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CRITERIA FOR TEMPERATURE SENSOR SELECTION OF T/C AND RTD SENSOR TYPES

The Basics of Temperature Measurement Using Thermocouples
Part 1 of 3

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Background

Temperature reigns as the most often measured process parameter in industry. While temperature measurement utilizes sensors of many forms, the actual measurement of temperature is accomplished via only five basic sensor types: Thermocouple (T/C), Resistance Temperature Detector (RTD), Thermistor, Infrared Detector, and via semiconductor or integrated circuit (IC) temperature sensors. Of these five common types, the thermistor is perhaps the most commonly applied for general purpose applications. Semiconductor sensors dominate most printed circuit board or board level sensing applications. Infrared is used for non-contact line-of-sight measurement. But for industrial applications that typically employ remote sensing, thermocouples and RTD's reign as the most popular sensor types.

Most industrial applications require that a temperature be measured remotely, and that this signal be transmitted some distance. An industrial transmitter is commonly used to amplify, isolate, and convert the low-level sensor signal to a high level signal suitable for monitoring or retransmission. With respect to these transmitters, your choice of sensor type is generally limited to T/C, or RTD. But given the wide variety of RTD and T/C types, how do you choose the best sensor type for your specific application? This paper will look at important characteristics of these two main industrial sensor types and offer information to help you select the best type for your application. Part 1 explores the thermocouple. Part 2 looks at the RTD. Part 3 compares thermocouples and RTD's and gives information for choosing between them.

The Basics of Temperature Measurement Using Thermocouples

You are probably somewhat familiar with the thermocouple, or you wouldn't be reading this whitepaper. But there are important points about thermocouples that must be understood and that will help you to make an informed selection between sensor types and avoid potential problems in your application.

First, we need to clear up a common misconception about how thermocouples work. You may have been told something like "a thermocouple produces a small voltage created by the junction of two dissimilar metals". This simplification of the thermocouple is at best only half true, and very misleading. The reality is that it is the temperature difference between one end of a conductor and the other end that produces the small electromotive force (emf), or charge imbalance, that leads us to the temperature difference across the conductor.

OK, simple enough, but how do you actually measure this emf in order to discern its relationship to temperature?

The "emf" or electromotive force refers to a propensity level, or potential for current flow as a result of the charge separation in the conductor. We refer to this propensity for current flow between two points as its potential difference, and we measure this difference of potential in volts. But in order to actually measure the emf or voltage difference, we need two points of contact. That is, we must complete the circuit by adding a return electrical path. If we simply choose to use the same metal as a return path, the temperature difference between the ends of your original conductor would simply create an equal and opposite EMF in the return path that would result in a net EMF of zero--not very useful for measuring temperature. This relationship is expressed by the "Law of Homogeneous Material" as follows (see Wikipedia.org):

A thermoelectric current cannot be sustained in a circuit composed of a single homogeneous material by the application of heat alone, and regardless of how the material may vary in cross-section. That is, temperature changes in the wiring between input and output will not affect the output voltage, provided all wires are made of the same material as the thermocouple. No current flows in the circuit made of a single metal by the application of heat alone.

Different conductive metals will produce different levels of emf or charge separation relative to the thermal gradient across the metal. Thomas Seebeck discovered this principle in 1822 and it is known today as the "Seebeck Effect". Thus, we can apply the "Seebeck Effect" and make it useful for measuring temperature by using a different metal for our return path, and then relating the differences in charge separation between the two metals to the temperature between the ends. We join these metals at the start of our return path by forming a junction between them—that is, the junction simply joins our circuit and is not the source of the emf, as is often inferred by the traditional definition of a thermocouple.

Now at the other end of our closed thermocouple circuit, we can measure a voltage between the two wires that will be proportional to the temperature between the ends. By the Law of Homogeneous Materials expressed earlier, the thermocouple wires can each pass into and out of cold areas along their path without the measuring instrument detecting the temperature changes along the path because the emf created as the continuous wire enters and leaves an area will sum to zero and have no net effect on our final measurement.

We still have a conceptual problem though—how do we measure the voltage at the open end of our thermocouple without introducing additional "thermocouple" voltages into our measurement system. That is, the connection points of the T/C to the measurement system (which is typically copper) will itself act as a thermocouple. It turns out that the effect of these additional thermocouples on our measurement system can be minimized by simply making sure the connections are at the same temperature. This principle is expressed by "The Law of Intermediate Materials" as follows (see Wikipedia.org):

The algebraic sum of the thermoelectric emf's in a circuit composed of any number of dissimilar materials is zero if all of the junctions (normally at the cold junction) are maintained at a uniform temperature. Thus, if a third metal is inserted in either or both wires while making our cold junction connections, then as long as the two new junctions are at the same temperature, there will be no net voltage contribution generated by the new metal in our measurement system.

So our ability to overlook these unintended thermocouples in our measurement will depend on how well we can maintain both cold junction connections at the same temperature. This is often easier said then done and small thermal gradients will usually occur, often as a result of the self-heating of components across the circuit board. Other thermal gradients can be driven by heat generated from adjacent circuits, nearby power supplies, or via variable wind currents or cooling fans in the system. For any thermocouple transmitter, special care must be taken to minimize these sources of error (more on this later).

A third law for thermocouples that helps us combine emf's algebraically is "The Law of Successive or Intermediate Temperatures" stated as follows (see Wikipedia.org):

If two dissimilar homogeneous materials produce thermal emf1 when the junctions are at T1 and T2, and produce thermal emf2 when the junctions are at T2 and T3 , then the emf generated when the junctions are at T1 and T3 will be emf1 + emf2, provided T1<T2<T3.

Still, our measurement of the open-end voltage across our thermocouple only relates the thermoelectric voltage to the difference in temperature between both ends. That is, we need to know the temperature of the cold junction at one end in order to extract the sensed temperature from the other end (hot junction). Ideally, if both connections made at the measuring end were at 0°C, their thermoelectric equivalent voltage contributions to our measurement would be 0mV, and we could easily determine the sensed temperature directly from our measured voltage. Since this can't be easily assured, the actual temperature of the cold junction connection point is usually measured separately. Then the measured T/C signal can be compensated for the thermoelectric contribution of the connection point or "cold junction", and we can extract the actual temperature of the remote end of our thermocouple by a mathematical combination of either the measured temperature or its thermoelectric equivalent voltage. See Figure 1 of Page 6.

Although we could form a thermocouple by joining any two dissimilar conductors, a number of standard thermocouple types are available that utilize specific metals combined to produce larger predictable output voltages with respect to their thermal gradients. The most common types are listed in Table 1 below.

Table 1: Common Thermocouple Types and Their Applications

ANSI TYPE	JUNCTION MATERIALS	TYPICAL USEFUL MEASURE RANGE	NOMINAL SENSITIVITY	Atmospheric Media[1]			
				I	R	O	V
K[2]	Chromel (Nickel & Chromium) – Alumel (Nickel & Aluminum)	-184°C to 1260°C	39uV/°C	Yes	No	Yes	No
	Most common general purpose type with a wide temperature range and lowest cost. Good for high temperatures with good corrosion resistance. Positive lead is non-magnetic, while the negative lead is magnetic[2]. Good for clean oxidizing atmospheres but vulnerable to sulfur attack and should be kept from sulfurous atmospheres.						
J	Iron - Constantan	0°C to 760°C	55uV/°C	Yes	Yes	Yes	Yes
	Second-most common type but limited in range. Good for general purpose dry applications where moisture is not present. Positive iron wire is magnetic, while negative wire is non-magnetic. Lower service life due to fine wire size and rapid oxidation of iron wire at temperatures above 540°C, not recommended for sulfurous atmospheres above 540°C. Ok for use in vacuum, air, and reducing or oxidizing atmospheres up to 760° and in the heavier gage sizes. Limited sub-zero use due to rusting and embrittlement of the iron wire. Should not be used above 760°C due to an abrupt magnetic transformation at the Curie point of iron (~770°C) which changes its characteristic and can cause permanent de-calibration.						
E	Chromel (Nickel & Chromium) – Constantan	0°C to 982°C	76uV/°C	Yes	No	Yes	No
	Non-magnetic with highest output voltage offering the best sensitivity and suitable for cryogenic use. Recommended for use up to 900°C in oxidizing or inert atmospheres. Vulnerable to sulfur attack and should be kept from sulfurous atmospheres.						

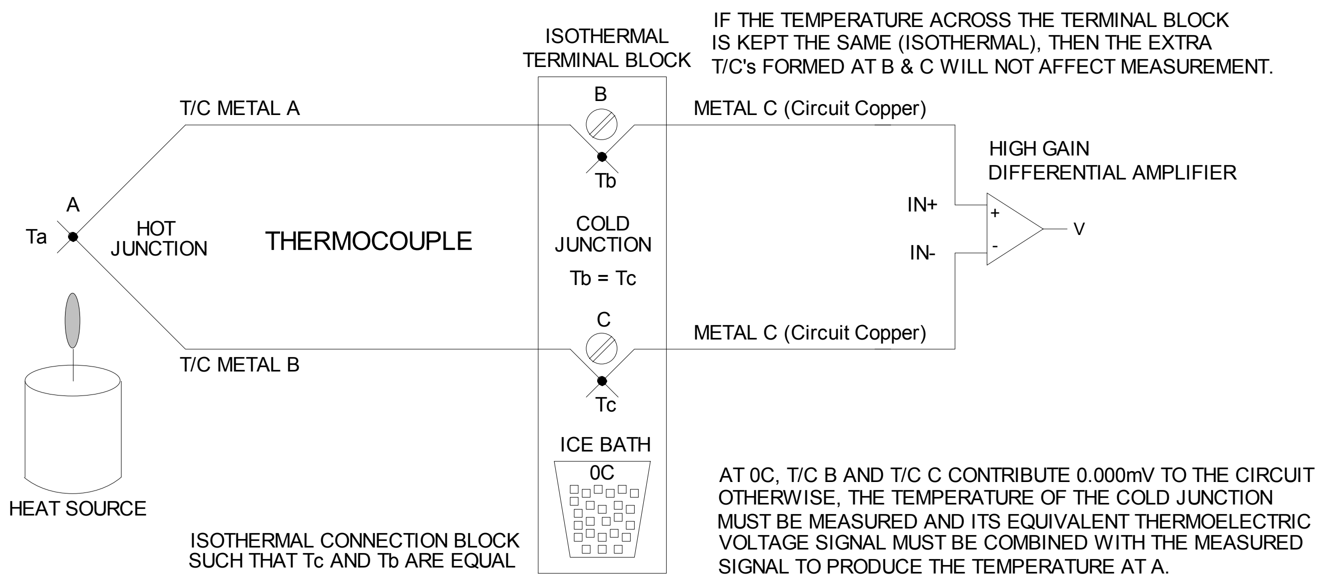
T	Copper - Constantan	-184°C to 400°C	45uV/°C	Yes	Yes	Yes	Yes
	Corrosion resistant from moisture and condensation and has high stability at low temperatures. Limits of error guaranteed for cryogenic temperatures and good for wet applications. Useful service in oxidizing, inert, or reducing atmospheres, or in a vacuum. Non-magnetic, useful up to about 370°C, very stable, and moisture resistant in air, appropriate for use down to -200°C.						
N	Nicrosil - Nisil	0°C to 1100°C	10.4uV/°C	Yes	Yes	Yes	Yes
	High stability and resistance to high temperature oxidation makes type N a lower cost alternative to B, R, and S types for some applications. Very accurate and reliable at high temperatures. Good for oxidizing, inert, or dry reducing atmospheres. Vulnerable to sulfur attack and should be kept from sulfur containing atmospheres						
*C	Tungsten (5%)/Rhenium – Tungsten (26%)/Rhenium	0°C to 2300°C	16uV/°C	Yes	No	No	Yes
	Recommended for high-temperature use in vacuum furnaces, high-purity hydrogen, or high-purity inert atmospheres. Must never be used in the presence of oxygen at temperatures above 260°C. Very poor oxidation resistance. *Not an ANSI type						
T/C types B, R, and S follow and are the most stable T/C types due to their low sensitivity (≤10uV/°C). T/C's with low sensitivity have lower resolution, are more expensive, and are typically only used for high temperatures.							
B	Platinum (6%)/Rhodium – Platinum (30%)/Rhodium	38°C to 1800°C	7.7uV/°C	Yes	No	Yes	Yes
	Least sensitive with lowest output voltage. For very high temperature applications. Always protected by high-purity ceramic. Because this type gives the same output at 0°C and 42°C, it is useless below 50°C. Useful in inert or oxidizing atmospheres, or for short periods of time in a vacuum. Easily contaminated and must be protected from reducing atmospheres and contaminating vapors.						
R	Platinum (13%)/Rhodium-Platinum	0°C to 1593°C	6uV/°C	Yes	No	Yes	Yes
	High temperature use. Usually with a ceramic sheath. Popular in UK. Useful in inert or oxidizing atmospheres, or short periods of time in a vacuum. Easily contaminated and must be protected from reducing atmospheres and contaminating vapors.						
S	Platinum (10%)/Rhodium – Platinum	0°C to 1538°C	10.4uV/°C	Yes	No	Yes	Yes
	Widest useful temperature range, but low sensitivity and high cost make it unsuitable for general purpose applications. Usually has a ceramic sheath. Useful in inert or oxidizing atmospheres, or short periods of time in a vacuum. Easily contaminated and must be protected from reducing atmospheres and contaminating vapors. Because of its high stability, type S is used as the standard for calibrating the melting point of Gold.						

