3-39 – Resistance Change vs. Temperature for Common Sensor Materials

The two most common styles of RTD sensors are wire-wound and thin-film. Wire-wound RTDs are manufactured either by winding the resistive wire around a ceramic mandrel or by winding it in a helical shape supported in a ceramic sheath – hence the name wire-wound. To manufacture thin film RTD sensors, a thin resistive coating is deposited on a flat (usually rectangular) ceramic substrate.

Copper and nickel are generally used in less critical industrial applications due to limited accuracy and linearity, and relatively narrow temperature ranges.

Nickel elements have a limited temperature range because the amount of change in resistance per degree of change in temperature becomes very non-linear at temperatures over 300 °C. Use of nickel RTDs has declined over the years due to its performance limitations and since the cost of Platinum RTDs is now a very small premium, if any at all.

Copper has a very linear resistance to temperature relationship, but, since copper oxidizes at moderate temperatures, it should not be used over 150 °C. Copper RTDs are commonly used in winding temperature measurements of motors, generators and turbines. 10 Ω copper RTDs have been the most common over the years, but are now giving way to 100 Ω and even 1000 Ω models to get better resolution thus providing a more accurate measurement. Platinum RTDs are also growing in popularity for these applications. Due to the harsh conditions in these windings and the fact that the sensors cannot be replaced without disassembly of the motor, many vendors and users are opting for dual element RTDs and some are using thin-film RTD designs due to their greater tolerance for vibration and subsequent longer life expectancy.

3.2.3.1 Common RTD Characteristics

Industrial sensors are rarely, if ever, used where they are exposed to the environment. They are encased in a metal tube or sheath that is welded closed at one end and that has lead wires protruding from the sealed other end. See Figure 3-40 and Figure 3-41.

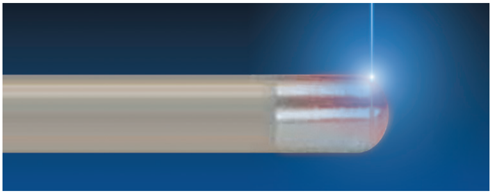


Figure 3-40 – Laser Welding of Sensor Sheath

Figure 3-41 – Potting Seal of Rear Sensor Housing

3.2.3.1.1 Sensing Element

The sensing element is located at the tip of the temperature sensor that is exposed to the process temperature. The sensing element responds to temperature by generating a measureable resistance change or a voltage signal that increases as the temperature increases. Sensors can be provided with either one or two elements in one sensor sheath. Dual elements provide a redundant measurement that may be useful for hot back-up, for drift monitoring using a comparison technique, or to provide inputs to two independent controllers or systems (control system or safety system). See Figure 3-42.

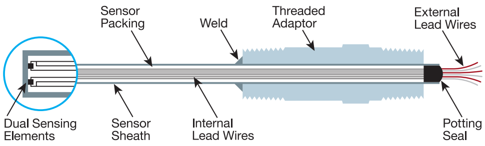


Figure 3-42 – Dual Element RTD

TIP: In some of these applications a case can be made for using two independently installed single sensors instead of a dual element in one sheath. See Chapter 4 for further discussion.

3.2.3.1.2 Sensor Sheath

The sensor sheath is made of metal, usually stainless steel (Hastelloy or Inconel is used for certain high temperature applications), and typically contains 2, 4, 6 or 8 conductors connecting the sensing element(s) to the lead wires. A single T/C requires two leads, while a dual T/C requires four leads. A single RTD can have two, three, or four leads, and a dual RTD can have four, six, or eight leads. The sensor sheath protects the element and the conductors from moisture and corrosive and/or abrasive process conditions and helps to shield the signal from electrical noise. To insulate the conductors from each other and from the sheath, the sheath is filled with a compacted finely powdered insulating packing material, typically magnesium oxide (MgO) or aluminum oxide (Al2O3), which surrounds the sensing element and conductors. See Figure 3-43.

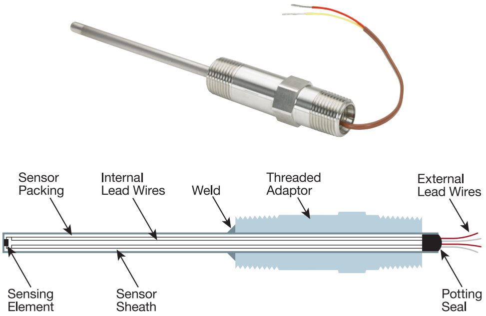


Figure 3-43 – Common Temperature Sensor Characteristics

Sensor sheath diameters vary with the more common dimensions being 6 mm (1/4-inch) and 3 mm (1/8-inch). The smaller diameters have a faster response time because there is less mass and insulating material. Also, smaller diameters can provide a more accurate measurement due to reduced sheath heat conduction error.

However, most industrial applications use a thermowell for installation, adding considerable mass to the overall assembly thus somewhat mitigating both of these factors. A thermowell is installed into the process, making a pressure tight seal and has an internal bore into which the sensor is installed. This allows for easy removal of the sensor for calibration or replacement. See section 3.3 for more information.

3.2.3.1.3 Lead Wires

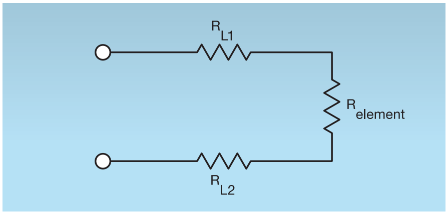
Lead wires are typically stranded, insulated wires which are attached to the conductors that run through the sensor sheath connecting the element to the lead wires. These lead wires are sealed at the end of the sheath and are used to connect the sensor to a terminal block, transmitter or other termination point. The length of these leads varies by vendor and the requirements of the user. Refer to Figure 3-41 in section 3.2.3.1.

3.2.3.1.3.1 Lead Wire Compensation

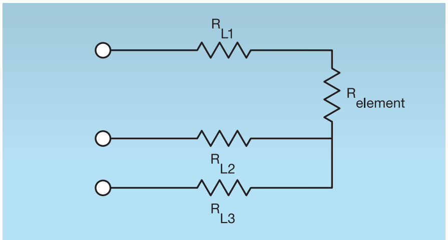
Since the lead wires are part of the RTD circuit, the lead wire resistance needs to be compensated for to achieve the best accuracy. This becomes especially critical in applications where long sensor and/or lead wires are used. There are three lead wire configurations commonly available.

In a two-wire configuration, there can be no compensation for lead wire resistance since the lead wires are in series with the element and appear to the transmitter as part of the sensor's resistance, causing inherent accuracy degradation. There are few applications where two-wire sensors are a good choice. In a three-wire configuration, compensation is accomplished using the third wire with the assumption that it will be the same resistance as the other two wires and the same compensation is applied to all three wires.

Figure 3-44 shows the equation for this compensation: *Rmeasurement = RL1 + Relement – RL3*. However, in the real world, there will always be some difference between L1 and L3 due to wire manufacturing irregularities, unequal lengths, loose connections, work hardening from bending, and terminal corrosion.



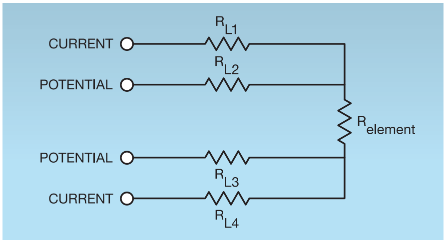
$$R_{measured} = R_{L1} + R_{element} + R_{L2}$$



$$R_{measured} = R_{L1} + R_{element} + R_{L2} - [R_{L2} + R_{L3}]$$

$$= R_{L1} + R_{element} - R_{L3}$$

$$= R_{element} \quad (\text{If } R_{L1} = R_{L3})$$



$$R_{measured} = R_{element}$$

Figure 3-44 – Two-, Three-, Four- Wire RTDs with Equations

Since a 100 Ω platinum RTD changes 0.39 Ω per degree C, for every one ohm of difference in the lead wire effective resistance, an error of up to 2.5 °C is produced (1÷0.39). This unbalance error is likely to change unexpectedly and unpredictably over time as corrosion increases and temperature and humidity changes etc. Refer to Figure 3-45.

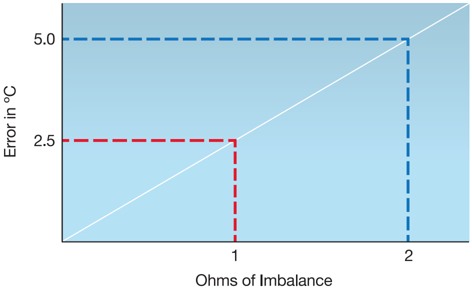


Figure 3-45 – Lead Imbalance vs. Error for 3-Wire RTD

A four-wire design is ideal because the lead wire resistance is inconsequential to the measurement. It uses a measurement technique where a very small constant current of about 150 micro amps is applied to the sensor through two leads and the voltage developed across the sensor is measured over the other two wires with a high-impedance and high resolution measuring circuit. In accordance with Ohm's Law, the high impedance virtually eliminates any current flow in the voltage measurement leads and therefore the resistance of the leads is not a factor. Refer to Figure 3-44 and Figure 3-45.

3.2.3.2 RTD Sensor Construction

Many factors must be considered in the manufacturing of high quality sensors. One method of constructing a wire-wound sensor element uses a very high purity wire that is wound onto a mandrel with a closely matching coefficient of expansion to the wire to minimize element strain effects. Another method is winding the wire in a helical shape that is then placed into a ceramic sheath. Any cement used in the manufacturing must not introduce any strain on the assembly. Assembly must be in a clean room type of environment to eliminate any contamination that could degrade the sensor and increase long term drift. Lead wire material must be selected to be compatible with the range of the sensor and carefully laser welded to the sensor avoiding any thermoelectric junctions. All internal components must be properly supported and strain relieved to eliminate mechanical and thermal induced strain and increase tolerance of shock and vibration. The lower the strain introduced by proper choice of material expansion coefficients, the better will be the repeatability and stability of the sensor assembly. Similar strain relief considerations apply to the manufacture of thin-film elements where a thin platinum film is deposited onto a ceramic substrate. Part of the process also includes annealing and trimming of the sensor resistance to the proper ice point value R0. The process is finished by applying a non-conductive encapsulating material, such as cement or glass material, to seal the sensor and the welds from potential contamination. Refer to Figure 3-43 and Figure 3-41. The completed sensing element is then assembled into a sheath as described above. Both nickel and copper RTDs follow a similar manufacturing process. In general, nickel and copper sensors cost slightly less since the price of the metal is far less expensive than ultra pure platinum. However, for thin-film platinum RTDs, such a small amount of platinum is required, that the price advantage of copper or nickel is reduced or eliminated.

3.2.3.2.1 Wire-Wound Elements

Mandrel style wire-wound elements manufactured as described above are commonly available as 100 Ω up through 1000 Ω with the 100 Ω being the most common choice for industrial applications. They have a range of -200 to 850 °C (-328 - 1562 °F) over which they conform to the 385 alpha curve, and they have a maximum range of -240 to 960 °C (-400 - 1760 °F). See Figure 3-46.

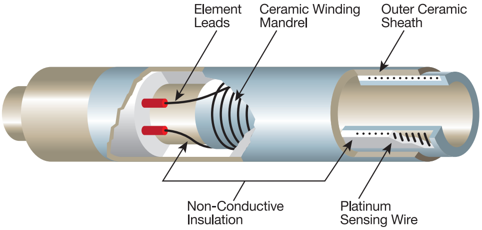


Figure 3-46 – Mandrel Style Wire-Wound Element

3.2.3.2.2 Thin-Film Elements

Thin-film elements are manufactured by depositing a thin film of pure platinum on a ceramic substrate in a maze-like pattern. Refer to Figure 3-47. The sensor is then stabilized by a high temperature annealing process and trimmed to the proper R0 value. These compact sensors are then encapsulated with a thin glassy material. The area where the lead wires are attached is given a much more robust glassy encapsulation to ensure mechanical protection and a moisture seal. With their small size and low mass, these sensors are more vibration resistant than a wire-wound style and are often a better choice for such applications.

Due to the difficulties associated with matching the thermal coefficients of expansion of the platinum coating with the substrate material, the range of these sensors is somewhat limited compared to a wire-wound style and is typically -200 °C to 800 °C. (-328 °F to 1472 °F).

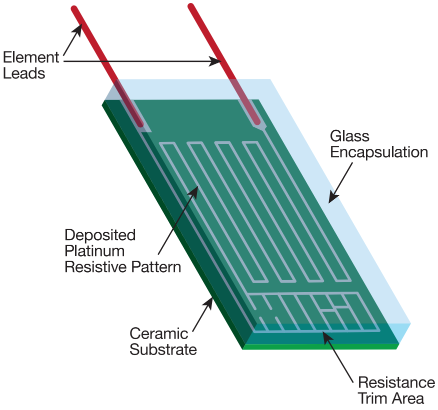


Figure 3-47 – Thin-Film RTD Element Construction

3.2.3.3 Sensor Styles

Different sensor styles exist, providing a variety of methods to install the sensor assemblies. Each has distinct attributes for each application and installation practices.

3.2.3.3.1 Capsule Style

The capsule style is simply a sensor sheath with lead wires. Capsules are commonly used with compression fittings and can be cost-effective when environmental conditions, such as high pressure or temperature, are not a concern.

3.2.3.3.2 Threaded Style

The threaded style is a capsule style with a threaded adaptor to provide a connection to the process and connection head or housing. The benefit of the threaded style is the ability to install it directly into a process or thermowell without an extension. Three common styles are:

General purpose weld – the capsule is welded to a threaded adapter, creating a process seal. When conditions allow, it can be directly immersed into the process without a thermowell to improve response time. The seal is limited by the thread connection and therefore has lower pressure ratings than can be achieved using welded or flanged thermowells. (See section 3.3 for details) General purpose weld styles are not recommended for use with thermowells because the sensor tip will not touch the bottom of the well, thus creating a thermal lag. See Figure 3-48.

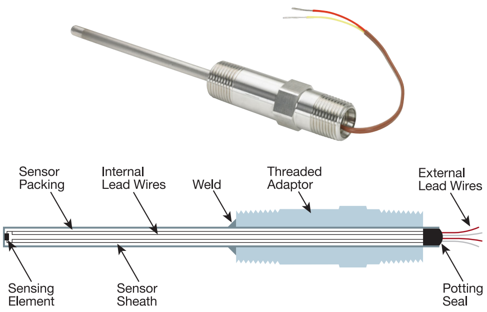


Figure 3-48 – General Purpose Welded Adapter Style

Spring-loaded – a spring located in the threaded adaptor allows the capsule to travel, ensuring contact with the bottom of a thermowell. This spring style provides continuous contact to the bottom of the well, which provides better tolerance of vibration and significantly faster speed of response of the measurement. See Figure 3-49.

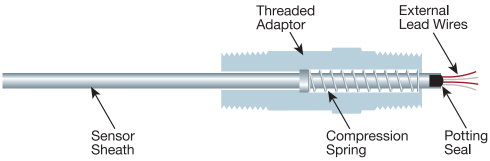


Figure 3-49 – Spring-Loaded Threaded Style

Bayonet spring-loaded –a bayonet spring-loaded style is similar to spring-loaded style, but allows removal of the capsule without disassembly of the threaded adapter from the thermowell. This saves twisting of the leads and potential damage when removing a threaded type. See Figure 3-50.

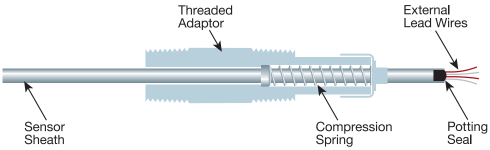


Figure 3-50 – Bayonet Style Spring-Loaded Sensor Assembly

3.2.3.3.3 DIN Style

The DIN style is a sensor capsule with a circular plate that provides an effective mounting method for connection heads or housings. Refer to Figure 3-51. The benefit of the DIN style is the ability to install and replace the sensors without removing the connection head or housing from the process as the sensor is inserted through the housing instead of threaded into the bottom. All DIN styles are spring-loaded. Two common styles are:

3.2.3.3.3.1 – ***Flying Leads –*** A DIN plate is attached to the end of the capsule. The flying lead style is most often used with a head mount transmitter. Spring loading is provided by the mounting screws of the transmitter.

3.2.3.3.3.2 – ***Terminal Block –*** A DIN plate with a terminal block is attached to the end of the capsule. The terminal block style is most often used in remote mount configurations where the transmitter is located elsewhere and wires are run between the sensor and the transmitter. Spring loading is provided by the mounting screws of the terminal block or transmitter.

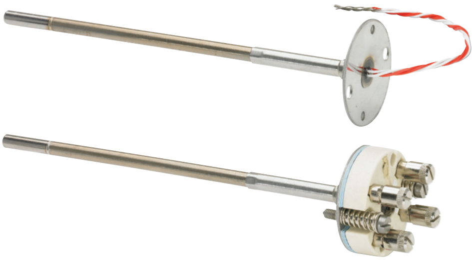


Figure 3-51 – DIN Mount Sensors – Flying Leads – Terminal Block

3.2.3.4 Extensions

Sensors can include extensions of various lengths to accommodate different insulation thicknesses and to distance the transmitter from high process temperatures that may affect the transmitter electronics. Extensions can be a combination of unions, nipples, and/or couplings. See Figure 3-52.

Figure 3-52 – Typical Nipple – Union Extension

3.2.3.5 Mounting Options

Temperature sensors may be either immersed in the process fluid or surface-mounted. The mounting selection depends on the measurement application, process conditions, and environmental constraints.

3.2.3.5.1 Immersion Mounting

As the name suggests, immersion temperature sensors are inserted into the process medium; furthermore, they are typically installed into a thermowell for protection against process conditions. Refer to section 3.3 for more detail. Refer to Figure 3-53 and Figure 3-54. Depending on sensor construction and process conditions, some sensors can be inserted directly into the process medium. While this is less expensive and provides faster response, it requires a process shutdown and draining of the process for removal of the sensor for calibration or replacement.

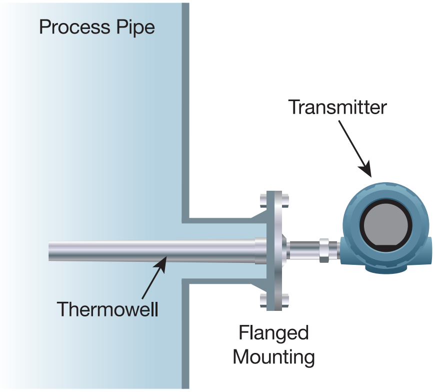


Figure 3-53 – Transmitter Assembly Pipeline Installation

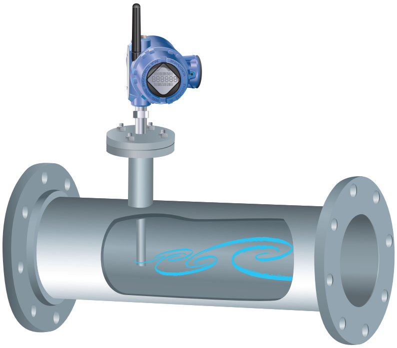


Figure 3-54 – Wireless Integral Mount Pipeline Installation

3.2.3.5.2 Surface Mounting

Surface mounting is an efficient and convenient installation method often used when it is impractical or impossible to insert a sensor assembly into the process. For example, this situation may exist because of frequent use of a "pig" to remove process material that builds up in the piping and the pig cannot pass by obstructions, such as a thermowell protruding into the pipe. Refer to Figure 3-55. Another application is to provide a new measurement where an expensive process shutdown would be required to install a system in a new thermowell. See section 3.3 for more information.

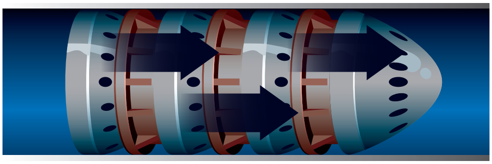


Figure 3-55 – Piping Cleaning Pig

However, surface measurement is only as reliable as the temperature on the surface of the pipe or vessel. In general, the goal is to maximize heat conduction from the pipe or vessel surface to the sensing element. Sensors can be mounted with adhesives, screws, clamps, or welds and good thermal contact is necessary. Refer to Figure 3-56. Thermal insulation is used to minimize the loss of heat energy from the surface of the pipe to its surroundings and should cover the sensor and the lead wires for some distance to minimize any conduction heat losses to the leads. This helps to ensure that that the sensor is at, or as close as possible to, the actual surface temperature of the pipe, which is assumed to be at the process fluid temperature. Process fluid flow rate and rate of temperature change significantly influence this assumption. Differing thermal coefficients of expansion of the pipe and the mounting assembly must also be considered to minimize stress to the sensor that would degrade the measurement, or even destroy the sensor.

Technology advancements have been recently developed to overcome many of the accuracy limitations discussed above with using a surface mount sensor. In particular, there are transmitter/sensor assemblies available that can convert a surface temperature measurement into a process temperature measurement. These non-intrusive assemblies combine the best of both worlds by providing a highly accurate process temperature measurement without making a physical penetration into the pipe or vessel. More information about this technology is discussed in section 3.4.

Figure 3-56 – Surface Mount Sensors - Pipe Clamp

TIP: For a more detailed discussion of the application of surface mounted sensors, refer to section 3.2.3.5.2 of this handbook.

3.2.3.6 Factors Affecting RTD Performance

3.2.3.6.1 Resistance - Alpha Values

RTD elements are characterized by their Temperature Coefficient of Resistance (TCR), also referred to as its alpha value. The IEC 60751-2008 standard defines these values for platinum element types. Refer to Figure 3-57.

The alpha value is the temperature coefficient for that specific material and composition. Copper elements have a different alpha value than platinum elements, and platinum elements themselves can vary depending on the purity of the platinum and any alloy content. Alpha values define sensor interchangeability. Various sensors with the same alpha value guarantees that the resistance vs. temperature relationship will be the same for each sensor within a specified precision specification. When replacing a sensor, the user should ensure that the same material with the same resistance and alpha value, e.g. Pt100: $\alpha = 0.00385$ is used.

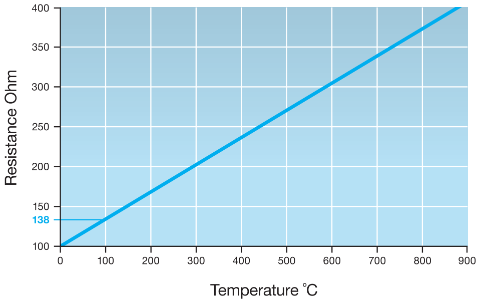


Figure 3-57 – Temperature Coefficient of Resistance (TCR) of a Pt100

3.2.3.6.1.1 The Alpha Equation defines the Alpha Value:

$$\text{Alpha} = (R100 - R0) \div 100\ R0$$

Where R0 is the resistance of the sensor at 0 °C and R100 is the resistance of the sensor at 100 °C

Platinum RTDs are available with alpha values ranging from 0.00375 to 0.003927. The highest alpha value indicates the highest purity platinum, and is mandated by the International Temperature Scale of 1990 (ITS-90) for standard (Laboratory) grade platinum thermometers.

There are no technical advantages of one alpha versus another in practical industrial applications. The 0.00385 platinum is the most popular and most commercially available worldwide standard and is available in various styles, including wire-wound and thin-film elements from 100 Ω to 1000 Ω. In most cases, all the user needs to know about the alpha value is that it must be properly matched when replacing RTDs or connecting them to instruments.

3.2.3.7 Self Heating

Self Heating is caused when the sensing current from the transmitter is passed through an RTD sensing element. Heating is caused according to the I2 R principle contained in Joule's Law, which states "power increases as the square of the current through the windings and in proportion to the electrical resistance of the conductors." Since the current supplied by most microprocessor based transmitters is very small, (typically 200 to 250 micro amps (μamps)), the heat produced is also very small and will have a negligible effect on the measurement accuracy.

TIP: Many older analog circuitry transmitters have a significantly higher excitation current that will cause significantly more sensor self heating and related measurement error. For high-accuracy applications, a wise user will consider an upgrade to a microprocessor-based transmitter.

3.2.3.8 Sensor Response Time

The Response Time of a sensor is the time required for the output of a sensor to change by a specified percentage of an applied step change in temperature for a specific set of conditions. Note that there are different standards for testing response time that will produce widely varying results. Only if the sensors are tested to the same standard can the response time of different sensors tested under identical conditions be compared. However, any change in such conditions, such as fluid density, temperature, or flow rate, will yield alternative results. For example, the response time will be much slower in a gas than it will be in a fast moving liquid.

Response Time is usually stated in seconds and the percentage at which the time was recorded is indicated by the number next to the response time value "t". For example, t(0.5) means the response time value for 50% of the step change and t(0.9) means the response time value for 90% of the step change. See Figure 3-58.

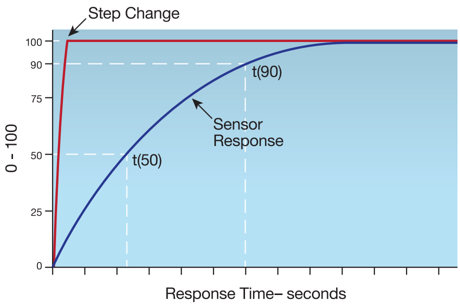


Figure 3-58 – Typical Sensor Response Time

Factors that affect response time include the thermal conductivity of the fill material between the inside wall of the thermowell and the sensor sheath, the distance of the gap between the sensor tip and the bottom of the well bore, the tip width, the well thickness and the positioning in the flow stream. Refer to Figure 3-59. Ideally, the "x" and" y" dimensions should approach zero and the "B" and "t" dimensions should be as small as possible while still taking into consideration the requirements defined in the ASME PTC 19.3 TW standard. Using a spring-loaded sensor helps to minimize the "x" distance. Proper insertion length of the well into the process should be determined to maximize thermal response. Refer to 3.3.7 for more detail.

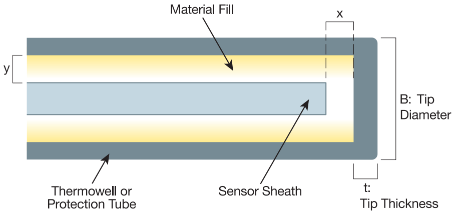


Figure 3-59 – Factors Affecting Response Time

3.2.3.9 Hysteresis

Hysteresis is a phenomenon that results in a difference in a sensor's output when approaching the same value from two different directions. For example, when the output is compared at a particular point after an increase in temperature above that point and then returning to that same point, it will be different than the output if the temperature is reduced below the point and then returned. In laboratory grade or standard RTDs, there is negligible hysteresis since there is minimal contact between the platinum element and the supporting media due to its coiled suspension design. These are very high precision and very high cost sensors used when calibration standards require the utmost care to prevent shock damage. An industrial grade sensor does have hysteresis error due in part to its inherent rugged design with the encapsulation essentially bonding the platinum to the supporting mandrel or substrate. The difference in thermal coefficients of expansion of the different materials produces a drift error. In 1982, D.J. Curtis of Rosemount Inc. investigated different RTD designs and found that wire-wound styles are the best with typical hysteresis spec of 0.008% and that thin-film styles exhibited greater typical hysteresis of 0.08%. See Figure 3-60. For most applications, this is negligible.

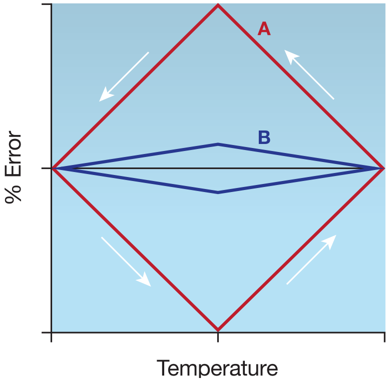


Figure 3-60 – Hysteresis for Thin Film (A) and for Helical Coil Wire-Wound Elements (B)

3.2.3.10 Lead Wire Colors

Lead wire colors are defined in the IEC 60751-2008 standard where all wire colors are shown as in the following figure. Refer to Figure 3-61. However, lead wire colors may vary with individual manufacturers.

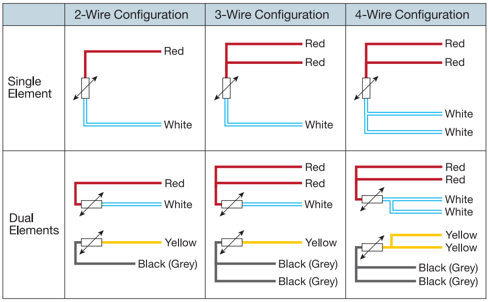


Figure 3-61 – RTD Lead Wire Colors per IEC 60751

3.2.3.11 RTD Accuracy/Interchangeability

When comparing accuracy/interchangeability, a ± percentage is only valid at the ice point (0 °C). To determine the tolerance at the intended operating temperature, a tolerance with an equation should be provided by the vendor, as is shown in Figure 3-62.

Tolerance Class	Temperature Range of Validity °C		Tolerance Values* °C
	Wire Wound Resistors	Film Resistors	
AA	-50 to +250	0 to +150	± (0.1 + 0.0017 | t |)
A	-100 to +450	-30 to +300	± (0.15 + 0.002 | t |)
B	-196 to +600	-50 to +500	± (0.3 + 0.005 | t |)
C	-196 to +600	-50 to +600	± (0.6 + 0.01 | t |)
ASTM E1137	Grade A	–	± (0.13 + 0.0017 | t |)
ASTM E1137	Grade B	–	± (0.25 + 0.0042 | t |)

Figure 3-62 – Platinum RTD Accuracy Classes per IEC 60751 and ASTM E1137

There are several classes of RTD accuracy/interchangeability that define the relationship of the amount of error allowed for a given RTD type at a given temperature as compared to the standard. Refer to Figure 3-63. The maximum allowable sensor interchangeability error at a given process temperature is defined by the two IEC 60751 standard classifications: Class A and Class B. These classifications are used to identify platinum RTD interchangeability tolerance, wherein the Class B sensors have about twice as big of a tolerance band as Class A sensors. Refer to Figure 3-63.

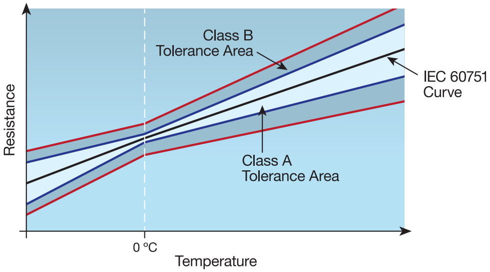


Figure 3-63 – IEC 60751 Ideal vs. Class A vs. Class B Tolerance Bands

Note also that the tolerance or error band widens for temperatures above or below the ice point R0. Refer to Figure 3-64. Typical manufacturer's data for a particular sensor is provided in a product data sheet. Refer to Figure 3-65. There are other classes defined, as shown in Figure 3-62. However, Class A and B (Or Grade A and B for the ASTM E1137 standard) are most frequently used in the process industries.

Element Interchangeability in °C				
Temp °C	Class B	Class A	Class AA (1/3 B)	Class 1/10 DIN
-196	1.28	–	–	–
-100	0.80	0.35	–	–
-50	0.55	0.25	0.18	–
-30	0.45	0.21	0.15	–
0	0.30	0.15	0.10	0.03
100	0.80	0.35	0.27	0.80
200	1.30	0.55	0.43	–
250	1.55	0.65	0.52	–
300	1.80	0.75	–	–
400	2.30	0.95	–	–
450	2.55	1.05	–	–
500	2.80	–	–	–
600	3.30	–	–	–

Figure 3-64 – Wire-wound RTD Element Interchangeability by Class vs. Temperature

* | t | Modulus of temperature in °C without regard to sign.

Series 78 Interchangeability	
Standard Series 78 IEC 60751 Class B	**Temperature**
±0.80 °C (±1.44 °F)	-100 °C (-148 °F)
±0.30 °C (±0.54 °F)	0 °C (32 °F)
±0.80 °C (±1.44 °F)	100 °C (212 °F)
±1.80 °C (±3.24 °F)	300 °C (572 °F)
±2.30 °C (±4.14 °F)	400 °C (752 °F)
Series 78 IEC 60751 Class A Option	**Temperature**
±0.35 °C (±0.63 °F)	-100 °C (-148 °F)
±0.15 °C (±0.63 °F)	0 °C (32 °F)
±0.35 °C (±0.63 °F)	100 °C (212 °F)
±0.75 °C (±1.35 °F)	300 °C (572 °F)
±0.95 °C (±1.71 °F)	400 °C (752 °F)

Figure 3-65 – Specific Product Interchangeability Data

3.2.3.11.2 Sensor Interchangeability Error

Sensor Interchangeability Error is defined as the difference between the actual RTD curve and the ideal RTD curve. Refer to Figure 3-63 and Figure 3-66. The IEC standard uses only the ice point resistance R0 and the sensor Alpha Number to define an approximation of an ideal curve. However, due to manufacturing tolerance variation and the degree of purity of the platinum, each individual sensor will have its own unique curve that will vary slightly from the ideal curve. IEC 60751 defines minimal acceptable accuracy tolerance for conformance to the standard for each class of sensor over a range of temperatures.

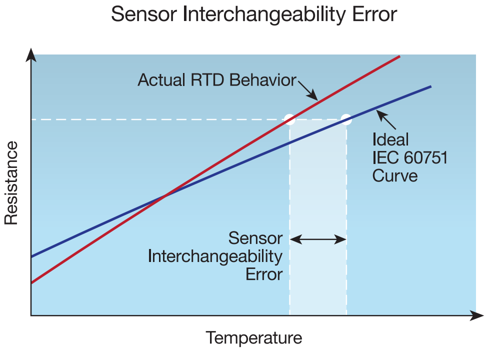


Figure 3-66 – Sensor Interchangeability Error

The IEC standard defines a PT100 sensor output using a 4th-order equation that was developed by Hugh Longbourne Callendar and M.S. Van Dusen, and is today known as the Callendar-Van Dusen (CVD) equation. Refer to Figure 3-67. The CVD equation can be used to define this unique RTD curve by finding the CVD constants using a calibration or characterization procedure. In this procedure, an RTD's resistance is measured in several different precision controlled temperature baths. The data collected are fit to a fourth-order curve, from which the four Callendar-Van Dusen constants are determined.

3.2.3.12 The Callendar-Van Dusen Equation

The Callendar-Van Dusen equation offers an alternative calibration technique to that in the IEC 60751 standard. It is used in transmitter-sensor matching to create a curve that closely approximates an RTD's resistance versus temperature relationship. This curve can be generated for any RTD by plugging the RTD's specific four constants into the Callendar-Van Dusen equation, which is programmed into many smart transmitters. Refer to Figure 3-67. In this way, the transmitter uses the actual RTD curve rather than an ideal curve to translate the sensor's resistance signal into a temperature value, thus providing extraordinary system accuracy.

While this matching is typically not required for all process measurements, it is the clear choice for those measurements requiring the best possible accuracy.

$$R_t = R_o + R_o\alpha\left[t - \delta(0.01t - 1)(0.01t) - \beta(0.01t - 1)(0.01t)^3\right]$$

Where:

R_t = Resistance (ohms) at Temperature t (°C)

R_o = Sensor-Specific Constant (Resistance at t = 0 °C)

α = Sensor-Specific Constant

δ = Sensor-Specific Constant

β = Sensor-Specific Constant (0 at $t > 0$ °C, 0.11 at $t < 0$ °C)

Figure 3-67 – Callendar-Van Dusen Equation

TIP: Temperature sensor-transmitter assemblies can be visualized as "good - better - best," where a transmitter used with a Class B sensor is "good," a transmitter used with a Class A sensor is "better," and a transmitter matched to a sensor using the x constant method is "best". There is little, if any, benefit to paying the extra cost for a Class A sensor when using the CVD method. Class B sensors will provide about the same accuracy results. See Figure 3-68.

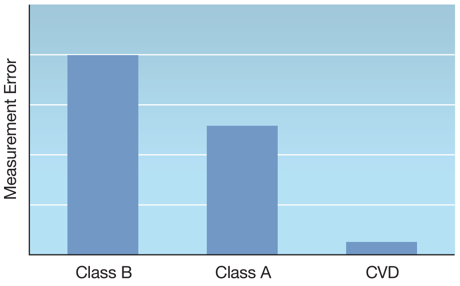


Figure 3-68 – Good - Better - Best: Calibration Comparison of Systems Using a Class B Sensor vs. Using a Class A Sensor vs. Using the CVD Method

3.2.3.13 RTD Stability - Drift

Stability is related to the amount of the sensor drift and is the relationship of a sensor's original resistance curve to its curve after being in service. Drift rates published by a manufacturer for a particular sensor must be assumed to be applicable in a controlled "laboratory-like" environment. The actual drift in an industrial application may be much different.

A variety of influencing factors affect stability in a platinum sensor used in industrial applications, and it will certainly not be as good as published drift rates at 0.0 °C (32.0 °F) in a controlled environment. Thermal and mechanical stresses cause physical changes in the crystalline structure of the platinum, causing a distortion in the normal resistance vs. temperature curve. Chemical reactions involving the platinum and impurities as well as migration of internal materials can also affect a sensor output. A shunting effect due to insulation resistance deterioration is another influencing occurrence. Operating at higher temperatures increases the speed of these reactions, thus causing increased drift.

The drift caused by these conditions is not normally catastrophic and may be considered to be very low when operated in temperatures below 300 °C (572 °F). (Typically < ±0.05 °C (0.09 °F) change to R0.) Operation at higher temperatures greatly increases the drift rate. For example, at 500 °C (932 °F) the drift can be as much as 0.35 °C (0.63 °F) after 1000 hours. Refer to Figure 3-69.

Repeated cycling causes a small drift contribution that increases with the number of accumulated cycles and the maximum temperature reached in each cycle. This contribution is typically negligible.

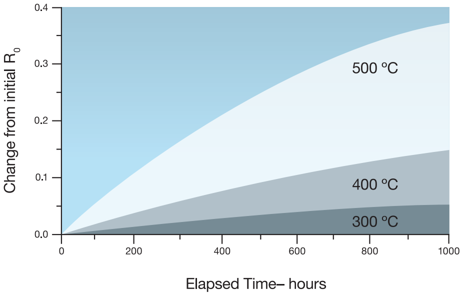


Figure 3-69 – Shift of R_0 vs. Time vs. Temperature

3.2.3.14 RTD International Standards

Several international standards define the relationship between resistance and temperature for RTD sensors. Over the years, and especially before 1990, there were many different "standards" for industrial RTDs. Many had unique coefficients due to unique doping of the platinum. Today, there are only two that are common: ASTM 1137 (American) and IEC 60751 (International). The International Electrotechnical Commission IEC 60751 standard describes the ideal relationship between the resistance of platinum RTDs and the temperature being measured. Refer to Figure 3-70. Many national standards are based on the IEC standard. Released in 2008, IEC60751-2008 includes new tolerance classes, specifies wire colors for RTDs as described, and expands the range of alpha (α) values used in the Callendar-Van Dusen equation.

IEC 60751 is equivalent to and supersedes the DIN 43760 and the BS-1904 standards.

IEC 60751 also is equivalent to the Japanese standard JS-C1604.

American Society for Testing and Materials (ASTM) E1137. This standard applies to platinum RTDs with an average temperature coefficient of resistance of 0.00385 %/ °C between 0 and 100 °C and nominal resistance at 0°C of 100 Ω or other specified value. This specification covers platinum RTDs suitable for all or part of the temperature range between -200 to 650 °C.

JJG 229 is a Chinese standard also known as "Regulations of Industry Platinum and Copper Resistance Thermometers". It is similar to the IEC 60751 standard.

International Standards	
Standard	**Comment**
IEC 60751	Defines Class A and B performance for 100Ω 0.00385 alpha Pt RTDs.
DIN 43760	Equivalent to IEC 60751.
BS-1904	Equivalent to IEC 60751.
JIS C1604	Equivalent to IEC 60751. Adds 0.003916 alpha.
ITS-90	Defines temperature scale and transfer standard.

Figure 3-70 – International Standards Requirements Comparison

3.2.4 Thermocouples

3.2.4.1 Overview

A thermocouple (T/C) is a closed-circuit thermoelectric temperature sensing device consisting of two wires of dissimilar metals joined at both ends. A current is created when the temperature at one end or junction differs from the temperature at the other end. This phenomenon is known as the Seebeck effect, which is the basis for thermocouple temperature measurements.

One end is referred to as the hot junction and the other end is referred to as the cold junction. The hot junction measuring element is placed inside a sensor sheath and exposed to the process. The cold junction, or the reference junction, is the termination point outside of the process where the temperature is known and where the voltage is being measured. (e.g. in a transmitter, control system input card or other signal conditioner.)

According to the Seebeck effect, a voltage measured at the cold junction is proportional to the difference in temperature between the hot junction and the cold junction. This voltage may be referred to as the Seebeck voltage, thermoelectric voltage, or thermoelectric EMF. As the temperature rises at the hot junction, the observed voltage at the cold junction also increases non-linearly with the rising temperature. The linearity of the temperature-voltage relationship depends on the combination of metals used to make the T/C.

3.2.4.2 Cold Junction Compensation (CJC)

The voltage measured at the cold junction correlates to the temperature difference between the hot and cold junctions; therefore, the temperature at the cold junction must be known for the hot junction temperature to be calculated. This process is known as “cold junction compensation” (CJC). CJC is performed by the temperature transmitter, T/C input cards for a control system, alarm trips, or other signal conditioner. Ideally, the CJC measurement is performed as close to the measurement point as possible because long T/C wires are susceptible to electrical noise and signal degradation. Refer to Figure 3-71.

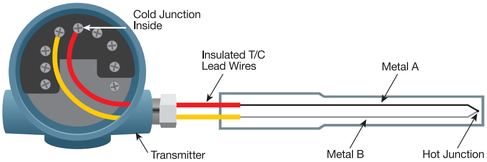


Figure 3-71 – Cold Junction Compensation

Performing an accurate CJC is crucial to the accuracy of the temperature measurement. The accuracy of the CJC is dependent on two things: the accuracy of the reference temperature measurement and the proximity of the reference measurement to the cold junction. Many transmitters use an isothermal terminal block (often made of copper) with an imbedded precision thermistor, an RTD or an integrated circuit transistor to measure the temperature of the block.

TIP: Refer to section 4.5.4 for a detailed discussion of why to use field transmitters vs. direct wiring to a control room.

3.2.4.3 Thermocouple Manufacturing

The process begins with the choice of high quality wire of the materials required for the T/C type being made. The wires are joined by various methods, including twisting, clamping, soldering, brazing, and various types of welds (e.g., bead and butt). For best performance, the hot junction must be mechanically sound, electrically continuous, and not poisoned by the chemical ingredients of the welding or brazing materials. For premium grade T/Cs, more care is given to the selection of the wire grade and control of the manufacturing process. Refer to Figure 3-72.

TIP: Twisted junction method is highly subject to rapid degradation and is not recommended.

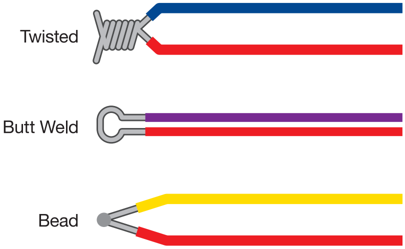


Figure 3-72 – Hot Conjunction Methods

3.2.4.3.1 Junction Types

T/C Junctions are manufactured in different configurations each with benefits for specific applications. Junctions can be grounded or ungrounded, and dual element thermocouples can be isolated or non-isolated. Refer to Figure 3-73.

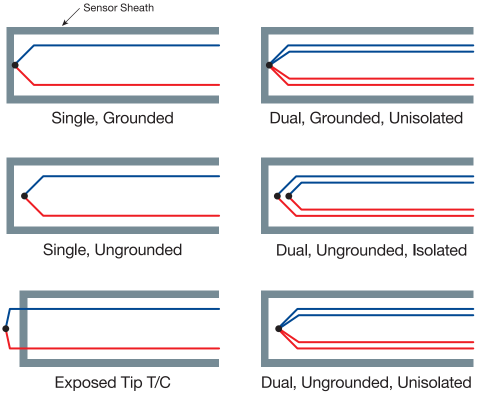


Figure 3-73 – Hot Junction Configurations

Grounded T/C junctions are formed when the thermocouple junction is connected to the sensor sheath. Grounded junctions have better thermal conductivity, which in turn produce the quickest response time. However, grounding also makes thermocouple circuits more vulnerable to electrical noise, which can corrupt the thermocouple voltage signal unless the measurement instrument provides isolation. (All high quality transmitters and I/O cards offer galvanic isolation as a standard feature.) The grounded junction may also be more prone to poisoning over time.

Ungrounded junctions exist when the T/C elements are not connected to the sensor sheath but are surrounded with insulating powder. Ungrounded junctions have a slightly slower response time than grounded junctions but are less susceptible to electrical noise.

Exposed junction T/Cs have the hot junction extending past the sealed end of the sheath to provide faster response. The seal prevents intrusion of moisture or other contaminants into the sheath. These are typically applied only with non-corrosive gases as might be found in an air duct.

3.2.4.3.2 Dual Element T/Cs

Dual element T/Cs are available in three different configurations. Refer to Figure 3-73.

