

Criteria for Temperature Sensor Selection of T/C and RTD Sensor Types

The Basics of Temperature Measurement Using RTDs

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Preface

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.](#)

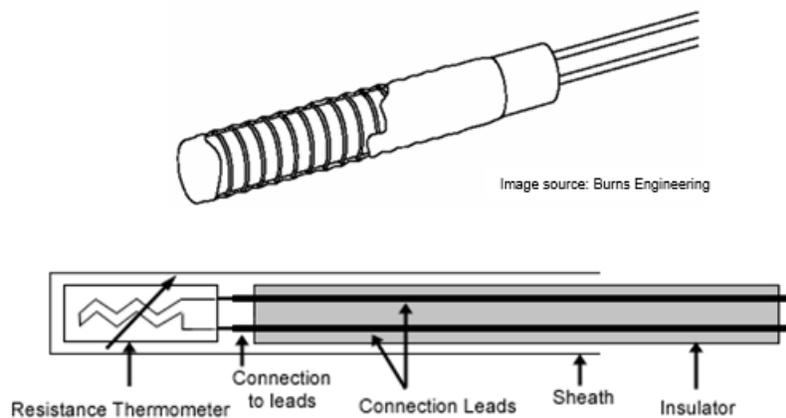
This part will look similarly at RTDs. After a review of the basic construction of an RTD, we will take look at an RTDs Temperature Coefficient of Resistance (TCR), its sensitivity, accuracy, interchangeability, repeatability, stability and drift, corrosion and contamination effects, shock and vibration 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.



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.

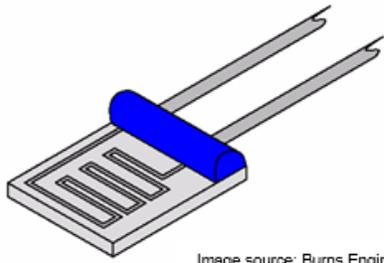
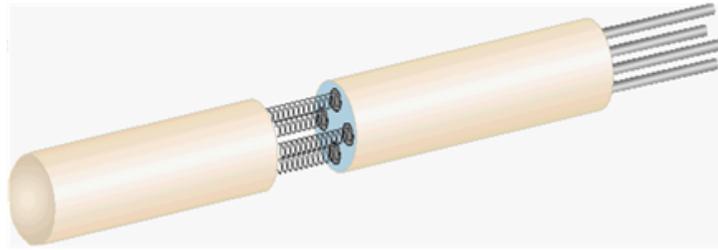


Image source: Burns Engineering



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/Fiberglass 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 \pm lead. As long as the \pm 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 \pm 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.

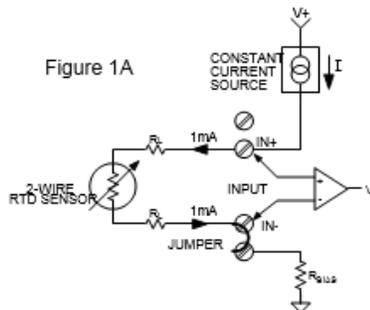


Figure 1A
 2-WIRE SENSOR w/SINGLE CURRENT EXCITATION. CONVERTS SENSOR WITH A SINGLE DIFFERENTIAL MEASUREMENT. DOES NOT COMPENSATE FOR LEAD RESISTANCE. LIMITED TO SHORT SENSOR-TO-INSTRUMENT DISTANCES.

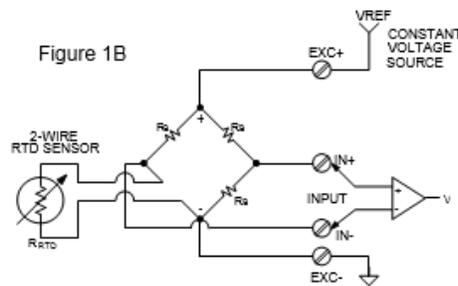


Figure 1B
 2-WIRE RTD SENSOR w/BALANCED BRIDGE CONNECTION. CONVERTS WITH A SINGLE MEASUREMENT. COMPENSATES FOR MATCHED LEAD RESISTANCES. REQUIRES BRIDGE RESISTANCE TO MATCH SENSOR BASE RESISTANCE. REQUIRES PRECISE AND STABLE VOLTAGE EXCITATION. WIRING AND CALIBRATION ARE COMPLEX.

