

RESISTANCE THERMOMETRY: Principles and applications of resistance thermometers and thermistors

Resistance thermometers and thermistors are temperature sensors which change electrical resistance with temperature. The superior sensitivity and stability of these devices, in comparison to thermocouples, give them important advantages in low and intermediate temperature ranges. In addition, resistive devices often simplify control and readout electronics.

Resistance thermometers are specified primarily for accuracy and stability from cryogenic levels to the melting points of metals. They are accurate over a wide temperature range, may be used to sense temperature over a

large area, and are highly standardized. The standard platinum resistance thermometer is specified by the ITS-90 (International Temperature Scale of 1990) to interpolate between fixed points in the range 13.80K (–259.35°C) to 1234.93K (961.78°C).

While normally less stable than resistance thermometers, thermistors offer lower cost and higher sensitivity over more limited ranges. Thermistor sensors can be relatively small and are well suited to product or equipment applications where quantities of use justify the design of special readout circuits.

Resistance Thermometers

Resistance thermometers may be called RTD's (resistance temperature detectors), PRT's (platinum resistance thermometers), or SPRT's (standard platinum resistance thermometers). These thermometers operate on the principle that electrical resistance changes in pure metal elements, relative to temperature.

The traditional sensing element of a resistance thermometer consists of a coil of small diameter wire wound

to a precise resistance value. The most common material is platinum, although nickel, copper, and nickel-iron alloys compete with platinum in many applications.

A relatively recent alternative to the wire-wound RTD substitutes a thin film of platinum or nickel-iron, which is deposited on a ceramic substrate and laser-trimmed to the desired resistance. Thin film elements attain high resistances with less metal, thereby lowering cost.

Resistance/temperature characteristics

Resistance thermometers exhibit the most linear signal with respect to temperature of any sensing device. Small deviations from straight line response, however, dictate the use of interpolating polynomials to calculate resistance values between fixed temperature points.

Platinum

The resistance/temperature characteristic for standard platinum resistance thermometers, as defined by the ITS-90, is a complex set of equations beyond the scope of this document. A good reference for understanding the ITS-90 is *NIST Technical Note 1265: Guidelines for Realizing the ITS-90*, B. W. Mangum and G. T. Furukawa, U. S. Department of Commerce, 1990.

Platinum generally follows the modified Callendar-Van Dusen equation over the range –200 to 850°C (–328 to 1562°F):

t(°C)	Equation
–200 to 0	$R_t = R_0 [1 + At + Bt^2 + Ct^3 (t - 100)]$
0 to 850	$R_t = R_0 [1 + At + Bt^2]$

R_t = Resistance at temperature t (in °C),

R_0 = Base resistance at 0°C, and

A , B , and C are constants that describe a given thermometer.

The A , B , and C coefficients, which can be individually determined for high precision laboratory thermometers, are entered into the Callendar-Van Dusen equation to generate resistance vs temperature tables.

Nominal values are:

$TCR^* = 0.003926 \Omega/\Omega^\circ C$ (Minco element code **PA** et al.)
 $A: 3.9848 \times 10^{-3}$ $B: -5.870 \times 10^{-7}$ $C: -4.0000 \times 10^{-12}$

$TCR = 0.003911 \Omega/\Omega^\circ C$ (Minco element code **PB** et al.)
 $A: 3.9692 \times 10^{-3}$ $B: -5.8495 \times 10^{-7}$ $C: -4.2325 \times 10^{-12}$

$TCR = 0.003850 \Omega/\Omega^\circ C$ (Minco element code **PD** et al.)
 $A: 3.9083 \times 10^{-3}$ $B: -5.775 \times 10^{-7}$ $C: -4.183 \times 10^{-12}$

To determine temperature from a measured resistance for t above 0°C:

$$t = \frac{-A + \sqrt{A^2 - 4B \left(1 - \frac{R_t}{R_0}\right)}}{2B}$$

*Temperature Coefficient of Resistance

Resistance Thermometers

Resistance/temperature characteristics (cont.)