Notes (Table 1):

1. From Table 1, the "I" designation refers to applications in Inert atmospheres, "R" refers to Reducing atmospheres, "O" refers to Oxidizing atmospheres, and "V" refers to operation in a vacuum. See below for a brief explanation of these environmental conditions.

2. The Type K thermocouples use the magnetic material Nickel. Magnetic materials will exhibit a step change in their output once they reach their Curie point, which for a Type K occurs at approximately 354°C. The Curie point refers to the temperature where a ferromagnetic material becomes paramagnetic when heated. For example, a magnet will lose its magnetism if heated above the Curie temperature. This is a reversible change on cooling for Nickel. Some Curie points for different materials are as follows: Iron (Fe) above 770°C, Cobalt (Co) above 1130°C, Nickel (Ni) above 358°C, and Iron Oxide (Fe_2O_3) above 622°C

FIGURE 1: A SIMPLIFIED THERMOCOUPLE MEASURING CIRCUIT



From Table 1, we see that the selection of a specific T/C type will be guided by the useful measurement range of the sensor, its sensitivity, its material, and its operating environment. Sensor cost may also play a role in this decision as certain types are more expensive than others—for example, the platinum based sensor types are generally more expensive by virtue of their platinum content.

Because materials used at extreme temperatures can be permanently altered by their application environment, you must also consider the atmospheric conditions of their application as noted in Table 1.

An "inert atmosphere" refers to an environment of a gaseous mixture that contains little or no oxygen and primarily consists of non-reactive gases, or gases that have a high threshold before they react. Nitrogen, argon, helium, and carbon dioxide are common components of inert gas mixtures.

A reducing or "reduction atmosphere" refers to an environment in which oxidation is prevented by the removal of oxygen and other oxidizing gases or vapors. This usually refers to environments containing nitrogen or hydrogen gas. For example, it is often imposed in annealing ovens to relax metal stresses and prevent metal corrosion. Nitrogen is also used in some electronic soldering ovens to improve the performance and/or appearance of the solder joint.

An “oxidizing atmosphere” is a gaseous environment in which the oxidation of solids readily occurs due to the presence of excess oxygen. Contrast this to the reducing atmosphere described above in which the available oxygen is reduced or eliminated. Many combustion processes will utilize oxidizing atmospheres. Many substances oxidize rapidly when heated sufficiently in the presence of free oxygen. The oxidation that results refers to the transformation that occurs when portions of compounds and molecules break free from the material allowing the free oxygen to attach to the remaining material and form oxides. For example, it is commonly used inside kilns for firing pottery in order to drive materials to convert to their oxide forms, or to control material color. When copper carbonate is fired, the carbon detaches and burns off as the copper-carbon bond is broken, the available oxygen rushes in to attach to the copper, forming a copper oxide.

A “vacuum atmosphere” refers to an environment or volume of space that has been evacuated of free matter, such that its gaseous pressure is much less than the surrounding atmospheric pressure. Note that a perfect vacuum is not practically achievable as atoms and particles are always present in the atmosphere, but the quality of a vacuum environment would refer to how well it approaches a perfect vacuum, as indicated by how low its environmental pressure is relative to atmospheric pressure.

The maximum temperatures of any thermocouple type are generally limited by the type of insulation used.

Points of Consideration When Using Thermocouples to Measure Temperature

Since accuracy will ultimately play a significant role in selecting a sensor type, we should be familiar with potential sources of error when making temperature measurements with thermocouples. Some of these considerations may steer us from one T/C type to another, or perhaps to another sensor type, like RTD for example.

T/C Sensor Inaccuracy

Some manufacturers of thermocouple sensors may have their own accuracy designations different from the standard designation described below, and those should always be consulted first, as they sometimes offer better than standard performance. But by the IEC 584-2 standard, thermocouple sensors are divided into three accuracy classes: Class 1, Class 2, and Class 3. By this standard, two tolerance values apply for a given temperature and thermocouple type: a fixed value, and a calculated value based on the sensor temperature. The larger of these two values is normally taken as the sensor tolerance (note that Type C has been excluded below as it is not an ANSI type designation).

Table 2: IEC 584-2 Standard Thermocouple Tolerances

Type	Class	Temperature Range	Fixed Tolerance	Calculated Tolerance at t°C
K	1	t = -40°C to +1000°C	± 1.5°C	± 0.004 * t°C
&	2	t = -40°C to +1200°C	± 2.5°C	± 0.0075 * t°C
N	3	t = -200°C to +40°C	± 2.5°C	± 0.015 * t°C
J	1	t = -40°C to +750°C	± 1.5°C	± 0.004 * t°C
	2	t = -40°C to +750°C	± 2.5°C	± 0.0075 * t°C
	3	NA	NA	NA
E	1	t = -40°C to +800°C	± 1.5°C	± 0.004 * t°C
	2	t = -40°C to +900°C	± 2.5°C	± 0.0075 * t°C
	3	t = -200°C to +40°C	± 2.5°C	± 0.015 * t°C
T	1	t = -40°C to +350°C	± 0.5°C	± 0.004 * t°C
	2	t = -40°C to +350°C	± 1.0°C	± 0.0075 * t°C
	3	t = -200°C to +40°C	± 1.0°C	± 0.015 * t°C
B	1	NA	NA	NA
	2	t = +600°C to +1700°C	± 1.5°C	± 0.0025 * t°C
	3	t = +600°C to +1700°C	± 4.0°C	± 0.005 * t°C
R	1	t = 0°C to +1600°C	± 1.0°C	± [1 + 0.003 * (t°C-1100°C)
&	2	t = 0°C to +1600°C	± 1.5°C	± 0.0025 * t°C
S	3	NA	NA	NA

T/C Sensor Non-Linearity

The non-linearity of the thermocouple output itself can vary up to several percent or more over the full temperature range of a T/C type. The mathematical relationship between sensor temperature and output voltage is modeled via a complex polynomial to the 5^{th} through 9^{th} order depending on the T/C type. Some transmitters will take special measures to adjust their output response for these non-linearities and make their outputs linear with the input temperature range. Other applications are not concerned with linearizing the transmitter's output response relative to the sensor temperature and their response will instead be linear with the thermoelectric voltage signal of the sensor. In many cases, a given thermocouple will be nearly linear over a smaller range of its application temperature and some non-linearity will be acceptable without applying special linearizing methods. Likewise, some low cost transmitters will use analog methods to shift the output to adjust for this non-linearity and this generally works best over smaller or truncated portions of the sensor range. Some modern digital instruments will actually store thermoelectric breakpoint tables in memory to accomplish multi-segment linearization of a T/C range and return the corresponding temperature for a given voltage measurement. Depending on your application, the lack of linearization can be a significant source of error if you fail to account for it.

T/C Sensor Sensitivity

As mentioned earlier, we noted that any conductor subject to a thermal gradient along a dimension will generate a voltage difference along that same path and this is known as the Seebeck effect. Different materials will exhibit different magnitudes of thermal emf related to the difference in temperature. Combining two different materials and joining them at one end allows us to complete a circuit, build the thermocouple, and actually measure the relative voltage. The relative sensitivity of the thermocouple refers to its Seebeck coefficient, which is simply a measure of its incremental change in thermocouple voltage corresponding to an incremental change in temperature (i.e. dV/dT in mV/°C or uV/°C). This is essentially the slope of the thermocouple function (voltage versus temperature) at a selected temperature. It's important to note that just as a thermocouple varies its linearity over temperature, its relative sensitivity is also temperature dependent. That is, some thermocouples will be more or less sensitive for smaller portions of their application temperature range. Table 1 gave a nominal sensitivity figure for the thermocouple over its entire application range to help differentiate the thermocouples by sensitivity, but over smaller ranges, this figure can vary considerably. T/C's that have lower sensitivity will have lower resolution. These are generally used at higher temperatures where the need to resolve a given temperature to a high degree of accuracy is not a requirement. Likewise, if you need to resolve temperature to a fraction of a degree, you would select a T/C with higher sensitivity, and a corresponding higher resolution.

Sensor Drift, Aging, and De-Calibration

Drift or de-calibration of a thermocouple sensor refers to the process in which the metallurgy of the thermocouple wire has been altered as a result of its exposure to temperature extremes, usually for prolonged periods of time. It may also occur inadvertently by failing to consider the "entire" operating range of a sensor application including its over-range and under-range or fault conditions. Drift usually occurs as a result of the diffusion of atmospheric particles into the metal at extreme temperatures. But it can also occur due to the diffusion of impurities and chemicals from a thermocouple's insulation or protective sheath into the T/C wire at temperature extremes. It is always good policy to check the specifications of the thermocouple or probe insulation, as it usually limits the effective operating ambient of the thermocouple itself.

Choice of Extension Wire

For thermocouples that must pass over a long distance, thermocouple extension cable is often used. Extension cables are generally used to lower the total cost of the sensor and will use similar materials to the thermocouple itself, or materials better suited for the intervening environment. The important thing to remember about the use of extension cable is that its thermoelectric behavior sometimes only approximates that of the thermocouple, and it will usually limit the applicable range of the thermocouple by virtue of its insulation. Be cognizant of the extension wire used in an application and its limitations, as it can be an increasing source of error if applied improperly with respect to temperature and environment. Note that for base metal thermocouples (J, K, N, E, and T), the extension wire conductor is the same composition as the corresponding thermocouple and will exhibit the same thermoelectric properties as the thermocouple itself. However, for noble metal thermocouples (R, S, and B), the wire is usually a different alloy which will only approximate the noble metal thermoelectric properties, but over a more limited range.

The conductor material is different because the noble metals contain Platinum, which would be very expensive to use as extension wire. Use of a different material is often not a problem, as these T/C types are generally used at higher temperatures and have a lower resolution, such that the small error contribution of using a different but similar extension wire is less significant. In all cases, the maximum application temperature will be limited by the type of insulation used by the extension wire and this is an important factor in selecting the proper extension wire for a given application.

Response Time

The response time refers to the time interval between the application of a sudden change in temperature to a sensor and its corresponding change in output. This change is frequently defined as the time it takes for the sensor to reach 63.2% of its final value. A rapid response time or shorter time constant helps to reduce error in systems that encounter rapid changes in temperature. It is dependent on several parameters, such as T/C dimensions (wire size), construction, tip configuration, and the medium to which it makes contact. For example, If a thermocouple penetrates a medium with high thermal capacity and rapid heat transfer, the effective response time would approach that of the thermocouple itself (its intrinsic response time). But if the thermal properties of the medium are poor, still air for example, the response time can be 100 times greater. For an insulated or ungrounded thermocouple, response time can vary from a fraction of a second (small diameter) to several seconds (large diameter). For non-insulated or grounded thermocouples, the typical time varies from a small fraction of a second (small diameter) to a few seconds (large diameter). In general, thermocouple temperature sensors have the fastest response times, especially when compared to RTD sensors. It is generally their small point of contact and low thermal mass that gives them a faster response time. But similar to an RTD, the response time of a thermocouple measurement will also depend on its insulation. That is, you can specify a grounded (non-insulated) or ungrounded (insulated) thermocouple. A grounded thermocouple junction puts the material junction in direct contact with the surrounding case metal which gives it a faster response time. But the grounded tip is also more prone to noise pickup and may increase measurement error, in particular when wired to non-isolated measuring instruments. You should tend to use an ungrounded (insulated) sensor to avoid these issues, but only when sensor isolation and response time are not over-riding issues for your application. If your application absolutely requires a fast response time, you will probably need a grounded tip and will have to take other measures to combat noise pickup or isolate your signal, such as selecting a compatible isolated transmitter.