Isolated configurations exist when two independent T/C junctions are placed inside one sheath. Isolated junctions may not read identical temperatures but can identify drift due to poisoning of one of the elements. If one junction fails, the second junction is not necessarily affected.

Un-isolated configurations exist when two T/C junctions are placed inside one sheath and all four T/C wires are mechanically joined. Un-isolated junctions measure identical temperature to increase the integrity of the measurement point. However, if one junction fails, it is likely that both junctions will fail at the same time.

3.2.4.4 Thermocouple Types

There are many types of T/C that use various metal combinations. These combinations have different output characteristics that define the applicable temperature range it can measure and the corresponding voltage output. Refer to Figure 3-74 and Figure 3-75. The higher the magnitude of the voltage output the higher the measurement resolution, which increases repeatability and accuracy. There are tradeoffs between measurement resolutions and temperature ranges, which suits individual T/C types to specific ranges and applications.

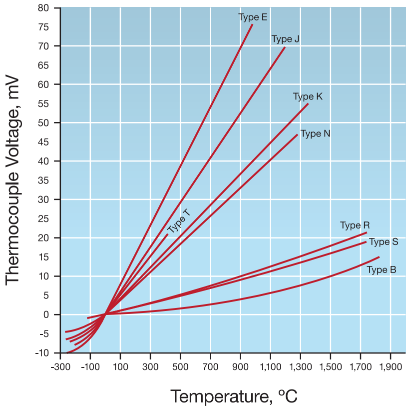


Figure 3-74 – T/C emf vs. Temperature Curves for Popular T/C Types

ANSI Letter Design	Leg	Metallic Composition	Melting Point		Potential Temperature Range
			°C	°F	
B	P	Platinum – 30% Rhodium	1825	3320	0 to 1820 °C 32 to 3308 °F
	N	Platinum – 6% Rhodium			
E	P	Chromel	1220	2230	-270 to 1000 °C -454 to 1832 °F
	N	Constantan			
J	P	Iron	1220	2230	-200 to 1200 °C -328 to 2192 °F
	N	Constantan			
K	P	Chromel	1400	2550	-270 to 1372 °C -454 to 2501 °F
	N	Alumel			
N	P	Nicrosil	1340	2440	-270 to 1300 °C -454 to 2372 °F
	N	Nisil			
R	P	Platinum – 13% Rhodium	1770	3215	-50 to 1768 °C -58 to 3214 °F
	N	Pure Platinum			
S	P	Platinum – 10% Rhodium	1770	3215	-50 to 1768 °C -58 to 3214 °F
	N	Pure Platinum			
T	P	Copper	1080	1980	-270 to 400 °C -454 to 752 °F
	N	Constantan			

P = Positive Leg, N = Negative Leg
® Trademark of Hoskins Mfg.

Table 3-75 – Detailed Thermocouple Data Chart

3.2.4.4.1 Type K Chromel® – Alumel®

- Chromel is 90% nickel and 10% chromium and Alumel is an alloy consisting of 95% nickel, 2% manganese, 2% aluminum and 1% silicon.
- Type K is one of the most common general purpose thermocouple with a sensitivity of approximately 41 µV/°C.
- The Chromel is positive relative to Alumel.
- It is inexpensive, and its potential range is -270 °C to +1372 °C (-454 °F to +2501 °F) and is relatively linear.
- The nickel constituent is magnetic and, as other magnetic metals, will undergo a deviation in output when the material reaches its Curie point, which occurs at around 350 °C (662 °F) for type K thermocouples. The Curie point is where a magnetic material undergoes a dramatic shift in its magnetic properties and causes a drastic shift to the output signal.
- It may be used in continuously oxidizing or neutral atmospheres.
- Most usage is above 538 °C (1000 °F).
- Exposure to sulphur contributes to premature failure.

WHAT ARE THE THERMOCOUPLE TEMPERATURE RANGES?

There are many types of T/C that use various metal combinations. These combinations have different output characteristics that define the applicable temperature range it can measure and the corresponding voltage output. The higher the magnitude of the voltage output, the higher the measurement resolution, which increases repeatability and accuracy. There are tradeoffs between measurement resolutions and temperature ranges, which suits individual T/C types to specific ranges and applications.

There are T/C types that can measure temperatures as low as - 270 °C (-464 °F) and other types that can measure up to 1768 °C (3214 °F).

Refer to:

3.2.4.4 – Thermocouple Types

Figure 3-75 – Detailed Thermocouple Data Chart

- Operation at certain low oxygen concentrations causes an anomaly called preferential oxidation of chromium in the positive leg, which causes a condition referred to as ‘green rot,’ which generates large negative calibration drifts that are most serious in the 816 to 1038 °C (1500 to 1900 °F) range. Ventilation or inert-sealing of the protection tube can prevent/mitigate this condition.
- Cycling above and below 1000 °C (1800 °F) is not recommended due to alteration of the output from hysteresis effects.

TIP: Historically it has been suggested to use type K unless you had a reason not to.

3.2.4.4.2 Type J (Iron/Constantan)

- Type J thermocouples have a more restricted potential range than type K of -200 to +1200 °C (346 to 2193 °F), but higher sensitivity of about 50 μV/ °C.
- It is very linear in the range of 149 to 427 °C (300 to 800 °F) and becomes brittle below 0 °C (32 °F).
- At the Curie point of the iron 770 °C (1418 °F), an abrupt and permanent change in the output characteristic occurs, which determines the practical upper temperature limit.
- The iron is subject to oxidation at higher temperatures above 538 °C (1000 °F), which adversely affects its accuracy. Only heavy gauge wire should be used in these conditions.
- Type J is suitable for use in vacuum, reducing, or inert atmospheres.
- It will have reduced life if used in an oxidizing atmosphere.
- Bare elements should not be exposed to sulphur carrying atmospheres above 538 °C (1000 °F).

3.2.4.4.3 Type E (Chromel/Constantan)

- Chromel is an alloy of 90% nickel and 10% chromium and is the positive lead.
- Constantan is an alloy usually consisting of 55% copper and 45% nickel.
- Type E has a potential range of -270 to 1000 °C (-454 °F to 1832 °F).
- It is non-magnetic and has the highest output voltage vs. temperature change of any standard type (68 μV/°C).
- It also has a tendency to drift more than the other types.
- It is recommended for continuously oxidizing or inert atmospheres.
- Its limits of error have not been established for use below zero.

3.2.4.4.4 Type T (Copper/Copper-nickel)

- Type T has a sensitivity of 38 μV/°C and has a potential range of from -270°C to 400°C (-454 °F to 752 °F).
- They can be used in oxidizing, reducing or inert atmospheres as well as in a vacuum.
- They exhibit a high resistance to moisture corrosion.
- They demonstrate a good linearity and are typically used from very low (cryogenic) to medium temperature ranges.

3.2.4.4.5 Type N (Nicrosil/Nisil)

- Nicrosil is a nickel alloy containing 14.4% chromium, 1.4% silicon, and 0.1% magnesium and is the positive lead.

- Nisil is an alloy of nickel alloyed with 4.4% silicon.
- The type N thermocouple is the newest design to have been approved by the international standards and is in ever increasing use throughput the world.
- These alloys allow the type N to achieve considerably higher thermoelectric stability than the base-metal types E, J, K and T.
- Type N thermocouples have a sensitivity of 39 μV/°C and a potential range of from -270 °C to 1300 °C (-454 °F to 2372 °F).
- Type N thermocouples have been used reliably for extended periods of time at temperatures up to at least 1200 °C (2192 °F).
- Some studies have shown that, in oxidizing atmospheres, the thermoelectric stability of the type N thermocouple is about the same as that of the noble-metal thermocouples of ANSI types R and S up to about 1200 °C (2192 °F) .
- Type N thermocouples should not be placed in vacuums or reducing or alternating reducing/oxidizing atmospheres.

3.2.4.4.6 Types R and S

- Type R (platinum-13% rhodium/platinum) and type S (platinum-10% rhodium/platinum) have a potential range of from -50 to1768 °C (58 °F to 3214 °F).
- They both have a sensitivity of about 10 μV/ °C and are not appropriate for low temperature applications where other types would be a better choice.
- Since they are constructed from a platinum alloy, they are quite costly and are generally reserved for extremely high temperature applications where other thermocouple types do not function well.
- Due to its high stability, type S thermocouples are used to define the International Temperature Scale between the point at which Antimony freezes (630.5 °C/1166.9 °F) and the melting point of gold (1064.43 °C (1945.4 °F).
- Proper installation requires that the thermocouples be protected with non-metallic protection tube and ceramic insulators.
- Long term high temperature exposure causes grain growth, which can lead to mechanical failure and a negative calibration drift caused by Rhodium diffusion to pure platinum leg as well as from Rhodium volatilization.
- In general, type R is used in industry and type S is primarily used in the laboratory.

3.2.4.4.7 Type B

- Type B thermocouples (platinum-30% rhodium/platinum-6% rhodium) have a potential range from about 0 °C to 1820 °C (32 °F to 3308 °F).
- Type B thermocouples are commonly placed in clean air/oxidizing environments but should not be used in reduction atmospheres.
- The increased amount of Rhodium in the Type B thermocouple helps to reduce the grain growth problem, allowing for a slightly increased temperature range as compared to the types R and S.

3.2.4.5 T/C Lead Wire Color Standards

Thermocouple lead wires consist of two individual wires (positive and negative), enclosed by colored insulation. Due to the Seebeck effect, thermocouple wires have a set polarity, so positive and negative wires must be connected to the correct terminals. A variety of standards exist for lead wire insulation colors to identify each thermocouple type. Refer to Figure 3-76. The different standards use unique wire colors to differentiate between the positive and negative leads. In North America, it is typical that the negative lead is red in accordance with ASTM E230. However, the most widely used global standard for T/C wires is IEC 60584 where the negative lead is typically white. It is clear that the standard to which the T/C was manufactured must be known so that the correct color code is followed. There are other standards used in various countries, including BS1843 (United Kingdom and Czech Republic), DIN43710 (Germany), JIS-C1610 (Japan), and NFC 42-324 (France). Refer to Figure 3-76.

TIP: The user must verify which standard is being used in his facility and ensure that the color codes are made available to installation, start-up and maintenance personnel.

3.2.4.6 Extension Wires

Extension wires are used to either wire thermocouples back to a control/monitoring system or to connect them to a remote transmitter. Thermocouple extension wires, with a few rare exceptions, are made of the same metal as the thermocouple wires. If the metals do not match, additional cold junctions are created at each end of the extension wire that will significantly affect the temperature measurement. In Figure 3-77, it can be seen that when copper wires are used to connect the T/C, a “premature cold junction” is created that could cause a very significant error that will vary considerably with the ambient temperature around junction 1. The measured voltage from the T/C with copper extension wires does not equal the measured voltage of the T/C with correct extension wires. In fact, if copper extension wires are used, it is nearly impossible to deduce any reasonably accurate process temperature from the measured voltage.

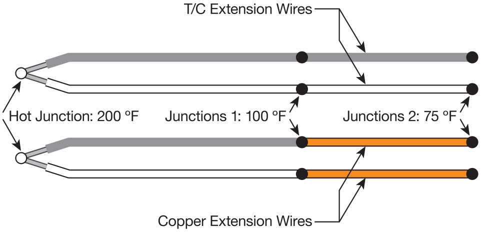


Figure 3-77 – Multiple Junctions Caused by Non-Similar Extension Wire

In some cases where economic considerations may preclude the high cost of exotic metal extension wires as are the platinum alloys used in Types R, S, and B, a less expensive copper alloy that has a similar emf to that of the T/C itself may be used over a narrow range. These leads are called Compensating Leads and somewhat reduce the error described above.

TIP: There are many negative impacts on measurement performance of remote mount T/Cs, including the potential errors that can be introduced into a T/C measurement by the use of extension wires or compensating leads from EMI and RFI, the costs of the specialized wire, cost of replacing T/C extension wire on a scheduled basis, and the possibility of wiring errors from color code mismatching. These considerations strongly suggest that consideration be given to using integrally mounted transmitters wherever possible.

3.2.4.7 Mounting Methods

Since T/Cs are constructed using similar sheath sizes as are RTDs, the mounting styles described above also apply to T/Cs. Refer to section 3.2.3.3.

3.2.4.8 Thermocouple Accuracy

Thermocouple accuracy is influenced by several factors including the T/C type, its range of interest, the purity of the material, electrical noise (EMI and RFI), corrosion, junction degradation, and the manufacturing process. T/Cs are available with standard grade tolerances or special grade tolerances called Class 2 and Class 1, respectively. The most common

T/C Type	**North America ASTM E230**		**International IEC 60584**	**UK BS 1843**	**Germany DIN 43710**	**Japan JIS C1610**	**France NFC 42-324**
	Thermocouple Grade	**Extension Grade**					
B	n/a n/a n/a	– Conductor: **Red** + Conductor: **Grey** Sheath: **Grey**	– Conductor: **White** + Conductor: **Grey** Sheath: **Grey**	n/a n/a n/a	– Conductor: **Grey** + Conductor: **Red** Sheath: **Grey**	– Conductor: **Grey** + Conductor: **Red** Sheath: **Grey**	n/a n/a n/a
E	– Conductor: **Red** + Conductor: **Purple** Sheath: **Brown**	– Conductor: **Red** + Conductor: **Purple** Sheath: **Purple**	– Conductor: **White** + Conductor: **Purple** Sheath: **Purple**	– Conductor: **Blue** + Conductor: **Brown** Sheath: **Brown**	– Conductor: **Black** + Conductor: **Red** Sheath: **Black**	– Conductor: **White** + Conductor: **Red** Sheath: **Purple**	– Conductor: **Purple** + Conductor: **Yellow** Sheath: **Purple**
J	– Conductor: **Red** + Conductor: **White** Sheath: **Brown**	– Conductor: **Red** + Conductor: **White** Sheath: **Black**	– Conductor: **White** + Conductor: **Black** Sheath: **Black**	– Conductor: **Blue** + Conductor: **Yellow** Sheath: **Black**	– Conductor: **Blue** + Conductor: **Red** Sheath: **Blue**	– Conductor: **White** + Conductor: **Red** Sheath: **Yellow**	– Conductor: **Black** + Conductor: **Yellow** Sheath: **Black**
K	– Conductor: **Red** + Conductor: **Yellow** Sheath: **Brown**	– Conductor: **Red** + Conductor: **Yellow** Sheath: **Yellow**	– Conductor: **White** + Conductor: **Green** Sheath: **Green**	– Conductor: **Blue** + Conductor: **Brown** Sheath: **Red**	– Conductor: **Green** + Conductor: **Red** Sheath: **Green**	– Conductor: **White** + Conductor: **Red** Sheath: **Blue**	– Conductor: **Purple** + Conductor: **Yellow** Sheath: **Yellow**
N	– Conductor: **Red** + Conductor: **Orange** Sheath: **Brown**	– Conductor: **Red** + Conductor: **Orange** Sheath: **Orange**	– Conductor: **White** + Conductor: **Pink** Sheath: **Pink**	– Conductor: **Blue** + Conductor: **Orange** Sheath: **Orange**	n/a n/a n/a	n/a n/a n/a	n/a n/a n/a
R	n/a n/a n/a	– Conductor: **Red** + Conductor: **Black** Sheath: **Green**	– Conductor: **White** + Conductor: **Orange** Sheath: **Orange**	– Conductor: **Blue** + Conductor: **White** Sheath: **Green**	– Conductor: **White** + Conductor: **Red** Sheath: **White**	– Conductor: **White** + Conductor: **Red** Sheath: **Black**	– Conductor: **Green** + Conductor: **Yellow** Sheath: **Green**
S	n/a n/a n/a	– Conductor: **Red** + Conductor: **Black** Sheath: **Green**	– Conductor: **White** + Conductor: **Orange** Sheath: **Orange**	– Conductor: **Blue** + Conductor: **White** Sheath: **Green**	– Conductor: **White** + Conductor: **Red** Sheath: **White**	– Conductor: **White** + Conductor: **Red** Sheath: **Black**	– Conductor: **Green** + Conductor: **Yellow** Sheath: **Green**
T	– Conductor: **Red** + Conductor: **Blue** Sheath: **Brown**	– Conductor: **Red** + Conductor: **Blue** Sheath: **Blue**	– Conductor: **White** + Conductor: **Brown** Sheath: **Brown**	– Conductor: **Blue** + Conductor: **White** Sheath: **Blue**	– Conductor: **Brown** + Conductor: **Red** Sheath: **Brown**	– Conductor: **White** + Conductor: **Red** Sheath: **Brown**	– Conductor: **Blue** + Conductor: **Yellow** Sheath: **Blue**

Figure 3-76 – International Color Coding for Thermocouple Insulation controlling international standard is IEC-60584-2. The most common U.S. standard is ASTM E230. Each standard publishes limits of tolerance for compliance. Refer to Figures 3-78 and 3-79.

<table>
<tr><th>Types</th><th>Tolerance Class 1</th><th>Tolerance Class 2</th><th>Tolerance Class 3 1)</th></tr>
<tr><td>Type T</td><td></td><td></td><td></td></tr>
<tr><td>Temperature Range</td><td>-40 °C to +125 °C</td><td>-40 °C to +133 °C</td><td>-67 °C to +40 °C</td></tr>
<tr><td>Tolerance Value</td><td>±0.5° C</td><td>±1 °C</td><td>±1 °C</td></tr>
<tr><td>Temperature Range</td><td>125 °C to 350 °C</td><td>133 °C to 350 °C</td><td>-200 °C to -67 °C</td></tr>
<tr><td>Tolerance Value</td><td>±0.004 · | t |</td><td>±0.0075 · | t |</td><td>±0.015 · | t |</td></tr>
<tr><td>Type E</td><td></td><td></td><td></td></tr>
<tr><td>Temperature Range</td><td>-40 °C to +375 °C</td><td>-40 °C to +333 °C</td><td>-167 °C to +40 °C</td></tr>
<tr><td>Tolerance Value</td><td>±1.5 °C</td><td>±2.5 °C</td><td>±2.5 °C</td></tr>
<tr><td>Temperature Range</td><td>375 °C to 800 °C</td><td>333 °C to 900 °C</td><td>-200 °C to -167 °C</td></tr>
<tr><td>Tolerance Value</td><td>±0.004 · | t |</td><td>±0.0075 · | t |</td><td>±0.015 · | t |</td></tr>
<tr><td>Type J</td><td></td><td></td><td></td></tr>
<tr><td>Temperature Range</td><td>-40 °C to +375 °C</td><td>-40 °C to +333 °C</td><td>–</td></tr>
<tr><td>Tolerance Value</td><td>±1.5 °C</td><td>±2.5 °C</td><td>–</td></tr>
<tr><td>Temperature Range</td><td>375 °C to 750 °C</td><td>333 °C to 750 °C</td><td>–</td></tr>
<tr><td>Tolerance Value</td><td>±0.004 · | t |</td><td>±0.0075 · | t |</td><td>–</td></tr>
<tr><td>Type K, Type N</td><td></td><td></td><td></td></tr>
<tr><td>Temperature Range</td><td>-40 °C to 375 °C</td><td>-40 °C to +333 °C</td><td>-167 °C to +40 °C</td></tr>
<tr><td>Tolerance Value</td><td>±1.5 °C</td><td>±2.5 °C</td><td>±2.5 °C</td></tr>
<tr><td>Temperature Range</td><td>375 °C to 1000 °C</td><td>333 °C to 1200 °C</td><td>-200 °C to -167 °C</td></tr>
<tr><td>Tolerance Value</td><td>±0.004 · | t |</td><td>±0.0075 · | t |</td><td>±0.015 · | t |</td></tr>
<tr><td>Type R, Type S</td><td></td><td></td><td></td></tr>
<tr><td>Temperature Range</td><td>0 °C to 1100 °C</td><td>0 °C to +600 °C</td><td>–</td></tr>
<tr><td>Tolerance Value</td><td>±1 °C</td><td>±1.5 °C</td><td>–</td></tr>
<tr><td>Temperature Range</td><td>1100 °C to 1600 °C</td><td>600 °C to 1600 °C</td><td>–</td></tr>
<tr><td>Tolerance Value</td><td>±[1 + 0,003 (t-1100)] °C</td><td>±0.0025 · | t |</td><td>–</td></tr>
<tr><td>Type B</td><td></td><td></td><td></td></tr>
<tr><td>Temperature Range</td><td>–</td><td>–</td><td>600 °C to 800 °C</td></tr>
<tr><td>Tolerance Value</td><td>–</td><td>–</td><td>+4 °C</td></tr>
<tr><td>Temperature Range</td><td>–</td><td>600 °C to 1700 °C</td><td>800 °C to 1700 °C</td></tr>
<tr><td>Tolerance Value</td><td>–</td><td>±0.0025 · | t |</td><td>±0.005 · | t |</td></tr>
</table>

1) Thermocouple materials are normally supplied to meet the manufacturing tolerances specified in the table for temperatures above -40 °C. These materials, however, may not fall within the manufacturing tolerances for low temperatures given under Class 3 for Types T, E, K and N. If thermocouples are required to meet limits of Class 3, as well as those of Class 1 or 2, the purchaser shall state this, as selection of materials is usually required.

Figure 3-78 – Thermocouple Tolerance Requirements for Compliance with IEC 60584-2

3.2.5 Measurement Response Time Considerations

A sensor's dynamic response time can be important when the temperature of a process is changing rapidly and fast inputs to the control system are needed. A sensor installed directly into the process will have a faster response time than a sensor with a thermowell.

It's important to note that when no thermowell is used, the sensing element is exposed to the process and cannot be replaced without interrupting the flow, which often requires a process shutdown and draining the process system. Engineering guidelines, in most process facilities, will not permit exposed sensors. Such installations are far less safe against potential loss of containment of process fluids, can cause more frequent sensor failure from exposure to adverse process conditions, and often require an expensive process shutdown to change out a failed sensor. Use of a thermowell is the solution to this problem.

However, when a thermowell is used, response time clearly increases due to the increased thermal mass of the assembly. The key to optimizing response time is to reduce the mass while maintaining adequate physical strength to withstand the process pressures and flow forces. Smaller diameter thermowells provide faster response, since less material needs to be heated or cooled. A properly fit sensor is also important to achieve a faster response time. The sensor needs to be long enough so its tip is touching the bottom of the thermowell bore for good conduction. The sensor diameter also needs to fit snugly into the thermowell bore so there is a minimum air gap between the sensor and the thermowell. Additionally, response time is improved by using a spring-loaded sensor and filling the voids in the well with thermally conductive fluid. The characteristics of the medium being measured are also factors, especially with regard to flow velocity and density. A fast moving medium transfers heat and changing temperature better than a slow moving one, and higher density media (fluids) are better heat conductors than lower density media (gases). (Refer to section 3.3 for more detail.)

When comparing the response of temperature measurement systems using an bare T/C or an bare RTD in a flowing water application, it has shown that a grounded tip T/C will respond about 2 times faster than will a spring-loaded RTD sensor. For measurements in flowing air an RTD is slightly faster than a T/C.

However, that advantage is greatly minimized, if not eliminated, when the sensor is installed in a thermowell. The mass of a thermowell is so large as compared to the mass of a sensor, that it clearly dominates the response characteristics of the system.

When using a 6 mm (1/4”) diameter sensor in a water measurement application, T/C and RTD response is about the same and when using a 3mm diameter sensor a T/C is slightly faster than an RTD. For measurements in air, the response is about the same for both RTDs and T/Cs using either a 3 mm (1/8”) or 6 mm sensor.

TIP: Since very few process applications use bare sensors for measurement, the inherent speed advantage of a T/C is greatly reduced and possibly eliminated for most applications. The wise engineer will select the best sensor for the application based on a myriad of other factors and not be influenced by the misleading statements made so often that “T/Cs are always faster than RTDs”.

Tolerances on Initial Values of Emf vs. Temperature for Thermocouples

Note 1 – Tolerances in this table apply to new essentially homogeneous thermocouple wire, normally in the size range 0.25 to 3mm in diameter (No. 30 to No. 8 AWG) and used at temperature not exceeding the recommended limits. If used at higher temperatures these tolerances may not apply.

Note 2 – At a given temperature that is expressed in ˚C, the tolerance expressed in ˚F is 1.8 times larger than the tolerance expressed in ˚C. Where tolerances are given in percent, the percentage applies to the temperature being measured when expressed in degrees Celsius. To determine the tolerance in degrees Fahrenheit, multiply the tolerance in degrees Celsius by 9/5.

Note 3 – Caution: Users should be aware that certain characteristics of thermocouple materials, including the Emf-vs.-temperature relationship, may change with time in use; consequently, test results and performance obtained at the time of manufacture may not necessarily apply throughout an extended period of use. The magnitude of such changes will depend on such factors as wire size, temperature, time of exposure, and environment. It should be further noted that due to possible changes in homogeneity, attempting to recalibrate *used* thermocouples is likely to yield irrelevant results, and is not recommended. However, it may be appropriate to compare used thermocouple *in-situ* with new or known good ones to ascertain their suitability for further service under the conditions of the comparison.

Thermocouple Type	**Temperature Range**		**Tolerances-Reference Junction 0 °C [32 °F]**			
			Standard Tolerances		**Special Tolerances**	
	°C	**°F**	**°C** (whichever is greater)	**°F**	**°C** (whichever is greater)	**°F**
T	0 to 370	32 to 700	±1.0 or ±0.75%	Note 2	±0.5 or ±0.4%	Note 2
J	0 to 760	32 to 1400	±2.2 or ±0.75%		±1.1 or ±0.4%	
***E**	0 to 870	32 to 1600	±1.7 or ±0.5%		±.01 °C or ±0.4%	
K or N	0 to 1260	32 to 2300	±2.2 °C or ±0.75%		±1.1 °C or ±0.4%	
R or S	0 to 1480	32 to 2700	±1.5 °C or ±0.25%		±0.6 °C or ±0.1%	
B	870 to 1700	1600 to 3100	±0.5%		±0.25%	
C	0 to 2315	32 to 4200	±4.4 or 1%	Note 2	Note applicable	
T[A]	-200 to 0	-328 to 32	±1.0 or ±1.5%		[B]	
***E**[A]	-200 to 0	-328 to 32	±1.7 or ±1%		[B]	
K[A]	-200 to 0	-328 to 32	±2.2 or ±2%		[B]	

* The standard tolerances shown do not apply to Type E mineral-insulated, metal-sheathed (MIMS) thermocouples and thermocouple cables as described in Specifications E608/E608M and E585/E585M. The standard tolerances for MIMS Type E constructions are greater of ±2.2 ˚C or ±0.75% from 0 to 870 ˚C and the greater of ±2.2 ˚C or ±2% from -200 to 0 ˚C.

[A] Thermocouples and thermocouple materials are normally supplied to meet the tolerances specified in the table for temperatures above 0 ˚C. The same materials, however, may not fall within the tolerances for temperature below 0 ˚C in the second section of the table. If materials are required to meet the tolerances stated for temperatures below 0˚ C, the purchase order shall so state. Selection of materials usually will be required.

[B] Special tolerances for temperatures below 0 ˚C are difficult to justify due to limited available information. However, the following values for Types E and T thermocouples are suggested as a guide for discussion between the purchaser and supplier:

Type E, -200 to 0 ˚C, ±1.0 ˚C or ±0.5% (whichever is greater)
Type T, -200 to 0 ˚C, ±0.5 ˚C or ±0.8% (whichever is greater)

Initial values of tolerance for Type J thermocouples at temperatures below 0 ˚C and special tolerances for Type K thermocouples below 0 ˚C are not given due to the characteristics of the materials. Data for Type N thermocouples below 0 ˚C are not currently available.

Figure 3-79 – Thermocouple Tolerance Requirements for Compliance with ASTM E230 -11

Summary

In this chapter, we have provided a detailed insight into the theory, design, construction, installation and operation of the two primarily used temperature sensors in the industrial process industries, RTDs and Thermocouples. From the discussion of each of these sensor's performance and accuracy capabilities, it may be deduced that there are many decision factors involved in choosing the correct sensor for your application. For some high temperature applications, T/Cs are the only choice and for other applications either sensor would function. The decision of choice lies with other considerations, including required measurement system accuracy, long term performance and cost of ownership.

These topics and many more are presented in further detail in Chapter 4.3.

3.3 Thermowells

3.3.1 Overview

Temperature sensors are rarely inserted directly into an industrial process. They are installed into a thermowell to isolate them from the potentially damaging process conditions of flow-induced stresses, high pressure, and corrosive chemical effects. Thermowells are closed-end metal tubes that are installed into the process vessel or piping and become a pressure-tight integral part of the process vessel or pipe. They permit the sensor to be quickly and easily removed from the process for calibration or replacement without requiring a process shutdown and possible drainage of the pipe or vessel.

The most common types of thermowells are threaded, socket weld, and flanged. Thermowells are classified according to their connection to a process. For example, a threaded thermowell is screwed into the process, a socket weld thermowell is welded into a weldalet and a weld-in thermowell is welded directly into the process pipe or vessel. A flanged thermowell has a flange collar, which is attached to a mating flange on the process vessel or pipe.

3.3.2 Thermowell Types

Thermowells are most often constructed from machined barstock in a variety of materials and may be coated with other materials for erosive or corrosive protection. They are available with threaded, welded or flanged connections. The stem or shank that extends into the process may be straight with constant diameter, tapered all the way from entry point to the tip, partially tapered, or stepped. See Figure 3-80.

A variety of performance criteria and process conditions must be considered when selecting the best design for an application. In the following sections, we will discuss detailed aspects of thermowell design and their applications.

Figure 3-80 – Thermowell Family

3.3.3 Thermowell Design Insights

3.3.3.1 Materials

The material of construction is typically the first consideration in choosing a thermowell for any given application. Three factors affect the choice of material:

- Chemical compatibility with the process media to which the thermowell will be exposed
- Temperature limits of the material
- Compatibility with the process piping material to ensure solid, non-corroding welds and junctions

It is important that the thermowell conforms to the design specs of the pipe or vessel into which it will be inserted to ensure structural and material compatibility. The original design of the process had most likely included temperature, pressure and corrosive considerations as well as cleaning procedures, agency approvals required and conformance with codes or standards. Since an installed thermowell effectively becomes part of the process, these original design considerations also apply to the thermowell and will drive the thermowell material of construction and mounting type selection. International pressure vessel codes are explicit about the types of materials and the methods of construction allowed. Although there is no equivalent to the pressure vessel codes for thermowells, the ASME BPVC and B31 standards do have considerations for the different types of pipe fittings, including flanged, socket-welded and threaded. Details on these considerations can be found in the following:

ASME B16.5 covers flanged fittings; ASME B16.11 covers socket-welded and threaded fittings. Also, for reference, the ASME B31.3 covers process piping while ASME B31.1 covers power piping, and ASME B40.9 covers thermowells specifically (although in a more general sense). Due consideration should be given to these codes when specifying thermowells as integral parts of the process structure.

Errors in the specification of pressure retaining components could have disastrous results leading to loss of life, loss of containment and even potential prosecution. See Figure 3-81.

Although there are many choices of thermowell material of construction, the most commonly used materials are 316 stainless steel, 304 stainless steel, Monel®, Inconel®, and Hastelloy®. See Figure 3-82.

There are also some exotic metals for very demanding applications.

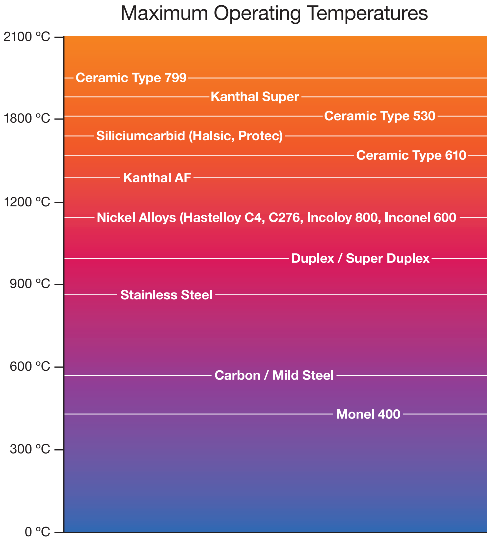


Figure 3-82 – Thermowell Material Recommendations

Figure 3-81 – Thermowell Installation Examples

3.3.3.2 Styles

Thermowells are generally either tubular or machined from barstock. Each style has pros and cons and selection of the proper thermowell depends on the requirements of the application.

***3.3.3.2.1* –** Protection tubes, sometimes called Tubular Thermowells, are fashioned by welding a flange or threaded fitting to one end of tube or small section of pipe or tubing and capping the other end. Protection tubes can also be constructed of ceramic material and bonded to a metal process fitting. Tubular thermowells can be constructed for very long immersion lengths and are often used for measurements where flow forces are low. Since they are fabricated from tubing, they have a much larger bore than other thermowells, which causes a considerable thermal lag. See Figure 3-83.

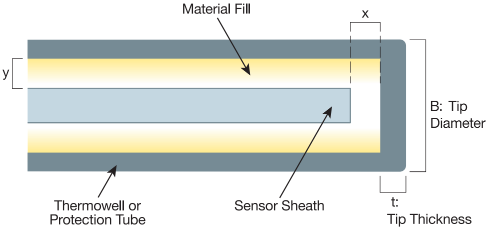


Figure 3-83 – Factors Affecting Response Time for a Large Bore Thermowell

Due to their construction, they have a much lower pressure rating and the choice of materials is limited. For measuring temperatures up to 1800 °C, the protection tubes are made from a ceramic material.

***3.3.3.2.2* –** Barstock thermowells are machined from a solid piece of round or hex shaped metal. Barstock thermowells can withstand higher pressures and faster flow rates than protection tubes. They have more material options and can be mounted in various ways to meet different process pressure requirements. Lengths are typically limited due to bore drilling limitations. See Figure 3-80 in section 3.3.2.

3.3.3.3 Stem Profiles

Factors to be considered when selecting a stem style include the process pressure, the required speed of response of the measurement, the drag force of the fluid flow on the well and the vortex shedding induced vibration effects.

The stem or shank is the part of a thermowell that is inserted into the process piping. The common stem profiles are straight, stepped, and tapered. See Figure 3-84.

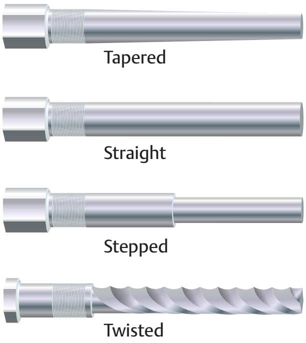


Figure 3-84 – Thermowell stem profiles

3.3.3.3.1* – *Straight profile thermowells have the same diameter along the entire immersion length. They present the largest profile to the process medium and therefore have the highest drag force as compared to other well styles with the same root diameter. Because of the large tip diameter, there is more mass to heat which slows the thermal response of the measurement assembly. See Figure 3-85.

Figure 3-85 – Straight Profile Thermowell

3.3.3.3.2* – *Stepped profile thermowells have two straight sections with the smaller diameter straight section at the tip. Refer to Figure 3-86. For the same root diameter as a straight profile thermowell, this design has less profile exposure to the flowing process and therefore exhibits less drag force and quicker response time due to the smaller mass at the tip. In general, stepped thermowells will have thinner walls. By the geometry of its design, the stepped well has a higher natural frequency than the other profile designs of the same root diameter and is therefore less susceptible to vibration induced failure. See section 3.3.7 below for more detail.

Figure 3-86 – Stepped Thermowell

3.3.3.3.3 – Tapered profile thermowells have an outside diameter that decreases uniformly from root to tip. For the same root diameter, this profile represents a good compromise between straight and stepped thermowells. It's drag will be less than a straight type well but greater than a stepped type well. Also, the response time will be faster than a straight type and slower than a stepped type. The two general forms of a tapered stem are uniform (tapered from root to tip) and non-uniform (straight portion followed by tapered portion). See Figure 3-87. Because of its profile shape, it is a good compromise for strength between the two other styles. It is the common choice for high velocity flow applications where the flow forces typically are too great to use a stepped well and the tapered design has faster response than the straight type, thus offering an optimal balance of strength and response factors.

Figure 3-87 – Tapered Threaded and Tapered Flanged Thermowells

3.3.3.3.4 – Twisted Square™ profile thermowells have a unique twisted design that is uniform for the entire length of the stem. This profile is a Rosemount patented design and was designed specifically to suppress the harmful vortex induced vibrations a thermowell experiences in process applications. Refer to Figure 3-88. This profile compared to all the others will provide the best results when it comes to suppressing harmful vortex shedding induced vibrations. This allows for proper stem immersion in the pipe (close to 50% immersion is ideal), which provides an accurate and, more importantly, a repeatable temperature measurement.

Figure 3-88 – Flanged Twisted Square Thermowell

3.3.4 Mounting Methods

Thermowells are typically mounted by one of the following methods: See Figure 3-89.

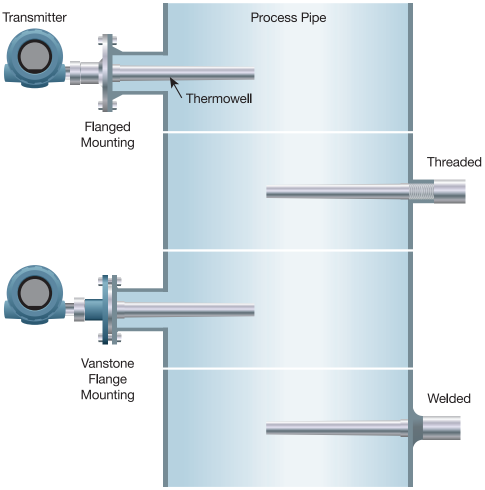


Figure 3-89 – Thermowell Mounting Methods

3.3.4.1 – Threaded thermowells are threaded into process piping or tank, which allows for easy installation and removal when necessary. While this is the most commonly used method of mounting, it has the lowest pressure rating of the three options. Threaded connections are also prone to leakage and therefore are not recommended for applications with toxic, explosive or corrosive materials.

3.3.4.2 – Welded thermowells are permanently welded to process pipes or tanks. Thus, removal is difficult and requires cutting the thermowell out of the system. Welded thermowells have the highest pressure rating and are generally used in applications with high velocity flow, high temperature, or extreme high pressure. They are necessary where a leak-proof seal is required.

3.3.4.3 – Flanged thermowells are bolted to a mating flange that is welded onto process pipe or tank. They provide high pressure ratings, easy installation, and simple replacement. Flanged thermowells are used in applications with corrosive environments, high-velocity, high temperature, or high pressure.

3.3.4.4 – Vanstone/Lap Flange thermowells are mounted between the mating flange and the lap flange. These thermowells allow for the use of different materials for the thermowell coming in contact with the process and the overlaying flange, which can save material and manufacturing costs. They are a good choice for corrosive applications since there are no welds in this design, eliminating weld-joint corrosion. As an option they can be provided as a forging.

3.3.5 Mounting Options

To accommodate pipe or vessel insulation layer thickness or other offset considerations like high ambient temperature, a thermowell may be specified with varying head lengths. See Figure 3-90 and section 4.3 for more detail.

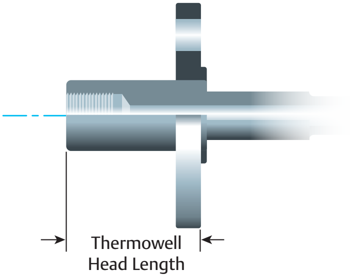


Figure 3-90 – Thermowell Head Length

3.3.5.1 Installation without a Thermowell

In the industrial process industry, thermowells are used for almost all applications. Some examples of exceptions to that rule include applications for very-low-pressure air or ventilating systems, bearing temperature measurement, and lube oil drain in compressors. Reasons for direct immersion are usually associated with a requirement for faster response or where there are space limitations, such as casing drain in compressors. Installing temperature elements without a thermowell is acceptable in some applications or where certain conditions exist:

- The process fluid is not corrosive or otherwise hazardous
- The process is not under significant pressure
- Air-in leakage is permissible
- The primary element has the necessary static and dynamic mechanical strength for the application
- A failure of the element may be tolerated until the process can conveniently be shut down and assuming the operation can continue without the use of the measurement
- There is no personnel hazard if the temperature sensor is inadvertently removed from the vessel, pipe or duct.

3.3.6 Manufacturing

Thermowells are machined on special-purpose high-accuracy machines exercising careful quality control to ensure concentricity of the bore with respect to the outside diameter and a consistent wall-thickness over the full length of the thermowell. Meeting these criteria is essential to ensure that the thermowell meets the stated pressure ratings that are related to uniform wall thickness. This in turn relates to code conformance as was described above.

3.3.7 Thermowell Failure Considerations

Thermowell failures are often associated with one or more of the following: high drag forces, excessive static pressure, high temperature, corrosion and fluid induced vibration.

3.3.7.1 Vibration

Most thermowell failures are caused by fluid induced vibration. See Figure 3-91.

When fluid flows past a thermowell inserted into a pipe or duct, vortices form at both sides of the well. These vortices detach, first from one side, and then from the other in an alternating pattern. This phenomenon is known as vortex shedding, the Von Karman Vortex Street or flow vortices. The differential pressure due to the alternating vortices produces alternating forces on the well, resulting in stresses that cause alternating transverse deflection. In addition, there are other forces produced along the axial or parallel axis of the flow. See Figure 3-92. The frequency of shedding of these vortices – called the vortex shedding frequency (or fs) – is a function of the diameter of the thermowell, the fluid velocity and, to a lesser extent, the Reynolds number.

Figure 3-91 – Example of a Thermowell Failure

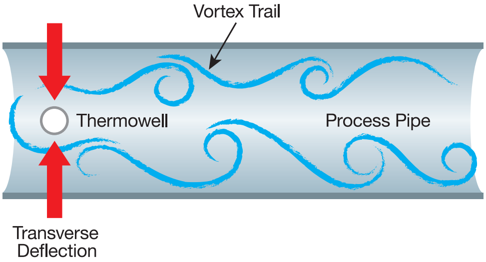


Figure 3-92 – The von Karman Trail, Showing Transverse Force Deflection and Direction

Each thermowell design has a natural frequency (referred to as fn) that is dependent on its shape, length, and material of construction.

As the vortex shedding frequency approaches the natural frequency of the thermowell, the thermowell will oscillate in resonance and may fracture with potentially dire consequences.

It is clear that the vortex shedding forces must be taken into account when selecting a thermowell of sufficient strength and stiffness to withstand the service conditions, and generally thermowells are selected such that the shedding frequency is always ≤ 80% of the natural frequency. Or mathematically as a ratio, where fs÷ fn ≤ 0.8. For liquid flow with a fs÷ fn ratio from 0.4 to 0.5, the axial forces are an important factor of concern.

By the geometry of its design, the stepped well has a higher natural frequency than the straight or tapered profile designs with the same root diameter and will typically produce a wider separation of the vortex shedding wake frequency fs from the natural frequency of the thermowell fn (Lower ratio), resulting in less chance of resonant oscillation leading to potential thermowell failure.

TIP: Wake frequency is a determining factor in selecting a thermowell for a high-velocity application. Most manufacturers have a software tool to provide an analysis of the wake frequency effects that predicts probability of failure of the thermowell. The Rosemount Thermowell Design Accelerator is a free online thermowell calculation tool that allows you to execute thermowell calculations up to 90% faster and reduces design time to just 15 minutes. It's easy to use and guides you through complex projects, saving hours of wasted labor and resources. Calculations use ASME PTC 19.3 TW criteria for safe results to protect processes and the people that operate them.

TIP: The ASME PTC 19.3 TW is a standard that establishes the practical design considerations for thermowell installations in power and process piping. This code is an expanded version of the thermowell section contained in the PTC 19.3-1974, and incorporates the latest theory in the areas of natural frequency, Strouhal frequency, in-line resonance and stress evaluation. It includes:

- *Expanded coverage for thermowell geometry*
- *Natural frequency correction factors for mounting compliance, added fluid mass, and sensor mass*
- *Consideration for partial shielding from flow*
- *Intrinsic thermowell damping*
- *Steady state and dynamic stress evaluations*
- *Improved allowable fatigue limit definition.*

See Reference Material in Chapter 7 for a white paper titled “Thermowell Calculations,” detailing insights into the provisions and requirements of PTC 19.3 TW.

3.3.8 Response Time Considerations

As was discussed in section 3.2, the speed of response of the sensor itself is dwarfed by the much slower response of the measurement system using a thermowell. The mass of the thermowell far exceeds that of the sensor and will always be the dominant factor of measurement response.

Several factors affect the overall response time of temperature measurements when thermowells are used, including:

- Stem style.
- Tip thickness and diameter.
- Sensor sheath OD to thermowell bore ID gap. (“y” dimension in Figure 3-94).
- Process media (liquid, steam or vapor). See Figure 3-93 – The more dense the fluid, the faster the response.
- Process flow rate with faster rates providing shorter response time.

