Calibration **Essentials**

Temperature

Introduction

Calibration Essentials: Temperature consists of multiple articles and resources for today's industry professionals. In it you will learn about:

- The AMS2750E standard, which is predominantly designed for heat treatment in the aerospace industries, and its focus on the requirements set for accuracy, calibration and test/calibration equipment.
- Useful and practical things to know about Pt100 sensors, including information on RTD and PRT sensors, different Pt100 mechani¬cal structures, the temperature-resistance relationship, and more.
- How the cold (reference) junction on thermocouples works, and how to avoid errors in measurement and calibration.
- Temperature calibration using a dry block, and the uncertainty that can come from the calibration procedure.
- Temperature scales, temperature units and temperature-unit conversions.
- Optimal testing parameters for process instrument calibration

Beamex and ISA are pleased to bring you latest information on innovation and instrumentation to ensure your calibration efforts remain as efficient as possible. The two organizations work together with the goal of helping to standardize calibration efforts and maintain a continuous automated production environment. Visit **Beamex.com** to find videos and other resources for upping your calibration game.

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Uncertainty components of a temperature calibration using a **dry block**

In some earlier articles, we have discussed temperature calibration and calibration uncertainty. This time we will be covering the different uncertainty components that you should consider when you make a temperature calibration using a temperature dry block.

Making a temperature calibration using a dry block seems like a pretty simple and straight forward thing to do, however there are many possible sources for uncertainty and error that should be considered. Often the biggest uncertainties may come from the procedure on how the calibration is done, not necessarily from the specifications of the components.

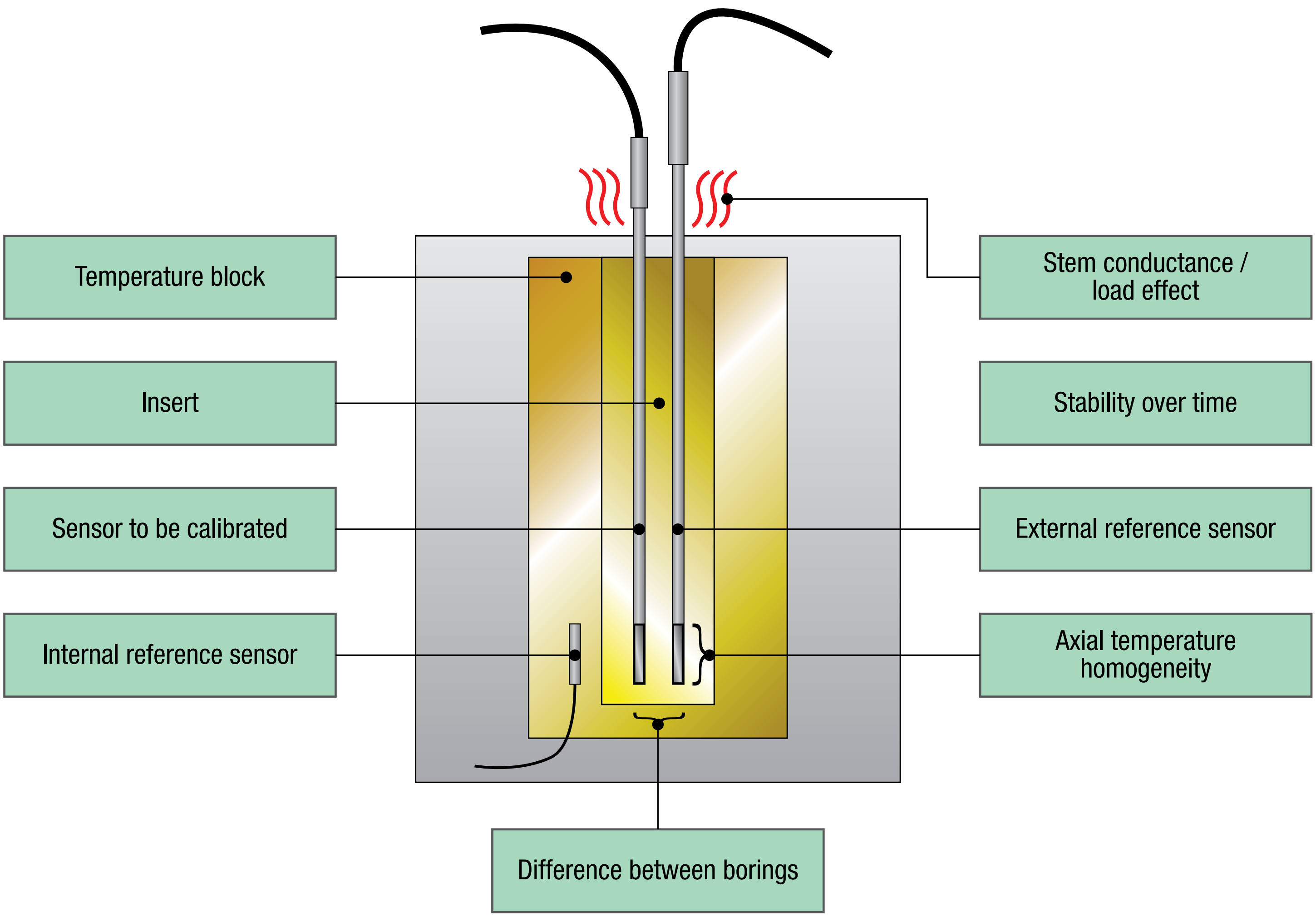
What is a "dry block"?

Let's start by discussing what I mean with a "temperature dry block" in the article.

A temperature dry block is sometimes also called a dry-well or a temperature calibrator.

It is a device that can be heated and/or cooled to different temperature values, and as the name hints, it is used dry, without any liquids.

A dry block typically has a removable insert (or sleeve) that has suitable holes/borings for inserting temperature sensors into.



The dry block typically has its own internal measurement for the temperature, or you may use an external reference temperature sensor that you will insert into one of the holes.

Commonly a dry block has interchangeable inserts, so you may have several inserts, each being drilled with different holes, to suit for calibration of different sized temperature sensors. It is very important in a dry block that the hole for the temperature sensor is sufficiently tight to enable low thermal resistance between the sensor and the insert. In too loose of a boring, the sensor stabilizes slowly or may not reach the temperature of the insert at all due to stem conduction.

Commonly, you would insert a temperature sensor in the dry block to be calibrated or calibrate a temperature loop where the temperature sensor is the first component in the loop.

The main benefits of a dry block are that it is easy to carry out in the field and there is no hot fluid that would spill when you carry it around. Also, a dry block will not contaminate the temperate sensors being calibrated.

Dry blocks are almost always used dry. In some very rare cases you may use some heat transfer fluids or pastes. In most cases you may damage the dry block if you use liquids.

Using oil or pastes also cause a potential health and fire risk if later used in temperatures higher than for example a flash point of the foreign substance. A 660°C dry block that has silicon oil absorbed into its insulation may look neat outside, but it will blow out a noxious fume when heated up. Calibration labs everywhere are probably more familiar with this than they would like to be…

As drawbacks for dry blocks, we could consider lower accuracy/stability than with a liquid bath and more difficult to calibrate very short and odd shaped sensors.

So, it's not a "bath"?

No, it is dry one.

There are also temperature baths available, having liquid inside. The liquid is heated/cooled and the temperature sensors to be calibrated are inserted into the liquid. Liquid is also being stirred to get even temperature distribution in the liquid.

There are also some combinations of dry block and liquid bath, these are devices that typically have separate dry inserts and separate liquid inserts.

The main benefits of a liquid bath are the better temperature homogeneity and stability and suitability for short and odd shaped sensors.

While the drawbacks of liquid bath are the bigger size, heavier weight, working with hot liquids, poorer portability and they're often slower than dry blocks.

In this article we focus on the temperature dry blocks, so let's get back to them.

EURAMET Guidelines

Let's take a quick look into Euramet guides before we proceed. And yes, it is very relevant for this topic.

EURAMET is the Regional Metrology Organization (RMO) of Europe. They coordinate the cooperation of National Metrology Institutes (NMI) in Europe. More on Euramet at https://www.euramet.org/.

Euramet has also published many informative guidelines for various calibrations.

The one that I would like to mention here is the one dedicated for temperature dry block calibration: EURAMET Calibration Guide No. 13, Version 4.0 (09/2017), titled "Guidelines on the Calibration of Temperature Block Calibrators."

The previous version 3.0 was published in 2015. The first version was published in 2007. That guideline was earlier called EA-10/13, so you may run into that name too.

The guideline defines a normative way to calibrate temperature dry blocks. Many manufacturers use the guideline when calibrating dry blocks and when giving specifications for their dry blocks.

To highlight some of the contents of the most recent version 4.0, it includes:

- Scope
- Calibration capability
- Characterization
  - Axial homogeneity
  - Temperature difference between borings
  - Effects of loading
  - Stability over time
  - Heat conduction
- Calibration
  - Measurements
  - Uncertainties
- Reporting results
- Examples

You can download the Euramet guide PDF free here: Guidelines on the Calibration of Temperature Block Calibrators

Uncertainty components

Let's get into the actual uncertainty components. When you make a temperature calibration using a dry block, these are the things that cause uncertainty/error to the measurement results.

Internal or external reference sensor?

There are two principle ways to measure the true (correct) temperature of a dry block. One is to use the internal measurement using the internal reference sensor that is built in into the dry block, the other is to use an external reference sensor that is inserted into the insert boring/hole.

There are some fundamental differences between these two ways, and they have a very different effect on the uncertainty, so let's discuss these two options next:

1. Internal reference sensor

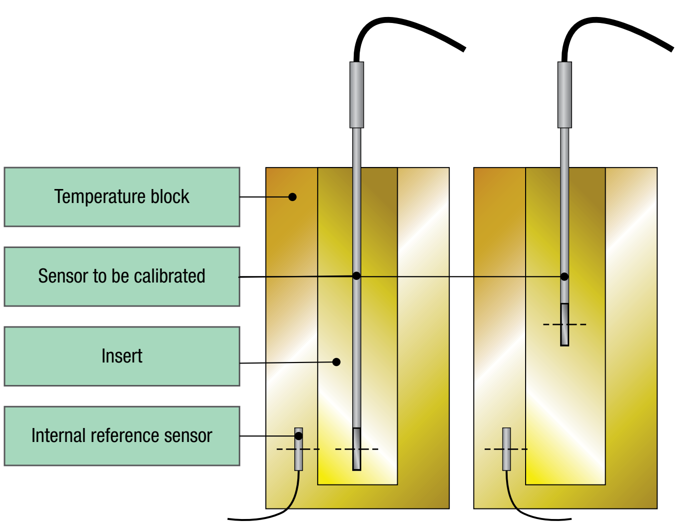
An internal reference sensor is permanently inserted into the metal block inside the dry block, it is typically close to the bottom part of the block and it is in the metallic block surrounding the interchangeable insert. So, this internal sensor does not directly measure the temperature of the insert, where you insert the sensors to be calibrated, but it measures the temperature of the surrounding block. Since there is always some thermal resistance between the block and the insert, this kind of measurement is not the most accurate one.

Especially when the temperature is changing, the block temperature normally changes faster than the insert temperature. If you make the calibration too quickly without waiting enough stabilization time, this will cause an error.

An internal reference sensor is anyhow pretty handy, as it is always readily inside the block, and you don't need to reserve a dedicated hole in the insert for it.

The recalibration of the internal measurement is a bit difficult, as you need to send the whole dry block into recalibration.

An internal measurement sensor's signal is naturally measured with an internal measurement circuit in the dry block and displayed in the block's display. The measurement typically has an accuracy specification given. As discussed earlier, in practice this specification is only valid in stable conditions and does not include the uncertainties caused if the calibration is done too quickly or the sensors to be calibrated are not within the calibration zone at the bottom part of the insert, in a sufficiently tight boring.



The pictures illustrate how the internal reference sensor is typically located in the temperature block, while the sensor to be calibrated is inserted into the insert. If the sensor to be calibrated is long enough and reaches the bottom on the insert, the boring is tight enough, and we waited long enough for stabilization, we can get good calibration with little error (first picture).

In the second picture we can what happens if the sensor to be calibrated is too short to reach to the bottom of the insert. In this case, the internal reference sensor and the sensor to be calibrated are located at different heights and are measuring different temperatures.

2. External reference sensor

The other way is to use an external reference sensor. The idea here is that you insert a reference sensor into a suitable hole in the insert, while you enter the sensors to be calibrated in the other holes in the same insert. As the external reference sensor is inserted into the same metal insert with the sensors to be calibrated, it can more precisely measure the same temperature as the sensors to be calibrated are measuring.

Ideally, the reference sensor would have similar thermal characteristics as the sensors to be calibrated (same size and thermal conductance). In that case, as the insert temperature changes, the external reference sensor and the sensor to be calibrated will more accurately follow the same temperature changes.

The external reference sensor naturally needs to be measured somehow. Often a dry block has internal measurement circuitry and a connection for the external reference sensor, or you can use an external measurement device. For uncertainty, you need to consider the uncertainty of the reference sensor and the uncertainty of the measurement circuitry.

Using an accurate external reference sensor results in a more accurate calibration with smaller uncertainty (compared to using an internal reference sensor).

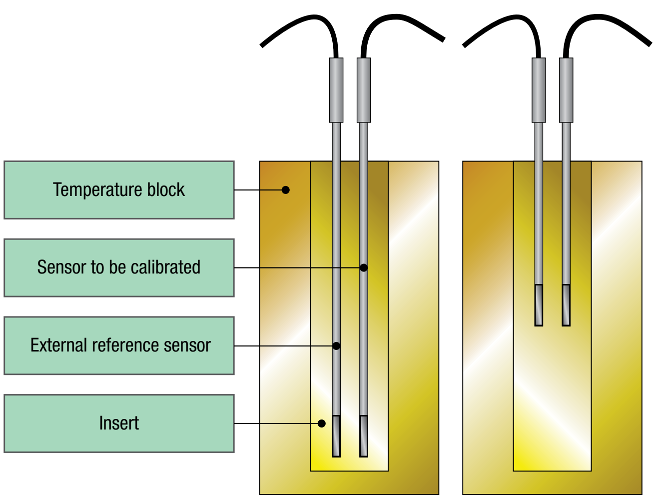
So, it is highly recommended to use one if you want good accuracy (small uncertainty).

An external reference sensor also promotes reliability. If the internal and external sensor readings differ a lot, it's a warning signal to the user that something is probably wrong and the measurements may not be trustworthy.

For recalibration, in the case of an external reference sensor, you can send just the reference sensor for recalibration, not the whole dry block. In that case, you naturally will not have the dry block's functionalities being checked (and adjusted if necessary), like the axial temperature homogeneity, for example.

If you don't send the dry block for calibration, be sure to measure and record the axial gradient regularly yourself, as it's typically the biggest uncertainty component also when the external reference sensor is used. Otherwise a strict auditor may profoundly question the traceability your measurements.

Another matter is whether you use the dry block or an external thermometer/calibrator to measure the reference sensor. If you use the build-in reference sensor measurement, it needs to be calibrated too.



The above pictures illustrate how the external reference sensor and the DUT sensor are both located in the insert. The first picture shows the case when both sensors reach the bottom of the insert. The second picture shows an example where the DUT sensor is short, and the reference sensor has been correctly positioned in the same depth as the DUT sensor.

If the sensor was located at a different height, that would cause additional error, but the error is still typically smaller than when using the internal reference sensor.

3. Axial temperature homogeneity

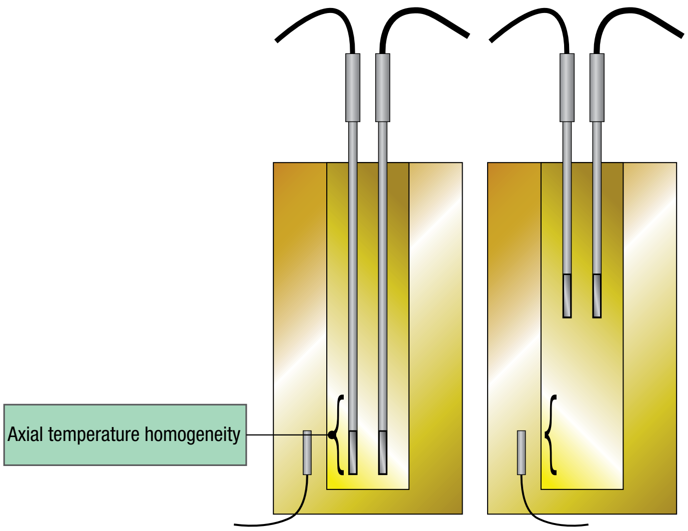
Axial homogeneity (or axial uniformity) refers to the difference in temperature along the vertical length of the boring in the insert. For example, the temperature may be slightly different in the very bottom of the boring in the insert, compared to the temperature a little higher in the boring. Typically, the temperature will be different in the very top of the insert, as the temperature is leaking to the environment, if the block's temperature is very different than the environmental temperature.

Some temperature sensors have the actual measurement element being shorter and some longer. Also, some have the element closer to the tip than others. To assure that different sensors are in the same temperature, the homogenic zone in the bottom of the block's insert should be long enough. Typically, the specified area is 40 to 60 mm.

A dry block should have enough area in the insert bottom within which the temperature homogeneity is specified. During a calibration of the block, this may be calibrated by using two high-accuracy reference sensors at different heights or using a sensor with a short sensing element that is gradually lifted higher from the bottom. This sort of short sensing element sensor needs to be stable but does not necessarily be even calibrated because it's used just for measuring temperature difference at different heights. If needed, the axial temperature gradient can typically be adjusted.

If you have a short (sanitary) temperature sensor that does not reach all the way to the bottom of the boring in the insert, then things will get a bit more complicated. In that case, the internal reference measurement in the dry block cannot really be used, as is typically in the bottom of the block. An external reference sensor should be used, and it should have the center of the measurement zone inserted as deep as the center of the measurement zone of the short sensor to be calibrated. Often, this means that a dedicated short reference sensor should be used and inserted into the same depth as the short sensor to be calibrated. It gets even more difficult if the short sensor to be calibrated has a large flange as that will soak up temperature from the sensor.

Summary – During the calibration you should ensure that your reference sensor is inserted to the same depth as the sensor(s) to be calibrated. If you know the lengths and the locations of the sensing elements, try to align the centers horizontally. If that is not possible, then you need to estimate the error caused by that. You should use an external temperature sensor, if the accuracy requirements of the calibration are higher, or if the sensor to be calibrated is not long enough to reach the bottom on the insert hole.

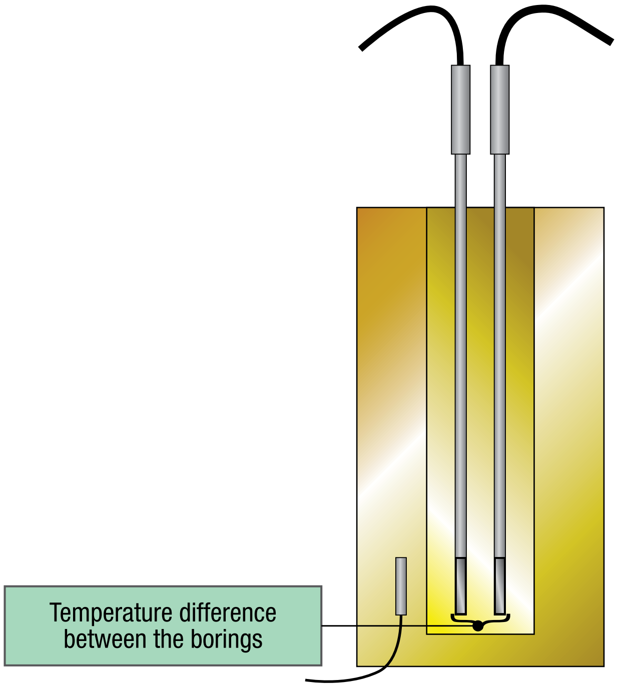


The above pictures illustrate what the "axial temperature homogeneity" means. Typically, a dry block has a specified area in the bottom that has a homogenic temperature, but as you start to lift the sensors higher, they will not be in the same temperature anymore.