Cold Junction Compensation

Near room temperature, the major source of error for any thermocouple sensor is that which is attributed to Cold Junction Compensation (CJC). Because thermocouples only measure the difference in temperature between two points and not the absolute temperature of the sensor, we must apply cold junction compensation (also reference junction compensation) in order to directly relate the measured voltage to the sensor temperature. Realistically, our temperature measurement can only be as accurate as our method of cold junction compensation. This compensation contributes significant error to our measurement and in order to minimize cold junction error, the measurement cold junction circuit has to accomplish two things very well:

- The connection points to the thermocouple must be kept at the same temperature, or “isothermal”. Any temperature gradient from one point to the other will be a source of error (Recall the Law of Intermediate Materials explored earlier).
- The actual temperature of the connection points must be measured accurately, or at least as accurate as the thermocouple itself. The response time of the CJC sensor can also be a factor in maintaining accuracy, in particular for systems that require a fast response time but may have unstable cold-junction ambient.

While our thermocouple allows us to make precise differential temperature measurements, we need to make sure that the pair of terminals that connect to the T/C and comprise our cold junction are at the same temperature or “isothermal” with one another. Not doing so would introduce an errant T/C voltage into our measurement. We also have to make sure that the cold junction has enough thermal mass so that it will not change temperature over the time it takes for us take the two measurements necessary to convert the T/C signal into the actual temperature at the remote end.

Connection Problems

Potential measurement error is often a result of poor connections which drive unintended thermoelectric voltage contributions to our measurement voltage. If you need to increase the length of thermocouple wires, you must use the correct type of T/C extension cable for the thermocouple. Substitution of any other type will add errant thermocouple junctions to our measurement system. If terminals are used to connect the wires, then you must additionally select connectors made up of the same material type, unless you can ensure that the connections are kept at the same temperature. You also need to observe the proper polarity when making connections.

Other connection problems arise when an incompatible material type is used for a given environment, or where extension wire has been mismatched to the sensor or its environment. For example, thermocouples that use iron as a material will be subject to corrosion that may impede continuity, particularly in wet environments.

Thermal Shunting and Immersion Error

All thermocouples have some mass, and heating this mass will absorb some energy that will ultimately affect the temperature you are trying to measure. In some applications, the T/C wire will act like a heat-sink at the point of measurement and that can result in significant measurement error. The use of thin T/C wires helps minimize this effect in many applications. For example, consider a thermocouple immersed in a small vial of liquid to monitor its temperature. Heat energy may travel up the T/C wire and dissipate to the atmosphere reducing the temperature of the liquid around the wires. Or, if the thermocouple is not sufficiently inserted into the liquid, the cooler ambient air surrounding the wires may actually conduct along the wire and cool the junction to a different temperature than the liquid itself. The use of thinner wires would cause a steeper thermal gradient along the wire at the junction between the ambient air and the liquid itself. However, thin wires have a higher resistance and this can drive other errors (see below). It may be better to use shorter thin T/C wires connected to much thicker thermocouple extension wires in order to alleviate the resistance effect for some applications.

Lead Resistance

To minimize the effects of thermal shunting and to improve response time, thin T/C wire is generally used. The use of thin wire is also at least partially driven by the type of wire which is more expensive, in particular for the platinum-based, noble metal types R, S, and B. But the downside to using thin wire in some systems is that it increases the sensor resistance making it more sensitive to noise, and potential IR errors driven by the measuring instrument. Care should be taken to ensure that the loop resistance of a wired thermocouple be kept low, and a general rule of thumb is to keep it below 350Ω to avoid excess error, and below 100Ω would be better.

Noise

The thermocouple output voltage is a small signal that is prone to errant noise pickup. Likewise, the fine leads are made from other materials than copper and have a higher resistance, making them more sensitive to noise pickup, in particular AC-coupled noise. Further, the high gain that generally operates on these small signals further amplifies this noise. Other sources of thermal noise result from unstable ambient temperatures at the cold junction. The generally fast response time of the thermocouple exhibits this noise at the output as the cold junction generally tracks the junction temperature much slower than the T/C sensor itself, usually as a result of its larger thermal mass and the sensor used to measure its temperature. Noise can usually be minimized by twisting the wires together to make sure that both leads pickup the same signal (i.e. common mode noise is rejected). Likewise, minimize the length or loop area where the cables part to make a connection to the instrument. Route T/C wires defensively, keeping them from combining with power wires. Operation in noisy environments or nearby electric motors may benefit from the use of screened extension cable. If noise pickup is suspected, simply switch off suspect equipment and observe if the reading changes.

Common-Mode Voltage

Although the thermocouple signals are small, much larger voltages may exist at the instrument itself due to the presence of common-mode voltages driven by inductive pickup along the sensor wire, or via multiple earth ground connections in the system. Inductive pickup is commonly a problem when using a thermocouple to sense the temperature of a motor winding or power transformer. Multiple earth grounds may be inadvertent, perhaps when using a non-insulated or grounded thermocouple to measure the temperature of a hot water pipe. In this instance, any poor connections to earth ground may drive a few volts of difference between the pipe and measuring instrument. The use of high-quality, high-gain, differential instrument amplifiers will generally reject this noise as it is common to both input leads, but only as long as the voltages remain within the common-mode input range of the instrument amplifier (usually limited to ±3V to ±5V by the internal DC voltage rail of the instrument). As noted with errant noise above, it usually helps to twist the wires together to make sure that both leads pickup the same signal (i.e. common mode noise is rejected by the amplifier). Also keep the length short or the loop area small where the cable conductors part to make a connection to the instrument.

Other Notable Points of Consideration for Thermocouples

- All TC types are color-coded and the RED wire is always the Negative Lead (opposite the convention used for DC power where Red typically denotes positive).

- One of the greatest advantages of thermocouples is their small point of contact that delivers generally fast response times.

- Thermocouple wires are very fine by design, as this helps to prevent the mass of the wire from affecting the sensed temperature at the point of contact (the junction). But this has a disadvantage in that the wires can be very delicate and may break easily. Special care must be taken to reduce the strain imposed on the thermocouple wires.

- Because thermocouple wire is often very fine, it will have generally higher resistance. The emf or voltage produced by a thermocouple is also very small. As a result, errant current flow through the thermocouple can produce an IR drop that can negatively affect the thermoelectric voltage being measured across the thermocouple. Thus, measurement equipment must have a very high input impedance so as not to introduce excess current flow that can affect the measured voltage. For example, you cannot obtain an accurate measurement of T/C millivolts using a low-cost hand-held meter because your meter would load the thermocouple with at least a few microamperes of current which is enough to add error to your measurement.

- Be aware of the error current introduced by thermocouple break detection circuitry which can negatively affect your measurement. Small break currents passing through high resistance T/C wire will drive IR voltage drops that generate voltage error. This will not normally be a problem as long as the break current is kept small and constant, or calibrated out at the factory or in the field. For example, 10uA of break current in 100Ω of T/C wire would produce 10uA*100Ω=1mV of error. This doesn't sound like much, but if you divide 1mV of IR drop by the nominal sensitivity of a J-Type T/C (1mV/55uV/C), you would get an IR error up to 18.2C.

- Again, the low thermoelectric voltages, high conductor impedances, and high impedance inputs of the measuring equipment make long thermocouple wires an easy pickup for errant signals from nearby equipment and power lines. This usually means that additional filtering in the form of a low-pass filtering may be required, in particular for removing power-line noise. Most modern instruments already include this filtering.

- Thermocouples will exhibit higher levels of drift over time than other sensor types.

- The junction of a thermocouple is commonly grounded and often in direct contact with surrounding case metal which drives a faster response time, but can be troublesome for noise pickup and potential ground loop error. Ungrounded junction sensors are available where isolation is required, but usually with an increase in response time. You may also use a grounded sensor if you connect your sensor to an isolated transmitter.

This concludes Part 1 of this three part series, and by now you should realize that choosing a temperature sensor for an application is not as simple as picking a thermocouple type with a compatible temperature range. You must give consideration to the sensor material type, the application temperature range, the relative sensitivity of the sensor, the limitations of its insulation material, and its reaction with the measurement environment. You must also be aware of the inherent limitations of the thermocouple and potential error sources in its application.

In Part 2 of this series, we will take a look at the features of Resistance Temperature Detectors (RTD's). Certain applications work better with one sensor type than another, and knowing the key differences will help you to make an informed decision between sensor types.

About Acromag

Acromag is a leading manufacturer of temperature transmitters and signal conditioners for use with thermocouple and RTD sensors. These instruments convert the sensor input to a proportional 4-20mA DC current, DC voltage, Modbus, Profibus, or Ethernet signal to interface with a PC, PLC, DCS, or other control equipment.

Acromag has designed and manufactured measurement and control products for more than 50 years. They are an AS9100 and ISO 9001-certified international corporation with a world headquarters near Detroit, Michigan and a global network of sales representatives and distributors. Acromag offers a complete line of industrial I/O products including a variety of process instruments, signal conditioners, and distributed fieldbus I/O modules that are available with a 7-year warranty. Industries served include chemical processing, manufacturing, defense, energy, and water services.

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CRITERIA FOR TEMPERATURE SENSOR SELECTION OF T/C AND RTD SENSOR TYPES

The Basics of Temperature Measurement
Using RTDs
Part 2 of 3

8500-917-A11E000

This is part two of a three part series that provides information for choosing an industrial temperature sensor from Thermocouple (T/C) and Resistance Temperature Detector (RTD) sensor types. Part 1 of this series took a close look at thermocouples. This part will look similarly at RTDs. After a review of the basic construction of an RTD, we will take look at an RTDs Temperature Coefficient of Resistance (TCR), its sensitivity, accuracy, interchangeability, repeatability, stability and drift, corrosion and contamination effects, shock and vibration effects, insulation resistance, lead-wire resistance, self-heating effects, meter-loading, packaging and thermal transfer considerations, response time, and thermoelectric effects.

In part 3 of this series, we will summarize and compare the thermocouple and RTD sensor types, and provide information for selecting the best sensor for a given application.

The Basics of Resistance Temperature Detectors

An RTD or Resistance Temperature Detector is a passive circuit element whose resistance increases with increasing temperature in a predictable manner.

The traditional RTD element is constructed of a small coil of platinum, copper, or nickel wire, wound to a precise resistance value around a ceramic or glass bobbin. The winding is generally done using one of two styles: birdcage or helix. The birdcage winding keeps the platinum wire loosely wound on the bobbin allowing it to expand and contract freely over temperature in order to minimize any stress-induced change in resistance. This style of winding is generally limited to laboratory use as it has poor resistance to shock and vibration. The helix wire-wound RTD uses a bifilar wound coil wrapped around a bobbin and then sealed with molten glass, ceramic cement, or some other high-temperature insulating coating. The helix winding style helps protect the wire element from shock and vibration induced changes to its resistance, but it may still be prone to stress induced resistance change due to the different coefficients of thermal expansion of the wire coil and bobbin material.

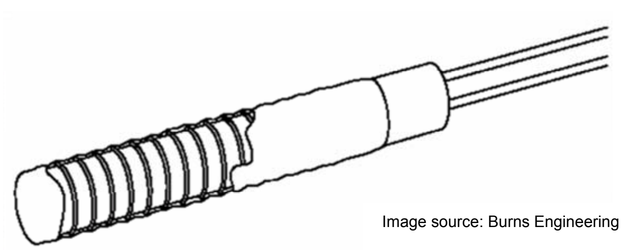
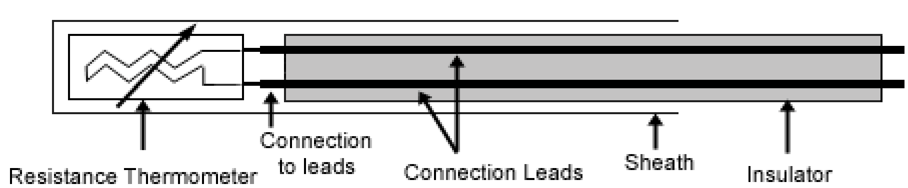
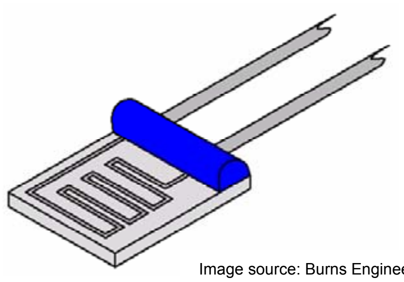


Image source: Burns Engineering



More recently, RTDs are also being constructed using a thin-film of platinum or nickel-iron metal deposited on a ceramic substrate and then laser-trimmed to a desired reference resistance. The advantage offered by this construction is that the thin-film elements can achieve a higher resistance with less metal, and over smaller areas. This makes them smaller, cheaper, and faster responding than their older wire-wound counterparts.