Refer to Figure 3-93. For systems where the fastest possible response is needed, there are system design considerations that will optimize measurement speed, including:

- Select a stepped well, which has less mass at the tip than do the straight and tapered thermowells. (Dimensions “B” and “t”) (Straight wells are the slowest and tapered are a compromise between the two.).
- Use a tip sensitive sensor so that the sensitive portion is at the thinnest part of the well.
- Select a spring-loaded sensor to ensure tight contact of the sensor to the bottom of the well. (“x” = 0 in Figure 3-94).
- Specify a thermally conductive media to fill the void between the sensor and the wall of the thermowell. (“y” dimension in Figure 3-94)
- Specify the proper immersion length to ensure that the tip of the well is in the faster moving part of the fluid flow stream. (The faster the flow, the faster will be the response for a given fluid density.)

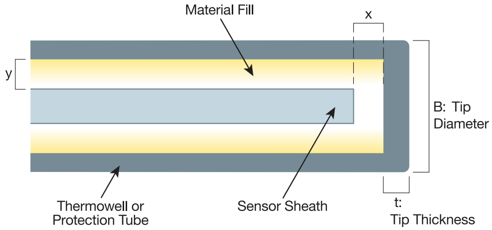


Figure 3-94 – Factors Affecting Response Time

3.3.9 Thermowell Standards

3.3.9.1 – The ASME PTC 19.3 TW is internationally recognized as a mechanical design standard yielding reliable thermowell service in a wide range of temperature measurement applications. It includes evaluation of stresses applied to a barstock thermowell as installed in a process based on the design, material, mounting method, and the process conditions. For detailed information about this standard, refer to the white paper “Thermowell Calculations” in Chapter 7, Reference Materials.

Thermal Time Response Data (per IEC 751)

Sensor and Thermowell in water flowing at 0.4 meters/sec

1067 Sensor - 6mm diameter											
1097 (D22) Thermowell		**Pt 100**			**Pt 100**			**Pt 100**			
Material	Material Code	t(0.5) [s]	t(0.63) [s]	t(0.9) [s]	t(0.5) [s]	t(0.63) [s]	t(0.9) [s]	t(0.5) [s]	t(0.63) [s]	t(0.9) [s]	Deviation
316L Stainless steel	A2	29	37	75	26	37	85	29	40	89	± 10%
304L Stainless steel	A5	29	37	75	26	37	85	29	40	89	± 10%
304L Stainless steel with carbon steel flange	A6	29	37	75	26	37	85	29	40	89	± 10%
316L Stainless steel with Tantalum sheath	B2	75	96	183	67	88	184	64	85	180	± 10%
316L Stainless steel with Tantalum sheath with Platinum beads	B3	75	96	183	67	88	184	64	85	180	± 10%
316L Stainless steel with PFA coating	B4	76	97	181	78	101	197	80	104	203	± 10%
Carbon Steel	C1	29	37	75	26	37	85	29	40	89	± 10%
Alloy 20	D1	27	35	71	34	46	98	31	41	90	± 10%

Figure 3-93 – Excerpt from Response Data Test Report

3.3.9.2 – The Energy Institute Section T.4, Guidelines for Avoidance of Vibration Induced Fatigue Failure in Process Pipework, provides an overview of vibration characteristics and how vibration affects piping systems. This is a useful document on the handling of vibration with some information that is specific to thermowells. Included is a quantitative assessment to determine the "likelihood of failure" (LOF) using a natural frequency calculation based on wall thickness. This document also presents valid information on corrective actions that can be taken to ensure longevity of existing thermowells.

3.3.9.3 – DIN 43772 is a European (German) standard with specifications for thermowell design, construction, and materials. The design specifications cover various types of thermowells, dimensions, wall thicknesses, types of construction, connection methods, and requirements for marking and testing thermowells and extension tubes. Also included are limited strength evaluations (load diagrams) based on flow conditions.

3.3.9.4 – ASME B16.5 standard controls the design of pipe flanges and flanged fittings. Included are pressure/temperature ratings for various fitting methods and materials of construction and complete dimensional specifications and tolerances. Pressure testing is also covered.

Summary

As has been discussed in this section, there are many considerations involved in selecting a proper thermowell for your temperature measurement system. The system design engineer must gather all available process information and performance expectations before beginning the system design. Front end engineering will pay large dividends by providing an optimally performing temperature measurement system with the lowest cost of ownership.

3.4 Rosemount X-well™ Technology

Temperature is the most commonly measured variable in the process industry. It is often a critical factor in determining process efficiency and product quality. There are several ways to measure temperature in the process industry and each present their own unique challenges. Rosemount X-well Technology can address the challenges and alleviate the pains inherent to traditional process temperature measurement practices.

A thermowell and temperature sensor assembly is the most frequently used method of measuring a temperature internal to a process. Thermowells allow for direct sensor immersion into a process, which helps provide an accurate measurement, but introduces many complex design challenges and risks associated with creating a possible leak point.

A traditional surface sensor measurement can remove the challenges presented by a thermowell by eliminating the need for a process intrusion. Unfortunately, this method comes with its own challenges, as it cannot provide an accurate or repeatable representation of an internal process temperature due to various factors that can impact the measurement.

Rosemount X-well Technology eliminates the challenges presented by thermowells and process intrusions while providing comparable measurement performance. This innovation implements a heat flux algorithm that applies known thermal conductivity properties of both the process pipe or vessel and the surface temperature measurement assembly to calculate an accurate and repeatable internal process temperature value.

Figure 3-95 – Rosemount X-well is Available in Both Wired or Wireless Offerings

3.4.1 Thermowell Technology Challenges

A thermowell installation is the most common method of measuring temperature in the process industry. A thermowell is a component of a temperature measurement point that acts as a protective barrier between the temperature sensor and process. It enables insertion of the temperature sensor into the process where it might not otherwise survive the harsh conditions present. These conditions include flow-induced stresses, high pressure, and corrosive or erosive process fluids.

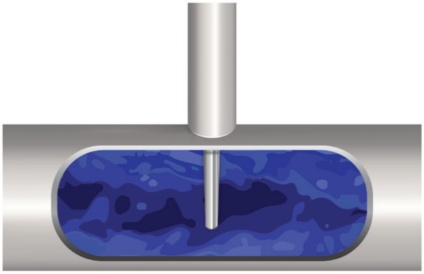


Figure 3-96 – Example of a Thermowell installation

A thermowell allows the sensor to be put directly into a process (see Figure 3-96) where the temperature measurement is needed, but, in doing so, also introduces a possible leak point and safety concern, as a penetration into the process is required. Since the thermowell directly contacts the process, several considerations are required for design and installation. The process fluid type, density and state as well as properties such as pressure, temperature, flowrate and viscosity all play roles in the design of a thermowell to ensure a proper selection and safe installation. Material compatibility is also a concern for corrosive or abrasive process fluids. Wake frequency calculations (based on ASME PTC 19.3 TW) are performed to ensure proper design for thermowells, however, this calculation is based on a single set of process data points. If the process parameters change from those used for wake frequency calculations, the thermowell may no longer be appropriately designed for the application. This could lead to fatigue, breakage and ultimately, failure of the thermowell (see Figure 3-97). To alleviate this risk, wake frequency calculations are often performed multiple times for each measurement point for several process cases across a range of temperatures, pressures and flowrates.

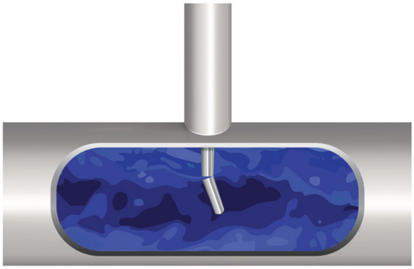


Figure 3-97 – Thermowell Breakage due to Fatigue caused by Internal Process Fluid Velocity and Ultimately, Failure of the Thermowell.

All these considerations drive increased complexity in thermowell design, which can require change if process requirements change. Design considerations for a thermowell include, but are not limited to:

-Stem Profile

-Immersion Length

-Material Type

-Process Connection Type

-Extension Length

-Tip Thickness

-Bore Diameter

Temperature measurement in small line sizes presents yet another challenge for thermowells. Stem conduction error (i.e. error induced on a temperature measurement by the ambient temperature and other external temperature sources via heat conduction) impacts accuracy when the immersion length is less than 10 times the thermowell tip diameter. It is often impossible to achieve this immersion length to tip diameter relationship in small line sizes.

For example, a thermowell with a tip diameter of 0.5 inches would require a minimum thermowell immersion length of five inches to avoid stem conduction errors. Obviously, this is difficult in line sizes under five inches. Thermowell installation in a pipe elbow can provide the proper immersion length in a small line size, but this is not always available.

Finally, since a thermowell is in direct contact with the process, any instance of visual inspection, new installation, or replacement requires process shutdown.

3.4.2 Traditional Surface Measurement Technology Challenges

A surface temperature measurement installation (see Figure 3-98) alleviates many of the pains associated with a thermowell installation, as it does not require direct contact with the process. Since the measurement point is external to the process being measured, there is no threat of internal conditions physically damaging it or creating potential leak points. The need for wake frequency calculations and other complex design considerations are eliminated.

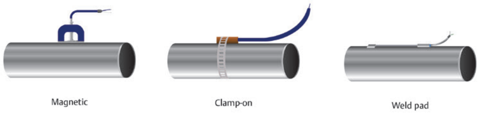


Figure 3-98 – Temperature Measurement Installation Examples

Although a traditional surface temperature measurement installation addresses many of these pains and challenges, in most cases, it cannot match the measurement performance of a thermowell installation. If an internal process temperature measurement is required, a surface temperature measurement is often not capable of providing an accurate or repeatable representation of an internal measurement.

Ambient factors can severely impact the surface measurement reading, producing unpredictable results and complicating any attempt to relate surface temperature to process temperature. The relationship between surface temperature and process temperature is heavily dependent on the difference between ambient temperature and internal process temperature. Even a uniformly applied correction to the surface temperature measurement as an attempt to equate it to an expected temperature drop through a pipe or vessel wall loses validity if either process or ambient temperature changes. The temperature surface sensor and associated assembly can act as a "heat sink," absorbing heat from either the process or external environment, producing inaccuracies similar to stem conduction errors common in small line size thermowell installations.

Figure 3-99 shows an example of how temperature from a pipe to a transmitter head can propagate in a surface sensor assembly. This non-linear relationship is difficult to model for a correction scheme. Application of insulation over the temperature assembly can reduce the majority of nonlinear heat flow and help create a one-dimensional heat flow profile through the temperature assembly and transmitter head. This linearization of the heat flow does not remove all inaccuracies from a surface measurement, but provides a path for a solution to correct for a varying ambient and process conditions.

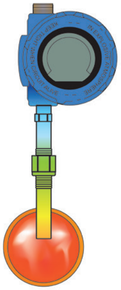


Figure 3-99 – Temperature Propegating from Pipe to Transmitter

Figure 3-100 and Figure 3-101 illustrate heat loss profiles on a surface temperature assembly to the environment in both free and forced convection environments.

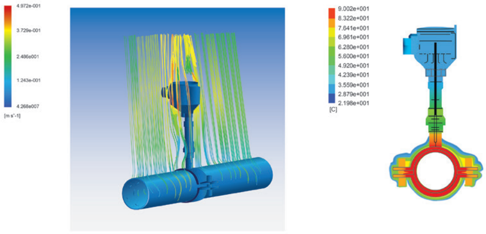


Figure 3-100 – Free Convection Model

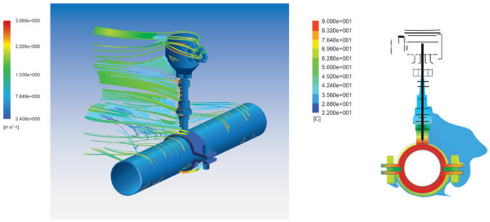


Figure 3-101 – Forced Convection Model

Figure 3-102 shows data from a water flow loop comparing an inserted RTD (resistance temperature detector) sensor temperature measurement and an insulated surface temperature measurement. In this trial, ambient temperature is kept fairly stable between 27 °C and 29 °C, while process temperature is increased from 40 to over 80 °C in a series of ramps. As the differential between process temperature and ambient temperature increases, the difference between process and surface temperatures increases from 1 °C to nearly 5 °C.

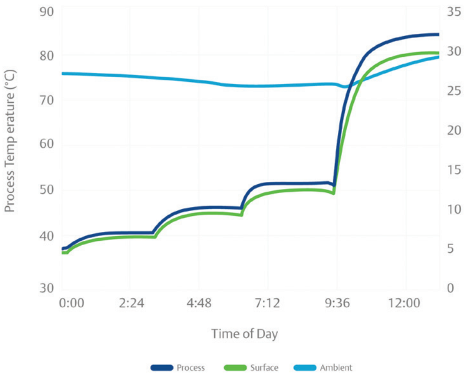


Figure 3-102 – Changing Process Temperature: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe)

Conversely, the same behavior can be observed from similar ambient temperature changes, as shown in Figure 3-103. Under the same test setup, ambient temperature is decreased from 80 °C to less than -40 °C. As the differential between process temperature and ambient temperature increases, the difference between process and surface temperatures increases from 2 °C to nearly 5 °C.

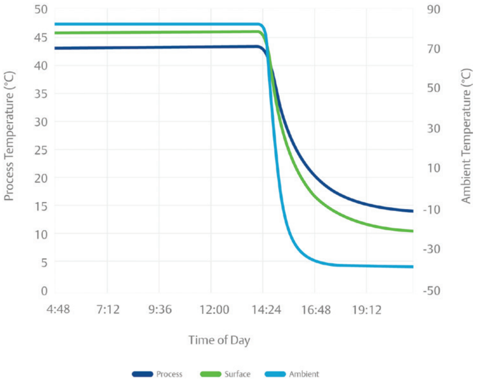


Figure 3-103 – Changing Ambient Temperature: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe)

Figure 3-104 revisits the first trial and plots the difference between process temperature versus surface temperature as a variable. As process temperature is increased, the error, or difference between process and surface temperature, increases. This relationship makes a comparison between the two values difficult, as it is dependent on process temperature, ambient temperature, and the thermal conductivity of the measurement installation.

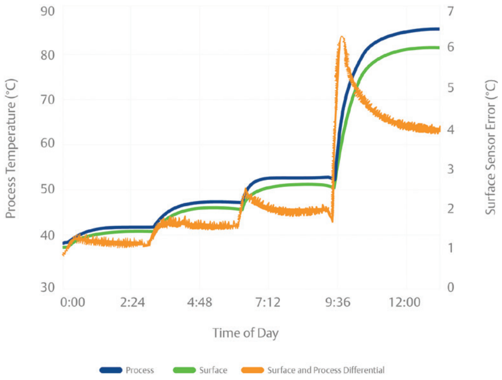


Figure 3-104 – Surface Sensor Error: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe, Ambient Temperature Constant)

3.4.3 Rosemount X-well Technology Addresses Challenges of Both Thermowell and Traditional Surface Measurement Technologies

As detailed in the previous section, there are many factors that can impact a traditional surface temperature measurement reading. This makes it difficult to use as a simple point of inference when determining the temperature of the associated internal process. However, by implementing an algorithm with an understanding of the thermal conductive properties of the temperature measurement assembly and corresponding piping or vessel, a surface temperature sensor solution can be utilized to accurately calculate internal process temperature.

By inputting ambient and surface temperature measurement values from Figure 3-102 and Figure 3-103 into a thermal conductivity algorithm, process temperature values can be calculated. Figure 3-105 and Figure 3-106 show the comparison between calculated “Corrected Temperature” and internally measured process temperature. The calculated values nearly overlay onto the measured values.

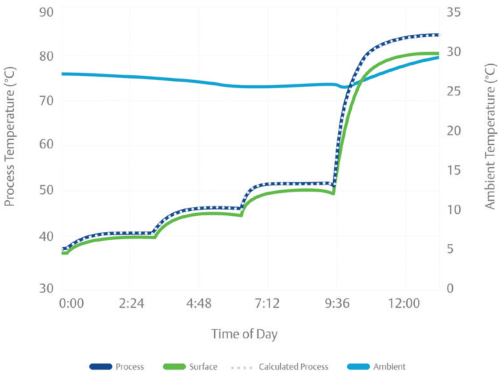


Figure 3-105 – Correction Applied to Changing Process Temperature: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe)

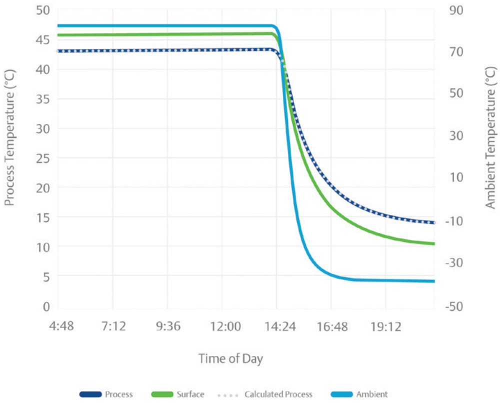
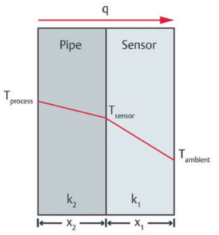


Figure 3-106 – Correction Applied to Changing Ambient Temperature: Insulated Surface Sensor and Inserted RTD Sensor Comparison (1-in. Carbon Steel Schedule 40 Pipe)

Assuming steady state conduction and negligible impact of ambient heat convection, which is eliminated by proper use of insulation, the process piping and temperature measurement assembly can be viewed as a series of planes with different thermal conductivities as shown in Figure 3-107.



Where:

q = Heat flux

$T_{ambient}$ = Measured ambient temperature

x_1 = Thickness of sensor assembly

k_1 = Thermal conductivity of sensor assembly

T_{sensor} = Measured surface temperature

x_2 = Thickness of process pipe wall

k_2 = Thermal conductivity of pipe wall

$T_{process}$ = Calculated process temperature

Figure 3-107 – Simplified Heat Flux through a Pipe and Temperature Sensor Installation

By applying Fourier's Law, heat flux can be calculated and used to solve for the internal process temperature. For one-dimensional heat flow, Fourier's law is simplified to:

$$q = -kdT$$

If process pipe or vessel wall thickness and thermal conductivity is represented by x2 and k2 and sensor assembly length and thermal conductivity are represented by x1 and k1 respectively, Fourier's Law can be used to express one-dimensional heat flow through the assembly as follows:

$$qsensor = (Tambient - Tsensor)/(x1/k1) \text{ and } qpipe = (Tsensor - Tprocess)/(x2/k2)$$

In this application, one-dimensional heat flow can be assumed constant throughout the assembly. Therefore, qsensor and qpipe are equal.

$$q = (Tambient - Tsensor)/(x1/k1) = (Tsensor - Tprocess)/(x2/k2)$$

Ambient temperature Tambient and surface temperature Tsensor can be measured and, in turn, can be used to calculate process temperature Tprocess. Solving for Tprocess gives the following:

$$Tprocess = Tsensor + (Tsensor - Tambient) \times (x2/k2)/(x1/k1)$$

Rosemount X-well Technology addresses the challenges of traditional thermowell and surface measurement technologies by placing this process temperature calculation functionality into a temperature transmitter and surface sensor assembly. By implementing this algorithm in a temperature transmitter, the process temperature calculation is greatly simplified for the user.

3.4.4 Performance Considerations

Total system performance of Rosemount X-well Technology can be viewed in terms similar to a standard temperature measurement assembly (i.e. transmitter digital accuracy and ambient temperature effects, sensor accuracy, etc.) In the case of applying the thermal conductivity algorithm to calculate process temperature from a surface measurement, one additional uncertainty component is required and is dependent on the differential between ambient and process temperature. This additional uncertainty consideration is called Process Temperature Effect (PTE) and testing has shown it is less than 1% of the ambient/process temperature delta. This uncertainty is due to imperfections of sensor-to-pipe surface contact. If the pipe surface inhibits any direct contact with the entirety of the sensor surface, accuracy is impacted, part of which is considered and included in the PTE specification, but extremely uneven or dirty surfaces will further impact accuracy. Examples of contact inhibition would be dimples or any physical imperfections in the pipe surface. Application of a thermal compound or material to improve sensor–to-pipe surface contact is not recommended, as it introduces a new material and thermal characteristics that are not accounted for within the algorithm, which will result in additional error.

Other considerations for performance are proper fluid mixing and sensor placement. Fluid must be flowing enough in a pipe to produce a uniform cross-sectional temperature. Without this, large temperature gradients may develop within the pipe. It is also important that the surface sensor be in contact with the part of the pipe that contacts the internal fluid (i.e. if the pipe is half full, the sensor must be on the lower half of the pipe).

Rosemount X-well Technology works best in steady state applications. If there is a fast process or ambient temperature change, there may be a delay in the correction due to time response characteristics of the sensors being used as well as the associated time response with taking a measurement through a pipe or vessel wall.

A surface measurement may exhibit an increase in time response in comparison to an intrusive thermowell. Time response in this comparison, however, is dependent on many factors including:

-Pipe Material
-Wall Thickness
-Fluid Type
-Flowrate
-Ambient/Process Data
-Thermowell Material Type and Design
-Sensor Type

Changes to pipe or vessel wall properties will impact the algorithm performance. The algorithm is based on pipe property parameters and if a change occurs, accuracy will be affected. Scaling or buildup inside the pipe will impede thermal conductivity through the pipe and will also negatively affect accuracy of the temperature measurement calculation. External buildup on pipe (at sensor contact point) and thinning of the pipe material will similarly impede accuracy.

3.4.5 Suitable Applications

Rosemount X-well Technology is intended for use in temperature monitoring applications. Due to slower response time in certain conditions, it is not currently intended for safety loops, fast control applications, or for custody transfer (fiscal metering) applications.

Summary

Rosemount X-well Technology is available in both the Rosemount 648 Wireless Temperature Transmitter and Rosemount 3144P Temperature Transmitter as an assembly with the Rosemount 0085 Pipe Clamp Sensor.

Rosemount X-well Technology offers accurate process temperature measurement without requiring any intrusions or penetrations into the process, which eliminates possible leak points and allows for faster, easier installation, as well as simplified long-term maintenance. Users do not have to design, size, or maintain thermowells. Wake frequency calculations are eliminated, as well as time spent determining material compatibility, the right insertion length, and the necessary profile.

With Rosemount X-well Technology, users can also add temperature measurement points without having to shut down a process. X-well Technology can be installed with a standard pipe clamp procedure and ordinary hand tools, and does not require a skilled contractor. Temperature monitoring applications include, but are not limited to, pipelines, high velocity flows, slurries, heavy particulate fluids, wellheads, CIP processes, high viscosity fluids, and harsh processes across all industries.

4

Engineering and Design

4.1 Understanding Your Temperature Measurement System

4.1.1 Overview

Temperature is a critical factor in many industrial processes, including reaction, fermentation, combustion, drying, calcinations, drying, crystallization, and extrusion.

If a temperature measurement is not accurate or reliable for any reason, it could have a detrimental effect on process efficiency, energy consumption, product quality and possibly, process safety. As an example; for incinerators, there is an optimum temperature control point to ensure complete destruction of hazardous compounds while maintaining minimum energy cost. Even a small measurement error can be disruptive in some processes, so it's extremely important to be certain your temperature measurements are accurate and reliable. However, there are other processes where temperature is only monitored for trends and absolute accuracy and stability are not important factors. For this reason, each measurement system needs to be evaluated and carefully engineered to satisfy the specific process requirements.

Obtaining the correct sensor, installing it properly, and conveying a temperature measurement signal to a control or monitoring system requires much more analysis than just selecting a thermocouple or RTD out of a catalog. Selecting the best transmitters for the application and how they should be mounted is equally important. Thorough investigations to understand the temperature measurement system requirements will pay off in providing a cost-effective installation that meets those requirements of measurement accuracy, response time, and signal reliability.

Even though it is such a common process variable, temperature is one that is the most misunderstood as to how to make a reliable measurement. These misunderstandings fool many users into believing that 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. Environmental conditions at the measurement site can also have a significant impact on the measurement performance.

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 input cards) have reasonable specifications, they are no match for the performance of today's quality temperature transmitters.

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.

4.1.2 Selection Criteria

When designing a temperature measurement point, the first decision that needs to be made is selecting the overall type of technology that will be used for the measurement. The two key methodologies to evaluate are:

- Traditional insertion measurement consisting of a sensor, thermowell and transmitter.
- Non-intrusive measurement using Rosemount X-well Technology

Some of the key factors that will impact which of the above methodologies to use include

- Retrofit vs. new installation
- Criticality of measurement (Control vs. monitoring vs. safety instrumented system)
- Operating conditions of the process (gas vs. liquid vs. steam, operating pressures and temperatures, flow rates, material compatibility with process)
- Environmental considerations (corrosion, vibration, ambient temperatures, EMI/RFI noise)

- Physical properties of the pipe or vessel (material type, thickness, tap location, upstream & downstream elbows, valves, etc.)

4.1.3 Application Considerations for Traditional Insertion Measurements

An insertion measurement consisting of a sensor, thermowell, and transmitter is the traditional industry practice for making a temperature measurement. The primary advantage of these assemblies is that they will offer the best performance in terms of accuracy and time response, because the sensor is as close to the process as possible by being inserted into the pipe or vessel by means of a thermowell.

Traditional insertion measurements are ideal in the following situations and applications:

- Control, SIS, and other critical applications where time response and accuracy are of upmost importance.
- If a thermowell is already installed, it is logical to go with an insertion measurement by specifying a sensor that is dimensionally compatible with the thermowell. As an example, if a sensor fails on a traditional insertion measurement, it is usually easiest to replace that sensor in kind.
- New facilities & turnarounds. Traditional insertion measurements cannot be installed when the process is up and running because a physical intrusion into the pipe or vessel is required. When a new process is not yet operational, or a process is down due to a turnaround or upgrade, installing an insertion measurement is much more feasible. Additionally, for situations where the piping for the processing unit is being designed from scratch, having the added flexibility to determine the location of the thermowell can be advantageous.

4.1.4 Application Considerations for Rosemount X-well Technology

Rosemount X-well Technology has the primary advantage of being able to provide an accurate process temperature measurement without a thermowell or intrusion into the pipe or vessel. Not having a sensor or thermowell that physically intrudes into the pipe can offer a number of significant advantages over traditional insertion measurements, including reduced design complexity, simplified installations, and reduced process and safety risk. Application considerations for Rosemount X-well Technology include:

- Monitoring applications. Rosemount X-well Technology works by converting an external surface temperature measurement into an internal process temperature measurement. X-well technology will usually have a slower time response than a traditional insertion measurement and may not be suitable for critical control applications. However, for monitoring and non-critical applications, the accuracy and time response of X-well technology is usually acceptable.
- Adding new measurements to existing processes. There can be a number of situations where it is deemed necessary to add new temperature measurement points to an existing process. Some common reasons for these include new industry or regulatory requirements, the need to drive efficiency improvements, and monitoring asset health. X-well technology is usually the most economical way to add a new measurement to an existing process because it can be installed without shutting the process down or making any modifications to existing piping. Additionally, X-well technology is available with *Wireless*HART protocol, which eliminates the need to run new instrument wiring back to the DCS or PLC.
- Challenging processes. There can be a number of different situations that can be challenging for traditional insertion measurements. Some examples include:
    - Corrosive processes that require expensive exotic alloy thermowells
    - Installations with high amplitude vibration, causing sensors to fail prematurely
    - High velocity flows and other similar situations where a traditional thermowell does not pass ASME PTC 19.3 TW calculations.
    - Large diameter pipes and vessels. A common practice for traditional insertion measurements is to have the thermowell installed 50% into the pipe. On larger pipes and vessels, longer thermowells can become quite expensive. They also have the challenge of being more susceptible to failure and can be challenging to find a working design that passes the ASME PTC 19.3 TW specifications. X-well technology offers a safe, reliable alternative with a lower total cost of ownership.

Knowing whether to go with a traditional insertion-based temperature measurement vs. X-well technology is not always a straightforward decision. Online Engineering Tools (discussed in the next section) and temperature instrumentation suppliers can further help with deciding which technology to use for a given application.

HOW TO CHOOSE THE CORRECT THERMOWELL

Temperature sensors are rarely inserted directly into an industrial process. They are installed into a thermowell to isolate them from the potentially damaging process conditions of flow-induced stresses, high pressure, and corrosive chemical effects. Thermowells are closed-end metal tubes that are installed into the process vessel or piping and become a pressure-tight integral part of the process vessel or pipe.

To select a proper thermowell, the process conditions must be identified, as they will influence decisions regarding the material of construction, the well design, the insertion length and the lagging required.

Refer to:

4.1.2 – Selection Criteria

4.3.2 – Thermowell Overview

3.3.7 – Thermowell Failure Considerations

4.2 Online Engineering Tools

4.2.1 Thermowell Design Accelerator

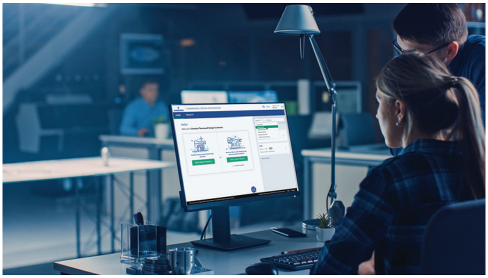
The Rosemount Thermowell Design Accelerator is the one-stop shop to ensure you get a reliable, accurate and safe temperature measurement for your process applications.

This software provides all you need to design, troubleshoot and evaluate a thermowell and make sure it is safe for your process. It performs thermowell calculations, suggests instrumentation that works, as well as guides designers through the entire process.

It reduces the complexity of thermowell calculations by simplifying the process, automating the difficult aspects and providing solutions based on the need of the specific application. This in turn will drastically reduce the amount of time and effort spent on thermowell calculations and free up the designer to concentrate on other vital issues. It is digital simplicity harnessed to tackle thermowell complexity.

Features of the Thermowell Design Accelerator include:

- **Strict adherence to the ASME PTC 19.3 TW –** Always updated with the latest revision
- **Automatic re-iteration of failed tags –** Will continuously do calculations until a solution is found
- **Allows calculations of multiple process conditions per tag –** Up to 8 process conditions per tag; makes sure thermowell will work in all conditions
- **Ability to perform mass uploads –** Upload more than 500 tags using our easy Microsoft® Excel template
- **Specifies valid Rosemount thermowell and sensor model codes**
- **Alternate solutions for calculation failures –** Rosemount Twisted Square thermowell & X-well technology are possible solutions when thermowells fail the ASME PTC 19.3 TW
- **Automated troubleshooting assistance –** Alerts you with calculation errors and provides suggestions for changes to help resolve them
- **Generates detailed thermowell calculations reports**
- **Integrated Technical Support Feature –** Connects users with experienced engineers that can answer questions
- **Inventory Optimization –** Helps you standardize your thermowell product models in a project with multiple thermowell tags



The Thermowell Design Accelerator is one of the many engineering software tools available on MyEmerson. Learn more at www.Emerson.com/RosemountAccelerate

4.3 Selecting the Correct Components

4.3.1 Overview

In this section, we will discuss the selection of the proper thermowell, sensor, and transmitter to best meet the physical and performance requirements of your temperature measurement system. As you proceed through this section, keep in mind the concept of cost of ownership. It is often foolish to "buy cheap" to meet a budget and then find later the cheap version has poor performance, higher maintenance costs or needs more frequent replacement, all of which will cost the facility many times over the original savings.

TIP: Before proceeding in this section, it will be assumed that you have read the "Understanding Your Temperature Measurement System" section 4.1 in this chapter and have gathered the required process information by obtaining answers to the questions provided.

4.3.2 Thermowell Overview

Temperature sensors are rarely inserted directly into an industrial process. They are installed into a thermowell to isolate them from the potentially damaging process conditions of flow-induced stresses, high pressure, and corrosive chemical effects. Thermowells are closed-end metal tubes that are installed into the process vessel or piping and become a pressure-tight integral part of the process vessel or pipe. They permit the sensor to be quickly and easily removed from the process for calibration or replacement without requiring a process shutdown and drainage of the pipe or vessel.

TIP: Refer to the "Thermowells" Section 3.3 in the Temperature Measurement Basics, Chapter 3 for additional thermowell information.

Thermowells are most often constructed from machined barstock in a variety of materials and may be coated with other materials for erosive or corrosive protection. Thermowells are classified according to their connection to a process. For example, a threaded thermowell is screwed into the process; a socket weld thermowell is welded into a fixture and a weld-in thermowell is welded directly into the process pipe or vessel; a flanged thermowell has a flange collar which is attached to a mating flange on the process vessel or pipe. The stem or shank that extends into the process may be straight with constant diameter, tapered all the way from entry point to the tip, partially tapered, or stepped. They are available with threaded, welded or flanged connections. Also, see Figure 4-1.

Figure 4-1 – Typical Thermowell Styles

4.3.2.2 Installing a New Thermowell

4.3.2.2.1 Locate the Point of Penetration

Start by locating a suitable measurement point that is representative of the desired measurement and is accessible. Determine the size of the pipe or vessel, the insulation thickness, and the presence of surrounding structures that may impede installation of the thermowell and future maintenance or replacement access. Take into consideration the dimension of the entire assembly including an integrally mounted transmitter or connection head.

For installations downstream of static mixers or heat exchangers, the insertion point must optimize the tradeoffs of minimal thermal loss with adequate mixing to avoid two phase flow or process noise. Generally, a downstream distance of about 25 pipe diameters is sufficient. There are special considerations for some other difficult applications like desuperheaters where stream velocity conditions must be considered. After a suitable location is chosen, determine if it will be necessary to drain and clean the pipe or vessel before cutting into it to install the well. Ensure that the appropriate permits and approvals are secured.

4.3.2.2.2 Select Material of Construction

The material of construction is typically the first consideration in choosing a thermowell for any given application. Factors that affect the choice of material include:

- Chemical compatibility with the process media
- Compatibility with the process piping or vessel material to ensure solid, non-corroding welds and junctions (Figure 4-2)
- Temperature limits of the material (Figure 4-3)

It is important that the thermowell conforms to the design specs of the pipe or vessel into which it will be inserted to ensure structural and material compatibility.

Materials	Recommended Usage	Process Rating[1] (psi) at Temperature (°F)						
		0 °F	300 °F	500 °F	700 °F	900 °F	1000 °F	1300 °F
304 SST	Good resistance to oxidation.	5600	4800	4700	4600	3400	2400	780
316 SST	Good resistance to corrosion. Better resistance to chemical attack than 304 SST.	5600	5400	5300	5200	4400	3200	1250
Carbon Steel	For non-corrosive service.	3700	3700	3700	3650	2000	–	–

(1) In case of an explosion, the integrity of the thermowell is maintained to the specified pressures.

Figure 4-2 – Materials of Construction

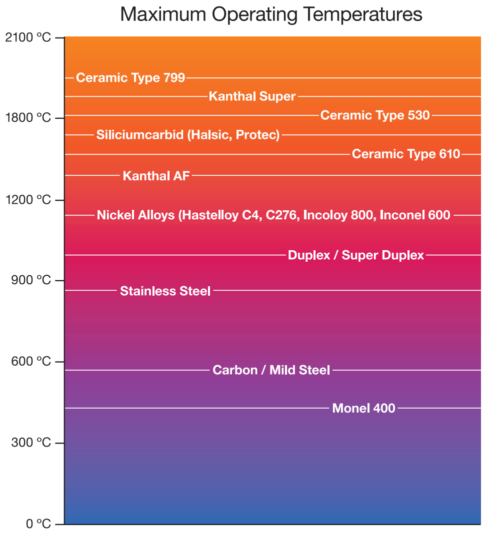


Figure 4-3 – Maximum Temperatures of Thermowell Materials

4.3.2.2.3 Determine Process Connection - Mounting Style

The choice of threaded, welded, flanged or Vanstone or lap joint flanged connection depends on the pressure rating of the installation, fluid velocity, type of fluid, conformance with codes and standards and plant piping specifications and preferences. See Figure 4-4.

Consider the following as a guideline:

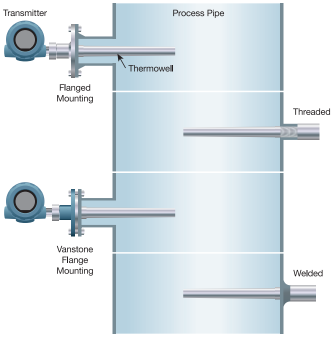


Figure 4-4 – Thermowell Mounting Methods

4.3.2.2.3.1 Threaded

Threaded thermowells are threaded into process piping or tank, which allows for easy installation and removal when necessary. While this is the most commonly used method of mounting, it has the lowest pressure rating of the three options. Threaded connections are also prone to leakage and therefore are not recommended for applications with toxic, explosive or corrosive materials.

4.3.2.2.3.2 Welded

Welded thermowells are permanently welded to process pipes or tanks. Thus, removal is difficult and requires cutting the thermowell out of the system. Welded thermowells have the highest pressure rating and are generally used in applications with high velocity flow, high temperature, or extreme high pressure. They are necessary where a leak-proof seal is required.

4.3.2.2.3.3 Flanged

Flanged thermowells are bolted to a mating flange that is welded onto process pipe or tank. They provide high pressure ratings, easy installation, and simple replacement. Flanged thermowells are used in applications with corrosive environments, high-velocity, high temperature, or high pressure.

4.3.2.2.3.4 Vanstone or Lap Joint

Vanstone or Lap Joint thermowells are mounted between the mating flange and the lap joint flange. These thermowells allow for the use of different materials for the thermowell coming in contact with the process and the overlaying flange which can save material and manufacturing costs and may be supplied as a forging.

4.3.2.2.4 Small Diameter Pipe Installations

Due to imperfect mixing and wall effects, the process temperature will vary with the fluid location in the vessel or pipe. For highly viscous fluids such as polymers, the fluid temperature near the wall can be dramatically different from that at the centerline. Since these pipes are often less than 4 inches in diameter, there can be a problem in getting sufficient immersion length and still having the tip near the centerline.

For these applications an angled “T” fitting or elbow mounting should be considered. By installing the well with the tip facing the oncoming flow, good thermal contact is maintained and response is optimized. See Figure 4-5 for an elbow installation.

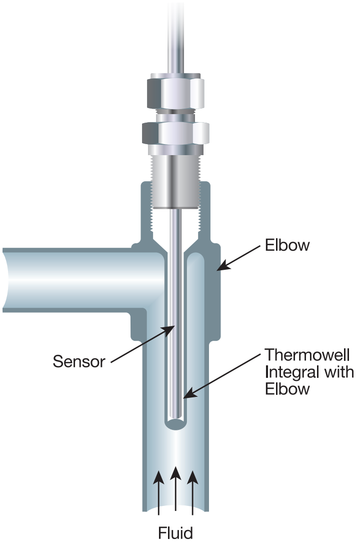


Figure 4-5 – Thermowell Elbow Installation

Figure 4-6 and Figure 4-7 show alternative mounting options numbered according to preference. If the well is facing away from the flow, swirling may cause a less representative measurement. Using a stepped thermowell optimizes speed of response.

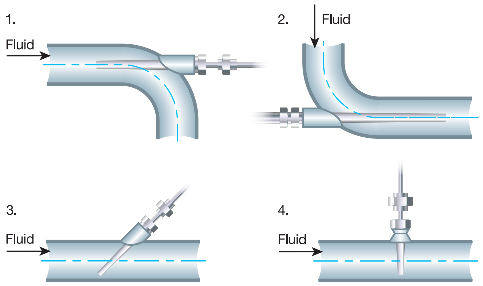


Figure 4-6 – Examples of Thermowell Insertions in Small Diameter Pipe Numbered by Preference

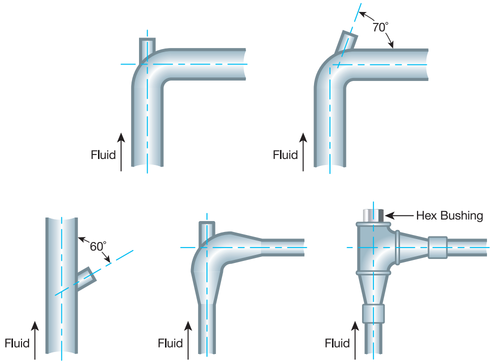


Figure 4-7 – Thermowell Angled Installation Options

> *TIP: Consideration must be given to impeded flow, pressure loss and pipe cleaning and flushing issues. Difficult-to-clean cavities may present a problem in sanitary applications.*

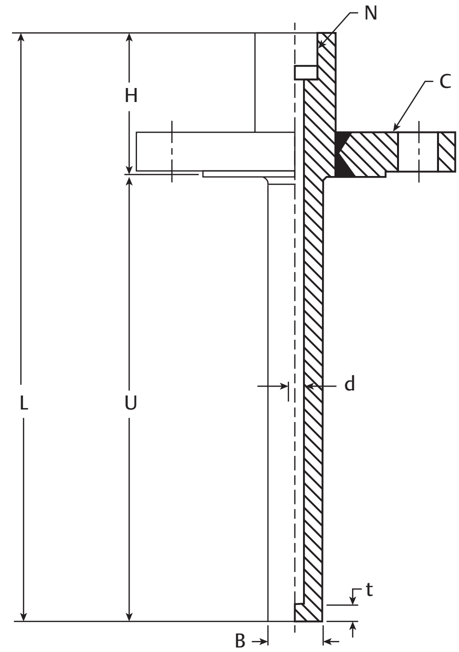
4.3.2.2.5 Determine Insertion Length

Confirm the pipe or tank diameter to determine the insertion length of the thermowell. There is no standard formula to determine the insertion length of the thermowell. Rather there are a few common practices that the process industry follows along with good engineering judgment. Ideally the tip of the thermowell should be located at an optimal process point, typically near the centerline, that is in turbulent flow conditions and is representative of the true process temperature. A measurement along a pipe wall would have an offset from the slower flow and wall temperature effects of the pipe. For tanks and other vessels, the internal flow pattern must be understood to ensure placement of the thermowell tip at the optimal point. A general guideline for insertion length into pipe for where optimal performance is required is ten times the diameter of the thermowell for air or gas and 5 diameters for liquids. Another guideline is at least one-third of the way into the pipe for liquids and two-thirds of the way into the pipe for air or gas measurements. The American Petroleum Institute (API) has a specific recommendation of using an insertion length of the sensing element plus 50 mm (2 inches).

Once the optimal insertion length has been determined, a thermowell may be specified with the required “U” dimension. See Figure 4-8. The other dimensions of the thermowell may be determined by consideration of factors, such as:

- Insulation thickness
- Connection type
- Lagging length
- Length of any required extensions to protrude through the insulation layer
    - Be aware of connection head or integral transmitter housing dimensions added to the extension length relative to interference with nearby structures or equipment.

With the process connection, pipe or tank diameter, and the pipe insulation dimensions, the overall dimensions of the thermowell can be determined. Consult vendor product data sheets for additional guidance.



A. Root diameter

B. Tip diameter

C. ASME B16.5 flange

L. Total length (U+H)

H. Head length

N. Instrument connection

U. Immersion length

d. Bore diameter

t. Tip thickness

Figure 4-8 – Typical Thermowell Dimensional drawing (English)

4.3.2.2.6 Selecting a Stem Profile Style

Factors to be considered when selecting a stem style include the process pressure, the required speed of response of the measurement, the drag force of the fluid flow on the well and the wake frequency.

The stem or shank is the part of a thermowell that is inserted into the process piping or vessel. The common stem profiles are straight, stepped, and tapered. See Section 3.3 and Figure 3-84. In general, tapered or stepped stems provide faster response, create less pressure drop, and are less susceptible to conduction error due to thermal lag and to failure due to vibration from wake frequency.

Refer to the Thermowell Chapter (Section 3.3) for complete detail.

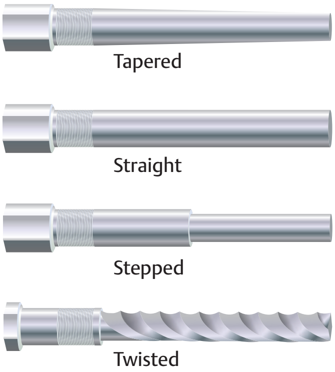


Figure 4-10 – Thermowell stem profiles

WHAT IS THE RECOMMENDED INSERTION LENGTH FOR A THERMOWELL?

Confirm the pipe or tank diameter to determine the insertion length of the thermowell. There is no standard formula to determine the insertion length of the thermowell. Rather there are a few common practices that the process industry follows along with good engineering judgment. Ideally the tip of the thermowell should be located at an optimal process point, typically near the centerline, that is in turbulent flow conditions and is representative of the true process temperature.

A measurement along a pipe wall would have an offset from the slower flow and wall temperature effects of the pipe. For tanks and other vessels, the internal flow pattern must be understood to ensure placement of the thermowell tip at the optimal point. A general guideline for insertion length into pipe for where optimal performance is required is ten times the diameter of the thermowell for air or gas and 5 diameters for liquids. Another guideline is at least one-third of the way into the pipe for liquids and two-thirds of the way into the pipe for air or gas measurements. The American Petroleum Institute (API) has a specific recommendation of using an insertion length of the sensing element plus 50 mm (2 inches).