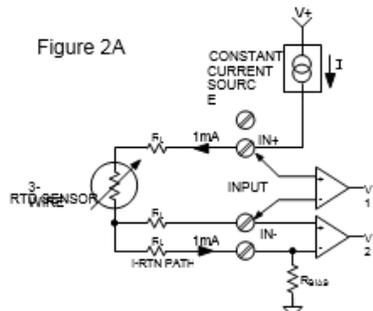


Figure 2A
 3-WIRE SENSOR w/SINGLE CURRENT EXCITATION. CONVERSION REQUIRES TWO DIFFERENTIAL MEASUREMENTS. COMPENSATED FOR MATCHED LEAD RESISTANCES.

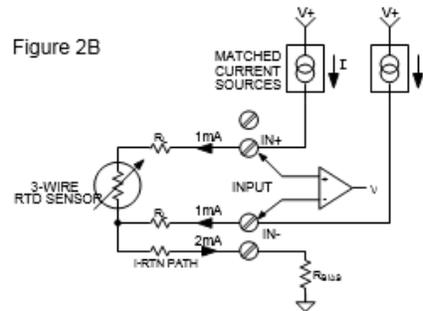


Figure 2B
 3-WIRE SENSOR w/DUAL MATCHED CURRENT EXCITATION. CONVERTS WITH A SINGLE DIFFERENTIAL MEASUREMENT. SELF-COMPENSATES FOR MATCHED +/- LEAD RESISTANCES.

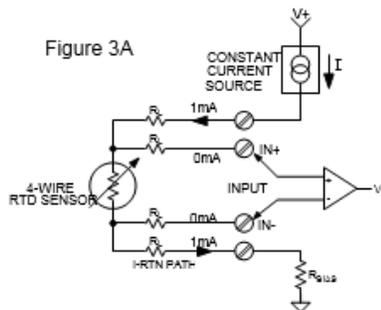


Figure 3A
 4-WIRE SENSOR w/KELVIN CONNECTION. CONVERTS WITH A SINGLE DIFFERENTIAL MEASUREMENT. DOES NOT REQUIRE MATCHED LEADS AS NO CURRENT FLOWS IN SENSE LEADS AND MEASUREMENT IS NOT AFFECTED BY LEAD RESISTANCE.

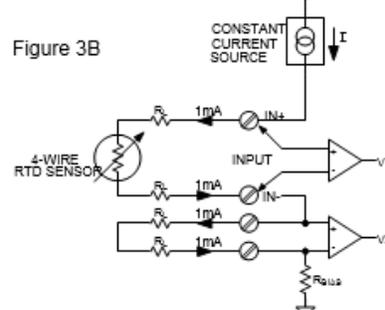


Figure 3B
 4-WIRE SENSOR w/COMPENSATING LOOP CONNECTION. CONVERSION REQUIRES TWO DIFFERENTIAL MEASUREMENTS. COMPENSATED FOR MATCHED LEAD RESISTANCES.

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

For Pt 100 Ω sensors of the DIN 43760 and IEC 751 standards, this is calculated via the expression $[(138.5\Omega - 100.0\Omega)/100.0\Omega]/100^\circ\text{C}$, or 0.00385 $\Omega/\Omega^\circ\text{C}$. 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:

$$\Delta R = \alpha R_0 \Delta T,$$

where: α = TCR in $\Omega/\Omega^\circ\text{C}$; R_0 = 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 $\alpha=0.00385\Omega/\Omega^\circ\text{C}$ 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:

$R_{0^\circ\text{C}}$ OHMS	ALPHA α ($\Omega/\Omega^\circ\text{C}$)	REFERENCE
100	0.00393	Highest purity Platinum
	0.003927	
	0.003926	ITS-90 Lab Standard Pt RTD, Requires $\geq 99.999\%$ Purity. This is the laboratory standard platinum RTD which requires the high purity platinum wire ($\geq 99.999\%$) 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:

$$R_T = [R_0 + (\alpha R_0 \Delta T)] = 100\Omega + (0.00385\Omega/\Omega/^\circ\text{C})(100\Omega)(1^\circ\text{C}) = 100.385\Omega.$$

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 any 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:

$$R_T = R_0 + R_0 \alpha [T - \delta (T/100 - 1) (T/100) - \beta (T/100 - 1) (T/100)^3], \text{ where:}$$

- R_T = RTD resistance at some temperature T°C in Ω
- R₀ = 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 (α) 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 = R₀ + R₀ * α * T, and the temperature as a function of the resistance as T = (R_T - R₀)/R₀ * α.