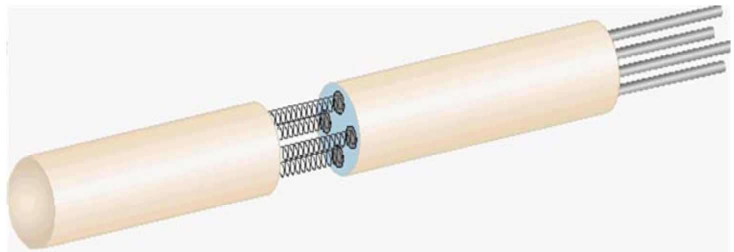


Image source: Burns Engineering

The most common RTD element material is Platinum, as it is a more accurate, reliable, chemically resistant, and stable material, making it less susceptible to environmental contamination and corrosion than the other metals. It’s also easy to manufacture and widely standardized with readily available platinum wire available in very pure form with excellent reproducibility of its electrical characteristics. Platinum also has a higher melting point, giving it a wider operating temperature range.

RTD Sensing Element Material and Relative Temperature Limits

RTD ELEMENT MATERIAL	USABLE TEMPERATURE RANGE
Platinum	-260°C to +650°C
Nickel	-100°C to +300°C
Copper	-75°C to +150°C
Nickel/Iron	0°C to +200°C

For an RTD sensor, it is the wires which connect to the sensing element and the wire insulation which generally limits the maximum application temperature of the sensor. The following table lists common wire and insulation materials and their maximum rated usage temperature:

RTD Sensing Element Material and Relative Temperature Limits

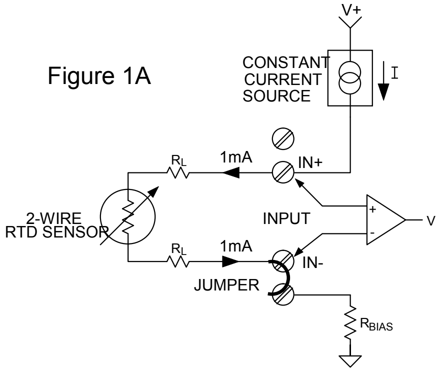
WIRE/INSULATION MATERIAL	USABLE TEMPERATURE RANGE
Tinned Copper/PVC Insulation	+105°C
Silver Plated Copper/FEP Teflon Insulation	+205°C
Silver Plated Copper/TFE Teflon Insulation	+260°C
Nickel Plated Copper/TFE Teflon Insulation	+260°C
Nickel Plated Copper/Fiberglas Insulation	+480°C
Solid Nickel Wire/No Insulation	+650°C

Measuring the temperature of an RTD involves measuring this resistance accurately. To measure the resistance, it is necessary to convert it to a voltage and use the voltage to drive a differential input amplifier. The use of a differential input amplifier is important as it will reject the common mode noise on the leads of the RTD and provide the greatest voltage sensitivity. The RTD signal is generally measured one of two ways: either by connecting the RTD element in one leg of a Wheatstone bridge excited by a constant reference voltage, or by running it in series with a precision current reference and measuring the corresponding IR voltage drop. The latter method is generally preferred as it has less dependence on the reference resistance of the RTD element.

The following figures denote some of the ways that RTD signals are sensed by mating instruments. Figure 1A shows a typical 2-wire connection. This method is limited to short distances between the sensor and measuring instrument because it does not compensate for lead-wire resistance. Excitation current flows through the sense leads and the resultant IR drop is included in the measurement. Figure 1B uses a Wheatstone bridge to connect to a 2-wire sensor, and adds lead-wire compensation, but has the disadvantage of requiring that the bridge resistance match the base resistance of the sensor. Figure 2A shows a traditional 3-wire connection which adds lead-wire compensation for matched leads, but it requires two measurements to convert the RTD signal. Figure 2B uses dual matched current sources to excite the 3-wire sensor, one at each ±lead. As long as the ±leads match, the IR drop in the leads does not affect the measurement. This has the added advantage of converting the RTD signal in a single differential measurement. In addition, only the ±leads to the sensor must match, as the third lead is just a return current path for the combined excitation currents. Figure 3A provides the most exacting method of conversion, 4-wire with Kelvin connections, but it needs four points of connection to the sensor. No current flows into the sense leads so the lead wires do not need to be matched.

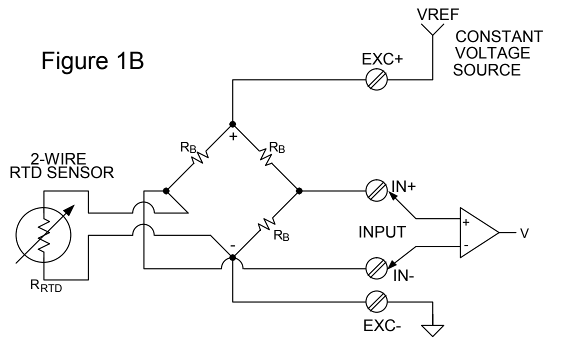
Figure 3B uses a 4-wire connection with a compensating loop. While it also compensates for lead resistance for matched leads, it requires two separate measurements to convert the RTD signal. We get the best performance from circuits of Figures 2B and 3A, both of which have the distinct advantage of being able to convert the RTD signal in a single differential measurement. This allows the fastest conversion and minimizes the potential error of combining two separate measurements that may not have occurred simultaneously. Figure 2B also uses less wire and one less termination than that of Figure 3A, but its accuracy relies heavily on your ability to closely match the excitation current sources. Its performance can be made to match that of the 4-wire sensor with Kelvin connection method of Figure 3A, as long as the current sources are exactly matched.

Figure 1A



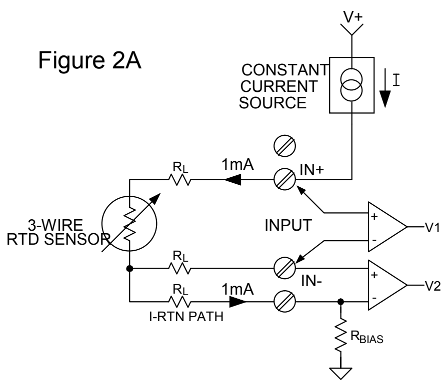
2-WIRE SENSOR w/SINGLE CURRENT EXCITATION. CONVERTS SENSOR WITH A SINGLE DIFFERENTIAL MEASUREMENT. DOES NOT COMPENSATE FOR LEAD RESISTANCE. LIMITED TO SHORT SENSOR-TO-INSTRUMENT DISTANCES.

Figure 1B



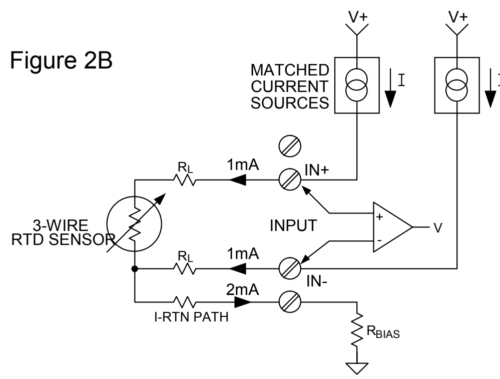
2-WIRE RTD SENSOR w/BALANCED BRIDGE CONNECTION. CONVERTS WITH A SINGLE MEASUREMENT. COMPENSATES FOR MATCHED LEAD RESISTANCES. REQUIRES BRIDGE RESISTANCE TO MATCH SENSOR BASE RESISTANCE. REQUIRES PRECISE AND STABLE VOLTAGE EXCITATION. WIRING AND CALIBRATION ARE COMPLEX.

Figure 2A



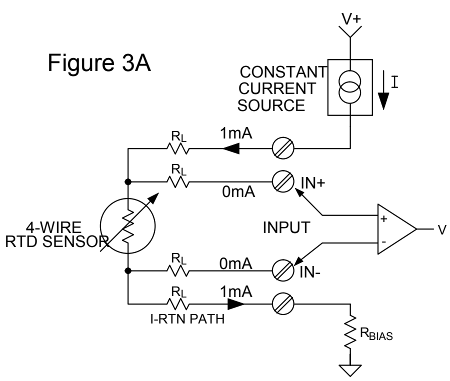
3-WIRE SENSOR w/SINGLE CURRENT EXCITATION. CONVERSION REQUIRES TWO DIFFERENTIAL MEASUREMENTS. COMPENSATED FOR MATCHED LEAD RESISTANCES.

Figure 2B



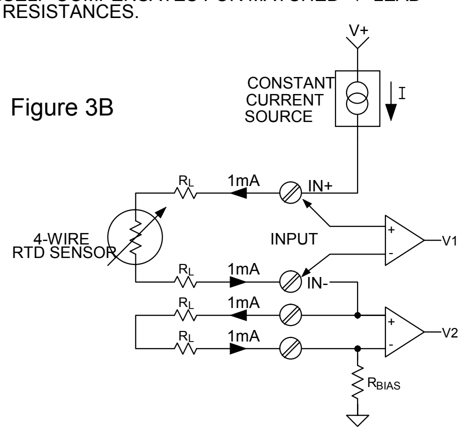
3-WIRE SENSOR w/DUAL MATCHED CURRENT EXCITATION. CONVERTS WITH A SINGLE DIFFERENTIAL MEASUREMENT. SELF-COMPENSATES FOR MATCHED +/- LEAD RESISTANCES.

Figure 3A



4-WIRE SENSOR w/KELVIN CONNECTION. CONVERTS WITH A SINGLE DIFFERENTIAL MEASUREMENT. DOES NOT REQUIRE MATCHED LEADS AS NO CURRENT FLOWS IN SENSE LEADS AND MEASUREMENT IS NOT AFFECTED BY LEAD RESISTANCE.

Figure 3B



4-WIRE SENSOR w/COMPENSATING LOOP CONNECTION. CONVERSION REQUIRES TWO DIFFERENTIAL MEASUREMENTS. COMPENSATED FOR MATCHED LEAD RESISTANCES.

Points of Consideration When Using RTDs to Measure Temperature

RTDs are susceptible to three dominant groups of errors: there are errors that result due to the inherent tolerances built into the element, errors due to the thermal gradients that develop between the element and the material being sensed, and electrical errors encountered in the wiring between the sensor element and the measuring instrument. While many of these errors are electrical, others simply occur as a result of the mechanical construction of the RTD. The following outlines many of the considerations in this regard.

Temperature Coefficient of Resistance (TCR) and Alpha (α)

A particular RTD curve is distinguished by its Temperature Coefficient of Resistance (TCR), also referred to as its alpha coefficient (α). The TCR or alpha value indicates the average resistance change of the sensor per degree °C over the range of 0°C to 100°C. The TCR or alpha value is also used as an indirect measure of the *sensitivity* of the resistive wire used in the RTD element (see Sensitivity in the next section). Its units are usually expressed in units of Ω/Ω/°C, or ppm/°C. Its value is derived by dividing the difference between the sensor resistance at 100·C and the sensor resistance at 0·C, by the sensor resistance at 0°C, and then again by 100°C as follows:

TCR = α = $[(R_{100°C} - R_{0°C})/R_{0°C}]/100°C$ in Ω/Ω/°C, or alternately $\alpha = 10^6*[(R_{100°C} - R_{0°C})/(100°C * R_{0°C})]$ in ppm/°C,
where $R_{0·C}$ is the element resistance at 0°C; and $R_{100·C}$ is element resistance at 100°C

For Pt 100Z sensors of the DIN 43760 and IEC 751 standards, this is calculated via the expression [(138.5Z - 100.0Z)/100.0Ω]/100°C, or 0.00385Z /Z / ·C. This is sometimes expressed as 3850ppm/°C, or 0.385%/°C.