Refer to:

4.3.2.2.5 – Determine Insertion Length

See also:

Figure 4-8 – Typical Thermowell Dimensional drawing

Consider the following as a guideline and note that complete detail on each type can be found in section 3.3

4.3.2.2.6.1 Straight

Straight profile thermowells have the same diameter along the entire immersion length. They have the highest pressure rating of the three profile types but, accordingly, they present the largest profile to the process medium and therefore have a high drag force.

4.3.2.2.6.2 Stepped

Stepped profile thermowells have two straight sections with the smaller diameter at the tip. They have the lowest drag force profile and have reduced pressure ratings than the straight type.

4.3.2.2.6.3 Tapered

Tapered profile thermowells have an outside diameter that decreases uniformly from root to tip. These are a compromise between the other two types for drag force profile and pressure rating.

4.3.2.2.6.4 Twisted

Rosemount Twisted Square profile thermowells have a unique twisted design that is uniform for the entire length of the stem. This profile is a Rosemount patented design and was designed specifically to suppress the harmful vortex induced vibrations a thermowell experiences in process applications. Refer to Figure 3-88. This profile compared to all the others will provide the best results when it comes to suppressing harmful vortex shedding induced vibrations. This allows for proper stem immersion in the pipe (close to 50% immersion is ideal), which provides an accurate and, more importantly, a repeatable temperature measurement. This is an excellent solution in high velocity gas/steam applications. It has also been a great solution for two-phase flow applications.

4.3.2.3 Reusing an Existing Thermowell

If only the sensor is being replaced, determine if the existing thermowell is satisfactory for continuing use. It would be appropriate to review the original selection criteria in light of the guidance discussed above. There is no time like the present to correct an improper installation. If the old sensor was not a spring loaded design, an upgrade to this design could increase response and reduce the potential for vibration damage. Historically, older installations often did not adequately take wake frequency into account. It is suggested that a new calculation be performed using the guidance in the latest version of ASME PTC 19.3 TW. (Note that the standard covers many – but not all – configurations and additional engineering judgment may be required for those applications to complete an analysis.) Wake frequency is a determining factor in selecting a thermowell for a high-velocity application. Our Thermowell Design Accelerator is a perfect tool to provide analysis of thermowell calculation to ensures a safe and robust thermowell. Once reuse of the thermowell is confirmed, determine the sensor insertion length from data on the sensor being replaced, by adding the well bore depth extension length and connection head allowance or by actual measurement. Vendor product data sheets typically provide guidance on this selection process.

4.3.3 Sensor Selection

While several types of temperature sensors may be used, resistance temperature detectors (RTDs) and thermocouples (T/Cs) are most common in the process industry. See Figure 4-11. Detailed discussion of sensors may be found in sections 3.2.3 and 3.3.2.

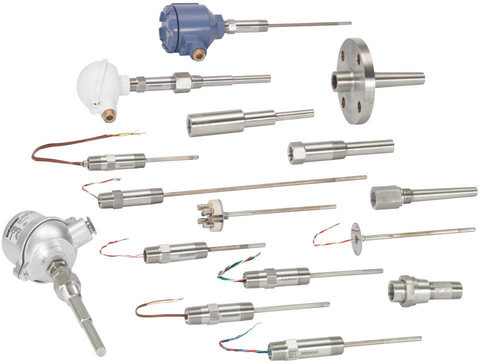


Figure 4-11 – Sensor Family

In the "Understanding Your Temperature Measurement System" section, a series of questions were provided to assist in system selection decisions. Those questions associated with sensor selection are listed below along with insights into the selection implications:

- Is the requirement to monitor temperature trends or an actual controlled value?
  - – Monitoring trends do not typically require high precision suggesting that either a T/C or an RTD would serve well enough.
- A basic transmitter or monitoring system input card would fill the need for signal conditioning.
  - – For control applications, more insight is required.
- What is the temperature range? The control point? Its maximum temperature? Its minimum temperature?
  - – If the maximum temperature to be measured is over 850 °C, a T/C is the only choice.
  - – For most other applications, either sensor would work.
- Are there established plant preferences for choice of sensor that may influence your selection? While Proven-in-Use is a valuable consideration, do not fall into the trap of following "we have always done it that way" mentality.
  - – Many plants have adopted the position that they will use an RTD unless limited by a high temperature application where using a T/C is the only practical choice.
  - – Others use specific sensor types on specific applications based on successful experience. It is often wise to follow this trend.
- Are certain sensor types kept in inventory?
  - – Using a normally stocked sensor may save inventory costs for spares assuming that the stocked model meets the requirements of your application.
- What is the control precision requirement?
  - – For example, furnace temperature control may tolerate ± 10 °C, while a pharmaceutical batch process may require ± 0.25 °C or better.
  - – If the accuracy requirement is for better than ± 2 °F, an RTD is the better choice.
  - – Long term stability highly favors an RTD.

  - Best accuracy is provided by a spring-loaded wire-wound design.
  - See sections 3.2.3.11, RTD Accuracy/ Interchangeability and 3.2.4.8, Thermocouple Accuracy.
- What is the speed of response to temperature change requirement?
  - Spring-loaded sensors and stepped thermowells optimize speed of response.
  - Use thermally conductive oil to fill the voids between the sensor and the inside bore of the thermowell to increase the speed of response.
  - See section 3.2.5 – Measurement Response Time Considerations.
- Is there a significant ROI for best possible accuracy and stability? (Custody transfer, energy optimization or distillation column throughput are examples providing significant ROI).
  - Consider using an RTD with sensor-transmitter matching option for system accuracy as good as 0.015 °C.
- What are the costs associated with a measurement failure? Production downtime costs? Off-spec product that requires reprocessing or selling at a reduced price? Energy inefficiency? Troubleshooting and maintenance time? Dangerous runaway reactions?
  - Even a one degree error could cost thousands of dollars in wasted energy per year
  - Any of these “cost of ownership” consequences suggest using a high quality transmitter integrally mounted with a quality sensor in a well-engineered system
  - Most often this will be a high-quality RTD
- What is the frequency and severity of the piping/ vessel vibration (typical and maximum?)
  - High vibration suggests using a thin-film spring-loaded RTD sensor

4.3.3.1 Comparison of RTD vs. T/C

T/Cs are said to be less expensive, but when the cost of extension wire, more frequent calibration and replacement, and lower accuracy impacts on the process are considered, this advantage disappears. In fact, in many cases, the cost of ownership of a T/C installation easily exceeds that of an RTD installation.

The most viable reason for using a T/C is if the measured temperature range exceeds what is practical for an RTD. The RTD potential upper limit is about 850 °C (1,500 °F).

For applications where only trends are monitored and errors of several degrees can be tolerated, multipoint or single T/C assemblies may have a cost advantage when wired to a multichannel transmitter or a multiplexer.

For process control applications and especially for SIS applications, a properly designed and installed RTD system is clearly the better choice for temperatures below 500 °C (900 °F). At higher temperatures up to 850 °C, there can be increased drift that may nullify some of the accuracy advantage. See Figure 4-12.

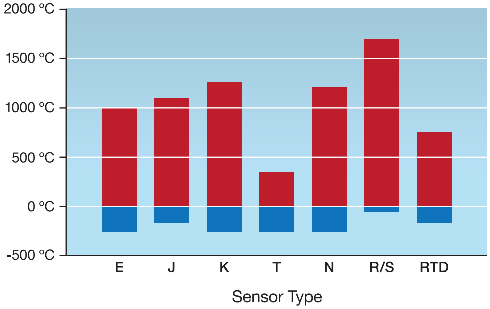


Figure 4-12 – Potential Sensor Ranges in °C

HOW TO CHOOSE THE RIGHT SENSOR TECHNOLOGY (RTD OR T/C)

Over the years, there have been purported advantages for using a T/C, but most of these are of little relevance for industrial process applications. Although some T/Cs made with heavy gauge wire are quite rugged with a high tolerance for vibration, in general, an RTD properly selected and installed in a properly designed thermowell is suitable for challenging high velocity steam or liquid applications and even applications in the nuclear industry.

Refer to:

4.3.3.1 – Comparison of RTD vs. T/C

4.3.3.1.1 – RTD Characteristics and Advantages

4.3.3.1.2 – T/C Characteristics and Advantages

Figure 4-13 – Sensor Comparison Table

Attribute	RTD	Thermocouple
Accuracy Interchangeability	Class A: ± [0.15 + 0.002 (t)] Class B: ± [0.30 + 0.005 (t)] Per IEC 60751	Typical is ± 1.1 °C or ± 0.4% of measured temperature (Greater). Depends on type and range. Degraded by extension wire.
Stability	± 0.05 °C per 1000 Hrs at ≤ 300 °C. Greater at higher temperatures. Wire-wound better than thin-film.	Highly dependent on T/C type, quality of the wire and operating temperature. Typical is ± 2 to 10 °C per 1000 Hrs.
Speed of Response in Thermowell Installation in Liquid	About the same as T/C.	About the same as RTD.
Calibration	Easily recalibrated for long service life. Best accuracy with Sensor-Transmitter Matching.	Limited to in-situ comparison to “Standard T/C”.
Potential Temperature Range	-200 to 850 °C	-270 to 2300 °C
Life Span	Many years. Shorter at higher temperatures.	Degradation indicates frequent replacement. Much shorter at high temperatures. Higher life cycle costs.
Installation Considerations	Use standard copper wire. Good EMI and RFI immunity.	Requires expensive matching extension wire. Low level signal is very susceptible to EMI and RFI.
Vibration Tolerance	Thin-film design is very good.	Larger wire diameters are very good.
Life Cycle Cost	Lower.	Higher.
Purchase Cost	Thin-film design about the same. Wire-wound higher.	Types R and S most expensive.
System Performance with Transmitter	Always better below 650 °C.	Order of magnitude lower.

Figure 4-13– Sensor Comparison Table

4.3.3.1.1 RTD Characteristics and Advantages

Refer to section 3.2.3 for a detailed discussion of RTDs.

- Potential range is -200 °C to 850 °C.
- Much better repeatability than a T/C.
- Long term drift is predictable while a T/C drift is erratic. This provides the benefit of less frequent calibration and therefore lower cost of ownership.
- Much better sensitivity than a T/C. When used with a high resolution transmitter, a much more precise measurement can be made.
- Excellent linearity. When coupled with the linearization performed in a quality transmitter, a precision of about 0.1 °C, is possible which is much better than what is possible with a T/C.
- Can be used with standard copper lead wires and connection cables.
- May be provided with CVD constants that allow matching the sensor to a transmitter to produce extraordinary accuracy (Up to 0.015 °C).
- Demonstrate negligible hysteresis.
- Normally supplied as 4-wire design and, when used with a quality transmitter, lead length is inconsequential.
- Low susceptibility to EMI and RFI.

4.3.3.1.2 T/C Characteristics and Advantages

Refer to section 3.2.4 for guidance in selecting the T/C type best suited to your measurement range and application.

- Practical range depends on T/C type and can be as low as -270 °C and up to 2300 °C.
- Linearity depends on type and can be extremely non-linear over wide ranges. This is compensated to a degree by the linearization performed by a transmitter.
- Measurement accuracy is dependent on an accurate Cold Junction Compensation (CJC) as performed by a transmitter or other signal conditioner.
- Subject to hot junction degradation over time and especially at higher temperatures causing unpredictable and erratic drift.
- Must be used with matching T/C extension wire, which is also subject to degradation.
- Susceptible to EMI and RFI. (Use with an integrally mounted transmitter minimizes this effect).
- Heavy gauge wire construction can withstand high vibration.
- When used in a thermowell, a T/C has a response time about the same as an RTD. Bare element installations are faster but are not widely used in

the process industries due to safety concerns of potential leakage and exposure of the sensor to adverse process conditions.

- T/Cs are available with standard grade tolerances or special grade tolerances called Class 2 and Class 1, respectively, with Class 1 having about twice as good of a tolerance specification. However, over time and depending on the application, the T/C degradation may nullify this advantage.

Refer to Figure 4-13 for a detailed comparison of RTDs and T/Cs.

4.3.3.2 Specifying a Sensor

4.3.3.2.1 Specifying an RTD Assembly

The following considerations are relevant to a proper selection of an RTD to best meet the requirements of your application:

- Refer to section 3.2.3 for a detailed discussion of RTDs.
- Consider plant standards and recommended practices for guidance.
- It is typically most cost-effective to specify and order the RTD as part of a factory assembled, tested, and calibrated measurement system complete with the thermowell and transmitter to assure proper fit and function. Receive approximately 50% savings vs. ordering individual components and assembling, testing and calibrating in the field.
- Consider what styles may be kept in inventory.
- A thin-film design will be the least expensive and fastest responding choice.
- A spring-loaded thin-film design is almost always the best choice for fastest time response and least susceptibility to vibration. See Figure 4-14. However, some designs of helical style wire-wound elements are another good choice. See Figure 4-15.

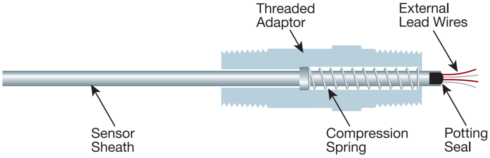


Figure 4-14 – Spring-Loaded Threaded Style

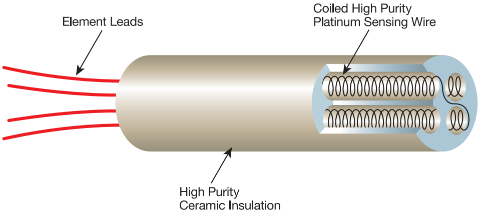


Figure 4-15 – Coiled Suspension RTD Sensor

- Best performance and accuracy is achieved by using 4-wire sensor-transmitter systems since they are immune from the lead wire resistance errors generated by 2 and 3-wire systems. See section 3.2.3.1.3.1 for a discussion.
- Mounting is dependent on choice of local or remote mounting with the transmitter and the connection head style chosen. A DIN style design is an option for some transmitter or connection head options, while a threaded style could be chosen for direct mounted dual-compartment and some other style housings.
- Immersion length must be suitable for the thermowell bore depth that has been specified. The vendor Product Data Sheet will provide guidance in determining this dimension.
- For improved speed of response, specify that the void between the sensor and the well bore be filled with thermally conductive fluid.
- Consider dual element sensors for redundancy and for the Hot Backup feature or where the measurement may be connected to two separate systems or devices. See Figure 4-16.

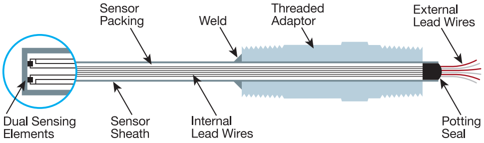
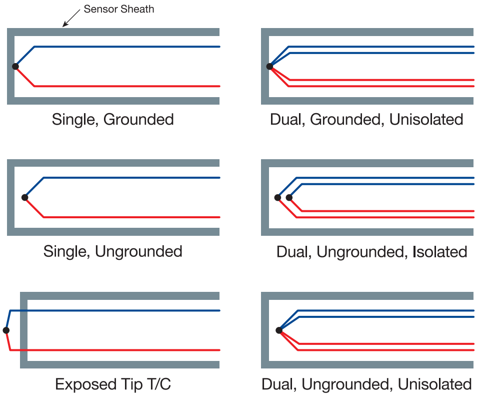


Figure 4-16 – Dual Element RTD

4.3.3.2.2 Specifying a Thermocouple Assembly

In addition to the considerations mentioned above for specifying an RTD, there are several other factors to be considered for selecting the best T/C type, style, and mounting options.

- Refer to section 3.2.4 for guidance in selecting the T/C type best suited to your measurement range and application.
- It is typically most cost-effective to specify and order the T/C as part of a factory assembled, tested, and calibrated measurement system complete with the thermowell and transmitter to assure proper fit and function. Receive approximately 50% savings vs. ordering individual components and assembling, testing and calibrating in the field.
- For profiling applications, consider multipoint assemblies.
- Ensure that the proper T/C extension wire is specified. It must match the T/C type and be produced in accordance with the same color code standard as the T/C.
- Choose either grounded or ungrounded sensor design. While grounded are somewhat faster responding, they are also more susceptible to noise pickup from the process and more prone to junction poisoning. Note that the response time of the measurement is mostly dependant on the thermowell mass as opposed to the sensor mass.
- Consider a dual element design where redundancy, the Hot Backup feature or Sensor Drift Alert may be a benefit or where the measurement may be connected to two separate systems or devices. Dual elements can be isolated or unisolated configurations. Isolated junctions may not read identical temperatures but can identify drift due to poisoning of one of the elements. If one junction fails, the second junction is not necessarily affected. Un-isolated junctions measure identical temperature to increase the integrity of the measurement point. However, if one junction fails, it is likely that both junctions will fail at the same time. Refer to Figure 4-17.



Single, Grounded

Dual, Grounded, Unisolated

Single, Ungrounded

Dual, Ungrounded, Isolated

Exposed Tip T/C

Dual, Ungrounded, Unisolated

Figure 4-17 – T/C Junction Configurations

4.3.4 Selecting Rosemount X-well Technology

When Rosemount X-well Technology is deemed an appropriate solution for an application, selection and specification of the assembly is fairly straightforward.

Mounting/Clamp Size – As it is usually installed on piping, selecting the clamp/mount size to match is the first step. The correct size will ensure a safe installation where sensor contact on the pipe surface is optimized.

Mounting/Clamp Material of Construction – Material compatibility between the clamp and the pipe surface is another consideration when selecting a Rosemount X-well device. Dissimilarity between pipe and clamp material can result in galvanic corrosion. A best practice is to select a clamp material that is identical to piping or close on the galvanic corrosion comparison chart (Figure 4-18). The corrosion protection inlay provides a layer of protection to help minimize the possibility of dissimilar metal corrosion between the pipe clamp and pipe.

4.3.4.1 System Error Analysis

As discussed in section 3.1.4.2, Worst Case Error (WCE) is the largest possible error expected under the anticipated conditions. A more realistic measure is the Total Probable Error (TPE), which is a root sum of the squares of multiple error producing factors affecting the accuracy.

Three calculations are presented that contrast the TPE of a basic transmitter using a standard Class B sensor a high accuracy transmitter matched with a Class A sensor using the Callendar-Van Dusen

Example 1: Standard Accuracy TPE Calculation

The conditions:

- Basic accuracy transmitter
- Class B RTD sensor
- Ambient temperature change: 20 - 40 °C
- Process temperature range: 40 - 400 °C
- Reference temperature is 20 °C

Digital Accuracy: ±0.150 °C for a PT 100 (alpha .00385) RTD sensor

D/A Accuracy = ±0.030% of transmitter span
= 0.030% x (400-40) °C
= 0.108 °C

Digital Temp Effects = 0.003 °C per 1.0 °C change in ambient temperature
= 0.003 x (40-20) °C
= 0.060°C

D/A Effect = 0.001% of span per 1.0 °C change in ambient temperature
= 0.00001 x (400-40) °C x (40-20) °C
= 0.072 °C

Sensor accuracy = ±2.30 °C @ 400 °C for a class B RTD sensor

TPE = $\sqrt{\textit{Digital Accuracy}^2 + \textit{D/AAccuracy}^2 + \textit{DigitalTempEffects}^2 + \textit{D/AEffects}^2 + \textit{SensorAccuracy}^2}$
= $\sqrt{0.150^2 + 0.108^2 + 0.060^2 + 0.072^2 + 2.300^2}$
= ± 2.309 °C

Example 2: High Accuracy TPE Calculation

The conditions:

- High accuracy transmitter
- Class A RTD sensor with CVD constants
- Ambient temperature change: 20 - 40 °C
- Process temperature range: 40 - 400 °C
- Reference temperature is 20 °C

Digital Accuracy = ±0.100 °C for a PT 100 (alpha .00385) RTD sensor

D/A Accuracy = ±0.020% of transmitter span
= 0.020% x (400-40) °C
= 0.072 °C

Digital Temp Effects = 0.0015 °C per 1.0 °C change in ambient temperature
= 0.0015 x (40-20) °C
= 0.030 °C

D/A Effect = 0.001% of span per 1.0 °C change in ambient temperature
= 0.00001 x (400-40) °C x (40-20) °C
= 0.072 °C

Sensor accuracy = ±0.420 °C @ 400 °C for a class A RTD sensor with CVD constants

TPE = $\sqrt{\textit{Digital Accuracy}^2 + \textit{D/AAccuracy}^2 + \textit{DigitalTempEffects}^2 + \textit{D/AEffects}^2 + \textit{SensorAccuracy}^2}$
= $\sqrt{0.1002 + 0.0722 + 0.0302 + 0.0722 + 0.4202}$
= ± 0.445 °C

constants of the sensor and a Rosemount X-well measurement solution. For precision applications, the results clearly show the benefit of sensor-transmitter matching.

For the most critical of applications, a more in-depth analysis of the overall temperature measurement system accuracy includes consideration not only of the sensor and transmitter accuracy specifications but also a variety of other factors including T/C junction degradation, sensor insulation deterioration, sensor cycling drift, flow rate variations, heat conduction losses, etc. Since many of these are difficult or impractical to measure, good engineering judgment should be applied starting with the selection of a high quality sensor-transmitter system and then adding a margin of error allowance. For example, instead of operating using standard calibration procedures, opt for sensor-transmitter matching to increase the system accuracy by about a factor of four.

Example 1: Rosemount X-well Accuracy TPE Calculation

$$\textbf{TPE} = \sqrt{(\textbf{Digital Accuracy}^2 + \textbf{Ambient Temperature Effects}^2 + \textbf{Sensor Accuracy}^2 + \textbf{Process Temperature Effect}^2)}$$

Conditions: 100°C process temperature and 30°C ambient temperature

Digital Accuracy: ±0.10 °C for a PT 100 (alpha .00385) RTD sensor

Ambient Temperature Effects = 0.0015 °C per 1.0 °C change in ambient temperature

Sensor accuracy = ±0.80 °C @ 100 °C for a class B RTD sensor

Process Temp Effect = 0.01 °C per 1.0 °C difference in process and ambient temperature

$$\textbf{TPE} = \sqrt{([0.10]^2+[0.015]^2+[0.80]^2+[0.70]^2)}$$

$$= \pm\ \mathbf{1.07^\circ C}$$

4.3.5 Configuration and Installation Considerations for Rosemount X-well Technology

1. Configuration of X-well Technology

Rosemount X-well technology relies on process piping information to extrapolate accurate process temperature measurements. Rosemount X-well transmitters ordered with process piping information will arrive configured and ready to install. Verification of the configuration is best practice to ensure the transmitter is being installed on the expected pipe. To configure a transmitter for Rosemount X-well sensor, enter the guided setup section and use the guided setup wizard for “Configure Sensor”. Inside the sensor configuration wizard, select the “Rosemount X-well process” sensor type for piping supported directly in the transmitter or “Rosemount X-well Custom” for process piping not supported directly in the “Rosemount X-well process” sensor type. A list of all supported materials can be found in the corresponding Product Data Sheets. If selecting “Rosemount X-well process,” the setup guide will request the process piping schedule, material, and diameter. For “X-well custom,” the set up guide will request the custom coefficient. This coefficient can be provided by Emerson temperature specialists for all conductive piping materials and schedules.

2. Mounting Considerations

Rosemount X-well technology uses the flow of heat through the transmitter and sensor body to extrapolate process temperature without the need for a thermowell. For this reason, it is important to ensure all X-well installations are installed away from any heat sources or sinks that could interrupt the flow of heat. This includes large flanges, boilers, air movers, and fired heaters. In addition, this heat flow through the head of the transmitter means all installations must have the transmitter installed directly on the sensor threads.

Rosemount X-well technology measurement points can be installed in any orientation on a pipe, but must be installed so that the sensor tip is in contact with the portion of the process pipe that contains the desired process flow. For pipes that contain mixed flow (such as a gas and liquid flows), Rosemount X-well technology measurement points should be installed on the underside of the pipe to measure liquid flow temperature or on the top of the pipe to measure gas flow temperature.

For vertical pipes, it is essential that Rosemount X-well technology measurement points be installed on fully filled piping sections. For installations on the underside of the process piping, the best practice is to tighten the nut retaining the O-ring on the clamp union. This will ensure proper ingress protection and prevent moisture from running into the transmitter terminals.

Finally, to ensure a proper surface temperature measurement, it is important to ensure the sensor tip is in full contact with the surface of the pipe.

Verify that the sensor has not caught on the edge of the pipe mount and clear the surface of any debris such as rust, dust, or paint bubbles. It is not required to remove process piping paint before installing new Rosemount X-well technology measurement points.

3. Installation of Rosemount X-well Technology Measurement Points

New Rosemount X-well Technology measurement points will arrive assembled. The pipe mount, sensor, and transmitter can all be installed in a single step or the clamp can be installed separately, and the transmitter and sensor threaded into the union. However, installing the clamp with the sensor already installed is best practice as it allows for verification that the sensor has fully passed through the opening in the clamp body. Once the transmitter, sensor, and pipe mount are fully installed, follow commissioning guides for respective transmitter. The clamp bolts should be torqued to 20 Nm to ensure the sensor is in full contact with the surface of the pipe.

The final step in installing all Rosemount X-well Technology temperature points is to insulate the 6” either side of the clamp and up the sensor body. The insulation should be a minimum of ½” thick with R-value of > 0.8 $m^2 \times K/W$

A corrosion protection inlay can provide a layer of protection to help minimize the possibility of dissimilar metal corrosion between the pipe clamp and pipe. The inlay is installed in between the pipe clamp and the pipe. Ensure the sensor is clearing the hole in the protection inlay after installation.

Procedure for replacing the spring-loaded sensor in the pipe clamp sensor.

1. Loosen and remove the original sensor from the extension of the pipe clamp.
2. Add pipe compound or PTFE tape (where local piping codes allow) to the threads of the new sensor.
3. Insert the new sensor into the extension of the pipe clamp sensor and ensure the sensor tip passes through the hole of the pipe clamp.
4. Screw in the sensor and tighten the union to 24 ft-lbs of torque.

4.3.6 Transmitter

The transmitter converts the sensor measurement input signal to a high level robust output signal. The output signal can be either analog or digital, both of which are highly accurate and reliable with strong noise immunity, and may be transmitted over long distances. The most common analog signal is 4-20mA, which can include a digital HART protocol signal overlaid on top. Common digital communication protocols are HART (including *Wireless*HART), FOUNDATION Fieldbus, and Profibus, all of which are open and interoperable standards. The use of digital technology adds flexibility to the output of each transmitter, enabling transmission of more than one temperature value as well as large amounts of diagnostic information.

Refer to section 3.1.3 for more detail.

Transmitters are available in a variety of housing styles that may be mounted into any of a wide selection of enclosures that are available in many different materials of construction. Refer to Figure 4-19. They may be mounted integrally with a sensor/thermowell assembly at the process measurement point and transmit either a hard-wired or wireless signal. Alternatively, they can be mounted remotely from the sensor assembly in any of several types of enclosures. They can be configured locally or remotely and can provide local indication. They have an array of standard and optional performance features to provide remarkable functionality. Systems may be provided to meet virtually any agency approval requirement.

Refer to section 3.1.10 for more detail.

Figure 4-19 – Transmitter Styles

4.3.6.1 Performance and Functionality Considerations

From the discussion in section 4.1.2, you should have analyzed your application to the point where you understand all aspects in detail. It is impractical to specify the best possible transmitter for simple applications where a basic model will provide adequate performance. These applications could include monitoring trends or where accuracy requirements are not as stringent and optimal accuracy and performance are not beneficial.

However, for systems requiring high accuracy and /or high reliability performance, a top-of-the-line model mounted into a dual-compartment housing and installed as close as possible to the measurement point is a wise choice. See Figure 4-20. As stated in the introduction, cost of ownership considerations should drive your selection.

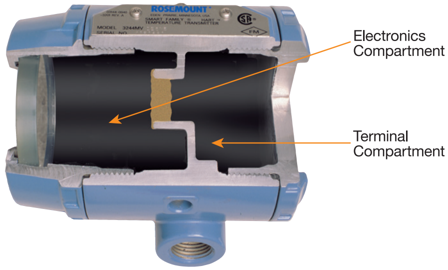


Figure 4-20 – Dual-Compartment Housing

Most transmitters accept RTD, T/C, mV, or ohm signals. Many transmitters have a dual input capability, allowing them to accept inputs from two sensors. Dual sensors offer the option of redundancy with the Hot Backup feature, monitoring for sensor drift, and allows for measurement of differential and average temperatures.

Where a large number of temperature measurement points are close together, a multi-input transmitter may be specified. These high density transmitters minimize installation costs in applications such as heat exchangers, boilers, chemical reactors, and distillation columns by reducing purchase, installation, operation and maintenance costs vs. multiple transmitters. They are also often used for temperature profiling applications. See Figure 4-21.

Figure 4-21 – High Density Field Mount Installation

4.3.6.2 Mounting Location

Mounting location is another guiding factor in transmitter style selection that begins with determining where the transmitter will be mounted relative to the sensor. Where possible and practical, transmitters should be mounted close to the measurement point to minimize potential EMI and RFI noise pickup. This is especially important for low level T/C signals which are especially susceptible to noise.

High process fluid temperature radiates from the pipe or vessel causing higher ambient temperatures that may be unsuitable for close coupled transmitter mounting. This situation may be addressed by installing an insulation layer and/or by using sensor extensions to position the transmitter housing further away from the heat source. See Figure 4-22 for an example of the temperature effects on the transmitter.

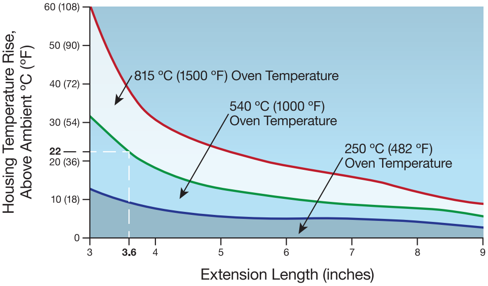


Figure 4-22 – Transmitter Housing Temperature Rise vs. Extension Length for a Test Installation

Example:
The maximum permissible housing temperature rise (T) can be calculated by subtracting the maximum ambient temperature (A) from the transmitter's ambient temperature specification limit (S).
For instance, if A = 40 °C.

T = S - A
T = 85 °C - 40 °C
T = 45 °C

For a process temperature of 540 °C (1004 °F), an extension length of 91.4 mm (3.6 inches) yields a housing temperature rise (R) of 22 °C (72 °F), providing a safety margin of 23 °C (73 °F). A 152.4 mm (6.0 inch) extension length (R = 10 °C (50 °F)) offers a higher safety margin (35 °C (95 °F)) and reduces temperature-effect errors, but would probably require extra transmitter support. Gauge the requirements for individual applications along this scale. If a thermowell with lagging is used, the extension length may be reduced by the length of the lagging. See Figure 4-23.

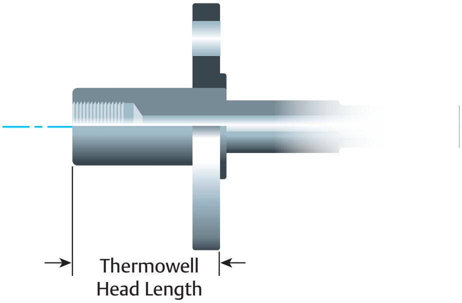


Figure 4-23 – Lagging Dimension

If the extension length that would be required to prevent excessive transmitter housing heating becomes unwieldy, consider remote mounting the transmitter. Remote mounting is also a good option when the pipe or vessel is under high vibration conditions. Frequently, transmitters are remote-mounted away from a connection head to make the instrument more accessible for calibration and maintenance, or to simply make it easier to view the display. It may also be desirable to group a number of transmitters together on an instrument stand for optimum operator and maintenance availability. These stands should be located where they can be easily accessed but where damage is unlikely.

Another alternative is high density DIN rail mounting into a local field mounted cabinet. However, this option does not support explosion proof requirements and should not be used in corrosive or excessively humid environments.

4.3.6.2.1 Additional Mounting Considerations

There are a variety of choices for mounting a transmitter that are driven by process conditions at the point of measurement, plant standards and policies, and user preference.

A methodical approach of reviewing all related factors will very likely present the best choice. Here are some examples of questions that must be answered to drive the selection process.

- Is the ambient temperature expectation at the measurement site within the limits of the transmitter specification?
  - If yes, integral mounting is acceptable
- Is the measurement site easily accessible?
  - If yes, integral mounting is acceptable
- Is local temperature indication required?
  - Specify an LCD indictor option
  - Refer to section 3.1.11.2
- Can operator see display if assembly is integrally mounted at the measurement point?
  - If yes, integral mounting is acceptable
  - If not, a remote mount option is required
- Is there high vibration at the measurement point?
  - If yes, a remote mount option is required
  - If no, integral mounting is acceptable
- What is the area classification? What is the approval agency?
  - Select a housing option that offers the protection and certification that is required. Check P&IDs, plant standards and vendor product data sheet
- Does the plant site require Intrinsically Safe (IS) installation?
  - If yes, specify a housing with IS certification

- Are there sources of EMI, RFI or electrical surges near the measurement point?
  - – If yes, integral mounting is desirable
  - – Refer to sections 3.1.2.4.1 and 3.1.11.3
- Is this measurement associated with a SIS?
  - – If yes, specify a model with appropriate certifications for the SIL required
  - – A top-of-the-line system offering maximum reliability and performance is most often the best choice for safety-related applications
  - – Verify the safety requirements with the designated Certified Fuctional Safety Expert (CFSE)
  - – Refer to section 3.1.12
- Is there a hygienic consideration?
  - – If yes, specify appropriately certified housing and thermowell assembly
  - – Refer to section 3.1.10.4
- Is there a corrosive environment?
  - – If yes, verify suitability of selected housing material with the contaminants present
  - – If material is not suitable, a remote mount may be required

TIP: Many times a site inspection and consultation with process engineering and operations will greatly facilitate the choice of the optimal system.

4.3.6.3 Model Styles

The most common mounting styles are:

Head Mount Transmitters are compact disc shaped transmitters most often mounted within a connection head which can be mounted in the field. Most common styles are DIN A and DIN B which differ slightly in dimensions and mounting method. See Figure 4-24.

Figure 4-24 – Head Mounted Transmitter

Dual-Compartment Transmitter Housings, often known as field mount, isolate the transmitter electronics module from the terminal strip compartment to protect it from exposure to harsh plant environments. The terminal compartment contains the terminal and test connections for the sensor and signal wires and provides access to the terminal block for wiring and maintenance while isolating the transmitter electronics. See Figure 4-25.

Figure 4-25 – Dual-Compartment Transmitter

Rail Mount Transmitters are thin rectangular transmitters that are typically attached to a DIN-rail (G-rail or top-hat rail) or fastened directly onto a surface. This provides a compact high-density installation where a number of rail mount transmitters can be placed very closely together on the same DIN-rail. Unlike the field mount transmitters, the DIN style are not designed for harsh environments nor can they be used in areas designated as explosion-proof. See Figure 4-26.

Figure 4-26 – Rail Mount Transmitters

4.3.6.4 Transmitter Standard Features

Smart transmitters offer many standard features including noise filtering, galvanic isolation, linearization of nonlinear input signals, cold junction compensation (CJC) for thermocouples, configurable input selection, bidirectional communication with the host, and internal and external self diagnostics.

In addition, there are many optional features that can be utilized to enhance the measurement reliability and functionality. All of these are discussed in detail in sections 3.1.6 and 3.1.8 and are listed below with reference sections.

4.3.6.5 Intelligent Filtering Features and Options

Tip: Refer to the sections listed below for a detailed explanation of each feature or option and then review your application requirements to determine which options would provide the added reliability and functionality needed.

3.1.6.1 - Damping

3.1.6.2 - Open Sensor Holdoff

3.1.6.3 - Transient Filtering

3.1.6.4 - EMF Compensation

3.1.6.5 - Line Voltage Filter

3.1.6.6 - The Hot Backup Feature

3.1.6.7 - Sensor Drift Alert

3.1.6.8 - Thermocouple Degradation

3.1.6.9 - Minimum - Maximum Tracking

4.3.6.6 Diagnostics

TIP: Refer to the sections below to better understand the functionality and benefits of the various diagnostic functions.

3.1.8 - Diagnostics

3.1.8.1 - Internal Diagnostics

3.1.8.2 - External Diagnostics

3.1.8.3 - Open/Short Sensor Diagnostics

3.1.8.4 - Measurement Validation Diagnostic

3.1.8.5 - Diagnostics Log

4.4 Installation Best Practices

The following sections are suggested best practices for designing, selecting, installing and configuring a properly engineered temperature measurement solution for your application.

4.4.1 Thermowell Installation

- Ensure that the proper thermowell design has been purchased and it is accordance with the specification for pressure rating and materials of construction Figure 4-27.
- Secure the proper permits and permissions to make the penetration into the pipe or vessel.
- Ensure that the pipe or vessel has been properly drained and cleaned as may be required. This is especially important for toxic or flammable materials.
- Follow the applicable vessel code requirements for weld certification and leak testing as is specified.

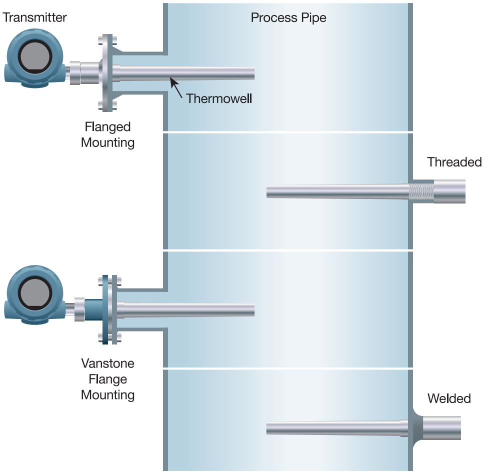


Figure 4-27 – Thermowell Mounting Methods

4.4.2 Transmitter Installation

4.4.2.1 Configuration

Depending on the ordering specification, the sensor-transmitter assembly may or may not have been factory configured and calibrated to the specific process requirements. It is always prudent to verify all settings to ensure that they conform to the latest revisions of the loop drawings. The vendor User's Manual will provide guidance on such things as ranging, alerts, alarms, damping, various intelligent filtering settings, etc.

4.4.2.2 Calibration

Once the transmitter is configured, calibration may be required. This calibration may have been performed by the manufacturer in which case it should not be changed. It may be prudent to verify the sensor-transmitter integrity however by using temperature baths or blocks to exercise the system over its range. Refer to section 5.7 for more calibration detail.

4.4.2.3 Installation Detail

Frequently, the transmitter is integrally mounted with the sensor and installed into a thermowell. Alternatively, the transmitter is remotely mounted as near the measurement point as is practical on a rack, pipe-stand or on a bracket. A connection head should be used in these installations such that the sensor leads may be kept as short as possible to reduce noise pickup and potential damage. There are typically plant standards and loop drawings that dictate the details of transmitter mounting and wiring, but in general, locations are selected to facilitate access for viewing of indicators if so provided, calibration and maintenance and away from areas of potential physical damage, splashing or dripping. See Figure 4-29.

Transmitters should be positioned higher than the conduit runs and with the conduit connection at the bottom to minimize potential egress of moisture from leaking conduit seals. Threaded connections may require PTFE tape. A pressure test should be completed and documented before wiring is installed and power is applied.

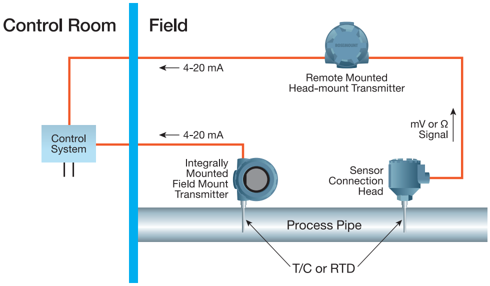


Figure 4-29 – Installation Options

4.4.2.3.1 Wireless Considerations

There are installation issues for wireless instrumentation that are unique, including:

- Proper height from ground or structure and with respect to neighboring device(s), see Figure 4-30
- Mounting position with respect to nearby structures or devices (305 mm (1 foot) minimum)
- Line of site to "neighbor" device
- Proper antenna for distance required (high gain/low gain)
- Follow proper configuration guidelines in vendor manual using typical HART configuration tools (Field configurator, laptop, asset management system)

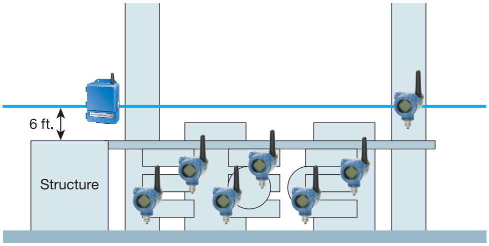


Figure 4-30 – Wireless Mounting Guideline

4.4.2.4 Wiring

Ideally the proper cable types have been specified during the design phase of the project. In all cases, the conductors should be twisted and shielded with an outer insulated sheath selected to be in conformance to the environmental conditions where the wiring trays will be installed. For multi-conductor cables, there are many designs. Some have individually shielded pairs with an overall shield with drain wire for maximum noise protection and have an overall insulated sheath.

The sensor wires and output cables should be pulled through the conduits and fittings and into the transmitter housing through a conduit seal similar to that shown in Figure 4-31 and secured to the instrument termination screws.

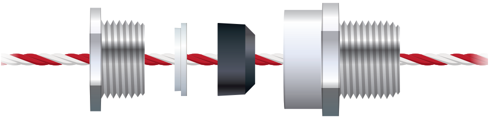


Figure 4-31 – Typical Conduit Seal

There are also poured seals and seals with drains that may be appropriate for some applications. See Figure 4-32.

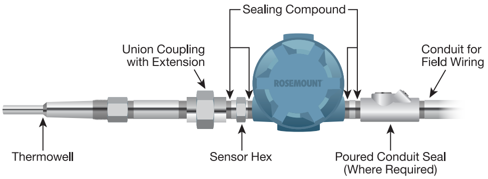


Figure 4-32 – Typical Mounting with Drain Seal

There are specific mounting recommendations for both North American and European accepted best practices as shown in Figure 4-33 and Figure 4-34.

Consult the Loop Diagram or the transmitter user manual for wiring termination designation. Appropriate tagging of all conductors should be attached.

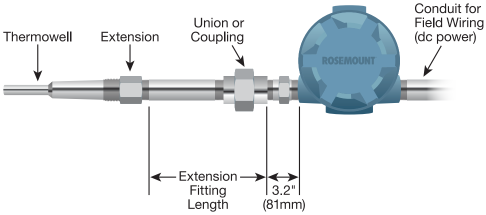


Figure 4-33 – Typical North American Mounting

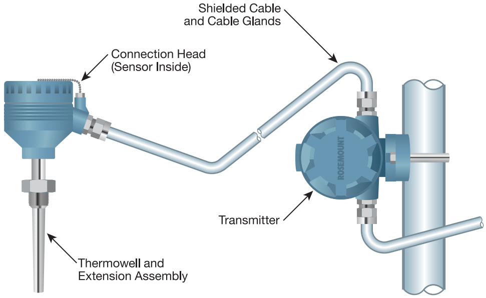


Figure 4-34 – Typical European Mounting

4.4.2.4.1 Grounding - Shielding

Each process facility has their own guidelines for the proper installation of grounds and shields. These guidelines should be followed where practical and appropriate. However, if it is desirable to verify that these guidelines are appropriate for your installation or if in doubt about how to proceed, the guidelines below should be followed. See Figure 4-35.

Option #1 – Remote mount with 2 separate grounding points

- Connect the sensor shield, if supplied, only at the remount mount head and ensure that it is not connected at any other point and is electrically isolated from any grounded equipment
- Ground signal wiring shield only at the power supply end to an instrument system grounding point and ensure that the transmitter end is carefully isolated
- See Figure 4-35

WHAT ARE THE RECOMMENDED GROUNDING BEST PRACTICES?

Each process facility has their own guidelines for the proper installation of grounds and shields. These guidelines should be followed where practical and appropriate. However, it is desirable to verify that these guidelines are appropriate for your installation or if in doubt about how to proceed.

Refer to:

4.4.2.4.1 – Grounding - Shielding

3.1.2.2 – Isolation

TIP: Instrument system ground should not be connected to power wiring ground, which can carry noise, surges and spikes that could interfere with measurement signals and/or destroy transmitters. Instrument system ground must be a very low resistance path to an earth grounding rod or grid.