4. Temperature difference between the borings

As the title hints, the temperature difference between the borings, sometimes referred as "radial uniformity," is the temperature difference between each boring (hole) in the insert. Although the insert is made of metal compounds and has a good thermal conductivity, there can still be a small difference between the borings, especially the opposite ones.

In practice, when you have two sensors in the insert installed in the different borings, there can be a small temperature difference between them.



The difference can be caused by the insert touching the block more on one side or the insert being loaded unequally (more sensors on one side, or thicker sensors in one side than on the other side). Of course, the heaters and Peltier elements, located on different sides, have their tolerances too.

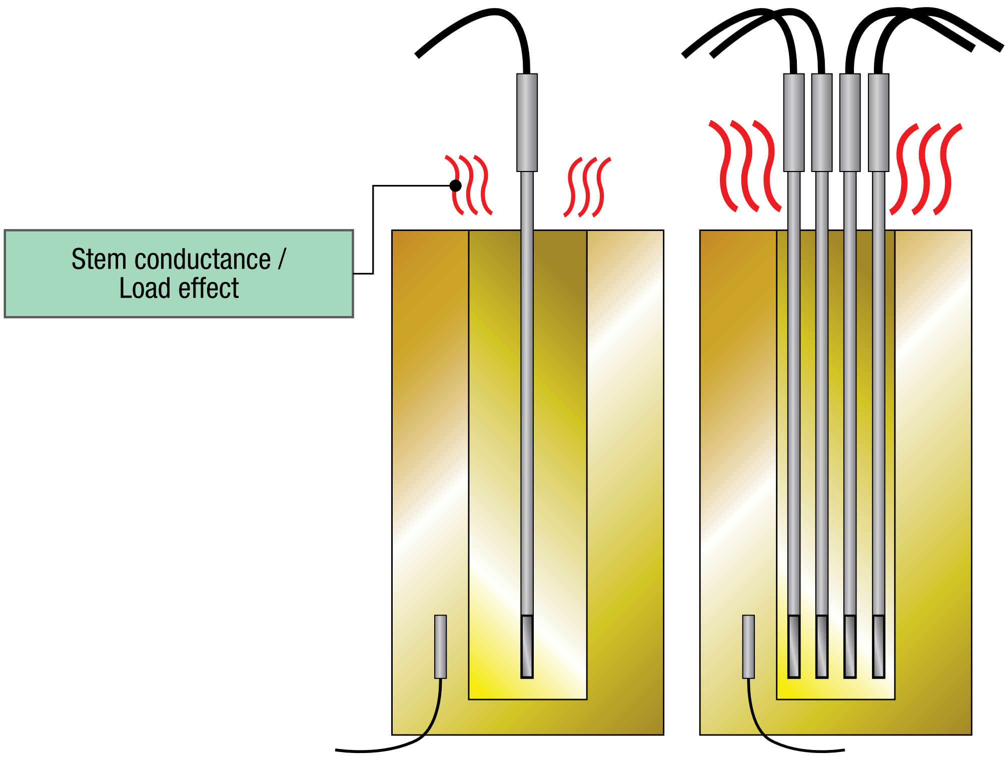
The temperature difference between the borings in normally relatively small in practice.

Summary—the specification of the temperature difference between borings should be taken into account.

5. Influence of loading

There is always some heat conducted through the sensors to the environment (stem conductance) if the block's temperature differs from the environmental temperature.

If there are several sensors installed in the insert, there will be more temperature "leaking" to the environment. Also, the thicker the sensors are, the more temperature leakage there will be.



The bigger the temperature difference between the insert and the environment temperature, the bigger the leakage will be.

For example, if you have the dry block at an elevated temperature, this temperature leakage will cause the insert to cool down because of the loading. The top of the insert will lose more temperature than the bottom of the insert and the top becomes cooler.

The deeper the insert is, the less loading effect there will be. Also, some dry blocks have two or more heating/cooling zones: one in the bottom, one in center and one in the top of the block. This will help to compensate the loading effect (e.g. the top heating can heat more to compensate the top of the insert to cool down).

If you use the internal reference measurement of the dry block, there will typically be a larger error since the internal reference is not in the insert but is in the bottom of the surrounding block. Therefore, the internal reference sensor does not see this effect of loading very well.

An external reference sensor can better see the effect of loading, as it is in the insert and it will also have the same change in the temperature. The error caused by the loading effect is much smaller when external reference sensors is used (compared to using internal reference sensor), and the results are better.

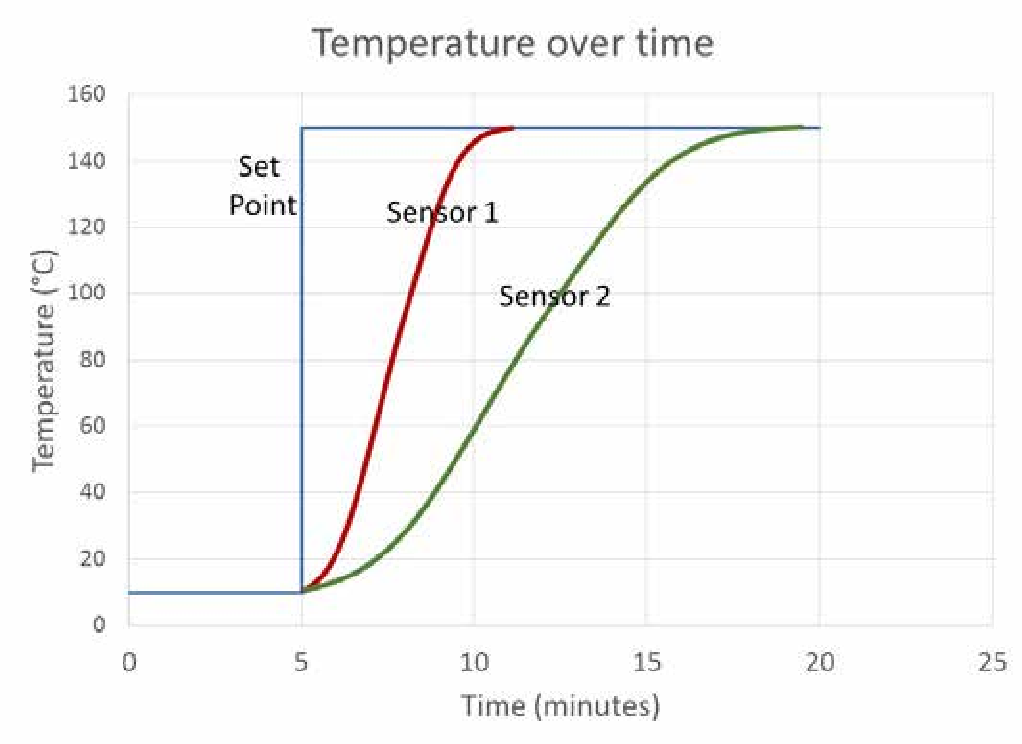
Summary—check out the loading effect of your dry block in your application (how many sensors, which type of sensor) and use that as one uncertainty component.

The above pictures illustrate the stem conductance caused by the sensors leaking the temperature to the environment. In the second picture there are several sensors at the same level, so the stem conductance/leakage will be larger.

6. Stability over time

Stability over time describes how well the temperature remains stable over a longer period. The temperature needs to be stable for certain time, as the different sensors may have different thermal characteristics and it takes different time for different sensors to stabilize. If the temperature is constantly creeping up and down, the different sensors may read different temperatures.

In case there is some fluctuation in the temperature,



an external reference sensor will anyhow result in more accurate results, compared to the use of an internal reference sensor.

Often a dry block manufacturer has given a stability specification, for example for a 30 minute period.

7. Don't be in a hurry!

It's good to remember the fact that a temperature sensor will always measure only its own temperature. So, it does not measure the temperature where it is installed, but it will measure its own temperature. Also, temperature changes pretty slowly and it takes some time before all parts of the system have stabilized to the same temperature, i.e. system has reached equilibrium.

If you make a temperature calibration with a dry block too fast, that will be the biggest source of uncertainty!

So, get to know your system and the sensors you calibrate and experiment to see how long time is enough for sufficient stabilization.

Especially if you use the internal reference sensor, it will reach the set temperature much faster than the sensors to be calibrated located in the insert. That is because the internal sensor is in the block that is heated/cooled, and the sensors to be calibrated are in the insert. Taking the results too soon can cause a big error.

In case of an external reference sensor, the need for stabilization depends on how different your reference sensor is compared to your sensors to be calibrated. If they have different diameter, they will most likely have different stabilization time. Anyhow, using an external reference sensor will be much more accurate than internal one, in case you don't wait long enough for stabilization.

Often a dry block will have a stability indicator, but that may be measuring the stability of the internal reference sensors, so don't trust only on that one.

Summary—shortly, if you do the temperature calibration too fast, the results will be terrible.

The above picture illustrates an (exaggerated) example where the temperature set point has been first 10°C and at the 5 minutes mark it has been changed to 150°C (blue line represents the set point).

There have been two sensors in the dry block—a reference sensor and a sensor to be calibrated.
We can see that the Sensor 1 (red line) changes much faster and reaches the final temperature at about 11 minutes point. The Sensor 2 (green line) changes

much slower and it reaches the final temperature at around the 18 minutes mark.

The Sensor 1 is our reference sensor and the Sensor 2 is the sensor to be calibrated. We can see that if we read the temperatures too early at 10 minutes mark, we will get a huge error (about 85°C) in our results. Even if we take the readings at the 15 minutes mark, we still have around 20°C difference.

So, we should always make sure that we wait long enough to make sure that all sensors are stabilized to the new temperature, before we read the readings.

Summary

Making a temperature (sensor) calibration using a dry block seems pretty simple and straight forward thing to do. But there are anyhow many possible sources for uncertainty and error that should be taken into account. Often the biggest uncertainties may come from the procedure on how the calibration is done, not necessarily from the specifications of the components.

For example, you may have an accurate dry block that has combined total uncertainty being 0.05°C and a high-quality reference sensor with uncertainty of 0.02°C. But anyhow calibrating a temperature sensor with these devices can have an uncertainty of several degrees, if it is not made properly. That is one reason I don't like the discussion of TAR (Test Accuracy Ratio) as it does not take into account all the uncertainties caused by the calibration procedure.

I hope these considerations listed in the article help you to realize the possible sources of uncertainty and how to minimize them.

BEAMEX OFFERING

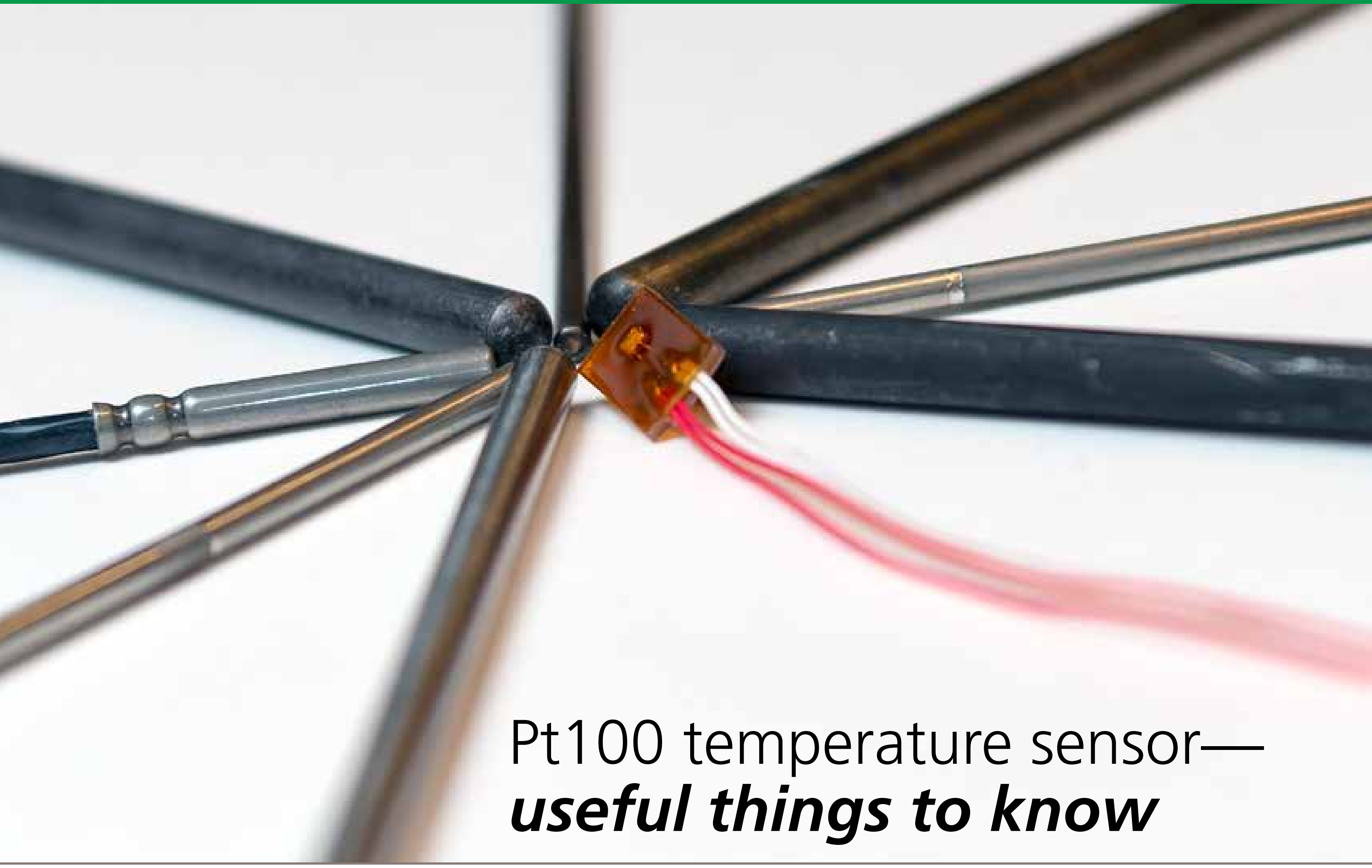
Beamex offers various temperature calibration products, including two different series of temperature dry blocks. Please check our offering in the below link:

Beamex temperature calibration products

RELATED BLOG POSTS

The main topics discussed in this article are temperature calibration and calibration uncertainty. Other blog posts on these topics, that you could be also interested in, are for example following:

- Measurement Uncertainty: Calibration uncertainty for dummies
- Metrological Traceability in Calibration—Are you traceable?
- Pt100 temperature sensor—useful things to know
- Thermocouple Cold (Reference) Junction Compensation
- Temperature units and temperature unit conversion



Pt100 temperature sensor—***useful things to know***

The Pt100 temperature sensors are very common sensors in the process industry. This article discusses many useful and practical things to know about the Pt100 sensors. There's information on RTD and PRT sensors, different Pt100 mechanical structures, temperature-resistance relationship, temperature coefficients, accuracy classes and on many more.

For terminology, both "sensor" and "probe" words are generally used, I mainly use "sensor" in this article.

Also, people write "Pt100" and "Pt-100," I will mainly use the Pt100 format. (Yep, I know that IEC / DIN 60751 uses the Pt-100 format, but I am so used to the Pt100 format).

RTD sensors

As the Pt100 is an RTD sensor, let's look first at what an RTD sensor is.

The abbreviation RTD comes from "Resistance Temperature Detector." It is a temperature sensor in which the resistance depends on temperature; when temperature changes, the sensor's resistance changes. So, by measuring the sensor's resistance, an RTD sensor can be used to measure temperature.

RTD sensors are most commonly made from platinum, copper, nickel alloys or various metal oxides.

PRT sensors

Platinum is the most common material for RTD sensors. Platinum has a reliable, repeatable and linear temperature-resistance relationship. RTD sensors made of platinum are called PRT, "Platinum Resistance Thermometer." The most common platinum PRT sensor used in the process industry is the Pt100 sensor. The number "100" in the name indicates that is has a resistance of 100 ohms in 0°C (32°F) temperature. More details on that later.

PRT versus thermocouple

In an earlier white paper, we discussed thermocouples. Thermocouples are also used as temperature sensors in many industrial applications. So, what's the difference between a thermocouple and a PRT sensor? Here's a short comparison between thermocouples and PRT sensors:

Thermocouples:

- Can be used to measure much higher temperatures
- Very robust
- Inexpensive
- Self-powered, does not need external excitation
- Not very accurate
- Requires cold junction compensation
- Extension wires must be of applicable material for the thermocouple type and attention must be paid to temperature homogeneity over all the junctions in the measurement circuit
- Inhomogeneities in wires may cause unexpected errors

Shortly, you can say that thermocouples are more suitable for high-temperature applications and PRTs for applications that require better accuracy.

PRTs:

- Are more accurate, linear and stable than thermocouples
- Does not require cold junction compensation, like thermocouples do
- Extension wires can be copper wires
- More expensive than thermocouples
- Need a known excitation current suitable for the sensor type
- More fragile

Shortly, you can say that thermocouples are more suitable for high-temperature applications and PRTs for applications that require better accuracy.
More information on thermocouples and the cold junction compensation can be found in this earlier blog post:
Thermocouple Cold (Reference) Junction Compensation

Measuring RTD/PRT sensor

Since the RTD sensor's resistance changes when temperature changes, it is pretty clear that when measuring the RTD sensor you need to measure resistance. You can measure the resistance in Ohms then convert that manually into a temperature measurement according to the conversion table (or formula) of the RTD type being used.

Nowadays, most commonly, you use a temperature measurement device or calibrator that automatically converts the measured resistance into a temperature reading, when the correct RTD type is selected in the device (assuming it supports the RTD type used). Of course, if the wrong RTD sensor type is selected in the device, it will result in incorrect temperature measurement results.

There are different ways to measure resistance. You can use a 2-, 3- or 4-wire connection. The 2-wire connection is only suitable for very low accuracy measurement (mainly troubleshooting) because any wire resistance or connection resistance will introduce error to the measurement. Any normal process measurement should be done using 3- or 4-wire measurement.

For example, the IEC 60751 standard specifies that any sensor better than accuracy class B must be measured with a 3- or 4-wire measurement. More on the accuracy classes later in this article.

Just remember to use a 3- or 4-wire measurement and you are good to go.

Sure for some high-impedance thermistors, Pt1000 sensors, or other high-impedance sensors the additional error caused by the 2-wire measurement may not be too significant.

More information on the 2-, 3- and 4-wire resistance measurement can be found in the blog post link below:
Resistance measurement; 2-, 3- or 4-wire connection—How does it work and which to use?

Just remember to use a 3- or 4-wire measurement and you are good to go.

Measurement current

As explained in the above-linked blog post in more detail, when a device is measuring resistance it sends a small accurate current through the resistor and then measures the voltage drop generated over it. Then, the resistance can be calculated by dividing the voltage drop by the current according to Ohm's law (R=U/I).

If you are interested in more detailed info on Ohm's law, check out this blog post:
Ohm's law—what it is and what an instrument tech should know about it

Self-heating

When the measurement current goes through the RTD sensor, it also causes the RTD sensor to slightly warm up. This phenomenon is called self-heating. The higher the measurement current is and the longer time it is on, the more the sensor will warm up. Also, the sensor's structure and its thermal resistance to its surroundings will have a big effect on the self-heating. It is pretty obvious that this kind of self-heating in a temperature sensor will cause a small measurement error.
The measurement current is typically a max of 1 mA when measuring a Pt100 sensor, but it can be as low as 100 µA or even lower. According to standards (such as IEC 60751), self-heating must not exceed 25% of the sensor's tolerance specification.