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 α (T = (R_T - R₀)/R₀ * α). This coefficient is calculated δ = [T_H - ((R_{T_H} - R₀)/R₀ * α)] / [(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 positive temperatures via the expression:

$$R_T = R_0 + R_0 \alpha [T - \delta (T/100 - 1) (T/100)]$$

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:

$$\beta = [T_L - [(R_{T_L} - R_0)/(R_0 \alpha) + \delta (T_L/100 - 1) (T_L/100)]] / [(T_L/100 - 1) (T_L/100)^3]$$

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

$$R_T = R_0 + R_0 \alpha [T - \delta (T/100 - 1) (T/100) - \beta (T/100 - 1) (T/100)^3], \text{ where } \beta = 0 \text{ for } t > 0^\circ\text{C:}$$

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:

$$R_T = R_0 * [1 + A * T + B * T^2 + C * (T - 100) * T^3],$$

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 = R₀ * [1 + A * T + B * T²] 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!). 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:

$$R_T = R_0 [1 + A \cdot T + B \cdot T^2 - 100 \cdot C \cdot T^3 + C \cdot T^4]$$

Comparing this to the Callendar-Van Dusen equation, we can derive the expressions for calculating the IEC751 coefficients A, B, and C as follows:
 $A = \alpha + (\alpha \cdot \delta) / 100$; $B = -(\alpha \cdot \delta) / 100^2$; $C = -(\alpha \cdot \beta) / 100^4$

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, $\alpha = [(R_{100^{\circ}\text{C}} - R_{0^{\circ}\text{C}})/R_{0^{\circ}\text{C}}]/100^{\circ}\text{C}$, we see that alpha really represents the fractional increase in resistance over 100°C. Stated another way, for $\alpha=0.00385$, 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 $\Omega/^{\circ}\text{C}$ 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:

$$\text{Sensitivity} = K_{\text{RTD}} = R_0 * \alpha.$$

For a 100Ω platinum RTD with $\alpha=0.00385 \Omega/\Omega/^{\circ}\text{C}$ and $R_0 = 100\Omega$, the sensitivity coefficient is computed via the expression $100\Omega * 0.000385\Omega/\Omega/^{\circ}\text{C} = 0.385\Omega/^{\circ}\text{C}$. Thus, a 100Ω sensor at 0°C will increase its resistance by 0.385Ω in 1°C, or 0.385Ω/°C.

Referring to the prior table, we see that the higher the alpha value, the more sensitive the sensor. Thus, a Nickel RTD ($\alpha=0.00672\Omega/\Omega/^{\circ}\text{C}$, $R_0=120\Omega$) is more sensitive to temperature change than a Platinum RTD, as it will change its resistance by $120\Omega * 0.00672\Omega/\Omega/^{\circ}\text{C} = 0.8064\Omega/^{\circ}\text{C}$, greater than the 0.385Ω/°C of the Platinum sensor, making it more than twice as sensitive.

Multiples of nominal resistance $R_0 = 100\Omega$ 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:

- 0.385Ω/°C for Pt100
- 1.925Ω/°C for Pt500
- 3.850Ω/°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)	$\alpha = 0.00385 \pm 0.000063\Omega/\Omega/^{\circ}\text{C}$	$\alpha = 0.00385 \pm 0.000063\Omega/\Omega/^{\circ}\text{C}$
Applicable Range	-200°C to +650°C	-200°C to +850°C
Resistance Tolerance	$\pm(0.06 + 0.0008 * T - 2 * 10^{-7} * T^2)\Omega$ (±0.06% at 0°C)	$\pm(0.12 + 0.0019 * T - 6 * 10^{-7} * T^2)\Omega$ (±0.12% at 0°C)
Temperature Deviation	$\pm(0.15 + 0.002 * T)^{\circ}\text{C}$	$\pm(0.3 + 0.005 * T)^{\circ}\text{C}$