Platinum (cont.)

For temperatures below 0°C, the equation is too complex to solve, so successive approximation is employed:

$$t_1 = \frac{R_t/R_0 - 1}{A + 100B} \quad (\text{initial approximation})$$

$$t_{n+1} = t_n - \frac{1 + At_n + Bt_n^2 + Ct_n^3(t_n - 100) - R_t/R_0}{A + 2Bt_n - 300Ct_n^2 + 4Ct_n^3}$$

This equation typically converges to sufficient accuracy within 2 iterations.

Copper

The corresponding equations for copper elements are:

t(°C)	Equation
-200 to -50	$R_t = R_0 [1 + A_1(t + 200) + B_1(t + 200)^2]$
-50 to 150	$R_t = R_0 [1 + A_2t]$
150 to 260	$R_t = R_0 [1 + A_3(t - 150) + B_3(t - 150)^2]$

R_t = Resistance at temperature t (in °C),

R_0 = Base resistance at 0°C, and

A , B , R_1 , and R_3 are constants that describe a given thermometer.

Nominal values are:

TCR ($\Omega/\Omega/^\circ\text{C}$) = 0.00427 (Minco element code **CA** et al.)

R_1 : 1.17058×10^{-1} A_1 : 3.92313×10^{-2} B_1 : -7.45044×10^{-6}
 A_2 : 4.2743×10^{-3}

R_3 : 1.641145 A_3 : 2.62628×10^{-3} B_3 : 2.43732×10^{-8}

Note that copper resistance is linear with temperature from -50 to 150°C, and nearly linear over other ranges.

Nickel-iron

The equations for nickel-iron are:

t(°C)	Equation
-200 to 0	$R_t = R_0 [1 + A_1t + B_1t^2 + C_1t^3]$
0 to 204	$R_t = R_0 [1 + A_2t + B_2t^2 + C_2t^3]$

R_t = Resistance at temperature t (in °C),

R_0 = Base resistance at 0°C, and

A , B , and C are constants that describe a given thermometer.

Nominal values are:

TCR ($\Omega/\Omega/^\circ\text{C}$) = 0.00518 (Minco element code **FA** et al.)

A_1 : 4.68699×10^{-3} B_1 : 8.58992×10^{-6} C_1 : 0
 A_2 : 4.59818×10^{-3} B_2 : 5.89404×10^{-6} C_2 : 0

TCR ($\Omega/\Omega/^\circ\text{C}$) = 0.00527 (Minco element code **FB** et al.)

A_1 : 4.63189×10^{-3} B_1 : 6.96196×10^{-6} C_1 : -1.72771×10^{-8}
 A_2 : 4.63189×10^{-3} B_2 : 6.96196×10^{-6} C_2 : -5.71203×10^{-9}

Nickel

Individual manufacturers have developed proprietary curves for nickel elements, working from direct measurements, but there is no simple formula for direct calculation of resistance. Figure 1 shows the nonlinear behavior of nickel in comparison to other elements.

This stepwise equation will closely approximate Minco's standard nickel curve:

$$R_t = R_0 [A + Bt + Ct^2 + Dt^3]$$

R_t = Resistance at temperature t (in °C),

R_0 = Base resistance at 0°C, and

A , B , C , and D are constants that describe a given thermometer.