Different mechanical structures of PRT sensors

PRT sensors are generally very delicate instruments and unfortunately, accuracy is almost without exception inversely proportional to mechanical robustness. To be an accurate thermometer, the platinum wire inside the element should be able to contract and expand with temperature as freely as possible to avoid strain and deforming. The drawback is that this sort of sensor is very sensitive to mechanical shocks and vibration.

Standard Platinum Resistance Thermometer (SPRT)

The more accurate Standard Platinum Resistance Thermometer (SPRT) sensors are instruments for realizing the ITS-90 temperature scale between the fixed points. They're made from very pure ($\alpha = 3.926 \times 10^{-3}\,°C^{-1}$) platinum and the wire support is designed to keep the wire as strain-free as possible. The "Guide to the Realization of the ITS-90" published by the BIPM (Bureau International des Poids et Mesures) defines the criteria the SPRT sensor must fulfill. Other sensors are not and should not be called SPRT's. There are glass, quartz, and metal sheathed sensors for different applications. SPRT's are extremely sensitive to any kind of acceleration such as minimal shocks and vibration, which limits their use to laboratories at the very highest-accuracy measurements.

Partially supported PRT

Partially supported PRT's are a compromise between the performance of a thermometer and mechanical robustness. The most accurate ones are often called Secondary Standard or Secondary Reference sensors. These sensors may adopt some structures from SPRTs and the wire grade may be the same or very close. Due to some wire support, they are less fragile than SPRTs. They're even usable for field applications if handled with care, still offering excellent stability and low hysteresis.

Industrial Platinum Resistance Thermometers (IPRT)

When the wire support is increased, the mechanical robustness increases, but so does the strain related to drift and hysteresis issues. These sensors are called Industrial Platinum Resistance Thermometers, IPRTs. Fully supported IPRTs have even more wire support and are mechanically very robust. The wire is encapsulated completely into ceramic or glass, making it very unsusceptible to vibration and mechanical shocks. The drawback is much poorer long-term stability and large hysteresis as the sensing platinum is bonded to the substrate that has different thermal expansion characteristics.

Film

Film PRT's have evolved a lot in recent years and better ones are now available. They come in many forms for different applications. The platinum foil is sputtered onto the selected substrate, the resistance of the element is often laser-trimmed to the desired resistance value and eventually encapsulated for protection. Unlike wire elements, thin film elements are much friendlier to automating the manufacturing process which makes them often cheaper than the wire elements. The advantages and disadvantages are typically the same as with fully supported wire elements except that film elements often have a very low time constant, meaning that they react very fast to temperature changes. As mentioned earlier, some manufacturers have developed techniques that better combine the performance and robustness.

Other RTD sensors

Other Platinum sensors

Although the Pt100 is the most common Platinum RTD/ PRT sensor, there are several others such as Pt25, Pt50, Pt200,Pt500, and Pt1000. The main difference between these sensors is pretty easy to guess, that is the resistance at 0°C, which is mentioned in the sensor name. For example, a Pt1000 sensor has resistance of 1000 ohms at 0°C. The temperature coefficient is also important to know as it affects the resistance at other temperatures. If it is a Pt1000 (385), this means it has a temperature coefficient of 0.00385°C.

Other RTD sensors

Although Platinum sensors are the most common RTD sensors, there are also sensors made of other materials including nickel, nickel-iron and copper sensors. Common nickel sensors include Ni100 and Ni120, nickel-iron sensor Ni-Fe 604-ohm and copper sensor Cu10. These materials each have their advantages in certain applications. Common disadvantages of these are rather narrow temperature ranges and susceptibility to corrosion compared to noble metal platinum.

RTD sensors can also be made with other materials like gold, silver, tungsten, rhodium-iron or germanium. They excel in some applications but are very rare in normal industrial operations.

Since an RTD sensor's resistance depends on temperature, we could also include all generic PTC (positive temperature coefficient) and NTC (negative temperature coefficient) sensors in this category. Examples of these are thermistors and semiconductors that are used for measuring temperature. NTC types are especially common to use for measuring temperature.

Pt100 sensors

Temperature coefficient

The most common RTD sensor in process industry is the Pt100 sensor, which has a resistance of 100 ohms at 0°C (32°F).

The resistance at higher temperatures depends on the version of the Pt100 sensor, as there are a few different versions of the Pt100 sensor, which have slightly different temperature coefficients. Globally, the most common is the "385" version. If the coefficient is not mentioned, it is typically the 385.

The temperature coefficient (indicated with Greek symbol Alpha => α) of the Pt100 sensor is indicated as the difference of the resistance at 100°C and 0°C, divided by the resistance at 0°C multiplied with 100°C.

The formula is pretty simple, but it does sound a bit complicated when written, so let's look at it as a formula:

$$\alpha = \frac{R100 \text{ - } R0}{R0 \times 100°C}$$

Where:
α = temperature coefficient
R100 = resistance at 100°C
R0 = resistance at 0°C

Let's take a look at an example to make sure this is clear:

Pt100 has a resistance of 100.00 ohms at 0°C and a resistance of 138.51 ohms at 100°C. The temperature coefficient can be calculated by the following:

$$\alpha = \frac{138.51°C \text{ - } 100.00\ \Omega}{100.00\ \Omega \times 100°C}$$

We get a result of 0.003851/°C.
Or as it is often written: $3.851 \times 10^{-3}\ °C^{-1}$
Often this is referred and rounded as a "385" Pt100 sensor. This is also the temperature coefficient specified in standard IEC 60751:2008. The temperature coefficient of the sensor element mostly depends on the purity of the platinum used to make the wire. The purer the platinum is, the higher is the alpha value. Nowadays it's not a problem to get very pure platinum material. For manufacturing sensors

to meet the IEC 60751 temperature/resistance curve, the pure platinum must be doped with suitable impurities to bring the alpha value down to $3.851 \times 10^{-3}\,°C^{-1}$.

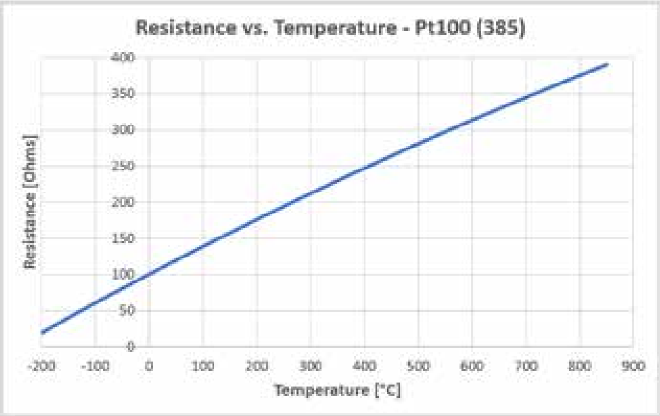
The alpha value descents from the times when the melting point (≈0°C) and the boiling point (≈100°C) of water were used as reference temperature points, but is still in use to define the grade of the platinum wire. Since the boiling point of water is actually a better altimeter than a reference temperature point, another way to define the wire purity is the resistance ratio at the gallium point (29.7646°C) which is a defined fixed point at the ITS-90 temperature scale. This resistance ratio is described with a Greek small letter (rho).

Typical value for a "385" sensor is 1.115817 and for an SPRT is 1.11814. In practice, the good old alpha is, in many cases, the most convenient, but rho may also be announced.

$$\rho = \frac{R(29.7646°C)}{R(0°C)}$$

Pt100 (385) temperature resistance relationship

In the graphics below, you can see how a Pt100 (385) sensor's resistance depends on temperature:



When looking at these, you can see that the resistance-temperature relationship of a Pt100 sensor is not perfectly linear, but the relationship is somewhat "curved."

The table below shows a Pt100 (385) temperature vs. resistance numerical values in a few points:

Temperature [°C]	Temperature [°F]	Resistance [Ohms]
-200.00	-328.00	18.5201
-100.00	-148.00	60.2558
0.00	32.00	100.0000
100.00	212.00	138.5055
200.00	392.00	175.8560
300.00	572.00	212.0515
400.00	752.00	247.0920
500.00	932.00	280.9775
600.00	1112.00	313.7080
700.00	1292.00	345.2835
800.00	1472.00	375.7040
850.00	1562.00	390.4811

Other Pt100 sensors with different temperature coefficients

Most of the sensors have been standardized, but there are different standards around the world. This is also the case with Pt100 sensors. Over time, there have been a few different standards specified. In most cases, there is only a relatively small difference in the temperature coefficient.

As a practical example, the standards that we have implemented into Beamex temperature calibrators are from following standards:

- IEC 60751
- DIN 43760
- ASTM E 1137
- JIS C1604-1989 alpha 3916, JIS C 1604-1997
- SAMA RC21-4-1966
- GOCT 6651-84, GOST 6651-94
- Minco Table 16-9
- Edison curve #7

Make sure your measurement device supports your Pt100 sensor

The good thing about the standard Pt100 probes is that each sensor should fulfill the specifications and you can just plug it into your measurement device (or calibrator) and it will measure its own temperature as accurately as the specifications (sensor + measurement device) define. Also, the sensors in the process should be interchangeable without calibration, at least for less critical measurements. Nevertheless, it would still be a good practice to check the sensor at some known temperature before use.

Anyhow, since the different standards have a bit different specification for the Pt100 sensor, it is important that the device you use for measuring your Pt100 sensor supports the correct sensor (temperature coefficient). For example, if your measuring device supports only Alpha 385 and you are using a sensor with an Alpha 391, there will be some error in the measurement. Is that error significant? In this case (385 vs 391), the error would be roughly 1.5°C at 100°C. So, I think it is significant. Of course, the smaller the difference between temperature coefficients, the smaller the error will be.

So, make sure that your RTD measurement device supports the Pt100 probe you are using. Most often if the Pt100 has no indication of the temperature coefficient, it is a 385 sensor.

As a practical example, the Beamex MC6 calibrator & communicator supports following Pt100 sensors (temperature coefficient in parenthesis) based on different standards:

- Pt100 (375)
- Pt100 (385)
- Pt100 (389)
- Pt100 (391)
- Pt100 (3926)
- Pt100 (3923)

Pt100 accuracy (tolerance) classes

Pt100 sensors are available in different accuracy classes. The most common accuracy classes are AA, A, B and C which are defined in the IEC 60751 standard. Standards define a sort of an ideal Pt100 sensor for the manufacturers to aim at. If it was possible to build an ideal sensor, tolerance classes would be irrelevant.

As Pt100 sensors cannot be adjusted to compensate for errors, you should buy a sensor with a suitable accuracy for the application. Sensor errors can be corrected in some measurement devices with certain coefficients, but more on that later.

Accuracies of the different accuracy classes (per IEC 60751:2008):

Accuracy class	Accuracy (Tolerance) Value
AA	±(0.1°C + 0.17% of temperature)
A	±(0.15°C + 0.2%)
B	±(0.3°C + 0.5%)
C	±(0.6°C + 1%)

There are also so-called 1/3 DIN and 1/10 DIN Pt100 accuracy classes in spoken language. They were standardized classes in, for example, DIN 43760:1980-10 that was withdrawn in 1987, but are not defined in the later IEC 60751 standard or its German language cousin DIN EN 60751. The tolerance of these sensors are based on the accuracy class B sensor, but the fixed part of the error (0.3°C) is divided by a given number (3 or 10). However, the terms are a set phrase when talking about Pt100's and we'll fluently use them here too. The accuracy classes of these sensors are following:

Accuracy class	Accuracy (Tolerance) Value
1/ 3 DIN	±(0.1°C + 0.5%)
1/ 10 DIN	±(0.03°C + 0.5%)

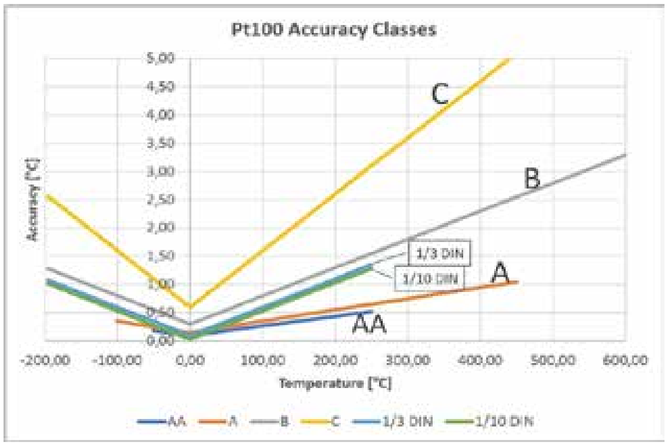
And of course, a sensor manufacturer can manufacture sensors with their own custom accuracy classes. IEC 60751 standard section 5.1.4 defines how these special tolerance classes should be expressed.

The formulas may be difficult to make a comparison with, in the below table the accuracy classes are calculated in temperature (°C):

Temp [°C]	AA	A	B	C	1/3 DIN	1/10 DIN
-196			1.28	2.56	1.08	1.01
-100		0.35	0.80	1.60	0.60	0.53
-50.00	0.19	0.25	0.55	1.10	0.35	0.28
0.00	0.10	0.15	0.30	0.60	0.10	0.03
100.00	0.27	0.35	0.80	1.60	0.60	0.53
200.00	0.44	0.55	1.30	2.60	1.10	1.03
250.00	0.53	0.65	1.55	3.10	1.35	1.28
300.00		0.75	1.80	3.60		
350.00		0.85	2.05	4.10		
400.00		0.95	2.30	4.60		
450.00		1.05	2.55	5.10		
500.00			2.80	5.60		
600.00			3.30	6.60		

One notable thing here is that even if the "1/10 DIN" sounds attractive with its low 0.03°C tolerance at 0°C, it's actually better than class A only within the narrow range -40…+40°C.

The graphic below shows the difference between these accuracy classes:



Coefficients

The accuracy classes are commonly used in industrial RTD sensors, but when it comes to the most accurate PRT reference sensors (SPRT, Secondary Standards…), those accuracy classes are not valid anymore. These sensors were made to be as good as a thermometer as possible for the purpose, not to match any standardized curve. They are very accurate sensors with very good long-term stability and very low hysteresis, but these sensors are individuals, so each sensor has a slightly different temperature/resistance relationship. These sensors should not be used without using the individual coefficients for every sensor. You can even find general CvD coefficients for SPRT's, but that will ruin the performance you've paid for. If you just plug in a 100 ohm Secondary PRT sensor like Beamex RPRT into a device measuring a standard Pt100 sensor, you may get a result that is several degrees or maybe even ten degrees incorrect. In some cases, it doesn't necessarily matter, but in other cases, it may be the difference between a medicine and a toxin.

So, these sensors must always be used with proper coefficients.

As mentioned before, RTD sensors cannot be "adjusted" to measure correctly. So, the correction needs to be made in the device (e.g. temperature calibrator) that is being used to measure the RTD sensor.

In order to find out the coefficients, the sensor should be first calibrated very accurately. Then, from the calibration results the coefficients for the desired equation, it can be fitted to represent the sensor's characteristic resistance/temperature relationship. The use of the coefficients will correct the sensor measurement and will make it measure very accurately. There are several different equations and coefficients to calculate the sensor's resistance to temperature. These are probably the most widespread:

As mentioned before, RTD sensors cannot be "adjusted" to measure correctly. So, the correction needs to be made in the device (e.g. temperature calibrator) that is being used to measure the RTD sensor.

Callendar-van Dusen

In the late 19th century, Callendar introduced a simple quadratic equation that describes the resistance/temperature behavior of platinum. Later, van Dusen found out that an additional coefficient was needed below zero. It's known as the Callendar-van Dusen equation, CvD. For alpha 385 sensors, it's often about as good as ITS-90, especially when the temperature range isn't very wide. If your certificate states coefficients R0, A, B, C, they are coefficients for IEC 60751 standard form CvD equation. Coefficient C is only used below 0°C, so it may be absent if the sensor was not calibrated below 0°C. The coefficients may also be R0, α, δ and β. They fit to the historically used form of CvD equation that is still in use. Regardless of being essentially the same equation, their written form and coefficients are different.

ITS-90

ITS-90 is a temperature scale, not a standard. The Callendar-van Dusen equation was the basis of the previous scales of 1927, 1948 and 1968, but ITS-90 brought significantly different mathematics. ITS-90 functions must be used when realizing the temperature scale using SRPTs, but also many lower-alpha PRTs benefit from it compared to CvD, especially when the temperature range is wide (hundreds of degrees). If your certificate states coefficients like RTPW or R(0,01), a4, b4, a7, b7, c7, they are coefficients for ITS-90 deviation functions. The ITS-90 document does not designate numerical notations for the coefficients or subranges. They are presented in NIST Technical Note 1265 "Guidelines for Realizing the International Temperature Scale of 1990" and widely adopted for use. The number of coefficients may vary and the subranges are numbered 1…11.

- RTPW, R(0,01°C) or R(273,16 K) is the sensor's resistance at the triple point of water 0.01°C
- a4 and b4 are coefficients below zero, may also be abz and bbz meaning "below zero," or just a and b
- a7, b7, c7 are coefficients above zero, may also be aaz, baz and caz meaning "above zero," or a, b and c

Steinhart-Hart

In case your sensor is a thermistor, you may have coefficients for Steinhart-Hart equation in the certificate. Thermistors are highly nonlinear and the equation is logarithmic. Steinhart-Hart equation has widely replaced the earlier Beta-equation. Usually the coefficients are A, B and C, but there may also be coefficient D or others, depending on the variant of the equation. The coefficients are usually published by manufacturers, but they can be fitted as well.

Finding out the sensor coefficients

When a Pt100 sensor is sent to a laboratory for calibration and fitting, the calibration points must be selected properly. A 0°C or 0.01°C point is always needed. The value itself is needed for fitting but typically ice point (0°C) or the triple point of water cell (0.01°C) is also used for monitoring the stability of the sensor and is measured several times during calibration. The minimum number of calibration points is the same as the number of coefficients that should be fitted. For example, for fitting ITS-90 coefficients a4 and b4 below zero, at least two known negative calibration points are needed to solve the two unknown coefficients. If the sensor's behavior is well known for the laboratory, two points might be enough in this case. Nevertheless, it's a good practice to measure more points than absolutely necessary, because there's no other way the certificate could tell how the sensor behaves between the calibration points. For example, CvD fitting for wide temperature range may look rather good if you only have two or three calibration points above zero, but there may be a systematic residual error of several hundredth parts of a degree between calibration points that you won't see at all. This also explains why you may find different calibration uncertainties for CvD and ITS-90 fitting for the same sensor and the exact same calibration points. Uncertainties of the measured points are no different, but the residual errors of different fittings are usually added to the total uncertainty.

Other "Temperature" related blog posts

If you are interested in temperature and temperature calibration, please take a look at these blog posts:

- Thermocouple Cold (Reference) Junction Compensation
- Temperature units and temperature unit conversion
- Calibration video: How to calibrate a temperature measurement loop
- How to calibrate an RTD HART temperature transmitter
- Measurement Uncertainty: Calibration uncertainty for dummies - Part 1

Thermocouple Cold (Reference) Junction Compensation

During the many years of working with process instrument calibration, it often surprises us that even people who work a lot with thermocouples don't always realize how the thermocouples, and especially the cold (reference) junction, works and therefore they can make errors in measurement and calibration.

In this article, we will take a short look at the thermocouple cold junction and the cold junction compensation. To be able to discuss the cold junction, we need to take first a short look into the thermocouple theory and how a thermocouple works.

We won't go very deep in the theoretical science but will stick more with practical considerations, the kind of things you should know when you work with thermocouple measurements and calibrations in a typical process plant.

Terminology: cold junction or reference junction

Thermocouple "cold junction" is often referred to as a "reference junction," but it seems to me that people use "cold junction" more often, so we will use that one in this text.