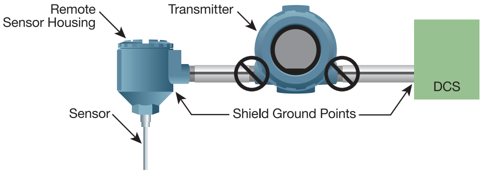


Figure 4-35 – Option #1 for Shield Grounding

Option #2 – Remote mount with a continuous shield

- Connect the sensor shield only to the signal cable shield and ensure that it is electrically isolated from the transmitter and all other field equipment
- Connect the signal cable shield to instrument system ground only at the power supply end
- See Figure 4-36

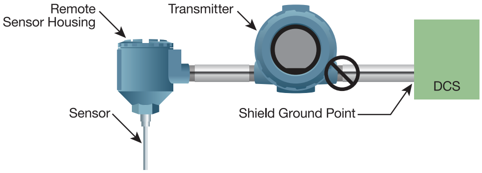


Figure 4-36 – Option #2 for Shield Grounding

Option #3 – Integral mount

- Ground the signal wiring shield at the power supply end only to instrument system ground ensuring that it is electrically isolated from the transmitter housing and all other field equipment
- This is used for integral mount installations
- See Figure 4-37

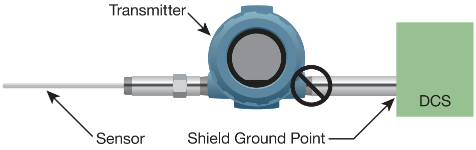


Figure 4-37 – Option #3 for Shield Grounding

4.4.2.5 Commissioning

Commissioning has been referred to over the years as “ringing out the system” or “loop checking the system”. Whatever it may be referred to as in your facility, the task is the same. It includes verifying every connection of every loop is properly secured, tagged and connected at both the field and control room ends. It further includes an operational check of each loop to verify that all settings are properly set and that the functionality of the design has been implemented. Extensive use of loop sheets and instrument specification sheets helps to guide this procedure.

For a Safety Instrumented System, it is mandatory to completely document this procedure. In other applications, complete and proper documentation is considered best practice.

4.4.2.6 Acceptance Testing

The acceptance testing procedure is similar to the commissioning procedure, but is intended for an official turn-over of a system that is operating according to design specification from the vendor to the owner. For some systems, especially for SIS, this is first conducted at the vendor facility, known as Factory Acceptance Testing, or FAT, and then again after installation and commissioning. The terms Site Acceptance Testing (SAT) and Pre-start-up Acceptance Testing (PSAT) are often applied.

4.4.3 Other Considerations

When installing your temperature measurement point, there are some other items you need to be aware of, including documentation, system accuracy and reliability, and some other general guidelines.

4.4.3.1 Documentation Considerations

A part of the engineering of each temperature measurement system is the development of documents that contain all of the necessary information about the application. These include the Plot Plan, Process Flow Diagram, Piping and Instrument Diagram (P&ID), Installation Details, Instrument Lists, Loop Sheets, and Specification Sheets.

4.4.3.1.1 – A Plot Plan is an engineering plan drawing or diagram which shows the buildings, utility runs, and equipment layout, the position of roads, and other constructions of an existing or proposed project site at a defined scale. Plot plans are also known more commonly as site plans. See Figure 4-38.

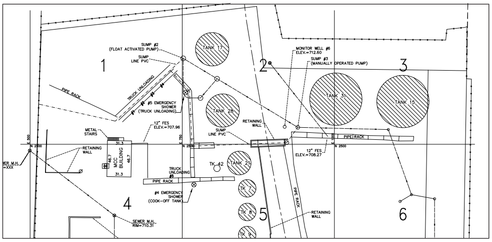


Figure 4-38 – Typical Plot Plan

4.4.3.1.2 – The Process Flow Diagram shows the major pieces of equipment in a process area and the design operating conditions. See Figure 4-39.

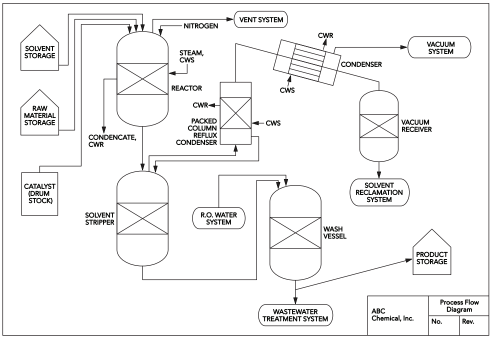


Figure 4-39 – Typical Process Flow Diagram

4.4.3.1.3 – Piping and Instrument Diagrams (P&ID) show the anticipated need for measurement and control instrumentation. See Figure 4-40.

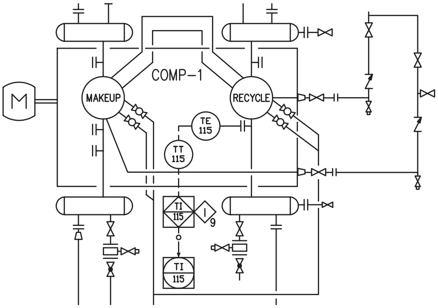


Figure 4-40 – Example of a P&ID

The P&ID does not indicate precisely where to install the sensors and transmitters, leaving a great deal of latitude in the selection and placement of the specific components by the engineering staff and piping designer. The P&IDs are to be used to describe the relationships between equipment and instrumentation as well as other relevant information that will enhance clarity. Computer software programs that do P&IDs or other diagrams useful to the information package may be used to help meet this requirement. Decisions regarding the use of specific components are often influenced by corporate standards, local preferences, and the existing infrastructure. For temperature loops, P&IDs will show such things as temperature sensing elements (TE), thermowells (TW), temperature indicating transmitters (TIT), temperature indicators (TI), and temperature indicating controllers (TIC). Figure 4-41 shows typical loop sheet ISA symbols for both an integrally mounted transmitter and a remote mounted transmitter.

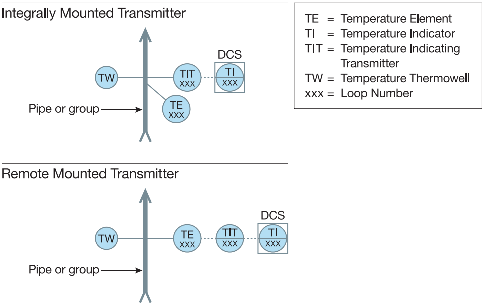


Figure 4-41 – Typical ISA Symbols for a Temperature Loop

The information pertaining to process equipment design must be documented. In other words, what codes and standards were relied on to establish good engineering practice? These codes and standards are published by such organizations as the American Society of Mechanical Engineers, the American Petroleum Institute, American National Standards Institute, National Fire Protection Association, American Society for Testing and Materials, The National Board of Boiler and Pressure Vessel Inspectors, National Association of Corrosion Engineers, American Society of Exchange Manufacturers Association, and Model Building Code groups.

For existing equipment designed and constructed many years ago in accordance with the codes and standards available at that time and no longer in general use today, the employer must document which codes and standards were used and that the design and construction along with the testing, inspection, and operation are still suitable for the intended use. Where the process technology requires a design that departs from the applicable codes and standards, the employer must document that the design and construction are suitable for the intended purpose.

4.4.3.1.4 – The Installation Detail Drawing tells contractors and pipefitters the location of each measurement point and how the components are to be installed. This construction document evolves from many decisions regarding thermowells, sensor elements, connection heads, transmitters, etc. See Figure 4-42.

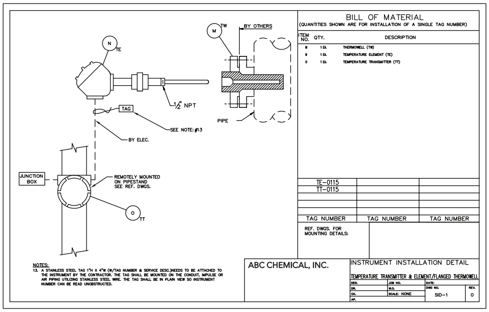


Figure 4-42 – Installation Detail Drawing

4.4.3.1.5 – Loop Sheets are developed in some cases, with detailed wiring schematics for the sensors, junction boxes, transmitters, power supplies, and marshalling points reflecting the system architecture. Every loop is numbered, and every sensor and device in the field is tagged. It is an engineering function to create these diagrams, which are cross-referenced with Instrument Lists, so that the system installers know where every single wire is terminated and how every device is grounded. As part of commissioning and before the system can be started and run, the engineers and technicians verify that the wires are installed correctly and that the loops are functioning. See Figure 4-43.

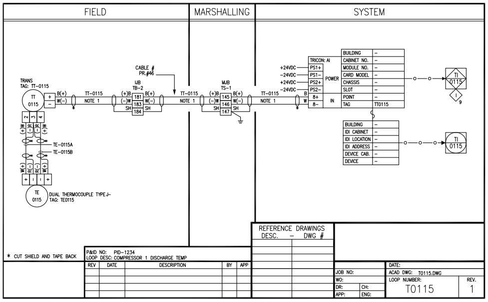


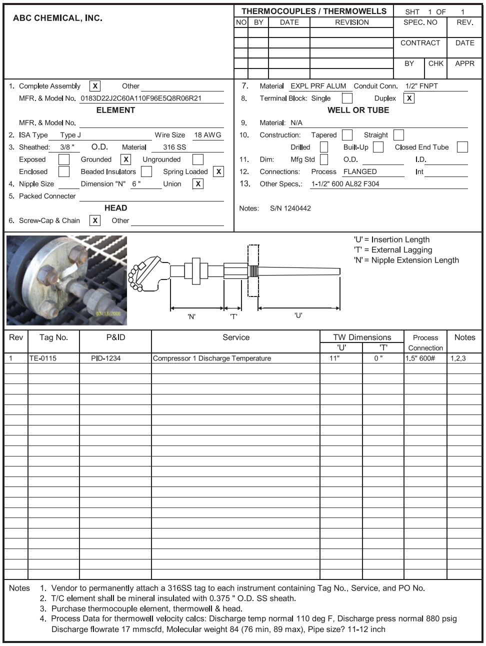
Figure 4-43 – Typical Loop Sheet

4.4.3.1.6– Instrument Lists document every instrument comprising the input/output loops, and there can be hundreds of such loops in one automated process. Columns show the type of sensor, its model number and manufacturer, the service, the transmitter type model number and manufacturer, the tag name/number for each device, and the location on the P&ID. See Figure 4-44. It may also include I/O detail information showing where every input is terminated by rack, card, and terminal, with the same detail for every output.

4.4.3.1.7 – ISA standard Specification Sheets are the basis for ordering instruments, so they must contain all the dimensions and other information needed by a manufacturer to configure each component to function according to the design and the demands of the process. Specification Sheets are generally kept on file in the plant along with P&IDs as reference documents. See Figure 4-45.

Sensor Type	Sensor Model #	Sensor Mfgr	Sensor Tag #	Transmitter Model #	Transmitter Mfgr	Transmitter Tag #	Service	P&ID Location
RTD	0078N21A30A075T22E5	Rosemount	TE 1234	3144PD1A1E5M5C8C2	Rosemount	TIT 1234	Fractionation	H-17

Figure 4-44 – Typical Instrument List



ABC CHEMICAL, INC.

THERMOCOUPLES / THERMOWELLS

SHT 1 OF 1

NO	BY	DATE	REVISION

SPEC. NO | REV.
CONTRACT | DATE
BY | CHK | APPR

1. Complete Assembly ☒ Other
MFR. & Model No. 0183D22J2C60A110F96E5Q8R06R21

ELEMENT

MFR. & Model No.
2. ISA Type Type J Wire Size 18 AWG
3. Sheathed: 3/8 " O.D. Material 316 SS
Exposed ☐ Grounded ☒ Ungrounded ☐
Enclosed ☐ Beaded Insulators ☐ Spring Loaded ☒
4. Nipple Size Dimension "N" 6 " Union ☒
5. Packed Connecter

HEAD

6. Screw-Cap & Chain ☒ Other
7. Material EXPL PRF ALUM Conduit Conn. 1/2" FNPT
8. Terminal Block: Single ☐ Duplex ☒

WELL OR TUBE

9. Material: N/A
10. Construction: Tapered ☐ Straight ☐
Drilled ☐ Built-Up ☐ Closed End Tube ☐
11. Dim: Mfg Std ☐ O.D. I.D.
12. Connections: Process FLANGED Int
13. Other Specs.: 1-1/2" 600 AL82 F304

Notes: S/N 1240442

'U' = Insertion Length
'T' = External Lagging
'N' = Nipple Extension Length

Rev	Tag No.	P&ID	Service	TW Dimensions		Process Connection	Notes
				'U'	'T'		
1	TE-0115	PID-1234	Compressor 1 Discharge Temperature	11"	0 "	1.5" 600#	1,2,3

Notes
1. Vendor to permanently attach a 316SS tag to each instrument containing Tag No., Service, and PO No.
2. T/C element shall be mineral insulated with 0.375 " O.D. SS sheath.
3. Purchase thermocouple element, thermowell & head.
4. Process Data for thermowell velocity calcs: Discharge temp normal 110 deg F, Discharge press normal 880 psig Discharge flowrate 17 mmscfd, Molecular weight 84 (76 min, 89 max), Pipe size? 11-12 inch

Figure 4-45 – ISA Temperature Transmitter Specification Sheet

WHAT IS THE BENEFIT OF TRANSMITTER-SENSOR MATCHING?

Temperature sensor-transmitter assemblies can be visualized as "good-better-best" where a transmitter used with a Class B sensor is "good";
a transmitter used with a Class A sensor is "better" and a transmitter matched to a sensor using the CVD constants method is "best".

Refer to:

Figure 3-68 – Good-Better-Best: Calibration Comparison of Systems Using a Class B Sensor vs. Using a Class A Sensor vs. Using the CVD Method

3.1.4.3.3 – Transmitter-Sensor Matching

4.3.4.1– System Error Analysis, with Example TPE Calculations

4.4.3.4 Durability and Reliability – The Confidence Factor

Selecting a temperature measurement system with a proven track record of reliability is valuable to process confidence. A system with documented results from long term operation and proof-testing will ensure confidence. If a problem is suspected with the process system, time is often wasted troubleshooting the source of the issue. If a particular sensor is determined to be the cause or a contributor to the issue, the sensor will need to be recalibrated or replaced. Replacement often requires shutting down the process, causing unplanned and expensive production downtime. Product quality issues or even product loss can occur when a process control loop is operating inconsistently or inaccurately.
If the solution is frequent replacement of a lower quality sensor, additional and often hidden costs are incurred, including additional spares inventory with related purchasing and stocking costs. Added to that overhead cost is the cost of recalibration services and process verification procedures. These costs are very real yet often are hidden and difficult to capture and measure.

It is important to match the sensor accuracy with the requirements of the process. General good practice would suggest that the sensor accuracy should be about four times better than the measurement accuracy required by the process. The value of this approach relates not only to process control confidence but also energy savings. For energy intensive processes, wasted thermal energy can add a significant amount of cost over time. For example, just a one degree error in control of a small heat exchanger could easily cost over $10,000 per year in wasted energy.

4.4.3.5 Guidance Review for Ensuring Optimal System Performance and Accuracy

Throughout this handbook, guidance has been offered for ensuring the best accuracy and performance of your temperature measurement system, including:

- Use a 4-wire spring-loaded RTD unless the measured range exceeds 850 °C
- Integrally mount the sensor with the transmitter whenever possible to minimize noise pickup
- Use a transmitter in a dual-compartment housing to minimize environmental influence on the transmitter
- Use a stepped well for fastest response
- Perform a wake frequency analysis to ensure selection of a proper thermowell configuration that will withstand the vibration caused by vortex shedding from the well

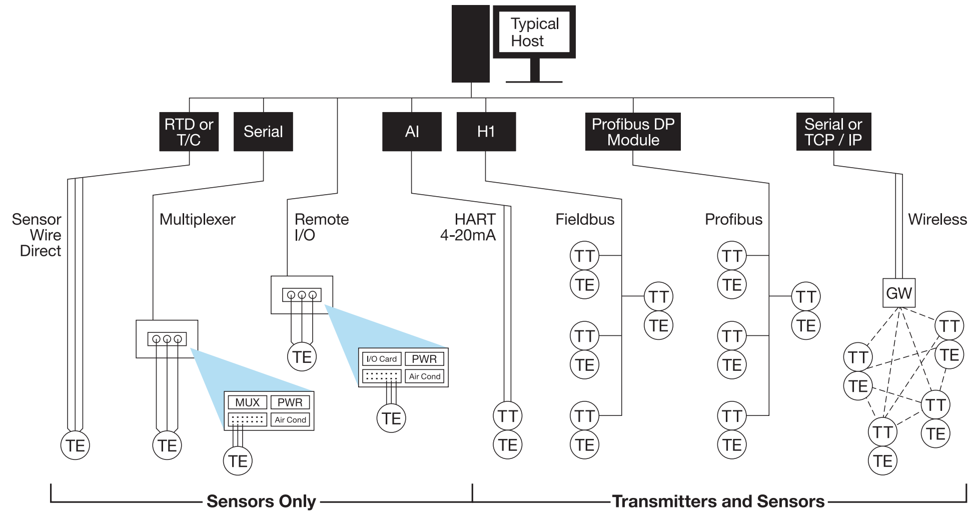


Figure 4-46 – Technology System Diagram

- Specify sensor-transmitter matching for best accuracy
- Consider use of dual element sensors for redundancy and drift monitoring
- For installations in electrically noisy environments, specify transient suppression
- Consider specifying intelligent filtering options, as they may be appropriate. See section 6.0 for a detailed description

> *TIP: Proceed to section 4.5, Connecting to the Control System for further guidance.*

4.5 Connecting to the Control System

4.5.1 Overview

To be useful for control, monitoring or logging of the measured temperature, the signal must be communicated from the field measurement site to the control room. Many plant sites have established preferences on how this is accomplished most commonly using field mounted transmitters or direct wiring from the field to control room device input cards. Each method has its proponents, but the following discussion will make the case for a strong preference for using transmitters over using direct wiring.

In the following sections, each available technology is discussed in detail.

A system diagram illustrating all technologies is in Figure 4-46.

Pros and Cons of these technologies are compared in Figure 4-47.

Technology	Pros and Cons
Wire Sensors Directly to DCS	• High Wiring and Infrastructure Cost • Prone to Interference • High Maintenance • Limited Feature Functionality and Performance vs. Transmitter
Multiplexors	• Dated Technology • Slow Updates • Reliability Issues • Limited Accuracy and Performance Specifications • Area Certification and Environmental Limitations • Limited Parts, Service
Control System Remote I/O Racks	• Good Basic Capability • Proprietary Infrastructure • Limited Feature Functionality and Performance vs. Transmitter • Area Certification and Environmental Limitations
Transmitters and Sensors	• Highest Accuracy • Excellent Noise Immunity • Lowest Cost of Ownership • Wide Choice of Measurement Enhancement Features

Figure 4-47 – System I/O Option Comparison

4.5.2 Transmitters

The transmitter converts the measurement input signal from RTDs, T/Cs, mV or resistance sensors to highly robust analog or digital signals for communicating with the host.

Transmitters are available in a variety of housing styles that may be mounted into any of a wide selection of enclosures that are available in many different materials of construction. They may be mounted integrally with a sensor/thermowell assembly at the process measurement point and transmit either a hard-wired or wireless signal. Alternatively, they can be mounted remotely from the sensor assembly in any of several types of enclosures. They can be configured locally or remotely and can provide local indication. They have an array of standard and optional performance features to provide remarkable functionality. Systems may be provided to meet virtually any agency approval requirement.

A smart transmitter provides a more accurate and robust temperature measurement than is provided by direct wired I/O systems. A smart transmitter provides signal isolation, filtering, linearization and sensor type or sensor specific compensation to the measurement before sending the value to the host system.

TIP: Refer to the Temperature Measurement Basics, Section 3.1 for a detailed discussion.

4.5.2.1 Output Signals

After the signal conditioning functions as described above are completed, the measurement is converted to a highly accurate analog or digital signal with excellent noise immunity as compared to the weaker and noise susceptible signals coming directly from the sensor.

4.5.2.1.1 Analog Current

Industry standard 4-20 mA analog signals are used globally to communicate with field mounted devices over long distances.

HART®
COMMUNICATION PROTOCOL

4.5.2.1.2 HART

The HART (Highway Addressable Remote Transducer) protocol is a hybrid protocol that provides for a digital signal superimposed onto the 4-20 mA signal. The protocol also has a provision for all digital multi-drop communication.

Fieldbus®
Foundation

4.5.2.1.3 FOUNDATION Fieldbus

FOUNDATION Fieldbus is an all-digital, serial, deterministic peer-to-peer communications protocol that serves as a field-based device network in a plant or factory automation environment.

PROFI®
PROCESS FIELD BUS
BUS

4.5.2.1.4 PROFIBUS

PROFIBUS PA is an all-digital parent/child communications protocol that serves as a field based device network in a plant or factory automation environment

*Wireless*HART®

4.5.2.1.5 *Wireless*HART

*Wireless*HART is an open-standard wireless self-organizing mesh network based wireless communication protocol developed to complement the existing HART protocol.

4.5.3 Direct Wiring

Direct wiring terminates the temperature sensors directly to control or monitoring system input cards where it is converted into a digital value of the temperature measurement for use in that system. These control room systems could be a DCS, PLC, data logger, or controller.

For RTD sensors, standard copper extension wire is used for all four leads. However, for thermocouple sensors, specially matched extension wire must be used or huge measurement errors will result.

4.5.3.1 Control System I/O

Field wiring may have each sensor cable run all the way to the control room in cable trays or conduits terminating at I/O cards in a rack room or control room. Care must be taken to separate and isolate the low level signal wiring from any higher voltage wiring to reduce EMI and RFI noise interference. Minimum separation distance is dependent on several factors, including voltage levels, current levels of switched signals, digital signal level, etc. and if they are shielded and properly grounded. Some facilities use separate trays for high level signals and others suggest separation distances ranging from 150 to 600mm (5.9 to 23.6 in). All signal conditioning takes place in the input card.

4.5.3.2 Remote I/O

Another alternative is using a field mounted I/O subsystem mounted into I/O cabinets. This subsystem uses a digital communication link to connect to control room systems. These com links may be Ethernet, vendor proprietary, or a fieldbus protocol which must also be separated and isolated from high voltage wiring. This approach can be cost effective for high density measurement applications where the higher accuracy and performance of a transmitter is not required. While this design reduces the length of sensor extension wire, it does have other limitations and requirements. Operating power must be supplied to the cabinet, which may limit access to the I/O without a hot work permit. There are also environmental concerns and limitations that may require purged cabinets. Environmental conditioning, such as heating and air conditioning, may be required, as control system I/O generally has more restrictive limits for operating temperature, humidity, corrosion, and other environmental factors. Explosion proof certification is impractical.

WHY SHOULD LONG SENSOR WIRES BE AVOIDED AND WHAT ARE THE ALTERNATIVES?

The cost of ownership of sensor extension wire far exceeds the cost for standard two-wire cable typically used for transmitter output signals. Just for this reason alone, mounting the transmitter as close as is practical to the sensor will be cost effective.

From a performance point-of-view, long leads act as an antenna for electrical noise that will always be present in a plant environment where there will be electrical interference sources like pumps, motors, Variable Frequency Drives (VFD's) and radios as well as sources of electrostatic discharge and other electrical transients. Low level sensor signals from RTDs and T/Cs are very susceptible to this noise potentially causing very large errors in the measurement. The longer the leads (the antenna), the greater will be the noise pickup.

The best alternative to this problem is to use a transmitter that is designed to reject common mode and normal mode interference as well as provide a high degree of immunity to EMI, ESD and RFI. Where possible and practical, transmitters should be mounted close to the measurement point to minimize potential noise pickup by the sensor leads. This is especially important for low level T/C signals which are especially susceptible to noise.

Refer to:

3.1.2.4.1 – Noise filtering
4.5.4 – Advantages of Using Transmitters vs. Direct Wiring

4.5.3.3 Multiplexers

Multiplexers communicate with the control system using either a serial transmission (RS232C or RS485) or Ethernet. The communications may utilize a proprietary protocol provided by the control system manufacturer or one of the other standard protocols, such as Modbus®, OPC, or Profibus. This is a dated technology that has serious reliability issues and that has decreasing usage in the process industries.

4.5.4 Advantages of Using Transmitters vs. Direct Wiring

Cost of installation and ownership of using a transmitter approach vs. direct wiring shows a clear advantage to the transmitter for most applications.

- Specifying a single temperature transmitter, sensor, and thermowell assembly to meet a specific performance goal places all the responsibility on a single vendor and saves multiple specification sheets, quotation requests, bid reviews and purchase orders.
- Drafting costs are lower with only a transmitter symbol to show for a field device and only copper wire to show on the P&ID and bill of material. Drafting costs can be further reduced using multi-point temperature transmitters on digital bus applications.
- Wiring between the transmitter and the control system is done using standard copper wires in shielded, twisted pairs. This is far less expensive than multiple types of T/C extension wire or 4-wire RTD extension cable. Note that 4-wire RTDs are highly recommended vs. 3-wire systems.
- Less wiring infrastructure is needed in transmitter based systems for RTD installations. Two wires instead of four saves wiring which can be used for other measurement needs. Two wire solutions also save on overall wiring infrastructure, including junction boxers, cable, conduit, cable trays, and the physical infrastructure to support and route all the wiring.
- The requirement for using different types of T/C extension wire often leads to wiring errors at installation. This problem is eliminated by having all copper for the field wiring.
- All transmitters can be the same manufacturer and model minimizing spares.
- Only one type of high level input card is required for the control system instead of a mixture of high level and low level cards. Low level sensor input cards are typically more expensive than 4-20 mA input cards and spares inventory is reduced.
- No need to periodically replace degraded T/C extension wire. Copper wire typically lasts for the life of the plant.
- Higher performance is assured since a transmitter-sensor assembly may be calibrated as a system for optimal accuracy which cannot be done with a direct wired system and sensor-transmitter matching may also be performed.
- Troubleshooting and maintenance time is reduced by utilizing transmitter diagnostics that are not available or are quite limited in input cards.
- Transmitter accuracy and performance is typically twice as good as direct wired temperature inputs.
- The robust transmitter output signal is far less susceptible to EMI and RFI interference than low level sensor signals where the extension cables act as antennas for the noise signals.
- Transmitters offer a local indication option which improves operator interface and reduces maintenance time.
- Intelligent filtering options, common in transmitters, must be done in system software (if at all) in the DCS.
- For T/C applications, accuracy deterioration due to extension wire degradation can be severe.
- Safety-related applications are by far best done in a transmitter system. In an SIS, an error in excess of 2% is considered an undiagnosed dangerous failure.
- Sensor types can be changed from T/C to RTD or to a different type of T/C or RTD and the same transmitter is easily reconfigured to the new sensor type. The output cable and the DCS input card stay the same. For direct wiring, extension cable would likely need to be changed as well as the DCS input card type.

4.5.5 Grounding and Shielding Considerations

In general, established facility policies and guidelines should be followed where appropriate. See section 4.3.6.2.1.

4.5.6 Loop Load Insights

The majority of field measurement 4-20 mA signals are connected to a single input on a control or monitoring system. However, there are some occasions when connecting two or more devices in series is required.

Typically, for a 24 VDC power supply and a transmitter requirement of 12 VDC, 12 Volts remain to drive the load. If we allow for a maximum loop current of 24 mA, the maximum load is 500 Ω. (12 V ÷ 24 mA.) Since the load of most input circuits in control systems is 250 Ω, one transmitter could drive two receiving channels in a series connection.

Increasing the power supply voltage to 42 VDC (The maximum voltage allowed for field devices is 42.4.) would allow a maximum load of 1250 Ω. See Figure 4-48.

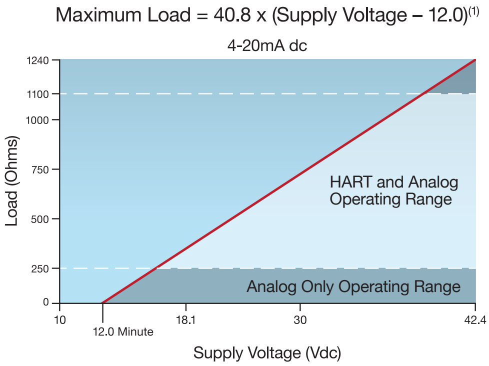


Figure 4-48 – Loop Loading

5

Maintenance and Calibration

5.0 Overview

Maintenance policies and procedures have evolved with instrumentation. Older transmitters using analog circuitry required maintenance much more frequently than do today's microprocessor-based transmitters. The analog devices had multiple potentiometers to adjust for various drifting or offset conditions and were repairable at the board level, while microprocessor-based units have almost negligible drift and are not unlike our cell phones, TVs, and laptop computers that have "no user-repairable parts".

Similarly, sensor technology has matured over the years with better manufacturing methods that tend to reduce long term drift and failure rates. However, sensor drift, degradation and failure are still the driving factor of temperature system maintenance scheduling. High quality RTDs can be expected to have minimal acceptable drift up to 5 years or even longer depending on the application. However, thermocouples inherently begin drifting to some extent from the beginning. This junction degradation-caused drifting is exacerbated by adverse operating conditions. In applications where errors of a few degrees are acceptable, the life may be several years. For other more demanding applications, the drift can be several percent per year, necessitating more frequent maintenance. Additionally, the special leadwire extension cable that must be used for thermocouples also degrades over time and must be replaced on a regular basis.

Proper maintenance planning should be done at the beginning of the lifecycle of the installation. Scheduling will vary dramatically depending on the application and the operating and environmental conditions. Critical measurement with serious consequences for inaccuracy or failure will have a higher priority than a simple monitoring or non-critical control measurement loop. There must be a balance struck between the lower costs of long maintenance intervals with the potential of consequences from measurement errors and the higher costs of shorter intervals. Maintenance costs include not only manpower, but also costs associated with taking a loop out of service for the maintenance duration. Some loops will operate just fine in manual, while others could precipitate process upsets if placed in manual and may necessitate a process shutdown.

Calibration is sometimes neglected due to cost. However, neglecting calibration can lead to unscheduled production or machine downtime, product and process quality issues, or even product recalls and rework.

Furthermore, if the instrument is critical to a process or is located in a hazardous area, allowing that sensor to drift over time could potentially result in risk to employee safety. Similarly, an end product manufactured by a plant with poorly calibrated instruments could present a risk to consumers. This is particularly true for the food and beverage sector and for pharmaceutical manufacturers where there are very specific requirements for documented calibration.

Calibration ensures that product or batch quality remains high and consistent over time. Quality systems, such as ISO 9001, ISO 9002 and ISO 14001, require systematic, well-documented calibrations with respect to accuracy, repeatability, uncertainty and confidence levels. This affects all process manufacturers.

In planning a maintenance strategy, it is wise to carefully evaluate the benefits of proper calibration intervals of increased throughput, less product waste, reduced energy costs, fewer unscheduled production shutdowns and regulatory compliance against the savings associated with the reduced labor requirements of longer intervals.

5.1 What Qualifications are Required for Maintenance Personnel?

Maintenance Technician qualifications will vary from company to company and from plant to plant within the same company. Experienced employees are an excellent resource during troubleshooting and maintenance. In many cases, however, young techs are thrust into the maintenance responsibility. For these people it is strongly suggested that they attend courses to obtain a Certified Control System Technician (CCST) accreditation.

ISA is very strong in providing such courses. (www.isa.org) There are also courses available through community colleges and other commercially taught programs, as well as apprenticeships and mentoring opportunities.

Since potential errors in calibration or other maintenance procedures can have expensive and even dangerous consequences, the technician must demonstrate a high degree of honesty and integrity, keen attention to detail and excellent documentation practices. Calibration Data Sheets must be neat, complete, signed and, if required, reviewed in a timely manner. When changes occur, all related documentation, such as drawings, manuals, specifications and databases, must also be updated.

Proper training and experience should be a requirement for control system technicians.

5.2 What is Included in a Maintenance Program?

Many plants rightfully get the maintenance technicians involved early on in the design phases to offer opinions that help to make equipment selection decisions based on user experience. Further, they may participate in commissioning and acceptance testing to help verify that a properly working system exists at start-up for which they will then have the responsibility to keep it operating that way throughout the life of the installation.

Tasks and responsibilities that typically fall under the maintenance department include:

- Participating in Site Acceptance Testing (SAT)
- Participating in commissioning and start-up procedures
- Maintenance scheduling and planning
- Physical inspection of field devices to verify physical and electrical integrity
- Routine analysis of diagnostic information
- Routine calibration or recalibration of sensors and instruments
- Loop tests
- Configuration verification and/or changes
- Troubleshooting and resolving abnormal performance issues
- Installation and commissioning of replacement or expansion equipment
- Documentation of all stages and facets of any procedure
- Continuing education and training
- Cross training with co-workers

5.3 Maintenance Scheduling and Planning Considerations

Several factors must be considered when creating a maintenance schedule:

- What measurement precision is required and with what tolerance for drift?
  - Critical loops always have a higher priority than other loops
- The drift aspects and expectations of the system sensor
  - RTD loops are typically more stable than T/C loops and would have a longer interval between calibrations
  - Control loops usually have higher priority than monitoring loops
- Any adverse operating conditions associated with the measurement installation that could accelerate drift requiring more frequent maintenance
  - High temperature, vibration, and corrosive environment can all accelerate drift
- What is involved to take each loop out of service for calibration/repair
  - What permits and permissions are required to work on the loop
  - Can the loop be bypassed/placed in manual?
  - Is advance notice to operations required?
  - Is any special equipment necessary and available?
  - Are equipment lock-outs and tagging involved (LOTO)?
  - Are there safety issues involved?
  - Is the transmitter in a hazardous area?
- Can the calibration be done in situ or does the transmitter and/or sensor need to be brought to the shop?
- Availability of any spares that may be needed for the maintenance procedure
- Is the measurement a safety instrumented function that is part of an SIS?

  - Safety related instrument loops are typically tested according to a very specific and detailed procedure in a SIS Test Plan for a unit operation
  - If redundancy is involved, as in dual sensors, 1 out of 2 (1oo2) or 2 out of 3 (2oo3) transmitter voting, the test plan will have very specific methodology that must be carefully followed and properly documented
  - See SIS section below
  - Evaluation of multiple before and after calibration results over time to adjust calibration scheduling
  - For critical loops, perform calibration checks often at first (perhaps once per month) for several months to get statistical data and then continue to extend interval to a time period where results are just at the edge of their allowable range
  - Loops with similar time schedules should then be grouped together
  - Consideration of process shutdown schedules
  - This process is greatly facilitated by using a calibration management software entity and/or an asset management system
- Coordination with any outside contractors that may be involved

TIP: Many of the considerations listed above may be implemented in an asset management system linked to a calibration suite of software and documenting calibrators. The benefits include faster and more accurate calibrations, improved scheduling and documentation. See Section 5.4 for more detail.

5.4 Maintenance Management

Historically, many companies performed maintenance on as-needed basis. Many followed the old adage that *"If it is not broken, don't fix it"*. However, today's modern process plants, production processes and quality systems put new and much tighter requirements on the accuracy of process instruments and on process control.

Quality systems, such as the ISO9000 and ISO14000 series of quality standards, call for systematic and well-documented calibrations, with regard to accuracy, repeatability, uncertainty, confidence levels etc. In today's world, there are techniques and calibrations systems that greatly facilitate meeting these calibration requirements.

The limiting factor in most processes is the quality of the measurements provided to the control system. Optimization of any process makes decisions based on the information provided. Inaccurate information will lead to less than optimal system performance. The more critical the process, the more important accurate and stable measurements become. Examples can include energy management, custody transfer, pharmaceutical production, and fractionation optimization.

All measurement instruments will drift over time. The only questions are how much will they drift and what amount is acceptable for that particular measurement. The pharmaceutical industry in the USA and for any company manufacturing for sale in the USA is particularly stringent about calibration procedures, test equipment, and documentation. Detailed requirements may be found in FDA regulation 21 CFR Part 11.

Maintenance Management Software Systems can greatly facilitate plant instrumentation maintenance programs. See Figure 5-1.

Choosing professional tools for maintaining calibration records and doing the calibrations can save a lot of time, effort and money.

A basic calibration management system consists of calibration management software and documenting calibrators.

Figure 5-1 – Documenting Calibrator and Calibration Management Software (Courtesy of Beamex)

Modern calibration management software can be a tool that automates and simplifies calibration work at all levels. It automatically creates a list of instruments waiting to be calibrated in the near future. If the software is able to interface with other systems like an asset management system with a device manager capability, the scheduling of calibrations can be done in the maintenance system from which the work orders can be automatically loaded into the calibration management software.

When the technician is about to calibrate an instrument, they simply download the instrument details from the calibration management software into the memory of a documenting calibrator; no printed notes, etc. are needed. The “As Found” and “As Left” are saved in the calibrator’s memory, eliminating the need for manual documentation with its associated potential for error.

The instrument’s measurement ranges and error limits are defined in the software and also downloaded to the calibrator. Thus the calibrator is able to detect if the calibration was passed or failed immediately after the last calibration point is recorded. There is no need to make tedious calculations manually in the field.

All this saves an extensive amount of time and prevents the user from making mistakes. The increase in work productivity using such a system allows for more calibrations to be carried out within the same period of time.

While the calibration results are uploaded onto the database, the software automatically detects the calibrator that was used, and the traceability chain is documented without requiring any further actions from the user.

Calibration records, including the full calibration history of an instrument, are kept in the database; therefore, accessing previous results is also possible in just a few seconds. When an instrument has been calibrated several times, software displays the “History Trend,” which assists in determining whether or not the calibration period should be changed.

One of today’s trends is to move towards a “paperless office”. If the calibration management software includes the right tools, it is possible to manage calibration records in a database with minimal paper. If paper copies of certificates are preferred, they may be printed with simple formatting.

Today’s documenting calibrators are capable of calibrating a variety of measurement signals and can interface with basic milliamp signals as well as HART, FOUNDATION Fieldbus and Profibus protocols (Optional on some models). See Figure 5-2.

These systems provide a great benefit to maintenance managers for planning purposes, QA departments, and outside auditors.

Figure 5-2 – Documenting Multifunction Calibrators (Courtesy of Beamex)

5.4.1 Additional Benefits of Asset Management Systems

Today’s widespread use of smart field instruments adds a new dimension to maintenance management. The wealth of operational and diagnostic data resident in smart instruments is extensive. Using HART or fieldbus protocol makes this information readily available. On a very basic level, field configuration tools can access any of this information by request one instrument at a time. If a maintenance technician does nothing else, he or she should review this information on a regular basis to catch performance or failure issues before they can affect the process. However, in most process plants there are manpower and priority issues that typically leave little time for this proactive type of activity, no matter how beneficial the practice would be to a better and more efficient maintenance plan.

An alternative solution to accessing this information exists on a higher level where this data can be accessed continuously from all field devices simultaneously using fieldbus or HART-enabled multiplexors interfaced with an asset management system suite. There are even wireless solutions to collect this data. When used with asset management system software suites, all performance and diagnostic data from all field devices can be immediately available. With these tools predictive scenarios can be recognized and action implemented proactively instead of reactively after a problem manifests itself and the process is affected and costs are incurred. See Figure 5-3.

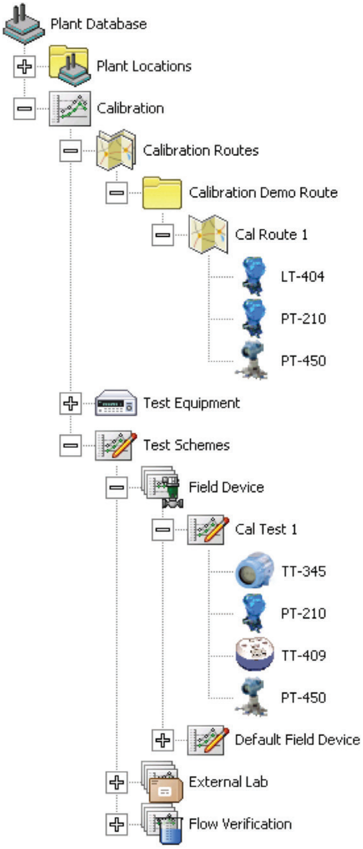


Figure 5-3 – Typical Asset Mangement System Calibration Screen

An asset management system with a device manager capability helps avoid these unnecessary costs with a universal window into the health of intelligent field devices. It provides maintenance and operations personnel the ability to work smarter. Based on real-time condition data from intelligent field devices, plant staff can respond fast and make informed decisions on whether to maintain or replace field devices.

With an asset management system, you can commission and configure instruments and valves, monitor status and alerts, troubleshoot from the control room, perform advanced diagnostics, manage calibration, and automatically document activities with a single application. There is also the ability to interface an asset management system to documenting calibrators as is described above with all of the data required to perform calibration. See Figure 5-4.

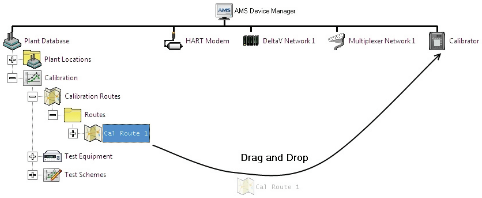


Figure 5-4 – Asset Mangement System Interface to Documenting Calculator

5.5 Maintenance Basics

5.5.1 Transmitters

- Mechanical inspection/repairs – Inspect for:
  - – Proper installation guidelines followed
  - – Corrosion
  - – Loose mounting
  - – Erosion
  - – Covers are on tight with metal-to-metal seal
  - – Conduit seals are tight
  - – Moisture intrusion
- Electrical inspection/repairs - Inspect for:
  - – Clean and tight terminations
  - – Corrosion on terminals or housing
  - – That the transient protector is not damaged
  - – LCD operating properly
  - – The shield and case grounding is correct and intact; refer to Section 4.4.2.4.1 in Chapter 4 for grounding detail
- Additional Considerations for Wireless Devices
  - – Verify that no new equipment or structures have been installed nearby to the wireless transmitter that could affect the wireless signal transmission
    - Must maintain about 1.8 meters minimum (6 ft)
  - – Verify power module voltage/replace if necessary
    - Slower update rates provide longer battery life

5.5.2 Sensors and Thermowells

- Remove sensor from thermowell for calibration or replacement
  - Refer to section 5.7
- Clean well bore of thermal paste and/or corrosion
- Inspect for corrosion on terminals, enclosures and on thermowell
- Inspect thermowell mounting for evidence of cracking indicating potential failure
- Inspect and tighten flange bolts
- For high temperature applications, verify integrity of protection tube
- For Rosemount X-well and other surface mount sensors:
  - Verify mounting is secure for good thermal contact of the sensor tip with the process vessel or pipe
  - Verify that the insulation surrounding the sensor is in place with minimal leakage
  - For pipe clamp units, ensure clamp bolts are tight and that no corrosion exists

5.6 Configuration

The process of configuration includes the selection and adjustment of a wide assortment of transmitter operating parameters, including the most simplistic to the more advanced features. Many of these are factory set to either a default or user specified condition or value. Others are application specific and are field set as part of commissioning of the measurement loop. While some settings are physical procedures on the transmitter (such as switches or jumpers), other settings are accessed using a field configurator, a laptop, an asset management system, a DCS or other electronic means. The majority of loops support HART, FOUNDATION Fieldbus, or Profibus protocols.

Since HART has been in widespread use in the process industry for many years, there are millions of the devices installed globally. These devices will likely stay in service and overlap with newer devices using newer technology protocols. As plants begin to use newer protocols for new operational units or upgrades of older units, there will be a requirement for the maintenance technician to have a working familiarity with more than one protocol.

HART and fieldbus devices typically have similar Device Description Languages (DDL) for configuration and diagnostic data contained in them and there are universal field communicators that can access some or all of the devices. See Figure 5-5. Each protocol uses its own specific method to access various menu trees for status, operational data, configuration and diagnostics.

Figure 5-5 – Trex Dashboard

5.7 Calibration

5.7.1 Overview and Definition

Calibration is distinctly different from transmitter ranging or adjustment of other transmitter configuration parameters that are normally entered during commissioning. Changes to these values are not typically part of a calibration procedure, although some parameters may be authorized by management to be done at that time, such as adjusting damping or changing an alarm setpoint.

There are as many definitions of calibration as there are methods. According to ISA's *"The Automation, Systems, and Instrumentation Dictionary,"* the word, *calibration*, is defined as "a test during which known values of measurement (the quantity being measured) are applied to the transducer and corresponding output readings are recorded under specified conditions." The definition includes the capability to adjust the instrument to zero and to set the desired span.

An interpretation of the definition would say that a calibration is a comparison of measuring instrument against a standard instrument of higher accuracy to detect, correlate, adjust, rectify and document the accuracy of the instrument being compared.

Another source defines *calibration* as “including the process of adjusting the output or indication on a measurement instrument to agree with the value of the applied standard, within a specified accuracy.” As an example, for a temperature transmitter, a known input is applied and the output adjusted so that the output as seen by the user is within a given tolerance of the actual value of the applied standard.

Typically, calibration of an instrument is checked at several points throughout the calibration range of the instrument. The *calibration range* is defined as “the region between the limits within which a quantity is measured, received or transmitted, expressed by stating the lower and upper range values.” The limits are defined by the zero and span values that were configured into the unit at commissioning.

The zero value is the lower end of the range. *Span* is defined as “the algebraic difference between the upper and lower range values.” The calibration range may differ from the instrument range, which refers to the capability of the instrument. As an example, a temperature transmitter with an RTD input has a potential range of -200 to 850 °C to produce a 4-20 mA output. However, for a specific application, it is to be calibrated to a range of 0 to 50 °C for 4-20 mA output. For this example, the input zero value is 0 °C and the input span is 50 °C and the output zero value is 4 mA and the output span is 16 mA.

Different terms may be used at your facility. Just be careful not to confuse the range the instrument is capable of with the range for which the instrument has been calibrated.