Note: The expression for Resistance Tolerance is only applicable to $\alpha=0.00385$ 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: $\pm(0.15 + 0.002*|T|)^{\circ}\text{C}$ (Matches IEC 751 Class A)

DIN Class B: $\pm(0.30 + 0.005*|T|)^{\circ}\text{C}$ (Matches IEC 751 Class B)

DIN Class C: $\pm(1.20 + 0.005*|T|)^{\circ}\text{C}$

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

Grade A: $\pm(0.13 + 0.0017*|T|)^{\circ}\text{C}$

Grade B: $\pm(0.25 + 0.0042*|T|)^{\circ}\text{C}$

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	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 $100\Omega \pm 0.12\Omega$ at 0°C, with a TCR of $0.00385 \pm 0.000063\Omega/\Omega/^\circ\text{C}$. This corresponds to a temperature deviation of $\pm 0.3^\circ\text{C}$ 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 $100\Omega \pm 0.12\%$ at 0°C, or to within $\pm 0.12\Omega$ ($\pm 0.3^\circ\text{C}$) at 0°C, but allows the slope or rate of change to deviate from nominal $0.00385\Omega/\Omega/^\circ\text{C}$ by $\pm 0.000012/^\circ\text{C}$. This results in a tolerance band that increases to $\pm 0.8^\circ\text{C}$ at 100°C, $\pm 0.1.3^\circ\text{C}$ at 200°C, and so on up to $\pm 4.6^\circ\text{C}$ 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 $\pm 0.1^\circ\text{C}$ 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 $\pm 0.5^{\circ}\text{C}$ or $\pm 0.1^{\circ}\text{C}$ per year for rated operation, but under normal conditions well within its operating range, the actual drift will be significantly less, perhaps $\leq \pm 0.1^{\circ}\text{C}$ in 5 years or more. The stability of platinum RTD sensors is the highest with typical drift rates $\leq 0.05^{\circ}\text{C}$ 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 100M Ω 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 25.5 Ω 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 ($\alpha=0.00385\Omega/\Omega/^\circ\text{C}$) located 100 feet from the instrument and wired using 24AWG extension wire (26.17Ω/1000feet) will potentially drive the following approximate error:

$$(2 \times 100\text{ft} \times 26.17\Omega/1000\text{ft}) / 0.385\Omega/^\circ\text{C} = 5.234\Omega/0.385\Omega/^\circ\text{C} = 13.59^\circ\text{C}$$

This is equivalent to taking the resistance of the lead wire and dividing it by the sensitivity of the element (Sensitivity = $R_0 \cdot \alpha = 100\Omega \cdot 0.00385\Omega/\Omega/^\circ\text{C} = 0.385\Omega/^\circ\text{C}$).

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 $1000\text{mW/W} \cdot I^2 \cdot R = 1000 \cdot (0.002\text{A})^2 \cdot 138.5\Omega = 0.55\text{mW}$. This results in a self-heating error of only $(0.55\text{mW})/(50\text{mW}/^\circ\text{C}) = 0.01^\circ\text{C}$.

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 I²R 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 $\sim 0.001\text{mW}/50\text{mW}/^\circ\text{C} = 0.00003^\circ\text{C}$, 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. $0.001A * 100\Omega / 10M\Omega = 10nA$).

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 $7\mu\text{V}/^\circ\text{C}$ 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

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.

Temperature Transmitters

Criteria for Temperature Sensor Selection of T/C and RTD Sensor Types more information that might interest you.

[The Basics of Temperature Measurement Using Thermocouples White Paper](#)

[A Comparison of Thermocouple and RTD Temperature Sensors White Paper](#)

[Temperature transmitters convert thermocouple, RTD, and low-level temperature sensor signals to 4-20mA, 0-10V, or other DC voltage/current outputs.](#) Acromag offers temperature transmitters in head-mount and DIN-rail form factors. Some temperature transmitters have software-configured universal input to convert a broad range of temperature sensor and other signals with a single unit.

[Thermocouple transmitters convert Type J, K, T, E, R, S, B, or N thermocouple sensor input signals to 4-20mA or 0-10V DC outputs](#) for interfacing to controllers or other instrumentation.

[RTD transmitters convert Platinum, Copper, Nickel RTD or resistance sensor input signals to 4-20mA or 0-10V DC outputs](#) for interfacing to controllers or other instrumentation.

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