Thermocouples

Thermocouples are very common temperature sensors in process plants. Thermocouples have few benefits that makes them widely used. They can be used to measure very high temperatures, much higher than with RTDs (Resistance temperature detector). The thermocouple is also a very robust sensor, so it does not break easily. Although thermocouples are not as accurate as RTD sensors, they are accurate enough in many applications. Thermocouples are also relatively cheap sensors and the thermocouple measurement circuit does not require excitation current like an RTD circuit does, so the circuit is in that sense, more simple to make. There are many different thermocouple types optimized for different applications.

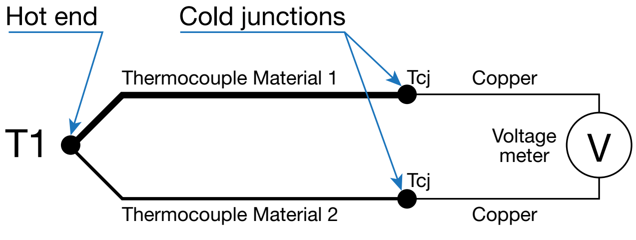
A thermocouple sensor seems very simple to use—just two wires—what could possibly go wrong?

But considering the cold junction, and all the junctions in the measurement circuit, it is not always as simple as it seems.

Let's start working our way towards the cold junction discussion, but before that, a few more words on the thermocouple theory to help better understand the cold junction discussion.

How does a thermocouple work?

Let's look at how a thermocouple works. A thermocouple consists of two wires made of different electrical conductors that are connected together at one end (the "hot" end), that is the end you want to use to measure the temperature with.
As discovered back in 1821 by Thomas Johann Seebeck, when the connection point of these wires is taken into different temperatures, there will be a thermo-electric current generated, causing a small voltage between the wires in the open end. The voltage depends on temperature and on the materials of the conductive wires being used. This effect was named as Seebeck effect.



Graph 1: Simplified principle picture of a thermocouple

In the above picture: the "Thermocouple material 1 and 2" represent the two different materials the thermocouple is made of, "T1" is the hot end of the thermocouple, i.e. the point that is used to measure temperature. The two "Tcj" are the temperatures of the cold junctions.

The above explanation is somewhat simplified, as the thermovoltage is actually generated by the temperature gradients in the thermocouple wire, all the way between the "hot" and "cold" junctions. So, it is not the junction points that actually generate the voltage, but the temperature gradient along the wire. It is easier to understand this by thinking that the thermovoltage is generated in the junctions, hot and cold ones. Maybe more scientific thermocouple theory can be provided in some other post later on, but in this one, let's stick with the practical considerations.

Thermocouple types and materials

There are many types of thermocouples being manufactured from different materials and alloys. Different materials will cause different sensitivity, different amount of thermovoltage being generated at the same temperature, and will affect other characteristics such as max temperature.

Several various thermocouple types have been standardized and names are given for specified materials being used. Names are typically very short names, often just one letter, such as type K, R, S, J, K, etc.

Some of the most common thermocouples and their materials are listed in the below table:

Type	Positive wire	Negative wire
B	70% Platinum 30% Rhodium	96% Platinum 6% Rhodium
E	Chromel	Constantan
J	Iron	Constantan
K	Chromel	Alumel
N	Nicrosil	Nisil
R	87% Platinum 13% Rhodium	Platinum
S	90% Platinum 10% Rhodium	Platinum
T	Copper	Constantan

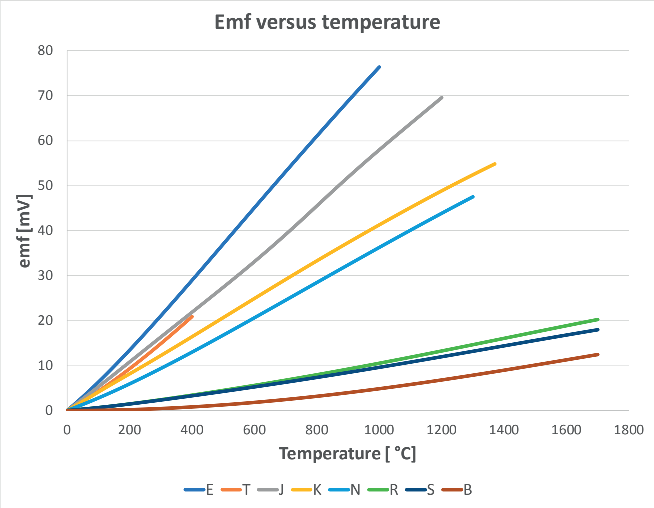
Wire colors

Good news is that the thermocouple wires are color coded for easier recognition.
Bad news is that there are many different standards for the color codes and they differ from each other.
The main standards are the IEC60584-3 (International) and ANSI (United States), but there are also many others, such as Japanese, French, British, Netherland, German, etc. standards. So unfortunately, it is a bit complicated to recognize the type by the color.

Thermocouple's thermovoltage

As different thermocouples are made of different materials, the thermovoltage is also different, this is illustrated in below picture. There is a big difference in the voltage being generated in the same temperature between the different types.

If you want to measure a lower temperature, it is obviously better to use the more sensitive types as they give a higher voltage which is easier to measure. But if you need to go to high temperatures, you need to choose some of the less sensitive types that can be used in such high temperatures.



Graph 2: Emf versus temperature

The Seebeck coefficient tells how much the thermocouple's voltage changes compared to a change in temperature. More on that later.

The above picture illustrating the different sensitivities between different thermocouples also explains why a thermocouple calibrator typically has different accuracy specifications for different thermocouple types. A measurement device, or calibrator, normally has the voltage measurement accuracy specified in voltage. For example, it can have an accuracy of 4 microvolts. This 4 microvolt accuracy equals a different temperature accuracy depending on the thermocouple type, due to the different thermocouple sensitivities.

Measurement device (calibrator) example

Let's look at the two extremities: the E and B type at 200°C temperature. The sensitivity (Seebeck coefficient) of type E at 200°C is about 74 µV/°C, while the coefficient for B type at 200°C is about 2 µV/°C. So, there is a difference of 37 times between these two.

For example, if your measurement device can measure with an electrical accuracy of 4 µV, that means that it offers accuracy of about 0.05°C (4 µV divided by 74 µV/°C) for the E type at 200°C, and accuracy of 2°C (4 µV divided by 2 µV/°C) with B type at 200°C.

So, we can see why there are often very different accuracy specifications for a thermocouple measurement device/calibrator for different thermocouple types.

Calibrator accuracy

If you see a data sheet of a temperature calibrator and it has the same accuracy specification for all thermocouple types, be careful! Normally this means that the specifications / data sheet has been done in the marketing department and not in the technical department… ;-)

This is just not very realistic.

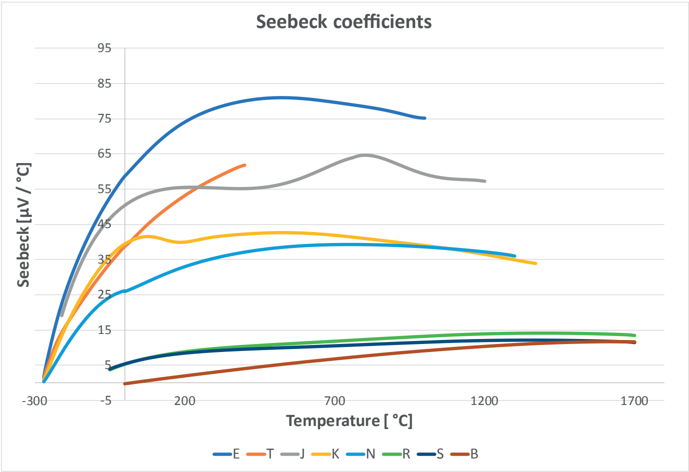
Standards

There are also some standards (for example AMS2750E) that require the same accuracy for all thermocouple types, and this does not make very much sense in practice, due to this huge difference in sensitivity with different types.

Seebeck coefficients

We already mentioned the Seebeck coefficient earlier. This is the sensitivity of the thermocouple, i.e. it explains how much voltage is generated per temperature change.

The below picture shows Seebeck coefficients for some different thermocouples:



Graph 3: Seebeck coefficient

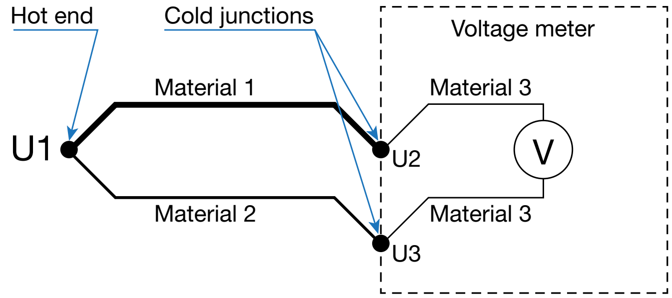
Cold junction

Earlier, we showed the picture of the simplified thermocouple principle showing that the thermovoltage is generated in the "hot" end connection, where the two different conductors are connected together. The big question you should be asking here is: But what about the other end of the wires?

What a good question! We are glad you asked… ;-)

When you measure the voltage of the thermocouple, you could connect the thermocouple wires into a multimeter, simple right? Not really! The multimeter connection material is typically copper or gold plated, so it is a different material than the thermocouple material, meaning you create two new thermocouples in the multimeter connections!

Let's illustrate that with a picture:



Graph 4: Cold Junction

In the above picture, the material 1 and material 2 are the two thermocouple materials that form the thermocouple. The "hot end" is the point where they are welded together and that is the point that measures process temperature, this is where the voltage U1 is generated. This U1 is what we want to measure. In the "cold junction" points, the thermocouple is connected to the voltage meter that has connections made of different material, material 3. In these connections, thermovoltage U2 and U3 are being generated. It is these U2 and U3 voltages that we do not want to measure so we want to get rid of these or to compensate them.

As we can see in the above picture, you are actually measuring the voltage of three (3) thermocouples connected in series. You would obviously like to measure only the voltage / temperature of the "hot" junction only and not the other two junctions.

So, what can you do?

You need to somehow eliminate or compensate for the thermocouples created in the cold junctions. There are different ways to do that. Let's look at those next.

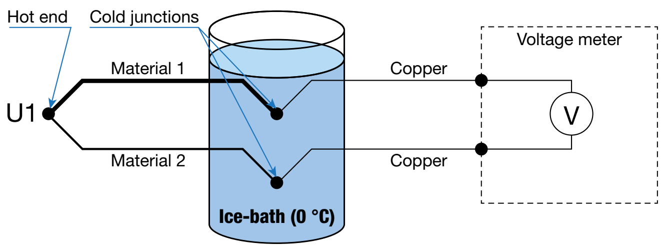
Cold junction compensation methods

1. Cold junction in ice-bath

By its nature, a thermocouple junction does not generate any thermovoltage when it is in 0°C (32°F) temperature. So, you could make the cold junction at that temperature, for example in an ice-bath or an accurate temperature block. You can connect the thermocouple wires into copper wires in the ice-bath, and there is no thermovoltage generated in that connection. Then you would not need to worry about the cold junction at all.

The connections need to be electrically isolated from the water in the ice-bath to avoid any leak currents causing errors, or possible corrosion being generated.

This is a very accurate way and it's something calibration laboratories typically do. It is anyhow not very practical on a process plant floor, so it is not normally used in process plants.



Graph 5: Cold junction in ice-bath

Example:

Type N thermocouple is connected as presented in the picture. Voltage meter shows 20808 µV. What is the measured temperature?

$E = E_N(t_{U1}) - E_N(tr)$

Where:

E = measured voltage = 20808 µV
$E_N(t_{U1})$ = voltage generated in hot junction
$E_N(t_r)$ = voltage generated in the cold (reference) junction
= 0 µV (IEC 60584 type N, 0°C)
$E_N(t_{U1}) = E + E_N(t_r)$ = 20808 µV + 0 µV = 20808 µV
= 605°C (IEC 60584 type N, 20808 µV)

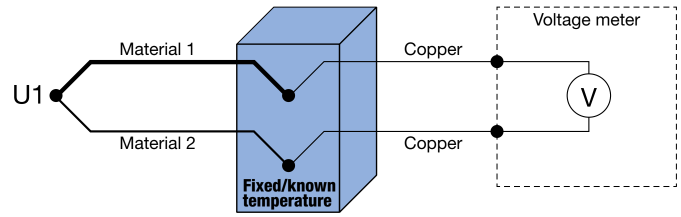
So, the temperature is 605°C.

2. Cold junction in a known, fixed temperature

Since the ice-bath was found to be impractical, you can also do the cold junction connection in some other known, fixed temperature. You can have a small connection box that has a temperature control keeping the box always at a certain temperature. Typically, the temperature is higher than environment temperature, so the box needs only heating, not cooling.

When you know the temperature that your cold junction is in, and you also know the type of your thermocouple, you can calculate and compensate the cold junction thermovoltage.

Many measurement devices or temperature calibrators have a functionality where you can enter the temperature of the cold junction and the device will do all the calculations for you and make the compensation.



Graph 6: Cold junction in a known, fixed temperature

Example:

Type N thermocouple is connected as presented in the picture. Voltage meter shows 19880 µV. The temperature of the cold (reference) junction is 35°C. What is the measured temperature?

$E = E_N(t_{U1}) - E_N(tr)$

Where:

E = measured voltage = 19880 µV
$E_N(t_{U1})$ = voltage generated by the hot end
$E_N(t_r)$ = voltage generated in reference (or cold) junction
= 928 µV (IEC 60584 type N, 35°C)
$E_N(t_{U1}) = E + E_N(t_r)$ = 19880 µV + 928 µV = 20808 µV
= 605°C (IEC 60584 type N, 20808 µV)

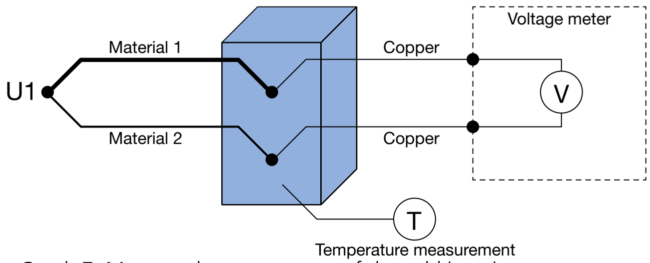
So, the measured temperature is 605°C.

Please note that thermocouple calculations must always be made in voltage. A common error is to look for the table value for the measured voltage and add the cold junction temperature. In this case, the corresponding temperature for the measured 19880 µV according to IEC 60584 standard is 581.2°C. Calculation using temperature values would give 581.2°C + 35°C = 616.2°C. The error is + 11.2°C.

3. Measure the temperature of the cold junction

If you don't adjust the cold junction temperature like in the previous example, you can anyhow measure the temperature of the cold junction with a temperature probe. You can then compensate the cold junction effect, but the compensation is a little bit more difficult as you need to measure the cold junction temperature all the time, and knowing your thermocouple type, make calculations to know the effect of the cold junction.

Luckily, many temperature calibrators provide a functionality to use a temperature probe to measure the cold junction temperature and the device makes all the compensations and calculations automatically.



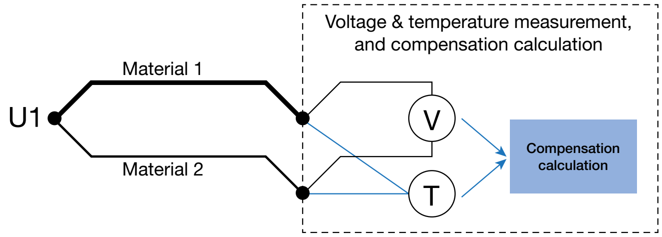
Graph 7: Measure the temperature of the cold junction

4. Automatic on-line compensation in the measuring device

We mentioned that the previous example was difficult as you need to calculate the compensation at all times, but you could leave that to the measuring device to do it automatically. The measuring device (being a transmitter, DCS input card or temperature calibrator) can be measuring the temperature of the cold junction all the time and automatically perform an on-line compensation of the cold junction error. Since the measuring device also knows the thermocouple type (you select that in the menu), it can make the compensation automatically and continuously.

This is naturally the easiest and most practical way to compensate the cold junction in normal measurements and calibrations, as you don't need to worry about the cold junction and leave for the equipment to take care of. You just plug in the thermocouple wire into the device.

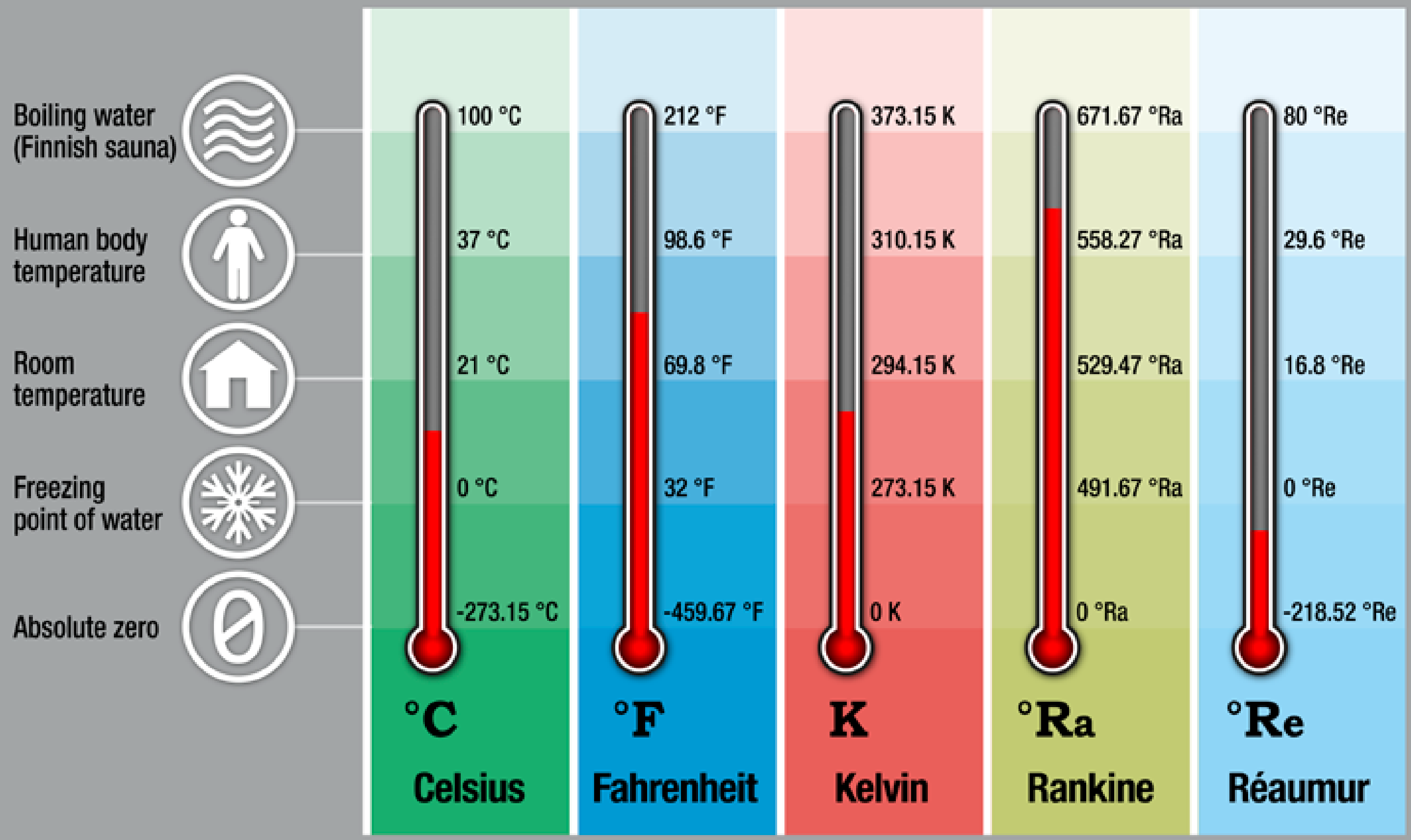
The Beamex temperature calibrators are also supporting this kind of automatic compensation.