5.7.2 When to Calibrate

Calibration is performed for one or more of the following reasons:

- During commissioning of a new instrument
- After a transmitter has been repaired or modified
- When a specified time period has elapsed
- When a specified usage, such as operating hours, has elapsed
- Before and/or after a critical measurement
- After an event has occurred that may have put it out of calibration or damaged it like shock, vibration, exposure to an adverse condition, such as a lightning strike or sudden changes in weather
- Whenever observations appear questionable or instrument indications do not match the output of related instruments
- As specified by a requirement, e.g., customer specification or instrument manufacturer recommendation

The calibration process for a temperature measurement system that includes a sensor and a transmitter is optimal when done as an operating system. While connected to the transmitter, the sensor is exposed to a precision temperature source, like a calibration block or a calibration bath held at a fixed temperature as measured by a standard sensor.

> *A standard sensor has accuracy traceability to a National Metrology Institute of the user country, such as NIST in the USA, NPL in the UK, and PTB in Germany, among others. To communicate the quality of a calibration standard, the calibration value is often accompanied by a traceable uncertainty statement to a stated confidence level.*

Since it is often impractical to calibrate the transmitter and the sensor as a system, they are often calibrated individually and the sensor calibration data is then loaded into the transmitter. This procedure is quite adequate for the majority of applications. For the best accuracy, sensor-transmitter matching should be performed and the system tested as a complete assembly.

WHAT ARE BEST PRACTICES FOR CALIBRATION?

Every industrial facility will have policies, procedures, and guidelines concerning calibration. Some may be well founded and based on years of experience and others may follow the “We have always done it this way” mentality, whether it is right or wrong.

For more insights and recommendations, refer to:

5.7.2 – When to calibrate
5.7.3 – Calibration Terms and Considerations
5.7.5 – Equipment
5.7.5.1 – Procedures
5.8 – High-Precision considerations

TIP: The individual testing method does not account for any errors introduced from degradation/variation of leadwire and terminal corrosion, which are a potential source of error for T/Cs and 3-wire RTD circuits. 4-wire RTD circuits are relatively immune from these issues.

5.7.3 Calibration Terms and Considerations

Calibration Tolerance: Every calibration should be performed to a *specified tolerance*, which is defined as, "permissible deviation from a specified value that may be expressed in measurement units, percent of span, or percent of reading."

This term should not be confused with a*ccuracy*, which is defined as, "the ratio of the error to the full scale output or the ratio of the error to the output, expressed in percent span or percent reading, respectively."

It is generally recommended that tolerance in measurement engineering units be used for calibration requirements. This will eliminate the potential errors in calculating % of span or % of reading values.

As an example from our transmitter range described above of 0 to 50 °C that has been specified with a tolerance of ± 0.25 °C, the calculation would be:

$$(0.25\ ^{\circ}\mathrm{C} \div 50\ ^{\circ}\mathrm{C}) \times 16\ \mathrm{mA} = 0.08\ \mathrm{mA}$$

Generally, the tolerance would be listed as ± 0.25 °C *and* ± 0.08 mA on the calibration data sheet.

The determination of the tolerance should take into account the following:

- Requirements of the process
- Capability of available test equipment
- Consistency with similar instruments at your facility
- Manufacturer's specified tolerance

TIP: Proper calibrator traceability should be an absolute requirement in any operating facility. Using calibration equipment that itself has not been properly calibrated will surely provide unreliable results that could lead to product quality issues, energy waste, non-optimal production rates, or possible dangerous conditions.

Accuracy Ratio: A good rule of thumb is to ensure an accuracy ratio of 4:1 when performing calibrations. This means the instrument or standard used should be four times more accurate than the instrument being checked. Therefore, the test equipment (such as a field standard) used to calibrate the process instrument should be four times more accurate than the process instrument, the laboratory standard used to calibrate the field standard should be four times more accurate than the field standard, and so on.

Using an accuracy ratio of 4:1 provides a safety margin that will make the calibration results less likely to be compromised by out-of-spec standards or test equipment or technician error.

Traceability: All calibrations should be performed traceable to a nationally or internationally recognized standard. As discussed above, the standards used for calibration should be traceable to a National Metrology Institute, such as NIST in the USA. There may be many levels of traceability between your shop and NIST, but the trail should exist and the tolerance of the standards fully understood. Your standards should be routinely calibrated by a "higher level authority" and the results properly documented. See Figure 5-6.

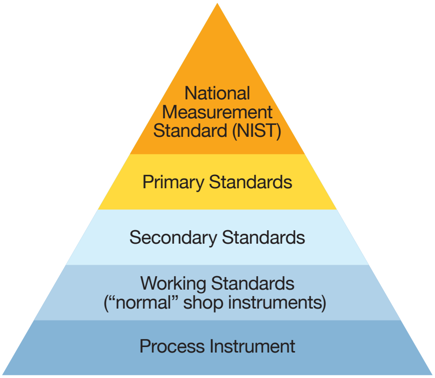


Figure 5-6 – Traceability Pyramid

The calibration technician's role in maintaining traceability is to ensure the test standard is within its calibration interval and the unique identifier is recorded on the applicable calibration data sheet when the instrument calibration is performed. Additionally, when test standards are calibrated, the calibration documentation must be reviewed for accuracy and to ensure it was performed using NIST traceable equipment.

5.7.4 Proof-Testing/Loop Testing

There are several terms applied to the process of verifying that an instrument loop is properly installed and functional in accordance with operational and functional specifications. A commonly used term is a loop test where a simulated signal is applied at the transmitter and the proper response is verified at the receiving device.

A more rigorous test is often referred to as proof-testing – a term commonly used in Safety Instrumented Systems (SIS). In a proof-test, the entire installation and functionality of the loop must be verified, including sensors, transmitter, cabling, junction boxes, receivers, outputs, final control elements, and alarm/shutdown elements. Mechanical, as well as electrical, verification is performed.

Proof-testing of safety related functions – referred to as safety instrumented functions – is typically a very detailed procedure and must be completely and thoroughly documented.

5.7.5 Calibration Equipment

To calibrate a temperature sensor, it must be inserted into a known temperature and compared against a precision calibration standard sensor either by using a temperature dry block or liquid bath, along with the appropriate display and control devices. For industrial applications, the field dry block is typically favored due to its ruggedness, portability and safety. Liquid baths are more suited for laboratory use. The most important criterion in the calibration of temperature sensors is how accurate the sensors are at the same temperature.

Dry blocks are available with an internal reference PRT that will provide an accuracy capability that will be adequate for most sensors (Typically ± 0.5 °C). For sensors in more critical applications, an external reference sensor will provide greatly enhanced calibration accuracy capability. However, the calibration accuracy is limited by the stability and resolution of the dry block system. There are higher accuracy and resolution dry block models available that offer laboratory grade calibration capability. These are referred to as metrology grade dry blocks. See Figure 5-7.

Figure 5-7 – Typical Field Dry Block and Metrology Grade Dry Blocks (Courtesy of Beamex)

When selecting a field dry block, you should consider:

- Temperature range
- Accuracy and stability
- Well flexibility (bore sizes and available inserts)
- Portability
- Sensor immersion (proper depth is important)
- Throughput (number of sensors accommodated and automation features)

Dry blocks use inserts for the heated/cooled cavity that are bored out to various diameters to accommodate a wide variety of sensor diameters. These inserts may be easily interchanged as may be required.

The uncertainty of calibration is not the same as the accuracy of the device. Many factors influence the total uncertainty, and performing calibration is not the least influencing factor. All heat sources show measurement errors due to their mechanical design and thermodynamic properties. These effects can be quantified to determine the heat source's contribution to the measurement uncertainty.

The major sources of measurement uncertainty are axial homogeneity (along the length of the sensor), radial homogeneity (horizontally between the sensors), loading effect (multiple sensors in the block), stability (in the measurement zone), and immersion depth (typically 10x to 15x sensor diameter). There are guidelines for minimizing measurement uncertainty that should be applied. In Europe, they are from the European Association of National Metrology Institutes, calibration guide for temperature blocks. (Euromet /cg-13/v.01).

Depending on the application, plant policies and procedures and accuracy requirements, sensors may be calibrated and the data recorded and subsequently loaded into the transmitter's database or to trim the transmitter. Alternatively, the sensor-transmitter assembly may be calibrated as a system.

TIP: It is important to note that calibrating the sensor and the transmitter separately does not take into account any error introduced by the interconnecting wiring. In the case of three-wire RTD and T/C installations, this error can be significant. Four-wire RTD installations are not affected by wiring resistance imbalance or terminal corrosion.

5.7.5.1 Using a Temperature Calibration Block

A dry block consists of a heatable and/or coolable metallic block, controller, an internal control sensor and optional readout for an external reference sensor. There are fast and lightweight dry blocks for industrial field use as well as models that deliver near bath-level stability and resolution typical of laboratory use. See Figure 5-8.

The temperature range of the dry block must meet your minimum test requirements for the sensors being calibrated. The ideal calibration spans the entire usable range of the test sensor.

Figure 5-8 – Temperature Field Dry Block (Courtesy of Beamex)

After a full-range calibration of your temperature sensor, it's a good idea to check its accuracy in the precise range it is most often used. For example, if you calibrate an RTD over its full 0 – 100% range but intend to use it at the 65% point, it would be appropriate to verify its calibration at that specific point.

TIP: All calibrations should be performed traceable to a nationally or internationally recognized standard, such as NIST in the USA. There may be many levels of traceability between your shop and NIST, but the trail should exist and the tolerance of the standards fully understood. Your standards should be routinely calibrated by a "higher level authority" and the results properly documented. Failure to follow this traceability will potentially lead to incorrect calibration of every temperature measurement system that is processed. Use of an inaccurate dry block system, decade box, millivolt or current source, and/or field calibrator could yield dozens or even hundreds of incorrectly calibrated instruments that could have a major impact on product quality, production throughput, energy usage and could even create dangerous operating conditions.

Accuracy and stability are the two most critical specs on a dry block. Accuracy is how close the dry-well is to the programmed set-point. Stability is the temperature fluctuation of the instrument around the desired set-point over time. These two parameters add together to create the uncertainty of your calibration. If your dry-well does not meet your accuracy requirements and does not maintain a stable temperature, your probe could be reading a much different temperature than your display indicates.

A good rule of thumb is to make sure that your dry block is at least twice as accurate as the sensors you are checking. For critical applications, three or four times better is suggested. A dry block calibration system should have accuracy traceability to a National Metrology Institute of the user country, such as NIST in the USA. See Figure 5-6.

The dry block should have at least the set-point resolution of the accuracy it claims or your target accuracy. For example, if you are calibrating an RTD to ±0.5 °C at 100 °C and your instrument only displays temperature to ±1 °C, you obviously can't claim better than 1 °C (1.8 °F) for your calibration.

Depending on the number of sensors to be calibrated in a given time period, there are two basic approaches:

- Use a single block with a capacity of one or more sensors and a reference standard. Typically three to five measurements are taken over the range of use of the sensor and the block must be stabilized at each of those temperatures before the measurement is taken. This is typically 15 to 30 minutes or more between readings. Some dry block systems are programmable to automatically cycle through the setpoint temperatures.
- Use multiple blocks with each one held at a specific calibration temperature and move the sensor being calibrated and the reference sensor sequentially to each block, allow them to stabilize, and then take the readings.

Assure that all connections to the measurement instruments are clean and tight.

5.7.5.2 Using a Universal Field Calibrator

Universal field calibrators are available in a variety of models from several major suppliers. Many models are HART compliant and others also interface with FOUNDATION Fieldbus and Profibus PA.

They have the ability to simulate RTD, T/C, mv, voltage, and frequency signals that may be connected to a transmitter for calibration purposes. Many provide a dual screen capability to simultaneously see the simulated signal and the transmitter output. Some also have the ability to read signals from sensors and display the actual value of the variable.

Some instrument shops do not have field calibrators and must still rely on using decade boxes to simulate resistance values, and a current/voltage source to simulate volt, millivolt and current signals. As with all calibration instrumentation, these devices must have certified traceability for accuracy four times better than the calibrated device requires. Refer to section 5.7.3.

TIP: For calibrations carried out in areas of the plant classified as hazardous locations, it is necessary to use a calibrator that is properly certified for use in hazardous areas. These are typically intrinsically safe models (IS) and a typical international certification is certification to Ex ia IIC T4. This would be applicable to all vapor hazards where a temperature class of 135 °C in a 50 °C ambient is acceptable. In the USA, FM certification is Intrinsically Safe for Class I/II/III, Division 1, Groups A, B, C,D, E, F, and G. Temperature Codes: T4A (T_{amb} = - 60 to 60 °C) and T5 (T_{amb} = – 60 to 50 °C)

5.7.5.3 Interfacing With HART Instruments

Multifunction or HART-specific calibrators can operate as a HART Communicator to access all HART data in the instrument and trim or reconfigure as may be required. Additionally, they can be connected using an internal or external power supply to measure the analog output value and measure the HART digital value while applying a simulated test signal to the transmitter input. (RTD, T/C, mV, ohms, etc.)

To begin calibration, the instrument's data must have been loaded into the calibrator either manually, from a calibration software entity, or from an asset management system. An input signal may now be applied to the transmitter and the output values read. If so authorized, the transmitter may be trimmed or adjusted as may be required. Consult the user guide for your calibrator for specific procedures.

5.7.5.4 Interfacing with FOUNDATION Fieldbus or Profibus PA Instruments

Interfacing to fieldbus enabled transmitters typically requires an interface module either within the calibrator or external from it. As with the HART devices, the instrument data must have been input to the calibrator either manually, from a calibration software entity, or from an asset management system. The transmitter may be individually connected as a stand-alone device with the calibrator providing the power or with an external power supply and, depending on the instrument's input signal, it is either generated/simulated or measured with the calibrator.

Alternatively, the calibrator may be connected to a live fieldbus segment for calibration, trimming and configuration verification or changes, if required. Theoretically, a segment may have up to 32 devices connected, but few users connect more than 16 due to power supply considerations and other factors. Refer to the calibrator user manual for specific procedures for connecting, calibrating, trimming or configuration.

5.8 Calibration for High-Precision Application

Increased accuracy is mandated for safety, product quality, production throughput, or custody transfer applications.

For high precision applications, it is recommended to perform sensor to transmitter matching. Although excellent results may be achieved by matching to sensors with 3-point or 5-point calibration curve data, the best possible accuracy is obtained when matching to a sensor using the sensor's Callendar-Van Dusen constants. Refer to section 3.1.4.3.3 for more detail.

5.9 Introduction to Troubleshooting

Everything will eventually fail and finding the cause of the failure is a big part of troubleshooting. Failures can take different forms, including both hardware and software failures, functional failures due to misapplication or abuse, or it could be systematic failures due to human error. Failures from a single source can affect multiple instruments or loops and have complex cause and effect relationships.

Instrument failures can be classified in a number of different ways. They can fail safely, fail dangerously, or in a known state (upscale drive or downscale drive, for example). The failures can be self-revealing or overt or it can be latent or covert.

The failed state in which you find an instrument is not always the actual failure. It may be in that state because it was "directed" to be in that state due to another failure unrelated to the instrument that stopped operating. An example would be an upscale or downscale drive of a transmitter with a sensor failure or shorted or open leadwire.

Others can be covert or hidden and may only be revealed when something is supposed to work on demand, such as a safety shutdown function, and fails to respond to that demand.

Always review the applicable loop drawings for directed failure states before beginning to troubleshoot the problem. Close coordination with the operators to assure that safety is maintained and which loops may be taken out of service when is vitally important. Systematic troubleshooting is a skill taught in many training courses that can help resolve issues more quickly and cost effectively.

Troubleshooting frameworks or methodology can use any or all of three basic formats. It is typical to start with the easiest methods first and then proceed to the structured procedure only if necessary.

5.9.1 Symptom-Cause Tables

- Often found in vendor user manuals

5.9.2 Flowcharts or Logical Decision Trees

- Consult vendor user manuals or troubleshooting training texts

5.9.3 Structured Approach to Troubleshooting

The following steps are typical of a structured approach to troubleshooting:

- Define the problem
- Get the facts - not just opinions
- Be sensitive to bias in the reporting, such as blaming the instrument when it is an operational issue
- Collect information regarding the problem
- Symptoms, characteristics and parameters
  - What is working and what is not?
  - Was anything changed since it was last operating properly?
  - Any recent weather related issues (lightning, heavy rain, snow)?
  - Any recent cleaning or maintenance activity in the area (welding)?
  - Inspect the instrument
  - Review all related documentation
- Analyze the information
- Categorize the information; eliminate the extraneous
- Is problem event or time driven?
- Is there a history of repeat occurrence?
- Similar-to analysis
  - How is this problem similar to another one; What is in common?
- What is the exact problem?
- Where was it first noticed?
- When was it discovered?
- Consult user manuals
- Determine if enough information has been gathered
- Incrementally gather data and then review if there is enough to propose a solution
- Propose a solution or several solutions
  - Which is most likely?
  - Which is quickest?
  - Which can be done without a shutdown?
  - What are the cost implications of each?

- Test the proposed solution
- Secure the proper permissions and permits first, if required
- Repair the problem
- Document completely (See section 5.12)
  - As found vs. as left
  - Failure analysis
  - Reports
  - Permit closeout
  - Update maintenance reports and databases
  - For transmitter replacement, confirm all configuration details

5.10 Safety Instrumented System (SIS) Considerations

5.10.1 Background

A transmitter that is used in a SIS will be part of a Safety Instrumented Function (SIF).

A SIF is defined as a function to be implemented by a SIS, which is intended to achieve or maintain a safe state for the process with respect to a specific hazardous event.

A SIF is a single set of actions and the corresponding equipment needed to identify a single hazard and act to bring the system to a safe state.

In the case of a temperature measurement, the function could be to identify a dangerously high or low temperature condition by comparing the measurement against a predefined safe value and initiating an action to arrest or contain the situation should it exceed this limit. An example might be to initiate emergency cooling to a runaway reactor.

Depending on the consequences of this event happening, the safety engineers will have selected a Safety Integrity Level (SIL) for this SIF, which defines a target for the probability of failure of this measurement. A SIL 2 must be more reliable than a SIL 1 and a SIL 3 must be more reliable than a SIL 2 function and will be designed accordingly.

5.10.2 The Technician’s Role and Responsibilities

For any safety related device there will be a very detailed and precise test plan for the unit operation. The safety standard requires that all personnel involved with SIS should have the proper qualifications and training.

Note that transmitter output is not safety-rated during configuration changes, multi-drop, and loop test. Alternative means should be used to ensure process safety during transmitter configuration, maintenance and testing activities.

To ensure compliance with the IEC 61511 safety standard, there are normally permissions and permits that must be completed to take a loop out of service and the testing procedure must be followed to the letter and often witnessed and signed and co-signed. Any abnormalities or failures must be carefully documented with multiple sign-off signatures. Any changes made to the loop must be incorporated into the Management of Change (MOC) documentation. These include any device replacement or upgrade and any configuration and calibration changes.

The test procedure will typically have steps to ensure that there is proper communication from the field transmitter to the DCS and that a proper signal is being received and that all alarm values are properly configured and operational.

The procedure will also include verification that the final control element properly functions in accordance with the Safety Requirements Specification (SRS).

Since the SIF also includes the sensor, its lead-wires, the signal wiring and any terminations, these also must all be tested and verified. The ultimate and ideal test is to subject the sensor in situ to a precisely known standard temperature, such as a calibration block or bath, which forces a simultaneous test of all components of the SIF. Since this is rarely practical in the real world, other simulation sources are typically used and the sensor and its circuitry independently tested and calibrated.

5.11 Diagnostics

While all smart transmitters have diagnostics, some are considerably more extensive than others. Those with a HART, FOUNDATION Fieldbus, or Profibus protocol offer the most sophistication. Each protocol uses different technologies and different ways of accessing the diagnostic information described below.

The Control System Technician (CST) should coordinate with operations to routinely review available diagnostic information reported via the DCS, PLC, field communicator, and/or asset management system.

Discussed below are common diagnostic capabilities and maintenance flags available on temperature transmitters. Consult the product data sheets and the user manuals for availability on your particular product.

5.11.1 Basic Transmitter Diagnostics

Typical information that is useful for diagnostic and maintenance purposes includes:

- Sensor(s) failures – open, shorted, intermittent
  - The transmitter has detected an open or shorted sensor condition. The sensor(s) might be disconnected, connected improperly, or malfunctioning. Check the sensor connections and sensor continuity.
- Field Device Malfunction
  - The device has detected a hardware error or failure on the device. This pertains to a variety of errors that can occur. Malfunctions in the memory, A/D converters, CPU, etc are covered under this status bit.
- Process Variable (PV) Out of Limits
  - The HART transmitter is reporting that the primary variable read by the transmitter is outside of the 4-20 mA range. This signal can be used to detect open/short circuits in the transmitter wiring.
- Process Variable (PV) Output Saturated
  - The analog and digital signals for the Primary Variable are beyond their limits and no longer represent the true applied process. If the process variable goes outside of the 4-20 mA range, the HART transmitter will drive the mA output and the PV to the saturation values, but no further. The transmitter will clamp the analog output and PV to the saturation values (not the 4 and 20 mA values). PV's between the 4-20 mA limits and the saturation limits may still be valid signals.
- Process Variable (PV) Output Fixed
  - The analog and digital signals for the Primary Variable are held at the requested value. They will not respond to the applied process. The output is fixed when a transmitter has been taken out of service during calibration or maintenance (changing a range, for example). Unless the transmitter has been put back in service, the outputs will continue to be fixed indefinitely.

WHAT BENEFITS CAN BE GAINED BY USING TRANSMITTER DIAGNOSTICS?

While all smart transmitters have diagnostics, some are considerably more extensive than others. Those with a HART, FOUNDATION Fieldbus, or Profibus protocol offer the most sophistication.

There are internal diagnostics that monitor transmitter functionality and output validity. Also, there are a wide range of external diagnostics that monitor the measurement signal for such things as drift, degradation, measurement validity, and broken or damaged leads, among others.

Transmitters initiate either Alerts or Alarms based on these diagnostic processes.

Alerts cover diagnostics that are determined not to affect the transmitter's ability to output the correct measurement signal and therefore will not interrupt the 4-20 mA output. An example is "Process Variable Out-of-Range".

Alarms cover diagnostics that are determined to affect the transmitter's ability to output a correct value of the measurement. Detected alarms will drive the transmitter output either high or low depending on user's choice.

Alerts and alarms can be read on a local indicator (if so specified), on a field communicator, or on a HART-compliant monitoring system, such as Emerson's AMS Suite application.

Refer to:

5.11.1 – Basic Transmitter Diagnostics

3.1.8 – Diagnostics

- Analog-Digital Mismatch
  - The HART transmitter is reporting a difference between the analog 4-20 mA signal and the digital Primary Variable (PV) signal. This functionality can be used to determine a small ground in the home run cable to the instrument or an intermittent device. If a small ground exists in the loop, any alarm trip limit of the loop may never be reached even under trip conditions due to earth leakage.
- Loss of Digital Communications
  - This status bit is set when the HART digital communications with the device is lost. The 4-20 mA analog signal may still be valid, but the digital HART signal is not available.
- Hot Backup Initiated (for Dual Sensors)
  - Upon failure of the primary sensor, the transmitter will instantly change over to the secondary sensor. The primary and secondary may be either RTDs or T/Cs or one of each to reduce common cause failure issues.
- Sensor Drift Alert (with Dual Sensors)
  - Sensor Drift Alert notifies the control system of the degradation of a sensor that is causing its measurement signal to drift away from the actual value, thus decreasing the measurement integrity. By using two sensor inputs, the difference between the two sensors is monitored. When the difference becomes greater than a value entered by the user, the transmitter sends an alert to indicate a sensor drift condition.
  - This feature may be used in conjunction with a hot backup feature to instantly switch the transmitter from the drifting sensor to the secondary sensor.
  - The two sensors can be RTDs, T/Cs or one of each for reduction of common cause factors
- Thermocouple Degradation Diagnostic
  - This feature acts as a gauge of general thermocouple health and is indicative of any major changes in the status of the thermocouple or the thermocouple loop. The transmitter monitors the resistance of the thermocouple loop to detect drift conditions or wiring condition changes. The transmitter uses a baseline and threshold trigger value and reports the suspected status of the thermocouple. This feature is not intended to be a precise measurement of thermocouple status, but is a general indicator of thermocouple and thermocouple loop health
- Measurement Validation
  - Deviation Alarming
    - Before a sensor fails, it will exhibit signs of degradation, such as increased signal noise, which will often result in inaccurate on-scale readings. Measurement Validation is a diagnostic that can provide validation of temperature measurement data, ensuring visibility of measurement and process abnormalities before a sensor failure occurs. Measurement Validation monitors the signal noise and uses it to calculate a deviation value indicating the magnitude of the noise which is compared to a user selected alert limit. When this limit is exceeded, the user is notified, allowing action to be taken. Measurement Validation can also detect on-scale failures associated with loose or corroded connections, high vibration and electronic interference, which can contribute to a signal noise increase.
  - Rate-of-Change Alarming
    - In addition to detecting on-scale failures and validating measurement values, Measurement Validation also performs a rate of change calculation which can be used to identify abnormally fast temperature changes that could indicate a runaway reaction condition even before alarm conditions are met.
- Minimum and Maximum Temperature Tracking
  - Minimum and Maximum Tracking can record lifetime minimum and maximum temperatures with date and time stamps. This feature records values for Sensor 1, Sensor 2, differential and terminal (body) temperatures.
- Statistical Process Monitoring Algorithm
  - This feature provides basic information regarding the behavior of process measurements, such as PID control block and actual valve position. The algorithm can monitor up to four user selected variables. All variables must reside in a scheduled function block contained in the device. This algorithm can perform higher levels of diagnostics by distribution of computational power to field devices. The two statistical parameters monitored by the Statistical Process Monitoring are mean and standard deviation. By using the mean and standard deviation, the process or control levels and dynamics can be monitored for change over time. The algorithm also provides:

  - Configurable limits/alarms for high variation, low dynamics, and mean changes with respect to the learned levels
  - Necessary statistical information for Regulatory Control Loop Diagnostics, Root Cause Diagnostics, and Operations Diagnostics.
- Transmitter Diagnostics Logging
  – This feature will store advanced diagnostics information between device resets. This feature stores what caused the transmitter to go into alarm, even if that event has disappeared. For example, if the transmitter detects an open sensor due to a loose terminal connection, the transmitter will go into alarm. If, due to vibration, that wire begins making a good connection, the transmitter will come out of alarm. This jumping in and out of alarm is very frustrating when determining what is causing the problem. However, the Diagnostics Logging feature will keep track of what caused the transmitter to go into alarm and will save valuable debugging time.

5.12 Documentation

Every plant will have documentation policies and procedures that must be followed. There are requirements before, during and after any procedure.

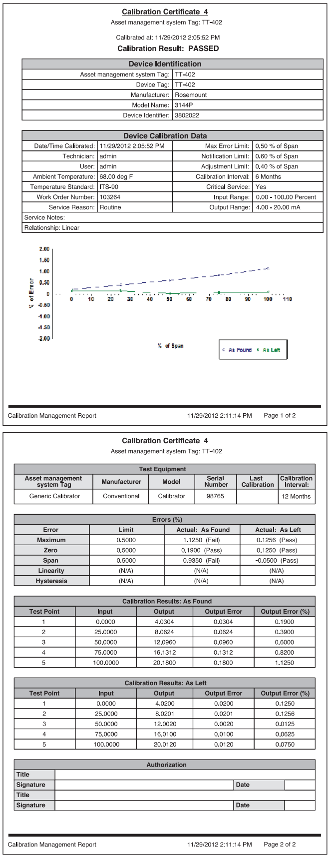
TIP: If a documenting calibrator is being used in conjunction with a calibration management software entity or an asset management system, much of the following information will be automatically provided in the form of reports, graphs and logs.

5.12.1 The Planning Stage

- Review trouble reports and operational requests for troubleshooting
- Review diagnostics logs looking for abnormalities
- Determine what requests for permits must be completed for any required procedures
- Secure required loop drawings, P&IDs, specification data sheets, vendor manuals, test procedure checklists, etc.

5.12.2 The Implementation Phase

- As-found reports
- Procedure checklists



Calibration Certificate 4
Asset management system Tag: TT-402

Calibrated at: 11/29/2012 2:05:52 PM
Calibration Result: PASSED

Device Identification

Asset management system Tag:	TT-402
Device Tag:	TT-402
Manufacturer:	Rosemount
Model Name:	3144P
Device Identifier:	3802022

Device Calibration Data

Date/Time Calibrated:	11/29/2012 2:05:52 PM	Max Error Limit:	0.50 % of Span
Technician:	admin	Notification Limit:	0.60 % of Span
User:	admin	Adjustment Limit:	0.40 % of Span
Ambient Temperature:	68.00 deg F	Calibration Interval:	6 Months
Temperature Standard:	ITS-90	Critical Service:	Yes
Work Order Number:	103264	Input Range:	0.00 - 100.00 Percent
Service Reason:	Routine	Output Range:	4.00 - 20.00 mA
Service Notes:			
Relationship: Linear			

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Calibration Certificate 4
Asset management system Tag: TT-402

Test Equipment

Asset management system Tag	Manufacturer	Model	Serial Number	Last Calibration	Calibration Interval:
Generic Calibrator	Conventional	Calibrator	98765		12 Months

Errors (%)

Error	Limit	Actual: As Found	Actual: As Left
Maximum	0.5000	1.1250 (Fail)	0.1256 (Pass)
Zero	0.5000	0.1900 (Pass)	0.1250 (Pass)
Span	0.5000	0.9350 (Fail)	-0.0500 (Pass)
Linearity	(N/A)	(N/A)	(N/A)
Hysteresis	(N/A)	(N/A)	(N/A)

Calibration Results: As Found

Test Point	Input	Output	Output Error	Output Error (%)
1	0.0000	4.0304	0.0304	0.1900
2	25.0000	8.0624	0.0624	0.3900
3	50.0000	12.0960	0.0960	0.6000
4	75.0000	16.1312	0.1312	0.8200
5	100.0000	20.1800	0.1800	1.1250

Calibration Results: As Left

Test Point	Input	Output	Output Error	Output Error (%)
1	0.0000	4.0200	0.0200	0.1250
2	25.0000	8.0201	0.0201	0.1256
3	50.0000	12.0020	0.0020	0.0125
4	75.0000	16.0100	0.0100	0.0625
5	100.0000	20.0120	0.0120	0.0750

Authorization

Title			
Signature		Date	
Title			
Signature		Date	

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Figure 5-9 – Typical Calibration Documentation

5.12.3 Completion Phase

- Complete calibration data sheet with as-left data (See Figure 5-9)
- Close out work permits including finalizing any LOTO locations
- Update loop sheets
- Update tagging
- Complete MOC report if required
- Update any associated operational procedures
- Update P&ID, if required
- Update specification sheet, if required
- Update appropriate computer databases
- File hard copies of completed reports as backups

6

Best Practices

Best Practices

A Compendium of Challenging Applications, Each with an Analysis and Recommended Solution(s)

How to engineer an accurate and reliable temperature point can be a challenge due to the variety of applications and installations where these measurements are made. And while there is no one-size-fits-all solution that will work for every installation, this chapter covers recommended design and installation practices that Emerson Temperature experts have found to hold true for the majority of temperature measurement needs.

Best Practice #1

Category:
Use transmitters in place of wired-direct installation.

The Challenge:
In most applications, a transmitter converts the temperature sensor output to 4–20-mA with HART or to a digital signal such as FOUNDATION Fieldbus.

Some users prefer to connect a thermocouple or RTD directly to a control system input. However, this complicates the installation and can impair performance — for example:

- The cabling from the sensor to the input card must match the sensor. Installing a different type of sensor requires changing the cabling.
- Likewise, the input card must match the sensor. Some cards allow for multiple options but only work with temperature sensors.
- The weak signals from a thermocouple or RTD can’t be sent over long distances and are subject to problems caused by electrical interference.
- Wired direct installations have minimal (or no) predictive diagnostics to minimize the effects of when a sensor fails, resulting in a higher likelihood of unplanned shutdowns or other negative impacts to the process.

Analysis and Solution:
Adding a temperature transmitter close to the sensor eliminates all these problems:

- A 4–20-mA with HART or FOUNDATION Fieldbus signal is much more robust, less susceptible to environmental interference and can be sent longer distances.
- Special cabling or a special input card isn’t necessary.
- Most transmitters work with a variety of thermocouple and RTD types, so changing the sensor when required is very easy.
- High density transmitters can capture data for multiple sensors and send these data back on one cable.
- Smart transmitters can collect and send diagnostic, calibration, and other data.
- *Wireless*HART transmitters also are an option. They eliminate wiring and the need for control system inputs, which may be in short supply. These smart transmitters have built-in battery modules and can run for years without any required maintenance. Wireless transmitters can be a cost-effective way to upgrade existing wired-direct installations, because you do not need to replace the existing sensor cabling with traditional copper transmitter cabling.

In summary, using a sensor wired into a transmitter offers numerous advantages over a wired-direct sensor installation. For a new measurement/installation point, Emerson recommends always using a transmitter. For existing wired-direct installations, consider upgrading to a transmitter if the measurement is experiencing some of the challenges previously discussed.

Best Practice #2

Category:
Use the Rosemount Thermowell Design Accelerator when engineering new measurement points or evaluating existing installations that have process condition changes.

Challenges with Traditional Thermowell Design:
Thermowells are an essential part of temperature measurement, protecting the sensor from the process and acting as a process retaining device. Thermowells in fluids experience Vortex Induced Vibrations (VIV) that may result in sensor damage or even compromise the integrity of the thermowell. To avoid these situations, thermowell calculations, according to the AMSE PTC 19.3 TW, are done to ensure a safe and reliable thermowell.

Traditionally, performing these calculations has been a manual, time-consuming process with a high risk of human error:

- Design tools have historically consisted of spreadsheets and basic online calculators that requires the user to have an intimate knowledge of the ASME PTC 19.3 TW specification.
- When designs do not pass, it is up to the user to decide what modifications to make to achieve a working result.
- Process conditions are often different for startups and shutdowns vs. normal operation, meaning that the calculations need to be performed multiple times for a given tag.

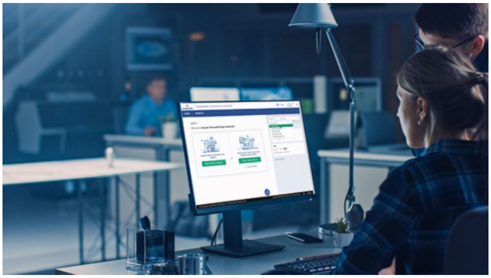
Because of these challenges, it could historically take over 40 hours of work to do the Thermowell sizings on a small project of 50 tags.

Improvements with Using Rosemount Thermowell Design Accelerator:
The Rosemount Thermowell Design Accelerator greatly simplifies the thermowell design process and can reduce the amount of time it takes to size thermowells by over 90%. All the user has to do is enter in the process conditions and an initial thermowell design, and the Accelerator does the rest of the work.

- If a thermowell does not pass the PTC calculations, the Accelerator automatically iterates the design until a passing result is achieved.
- The Accelerator can perform the calculations for various profiles on the same tag (startup, shutdown, operation) to ensure the design will work for all potential conditions.
- The Accelerator will alert you when a traditional thermowell will not work and if a Twisted Square or X-well solution should be considered instead.
- Preliminary model numbers for the thermowell and a matching temperature sensor are provided, which minimizes specification and procurement errors.
- Bulk thermowell sizing of up to 1000 tags can be performed at a single time.
- The Troubleshooting Assistance feature checks through your data to make sure there aren't any mistakes and alerts you if it finds any errors.

The Rosemount Thermowell Design Accelerator is a free online tool.

[Learn more and try out the Rosemount Thermowell Design Accelerator today.]



Best Practice #3

Category:
Use field mount transmitters for maximum ease-of-use, reliability, and flexibility.

The Challenge:
Traditional head mount transmitters can be difficult to wire due to small size. The single compartment design of head mount transmitters provides no separation between terminal blocks and electronics, unnecessarily exposing electronics to environment during commissioning and maintenance.

Analysis and Solution:
Field mount, dual-compartment transmitters solve many challenges posed by smaller, head mounted temperature transmitters.

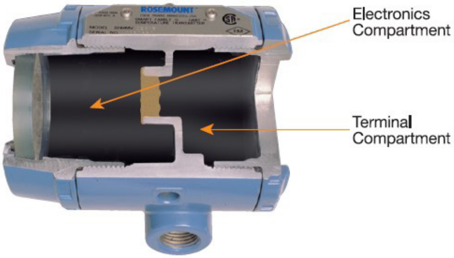


Figure 6-1 – Dual-Compartment Housing

- To maximize performance and minimize installation costs, it is preferable to mount the transmitter integrally with the sensor-thermowell assembly.
- Dual-compartment transmitters ensure the greatest tolerance for adverse environmental conditions.
  - Allow for easier wiring and maintenance as the terminal compartment and electronics compartment are separate.
  - Can withstand greater humidity and provide corrosion protection.
  - Protect against electromagnetic interference, which can disrupt communication, reduce your ability to accurately control, damage the device, and create safety issues within your process.
- These transmitters are typically available with large, easy-to-read displays to assist with operator rounds, troubleshooting, and other maintenance and commissioning tasks.
- Ease-of-wiring is also a significant advantage for field-mount transmitters. The amount of space in the housing to accommodate up to two sensors and the loop wiring is significantly greater than in most connection heads or junction boxes used with head mount transmitters. The terminals are also typically larger and more spaced out compared to head mount transmitters.
- The HART signal, that is superimposed on the analog output signal of transmitters, has a wealth of data that can provide useful information. This typically includes the temperature inside the transmitter housing and the process temperature. Some transmitters have an on-board feature that keeps records of both the process and ambient temperature values. Alternatively, the HART data may be accessed using a field communicator or by an asset management system. This enables a user to verify that housing temperatures have not exceeded recommended limits. Operating a transmitter above its published maximum operating temperature may cause premature failure and/or invalid outputs. Operating it below its rated ambient temperature may lead to degradation of the accuracy.
- The HART data also includes sensor diagnostics information for open or shorted leads that often is accessed by the internal transmitter diagnostics and displayed on the LCD or alternatively or supplementally, they can also be accessed by a field communicator or an asset management system. In an asset management system, any abnormal conditions can be configured to trigger an alert or alarm in the Distributed Control System (DCS).

Best Practice #4

Category:
Use Rosemount X-well Technology to simplify the installation of new temperature monitoring points.

The Challenge:
While temperature is critical to safety and control systems, the most common application of temperature measurement is in monitoring applications. As more emphasis is put on increasing energy and labor efficiencies, more temperature monitoring points are needed to gather the necessary data. In existing applications, this requires installation of a new thermowell. Installing a thermowell into an existing application requires process shutdown, cutting into the existing process piping, installing process connections, and finally, running the necessary wiring to support the new temperature transmitter or sensor. This is a time-consuming and resource intense process that is typically limited to a small window of time during turnaround.

Analysis and Solution:
Use Rosemount X-well Technology.

X-well Technology allows users to install new temperature monitoring points without the need for a thermowell. Eliminating the need for a thermowell significantly simplifies the installation of new temperature points, as no cutting, welding, or other piping modifications are required to install the new measurement. Additionally, this frees up labor and resources during a turnaround, which typically are time and budget constrained.

X-well also allows users to install new temperature points without worrying about how unplanned changes to process conditions may impact the measurement. The best practice for thermowells is to reperform wake frequency calculations any time the flow conditions in the pipe change. This could require redesigning and replacing existing thermowells to ensure they can meet the process needs. Because X-well technology doesn't use a thermowell, changes to process conditions do not require any recalculation or redesign.

X-well enables users to install new temperature monitoring points on equipment that was previously not instrumented, allowing for new process insight. This insight is invaluable in improving equipment health, maintenance cycles, and energy efficiency.

Challenging applications, such as high velocity, corrosive flows, or abrasive flows, can quickly damage thermowells or require exotic metals for thermowell construction. These requirements can quickly drive up the material and lifetime cost of a thermowell installation. X-well technology is an excellent solution for monitoring process temperature in these applications. Removing the need for a thermowell means that new temperature points can be added without using exotic materials or frequent maintenance.

Finally, X-well technology is offered with *Wireless*HART functionality. This further simplifies the installation of new temperature monitoring points. New temperature points can be added without the need for pulling wires or installing conduit, limiting work to installing the X-well clamp and insulating the measurement point.

Best Practice #5

Category:
Use Rosemount Twisted Square thermowells in critical control applications.

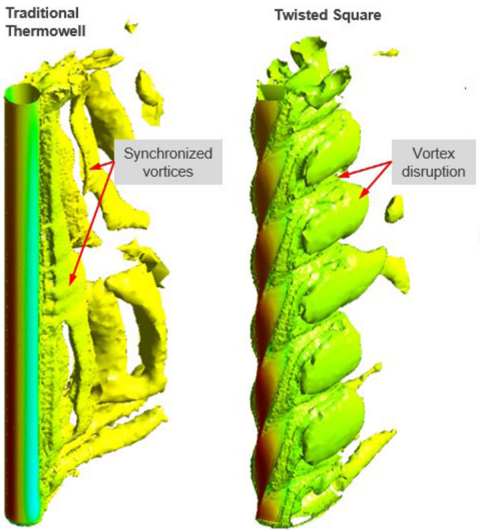
The Challenge:
Measuring temperature in critical control applications requires accuracy, repeatability, and safety. When designing a thermowell, it is essential that you do thermowell calculations to ensure it is safe for the application. In many cases, the result of having a thermowell in a challenging process is that the thermowell typically gets shortened and the stem thickens to help it pass thermowell calculations done according to ASME PTC 19.3 TW.

Short thermowells or thermowells that are close to the pipe wall are plagued with issues such as stem effects and ambient temperature changes. These issues result in non-repeatable and inaccurate process temperature measurements. Because of this, a common industry practice is to have the tip of the thermowell be one-third to one-half of the way into the pipe to ensure the most accurate and repeatable measurement.

Analysis and Solution:

- The Rosemount Twisted Square thermowell is a unique type of thermowell that is designed to suppress over 90% of the harmful vortex induced vibrations that a regular thermowell would experience. This allows Twisted Square to be installed with maximum immersion into the pipe to ensure accurate and repeatable measurements in critical or difficult applications.

- Its highly engineered design distorts the synchronized destructive vortices as shown the image on the right side. Due to its designed twist, the vortices are also out of phase, which further reduces their effect on the thermowell. This reduces the dynamic stresses on the thermowell, allowing it handle challenging applications that a traditional thermowell would fail in. [This video](#) shows how a traditional thermowell compares to the Twisted Square thermowell.



- The Twisted Square thermowell is an excellent solution for challenging applications where high velocity, pressure and density are involved. Using the [Rosemount Thermowell Design Accelerator](#), you will be able to design and evaluate this thermowell for your specific application needs.

[Learn more about the Twisted Square thermowell.](#)

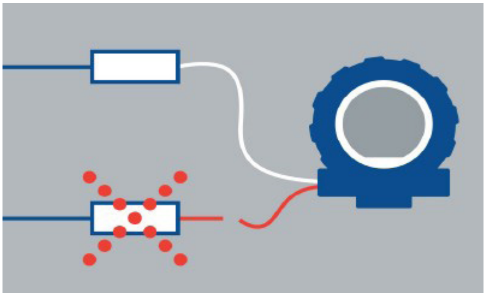
Best Practice #6

Category:
Use diagnostics to eliminate disruptions from sensor failures.

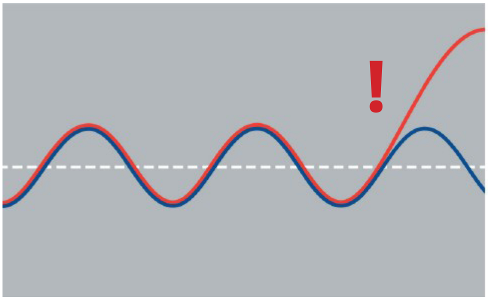
Legacy Practice and Associated Challenges:
Wired-direct installations leave you prone to unexpected failures with minimal diagnostics coverage. Degraded or broken elements, loose or open connections, moisture in housings, frayed or damaged wiring, and electrical noise can all create risks for maintaining an accurate reading and keeping your process up and running.

Solution and Benefits:
Temperature transmitter diagnostics help you avoid measurement failure and process shutdown.

- Dual sensor inputs allow you to reduce measurement risk.
  - Hot Backup functionality allows for a seamless transfer from a failed sensor to a backup sensor, which improves process availability by preventing a failure of the primary sensor from disrupting process control and shutdown.



  - Sensor Drift Alert can indicate that a sensor is starting to go bad. If two sensors are measuring the same process, the diagnostic will monitor how closely the two readings trend together. If the two measurements stop trending, this can indicate that one of the two sensors is failing.