The RTD temperature coefficient of resistance is also representative of the sensors' sensitivity to temperature change. That is, the larger the temperature coefficient (α), the larger the resistance change (ΔR) in response to an ambient temperature change (ΔT). Thus, we calculate:

$\Delta R = \alpha R_o \Delta T$,
where: α = TCR in Ω/Ω/°C; R_o = nominal sensor resistance at 0°C in Ω; ΔT = temperature change from 0°C in °C.

The most common RTD element material is platinum with α=0.00385Ω/Ω/°C and specified per DIN EN 60751. The value of α will vary and depends on the grade of platinum used. Other commonly use α values include 0.3911%/°C and 0.3926%/°C. While the α value indirectly defines the sensitivity of the metallic element, it is normally used to distinguish between resistance/temperature curves of various RTDs.

RTDs are constructed using Platinum, Copper, Nickel, and Nickel-Iron alloy element materials, with each type achieving different TCRs. Metal impurities and stresses during manufacture lower the relative TCR for a given metal element. For example, there are many variations of platinum RTDs available as follows:

$R_{0°C}$ OHMS	ALPHA α (Ω/Ω/°C)	REFERENCE
100	0.00393	Highest purity Platinum
	0.003927	
	0.003926	ITS-90 Lab Standard Pt RTD, Requires ≥ 99.999% Purity. This is the laboratory standard platinum RTD which requires the high purity platinum wire (≥ 99.999%) and must be wound in a strain-free configuration which is difficult to achieve. However, some manufacturers come close and offer nominal TCR's of 0.00392 or 0.003923.
	0.003925	Very Pure Platinum for High Precision RTDs
	0.003923	SAMA
	0.003920	Old US Standard
	0.003916	Per JIS C1604-1981 and US Standard Curve, Common in US and Japan where it is the accepted standard
	0.00392	
	0.003911	This is the "American" or "US Industrial Standard" platinum RTD which has a lower TCR due to the imposition of strain imposed on the platinum wire from the high-temperature ceramic materials used in its construction.
	0.00391	
	0.003902	Another US Industrial Standard
	0.003900	Per BS 2G 148, Originally Specified for British Aircraft Industry
	0.00389	
	0.00385	Per IEC Publication 751-1983, DIN 43760, DIN-IEC-761, Majority standard outside US and Japan. This is the standard platinum RTD defined via DIN43760 and IEC 751 and the most popular one recognized nationally and internationally.
	0.00375	This is a low-cost alternative to the more expensive platinum RTDs outlined above.

From the numbers, there is little advantage to specifying one platinum TCR over another, as they are so close in magnitude for different grades of platinum. But laboratory measurement systems will tend to use the highest-grade platinum wire (purest metal), while industrial applications will tend to choose an RTD TCR that has the greatest standardization. According to the DIN 43760 standard, the resistance-temperature coefficient of platinum wire typically used in RTD manufacturing is 0.00385 Ω/Ω/°C at 0°C. Another frequently mentioned value of α is 0.00392 Ω/Ω/°C at 0°C, which represents the resistance-temperature coefficient of chemically pure platinum wire used for standards. In any case, it is important to make sure that the sensor TCR you select is compatible with your choice of measuring instrument. In general, and with respect to industrial users, the 0.00385 TCR RTD sensors will be most compatible with the broadest range of measurement equipment from the largest number of manufacturers.

To illustrate the use of alpha α to calculate the resistance of an RTD at some other temperature, consider an ideal 100Ω RTD that has a resistance of 100.000 Ω at 0°C. Therefore, at +1°C the RTD resistance will be:

$\mathbf{R_T = [R_o + (\alpha R_o \Delta T)] = 100\Omega + (0.00385\Omega/\Omega/°C)(100\Omega)(1°C) = 100.385\Omega.}$
But we have a problem extending the use of α over wider change in temperature. That is, the RTD temperature coefficient changes slightly over the temperature range. Thus, to obtain an accurate value at <u>any</u> given temperature, a curve-fitting process is required and we will instead refer to the Callender-Van Dusen equation to calculate the RTD resistance over the entire temperature range as follows:

$R_T = R_o + R_o*\alpha*[T – \delta*(T/100 – 1)*(T/100) – \beta*(T/100 – 1)(T/100)^3]$, where:

R_T = RTD resistance at some temperature T°C in Ω
R_o = Nominal RTD resistance at 0°C in Ω
α = temperature coefficient of the element material in Ω/Ω/°C
δ = 1.49 for pure Platinum =
β = 0 if T > 0 or β = 0.11 if T < 0

The linear alpha coefficient (d) refers to the normalized slope between 0°C and 100°C and calculated as

$[(R_{100\,C} - R_{0\,C})/R_{0\,C}]/100°C$. If this approximation is good enough (it will be for temperatures in the range of 0 to 100°C), then you can calculate the resistance at another temperature as $R_T = R_o + R_o*\alpha*T$, and the temperature as a function of the resistance as $T = (R_T - R_o)/R_o*\alpha$.

The second order term δ comes from Callendar and is based on the disparity that exists between the actual temperature T_H and the temperature that is calculated above using only the linear coefficient term d ($T = (R_T - R_o)/R_o*\alpha$). This coefficient is calculated $\delta = [T_H – ((R_{TH} - R_o)/R_o*\alpha)]/[(T_H/100)-1]*(T_H/100)]$. With the added δ term, our resistance-temperature polynomial can be used to more accurately calculate the resistance value for <u>positive</u> temperatures via the expression:

$R_T = R_o + R_o*\alpha*[T – \delta*(T/100 – 1)*(T/100)]$

The third order coefficient β comes from Van Dusen and is only required for converting negative temperatures with t < 0°C. It is based on the disparity between the actual temperature T_L and the temperature calculated using only α and δ above. We can calculate β as follows:

$\beta = [T_L – [(R_{TL} - R_o)/(R_o*\alpha) + \delta*(T_L/100 – 1)*(T_L/100)]] / [(T_L/100 – 1)*(T_L/100)^3]$

Now by including both the Callendar and Van Dusen coefficients in our expression, we can calculate the resistance for the entire temperature range as:

$R_T = R_o + R_o{*}\alpha{*}[T - \delta{*}(T/100 - 1){*}(T/100) - \beta{*}(T/100 - 1)(T/100)^3]$, where $\beta = 0$ for $t > 0°C$:

Callendar-Van Dusen Coefficients for Pt100	
α	0.00385
δ	1.4999
β	0.10863 (t < 0°C)

A simpler representation of the non-linearity of a Platinum RTD is given by IEC751 and ITS-90 as follows:
$R_T = R_o{*}[$

The full expression above is used between -200°C and 0°C. The C coefficient term is only applicable for T < 0°C and the expression becomes $R_T = R_o{*}[1 + A{*}T + B{*}T^2]$ for the range from 0°C to approximately 660°C.

IEC751 defines the coefficients for A, B, and C of a standard Pt100 sensor as follows:

IEC751 Coefficients for Pt100	
A	3.908×10^{-3}
B	-5.775×10^{-7}
C	-4.183×10^{-12}

If a standard sensor is not available, or if greater accuracy is required than can be obtained using the IEC751 standard coefficients above, then the coefficients can be measured individually for a given sensor by measuring the resistance at a number of known temperatures, and then determining A, B, and C via regression analysis (I promise I will not go there M). Where high accuracy is paramount, use the full Callendar-Van Dusen equation for calculating RTD sensor resistance.

An alternative to the Callendar-Van Dusen expression, and with greater accuracy than can be obtained by the standard IEC751 expression, we can use the expanded expression:

$R_T = R_o{*}[1 + A{*}T + B{*}T^2 - 100{*}C{*}T^3 + C{*}T^4]$.

Comparing this to the Callendar-Van Dusen equation, we can derive the expressions for calculating the IEC751 coefficients A, B, and C as follows:

$A = \alpha + (\alpha{*}\ \delta)/100$; $B = -(\alpha{*}\ \delta)/100^2$; $C = -(\alpha{*}\ \beta)/100^4$

While Platinum RTD elements are most preferred for their wide temperature range and best stability, Nickel, Copper, and Nickel-Iron alloy elements each offer their own benefits for consideration as follows:

RTD MATL	$R_{0°C}$ OHMS	ALPHA α (Ω/Ω/°C)	TEMPERATURE RANGE[1]	PRIMARY BENEFITS
Pt	100	0.00385	-260°C to 850°C	Best Stability, Good Linearity, Widest Range
	1000	0.00385	(-200°C to 660°C Typical)	
	100	0.00392		
	100	0.00391		
	25.5[2]	0.00392		
	200	0.00385		
	470	0.00392		
	500	0.00392		
	500	0.00391		
	500	0.00385		
	1000	0.00395		
	100	0.00393		
	100	0.00389		
	98.129	0.00392		
	200	0.00392		
Cu	9.035	0.00427	-100°C to 260°C	Best Linearity
	100	0.00427	(-80°C to 260°C Typical)	
Ni	100	0.00618	-100°C to 260°C	Highest Sensitivity, Low Cost
	120	0.00672	(-80°C to 260°C Typical)	
Ni-Fe	604	0.00518	-200°C to 200°C	Lowest Cost, Higher Sensitivity
	908.4	0.00527	(0°C to 200°C Typical)	
	1816.81	0.00527		

1 This indicates a ballpark range for the sensor. Actual range endpoints will vary between sensor manufacturers according to sensor construction and its insulating material.

2 The 25.5Ω Pt sensor is primarily used for laboratory work and designed to minimize the insulation resistance shunting effect on element resistance.

Perhaps the most important point about TCR is that you primarily use it to distinguish between different curves of platinum sensors, and for most applications, your choice of TCR must properly match the mating instrument when replacing RTD sensors.

Sensitivity

The RTD is a temperature sensitive resistance. So an indication of its “sensitivity” should indicate the amount to which the resistance changes as temperature changes. Some discussions of RTD sensitivity simply use the alpha value of the element to denote the sensitivity of the RTD element, and this can be misleading since it doesn’t directly indicate the amount the resistance changes in 1 degree. But if we examine how alpha is calculated, d = $[(R_{100·C} - R_{0·C})/R_{0·C}]$/100°C, we see that alpha really represents the fractional increase in resistance over 100°C. Stated another way, for α=0.00385, the resistance increases 38.5% from 0-100°C, or 0.385% for each °C. Thus, we could use 0.385%/°C to indicate the sensitivity of our sensor, or we could convert it to its native units of measure and use Ω/°C instead.

More simply stated, we can calculate the sensitivity of a resistance thermometer by multiplying the resistance of the RTD at the reference temperature R_0 (i.e. its calibration temperature) by the Temperature Coefficient of Resistance (TCR, or alpha value) as follows: Sensitivity = $K_{RTD} = R_0 * \alpha$.

For a 100Ω platinum RTD with α=0.00385 Z/Z/·C and R_0= 100Ω, the sensitivity coefficient is computed via the expression 100Ω * 0.000385Z/Z/·C = 0.385Ω/°C. Thus, a 100Ω sensor at 0°C will increase its resistance by 0.385Ω in 1°C, or 0.385Z/·C.

Referring to the prior table, we see that the higher the alpha value, the more *sensitive* the sensor. Thus, a Nickel RTD (α=0.00672Z/Z/·C, R_0=120Ω) is more sensitive to temperature change than a Platinum RTD, as it will change its resistance by 120Z*0.00672Z/Z/·C=0.8064Z/·C, greater than the 0.385Z/·C of the Platinum sensor, making it more than twice as sensitive.

Multiples of nominal resistance R_0 =100Ω are sometimes used to produce sensors having greater sensitivity. For example, a 500Ω Pt RTD (Pt500) would be 5x more sensitive than a 100Ω Pt RTD (Pt100). Likewise, a 1000Ω Pt RTD (Pt1000) would be ten times more sensitive than a 100Ω Pt RTD. Their resistance changes are as follows:

0.385Z/·C for Pt100

1.925Z/·C for Pt500

3.850Z/·C for Pt1000

In summary, the sensitivity of an RTD sensor refers to its *change in resistance per degree change in temperature*. It is both a function of its base resistance and its Temperature Coefficient of Resistance (TCR). A sensor with higher sensitivity is not necessarily more accurate, but the larger signal it produces will tend to be less susceptible to lead-wire effects and electrical noise, as it generally improves the signal-to-noise ratio of the sensor interface. A larger resistance also produces the same output voltage with less excitation current, which helps to mitigate self-heating effects in the sensor element by allowing lower currents to be used to excite it.