Graph 8: Automatic on-line compensation in the measuring device

RELATED BEAMEX PRODUCTS

Several temperature calibrators support all the above-mentioned cold junction compensation methods.
As example, have a look at the Beamex MC6 calibrator for reference. MC6 has an automatic compensation of the internal reference junction. It also offers a versatile connector where you can connect different thermocouple connectors, or bare thermocouple wires.



Temperature units and temperature unit conversion

In this paper we discuss temperature, temperature scales, temperature units and temperature unit conversions. Let's first take a short look at what temperature really is, then look at some of the most common temperature units and finally the conversions between them.

What is temperature?

Temperature is an intensive quantity and describes the energy state of the matter. All materials have atoms and molecules that are in constant movement, vibrating or rotating. A difficult subject simplified, the more they move, the more temperature the material will have. The temperature of an object can be defined by the average kinetic energy of its atoms and molecules, a definition for temperature that we can understand relatively easily.

The temperature of an object can be defined by the average kinetic energy of its atoms and molecules, a definition for temperature that we can understand relatively easily.

Kelvin is the unit of fundamental physical quantity called thermodynamic temperature (T) and is currently defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water (exactly 0.01°C / 32.02°F).

So, what is hot and what is cold?

It is all pretty relative, so these terms hot and cold are not very accurate or scientific. Hence, we need a more specific way to indicate temperature. Several different temperature scales and units have been developed during the recent centuries. And since different scales have been used in different parts of the world, there are still several different scales in use. The actual specifications of some of the old temperature scales were not initially very accurate (such as a human's body temperature), but later on specific and accurate reference points and specifications were created.

For high temperatures, there is not really any limit, and it is possible to go to a very high temperature. For example, the temperature at sun's surface is 5800 kelvin, while the temperature inside the sun is up to 13.6 million of kelvins.

But for the low end of temperature, there is a very specific limit, being the absolute zero temperature, which is the lowest possible temperature. Absolute zero is a theoretical state that possibly cannot ever be achieved. Theoretically all the movement of atoms would cease almost completely, retaining only quantum mechanical zero-point energy. Absolute zero temperature equals 0 kelvin, -273.15 °Celsius or -459.67 °Fahrenheit. In outer space the temperature is pretty cold and the average temperature of universe is less than 3 kelvin.

But let's next take a look at some of the most common temperature scales and units.

International temperature scales

Thermodynamic temperature is very difficult to measure and several international temperature scales for practical measurements have been published:

- ITS-27; International Temperature Scale of 1927
- IPTS-48; International Practical Temperature Scale of 1948
- IPTS-68; International Practical Temperature Scale of 1968
- ITS-90; International Temperature Scale of 1990

Some additional scales have also been used, for example PLTS-2000 for improved measurements of very low temperatures in the range 0.9 mK...1 K (Provisional Low Temperature Scale of 2000).

By international agreement, the current ITS-90 scale is based on the before mentioned thermodynamic temperature (T). The scale defines the methods for calibrating a specified kind of thermometers in a way that the results are precise and repeatable all over the world. Also the numerical values are believed to be as close to the actual thermodynamic temperature (T) as possible at the time. The methods for realizing the ITS-90 temperature scale include fixed points and functions for interpolating the temperatures in between the fixed values.

The fixed points in the ITS-90 scale are the following:

Temperature units

Kelvin (K)

Kelvin is the base unit of temperature in the SI system (International System of Units). The Kelvin unit's abbreviation is K (no degree or degree sign). The Kelvin unit was first presented by William Thomson (Lord Kelvin) in 1848.

As mentioned earlier, Kelvin is currently defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water, absolute zero point being 0 K. The size of one Kelvin is the same as a Celsius degree. The temperature of melting ice is 273.15 K (the triple point of water is 273.16 K).

Kelvin is often used in science and technology. It is anyhow not that much used in everyday life. The symbol of kelvin temperature in terms of ITS-90 is the upper case letter T90.

A new definition of Kelvin is expected to be published in the near future linking Kelvin to the Boltzmann constant, continuing the work for defining all the SI units by fundamental physical constants.

Celsius (°C)

Celsius is currently a derived unit for temperature in the SI system, Kelvin being the base unit. The abbreviation of Celsius is °C (degree Celsius) and the size of one Celsius degree is the same size as one Kelvin. The unit and the actual Celsius scale was first presented by the Swede Andreas Celsius in 1742. The two main reference points of the Celsius scale were the freezing point of water (or melting point of ice) being defined as 0°C and the boiling point of water being 100°C.

The melting point of ice is a relative accurate specification (assuming you have purified ice and it is properly stirred), but the boiling temperature of water is not such an accurate temperature in practice as the boiling temperature depends a lot on the atmospheric pressure. As the Celsius is SI unit derived from Kelvin, it's also linked to ITS-90 and its symbol is lower case letter t90. In terms of ITS-90 the melting point of the ice is slightly below 0°C and the boiling point of the water at the normal atmospheric pressure is approximately 99.974°C.

The Celsius unit is better suited for everyday use than Kelvin and is very popular globally, although not so much used in the USA. A Celsius degree is sometimes also called Centigrade.

Fahrenheit (°F)

Fahrenheit unit's abbreviation is °F. The Fahrenheit scale was first introduced by a Dutchman named Gabriel Fahrenheit in 1724. The two main reference points of the scale are the freezing point of water being specified as 32°F and the temperature of human body being 96°F.

In practice it is easy to see that the temperature of a human body is not a very precise definition.

Nowadays the Fahrenheit scale is redefined in a way that the melting point of ice is exactly 32°F and the boiling point of water exactly 212°F. The temperature of the human body is about 98°F on the revised scale.

In many areas the Fahrenheit has been replaced

Substance and its state	Defining point			
	K	°C	°R	°F
Triple point of hydrogen	13.8033	-259.3467	24.8459	-434.8241
Triple point of neon	24.5561	-248.5939	44.2010	-415.4690
Triple point of oxygen	54.3584	-218.7916	97.8451	-361.8249
Triple point of argon	83.8058	-189.3442	150.8504	-308.8196
Triple point of mercury	234.3156	-38.8344	421.7681	-37.9019
Triple point of water	273.16	0.01	491.69	32.02
Melting point of gallium	302.9146	29.7646	545.2463	85.5763
Freezing point of indium	429.7485	156.5985	773.5473	313.8773
Freezing point of tin	505.078	231.928	909.140	449.470
Freezing point of zinc	692.677	419.527	1246.819	787.149
Freezing point of aluminum	933.473	660.323	1680.251	1220.581
Freezing point of silver	1234.93	961.78	2222.87	1763.20
Freezing point of gold	1337.33	1064.18	2407.19	1947.52
Freezing point of copper	1357.77	1084.62	2443.99	1984.32

Table 1: The fixed points in the ITS-90 scale

with Celsius as a temperature unit, but Fahrenheit is still is use in USA, the Caribbean and also in parallel use with Celsius in Australia and in UK.

Rankine (°R, °Ra)

Rankine scale is abbreviated as °R or °Ra. Rankine scale was presented by a Scottish man named William Rankine in 1859, so a few years after the Kelvin scale. The reference point of the Rankine scale is absolute zero point being 0 °R, like in Kelvin scale. The size of one Rankine degree is the same as the size of one Fahrenheit degree, but the zero point is very different. The freezing point of water equals 491.67 °Rankine.

Rankine is not a widely used scale. It was used in some fields of technology in USA, but NIST does not recommend the use of Rankine anymore.

Réaumur (°Ré, °Re)

Réaumur scales were introduced by Réne de Réaumur in 1730. It has the reference points being the freezing point of water 0 °Ré and boiling point of water being 80 °Ré.

The Réaumur scale was used in some parts of Europe and Russia, but it has mainly disappeared during the last century.

Conversions between temperature units

The table below provides calculation formulas for converting temperature readings from one unit to another unit.

Temperature unit converter

I know that the presented conversion table may not be the easiest one to use…

We developed a free and easy to use temperature unit converter on our web site that converts between the above listed five different temperature units. Hopefully you will find this converter helpful. Have a look: www.beamex.com/resources/temperature-unit-converter/

From\ To	To °C	To °F	To K	To °Ra	To °Re
From °C	1	$T_{(°C)} \times 1.8 + 32$	$T_{(°C)} + 273.15$	$(T_{(°C)} + 273.15) \times 1.8$	$T_{(°C)} \times 0.8$
From °F	$(T_{(°F)} - 32) / 1.8$	1	$(T_{(°F)} + 459.67) / 1.8$	$T_{(°F)} + 459.67$	$T_{(°F)} - 32) \times 4/9$
From K	$T_{(K)} - 273.15$	$T_{(K)} \times 1.8 - 459.67$	1	$T_{(K)} \times 1.8$	$(T_{(K)} - 273.15) \times 0.8$
From °Ra	$(T_{(°Ra)} - 491.67) / 1.8$	$T_{(°Ra)} - 459.67$	$T_{(°Ra)} / 1.8$	1	$(T_{(°Ra)} - 491.67) \times 4/9$
From °Re	$T_{(°Re)} / 0.8$	$T_{(°Re)} \times 9/4 + 32$	$T_{(°Re)} \times 1.25 + 273.15$	$T_{(°Re)} \times 9/4 + 491.67$	1

Table 2: calculation formulas for converting temperature readings from one unit to another unit

How to **calibrate** temperature sensors

Temperature measurement is one of the most common measurements in the process industry.

Every temperature measurement loop has a temperature sensor as the first component in the loop. So, it all starts with a temperature sensor. The temperature sensor plays a vital role in the accuracy of the whole temperature measurement loop.

As any measurement instrument you want to be accurate, also the temperature sensor needs to be calibrated regularly. Why would you measure temperature, if you don't care about the accuracy?

In this article, we will take a look at how to calibrate temperature sensors and what are the most common things you should consider when calibrating temperature sensors.

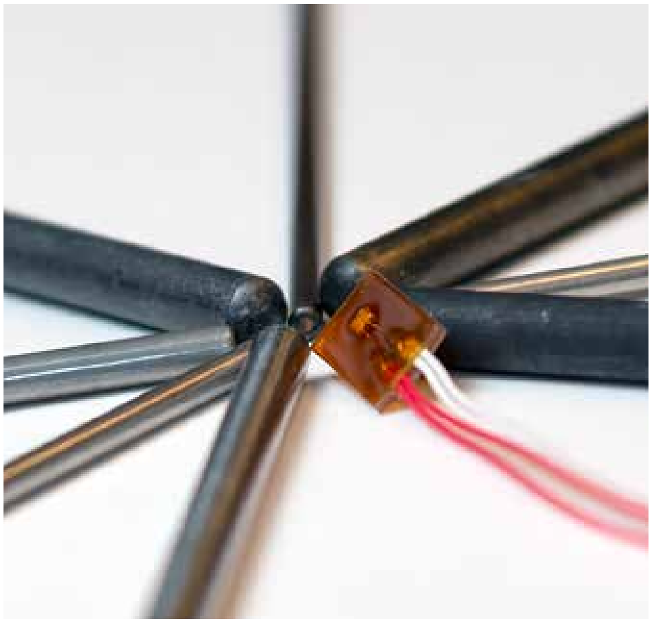
What is a temperature sensor?

Let's start from the basics... discussing what a temperature sensor is:

As the name indicates, a temperature sensor is an instrument that can be used to measure temperature. It has an output signal proportional to the applied temperature. When the temperature of the sensor changes, the output will also change accordingly.

There are various kinds of temperature sensors that have different output signals. Some have a resistance output, some have a voltage signal, some have a digital signal and many more.

In practice, in industrial applications, the signal from temperature sensor is typically connected to a temperature transmitter, that will convert the signal into a format that is easier to transfer for longer



distances, to the control system (DCS, SCADA). The standard 4 to 20 mA signal has been used for decades, as a current signal can be transferred longer distances and the current does not change even if there is some resistance along the wires. Nowadays transmitters with digital signals or even wireless signals are being adopted.

Anyhow, to measure temperature, the measuring element that is used is the temperature sensor.

Measuring the temperature sensor output

As most temperature sensors have an electrical output, that output obviously needs to be measured somehow. That being said, you need to have a measurement device to measure the output, resistance or voltage, for example.

The measurement device often displays an electrical quantity (resistance, voltage), not temperature. So it is necessary to know how to convert that electrical signal into a temperature value.

Most standard temperature sensors have international standards that specify how to calculate the electrical/temperature conversion, using a table or a formula. If you have a non-standard sensor, you may need to get that information from the sensor manufacturer.

There are also measuring devices that can display the temperature sensor signal directly as temperature. These devices also measure the electrical signal (resistance, voltage) and have the sensor tables (or polynomials/formulas) programmed inside, so they convert it into temperature. For example, temperature calibrators typically support the most common RTD (resistance temperature detector) and thermocouple (T/C) sensors used in the process industry.

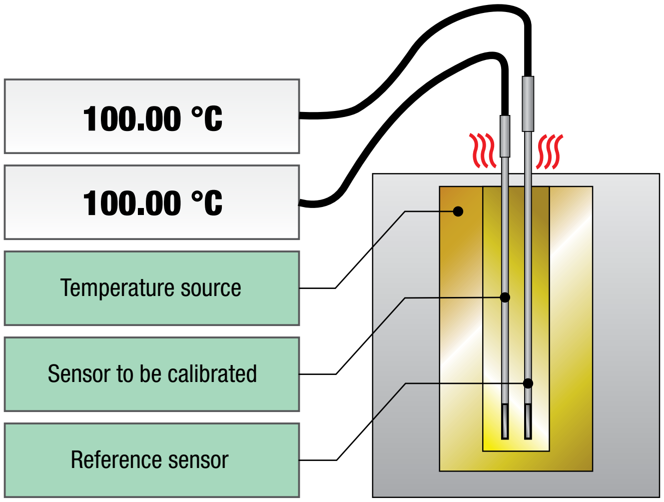
So how to calibrate a temperature sensor?

Before we go into the various things to consider when calibrating a temperature sensor, lets take a look at the general principle.

First, since the temperature sensor measures temperature, you will need to have a known temperature to immerse the sensor in to calibrate it. It is not possible to “simulate” temperature, but you must create a real temperature using a temperature source.

You can either generate an accurate temperature, or you can use a calibrated reference temperature sensor to measure the generated temperature. For example, you may insert the reference sensor and the sensor to be calibrated into a liquid bath (preferably a stirred one) and you can perform calibration at that temperature point. Alternatively, a so called dry-block temperature source can be used.

As an example, using a stirred ice-bath provides pretty good accuracy for the 0°C (32°F) point calibration.



For industrial and professional calibration, typically temperature baths or dry-blocks are used. These can be programmed to heat or cool the temperature into a certain set point.

In some industrial applications, it is a common practice to replace temperature sensors on regular intervals and not to calibrate the sensors regularly.

How to calibrate temperature sensors—things to consider

Lets start digging into the actual calibration of temperature sensors and the different things to consider....

1. Handling temperature sensor

Different sensors have different mechanical structures and different mechanical robustness.

The most accurate SPRT (standard platinum resistance thermometer) sensors, used as reference sensors in temperature laboratories, are very fragile. Our temperature calibration laboratory people say that if a SPRT touches something so that you can hear any sound, the sensor must be checked before any further use.

Luckily most of the industrial temperature sensors are robust and will survive normal handling. There are some industrial sensors that are made very robust and then can withstand pretty rough handling.

But if you are not sure of the structure of the sensor you should calibrate, it is better to be safe than sorry. It's never wrong to handle any sensor as if it was a SPRT.

In addition to mechanical shocks, a very fast change in temperature can be a chock to the sensor and damage it or affect the accuracy.

Thermocouples are typically not as sensitive as RTD probes.

2. Preparations

There are normally not that many preparations, but there are some things to take into account. First, a visual inspection is performed in order to see that the sensor looks ok and make sure it has not been bent or damaged, and that the wires look ok.

External contamination can be an issue, so it is good to know where the sensor has been used and what kind of media it has been measuring. You may need to clean the sensor before calibration, especially if you plan to use a liquid bath for calibration.

The insulation resistance of an RTD sensor can be measured in prior to calibration. This is to make sure that the sensor is not damaged and the insulation between the sensor and the chassis is high enough. A drop in insulation resistance can cause error in measurements and is a sign of a sensor damage.

3. Temperature source

As mentioned, you need to have a temperature source to calibrate a temperature sensor. It is just not possible to simulate temperature.

For industrial purposes, a temperature dry-block is most commonly used. It is handy and portable and typically accurate enough.

For higher accuracy needs, a liquid bath can be used. That is anyhow not typically easily portable but can be used in laboratory conditions.

For zero Centigrade point, a stirred ice-bath is often used. It is pretty simple and affordable yet provides a good accuracy for the zero point.

For the most accurate temperatures, fixed-point cells are being used. Those are very accurate, but also very expensive. Those are mostly used in accurate (and accredited) temperature calibration laboratories.

4. Reference temperature sensor

The temperature is generated with some of the heat sources mentioned in the previous chapter. You obviously need to know with a very high degree of accuracy the temperature of the heat source. Dry-blocks and liquid baths offer an internal reference sensor that measures the temperature. But for more accurate results, you should be using a separate accurate reference temperature sensor that is inserted in the same temperature as the sensor(s) to be calibrated. That kind of reference sensor will more accurately measure the temperature that the sensor to be calibrated is measuring.

Naturally the reference sensor should have a valid traceable calibration. It is easier to send a reference sensor out for calibration than sending the whole temperature source (it is good also to keep in mind the temperature gradient of the temperature block if you always only have the reference sensor calibrated not the block).

As for thermodynamic characteristics, the reference sensor should be as similar as possible compared to the sensor to be calibrated, to ensure they behave the same way during temperature changes.

The reference sensor and sensor to be calibrated should be immersed in the same depth in the temperature source. Typically, all sensors are immersed to the bottom of a dry-block. With very short sensors, it gets more difficult as they will only immerse a limited depth into the temperature source, and you should make sure that your reference sensor is immersed equally deep. In some cases, this requires a dedicated short reference sensor to be used.

Using fixed-point cells, you don't need any reference sensor, because the temperature is based on physical phenomena and is very accurate by its nature.

5. Measuring the temperature sensor output signal

Most temperature sensors have an electrical output (resistance or voltage) that needs to be measured and converted to temperature. So, you need to have some device to be used for the measurement. Some temperature sources offer also a measurement channels for the sensors, both device under test (DUT) and reference.

If you measure the electrical output, you will need to convert that into temperature, using international standards. In most industrial cases, you will use a measurement device that can do the conversion for you, so you can see the signal conveniently in the temperature unit (Centigrade or Fahrenheit).

What ever means you use for the measurement, make sure you know the accuracy and uncertainty of the device and ensure it has valid traceable calibration.

6. Immersion depth

Immersion depth (how deep you insert the sensor into temperature source) is one important consideration when calibrating temperature sensors.

Our temperature calibration lab people gave this rule of thumb when using a stirred liquid bath:

- 1% accuracy - immerse 5 diameters + length of the sensing element
- 0.01% accuracy - immerse 10 diameters + length of the sensing element
- 0.0001% accuracy - immerse 15 diameters + length of the sensing element

Heat conduction in a stirred liquid bath is better than in a dry-block and the required immersion depth is smaller.

For dry-blocks, there is an Euramet recommendation that you should immerse 15 times the diameter of the sensor added with the length of the sensor element. So, if you have a
6 mm diameter sensor, which has a 40 mm element inside, you immerse it (6 x 15 mm + 40 mm) 130 mm.

Sometimes it is difficult to know how long the actual element is inside the sensor, but it should be mentioned in the sensor specifications.

Also, you should be aware of where the sensor element is located (it is not always in the very tip of the sensor).

The sensor to be calibrated and the reference sensor should be immersed into the same depth so that the middle points of the actual sensor elements are in the same depth.

Naturally with very short sensors, it is not possible to immerse them very deep. That is one reason for the high uncertainty when calibrating short sensors.