- Electromagnetic Field Compensation will filter small voltages from RTD installations, eliminating errors from measurement. Corrosion and poor terminations can result in small voltages being present on the sensor wiring, causing false temperature readings.
- Thermocouple Degradation and Measurement Validation can identify failing or degrading sensors and connections by monitoring and evaluating sensor loop resistance and sensor signal noise.
- Transient Filtering prevents intermittent transient signals from affecting the measurement by filtering short duration transient spikes that may influence the output.
- Open Sensor Hold-Off prevents high voltage intermittent transient signals from creating false open sensor conditions, avoiding unnecessary alarms caused by high voltage transients such as lightning or electrostatic discharge.
- Line Voltage Filters can filter out noise caused by AC power sources at either 50 or 60 Hz. This noise can easily degrade low-amplitude sensor signals.

Best Practice #7

Category:
Maximize sensor performance and reliability.

The Challenge:
With a seemingly endless variety of sensor types and configurations, selecting the right sensor for the application can feel like an overwhelming decision. The information below contains general best practices to help you get the right fit and maximum reliability for various applications.

General Purpose Monitoring:

Recommendation: 4-wire spring-loaded RTD

This configuration is an all-around great general-purpose sensor that can handle most applications. Benefits of this configuration:

- Performance: 4-wire RTDs offer the greatest amount of stability and repeatability by compensating out all measurement error from the sensor wires. Most modern transmitters can accept 4-wire RTDs as sensor inputs, so defaulting to this configuration when possible is a good starting point. If a 4-wire configuration is not possible, 3-wire sensors still offer some amount of compensation. 2-wire sensors should be avoided when possible. Additionally, the spring-loaded adapter ensures that the sensor tip is in contact with the thermowell to ensure best possible heat transfer and time response.
- Convenience: a Class B or Class A uncalibrated 4-wire sensor provides a nice balance of performance and ease of use without undertaking the additional steps of entering CVD coefficients into the transmitter.

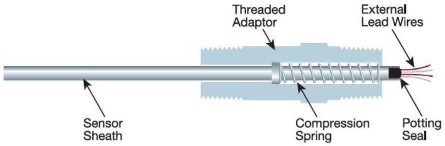


Figure 6-2 – Spring-Loaded Sensor

Extreme Temperatures:

Recommendation: Ungrounded Thermocouple

RTDs can be used in applications with process temperatures from -60°C to +600°C (-76°F to +1112°F). In applications that are above or below those limits, thermocouples should be used. For cryogenic and other types of cold applications, Type T thermocouple can measure temperatures down to -196°C (-321°F). For high temperature applications, Type K thermocouples can go up to 1200°C (2192°F).

High Vibration:

Recommendation: Ungrounded Thermocouple

Because a thermocouple is such a simple device that only consists of two wires of dissimilar metals joined together, it will generally perform better in high-vibration installations compared to an RTD, which has a dedicated sensing element that can break when exposed to vibration and other stresses.

Figure 6-3 – Simple Diagram of Thermocouple construction

High-Accuracy/Critical Applications:

Recommendation: Calibrated RTD sensors (Callendar-Van Dusen)

For applications that require the best possible accuracy, sensors should be ordered with Callendar-Van Dusen calibration. The sensor manufacturer will calibrate the sensor by measuring the sensor resistance at various temperature points to determine the exact relationship between resistance and measured temperature for that specific sensor. The sensor manufacturer will then document these CVD coefficients, which can be entered into a transmitter that has the CVD polynomial equation programmed into it. The one drawback to using CVD sensors is that it does require the extra step of programming these coefficients into the transmitter. Some suppliers can do this for you if the sensor and transmitter are ordered together at the same time.

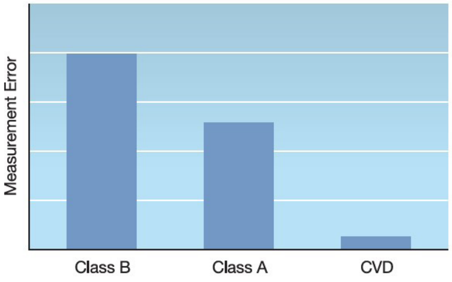


Figure 6-4 – Performance Comparison of Uncalibrated Class B and A Sensors to a CVD Sensor

Best Practice #8

Category:
Find solutions for challenging applications.

The Challenge:
Given that temperature is the most common measurement made in many facilities, you are likely to encounter a handful of challenging or extreme applications where it can be difficult to find a solution that offers the right balance of performance and reliability. This section will evaluate some of the more common situations that are often encountered, along with potential temperature measurement solutions.

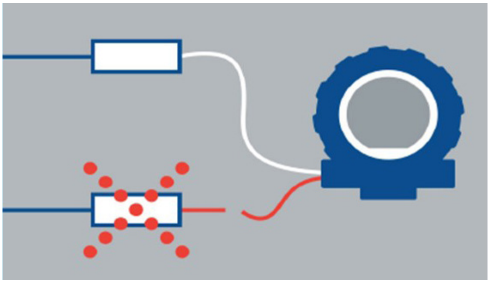
High Vibration Installations:

Vibration is the most common cause for a temperature measurement to fail. RTD sensors in particular are notorious for breaking after being exposed to continuous and/or high amplitude vibration. Below is a list of solutions that can be taken to minimize the likelihood that you will experience a measurement failure due to vibration.

1. Use thin-film RTDs in place of wire-wound RTDs. Wire-wound RTDs are more mechanically complex than thin-film RTDs and thus are more likely to fail when exposed to vibration. Using thin-film RTDs can be enough of an improvement to ensure adequate longevity in applications with low-to-moderate vibration (up to 10G amplitude).

Figure 6-5 – Traditional Wire-wound RTDs are Not Well-Suited for Vibration

2. Use Thermocouples in place of RTDs. Thermocouples will usually perform better than RTDs in higher vibration environments. If thin-film RTDs are experiencing failures, consider using a thermocouple instead.
3. Use redundant sensors. If vibration is persistent enough to cause frequent sensor failure (either RTD or Thermocouple), consider using a dual-sensor configuration. Many transmitters can process signals from two sensors, either from separately mounted sensors, or from dual sensors built into a single sheath. If the measurements from the two sensors differ by an amount programmed into the transmitter, an alert is triggered. Similarly, if one sensor fails, automated Hot Backup functionality allows the transmitter to switch immediately from the primary to the backup sensor without losing the reading. This can allow you to replace the faulty sensor without losing the measurement.



4. Evaluate the Thermowell geometry. Fluids flowing past the installed thermowell often create vortex-induced vibration (VIV). If not properly accounted for, VIV can cause fatigue-induced failures of the thermowell, potentially resulting in a loss of process containment. It is recommended that you use a thermowell sizing program, such as the Thermowell Design Accelerator, to ensure that the thermowell will not experience a VIV-induced failure. The Accelerator will also modify the proposed thermowell geometry as needed, such as shortening the thermowell insertion length and/or increasing the thermowell diameter.
5. Use Rosemount Twisted Square Thermowell. The helical geometry of the Twisted Square suppresses VIV by up to 90%, enabling a much more reliable solution in challenging applications where a traditional insertion measurement is still needed.

6. Use Rosemount X-well Technology. In some of the more extreme environments, a Twisted Square thermowell may not even be able to withstand the operating conditions. Rosemount X-well Technology eliminates potential vibration failures altogether because it is not physically installed into the pipe or vessel.

Corrosive & Erosive Process Conditions:
Another common cause of temperature measurement failure is corrosive and erosive process medium. As a thermowell is installed to years of continuous contact with abrasive or corrosive medium, microscopic irregularities in the molecular structure of the thermowell can become more pronounced. This can cause the thermowell to become structurally compromised, creating a situation for a loss of process containment and/or the temperature sensor itself to become exposed to the process medium.

Often times, thermowells fail in these conditions because it was simply unknown that the process contained corrosive or erosive medium. 304 SST can only handle up to 200 ppm of chlorine, and 316 SST is slightly higher at 1000 ppm.

Below are some strategies for maximizing reliability in corrosive & erosive applications:

1. Re-evaluate the material of the thermowell. Suppliers typically offer thermowells in a wide variety of materials to meet the vast demand of temperature measurement applications. When selecting a thermowell, three factors need to be considered regarding the material of construction:

   - Chemical compatibility with the process medium to which the thermowell will be exposed.
   - Temperature limits of the material.
   - Compatibility with the process piping material to ensure solid, non-corroding welds and junctions.

   It is important that the thermowell conforms to the design specifications of the pipe or vessel it will be inserted into to ensure structural and material compatibility. The original process design most likely included temperature, pressure, and corrosive considerations, as well as cleaning procedures, agency approvals required, and conformance with codes or standards. Since an installed thermowell essentially becomes part of the process, these original design considerations also apply to the thermowell and will drive the thermowell material of construction and mounting type selection. International pressure vessel codes are explicit about the types of materials and methods of construction allowed.

2. Consider use of coatings when measuring temperature in abrasive/erosive environments. The purpose of a coating is to prevent the physical erosion of the thermowell when under long-term exposure to processes with abrasive particulates. PFA and PTFE are two of the more common coating options. It is important to note that these coatings only serve as a physical barrier, and the underlying material of the thermowell must still be chemically compatible with the process medium as well.

3. Use Rosemount X-well Technology. In monitoring applications that have erosion or corrosion challenges, X-well technology is often the safest and most reliable solution to making a temperature measurement. Because X-well Technology is not physically installed inside the pipe or vessel, it is not exposed to these conditions. In addition to offering enhanced reliability, X-well Technology will often be a more cost-effective solution as well. When dealing with corrosive applications, thermowells often need to be specified using expensive, exotic materials. Alternatively, X-well technology can be specified and installed with traditional SST materials.

7

Documentation

7.1 – White Papers

White Paper - Thermowell Calculations
00840-0200-2654, Rev AB
January 2012

Thermowell Calculations

Dirk Bauschke
Engineering Manager

David Wiklund
Senior Principal Engineer

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Mechanical Project Engineer

Alex Cecchini
Senior Marketing Engineer

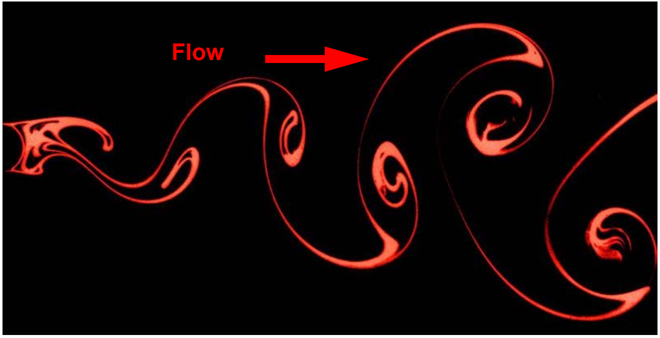
White Paper - Thermowell Calculations

00840-0200-2654, Rev AB
January 2012

Thermowells

INTRODUCTION

Thermowells are essentially a circular cylinder installed like a cantilever into the process piping. They provide process condition protection and a process seal for temperature sensors. As a process fluid passes around the thermowell, low pressure vortices are created on the downstream side in laminar, turbulent, and transitional flow. The combination of stresses, generated by the static in-line drag forces from fluid flow and the dynamic transverse lift forces caused by the alternating vortex shedding, create the potential for fatigue-induced mechanical failures of the thermowell. Piping designers may use a variety of tools to predict and avoid thermowell failures in their systems, but ASME PTC 19.3-1974 had been the standard by which most thermowells were designed.



Color enhanced smoke trail showing von Karman Vortex Street in laminar fluid flow.(1)

BRIEF HISTORY OF ASME PTC 19.3

The standard dates back to 1957 when ASME (American Society of Mechanical Engineers) determined that the 1930's Supplement on Temperature Measurement was unsatisfactory because it did not include thermal and stress effects. ASME asked the Boiler and Pressure Vessel Committee to create a document, but it was deemed outside their scope. A stand-alone committee was then charged with all of temperature measurement with thermowell design as a section. The basis for ASME PTC 19.3-1974 was a paper authored by J.W. Murdock (1959).(2)

John Brock of the Naval Post Graduate School conducted some follow-on work in 1974 that uncovered several items that Murdock either assumed or ignored. Brock suggested such ideas as using a variable Strouhal Number rather than a fixed Strouhal Number, applying installation factors in the approximation of the natural frequency of the thermowell, and reviewing the frequency ratio limit of 0.8 to account for uncertainty in the natural frequency calculations(3). Some of these demonstrated that there could be improvements made to ASME PTC 19.3-1974.

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(1) Wikipedia http://en.wikipedia.org/wiki/Vortex_induced_vibration as of 5/20/2011

(2) Murdock, J.W., "Power Test Code Thermometer Wells" Journal of Engineering for Power (1959).

(3) Brock, John E., "Stress Analysis of Thermowells," Naval Postgraduate School, Monterey CA (1974).

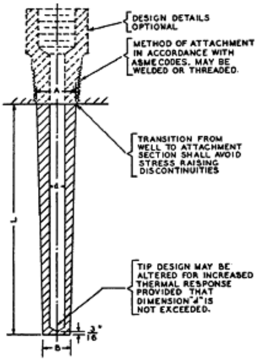
ASME PTC 19.3-1974 did not seem to account for all installations. An example of a high profile catastrophic thermowell fatigue failure came when the Monju (Japan) Fast Breeder reactor was shutdown due to a leak in a liquid sodium coolant system in 1995. The investigation revealed that the thermowell was designed in accordance to ASME PTC 19.3-1974 but the failure mode was due to the in-line resonance, which is not accounted for in the standard. The result was the development of the Japanese version of the standard, called JSME S012(1). The reactor was eventually restarted in May of 2010 after years of investigation and legal battles.

For the most part, though, ASME PTC 19.3-1974 was used successfully in both steam and non-steam applications. Several key factors caused ASME to re-form the committee in 1999 to completely rewrite the standard; advances in the knowledge of thermowell behavior, a number of catastrophic failures (Monju among them) and the increased use of Finite Element Analysis for stress modeling. When combined, these factors caused many in the industry to move away from the rudimentary methods and simplified tables laid out in ASME PTC 19.3-1974 in favor of more advanced methods for predicting the thermowell natural frequency and calculating the forced frequency.

Rather than simply update the existing version of ASME PTC 19.3-1974, the committee decided to release a new standard due to the significant changes associated with the effort. The thermowell calculation portion of ASME PTC 19.3-1974 was 4 pages. By comparison, the new standard, known as ASME PTC 19.3 TW (“TW” for thermowell), is over 40 pages due to the explanations of theory and the sheer complexity of the process.

ASME PTC 19.3 TW was released in July 2010.

ASME PTC 19.3-1974 METHODOLOGY



As previously stated, the 1974 standard is very brief. It allows few stem profiles and uses simplified equations to model the thermowell for natural frequency calculations. Even though it allows any attachment method that is approved by the ASME Boiler and Pressure Vessel and Piping Codes, the equations do not differentiate between common mounting style variations such as flanged, threaded, and socket weld, and ignores the effects of different stem profiles, such as straight, taper, and stepped. Bore dimensions not in the tables are not accounted for, so bores for 1/4-in. and 6 mm diameter sensors share the same constants in the equations and no constants are provided for 3 mm diameter sensor bores.

For all its drawbacks, though, ASME PTC 19.3-1974 does have a simple process for thermowell evaluation that helped make it widely accepted in the industry; gather the process data and the thermowell materials information, calculate the natural and Strouhal Frequency, compare the ratio to 0.8, calculate the bending stress, compare maximum pressure to process pressure, and check the maximum length to the desired length.

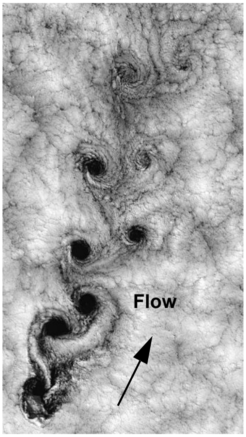
(1) *Odahara, Sanoru, et al. “Fatigue Failure by In-line Flow-induced Vibration and Fatigue Life Evaluation,” JSME International Journal, Series A, Vol. 48, No. 2 (2005).*

Gathering the process data and materials information is a straightforward step except that there is one piece of data that is no longer readily available. The “Ratio of frequency at process temperature to frequency at 70 °F” is not easily found.

The method of calculating the thermowell natural frequency uses a simple equation, but some of the terms, such as K_f, are not well defined. If the thermowell U-length does not match one of those listed in the table, the designer should use the data for the length longer than the thermowell to be conservative. For an acceptable thermowell design, the ratio of the Strouhal frequency and the natural frequency “shall not exceed” 0.8.

The final step is an evaluation of the thermowell length based on the steady state stress. This determines the maximum length the thermowell can be in order to handle the bending stress. This length is compared to the desired length to determine if it is acceptable or if it must be shortened.

VORTEX SHEDDING THEORY (basis for ASME PTC 19.3 TW)



Landsat 7 image of a von Karman Vortex Street in the clouds off the Chilean coast near the Juan Fernandez Islands (15 Sept 99). (1)

When a fluid flows around a blunt object in its path, vortices are formed downstream of the object. This is commonly referred to as vortex shedding, Von Karman Vortex Street, or flow vortices. The vortices are low pressure cells that are created and shed downstream in an alternating pattern. The differential pressure due to the alternating vortices produces alternating forces on the object. This results in alternating stresses on the object as it deflects. This phenomenon is observed in nature as eddies in the current downstream of bridge piers, swirls in the clouds downwind of the peaks of mountains, or Aeolian tones heard as the wind passes around utility lines. While vortex shedding is useful for process flow measurements, thermowell designers should avoid it due to the potential for failure.

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(1) *NASA Earth Observatory Website “http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=3328.”*

Thermowells

Because the major cause of thermowell failure is fatigue due to resonance, the designer needs to understand vortex shedding in order to avoid its effects and predict the vortex shedding frequency. Since vortex shedding occurs at frequencies anywhere from about 50Hz to 1500Hz, the thermowell can experience a large number of cycles in a short amount of time.

Example of a thermowell failure due to vortex induced vibration(1)

As the vortex shedding frequency, or Strouhal Frequency, approaches the thermowell natural frequency, the tip displacement and stresses are greatly magnified and the thermowell can fail due to the large amount of energy it must absorb. So, in addition to process conditions such as pressure, temperature, and corrosion, the designer must account for the high cycle fatigue strength for overall suitability in the application.

Minimum Velocity

For slow flowing process fluids, there is not enough energy transferred from the process fluid to the thermowell to cause fatigue failure. If the following conditions are met, there is no need to conduct frequency limit calculations as the risk of thermowell failure is negligible.

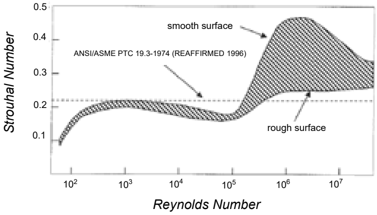
1. Process Fluid Velocity, $V < 0.64$ m/s (2.1 ft./sec)
2. Wall Thickness, $(A - d) \geq 9.55$ mm (0.376 in)
3. Unsupported Length, $L \leq 0.61$ m (24 in)
4. Root and Tip Diameter (A and B) ≥ 12.7 mm (0.5 in)
5. Maximum Allowable Stress, $S \geq 69$ Mpa (10 ksi)
6. Fatigue Endurance Limit, $S_f \geq 21$ Mpa (3 ksi)

Even so, these low velocities could still excite the in-line resonance and cause sensor failure due to the high vibration that exists at resonance. If these criteria are not met, or if there is a chance of stress corrosion or material embrittlement due to fluid interaction (which would cause a change to the fatigue endurance), the designer must fully evaluate the thermowell design.

Strouhal Number

There has been much discussion on the topic of whether to use a fixed or variable Strouhal Number. ASME PTC 19.3-1974 used a fixed Strouhal Number of 0.22 while Brock recommended a variable Strouhal Number depending on the Reynolds Number. Many in the industry began to incorporate the variable Strouhal Number to the vortex shedding frequency equations within the framework of ASME PTC 19.3-1974 calling it “the Brock Method” or something similar.

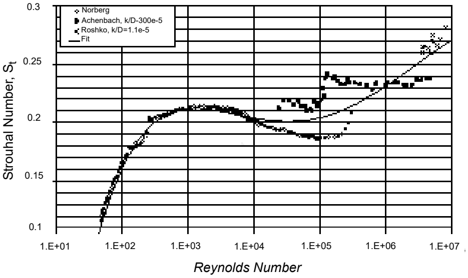
(1) *Energy Institute, “Guidelines for the Avoidance of Vibration Induced Fatigue in Process Pipework” 2nd Edition, (2008), Publication Number 978-0-85293-463-0.*



Typical chart showing Strouhal Number as a function of Reynolds Number

The ASME PTC 19.3 TW committee reviewed the subsequent experiments before deciding on how to use the variable Strouhal Number. Two papers published in the JSME International Journal in 2001 showed interesting test results for machined straight and tapered cylinders that were similar to thermowells in form. The forces and vibration amplitudes were measured while the cylinders were immersed in a fluid flow. The conclusion was that the evidence of a high Strouhal Number in previous experiments was based on measurements of the vortex shedding and not of the actual forces on the thermowell.(1) (2)

“Rough” surfaces were defined in the experiments as measuring in excess of 128 Ra. No thermowell in the process industry has a surface finish of more than 32 Ra and the stress limits and calculations in ASME PTC 19.3 TW are not valid for surface finishes rougher than 32 Ra.



Actual data of Strouhal Number of a rough cylinder as a function of Reynolds Number.(3)

Based on this data, the ASME PTC 19.3 TW committee decided to incorporate a variable Strouhal Number defined by the rough cylinder curve. To simplify calculations, the designers are also allowed to conservatively approximate the Strouhal Number as 0.22. This is especially useful if the designer cannot establish the dynamic or kinematic fluid viscosity to determine the Reynolds Number.

(1) *Sakai, T., Iwata, K., Morishita, M., and Kitamura, S., “Vortex-Induced Vibration of a Circular Cylinder in Super-Critical Reynolds Number Flow and Its Suppression by Structure Damping,” JSME Int. J. Ser. B. 44, 712-720 (2001).*

(2) *Iwata, K., Sakai, T., Morishita, M., and Kitamura, S., “Evaluation of Turbulence-Induced Vibration of a Circular Cylinder in Super-Critical Reynolds Number Flow and Its Suppression by Structure Damping,” JSME Int. J. Ser. B. 44, 721-728 (2001).*

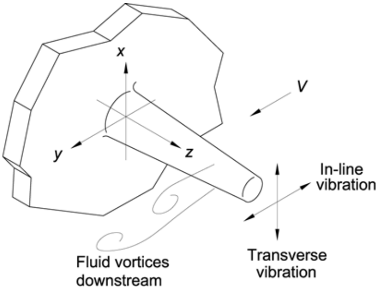
(3) *ASME Standard, Performance Test Codes 19.3TW (draft 7).*

White Paper - Thermowell Calculations
00840-0200-2654, Rev AB
January 2012

Reynolds Number

In any fully immersed flow, a fundamental parameter is the Reynolds Number. The Reynolds Number is the ratio of the inertial forces to the viscous forces in the flow field. For the purposes of vortex shedding elements, the length input for the Reynolds Number is the width of the shedding element. In the case of thermowells, this is the tip diameter.

Thermowell Natural Frequency



Fluid induced forces and assignment of axes for calculation of thermowell stresses(1)

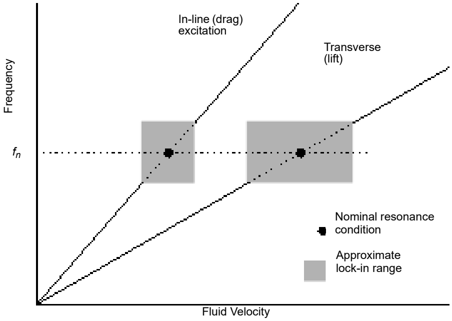
ASME PTC 19.3 TW models the thermowell as a simple cantilever beam and applies a series of correction factors to account for the differences from the ideal beam by including added fluid mass, added sensor mass, non-uniform profile beam, and mounting compliance. For stepped stem thermowells, most all the correlations and calculations are more complex due to the geometry and stress concentration points.

Because of this, ASME PTC 19.3 TW restricts the dimensional variation of stepped stem thermowells considered within the scope of the standard.

After all the correction factors are applied, the “in-situ”, or installed natural frequency, f_n^c, is calculated and used for the rest of the frequency analysis.

Critical Velocities

Once the thermowell natural frequency has been established, the designer needs to set the margin of safety between the natural frequency and the Strouhal frequency.



In-line and transverse excitation schematic showing “lock-in” region.(1)

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(1) *ASME Standard, Performance Test Codes 19.3TW.*

There are actually two modes of thermowell excitation. The transverse (lift) force that causes the thermowell to vibrate perpendicular to the flow while the in-line (drag) force causes the thermowell to vibrate parallel to the flow. The in-line vibration is approximately twice the frequency of the transverse. The in-line “velocity critical” (where the Strouhal Frequency equals the natural frequency) is approximately half the velocity as the transverse. ASME PTC 19.3-1974 does not address the in-line vibration, only the steady state bending stress.(1)

While the change in the shedding frequency is proportional to the fluid velocity, the thermowell locks-in to the resonance frequency very easily. It can also take a considerable change in velocity to get the thermowell out of shedding vortices at its natural frequency. Since the damping of typical thermowells is very low, it is vital to stay out of resonance. At resonance the forces and displacements are greatly magnified.

$$f_s < 0.8\ f_n^c$$

The 20% guard band accounts for the significant variability due to:

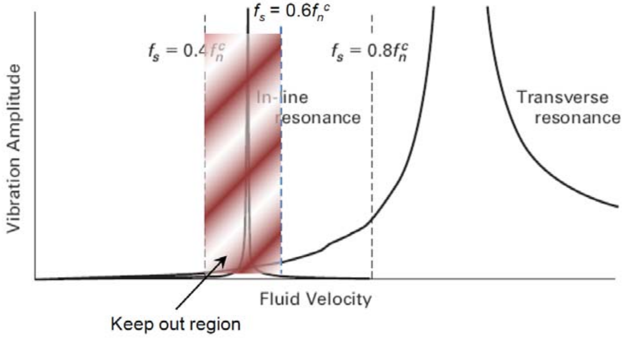
- the non-linearity of the thermowell elastic response
- loose thermowell manufacturing tolerances
- material property information established to only 3 significant digits
- minor, routine variations in flow rate, temperature, density, or viscosity in the process

Since the in-line vibration occurs at roughly half the velocity of the transverse (or twice the frequency), liquids have further limitations.

$$2f_s < 0.8\ f_n^c$$

Viewing this a bit differently gives a wider perspective on where thermowell operation is allowed.

$$f_s \text{ (steady state)} < 0.4\ f_n^c \qquad \text{or} \qquad 0.6\ f_n^c < f_s \text{ (steady state)} < 0.8\ f_n^c$$



Graph depicting the amplitude response of a thermowell to fluid-induced forces. (2)

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(1) ASME Standard, Performance Test Codes 19.3-1974 (Reaffirmed 1998).

(2) Adapted from ASME Standard, Performance Test Codes 19.3TW.

ASME PTC 19.3 TW also contains a provision for “super critical” operation where the thermowell is operated above the thermowell natural frequency. Emerson strongly discourages operating thermowells in this region.

Scruton Number

New to the theory is the use of the Scruton Number, which represents the intrinsic damping of the thermowell. ASME PTC 19.3 TW takes a very conservative perspective and sets the damping factor to 0.0005 unless it is otherwise determined.

A Scruton Number less than 2.5 means that there is no intrinsic damping and the thermowell must be evaluated at the in-line resonance frequency and stay away from the transverse resonance frequency. As the Scruton Number increases, there is an increased level of intrinsic damping that reduces the deflections and, therefore the stresses. An acceptable level of damping will allow the thermowell to operate at the in-line and maybe even the transverse resonance frequencies.

If the conditions are such that the thermowell will be operating above the natural frequency, higher order resonances must be considered, but ASME PTC 19.3 TW does not provide any guidance in this and Emerson strongly discourages operating thermowells in this region.

BENDING AND PRESSURE STRESS (as used in ASME PTC 19.3 TW)

While it seems that there is a lot of attention being given to the vortex shedding theory and application, the stresses within the thermowell and forces applied are also critical to evaluating suitability for specific process applications. In contrast to the simple method in the 1974 version, ASME PTC 19.3 TW takes a much more detailed look at both the frequency and the stresses on the thermowell. This allows a wider variety of mounting styles, profiles, and bore sizes that reflect the offerings available in the industry today.

In total, there are 4 quantitative criteria in ASME PTC 19.3 TW for a thermowell to be found acceptable for a particular set of process conditions:

1. **Frequency Limit:** the resonant frequency of the thermowell must be sufficiently high so that destructive oscillations are not excited by the fluid flow.
2. **Dynamic Stress Limit:** the maximum primary dynamic stress must not exceed the allowable fatigue stress limit. If the design requires that the thermowell pass through the in-line resonance to get to the operating conditions, there is an additional fatigue check at resonance.
3. **Static Stress Limit:** the maximum steady-state stress on the thermowell must not exceed the allowable stress, as determined by the Von Mises criteria.
4. **Hydrostatic Pressure Limit:** the external pressure must not exceed the pressure ratings of the thermowell tip, shank, and flange (or threads).

In addition, the suitability of the thermowell material for the process environment must be considered. This means the designer must evaluate how corrosion and erosion affects the thermowell as well as how exposure to the process conditions affects material properties.

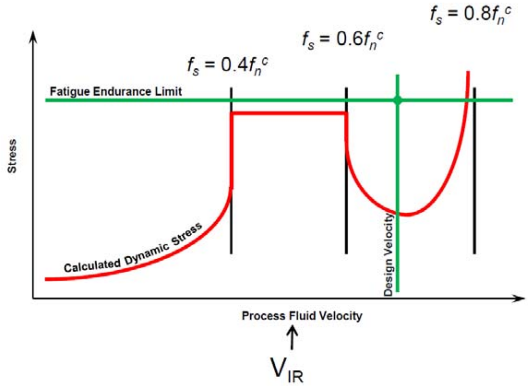
Frequency Limit

The vortex shedding theory section discusses the ASME PTC 19.3 TW method for Strouhal Frequency calculation. If the Strouhal Frequency is between the in-line critical frequency lock-in band and the transverse critical frequency lock-in band, and the Scruton Number evaluation indicates insufficient damping, the thermowell design must be modified unless all of the following conditions are met:

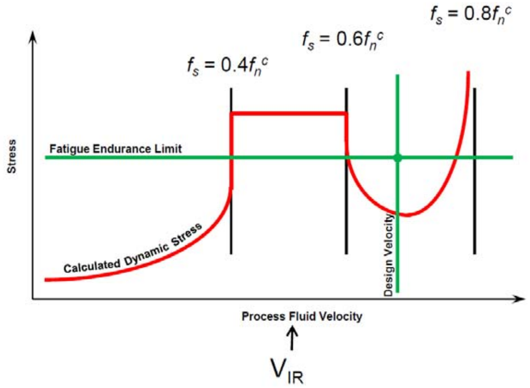
1. The process fluid is a gas
2. The thermowell passes through in-line resonance only during start-up, shut-down, or otherwise infrequently during operation
3. The peak stress at resonance is less than the fatigue limit of the material
4. The process fluid does not cause the material properties to change (esp. fatigue resistance)
5. The consequences of thermowell failure are an acceptable risk

Passing Through In-line Resonance

If the thermowell Peak Oscillatory Bending Stress is less than the Fatigue Endurance Limit at the in-line velocity critical, then the thermowell may pass through the in-line resonance lock-in region on the way to the steady state design velocity. Steady state velocities within the in-line resonance lock-in region are not allowed due to the high number of fatigue cycles imposed on the thermowell as well as the increased likelihood of sensor damage.

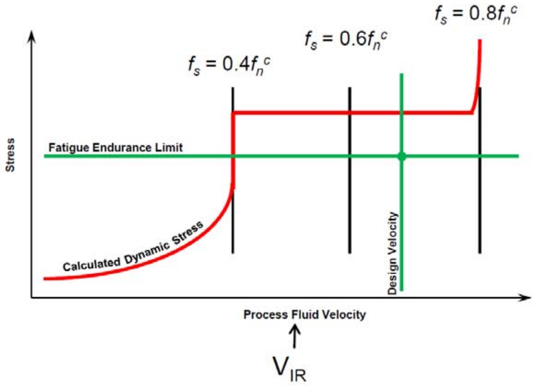


Example chart showing thermowell design that passes in-line resonance evaluation.



Example chart showing thermowell design that does not pass in-line resonance evaluation. This design may be acceptable per ASME PTC 19.3 TW.

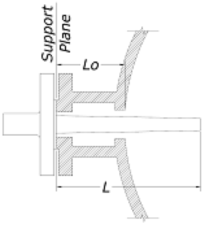
If the thermowell Peak Oscillatory Bending Stress is greater than the Fatigue Endurance Limit at the in-line velocity critical, there is more ambiguity about whether the thermowell can operate above the in-line velocity critical. Theoretically, if the thermowell is passing quickly through the in-line resonance lock-in region, it is allowed to operate between 0.6 f_n^c and 0.8 f_n^c. Fatigue cycle count is cumulative over the life of the thermowell, so it is critical to know how long the thermowell is in resonance. Since fatigue life is dependant on many factors, the longer the thermowell operates in resonance the less certain its lifespan.



Example chart showing how Emerson will interpret the in-line resonance evaluation. Emerson would find this design unacceptable.

Due to the fact that design details about ramp up speed are not known by the instrumentation providers, thermowells that do not pass the Peak Oscillatory Bending Stress evaluation and are operating above the in-line critical velocity will be reported as unacceptable by Emerson.

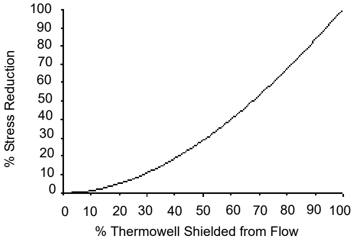
Thermowells Partially Shielded from the Flow



Tapered thermowell partially shielded from flow

Most thermowell installations are partially shielded from flow; the length of the thermowell exposed to the flow is not the full unsupported length and the equations for bending moment and bending stress need to be adjusted.

The effect of the shielding on a tapered thermowell is easily shown, but the effect of shielding on stepped stem thermowells is much more difficult to predict or model because the exposed surface is not a uniformly changing shape and there is a large discontinuity in the data. As a result, there are two sets of evaluations performed for stepped stem shielded thermowells based on the position of the step relative to the fluid flow. The stress calculations must also be performed twice to determine stresses at both the thermowell root and at the step.



Effect of shielding on a tapered thermowell

Once the installation and process conditions are understood as well as where the Strouhal Frequency sits in the frequency domain, the analysis of the actual stresses applied to the thermowell can be performed. As previously mentioned, if the thermowell is intended to operate above the in-line velocity critical, there are cyclic stresses at the in-line resonance to consider as it passes through that region on the way to the design velocity. Also the steady state and dynamic stresses at the design velocity must be evaluated.

Evaluation of In-line Cyclical Stress

The cyclic stresses, resulting from the in-line and transverse forces on the surface of the thermowell, are concentrated at the root. To account for the resonance conditions, the calculations must be performed at the in-line resonance velocity critical to see if the Peak Bending Stress at resonance is less than the Fatigue Endurance Limit of the material. Because this analysis is conducted at the in-line critical point, the magnification due to the in-line resonance overshadows the lift forces so the lift forces can be ignored to simplify the calculations. This evaluation need only be conducted if the Scruton Number evaluation indicates that the process conditions require it.

The in-line velocity critical is used to calculate the force per unit area applied to the thermowell. Since the process fluid velocity is given as an average rather than a velocity profile, the calculations also assume that the unit area is the entire exposed length of the thermowell. If some of the thermowell is partially shielded from the flow (as in the case of a standoff pipe), this must also be taken into account. For stepped stem thermowells, this analysis must be performed at both peak stress locations (root and base of stepped stem).

To ensure that the calculations are conservative, the intrinsic damping factor, is set to 0.0005. Stepped shank thermowells must be evaluated at two places to identify the highest stress of the two.

One of the major changes in the ASME PTC 19.3 TW is the use of a table to specify the Allowable Fatigues Stress Limits. The table groups materials together into a Material Class and cross references them to the installation method to determine the stress limit.

It is important to note that partial penetration welds are viewed as having less fatigue resistance than full penetration welds and are given lower values in this table. See Thermowell Construction Requirements below for more information.

Evaluation of Steady State Stress at Design Velocity

Thermowells must also be evaluated at the design velocity as well to ensure that they meet the demands of the process environment. The steady state stress is a combination of the external pressure from the process as well as the drag force. Again, these are calculated for the location of maximum stress, so if the thermowell is partially shielded, or if it is a stepped stem, the calculations should be performed with those installation considerations.

Once the Maximum Stress is calculated it can be used to determine if the Von Mises Criteria is met. The Von Mises Criteria is used to evaluate shear and pressure stress conditions in spheres and circular cylinders. It predicts the plastic yielding condition of materials.(1) Success in this evaluation means that the steady state stresses do not exceed the material fatigue strength and the thermowell can be used at the desired design velocity.

Evaluation of Dynamic Stress at Design Velocity

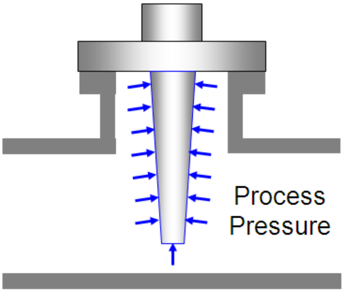
The dynamic stresses on the thermowell are attributed to the oscillating lift (transverse) and drag (in-line) forces. The magnification factor represents the exponential nature of the increase in forces as the Strouhal Frequency nears the thermowell natural frequency such as near the in-line velocity critical. If the Strouhal Frequency does not fall into the in-line or transverse natural frequency lock-in bands, then magnification factors are calculated and applied to the cyclical stress equations. The cyclic drag and lift forces need to be calculated at the design velocity in the same way as the in-line cyclical stress evaluation was performed. Unlike the in-line cyclical stress evaluation previously performed, the lift forces are not zeroed out.

If the design velocity is greater than the in-line velocity critical, the thermowell might have to be treated as if it will operate at in-line resonance stress levels indefinitely. See section above on Passing Through In-Line Resonance.

Obviously there are a number of evaluations performed on the thermowell design, but with information such as the in-line velocity critical, the steady state, and dynamic stress evaluations, the designer can have a detailed picture about where the thermowell is operating in the frequency domain as well as how close it is operating to its fatigue limit. This information will allow the designer to decide what safety factors to maintain in their process.

(1) *Brock, John E., "Stress Analysis of Thermowells," Naval Postgraduate School, Monterey CA (1974).*

Pressure Stress Evaluation



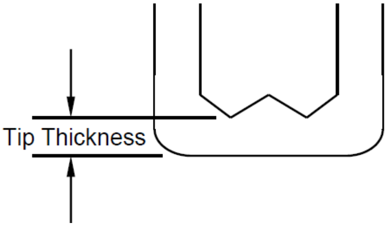
The final check necessary to see if the thermowell design is acceptable for the application is the pressure stress evaluation. This is often overlooked as it generally is not the cause of design unsuitability, but it is critical nonetheless. The pressure stress check must be performed on both the shank and the tip separately.

To calculate the pressure on the shank as a check for suitability there are two methods offered depending on the process pressure. For process pressures less than 103 MPa (15 ksi), ASME PTC 19.3 TW recommends using ASME Boiler Pressure Vessel Code (BPVC) Section VIII Paragraph UG-28, to calculate the allowable external pressure. The temperature restrictions listed in this section of the BPVC do not apply as most thermowells are designed under ASME B31.1 or ASME B31.3. Maximum allowable stress values should be sourced from either of those two standards instead. The reason the calculation from the BPVC is referenced in ASME PTC 19.3 TW is that the equation has a history of successful use and is relatively known in the industry.

In the event that the desired thermowell material is not in the BPVC or if a simpler method is desired, ASME PTC 19.3 TW provides an alternative simplified relationship. The drawback to using the simplified method is that the shank pressure determined by this method may be as much as 17% lower than the value calculated by UG-28 method for some materials at some temperatures. The benefit is a less complex calculation and an additional safety margin.

For high pressure (> 103 MPa (15 ksi)) applications, ASME PTC 19.3 TW points to ASME BPVC Section VIII Division 3 or ASME B31.3, Chapter IX for the calculation. Pressures this high (exceeding the pressure limits for 2500# flanges in ASME B16.5) will need to be carefully evaluated and not performed through an automated tool.

The tip thickness is the thinnest dimension from the outside tip to the furthest point of the drill. Since most thermowells are manufactured using gun drills, it is critical that the tip thickness used is the actual measure of the thinnest point. The peak dimension is used to calculate the sensor length since the peak will contact the sensor, not the “valley.” When the gun drill is sharp, the valley can be as much as 0.060” [1.5mm] deeper (thinner) and becomes thicker as the drill wears.



Thermowell tip thickness detail.

The maximum pressure that the thermowell can withstand is the lesser of the shank or tip pressure limit.

IMPORTANT NOTE:
Whether referring to ASME PTC 19.3 or ASME PTC 19.3 TW, the pressure stress evaluation only refers to the stress that the thermowell stem (or shank) and tip can withstand, not what the thread or the flange can withstand. Process connection selection and pressure rating evaluation should be performed before the thermowell design is evaluated for vortex induced vibrations.

Materials Information

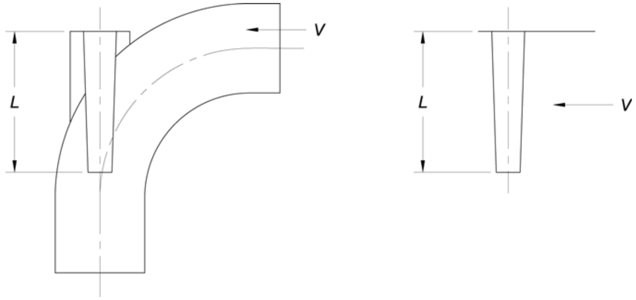
The best engineering practice for materials information is to use reliable and standardized information whenever possible. Emerson only uses materials information from open source standards such as ASME Boiler and Pressure Vessel Code and ASME B31.1/B31.3. This information is generally conservative and industry accepted. In theory, Emerson could use vendor information to populate our materials database. This practice is discouraged, however, because Emerson cannot ensure that a specific batch of material is used on a particular thermowell to match a particular report. This is not a practical or reliable method of optimizing thermowell performance.

INSTALLATION VARIATIONS

The manner in which thermowells are installed in a process can have a significant effect on the thermowell stress calculations and the vortex shedding. The variations discussed here are beyond the “standard” installations such as flanged, threaded, and welded thermowells, or partial shielding of the thermowell.

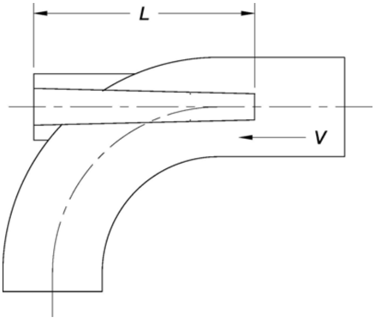
Elbow Installations

ASME PTC 19.3 TW gives no meaningful guidance on the installation of thermowells in an elbow. Modeling the flow in an elbow is extremely difficult due to the turbulence and complexity. ASME PTC 19.3 TW suggests that to be conservative, consider the entire unsupported, unshielded length to be exposed to the flow with the forces acting perpendicular (i.e. “normal”) to the thermowell axis. To many, this is not an acceptable answer. Some comments in ASME PTC 19.3 TW and committee discussions yielded an alternative to this overly conservative view. If the tip is sufficiently upstream or downstream from the elbow such that the fluid flow is parallel to the thermowell axis at the tip, then the Strouhal Number is very small because the flow across the tip is negligible. ASME PTC 19.3 TW states that this is beyond the scope of the standard, while others in the industry maintain that this type of installation would be a simple solution for thermowell designs that are too close to the natural frequency.



Thermowell installed with tip facing downstream in an elbow.[1]

ASME PTC 19.3 TW suggests that the thermowell pointed in the upstream direction is the better installation because the amount and location of the flow stream applies a smaller moment arm and force to the thermowell and the flow over the tip is more laminar. If the tip is pointed downstream, the swirling of the fluid after passing around the thermowell could have some cross tip components, but this is extremely difficult to model. As with angled installations below, the moment arm calculation is complicated, therefore the changes in force, moment arm, and stress, are not easily predicted.