Accuracy

The practical accuracy of an RTD thermometer will depend on the tolerance of the RTD, the measurement temperature, the accuracy of the mating instrument, and the effects of the interconnecting lead wire and the installation. But when we speak of the accuracy of an RTD sensor, we are usually referring to its temperature deviation or tolerance grade at some reference temperature, as its "real" tolerance is temperature dependent.

There are a number of international standards that define the tolerance and accuracy limits of RTDs. The most common standard used for grading Platinum RTDs is IEC 751 (1995). IEC 751 defines two performance classes for 100Ω Platinum RTDs with alpha 0.00385, Class A and Class B, as follows:

PARAMETER	IEC 751 Class A	IEC 751 Class B
R_0 (Base Resistance)	100Ω ± 0.06%	100Ω ± 0.12%
α (Alpha)	α = 0.00385±0.000063Ζ/Ζ/·C	α = 0.00385±0.000063Ζ/Ζ/·C
Applicable Range	-200°C to **+650°C**	-200°C to **+850°C**
Resistance Tolerance	±(**0.06** + **0.0008***|T| - $2*10^{-7}*T^2$)Ω (±0.06% at 0°C)	±(**0.12** + **0.0019***|T| - $6*10^{-7}*T^2$)Ω (±0.12% at 0°C)
Temperature Deviation	**±(0.15 + 0.002*|T|)°C**	**±(0.3 + 0.005*|T|)°C**

Note: The expression for Resistance Tolerance is only applicable to α=0.00385 Pt RTDs. The symbol "|T|" in the table expressions refers to the absolute value of the sensor temperature.

Other standards such as DIN 43760, BS-1904, BS EN60751 (1996), and JIS C1604 generally match the IEC 751. While IEC 751 only addresses 100Ω Platinum RTDs with alpha 0.00385, its temperature tolerance and accuracy requirements are often applied to other platinum RTD types. For example, the JIS C1604 standard also adds recognition of the 0.003916 alpha type and applies the same tolerance standards. Performance classes A & B are also referred to as DIN A and DIN B with respect to the DIN 43760 standard. Note that Class C and Class D designations are sometimes used and each Class doubles the prior tolerance level.

DIN Standard (DIN 43760) similarly recognizes three different temperature deviation classes as follows:

DIN Class A: ±(0.15 + 0.002*|T|)°C (Matches IEC 751 Class A)

DIN Class B: ±(0.30 + 0.005*|T|)°C (Matches IEC 751 Class B)

DIN Class C: ±(1.20 + 0.005*|T|)°C

In the US, ASTM Specification E1137 is also referenced and defines two RTD temperature tolerance grades, A and B, as follows:

Grade A: ±(0.13 + 0.0017*|T|)°C

Grade B: ±(0.25 + 0.0042*|T|)°C

By IEC 751, the accuracy or tolerance grade of an RTD element is a function of its resistance tolerance and its temperature deviation. In accordance with DIN 43760 and IEC 751, its class designation will be denoted by its resistance tolerance and temperature deviation at its calibration temperature (typically 0°C) and base resistance R_0 (typically 100Ω), and will be divided into two major classes as follows:

Temp & Resistance Tolerance vs Temperature for Platinum RTDs Per IEC 751 (1995) & BS EN60751 (1996)

TEMPERATURE		CLASS A TEMP & RES TOLERANCE			CLASS B TEMP & RES TOLERANCE		
°C	°F	TEMP DEVIATION		RES TOLERANCE	TEMP DEVIATION		RES TOLERANCE
-200°C	-328°F	±0.55°C	±0.99°F	±0.24Ω	±1.3°C	±2.34°F	±0.56Ω
-100°C	-148°F	±0.35°C	±0.63°F	±0.14Ω	±0.8°C	±1.44°F	±0.32Ω
-50°C	-58°F	±0.25°C	±0.45°F	±0.10Ω	±0.55°C	±0.99°F	±0.22Ω
0°C	+32°F	±0.15°C	±0.27°F	±0.06Ω	±0.3°C	±0.54°F	±0.12Ω
+100°C	+212°F	±0.35°C	±0.63°F	±0.13Ω	±0.8°C	±1.44°F	±0.30Ω
+200°C	+392°F	±0.55°C	±0.99°F	±0.20Ω	±1.3°C	±2.34°F	±0.48Ω
+300°C	+572°F	±0.75°C	±1.35°F	±0.27Ω	±1.8°C	±3.24°F	±0.64Ω
+400°C	+752°F	±0.95°C	±1.71°F	±0.33Ω	±2.3°C	±4.14°F	±0.79Ω
+500°C	+932°F	±1.15°C	±2.07°F	±0.38Ω	±2.8°C	±5.04°F	±0.93Ω
+600°C	+1112°F	±1.35°C	±2.43°F	±0.43Ω	±3.3°C	±5.94°F	±1.06Ω
+650°C	+1202°F	±1.45°C	±2.61°F	±0.46Ω	±3.6°C	±6.48°F	±1.13Ω
+700°C	+1292°F	NA	NA	NA	±3.8°C	±6.84°F	±1.17Ω
+800°C	+1472°F	NA	NA	NA	±4.3°C	±7.74°F	±1.28Ω
+850°C	+1562°F	NA	NA	NA	±4.6°C	±8.28°F	±1.34Ω

Note: The tolerances provided above are assumed to apply to three and four wire Platinum sensor connections, as two wire RTD sensor connections will require special consideration due to the negative effects of lead resistance, as two wire sensors cannot achieve these tolerances without the benefit of lead compensation provided by three and four wire sensors.

Most RTD sensors will use the Class A or Class B designation as set forth in International Standard IEC 751 and will be denoted simply by their temperature deviations at their reference temperature: Class A, with a tolerance of ±0.15°C at 0°C; or Class B, with a tolerance of ±0.3°C at 0°C. But there are additional class designations such as “1/10 DIN” and “1/3 DIN” used to denote sensors of greater precision and these will have a tolerance of 1/10 or 1/3 of the Class B specification at 0°C, respectively.

While the “accuracy” of an RTD element is usually denoted by its initial element accuracy measured at one point, usually 0°C (32°F), it does vary with temperature. Further, it is also dependent on the tolerance of the base resistance at the calibration temperature of the element. So the effective tolerance of an RTD sensor is really a combination of both the base resistance tolerance (the resistance tolerance at the calibration temperature), and the Temperature Coefficient of Resistance tolerance (TCR or tolerance of the characteristic slope). For most RTDs, the calibration temperature is 0°C, and it is understood that any temperature above or below this temperature will have a wider tolerance band and lower accuracy.

Interchangeability and Conformity (Maintenance Issue)

Temperature sensors exposed to extreme temperatures are subject to wear and failure in the field and their interchangeability is an important service consideration. Interchangeability refers to how closely a sensing element follows its nominal resistance versus temperature curve, and the maximum variation that may exist in the readings of identical thermometers mounted side-by-side under identical conditions. Sensors with good interchangeability are desirable from a maintenance perspective as their replacement is less disruptive to the process application.

The interchangeability of an RTD consists of both the tolerance at one reference temperature (usually 0°C), and a tolerance applied to its slope, or Temperature Coefficient of Resistance (TCR). Because the slope may vary slightly, the tightest conformity to the nominal curve is at 0°C, and the tolerance at 0°C is typically used to judge the interchangeability between two sensors. For example, in the prior section we saw that a Class “B” resistive sensor requires that R_0 be 100Ω ± 0.12Ω at 0°C, with a TCR of 0.00385 ± 0.000063Z/Z/·C. This corresponds to a temperature deviation of ±0.3°C at 0°C.

Interchangeability refers to the variance in readings between two sensors at a given temperature and good interchangeability can allow replacement of the sensor without requiring recalibration. The interchangeability of an RTD sensor is simply the tolerance of the element at various temperatures over the sensor range. The tolerance table given above in the discussion of accuracy is often used to determine the interchangeability of a given sensor at an application temperature

The Conformity of an RTD sensor refers to the amount of resistance the thermometer is allowed to deviate from a standard curve, such as the curve produced by the Calendar-Van Dusen equation for Platinum RTDs. Conformity will have two components—the tolerance of its resistance and the tolerance or deviation of its temperature. When considering accuracy in the prior section, we saw that the effective tolerance of the sensor was defined by the tolerance at the reference temperature, plus the tolerance of the slope or TCR which increased at higher temperatures. The interchangeability between two sensors is no more than twice the value of their conformity

For example, by IEC 751, a Class B sensor requires resistance versus temperature calibration of 100Ω±0.12% at 0°C, or to within ±0.12Ω (±0.3°C) at 0°C, but allows the slope or rate of change to deviate from nominal 0.00385Z/Z/·C by ±0.000012/°C. This results in a tolerance band that increases to ±0.8°C at 100°C, ±0.1.3°C at 200°C, and so on up to ±4.6°C at 850°C

Repeatability

The degree to which two successive readings of a temperature sensor agree refer to its "repeatability". That is, a sensors ability to repeat the same behavior under the same conditions for any given temperature, even though it has been used and exposed to different temperatures, refers to its repeatability (e.g. its ability to remain stable over many heating and cooling cycles). A repeatability test will cycle the sensor between its low and high operating temperatures, and note any changes to its base resistance at some reference temperature. Any loss of repeatability will be exhibited by a temporary or permanent change to its element resistance measured at its reference temperature, usually 0°C. Repeatability is often lumped together with the measure of stability and ordinary industrial platinum RTD sensors will specify repeatability less than ±0.1°C per year of normal use and measured at 0°C. High precision RTD sensors can be obtained with repeatability as low as 0.0025°C per year.

A loss of repeatability is usually driven by exposing the sensor to temperatures beyond its rated operating range, or simply as a result of prolonged operation at or beyond its range limits. Note that the choice of insulating material will usually limit the maximum operating range of the Platinum element below that which is expected, or identified on a chart of resistance over temperature for a particular RTD type.

The reality is that most applications do not require a high degree of absolute accuracy, but rather stability and repeatability, as any error in RTD temperature measurement can usually be compensated for, or calibrated out by the connecting instrument. Often, the repeatability of a temperature sensor is simply lumped into its stability specification (see below).

Stability/Drift

The stability of an RTD sensor refers to its ability to maintain the same resistance versus temperature relationship for the same conditions over time. Stability and drift are often used interchangeably and sometimes lumped together with repeatability measurements (see above). Similar to repeatability, a typical stability specification will limit drift to less than 0.1°C per year for rated operation.

Many of the same factors that drive drift in thermocouples will also drive drift in RTDs. In general, drift in the resistance versus temperature characteristic is generally a product of the choice of element material (with platinum being the most stable), the encapsulation or insulating material (this may contaminate the element), and the mechanical stress placed on the element (usually a byproduct of the expansion of its winding bobbin or other supporting structure). Physical or thermal shock can also drive small one-time shifts in R vs T. Drift imposed via contamination and mechanical stress is avoidable by careful selection of insulating material with respect to the operating temperature range for a particular application environment. In general, an RTD will have much greater stability than a thermocouple, particularly when used well within its temperature range in a normal service environment. Typical specifications for RTD drift are on the order of about ±0.5°C or ±0.1°C per year for rated operation, but under normal conditions well within its operating range, the actual drift will be significantly less, perhaps ≤ ±0.1°C in 5 years or more. The stability of platinum RTD sensors is the highest with typical drift rates ≤ 0.05°C over a five year period.

Corrosion and Contamination

Corrosion is the process by which the metal element wire converts from its pure form to a more complex compound or metal oxide, which will tend to increase the resistance of the pure metal. As the corrosion works through the surface of the metal, it reduces the cross-sectional area of the conductor raising the resistance of the element independent of any temperature change. This makes the choice of a noble metal like platinum an important one for helping to inhibit corrosion.

Contamination can actually reduce the RTD resistance by building a partially conductive material on the outside of the element that provides an alternate, or shunt path, for conduction, effectively reducing the element resistance (see Insulation Resistance). This negative effect is also compounded by the fact that this errant material will have a different temperature coefficient and a different linearity characteristic than the base material. This is why many RTD manufacturers will choose to create a passivating layer of electrically insulating barrier material on the surface of the RTD element, such as glass, specifically to help inhibit contamination via the insulating sheath.