Remember that a temperature sensor always measures its own temperature!

7. Stabilization

Remember that a temperature sensor always measures its own temperature!

Temperature changes pretty slowly and you should always wait long enough to have all parts stabilized to the target temperature. When you insert the sensor into a temperature, it will always take some time before the temperature of the sensor has reached that temperature and stabilized.

Your reference sensor and the sensor to be calibrated (DUT) may have very different thermodynamic characteristics, especially if they are mechanically different.

Often one of the biggest uncertainties related to temperature calibration can be that the calibration is done too quickly.

If you most often calibrate similar kinds of sensors, it is wise to make some type tests to learn the behavior of those sensors.

Often one of the biggest uncertainties related to temperature calibration can be that the calibration is done too quickly.

8. Temperature sensor handle

The sensor handle part, or the transition junction, typically has a limit of how hot it can be. If it is heated too hot, the sensor may be damaged. Make sure you know the specifications of the sensors you calibrate.

If you calibrate in high temperatures, it is recommended to use a temperature shield to protect the sensor handle.

9. Calibrated temperature range

With temperature sensors, it is pretty common that you don't calibrate the whole temperature range of the sensor.

The very top of the range is something you should be careful in calibrating. For example, a RTD sensor can drift permanently if you calibrate it in too high temperature.

Also, the coldest points of the sensor's temperature range can be difficult/expensive to calibrate.

So, it is recommended to calibrate the temperature range that the sensor is going to be used in.

10. Calibration points

In industrial calibration, you need to pick enough calibration points to see that the sensor is linear. Often it is enough to calibrate 3 to 5 points throughout the range.

Depending on the sensor type, you may need to take more points, if you know that the sensor may not be linear.

If you calibrate platinum sensors and you plan to calculate coefficients based of the calibration results, you will need to calibrate at suitable temperature points to be able to calculate the coefficients. The most common coefficients for the platinum sensors are the ITS-90 and Callendar van Dusen coefficients. For thermistors, Steinhart-Hart coefficients can be used.

When sensors are calibrated in an accredited laboratory, the points may also be selected based on the lab's smallest uncertainty.

11. Adjusting / trimming a temperature sensor

Unfortunately, most temperature sensors can not be adjusted or trimmed. So, if you find an error in calibration, you cannot adjust that. Instead you will need to use coefficients to correct the sensor's reading.

In some cases, you can compensate the sensor error in other parts of the temperature measurement loop (in transmitter or in DCS).

Other things to consider

Documentation

As with any calibration, the temperature sensor calibration needs to be documented in a calibration certificate.

Traceability

In calibration, the reference standard used, must have a valid traceability to National Standards, or equivalent. The traceability should be an unbroken chain of calibrations each having stated uncertainties.

More info on metrological traceability, please see the blog post [Metrological Traceability in Calibration – Are you traceable?]

Uncertainty

As always in calibration, also in temperature sensor calibration, you should be aware of the total uncertainty of the calibration process. In temperature calibration the calibration process (the way you do the calibration) can easily be by far the biggest uncertainty component in the total uncertainty.

More information on calibration uncertainty, please see the blog post [Calibration uncertainty for dummies].

Automating the calibration

Temperature calibration is always a pretty slow operation since temperature changes slowly and you need to wait for the stabilization. You can benefit a lot, if you can automate your temperature calibrations. The calibration will still take long time, but if it is automated, you don't need to be there to wait for it.

This will naturally save time and money for you.

Also, when automated, you can be sure that the calibration gets always done the same way.

BEAMEX OFFERING

Please check what Beamex can offer you for temperature calibration or for temperature calibration services.

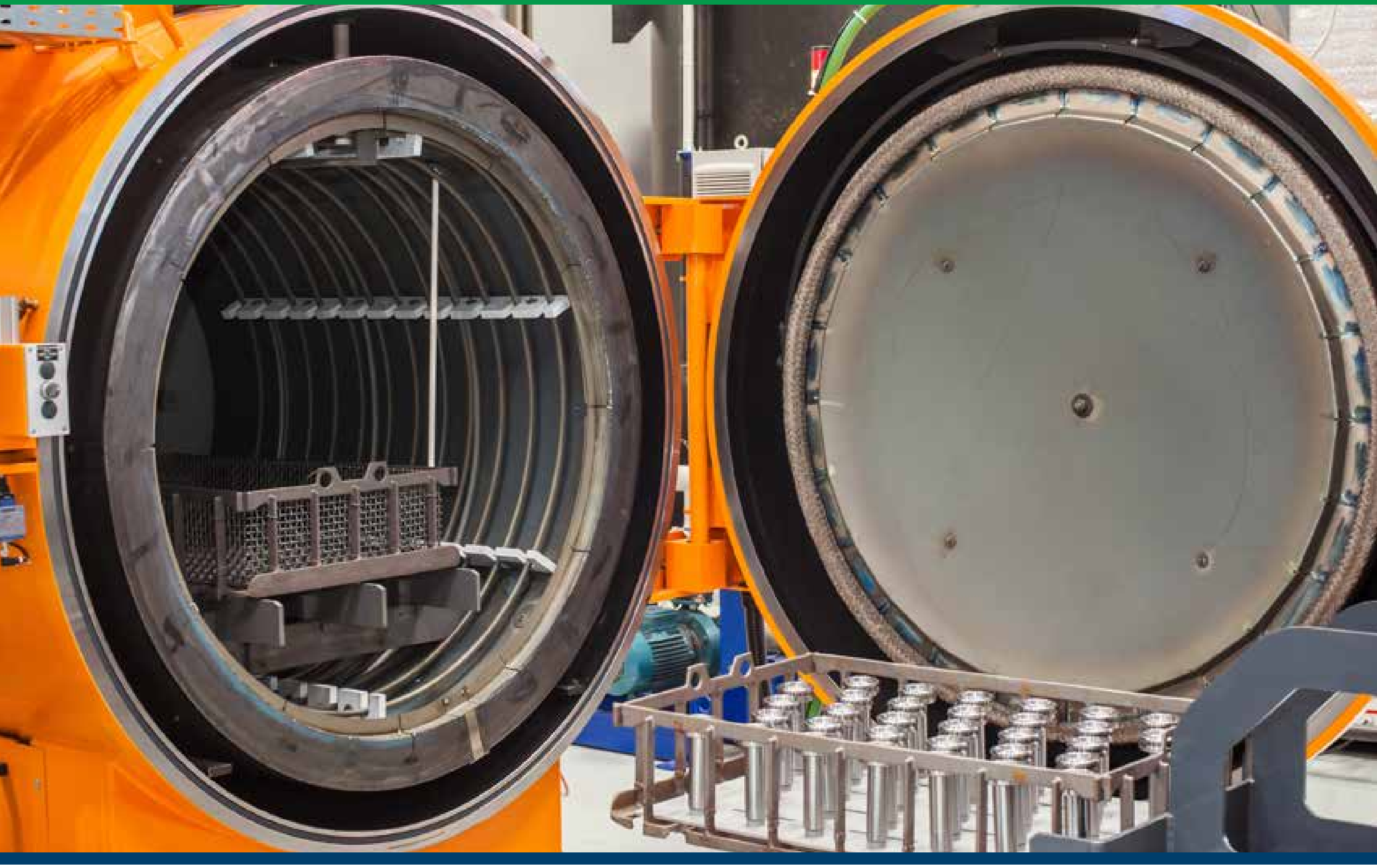
Beamex temperature calibration products

RELATED BLOG POSTS

If you found this blog post interesting, you may also like these ones listed below. Please feel free to browse all the articles in the Beamex blog, maybe you find some interesting articles to read.

- Uncertainty components of a temperature calibration using a dry block
- Pt100 temperature sensor – useful things to know
- Thermocouple Cold (Reference) Junction Compensation
- Temperature units and temperature unit conversion
- How to calibrate temperature instruments [Webinar]

Thanks to our accredited temperature calibration laboratory persons for their help in making this article. Special thanks to Mr. Toni Alatalo, the head of our accredited temperature laboratory!



AMS2750E heat treatment standard and calibration

In this white paper, we will take a look at the AMS2750E standard, with a special focus on the requirements set for accuracy, calibration and test/calibration equipment.

The AMS2750E is predominantly designed for heat treatment in the aerospace industries. Heat treatment is an essential process for many critical parts of an airplane, so it is understandable that there are tight regulations and audit processes set.

While the results and success of some other industrial processes can be relatively easily measured after the process, this is not the case in a heat treatment process. Therefore, very tight control and documentation of the heat treatment process is essential to assure the quality of the end products.

AMS2750 standard

As mentioned, the AMS2750E is a standard for heat treatment. The “AMS” name in the standard is an abbreviation of “Aerospace Materials Specifications”. The standard is published by SAE Aerospace, part of SAE International Group. The first version of the AMS2750 standard was published in 1980. Followed by revisions: revision A in 1987, B also in 1987, C in 1990 and D in 2005. The current revision AMS2750E was published in 2012.

The AMS2750 standard was initially developed to provide consistent specifications for heat treatment through the aerospace supply chain. The use of the standard is audited by PRI (Performance Review Institute) for the Nadcap (National Aerospace and Defense Contractors Accreditation Program). Prior to Nadcap, aerospace companies each audited their own suppliers, so there was a lot of redundancy and duplication of efforts. In 1990, the PRI was established to administer the Nadcap program.

AMS2750E scope

According to the standard itself, the scope of the AMS2750E standard is the following:

"This specification covers pyrometric (high temperature) requirements for thermal processing equipment used for heat treatment. It covers temperature sensors, instrumentation, thermal processing equipment, system accuracy tests, and temperature uniformity surveys. These are necessary to ensure that parts or raw materials are heat treated in accordance with the applicable specification(s)".

Why heat treatment?

In some industrial processes, it is relatively easy to measure and check the quality of the final product and judge if the product fulfills the requirements after the process is complete. You may be able to simply measure the end product and see if it is good or not. In other processes where it is not possible/easy/practical to measure the quality of the final product you need to have a very tight control and documentation of the process conditions, in order to be sure that the final product is made according to the requirements.

It is easy to understand that heat treatment is a process where you need to have a very good control in order to assure that you get the required end product, especially since the products are mostly used by the aerospace industry.

Who is it for?

The AMS2750E is predominantly designed for the aerospace industries. But the same standards and processing techniques can be used within any industry which requires control of the thermal processing of raw materials and manufactured components, such as automotive, rail and manufacturing.

What about the CQI-9?

The CQI-9 is a similar set of requirements for heat treatment, mainly aimed for the automotive industry. The first edition of CQI-9 was published in 2006. The CQI-9 "Heat Treatment System Assessment" is a self-assessment of the heat treatment system, published by AIAG (Automotive Industry Action Group). More details about CQI-9 maybe in an other article later on.

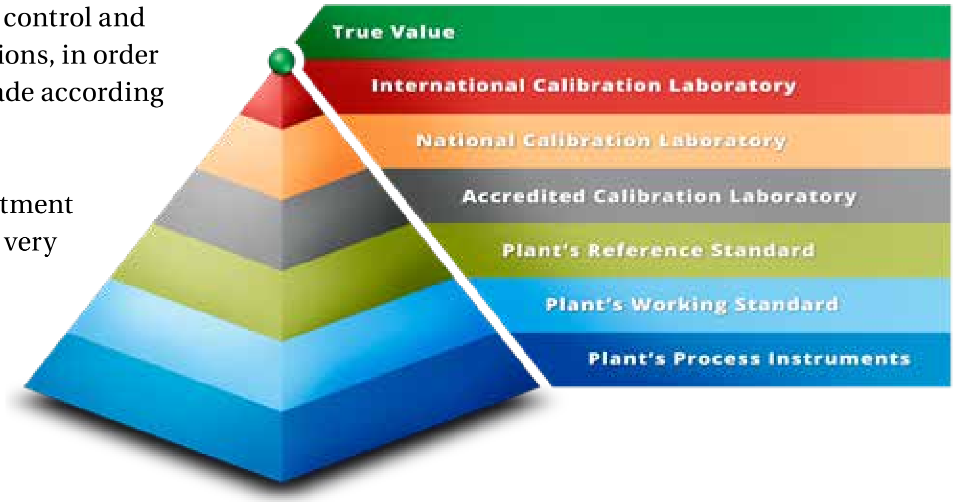
Test instruments and calibration

Let's discuss Test Instruments (calibrators) and what AMS2750E says about them.

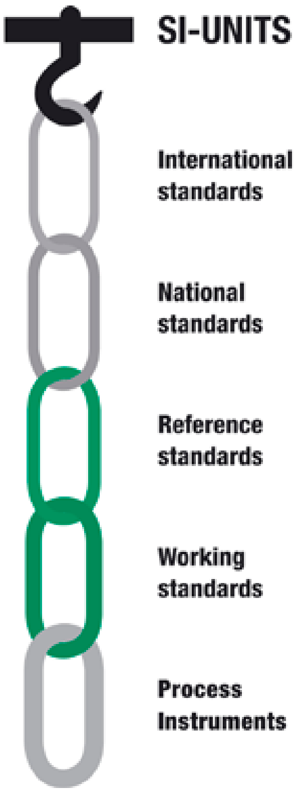
A traceable calibration of different levels of measurement instruments is obviously required. The higher level standards are typically calibrated in an external calibration laboratory. The process measurements are calibrated internally using "field test instruments".

Traceability is often described as traceability pyramid, or as a traceability chain:

Traceability pyramid:



Traceability chain:



To learn more about the metrological traceability in calibration read this blog post:

[Metrological Traceability in Calibration – Are you traceable?]

In Table 3 in the AMS2750E standard, there are different specifications for the test standards and test equipment/calibrators. The different levels of instruments are classified as follows:

- Reference standard
- Primary standard
- Secondary standard instruments
- Secondary standard cell
- Field test instrument
- Controlling, monitoring or recording instruments

For each instrument class, there are specifications for the calibration period and calibration accuracy. If we think about calibrators/calibration equipment, it is typically used as "field test instrument" or sometimes as "secondary standard instrument."

Secondary standard instrument

Limited to laboratory calibration of field test instruments, system accuracy test sensors, temperature uniformity survey sensors, load sensors and controlling, monitoring or recording sensors

Field test instrument

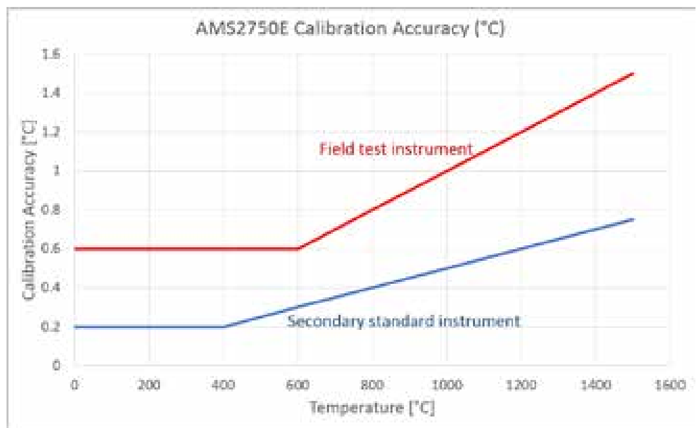
Calibration of controlling, monitoring, or recording instrument, performance of system accuracy tests, and temperature uniformity surveys

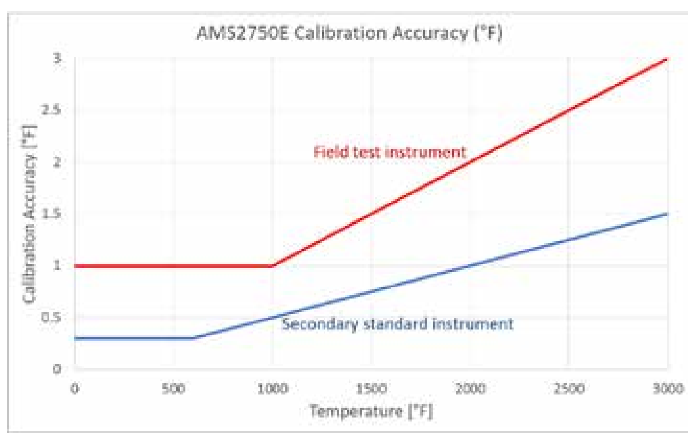
AMS2750E accuracy requirements

AMS2750E also specifies the calibration period and accuracy requirements for the different levels of instruments:

Instrument	Max calibration period (months)	Calibration accuracy
Secondary standard instrument	12	±0.3°F (±0.2°C), or ±0.05% of reading, whichever is greater
Field test instrument	3	±1°F (±0.6°C), or ±0.1% of reading, whichever is greater

Sometimes it is easier to look at a visual, so let's look at the required calibration accuracy graphically for "field test instrument" and "secondary standard instrument". And as the Centigrade and Fahrenheit are different, below is a graph of both:





Contradiction with different thermocouples types and accuracy

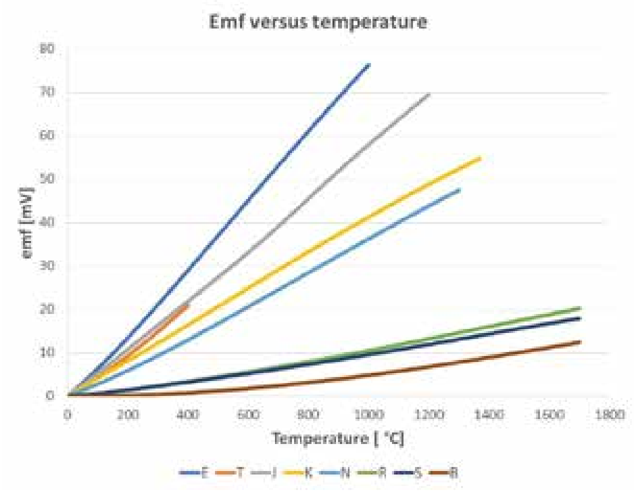
The AMS2750E standard specifies different thermocouple types for different usage. Types B, R and S are included for more demanding use, while types J, E, K, N, T are also included in the standard.

The standard has the same accuracy specification regardless of the thermocouple type. This is a slightly strange requirement, as different thermocouples have much different sensitivities.

In practice, this means that a test field instrument (calibrator) normally has a specification for millivoltage, and when this mV accuracy is converted to temperature it means that the calibrator normally has different specifications for different thermocouple types. Some thermocouple types have very low sensitivity (voltage changes very little as temperature changes), especially in the lower end.

For example - a calibrator can have an electrical specification of 4 microvolts at 0 V. With a K type, this 4 µV equals a temperature of 0.1°C (0.2°F), but for a S type, this equals 0.7°C (1.3°F), and for a B type it equals almost 2°C (3.6°F). Therefore, calibrators normally have very different accuracy specifications for different thermocouple types.

To illustrate the different sensitivities of different thermocouple types, please see the graphics below:



To learn more about thermocouples, different thermocouple types and thermocouple cold junction compensation, please read this blog post: [Thermocouple Cold (Reference) Junction Compensation]

AMS2750E contents in a nutshell

Let's take a brief look at the contents of the AMS2750E standard and further discuss a few key points in the standard.

The AMS2750E standard starts with sections:

1. Scope
2. Applicable documents

Chapter 3 "Technical Requirements" of AMS2570E includes the following key sections. (These sections are discussed in more details in the next chapters):

3.1. Temperature sensors
3.2. Instrumentation
3.3. Thermal processing equipment
3.4. System Accuracy Tests (SAT)
3.5. Furnace Temperature Uniformity Survey (TUS)
3.6. Laboratory furnaces
3.7. Records
3.8. Rounding

The remaining sections are:

4. Quality assurance provisions
5. Preparation for delivery
6. Acknowledgement
7. Rejections
8. Notes

3.1 Temperature sensors

Section 3.1 discusses temperature sensors. Some key bullets from that section:

- The AMS2750E standard specifies the thermocouple sensors to be used, as well as the sensor wire types
- The voltage to temperature conversion standard to be used (ASTM E 230 or other national standards)
- Correction factors may be used to compensate for the errors found in calibration

The temperature range for the sensors used

- Allowance to use wireless transmitters
- Contents of a sensor calibration certificate
- The max length of sensor wire/cable
- The max number of usage of thermocouples in different temperatures
- Types of thermocouple sensors to be used, the use for thermocouples (primary calibration, secondary calibration, sensor calibration, TUS, SAT, installation, load sensing), calibration period for thermocouples, and maximum permitted error

3.2 Instrumentation

Section 3.2 covers the instrumentation that the sensors are used with. This includes control, monitoring, recording, calibration, instrumentation, etc.