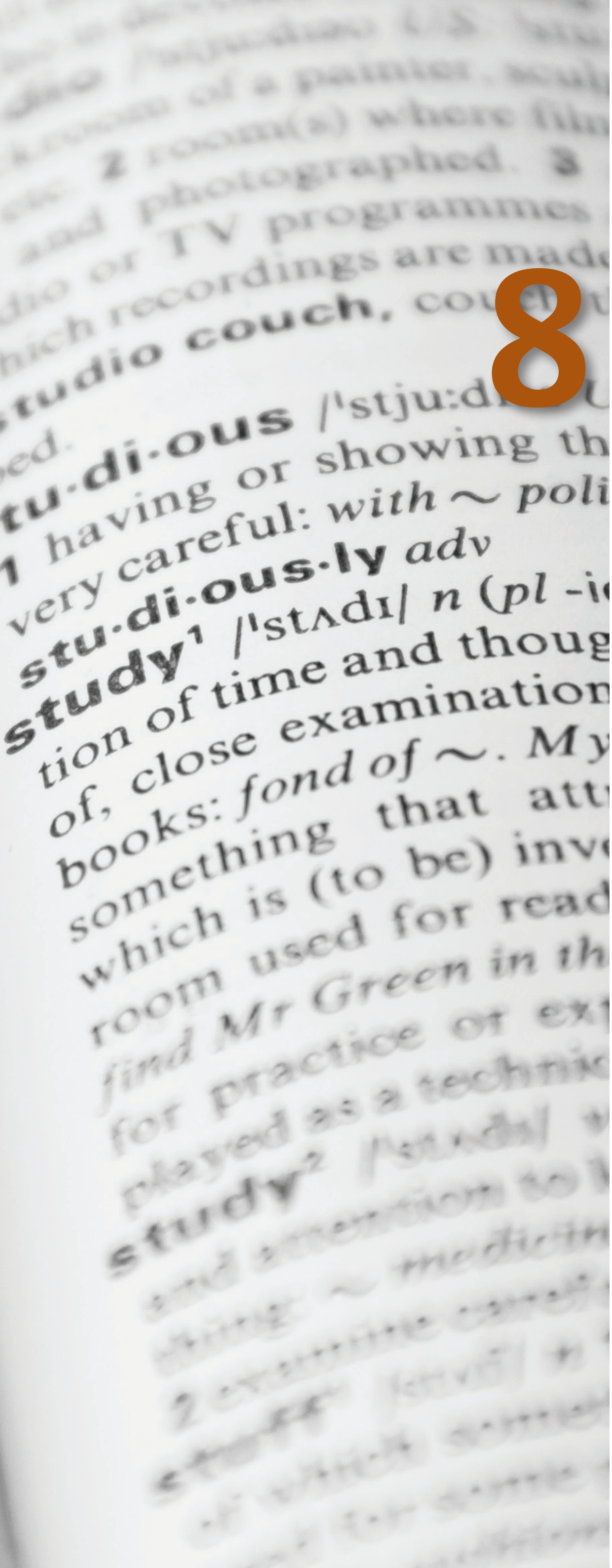
Thermowell installed with tip facing upstream in an elbow.[2]

Emerson is considering a more extensive investigation into these installation methods to provide some justification for the benefits of these solutions.

Angled Installations

Customers frequently install thermowells at an angle to the flow for accessibility, to reduce the forces acting on the thermowell, or to increase the exposure to the flow in smaller line sizes in order to obtain a more accurate temperature reading. The effect of the “yaw” angle on the tip velocity is not a matter of simple trigonometry. It also complicates the prediction of the stresses and forces acting on the thermowell.

(1) *ASME Standard, Performance Test Codes 19.3TW.*
(2) *ASME Standard, Performance Test Codes 19.3TW.*



8

Glossary

A

Absolute Zero
Lowest possible point on the scale of absolute temperature. The point at which molecular activity ceases and thermal energy is at a minimum. Defined as -272.3 °C; -489.7 °F; or 0 °K

Acceptance Testing
The acceptance testing procedure is similar to the commissioning procedure, but is intended for an official turn-over of a system that is operating according to design specification from the vendor to the owner. For some systems, especially for SIS, this is first conducted at the vendor facility, known as Factory Acceptance Testing or FAT, and then again after installation and commissioning. The terms Site Acceptance Testing (SAT) and Pre-start-up Acceptance Testing (PSAT) are often applied. (See Section 4.4.2.6)

Accuracy
Accuracy of a measurement system is the degree of closeness of measurements of a quantity to that quantity's actual (true) value.

Accuracy Ratio
A good rule of thumb is to ensure an accuracy ratio of 4:1 when performing calibrations. This means the instrument or standard used should be four times more accurate than the instrument being checked. Therefore, the test equipment (such as a field standard) used to calibrate the process instrument should be four times more accurate than the process instrument, the laboratory standard used to calibrate the field standard should be four times more accurate than the field standard, and so on. (See Section 5.7.3)

Alarm
Alarms cover diagnostics that are determined to affect the transmitter's ability to output a correct value of the measurement. In a transmitter, the output signal will drive to a predetermined value.

Alert
Alerts cover diagnostics that are determined not to affect the transmitter's ability to output the correct measurement signal and therefore will not interrupt the 4-20 mA output.

Alpha value
RTD elements are characterized by their Temperature Coefficient of Resistance (TCR) also referred to as its alpha value. The alpha value is the temperature coefficient for that specific material and composition. (See Section 3.2.3.6.1)

Alumel
An alloy consisting of approximately 95% nickel, 2% manganese, 2% aluminum and 1% silicon. This magnetic alloy is used for making Type K thermocouples and thermocouple extension wire. Alumel is a registered trademark of Hoskins Manufacturing Company.

Ambient temperature compensation
Both input and output accuracy will vary with fluctuations in the ambient temperature of the transmitter. Transmitters are characterized during manufacturing over their specified operating range to compensate for these fluctuations to maintain measurement accuracy and stability. (See Section 3.1.4.1.5)

Analog output
Industry standard 4-20 mA analog signals are used globally to communicate from field mounted devices over long distances to control systems, data loggers and recorders.

Analog-to-digital (A/D)
Conversion of an analog signal to a digital signal.

Analog-to-digital converter (ADC)
In a temperature transmitter, the input subsystem converts the sensor measurement signal into a digital signal for further processing within the transmitter.

ASTM E1137
American Society for Testing and Materials standard applies to platinum RTDs with an average temperature coefficient of resistance of 0.385 %/ °C between 0 and 100 °C and nominal resistance at 0 °C of 100 Ω or other specified value. This specification covers platinum RTDs suitable for all or part of the temperature range between -200 to 650 °C. (See Section 3.2.3.11)

B

Barstock thermowells
Are machined from a solid piece of round or hex shaped metal and can withstand higher pressures and faster flow rates than protection tubes. They have more material options and can be mounted in various ways to meet different process pressure requirements.

BPCS
Basic Process Control System aka a DCS or PLC

Bayonet spring loaded
A bayonet spring-loaded style of sensor that is similar to spring loaded style, but allows removal of the capsule without disassembly of the threaded adapter from the thermowell.

C

Callendar-Van Dusen Equation (CVD)
This equation describes the relationship between resistance and temperature of platinum resistance thermometers (RTDs). For the sensor – transmitter matching process, the user enters the four sensor specific Callendar-Van Dusen constants into the transmitter. The transmitter uses these sensor-specific constants in solving the CVD equation to match the transmitter to that specific sensor, thus providing outstanding accuracy. (See Section 3.2.3.12)

Calibration
A comparison of measuring instrument against a standard instrument of higher accuracy to detect, correlate, adjust, rectify and document the accuracy of the instrument being compared. (See Section 5.7)

Calibrator
Any of a variety of devices that can generate a known signal to be applied to an instrument to be calibrated and can read the response of that instrument for verification and/or adjustment. There are bench models and battery powered field models. Some have a wide variety of signal generation capability and some models have fieldbus interface capability.

Capsule style
A sensor sheath with lead wires. Capsules are commonly used with compression fittings and can be cost-effective mounting method when environmental conditions are not a concern.

CCST
Certified Control System Technician accreditation from ISA or other training program.

Certifications
Instruments typically offer a variety of certifications that include manufacturing locations, EU directives, hazardous locations, and safety.

Chromel
An alloy made of approximately 90 % nickel and 10 % chromium that is used to make the positive conductors of ANSI Type E (chromel-constantan) and K (chromel-alumel) thermocouples. It can be used up to 1100 °C in oxidizing atmospheres. Chromel is a registered trademark of the Hoskins Manufacturing Company.

Coiled sensors (also called Coil Suspension)
A style of RTD sensor that is designed for rugged applications that also require high accuracy and fast response. The element is constructed with a high purity platinum wire that is wound in a helical coil to minimize stress and assure accurate readings over long periods of time. Each coil is fully suspended in a high purity ceramic insulator and surrounded by a ceramic powder with a binder additive. (See Section 3.2.3.9)

Cold junction
Known as the reference junction, is the termination point outside of the process where the temperature is known and where the voltage is being measured. (Typically in a transmitter or signal conditioner.)

Cold junction compensation (CJC)
The voltage measured at the cold junction correlates to the temperature difference between the hot and cold junctions; therefore, the temperature at the cold junction must be known for the hot junction temperature to be calculated. This process is known as “cold junction compensation” (CJC). CJC is performed by the temperature transmitter, T/C input cards for a DCS or PLC, alarm trips, or other signal conditioner. Ideally, the CJC measurement is performed as close to the measurement point as possible because long T/C wires are susceptible to electrical noise and signal degradation. Also described as the adjustment made by a temperature transmitter to improve accuracy by factoring in the actual cold junction temperature of a thermocouple. The CJC depends on a reference temperature device built into the transmitter. (See Section 3.2.4.2)

Commissioning
Includes verifying every connection of every loop is properly secured, tagged and connected at both the field and control room ends. It further includes an operational check of each loop to verify that all settings are properly set and that the functionality of the design has been implemented. Extensive use of loop sheets and instrument specification sheets helps to guide this procedure.

Compensating Leads
In some cases where economic considerations may preclude the high cost of exotic metal extension wires as are used in Types R, S, and B thermocouples, a less expensive alloy that has similar emf may be used. Performance will be compromised to a degree.

Convection
The transfer of heat from one place to another by the movement of fluids. Convection is usually the dominant form of heat transfer in liquids and gases. This effect is evidenced in heat transfer from a process to a sensor for temperature measurement.

Copper RTD
Commonly used in winding temperature measurements of motors, generators and turbines. 10 Ω copper RTDs have been most common over the years, but are now giving way to 100 Ω and even 1000 Ω models to get better resolution of the measurement. Note that Platinum RTDs are also growing in popularity for these applications.

Conduction error
The transfer of heat energy where heat spontaneously flows from a body at a higher temperature to a body at a lower temperature. In the case of a temperature sensor, this conductive heat loss tends to change the actual temperature being measured thus causing a measurement error.

Conduit Seal
Any of a variety of methods to seal the wiring openings on an instrument or field junction box housing to prevent egress of water, moisture, or other contaminants.

Configuration
The process of configuration includes the selection and adjustment of a wide assortment of transmitter operating parameters, including the most simplistic to the more advanced features.

Cost of ownership
A purchase validation technique that considers not only purchase price but also the costs associated with installation, operation, maintenance and return on investment (ROI).

Cryogenic
Means “producing, or related to, low temperatures,” and all cryogenic liquids are extremely cold. Cryogenic liquids have boiling points below -150 °C (- 238 °F)

D

Damping
A transmitter function that reduces temperature fluctuations by slowing and smoothing the output, resulting in a more stable temperature readings. (See section 3.1.6.1)

DCS
Distributed Control System a.k.a. Basic Process Control System (BPCS).

DIN
Acronym for Deutsche Industrie Normenausschuss, which is a German agency that sets engineering and dimensional standards that are globally recognized.

DIN Style Sensor
A sensor capsule with a circular plate that provides a connection to the connection head or housing. The benefit of the DIN style is the ability to install and replace the sensors without removing the connection head or housing, as it is inserted through the housing instead of threaded into the bottom. All DIN styles are spring-loaded.

Direct Mounting
Attachment of a transmitter directly to a sensor or well assembly. Also called integral mounting. (See Section 3.1.10)

Drift
In temperature measurement, it is the movement of the measured value away from the actual value. There is a very small drift in a transmitter and there is a small and predictable drift with an RTD when operated at temperatures below 300ºC and there is a more significant and unpredictable or erratic drift with a thermocouple that is related to junction degradation. Higher temperature operation greatly exacerbates sensor drift error. (See Section 3.2.3.13)

Dry Block
Also called a temperature calibration block – consists of a heatable and/or coolable metallic block, controller, an internal control sensor and optional readout for an external reference sensor. It is used to compare a temperature sensor against a known temperature as part of the calibration process. (See Sections 5.7.5 and 5.7.5.1)

Dual-Compartment
A two part housing, often known as field mount, that isolates the transmitter electronics module from the terminal strip compartment to protect it from exposure to harsh plant environments. The terminal compartment contains the terminal and test connections for the sensor and signal wires and provides access to the terminal block for wiring and maintenance while isolating the transmitter electronics, which are in the second compartment. (See Section 3.1.10.2)

Dual element
Type of RTD or T/C sensor with two independent sensing elements within the sensor sheath. With RTDs, they are always isolated from each other. Isolated configurations exist when two independent T/C junctions are placed inside one sheath. Unisolated configurations exist when two T/C junctions are placed inside one sheath where all four T/C wires are mechanically joined.(See Section 3.2.3.1.1 and 3.2.4.3.2)

E

EMC
Electromagnetic compatibility. Compliance with national or international standards is often required by laws passed by individual nations. (See Section 3.1.7)

EMF
Electromotive Force. An electrical potential energy measured in volts. It is the term given to the millivolt signal produced by a thermocouple sensing element.

EMI
Electromagnetic Interference, caused by large motors, motor starters, welders, contactors and other electrical equipment that dramatically effects electronic devices. Quality devices will incorporate filtering algorithms to eliminate the influence of this interference.

Endothermic
A process that absorbs heat.

Errors
The deviation of a value from its true value. There will always be some error in a temperature measurement system. Proper choice of components, installation and operation will tend to minimize the error value.

ESD
Electrostatic Discharge, characterized by a sudden flow of electricity most often associated with lightning and other arcing sources.

Exposed junction
Associated with T/Cs that have the hot junction extending past the sealed end of the sheath to provide faster response. The seal prevents intrusion of moisture or contaminants. These are typically applied only with non-corrosive gases as might be found in an air duct.

Exothermic
A process that gives off or produces heat.

Extensions
Sensor assemblies can include extensions of various lengths to accommodate for different insulation thicknesses and high process temperatures that may affect the transmitter electronics. Extensions can be a combination of unions, nipples, and/or couplings.

External diagnostics
Monitor measurement validity due to external sources, such as the sensor wiring connections, noise on the sensor, and sensor failure. (See Section 3.1.8)

F

Four-wire RTD
It uses a measurement technique where a very small constant current is applied to the sensor through two leads and the voltage developed across the sensor is measured over the other two wires with a high-impedance and high resolution measuring circuit. (See Section 3.2.3.1.3.1)

FOUNDATION Fieldbus
An all-digital, serial, two-way communication system that can serve as the base-level network in a plant or factory automation environment. It is an open architecture, developed and administered by the Fieldbus Foundation. (See Section 3.1.3.3)

Frictional Heating
Heating effects upon a sensor that is immersed in a high viscosity fluid moving at high flow rates. The heating effects are proportional to the square of the fluid velocity.

G

Ground/Grounding
A reference point in an electrical circuit that is physically connected to an earth ground point. For instrumentation applications, this connection must have a very low resistance path to earth to ensure proper operation of electronic devices and should never be connected to the same location as power ground. Multiple ground points in any circuit can cause disruptive ground loops. (See 4.4.2.4.1)

Grounded T/C junctions
Created when the thermocouple junction is connected to the sensor sheath, which is in turn connected to the process vessels or piping, which is assumed at a ground potential.

H

HART
The HART (Highway Addressable Remote Transducer) protocol is a digital protocol that provides for the superimposing of a digital signal onto the 4-20 mA signal wires. This superimposed digital signal allows two-way communications for configuration and for extracting operational and alarm data from the transmitter. (See 3.1.3.2)

Head Mount Transmitter
Head mount transmitters are compact, disc-shaped transmitters most often mounted within a connection head. The most common types are referred to as DIN A and DIN B, which are differentiated by mounting style and dimensions. (See 3.1.10.1)

Heat Transfer
The process of thermal energy flowing from a body of high energy to a body of low energy. Energy transfer is by conduction, convection and radiation. The process is the very basics of temperature measurement.

Hermetic Seal
A protective method to prevent the intrusion of air, gas or liquid into a device. Most temperature sensors have a hermetic seal where the leads protrude from the sheath to preserve the integrity of the sensing element.

Hot Junction
The hot junction measuring element of a thermocouple is placed inside a sensor sheath and exposed to the process. (See Section 3.2.4.1)

Hysteresis
Is a phenomenon that results in a difference in an item's behavior when approached from a different direction. In laboratory grade RTDs, there is negligible hysteresis, while an industrial grade sensor, with its inherent rugged design, does have a small hysteresis error. (See Section 3.2.3.9)

I

Ice Point
The temperature, equal to 0 °C (32 °F), at which pure water and ice are in equilibrium in a mixture at 1 atmosphere of pressure.

IEC 60751
The most commonly used standard for Platinum RTDs defines two performance classes for 100Ω, 0.00385 alpha Pt RTDs: Class A and Class B. These performance classes (also known as DIN A and DIN B due to DIN 43760) define tolerances on ice point and temperature accuracy. These tolerances are also often applied to Pt RTDs (See Section 3.2.3.10)

IEC 61511
A performance based safety standard endorsed by OSHA and ISA. It includes a safety lifecycle that provides user guidance for systems from conception to de-commissioning. (See section Section 3.1.12)

Immersion
The condition where temperature sensors are inserted into the process medium; furthermore, they are typically installed into a thermowell for protection against process conditions. As contrasted to surface mounted sensors.

Input Accuracy
Also called digital accuracy, is unique for each type of sensor input. For example, the input accuracy of an RTD is about ±0.1 °C (0.18 °F) for a high quality transmitter. The input accuracy of a T/C varies by T/C

type from about ±0.2 °C (0.36 °F) up to ±0.8 °C (1.44 °F). There are many factors that affect the accuracy of a transmitter, including ambient temperature compensation, CJC and sensor selection. (See Section 3.1.4.1.3)

Instrument Error
The difference between the actual value of a measurement and the value being presented by the instrument. The error has components related to the design of the instrument as well as external factors, such as ambient temperature variation, lead wire issues, and electrical and electronic noise.

Insulation Resistance
The resistance measured between the sensing element and the protective sheath. As a sensor ages and the insulation begins to deteriorate or absorb moisture from leaks in the sensor hermetic seal, the performance of the sensor deteriorates.

Integral Mount
Where the transmitter is mounted directly to a thermowell. As contrasted to remote mounting. (See Section 3.1.10.1)

International Standards
Several international standards define the relationship between resistance and temperature for RTD sensors. The two that are most common are ASTM 1137 (American) and IEC 60751 (European). For T/Cs, ASTM E230 -11 and IEC 60584-2 are predominant. (See Sections 3.2.3.14 and 3.2.4.5)

Input
The low-level signal from a temperature sensing element to a transmitter or an input card. It can be resistance from an RTD or a millivoltage from a T/C.

Input Card
A generic name given to any of a variety of input modules typically associated with the I/O subsystem of a distributed control system (DCS). Different versions accept low level sensor signals, 4-20 mA current signals, and frequency signals. It may be located in a junction box in the field or near the control room.

Immersion Length
The length from the tip end to the mounting shoulder of an RTD, either for immersion directly into a process fluid or insertion into a thermowell.

Insertion length
The portion of a thermowell exposed in a process fluid measured from the face of the flange surface or the base of the weld to the tip of the well. (See Section 4.3.2.2.5)

Installation Detail Drawing
Tells contractors and pipefitters the location of each measurement point and how the components are to be installed. This construction document evolves from many decisions regarding thermowells, sensor elements, connection heads, transmitters, etc. (See Section 4.4.3.1.4)

Instrument Lists
Document every instrument comprising the input/output loops, and there can be hundreds of such loops in one automated process. Columns show the type of sensor, its model number and manufacturer, the service, the transmitter type model number and manufacturer, the tag name/number for each device, and the location on the P&ID. (See Section 4.4.3.1.6)

Insulation Error
Temperature measurement error caused by an electrical shunt or degraded insulation between a sensor element and its sheath.

Insulation Resistance
The resistance of the insulating material used to fill in the sheath around the sensor element. It is typically Aluminum oxide or magnesium oxide.

Intelligent devices
Another term for Smart devices that are microprocessor-based and capable of extraordinary capabilities to process a measurement signal, apply intelligent filtering, apply a wide array of diagnostic functions and condition it for transmission via either an analog or digital signal.

Interchangeability
All sensors have inherent inaccuracies or offsets from an ideal theoretical performance curve referred to as sensor interchangeability. IEC standard 751 sets two tolerance classes for the interchangeability of platinum RTDs: Class A and Class B. (See Section 3.2.3.11)

Interchangeability Error of a Sensor
Defined as the difference between the actual RTD curve and the ideal RTD curve. The IEC 60751 standard uses only the ice point resistance R0 and the sensor Alpha Number to define an approximation of an ideal curve.

Internal Lead Wires
Very fine wires are used inside the sheath to connect to the sensing element and then are welded to heavier lead wires at the end of the sheath that are used to connect to a terminal block, transmitter or other termination point.

Isolation
Most transmitter designs incorporate a means of galvanic isolation using either optic or transformer isolation stages to eliminate ground loop problems and to block both normal mode and common mode voltages that may inadvertently come in contact with the measurement circuit. (See Section 3.1.2.2)

Isothermal
Of or relating to constant temperature and is usually applied to the terminal area of a thermocouple transmitter where the cold junction temperature is measured.

J

JJG 229
A Chinese standard is also known as “Regulations of Industry Platinum and Copper Resistance Thermometers.”

Junction Types
T/C Junctions are manufactured in different configurations each with benefits for specific applications. Junctions can be grounded or ungrounded, and dual element thermocouples can be isolated or non-isolated.

> ***Grounded T/C junctions*** are formed when the thermocouple junction is connected to the sensor sheath. (See Section 3.2.4.3.1)
>
> ***Ungrounded junctions*** exist when the T/C elements are not connected to the sensor sheath, but are surrounded with insulating MgO powder.
>
> ***Exposed junction T/Cs*** have the hot junction extending past the sealed end of the sheath to provide faster response.

L

LCD Display
An option on a temperature transmitter that displays the measured temperature, range, engineering units, device status, error messages and diagnostic messages. (See Section 3.1.11.2.1)

Lead Wires
The wires protruding from the end of a sensor sheath that are connected to a transmitter or other terminal strip.

Lead Wire Color Coding
The IEC 60751 defines the standard colors for RTD lead wire combinations. ASTM E230 and IEC 60584 are the most commonly used standards for thermocouple lead wire colors. See Figure 3-61 for more detail.

Lead Wire Compensation
RTD - Since the lead wires are part of the RTD circuit, the lead wire resistance needs to be compensated for to achieve the best accuracy. This becomes especially critical in applications where long sensor and/or lead wires are used. (See Section 3.2.3.1.3.1)

Lead Wire Error
The error created by lead wires is vastly different for 2, 3 and 4 wire RTD circuits. Very large errors are associated with 2-wire circuits with long lead wires. The error is much less with 3-wire circuits and is almost nil with 4-wire circuits. (See 3.2.3.1.3.1)

Line Voltage Filter
Noise from nearby 50 or 60Hz AC voltage sources, such as pumps, variable frequency drives, or power lines, is easily detected by low-amplitude sensor signals. If not recognized and removed, this noise can compromise the transmitter’s output signal. A transmitter’s Line Voltage Filter can be customized at 50 or 60 Hz to protect temperature measurements from AC voltage interference and to filter out this noise. (See Section 3.1.6.5)

Linearization
All T/Cs and RTDs have a nonlinear output vs. temperature relationship. If this relationship was ignored, significant errors would result, especially for wider ranges. The transmitter applies a linearization technique that greatly reduces the errors caused by the nonlinearities of sensors, thus providing a much more accurate measurement. (See Section 3.1.2.4.2)

Local Operator Interface (LOI)
The LOI interface provides the ability for local configuration of the device to make changes in real time without having to attach a laptop or field communicator. The buttons on the LOI are used to perform the configuration tasks by following a menu of configuration information. (See Section 3.1.11.2.2)

Logic Solver
The term given to the safety certified controller that implements the required logic in a safety instrumented system (SIS). It may be as simple as a single channel safety-certified alarm trip module or as complex as a quad-redundant PLC system.

Loop Sheets
Are developed in some cases, with detailed wiring schematics for the sensors, junction boxes, transmitters, power supplies, and marshalling points reflecting the system architecture. Every loop is numbered, and every sensor and device in the field is tagged. (See Section 4.4.2.5 and Figure 4-41)

Loop Test
A term applied to the process of verifying that an instrument loop is properly installed and functional in accordance with operational and functional specifications by applying a simulated signal at the transmitter and verifying the proper response at the receiving device. (See Section 5.7.4)

M

Management of Change (MOC)
Is the process where any changes are proposed to the Safety Instrumented System that are not like-in-kind changes. An example is using a different model or supplier from that in the original design. The Management of Change procedures for the facility should be followed to completely evaluate and consider the impact of those changes to identify any potential hazards that could result from those changes prior to implementation.

Mandrel
Wire-wound RTDs are manufactured by winding the resistive wire around a ceramic mandrel with a closely matching coefficient of expansion to the wire to minimize element strain effects. (See Section 3.2.3)

Matching
A precise compensation for RTD inaccuracies is provided by Transmitter-Sensor Matching using the transmitter's factory programmed Callendar–Van Dusen equation. This equation describes the relationship between resistance and temperature of platinum resistance thermometers (RTDs). The matching process allows the user to enter the four sensor specific Callendar-Van-Dusen constants into the transmitter. The transmitter uses these sensor-specific constants in solving the CVD equation to match the transmitter to that specific sensor, thus providing outstanding accuracy. (See Section 3.2.3.12)

Measurement Instruments Directive (MID)
Is a directive by the European Union that intends to create a common market for measuring instruments across the 28 countries of the EU. Its most prominent tenet is that all kinds of meters that receive a MID approval may be used in all countries across the EU. High-end temperature measurement systems for temperature compensation of custody transfer must be certified for compliance.

N

National Metrology Institute
A standard sensor has accuracy traceability to a National Metrology Institute of the user country, such as NIST in the USA, NPL in the UK, and PTB in Germany among others. These institutes have the highest precision standards against which others are compared for certification. (See Section 5.7.2)

Nickel RTD
Nickel elements have a limited temperature range because the amount of change in resistance per degree of change in temperature becomes very non-linear at temperatures over 300 °C. Use of nickel RTDs has declined over the years due to its performance limitations and since the cost of Platinum RTDs is now a very small premium, if any at all.

Noise
Virtually every plant environment contains electrical interference sources like pumps, motors, Variable Frequency Drives (VFD's) and radios, as well as sources of electrostatic discharge and other electrical transients. These are Electromagnetic Interference (EMI), Electrostatic Discharge (ESD), and Radio Frequency Interference (RFI).

Nuclear Radiation
Radiation effects that can induce measurement error in temperature measurements. Effects include gamma, fast neutron, and thermal neutron radiation.

O

Output Accuracy
Is a statement of the accuracy of the D/A converter stage of a transmitter given as a percentage of span.

P

P&ID
Piping and Instrumentation Diagram. Shows the anticipated need for measurement and control instrumentation. The P&ID does not indicate precisely where to install the sensors and transmitters, leaving a great deal of latitude in the selection and placement of the specific components by the engineering staff and piping designer. (See Figure 4-40.)

Peltier–Seebeck effect
The Peltier effect, first exhibited by Jean Peltier in 1834, is viewed as the compliment to the Seebeck effect and describes the ability to generate a heat variation due to a voltage difference across a two dissimilar metals at the junction.

Pipe Cleaning Pig
A cylindrical device that fits tightly inside a pipeline and is propelled or towed through the line to clean out deposits and residue.

Platinum wire
Used for the manufacture of platinum RTDs, it typically has a purity of about 99.99% so that its temperature response characteristics are very predictable against published resistance vs. temperature curves. (See Alpha curve)

Plot Plan
An engineering plan drawing or diagram which shows the buildings, utility runs, and equipment layout, the position of roads, and other constructions of an existing or proposed project site at a defined scale. Plot plans are also known more commonly as site plans. (See Section 4.4.3.1.1)

Potentiometer
A variable resistance device where a pickup or "wiper" slides along the resistance in accordance with some external physical movement, thus developing a variable resistance output to the transmitter.

Primary Standard
A standard sensor has accuracy traceability to a National Metrology Institute of the user country, such as NIST in the USA, NPL in the UK, and PTB in Germany among others. To communicate the quality of a calibration standard, the calibration value is often accompanied by a traceable uncertainty statement to a stated confidence level. (See Section 5.7.2)

Process Connection
Usually refers to the design of the thermowell or sensor that mounts into the process. For bare sensors, it is usually threaded, and for sensors in a thermowell, they are typically threaded, welded or flanged.

Process Flow Diagram
Shows the major pieces of equipment in a process area and the design operating conditions.

PROFIBUS
Is an international communications standard for linking process control and plant automation modules. Instead of running individual cables from a main controller to each sensor and actuator, a single multi-drop cable is used to connect all devices, with high speed, bi-directional, serial messaging used for transfers of information. (See Section 3.1.3.4)

Protection Tubes
Sometimes called Tubular Thermowells - are fashioned by welding a flange or threaded fitting to one end of tube or small section of pipe or tubing and capping the other end. Protection tubes can also be constructed of ceramic material and bonded to a process fitting. Tubular thermowells can be constructed for very long immersion lengths and are often used for measurements where flow forces are low. (See Section 3.3.3.2.1)

Proven-in-Use
In a SIL rated safety loop, there are occasions when it is thought desirable to use an instrument or a component well known to the user that has not been assessed under the IEC61508 group of standards, e.g. by an FMEDA*. The Functional Safety standards allow the use of such equipment only on the basis that it has been "proven-in-use" (61508) or has a history of "prior use" (61511).

It is the end user who must ensure that the Safety Instrumented System (SIS) meets the requirements of the standard. He or she can do that by assessing the SIS himself or herself or by devolving the assessment to a supplier or system integrator. However, the user retains overall responsibility.

The requirements of 61508 and 61511 for "proven-in-use" are very demanding. The user is required to have appropriate evidence that the components and subsystems are suitable for use in the SIS. This means that, at a minimum, the user must have:

- A formal system for gathering reliability data that differentiates between safe and dangerous failures
- Means of assessing the recorded data to determine the safety integrity of the device/equipment, and its suitability for the intended use.
- Evidence that the application is clearly comparable
- Recorded historical evidence of device hours in use
- Evidence of the manufacturer's management, quality and configuration manufacturing systems
- Device firmware revision records
- Proof that reliability data records are updated and reviewed regularly

R

Rail Mount Transmitters
Thin rectangular transmitters that are typically attached to a DIN-rail (G-rail or top-hat rail) or fastened directly onto a surface. (See Section 3.1.10.3)

Response Time
The Response Time of a sensor is the time required for the output of a sensor to change by a specified percentage of an applied step change in temperature for a specific set of conditions. (See Section 3.2.3.8)

RFI – Radio Frequency Interference
This interference is at the higher end of the electromagnetic interference (EMI) scale and emanates from most types of radios, TV broadcast antennas, radar antennas, routers and some cell phones. Many field transmitters use sophisticated filtering to prevent this noise from impacting the measurement.

Root Sum Squares Technique
The square root of the sum of the squares (RSS) can be used to calculate the aggregate accuracy of a measurement when the accuracies of the all the measuring elements are known. The average accuracy is not merely the arithmetic average of the accuracies (or uncertainties), nor is it the sum of them.

RTD - Resistance Temperature Detector
Sometimes referred to as Platinum Resistance Thermometers (PRT). They are based on the principle that the electrical resistance of a metal increases as temperature increases – a phenomenon known as thermal resistivity. (See Section 3.2.3)

RTD accuracy
There are several classes of RTD accuracy/interchangeability that define the relationship of the amount of error allowed for a given RTD type at a given temperature as compared to the standard. Refer to Figure 3-63. The maximum allowable sensor interchangeability error at a given process temperature is defined by the two IEC 60751 standard classifications; Class A and Class B. (See Section 3.2.3.11)

Redundancy
Refers to using multiple sensors and/or multiple transmitters to add reliability to a measurement. (See 3.1.2.3)

Reference element
Curve utilized within a transmitter to stabilize sensor inputs.

Remote Mount
Transmitter is mounted reasonably near but not directly onto a sensor. This is the preferred method where the measurement point is inaccessible or process environment at the measuring point is adverse. (See Section 3.1.10.2)

Resolution
The smallest change in the underlying physical quantity that produces a response in the measurement.

Reliability
A measure is said to have a high reliability if it produces consistent results under consistent conditions. (See Section 4.3.6.1)

Repeatability
The repeatability of a measurement system, also called precision, is the degree to which repeated measurements under unchanged conditions show the same results. As an example, an instrument could present the same value for temperature every time (under the same measurement conditions), but the value is offset from the correct value. This is repeatable, but not accurate. The ideal measurement therefore would be both accurate and repeatable. (See Section 3.1.4.1.2)

Response Time
The amount of time required for a temperature change in the measured media to be reflected by the sensor output or a transmitter's output.

Response time is the sensor's ability to react to a change in temperature, and depends on the sensor's thermal mass and heat transfer from the material being tested. For instance, an RTD probe in a thermowell will react much more slowly than the same sensor immersed directly into a fluid. A spring-loaded sensor with thermally conductive fluid responds twice as fast as one with a free hanging sensor with no fill in the same assembly. (See Section 3.2.3.8)

A sensor's dynamic response time can be important when the temperature of a process is changing rapidly and fast inputs to the control system are needed. A sensor installed directly into the process will have a faster response time than a sensor with a thermowell.

S

Safety-Certified Transmitters
A transmitter to be used for a safety function in an SIS must meet certain design and performance criteria and be certified for use in accordance with IEC 61508 or IEC 61511.

Safety Requirements Specification (SRS)
Per IEC 61511, it is a specification that contains all the requirements of the safety functions that must be performed by the safety instrumented system. Its objective, per IEC 61511, is to specify all of the requirements of safety instrumented systems needed for detailed engineering and process safety information purposes.

Sample time
Frequency with which a transmitter processes inputs from a temperature sensor and updates the output signal.

Seebeck effect
According to the Seebeck effect, a voltage measured at the cold junction is proportional to the difference in temperature between the hot junction and the cold junction. This voltage may be referred to as the Seebeck voltage, thermoelectric voltage, or thermoelectric emf.

Self-diagnostics
Also called Internal Diagnostics – diagnostics in a microprocessor-based transmitter that monitor transmitter memory and continuously examine its own performance and verify output validity.

Self-Heating
Heating is caused when the sensing current from the transmitter is passed through an RTD sensing element. Since the current supplied by the transmitter is very small (typically 150-250 μamps), heat produced is also very small and will be dissipated in the flowing process medium and contribute a negligible measurement error. Note that older analog circuitry transmitters use a much higher excitation current and produce far more heat causing a significant error.

Secondary Standard
A general term used to refer to a calibration standard that is traceable to a higher level. All calibrations should be performed traceable to a nationally or internationally recognized standard, such as NIST in the USA. There may be many levels of traceability between your shop and NIST, but the trail should exist and the tolerance of the standards fully understood.

Sensing Element
The sensing element responds to temperature by generating a measureable resistance change (RTD) or voltage signal (T/C) that changes as the temperature changes.

Sensitivity
The ratio of the size of the response of a measuring device to the magnitude of the measured quantity change.

Sensor
See Sensing Element.

Sensor Interchangeability Error
See Interchangeability Error.

Sensor Response Time
The Response Time of a sensor is the time required for the output of a sensor to change by a specified percentage of an applied step change in temperature for a specific set of conditions. (See Section 3.2.3.8)

Sensor Sheath
A tube made of metal, usually stainless steel, into which a sensing element is placed, lead wires are connected, insulation is added, the tip is welded shut and a hermetic potting seal is placed at the end where the wires emerge. (See Section 3.2.3.1.2)

SIF - Safety Instrumented Function
Is defined as a function to be implemented by a SIS which is intended to achieve or maintain a safe state for the process with respect to a specific hazardous event. A SIF is a single set of actions and the corresponding equipment needed to identify a single hazard and act to bring the system to a safe state.

SIL - Safety Integrity Levels
As defined in part 4 of the IEC 61508 standard, is “the likelihood of a safety-related system satisfactorily performing the safety functions under all the stated conditions, within a period of time.” A safety integrity level is further defined as “a discrete level (one of four) for specifying the safety integrity requirements of safety functions.”

SIS- Safety Instrumented System
Is defined by the IEC 61511 Safety Standard as an instrumented system used to implement one or more safety instrumented functions. An SIS is composed of any combination of sensors, logic solvers, and final elements.

Specification Sheets
Are the basis for ordering instruments, so they must contain all the dimensions and other information needed by a manufacturer to configure each component to function according to the design and the demands of the process.

Spring-Loaded
A spring located in the threaded adaptor allows the capsule to travel, ensuring contact with the bottom of a thermowell. This spring style provides continuous contact in high vibration applications and significantly faster speed of response of the measurement. (See Section 3.2.3.3.2)

Stability
The ability of the transmitter to overcome drift in order to maintain accuracy over time. It is related to the sensor’s measurement signal, which can be influenced by humidity and prolonged exposure to elevated temperatures. Stability is maintained by using reference elements in the transmitter to stabilize sensor input. (See Section 3.2.3.13)

Stem Conduction
See Conduction error.

Surface Mounting
An efficient and convenient installation method when a thermowell installation is not possible or appropriate. Sensors can be mounted with adhesives, screws, clamps, magnets or welds. Good thermal contact with the process surface is necessary as well as preventing heat loss by using a good thermal insulation over the sensor and its connecting wires. (See Section 3.2.3.5.2)

T

TCR - RTD Elements
Are characterized by their Temperature Coefficient of Resistance (TCR), also referred to as its alpha value. The IEC 60751-2008 standard defines these values for different element types. (See 3.2.3.6.1)

Thermal Conductivity
Heat transfer across materials of high thermal conductivity occurs at a higher rate than across materials of low thermal conductivity. In temperature measurement, it infers that a spring-loaded sensor in contact with the thermowell will have faster heat transfer than if it were in an air gap and therefore faster response. It also infers that sensors in a liquid will have a faster response than those in a gas.

Thermal Resistivity
The principle that the electrical resistance of a metal increases as temperature increases.

Thermocouple (T/C)
A thermocouple (T/C) is a closed-circuit thermoelectric temperature sensing device consisting of two wires of dissimilar metals joined at both ends. A current is created when the temperature at one end or junction differs from the temperature at the other end. This phenomenon is known as the Seebeck effect, which is the basis for thermocouple temperature measurements. (See Section 3.2.4)

Thermocouple Accuracy
Thermocouple accuracy is influenced by several factors, including the T/C type, its range of interest, the purity of the material, electrical noise, corrosion, junction degradation, and the manufacturing process. T/Cs are available with standard grade tolerances or special grade tolerances called Class 2 and Class 1, respectively. The most common controlling international standard is IEC-60584-2. The most common U.S. standards are ISA-MC96.1 and ASTM E230. Each standard publishes limits of tolerance for compliance. (See Section 3.2.4.8)

Thermocouple Types
There are many thermocouple types, each made from different combination of metals or metal alloys. They include types E, J, K, T, R, S, B and N. (See Section 3.2.4)

Thermocouple Response Time
For bare probes or exposed tip designs, T/Cs are significantly faster – 2 to 5X – than bare RTD probes. However, since the vast majority of industrial measurements are made using thermowells, the time response for T/Cs and RTDs is about equal.

Thermocouple Degradation
Thermocouple junctions of two dissimilar metals begin to degrade over time at a rate largely dependent on the temperature they are exposed to and corrosive elements in their surrounding environment. (See Section 3.1.6.8)

Thermowell
Thermowells are most often constructed from machined barstock in a variety of materials and may be coated with other materials for erosive or corrosive protection. They are available with threaded, welded or flanged connections. See also Protection Tubes.

Thermowell Mounting Methods
(See Section 4.3.2.2.3)

- ***Threaded -*** Provides for easy installation and removal. Not suited to high pressure applications.
- ***Flanged -*** Flanges are bolted into place, providing secure installation for high pressure, high velocity, high temperature applications and corrosive processes.
- ***Welded -*** Permanently installed for no-leak high pressure ratings.

Thermowell Standards
ASME PTC 19.3 TW is internationally recognized as a mechanical design standard yielding reliable thermowell service in a wide range of temperature measurement applications. It includes evaluation of stresses applied to a barstock thermowell as installed in a process based on the design, material, mounting method, and the process conditions. (See Section 3.3.9)

Thin-film Elements
Are manufactured by depositing a thin film of pure platinum on a ceramic substrate in a maze-like pattern. Refer to Figure 3-48. The sensor is then stabilized by a high temperature annealing process and trimmed to the proper R0 value. These compact sensors are then encapsulated with a thin glassy material. For many applications, they have superior resistance to vibration. (See Section 3.2.3.2.2)

Three-wire RTD
In a three-wire configuration, compensation is accomplished using the third wire with the assumption that it will be the same resistance as the other two wires and the same compensation is applied to all three wires. However, in the real world, there will always be some difference due to wire manufacturing irregularities, unequal lengths, loose connections, work hardening from bending, and terminal corrosion. (See Section 3.2.3.1.3.1)

Threaded Style
A capsule style sensor probe with the threaded adaptor to provide a connection to the process and connection head or housing. Can also refer to a threaded connection for a thermowell to the process.

Time Constant
The Time Response of a sensor is the time required for the output of the sensor to change by 63.2% of the step change in temperature while in water moving at 3 ft/sec. The Time Constant is the time required for a sensor at 0° that is then thrust into 100 °C water flowing at 3 fps to reach 63.2 °C.

Total Probable Error (TPE)
A calculation that reflects the probable error of the transmitter and sensor system, based on anticipated installation conditions. The components of this calculation include the root sum square of the multiple transmitter accuracy effects. (See 4.3.4.1)

Traceability
All calibrations should be performed traceable to a nationally or internationally recognized standard. The standards used for calibration should be traceable to a National Metrology Institute, such as NIST in the USA. There may be many levels of traceability between your shop and NIST, but the trail should exist and the tolerance of the standards fully understood. (See Section 5.7.3)

Transient Protection
Many transmitters offer transient suppression options that can be integrally mounted onto the terminal strip within the housing. For other transmitters, an external protection device may be used. (See Section 3.1.6.3)

Transmitter
An instrument capable of receiving low-level inputs from temperature sensors (Typically RTDs and T/Cs); filtering, conditioning, and converting the signal and communicating a robust accurate and stable analog or digital output to the receiving system.

Two-wire RTD
In a two-wire configuration, there can be no compensation for lead wire resistance since the lead wires are in series with the probe resistance and appear to the transmitter as part of the sensor causing an inherent accuracy degradation. There are few, if any, applications where two wire sensors are a good choice.

U

Ungrounded Junctions
Exist when the T/C elements are not connected to the sensor sheath, but are surrounded with insulating MgO powder. Ungrounded junctions have a slightly slower response time than grounded junctions, but are less susceptible to electrical noise. (See Section 3.2.4.3.1)

Universal Field Calibrator
Universal field calibrators are available in a variety of models from several major suppliers. Many models are HART compliant and others also interface with FOUNDATION Fieldbus and Profibus PA.

They have the ability to simulate RTD, T/C, mv, voltage, and frequency signals that may be connected to a transmitter for calibration purposes. Many provide a dual screen capability to simultaneously see the simulated signal and the transmitter output. Some also have the ability to read signals from sensors and display the actual value of the variable. (See Section 5.7.5.2)

Update rate
Frequency of sampling by a transmitter from a sensing element.

Uncertainty
The lack of certainty of the validity of the value being presented.

V

Vibration
Most thermowell failures are caused by fluid induced vibration associated with Vortex Shedding. Wake frequency calculations should be performed to verify design parameters of each thermowell.

Vortex Shedding
When fluid flows past a thermowell inserted into a pipe or duct, vortices form at both sides of the well and these vortices detach, first from one side, and then from the other in an alternating pattern. This phenomenon is known as vortex shedding, the Von Karman Vortex Street or flow vortices. (See Section 3.3.7.1)

W

Wake Frequency Calculations
Complex calculations required to select the proper thermowell design for a given application. Typically implemented in a "tool" used by a thermowell supplier and are defined in ASME PTC 19.3 TW. Consideration is given to all of the flow parameters, including pressure, temperature, flow rate , fluid viscosity and rangeability.

***Wireless*HART**
*Wireless*HART is an open-standard wireless networking technology developed to complement the existing HART standard. The protocol was defined specifically for the requirements of process field device networks and utilizes a time synchronized, self-organizing, and self-healing mesh architecture. (See Section 3.1.3.5)

Wire-wound
Wire-wound RTDs are manufactured either by winding the resistive wire around a ceramic mandrel or by winding it in a helical shape supported in a ceramic sheath – hence the name wire-wound. (See Section 3.2.3.2.1)

Worst Case Error (WCE)
The largest possible error expected under the anticipated conditions. These calculations are a summation of the raw values of reference accuracy, digital temperature effect, and ambient temperature effects on the input and output. (See Section 4.3.4.1)

Notes

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