Although I mention contamination and corrosion separately from drift, both of these factors contribute to drift in the RTD (see Stability and Drift above).

Shock and Vibration

Prolonged mechanical shock and vibration can alter RTD readings and even drive intermittent or complete failure. These effects are additional contributors to sensor drift and reduced stability in RTD measurement systems. Most industrial RTD elements are fully supported by a bobbin and packing material that stands up well to extreme shock and vibration. The most common mode of failure in this construction will occur in the delicate transition point from the element to the sensor lead wires which must be properly secured against breaking open or intermittent. A typical RTD will specify shock resistance to 100G of 8ms duration, and vibration immunity to 20G from 10Hz to 2KHz. Look for this specification or better when specifying an RTD sensor.

Insulation Resistance

If the sensing elements and leads are not completely insulated from the case or sheath of the RTD, then the case can form a parallel resistance path or shunt across the element that will lower its apparent reading. Most industrial RTD elements will have insulation resistances on the order of 100MΩ or more, making this error contribution negligible. But, operation at extreme temperatures, in wet locations, or in the presence of reactive materials can lower the insulation resistance and drive these shunting errors. Because of this, most RTD manufacturers will take special care to seal the moisture-absorbing materials used in the construction of the RTD element. The negative effect of shunting is also reduced by using a lower resistance element, and this is why 25.5Ω Platinum RTDs are sometimes used for critical laboratory measurements.

Lead-Wire Resistance

RTDs generally use copper leads bonded to the platinum element. These leads normally connect close to the element and close to each other (so that both junctions will be at same temperature), in order to prevent Seebeck voltages from also affecting the measurement. However, the resistance of the copper leads can still negatively affect the measurement, in particular where the RTD element is a long distance from the measuring instrument, or where a two wire RTD sensor is used. The increased resistance of long copper leads can also degrade the RTD signal-to-noise ratio, particularly when a low resistance RTD element is used. The negative effects of lead resistance are minimized by using only three-wire or four-wire RTD sensors, which compensate for lead resistance error when coupled to compatible instruments.

For example, note that the resistance of copper wire changes approximately 0.4%/°C near 25°C. Similarly, a platinum RTD element changes at 0.00385Ω/Ω/°C, or 0.385%/°C near 25°. Note that 30 AWG copper wire is approximately 0.105Ω/foot. Thus, a 100 foot long, two-wire, 100Ω platinum RTD element with 30 AWG leads will have 10.5Ω/lead, or 21Ω of IR drop to the sensor loop. For a temperature span of 0-100°C, this represents a 38.5Ω change in element resistance. Thus, in a 2-wire configuration, the leads contribute 21Ω/38.5Ω or up to 55% of error. Further, because the temperature coefficient of copper resistance is slightly larger than that of Platinum at 0.4%/°C versus 0.385%/°C, the growth in lead resistance over temperature will outpace that of the platinum element causing the error to actually grow as the temperature increases. Of course, a wider temperature span will reduce this error, but it remains significant even for a span of 0-500°C (100-280.98Ω), at 21/180.98 or 12%. The bottom line is that two wire RTD sensors may only be useful when the RTD is close to the measuring instrument.

Lead wire resistance is mostly a problem for 2-wire sensors which are not compensated for. Some instruments do make provisions for crudely compensating two wire sensors by allowing you to enter the measured lead resistance as part of the instrument configuration. However, this only works when the lead wires are held at a constant temperature, as variations in ambient temperature will change the resistance of the leads. Two wire sensor connections may be OK when the sensing element has a high resistance and the leads have a low resistance, or when the sensor is located close to the instrument, but it should be considered carefully. To calculate the error that can be generated by an uncompensated two-wire sensor connection, multiply the length of both extension leads by its resistance per unit length. Then divide this resistance by the sensitivity of the element (its TCR) to approximate the error. For example, a two wire Pt RTD (α=0.0038500Ω/Ω/°C) located 100 feet from the instrument and wired using 24AWG extension wire (26.17Ω/1000feet) will potentially drive the following approximate error:

(2*100ft*26.17Ω/1000ft) / 0.385Ω/°C= 5.234Ω/0.385Ω/°C =13.59°C

This is equivalent to taking the resistance of the lead wire and dividing it by the sensitivity of the element (Sensitivity = R_0 * α = 100Ω*0.00385Ω/Ω/°C=0.385Ω/°C).

Self-Heating

Heat energy is generated while applying current to excite the RTD element in order to measure its signal. The self-heating that occurs will drive error in temperature measurement. Because the RTD changes its resistance in response to temperature, the most practical way to measure it is to pass a current through it and measure the resulting voltage drop. Unfortunately, this excitation current passing through the element resistance raises the element temperature as it attempts to dissipate this electrical energy via heat, adding error to our temperature measurement. The way to combat the positive shift driven by self heating is to increase thermal contact with the material we are sensing, and/or reduce the excitation current.

The self-heating of an RTD sensor is most often expressed in mW/°C, which refers to the power required to raise the internal element temperature 1°C. Thus, the higher this figure, the lower the self-heating will be. For example, assume that 2mA of excitation current is used to drive a 100Ω platinum RTD at 100°C. This produces a sensor resistance of 138.5Ω. Its self-heating specification is 50mW/°C in water moving at 1m/second. Thus, the amount of heat generated by this configuration is 1000mW/W * I^2 *R = 1000 * $(0.002A)^2$ * 138.5Ω = 0.55mW. This results in a self-heating error of only (0.55mW)/(50mW/°C)=0.01°C.

It is important to note that the effective self-heating of an element depends strongly on the medium in which it is immersed. For example, an RTD can self heat 100x higher in still air than in the moving water to which this specification applied.

Because we measure an RTDs resistance by drawing current through it, the I^2R power dissipated by the RTD causes self-heating of the element. Self-heating will change the RTD resistance and drive increased error in the measurement. The negative effect of self-heating can be minimized by supplying lower excitation current. Some instruments will use RTD excitation currents down to 0.1mA to minimize this error. In the above example, this would reduce self-heating to ~0.001mW/50mW/°C=0.00003°C, an insignificant amount, even in still air.

The magnitude of this error is inversely proportional to the capacity of the sensor element to dissipate the heat. This is a product of its materials, construction, and its environment. Small bodied RTD elements will have higher self-heating effects as they have smaller surface areas over which to dissipate the heat. Perhaps the worst case would be a thin-film RTD which would typically have a high thermal resistance and corresponding little surface area to dissipate the heat.

Typically, a *dissipation constant* is provided in RTD sensor specifications. This number relates the power required to raise the RTD temperature by one degree of temperature. Thus, a 25mW/°C dissipation constant shows that if I^2R power losses in the RTD equal 25 mW, then the RTD will be heated by 1 °C. The dissipation constant is usually specified under two conditions: free air and a well-stirred oil bath. This is because of the difference in capacity of the medium to carry heat away from the device. The self-heating temperature rise can be found from the power dissipated by the RTD and the dissipation constant via the following:

$\Delta T = P/ P_D$

where ΔT = temperature rise because of self-heating in °C; P = power dissipated in the RTD from the circuit in W; and P_D = dissipation constant of the RTD in W/°C.

Meter Loading

Meter loading refers to the negative effect resulting when some current is shunted away from the RTD element through the voltmeter, or other measuring instrument in order to make the measurement. This is historically only a problem with the older D'Arsonval analog meters, as modern DVM's and measuring instruments usually employ high impedance inputs in the tens of megohms. Their high input impedance coupled to the relatively low impedance RTD output signal reduces meter loading to the nanoampere range, where it is normally not a significant factor. It's only mentioned here to make you aware of it and to check that your measuring instrument does indeed have high input impedance. Note that a standard 100Ω platinum RTD with 1mA of excitation feeding a meter with 10MΩ of input impedance will only be loaded by 10nA or 10ppm (i.e. 0.001A*100Ω/10MΩ = 10nA).

Packaging and Thermal Transfer

In addition to protecting the delicate RTD element, the sheath or surrounding medium of the RTD element must maximize the heat transfer from the sensed material to the element, but also minimize the heat transfer from the ambient to the element itself. The proper choice of materials in construction becomes very important to ensuring the accuracy of your reading for a given application. Likewise, application considerations like the immersion depth of a probe are important.

One advantage that a wire-wound sensing element like the RTD has over other point-of-contact temperature sensing devices like thermocouples, thermistors, or integrated circuit elements, is that it can be constructed to average its sensed temperature over larger surface areas and even over lengths up to a hundred feet.

Response Time or Time-Constant

The time constant of an RTD refers to the speed with which its element changes resistance in response to a change in contact temperature. A rapid time constant helps to reduce error in a measurement system that encounters rapid changes in temperature. When we consider the construction of an RTD, we can infer that response time will have a strong dependence on the mass of the sensor element and its insulating structure, as well as the heat transfer capability to the material being sensed. This directly affects the rate at which heat transfers from the outer sensing surface to the core sensing element. Comparatively, because an RTD measures temperature over a larger area, rather than small point of contact like the thermocouple, and because the RTD sensing element must be insulated, it has a much slower response time than a thermocouple. Likewise, an RTD probe in a thermowell will react more slowly than the same sensor immersed directly into a fluid. A sensor in a solidly bonded internal assembly would respond twice as fast as one with a single loose interface in the same assembly. A surface RTD will respond more quickly to a surface temperature change.

The response time for a given sensor is typically defined as the time it takes the sensor to reach 63% of its final value at thermal equilibrium in response to a step-change in contact temperature. These times are typically expressed as measured in water flowing at 1m/sec (3ft/sec), and/or in air flowing at 3m/sec (10ft/sec).

Although less common, sometimes the response time will refer to the time interval for the Platinum RTD to reach 90% of its final value (as opposed to 63%). Be sure to make note of this distinction when making comparisons between sensor types.

Seebeck or Thermoelectric Effect

Perhaps you thought that the Seebeck effect only applied to thermocouples? But similar to thermocouples, platinum RTDs are also constructed using two different metals--the platinum RTD element and the copper of the lead wires. For some applications, these connections in the sensor loop can generate Seebeck voltages that can counter the IR drops produced in the resistance element and throw off the reading slightly. For example, if a temperature gradient is allowed to develop along the sensing element, then a thermoelectric voltage of approximately 7uV/°C can develop as a result of the junctions between the platinum sensor element and the copper lead wire. For most applications, this small counter-emf will not be a significant source of error, but can lead to problems in very high precision measurement systems operating at low excitation currents (perhaps done to minimize self-heating errors)—conditions usually only encountered in laboratory measurements.

The material and construction of an RTD make it a relatively bulky element, and this also makes it difficult to use the RTD to measure temperature at a single point of contact. However, an RTD provides an excellent means of measuring the average temperature over a surface, and it does this by spreading the resistance wire contact over a surface area. But if this surface contact also spreads over some distance, such that the lead wire connections at each end of the element are displaced too far apart, then this can lead to Seebeck error, which is a byproduct of the thermal gradient that occurs between the two Platinum-Copper connections to the lead wires.

These errors can be prevented by using appropriate lead wire and careful sensor positioning relative to the lead wires. In a nutshell, a different lead material like copper can produce a T/C junction where it connects to the platinum element, and then another T/C junction at the other end. If the two junctions are at different temperatures, then a thermoelectric emf will develop that can throw off the IR measurement of the RTD element. Do you remember the Law of Intermediate Metals that was stated in Part 1 of this series?

The algebraic sum of the thermoelectric emf in a circuit composed of any number of dissimilar materials is zero, if all of the junctions are maintained at a uniform temperature.

So you only have two remedies to combat this effect: either use a lead-wire of the same material as the element (not practical, as this would be very expensive for a platinum element with long leads), or simply keep the temperatures at each junction the same (i.e along the element), or nearly the same, which would result in negligible net emf contribution to your voltage measurement.

Conclusion

This concludes Part 2 of this three part series, and like we saw with thermocouples, there are many considerations when selecting among RTD types, or between RTDs and thermocouple types. You must consider an RTDs Temperature Coefficient of Resistance (TCR), its relative sensitivity, its accuracy and repeatability, interchangeability, stability and drift characteristics, its insulation resistance, its response time, plus its packaging and the thermal transfer mechanism between the sensed material and the sensor element. You must also consider the negative effects of corrosion and contamination, shock and vibration, self-heating, meter loading, and in some cases, even thermoelectric effects. In Part 3 of this series, we will summarize the salient aspects of thermocouple and RTD sensor types and highlight the key differences that might make one sensor type better than another for a given application.