- Instruments need to be traceably calibrated
- Minimum resolution/readability of test instruments (1°F or 1°C)
- Specifications for electronic records
- Contents of calibration sticker: Date, due date, performed by, any limitations
- Contents of calibration record: Instrument identification, make and model standard(s) used, calibration method, required accuracy, as found and as left data of each calibration point, offset, found/left, sensitivity, statement of acceptance or rejection, any limitations or restrictions, calibration date, due date, performed by, calibration company, signature, quality, organization approval

3.3 Thermal processing equipment

Section 3.3 discusses the furnace classification and the temperature uniformity requirements in each class. Going from class 1 having uniformity requirement of ±5°F / ±3°C, to class 6 with ±50°F / ±28°C.

3.4 System accuracy test (SAT)

Section 3.4 discusses the system accuracy tests (SAT). The SAT is an on-site test where the whole measurement loop (instrument / lead wire / sensor) is calibrated using appropriate calibration equipment. This is typically done by placing a reference thermocouple close to the thermocouple to be calibrated and comparing the read-out of the measurement loop to the reference.

SAT shall be performed with a “field test instrument,” specified in the standard’s Table 3. SAT should be performed periodically or after any maintenance. SAT interval is based on equipment class and instrumentation type.

SAT test records shall include:

- identification of sensor calibrated
- ID of reference sensor
- ID of test instrument
- Date and time
- Set points
- Readings of furnace under test
- Test instrument readings
- Test sensor correction factors
- Corrected test instrument reading
- Calculated system accuracy difference
- An indication of acceptance or failure
- Who performed the test
- Signature
- Quality organization approval

3.5 Temperature uniformity surveys (TUS)

Section 3.5 is about furnace temperature uniformity survey (TUS). The TUS is the testing of the temperature uniformity in all sections/zones of the furnace in the qualified operating range. An initial TUS needs to be performed for any new, modified (example modifications are listed in the standard) or repaired furnace, and thereafter it should be performed in accordance with the interval specified in the standard. For furnaces with multiple qualified operating ranges, TUS shall be performed within each operating range.

There are many detailed specifications for TUS testing in the AMS2750E standard.

The TUS report shall include:

- Furnace identification
- Survey temperatures
- Sensor location and identification including detailed diagrams
- Time and temperature data from all sensors
- Correction factors for sensors in each temperature
- as found and as left offsets
- Corrected/uncorrected readin)gs of all TUS sensors at each temperature
- Testing company identification and signature identification of the person who performed the survey
- Survey start date and time
- Survey end date and time
- Test instrumentation identification
- Identification of pass or fail
- documentation of sensor failures (when applicable)
- Summary of corrected plus and minus TUS readings at each temperature after stabilization
- Quality organization approval

An example customer case story

Here's an example case story of Trescal, UK. They are a calibration service provider for aerospace customers and have to follow the AMS2750 standard. Trescal have found Beamex calibrators (MC2, MC5 and MC6) as a good fit for the work they do. Click the link below to read the case Trescal story:
Case story: Trescal, UK - Extreme accuracy calibrations for aerospace giant

Summary

The AMS2750E specifications set a high standard for the aerospace industry. After reviewing sensor technology and the challenges for test equipment to make proper measurements, meeting accuracy requirements takes careful analysis and continuous supervision. It should be noted that the AMS2750E specifications are not easily met and accurate test equipment must be utilized. By addressing calibration requirements up front, maintenance personnel will be equipped with the proper tools and procedures to not only maintain compliance but ensure the best product quality. Good sensor measurements set the stage for good process control with repeatable results – a good formula for staying in business.

Beamex solutions for AMS2750Ej

Beamex offers various temperature calibration products that can be used (and are being used) in an AMS2750E environment. You can find the detailed information of our offering on our website in the below link:
Beamex temperature calibration products

Please contact us for information on how our products can be used in an AMS2750 environment.

RELATED BLOG POSTS

If you found this article interesting, you might also like these:

Pt100 temperature sensor – useful things to know

Thermocouple Cold (Reference) Junction Compensation

Temperature units and temperature unit conversion

Metrological Traceability in Calibration – Are you traceable?

Q&A session with Deutsche Edelstahlwerke

We asked a few questions from one of our customers who is following the AMS2750 standard. Please see the questions and answers below:

Tell us a little about you and your company?

I am Julian Disse (Team Coordinator Quality Assurance Special Standards) at Deutsche Edelstahlwerke.

Deutsche Edelstahlwerke is one of the world's leading manufacturers of special steel long products. Deutsche Edelstahlwerke can look back on over 160 years of experience in the production of high-grade steel products. The range of products is unique worldwide and includes tool steels, stainless, acid- and heat-resistant steels, engineering and bearing steels, and special materials. The product portfolio ranges from 0.8 mm drawn wire to forged products of up to 1,100 mm in diameter. Deutsche Edelstahlwerke customers receive the entire manufacturing chain from a single source: from production to prefabrication to heat and surface treatment. Deutsche Edelstahlwerke is a company of the SCHMOLZ + BICKENBACH Group.

More information on Deutsche Edelstahlwerke can be found at www.dew-stahl.com

What do you think is the biggest challenge to follow the AMS2750E standard?

- Building, rebuilding or modifying a furnace to meet all requirements for each furnace class.
- Documentation in line with requirements.
- Qualification of all external suppliers for the calibration of devices and sensors according to the calibration traceability chain required by the AMS2750.

By who are you being audited against the AMS2750 standard?

Since 2016 we are certified by the NADCAP management council, audited by the Performance Review Institute.

What would you consider being your most critical measurement?

Every measurement in our furnaces is extremely relevant. Determining and maintaining temperature accuracy plays an essential role in our process safety. In this case, temperature measurement and simulation is the most important measurement for us.

What are the most common instruments to be calibrated?

Mainly, instruments for pressure measurement, temperature instruments for monitoring, controlling, recording and verification as well as sensors like resistance thermometer and thermocouples.

Which are your most common temperature sensor types and their rough shares?

- Thermocouples:
  Type K 60%, N 10%, B 10% and S 10%
- Resistance Thermometer 90% of all RTDs are Pt100 α385; 10% are Pt1000 α385

Which are your important measurement ranges for temperature sensors?

- Type K: 0°C - 1200°C in 100 K steps
- Type N: 0°C - 1200°C in 100 K steps
- Type B: 400°C - 1300°C in 100 K steps
- Type S: 0°C - 1300°C in 100 K steps
- Pt100: -200°C - 850°C
- Pt1000: -200°C - 850°C

Which thermocouple types do you use and in which application?

Type	Use on AMS2750 Furnace	Use on normal Furnace
K	Over temperature protection	TC for controlling, recording, monitoring,
N	SAT-TC, TC for controlling, recording, monitoring, verification	X
S	SAT-TC, TC for controlling, recording, monitoring,	TC for controlling, recording, monitoring,
B	TC for controlling, recording, monitoring, verification	TC for controlling, recording, monitoring,

Q&A session cont.

What kind of field test equipment do you use?

For us it is very important to fulfill all requirements regarding the AMS2750, other specification and our own quality standards. Due to this, we need a reliable field-test-instrument with a small range of measurement uncertainty. Beamex MC5 as Field-Test-Instrument fulfills our requirements.

To achieve the best calibration standard, an accredited laboratory calibrates our Beamex MC5 according to the German national standard DAkkS annually. Beamex MC6 is used as our secondary standard.

What is the metrological traceability chain like at your site?

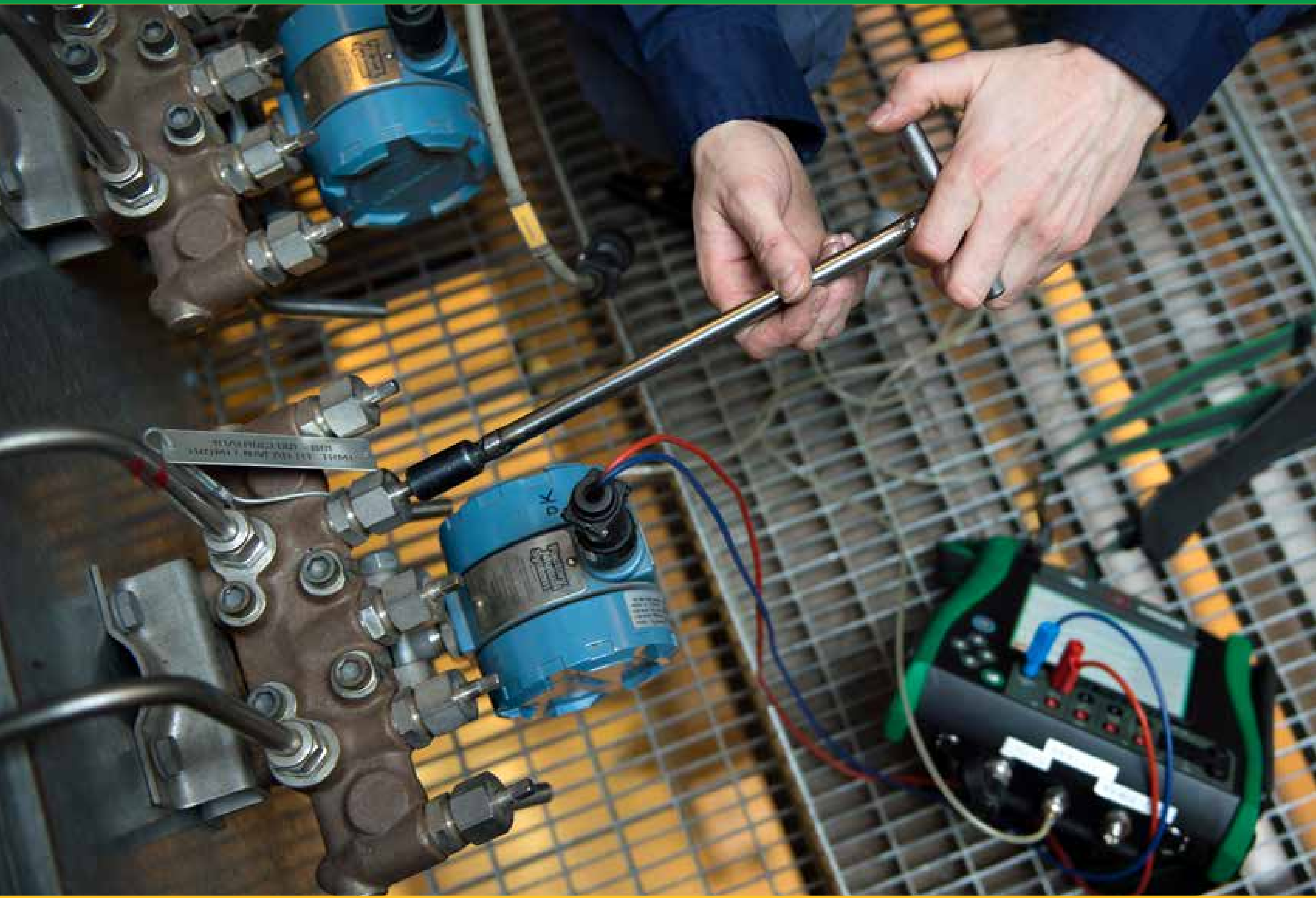
Short version:

- Reference standard: PTB (Physikalisch-Technische Bundesanstalt Deutschland)
- Primary standard: external laboratory for calibration (Reference Standard as Reference)
- Secondary standard: Our MC6 (DAkkS as reference)
- Field-test-standard: Our MC5 (MC6 as reference)
- Instruments: Siemens S7 TC IN (MC5 or MC6 as reference)

Finally, what do you think are the best advantages of the Beamex equipment?

Mainly:

- Interface communication module
- Paperless documentation with calibration management software
- The system creates electronic records that can be reviewed, but cannot be altered
- Easy handling, device settings are easy to understand
- It´s possible to handle and set the device with gloves
- Reduction of wrong connection for different type of measurement or simulation
- It’s possible to use different modules simultaneously
- Long battery life
- Small measurement uncertainty
- Long historical experience in our department
- Modular hardware for individual use of the calibrator



Optimal testing parameters for process instrument calibration

Abstract

Most calibration technicians follow long-established procedures at their facility that have not evolved with instrumentation technology. Years ago, maintaining a performance specification of ±1% of span was difficult, but today's instrumentation can easily exceed that level on an annual basis. In some instances, technicians are using old test equipment that does not meet new technology specifications. This paper focuses on establishing base line performance testing where analysis of testing parameters (mainly tolerances, intervals and test point schemes) can be analyzed and adjusted to meet optimal performance. Risk considerations will also be discussed—regulatory, safety, quality, efficiency, downtime and other critical parameters. A good understanding of these variables will help in making the best decisions on how to calibrate plant process instrumentation and how to improve outdated practices.

Introduction and background

The most basic question facing plant calibration professionals is how often should a process instrument be calibrated? There is not a simple answer, as there are many variables that effect instrument performance and thereby the proper test interval, these include:

- Manufacturer's guidelines (a good place to start)
- Manufacturer's accuracy specifications
- Stability specification (short term vs. long term)
- Process accuracy requirements
- Typical ambient conditions (harsh vs. climate controlled)
- Regulatory or quality standards requirements
- Costs associated with a failed condition

The next question for a good calibration program is what is the "Pass/Fail" tolerance? Again, there is no simple answer and opinions vary widely with little regard for what is truly needed to operate a facility safely while producing a quality product at the best efficiency. A criticality analysis of the instrument would be a good place to start. However, tolerance is intimately related to the first question of calibration frequency. A "tight" tolerance may require more frequent testing with a very accurate test standard, while a less critical measurement that uses a very accurate instrument may not require calibration for several years.

What is the best way to determine and implement proper testing procedures and practices is another question to be answered. In most cases, methods at a particular site have not evolved over time. Many times, calibration technicians follow practices that were set up many years ago and it is not uncommon to hear, "this is the way we have always done it." Meanwhile, measurement technology continues to improve and is becoming more accurate. It is also getting more complex—why test a fieldbus transmitter with the same approach as a pneumatic transmitter? Performing the standard five-point, up-down test with an error of less than 1% or 2% of span does not always apply to today's more sophisticated applications. As measurement technology improves, so should the practices and procedures of the calibration technician.

Finally, plant management needs to understand the tighter the tolerance, the more it will cost to make an accurate measurement. It is a fact that all instruments drift to some degree. It should also be noted that every make/model of instrument has a unique "personality" for performance in a specific process application. The only true way to determine optimum testing parameters is to somehow record calibration testing in a method that allows performance and drift to be analyzed. With good data and test equipment, the lowest, practical tolerance can be maintained while balancing that with an optimum schedule. Once these parameters are established, associated costs to perform a calibration can be estimated to see if there is justification to purchase a more sophisticated instrument with better performance specifications or purchase more accurate test equipment in order to achieve even better process performance.

Calibration testing basics

Optimum testing interval

Determining a proper testing interval is an educated guess based on several factors. A best practice is to set a conservative interval based on what the impact of a failure would be in terms of operating in a safe manner while producing product at the highest efficiency and quality. It is also important to determine what testing would have minimal impact on plant operations. By focusing on the most critical instruments first, an optimum schedule can be determined and would allow for less critical testing if personnel has availability.

Since all instrumentation drifts no matter the make/model/technology, suppliers end up creating vastly different specifications making it difficult to compare performance. Many times there are several complicating footnotes written in less than coherent terminology. Instrument performance is not always driven by price. The only true way to determine an optimum interval is to collect data and evaluate drift for a specific make/model instrument over time.

Starting off with a conservative interval, after three tests, a clear drift pattern may appear. For example, a particular RTD transmitter is tested every three months. The second test indicates a maximum error drift of +0.065% of span. The third test indicates another +0.060% of span (+0.125% of span over 6 months). While more data should be used for analysis, a good guess is that this instrument drifts +0.25% per year. Statistically, more data equates to a higher confidence level. If this pattern is common among many of the same make/model RTD transmitters in use throughout the plant, the optimum interval for ±0.50% of span tolerance could be set between 18 to 24 months with a very high level of confidence.

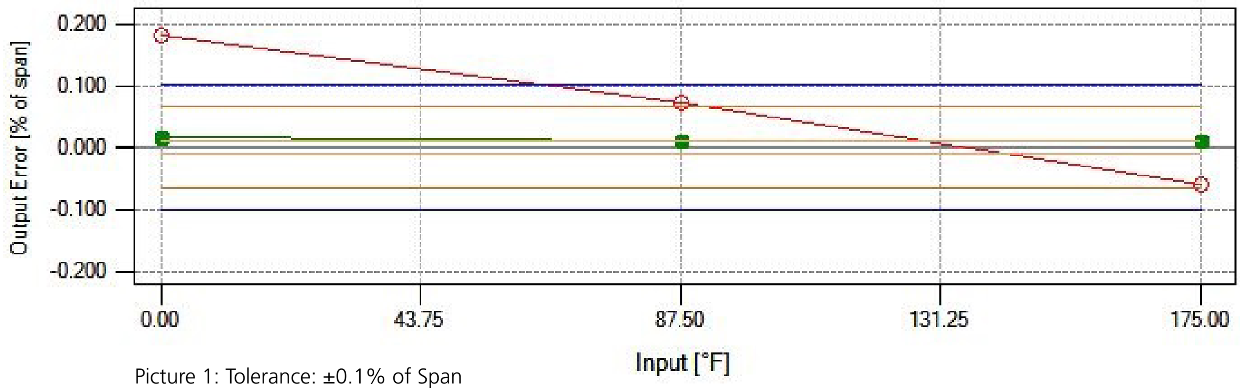
When collecting data on calibration, it is critical that unnecessary adjustments are not made. For example, if the tolerance is ±1% of span and the instrument is only out by -0.25% of span, an adjustment should not be made. How can drift be analyzed (minimum of three points) with constant adjustment? For certain "personalities," not adjusting can be a challenge, but every time an adjustment is made, drift analysis is compromised. A good metrology lab standard practice is to delay adjustment until a specification is out by 2/3 (or ±0.67% with a tolerance of ±1% of span). A best practice is to do the same with process instrumentation. This may be difficult for a conservative control engineer, however, an adjustment level of less than 1/2 of the tolerance will compromise drift analysis.

What if the drift is inconsistent, both increasing, then decreasing over time? More analysis is required; for instance, are the ambient conditions extreme or constantly changing? Depending on the process application, instrument performance may be affected by media, installation, throughput, turbulence or other variables. This situation indicates there is a level of "noise" associated with drift. When this is the case, analysis should show there is a combination random error and systematic error. Random error consists of uncontrollable issues (ambient conditions and process application) vs. systematic error that consists of identifiable issues (instrument drift). By focusing on systematic error and/or clear patterns of drift, a proper testing interval can be set to maximize operation efficiencies in the safest manner possible.