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Acromag is a leading manufacturer of temperature transmitters and signal conditioners for use with thermocouple and RTD sensors. These instruments convert the sensor input to a proportional 4-20mA DC current, DC voltage, Modbus, Profibus, or Ethernet signal to interface with a PC, PLC, DCS, or other control equipment.

Acromag has designed and manufactured measurement and control products for more than 50 years. They are an AS9100 and ISO 9001-certified international corporation with a world headquarters near Detroit, Michigan and a global network of sales representatives and distributors. Acromag offers a complete line of industrial I/O products including a variety of process instruments, signal conditioners, and distributed fieldbus I/O modules that are available with a 7-year warranty. Industries served include chemical processing, manufacturing, defense, energy, and water services.

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CRITERIA FOR TEMPERATURE SENSOR SELECTION OF T/C AND RTD SENSOR TYPES

A Comparison of Thermocouple and RTD Temperature Sensors
Part 3 of 3:

8500-906-A10L000

This is part 3 of a comprehensive three part series that provides information for choosing an industrial temperature sensor from Thermocouple (T/C) and Resistance Temperature Detector (RTD) sensor types.

Part 1 of this series (8500-911) titled “The Basics of Temperature Measurement Using Thermocouples“, takes a close look at thermocouples, their construction, and how they operate. That document reviewed three important scientific laws that govern the operation of thermocouples: The Law of Homogeneous Material, The Law of Intermediate Materials, and The Law of Successive or Intermediate Temperatures. We saw that choosing between thermocouple types gave consideration to the thermocouple materials, temperature range, sensitivity, and behavior in four primary application atmospheres (i.e. inert atmosphere, reducing atmosphere, oxidizing atmosphere, and operation in a vacuum). Some thermocouple types work better in certain atmospheres than others. Some thermocouples use non-magnetic materials, making them a better choice for temperature sensing near electric motors. Other thermocouple applications will favor T/C materials that are more stable and have better corrosion resistance. We also looked at measures of performance associated with thermocouples including accuracy, non-linearity, sensitivity, sensor drift or de-calibration, and response time. Part 1 also talked about thermocouple connection problems, T/C extension wire, cold junction compensation, lead resistance, thermal shunting, plus noise and common-mode voltage issues.

Part 2 of this series (8500-917), titled “The Basics of Temperature Measurement Using RTD’s” looked similarly at the Resistance Temperature Detector (RTD), its construction, and how it operates. We saw that choosing one RTD type over another gave consideration to its physical construction, sensitivity, material and insulation, and temperature range. We also looked at the RTD Temperature Coefficient of Resistance (TCR) and its relationship to RTD sensitivity. Part 2 summarized two common polynomial expressions used to predict the resistance of an RTD: the Callendar-Van Dusen equation and its IEC751/ITS-90 derivative. Part 2 shows how the input wiring of the RTD is also an important consideration, and how it is used to accomplish lead-wire compensation, improve accuracy and common-mode noise rejection. Part 2 also showed how an RTD’s insulation material often limits its useful temperature range to lower application temperatures. It also examined the role of lead resistance and how it can drive measurement error if not considered carefully. Part 2 also looked at RTD performance measures including accuracy, interchangeability, repeatability, stability/drift, and response time. It talked about application issues with RTD’s, including corrosion and contamination, shock and vibration, insulation resistance, lead-wire resistance, self-heating error, meter loading, packaging and thermal transfer, and even thermoelectric effects.

This Part 3 will summarize and compare some common aspects of both sensors to help you choose between the two in your quest to find the best sensor for your particular industrial application. Part 3 relies heavily on information provided in Parts 1 and 2 and you should review Parts 1 and 2 before reading this material. You can download any of these documents and more, free of charge from our web site at www.acromag.com.

Thermocouples versus Resistance Temperature Detectors

Many users simply look to fill the basic needs of their application and do not worry much about their choice of temperature sensing technology. That is, they will make a selection based simply on temperature range and their own bias, perhaps based on their familiarity with a particular sensor type.

At a minimum, an informed sensor choice should first consider the following:

- Measurement range, including the range extensions of shutdown, startup, and process upset.
- The response time.
- The sensor stability, accuracy, and sensitivity in the application environment.

When we start to cross the boundaries between choosing one type of sensor over another, the optimum choice between thermocouple and RTD can be difficult. There is a lot of overlap between these sensors at the more popular lower end of the operating temperature range. So for sensors that cover the same operating range, and applications where response time is not a driving issue, plus stability, accuracy, and sensitivity are acceptable, we really have to drill deeper and compare characteristics between sensors to find the best fit for a given application. Table 1 below summarizes many of the comparative differences between thermocouple and RTD sensor types.

Table 1: Comparison of Salient Features of RTD and T/C Temperature Sensors

Characteristic	Thermocouple (T/C)	Resistance Temperature Detector (RTD)
Measurement Range	Wide, -250°C to +2600°C	Narrower, -200°C to +850°C, often limited to a lower temperature by its insulation.
Output Signal	Voltage wrt difference in end-to-end temperature	Resistance change wrt actual temperature
Accuracy	Less accurate, 2-4°C typical	More accurate, up to 1°C typical
Long Term Stability	Fair, limited to shorter periods	Good, stable over long periods
Stability/Drift	Good, but more subject to drift	Excellent, better long-term stability
Sensitivity	Lower	Higher sensitivity
Interchangeability	Good	Excellent
Linearity	Fair linearity, special linearization generally required.	Better linearity, special linearization still required, but to a lesser degree
Self-Heating Error	No self-heating error	Some self-heating error, but low
Extension Cable	High effect, must match T/C type and is more expensive	Lower effect, can use different material, but ultimately limited by lead wire resistance
Response Time	Fast (≤ 0.1 seconds typical), but CJC has thermal lag	Slower (1 to 7 seconds typical)
Repeatability	Reasonable	Better & greater standardization
Hysteresis	Excellent	Good
Signal Strength	Low, prone to EMI	Higher, more EMI resistant
Vibration/Shock Resistance	Good resistance	Less resistant than T/C
Robustness/Ruggedness	Very good	Good
Sensor Dimensions	Very small to very large	Small to medium
Measurement Area	Small, single point-of-contact	Larger, whole element must contact, 1" typical
Fine Wire Diameter	Small down to 0.25mm diameter	Larger up to 3mm diameter
Reference Junction	Required and a significant source of measurement error. Usually requires a stable ambient at cold junction.	Not required and not a source of error
Excitation Required	Not required, self-powered	Yes, reference voltage or current source
Lead-Wire Resistance	High, but often mitigated by mating technology	Must be considered wrt maximum added resistance and potential resistive imbalance between leads
Cost	Less expensive	More expensive
Complexity	Very simple and less subject to mechanical stress	Physically larger and has a more complex construction making it more subject to mechanical stress
Calibration Ease	More difficult and adds CJC calibration	Less difficult, no CJC to contend with
Noise Immunity	Lower noise immunity but often mitigated by good wiring practice. Small signals and high impedance leads can easily pick up noise.	Better noise immunity than a T/C

In general, if your application requires the highest accuracy, cost is not a concern, and your operating ambient is less than 800°C, then the choice of an RTD over a thermocouple sensor is probably the right one. The RTD is more accurate, more stable, more repeatable, and offers a more robust output signal with better sensitivity and linearity than a thermocouple. However, the RTD does have a narrower operating range with a lower maximum operating temperature, it is generally more expensive, and it does require excitation which might drive the need for an external power source (a Wheatstone bridge for example). Please review Part 2 of this series for other differentiating features of RTD sensors.

If you instead decide that a thermocouple is best for your application, perhaps because of its lower cost, wider temperature range, faster response time, and simpler construction, plus its many physical sizes and wider range of configurations available, then you might start by picking a Type K thermocouple until you can find a specific reason to choose another type. That is, type K is the most common and least expensive of available T/C types, and it also has a wide operating temperature range with high sensitivity. It is constructed from nickel-based metals which have good resistance to corrosion and are cheaper than the comparable platinum-based metals. So with this in mind, why would you choose anything else? Well, it does have one lead that is magnetic (the Red or negative lead), and this might not work well around electric motors. It is also vulnerable to sulfur attack and should not be used in sulfurous atmospheres. Please consult Part 1 of this series to review other differentiating characteristics between thermocouple types.

Other Points of Contrast Between the Thermocouple and the Resistance Temperature Detector

Although a thermocouple sensor system usually has a generally faster response time to changing temperature at its point of contact, it generally takes longer to reach thermal equilibrium after power is applied. This is largely due to the presence of cold junction compensation, which does not respond to temperature changes at the cold junction as quickly as the T/C junction responds to changes in contact temperature. The thermal lag of cold junction compensation might make a thermocouple a poor choice where its mating amplifier or cold junction is subject to rapid or quickly changing ambient temperatures. Further, the presence of cold junction compensation in the mating amplifier often makes it subject to the self-heating or warm-up of the measuring circuit itself, driving longer warm up periods for the measuring system to reach thermal equilibrium. Thus, applications where temperature measurement is done discontinuously, perhaps only during part of the day and then shut-down overnight, might favor the choice of an RTD sensor over that of a thermocouple.

If you are looking for a temperature sensor that requires the lowest possible current consumption, perhaps in an energy-harvesting application, or for use in a circuit that runs on batteries, then the use of a thermocouple might be a better choice, simply because the RTD sensor requires excitation to operate, typically in the range of about 1mA. While some RTD amplifiers run fine on less than 1mA of excitation current, it still may not be low enough to ensure long battery life.

If the distance between the measuring instrument and the sensor is very long, this might favor the use of a thermocouple over that of an RTD, because minimizing lead-wire resistance can be a big factor in long-distance RTD applications. In general, because you are reading the resistance of the sensor, you try to keep the sensor closer to the instrument such that lead wire resistance is not a negative factor. For long distance runs, some applications will use larger diameter lead wires to minimize lead resistance, but this also has the negative effect of potentially “heat-sinking” the sensor element and artificially reducing the measured temperature.

If reducing wiring or the number of terminal connections is important to your application, then this would again favor the use of thermocouples, which only require two connections to the measuring instrument or transmitter. Although two wire RTD sensors do exist, they are limited to short coupled distances because of the negative effect the uncompensated lead-wire resistance has on the measurement. For comparable or better performance, an RTD will require at least three wired connections per channel versus only two for the thermocouple. This could be a factor for high-density, high channel count installations.

Whatever the material and construction, an RTD is still relatively bulky by comparison to the thermocouple, and as a result, cannot be used to measure temperature at a single point, like that of a thermocouple. But on the other hand, RTD technology provides an excellent means of measuring the average temperature over a surface by spreading the resistance wire over that surface, and this ability to average temperature over a surface area (or an immersion depth) will be more desirable for some applications.

The use of a platinum RTD sensor may be preferred when a temperature measurement accuracy of better than 1°F or 1°C is required. By comparison, thermocouple accuracy will be on the order of 2°C to 4°C, typical. However, for point-of-contact measurement at temperatures above about 800°C (the maximum temperature at which platinum RTDs can be used), a thermocouple is the better choice due to its higher rated operating temperature.

By now, you should realize that one type of sensor, thermocouple or RTD, is not always a better choice than the other. It really depends on your application and what characteristics you consider important to your application. You must always consider your operating environment and any potentially negative effects it may have on your choice of temperature sensor and measurement system.

About Acromag

Acromag is a leading manufacturer of temperature transmitters and signal conditioners for use with thermocouple and RTD sensors. These instruments convert the sensor input to a proportional 4-20mA DC current, DC voltage, Modbus, Profibus, or Ethernet signal to interface with a PC, PLC, DCS, or other control equipment.

Acromag has designed and manufactured measurement and control products for more than 50 years. They are an AS9100 and ISO 9001-certified international corporation with a world headquarters near Detroit, Michigan and a global network of sales representatives and distributors. Acromag offers a complete line of industrial I/O products including a variety of process instruments, signal conditioners, and distributed fieldbus I/O modules that are available with a 7-year warranty. Industries served include chemical processing, manufacturing, defense, energy, and water services.

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