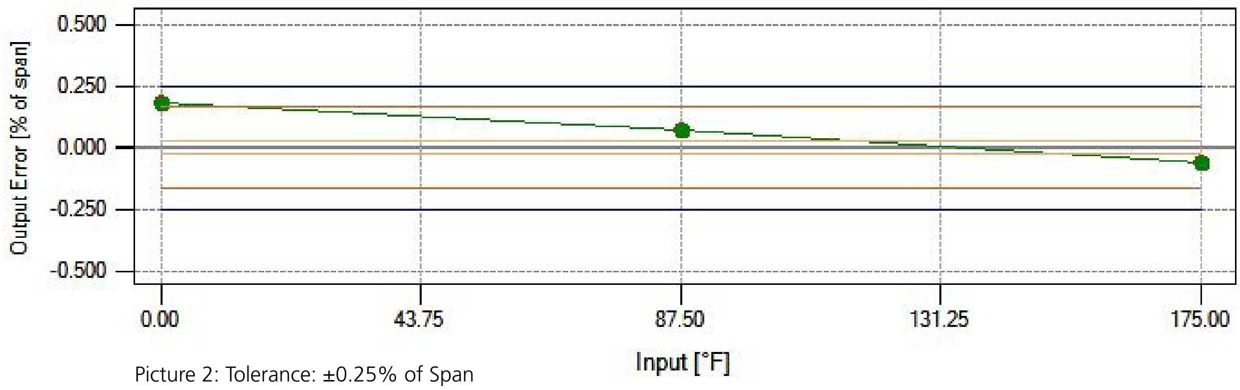
Setting proper process tolerance error limits

Accuracy, Process Tolerance, Reject Error, Error Limit, Error Allowed, Deviation, etc.—these are a few of the many terms used to specify instrument performance in a given process. Transmitter manufacturers always specify accuracy along with several more parameters associated with error (long term stability, repeatability, hysteresis, reference standard and more). When looking at setting a process tolerance, manufacturer accuracy offers a starting point, but it is not always a reliable number. Also, no measurement is better than the calibration standard used to check an instrument. What is behind a manufacturer's accuracy statement in making an accurate instrument? For pressure, a good deadweight tester in a laboratory should be part of the formula. At the plant level, a well-known rule of thumb is to have a 4:1 ratio for the calibrator's uncertainty (total error) vs. the process instrument tolerance.

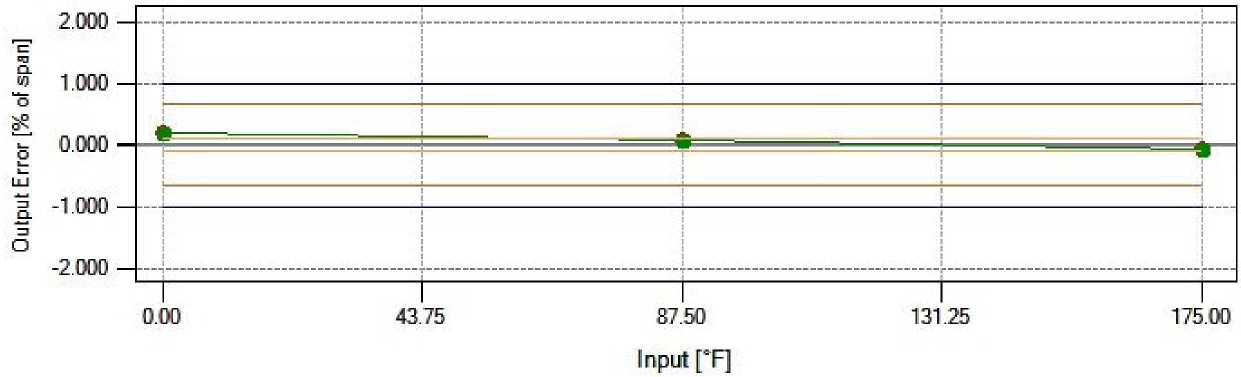
When setting a process tolerance, a best practice is to ask the control engineer what process performance tolerance is required to make the best product in the safest way? Keep in mind the lower the number, the more expensive the calibration costs may be. To meet a tight tolerance, a good calibration standards will be required. Also, another issue is to determine whether testing should be performed in the field or in the shop. If instrumentation is drifting, a more frequent interval



Picture 1: Tolerance: ±0.1% of Span



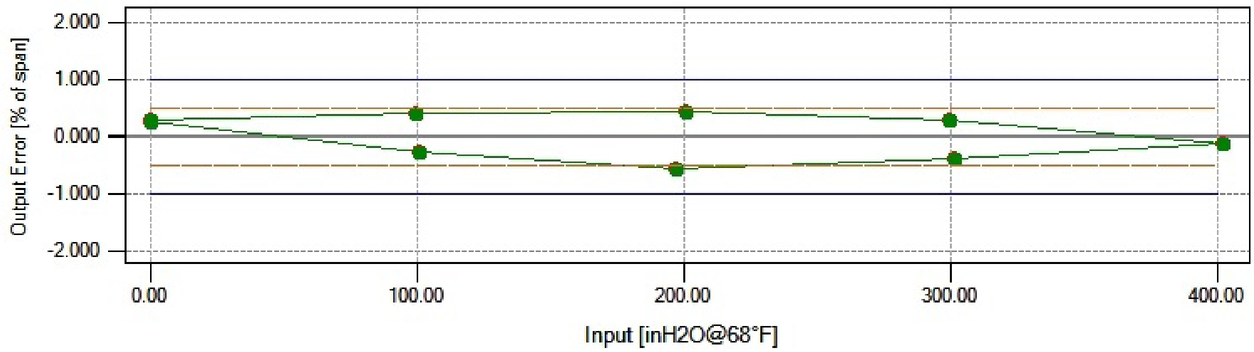
Picture 2: Tolerance: ±0.25% of Span



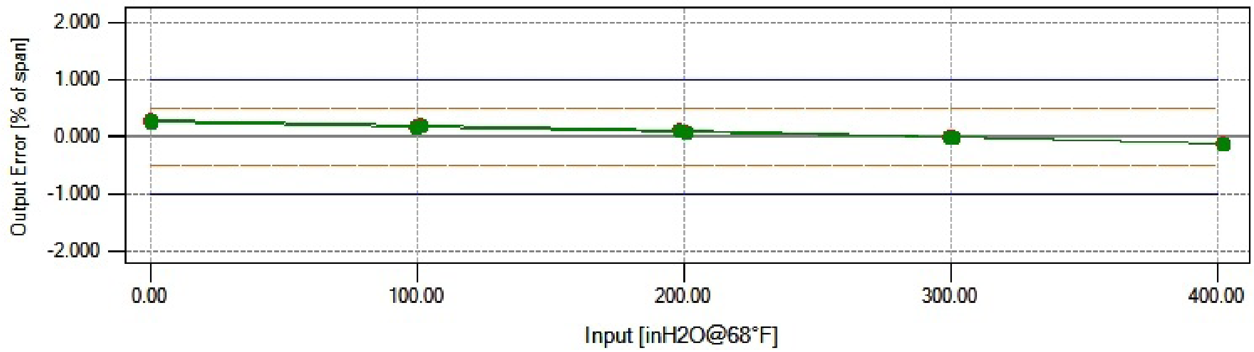
Picture 3: Tolerance: ±1% of Span

will need to be set to catch a measurement error. This may mean increased downtime along with the costs associated with making the actual calibration tests. As an example, review the three graphs of instrument performance:

Note the first graph shows a failure (nearly double the allowed value), the second shows an adjustment is required (barely passing) and the third shows a transmitter in relative good control. The test data is identical for all 3 graphs, the only difference is the tolerance. Setting a very tight tolerance of ±0.1% of span can cause several problems: dealing with failure reports, constant adjustment adds stress to the calibration technician, operations does not trust the measurement, and more. Graph #2 is not much better, there is not a failure but 0.25% of span is still a tight tolerance and constant adjusting will not allow analysis of drift nor for evaluation of random error or systematic error. There are many benefits in Graph #3 (note that ±1% of span is still a tight tolerance). If a failure were to occur, that would be an unusual (and likely a serious) issue. The calibration technician will spend less time disturbing the process and



Picture 4: 5-Point Up/Down Test with Hysteresis



Picture 5: 5_point Up/Down Test with No Hysteresis

overall calibration time is faster since there is less adjusting. Good test equipment is available at a reasonable cost that can meet a ±1% of span performance specification.

There may be critical measurements that require a demanding tolerance and thereby accrue higher costs to support, but good judgements can be made by considering true performance requirements vs. associated costs. Simply choosing an arbitrary number that is unreasonably tight can cause more problems than necessary and can increase the stress level beyond control. The best approach would be to set as high a tolerance as possible, collect some performance data and then decrease the tolerance based on a proper interval to achieve optimum results.

Testing parameters?

A subtle yet important detail is to review calibration procedures to see if further efficiencies can be gained without impacting the quality of the data. Years ago, technology was more mechanical in nature, board components were more numerous/ complex, and instruments were more sensitive to ambient conditions. Today's smart technology offers better accuracy and "brain power" with less, simplified components and with improved compensation capabilities. In many cases, old testing habits have not evolved with the technology. A good example is an older strain gauge pressure sensor that when starting from zero "skews" toward the low side as pressure rises due to the change from a relaxed state. Likewise, when the sensing element is deflected to its maximum pressure and as the pressure then decreases, there is a mechanical memory that "skews" the measure pressure toward the high end. This phenomenon is called hysteresis and graphically would resemble the graph #4 when performing a calibration.

Today's smart pressure sensors are much improved and hysteresis would only occur if something were wrong with the sensor and/or it has been damaged. If the same test was performed on a modern sensor, the typical graphical representation would look like this (Graph #5).

This may look simple, but it takes significant effort for a calibration technician to perform a manual pressure calibration with a hand pump. Testing at zero is easy, but the typical practice is to spend the effort to hit an exact pressure test point in order to make an error estimate based on the "odd" mA signal. For example, if 25 inH2O is supposed to be exactly 8 mA, but 8.1623 mA is observed when the pressure is set to exactly 25 inH2O, an experienced technician knows he is dealing with a 1% of span error (0.1623 ÷ 16 x 100 = 1%). This extra effort to hit a "cardinal" test point can be time consuming, especially at a very low pressure of 25 in H2O. In order to perform a 9-point check, it might take 5 minutes or more and makes this example test unnecessarily longer. It is possible to perform a 5-point check and cut the time in half – the graph would look identical as the downward test points are not adding any new information. However, a pressure sensor is still mechanical in nature and, as mentioned, could have hysteresis. A best practice would be to perform a 3-point up/down test on a pressure transmitter. The quality of the test point data is equivalent to a 9-point test and if there is hysteresis, it will be detected. This also places the least stress on the technician as there are only 3 "difficult" test points (zero is easy) compared to 4 points for a 5-point test and 7 for a 9-point up/down test. Savings can be significant over time and will make the technician's day to day work much easier.

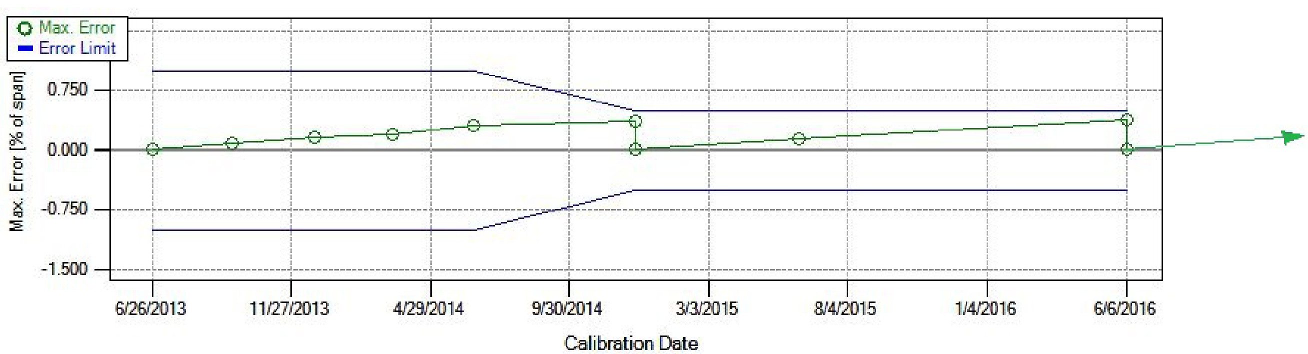
Using this same approach can work for temperature instrumentation as well. A temperature sensor (RTD or thermocouple) is electromechanical in nature and typically does not exhibit hysteresis – whatever happens going up in temperature is repeatable when the temperature is going down. The most common phenomenon is a "zero shift" that is indicative of a thermal shock or physical damage (rough contact in the process or dropped). A temperature transmitter is an electronic device and with modern smart technology exhibits excellent measurement properties. Therefore, a best practice is to perform a simple 3-point test on temperature instrumentation. If testing a sensor in a dry block or bath, testing more than 3 points is a waste of time unless there is a high accuracy requirement or some other practical reason to test more points.

There are other examples of optimizing test parameters. Testing should relate to the process; if the process never goes below 100°C, why test at zero? When using a dry block, it can take a very long time to reach a test point of 0°C or below – why not set an initial test point of 5°C with an expected output of 4.8 mA, for example, if it is practical and will save time and make testing easier. Another good example is testing a differential pressure flow meter with square root extraction. Since a flow rate is being measured, output test points should be 8 mA, 12 mA, 16 mA and 20 mA, not based on even pressure input steps. Also, this technology employs a "low flow cut-off" where very low flow is not measurable. A best practice is to test at an initial test point of 5.6 mA output (which is very close to zero at just 1% of the input span).

Do not overlook how specific tests are performed. Why collect unnecessary data? It is simply more information to process and can have a very significant cost. Why make the job of calibration harder? Look at the historical data and make decisions that will simplify work without sacrificing quality.

Calibration trend analysis and costs temperature transmitter example

As mentioned, the best way to optimize calibration scheduling is to analyze historical data. There is a balance of process performance vs. instrument drift vs. tolerance vs. optimum interval vs. cost of calibration and the only way to truly determine this is through historical data review. Using similar data for the temperature transmitter example in the Tolerance Error Limits section, apply the concepts to optimize the calibration schedule with this scenario (Graph #6):



Picture 6: History Trend Example

After a discussion between the Control Engineer and the I&C Maintenance group, a case was made for a tolerance of ±0.5% of span, but it was agreed that ±1% of span was acceptable until more information becomes available. This particular measurement is critical, so it was also agreed to test every 3 months until more information becomes available. At the end of the first year, a drift of approximately +0.25% of span per year was observed and no adjustments were made. After further discussion, it was agreed to lower the tolerance to ±0.5% of span (the Control Engineer is happy) and to increase the interval to 6 months. An adjustment was finally made 1-1/2 years after the initial calibration. At the end of year 2, no adjustment was required and the interval was increased to 1 year. At the end of year 3, an adjustment was made and the interval was increased to 18 months (now the Plant Manager, the I&C Supervisor and the I&C Technicians are happy). All this occurred without a single failure that might have required special reporting or other headaches.

Obviously this scenario is perfect, but if there are multiple instruments of the same make/model, strong trends will emerge with good historical data; affirming best practices and allowing best decisions to be made. For critical instrument measurements, most engineers are conservative and "over-calibrate". This example should open a discussion on how to work smarter, save time/energy and maintain a safe environment without compromising quality.

Cost of calibration

One other best practice is whenever possible, try to establish the cost to perform a given calibration and include this in the decision process. Consider not only the man hours, but the cost of test equipment, including annual recertification costs. When discussing intervals and tolerances, this can be very important information in making a smart decision. Good measurements cannot be made with marginal test equipment. As an example, in order to meet an especially tight pressure measurement tolerance, a deadweight tester should be used instead of a standard pressure calibrator—this is a huge step in equipment cost and technician experience/training. By outlining all the extra costs associated with such a measurement, a good compromise could be reached by determining the rewards vs. risks of performing more frequent testing with slightly less accurate equipment or by utilizing alternative test equipment.

Another overlooked operational cost is the critical need to invest in personnel and equipment. With either new technology or new test equipment, maintenance and/or testing procedures should be reinforced with good training. ISA offers several excellent training options and consider local programs that are available for calibration technicians via trade schools or industry seminars. Finally, a review of testing assets should be done annually to justify reinvestment by replacing old equipment. Annual recertification can be expensive, so when choosing new test equipment, look for one device that can possibly replace multiple items.

One other important cost to consider is the cost of failure. What happens when a critical instrument fails? If there are audits or potential shut-down issues, it is imperative to have a good calibration program and catch issues before they begin in order to avoid a lengthy recovery process. If test equipment comes back with a failed module, what is the potential impact on all the calibrations performed by that module in the past year? By understanding these risks and associated costs, proper decisions and investments can be made.

Conclusion

Obviously, not all instrumentation is going to offer easy analysis to predict drift. Also, calibration schedules get interrupted and many times work has to be done during an outage regardless of careful planning. In some areas there are regulatory requirements, standards or quality systems that specify how often instrument should be calibrated—it is difficult to argue with auditors. A best practice is to establish a good program, focusing on the most critical instruments. As the critical instruments get under control, time will become available to expand to the next level of criticality, and on and on.

Alternate or "hybrid" strategies should be employed in a good calibration management program. For example, loop testing can lower calibration costs, which is performing end-to-end tests and only checking individual instruments when the loop is out. A good "hybrid" strategy is to perform a "light" testing schedule combined with a less frequent "in-depth" test. As an example, make a minimally invasive "spot check" (typically one point) that has a lower tolerance than normal (use the recommended 2/3 of the normal tolerance value). Should the "spot check" fail, the standard procedure would be to perform the standard in-depth test in order to make necessary adjustments. A technician may have a route of 10 "spot checks" and end up only performing 1 or 2 in-depth tests for the entire route. Performing "spot checks" should still be documented and tracked, as good information about drift can come from this type of data.

To summarize, several best practices have been cited:

- Set a conservative testing interval based on what the impact of a failure would mean in terms of operating in a safe manner while producing product at the highest efficiency and quality
- Do not adjust until a tolerance specification is out by 2/3 (or ±0.67% with a tolerance of ±1% of span); this may be difficult for a conservative control engineer, however, an adjustment level of less than 1/2 of the tolerance will compromise drift analysis
- Ask the control engineer what process performance tolerance is required to make the best product in the safest way?
- Set as high a tolerance as possible, collect some performance data and then decrease the tolerance based on a proper interval to achieve optimum results
- Perform a 3-point up/down test on a pressure transmitter; the quality of the test point data is equivalent to a 9-point test and if there is hysteresis, it will be detected.
- Perform a simple 3-point test on temperature instrumentation. If testing a sensor in a dry block or bath, testing more than 3 points is a waste of time unless there is a high accuracy requirement or some other practical reason to test more points.
- Test a differential pressure flow transmitter with square-root extraction at an initial test point of 5.6 mA output (which is very close to zero at just 1% of the input span). Also, since a flow rate is being measured, the sequential output test points should be 8 mA, 12 mA, 16 mA and 20 mA, not based on even pressure input steps.
- Whenever possible, try to establish the cost to perform a given calibration and include this in the decision process.
- Focus on the most critical instruments, establish a good program and as the critical instruments get under control, time will become available to expand to the next level of criticality, and on and on.

Always keep in mind that instruments drift, some perform better than others. The performance tolerance set will ultimately determine the testing schedule. Via documentation, if there will be capability to distinguish systematic error (drift) from random error ("noise") and a systematic pattern emerges, an optimal test interval can be determined. The best tolerance/interval combination will provide good control data for the best efficiency, quality and safety at the lowest calibration cost with minimal audit failures and/or headaches. Establishing best practices for calibration should be a continuous evolution. Technology is changing and testing should evolve along with it. As discussed, there are many variables that go into proper testing – by establishing base line performance, as observed in the operating environment, smart decisions can be made (and modified) to operate at optimal levels when it comes to calibration.

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BEAMEX is a leading worldwide provider of calibration solutions with the sole purpose to create better ways to calibrate for the global process industry. Beamex offers a comprehensive range of products and services — from portable calibrators to workstations, calibration accessories, calibration software, industry-specific solutions and professional services. Through Beamex's subsidiaries, branch offices and an extensive network of independent distributors, their products and services are available in more than 80 countries. Beamex has more than 12,000 customers worldwide.

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