Nominal values are:

TCR ($\Omega/\Omega/^\circ\text{C}$) = 0.00672 (Minco element code **NA**)

t(°C)	A	B
-80 to -60	$9.980384367 \times 10^{-1}$	$5.779005438 \times 10^{-3}$
-60 to -30	$9.995545058 \times 10^{-1}$	$5.854808892 \times 10^{-3}$
-30 to 0	1.0	$5.899358312 \times 10^{-3}$
0 to 30	1.0	$5.899358312 \times 10^{-3}$
30 to 60	1.000118847	$5.887473643 \times 10^{-3}$
60 to 90	1.002329124	$5.776959768 \times 10^{-3}$
90 to 120	$9.940315172 \times 10^{-1}$	$6.053466667 \times 10^{-3}$
120 to 150	1.007022904	$5.728761999 \times 10^{-3}$
150 to 180	$8.918592090 \times 10^{-1}$	$8.032035898 \times 10^{-3}$
180 to 210	$9.060247382 \times 10^{-1}$	$7.795943744 \times 10^{-3}$
210 to 240	1.103473241	$4.975250849 \times 10^{-3}$
240 to 260	1.437355995	$8.017164189 \times 10^{-4}$

t(°C)	C	D
-80 to -60	$4.519218356 \times 10^{-6}$	$1.883007648 \times 10^{-8}$
-60 to -30	$5.782609262 \times 10^{-6}$	$2.584891485 \times 10^{-8}$
-30 to 0	$7.267589932 \times 10^{-6}$	$4.234870007 \times 10^{-8}$
0 to 30	$7.267589932 \times 10^{-6}$	$1.154640832 \times 10^{-8}$
30 to 60	$7.663745572 \times 10^{-6}$	$7.144678985 \times 10^{-9}$
60 to 90	$9.505643490 \times 10^{-6}$	$-3.088087226 \times 10^{-9}$
90 to 120	$6.432455728 \times 10^{-6}$	$8.294089672 \times 10^{-9}$
120 to 150	$9.138994624 \times 10^{-6}$	$7.759260700 \times 10^{-10}$
150 to 180	$-6.216164699 \times 10^{-6}$	$3.489850234 \times 10^{-8}$
180 to 210	$-4.904541625 \times 10^{-6}$	$3.246957072 \times 10^{-8}$
210 to 240	$8.527329303 \times 10^{-6}$	$1.114941068 \times 10^{-8}$
240 to 260	$2.591705610 \times 10^{-5}$	$-1.300325764 \times 10^{-8}$

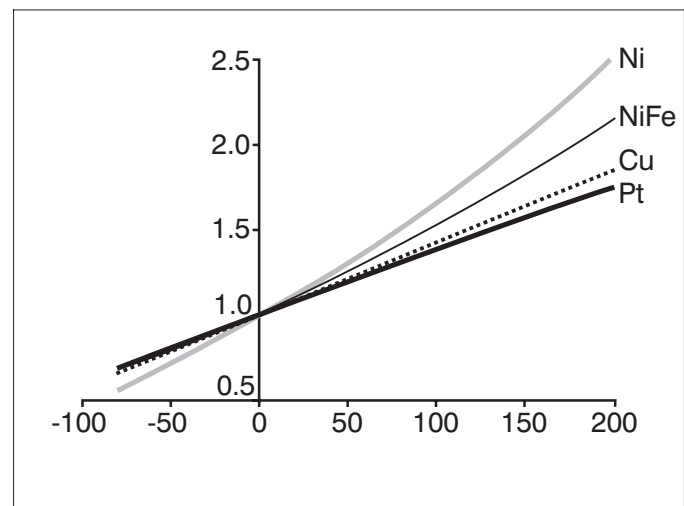


Figure 1: Linearity of metals used in resistance thermometers.

Resistance Thermometers

Resistance/temperature characteristics (cont.)

Until recently, equations relating resistance to temperature were of interest mainly to researchers and designers of linearizing analog circuits. Now many common instruments such as readouts, data loggers, and controllers contain microprocessors. Interest in direct digital computation of temperature has increased accordingly. A few considerations for the designer or programmer of digital instruments are:

1. Converting resistance to temperature requires finding the root of a third or fourth order polynomial. Instead, many manufacturers use a lookup table, with resistance/temperature values stored in ROM (read only memory). Choosing values sufficiently close together, on a 5°C interval for example, with linear

interpolation between will usually produce acceptable readings.

2. The use of resistance ratios, instead of absolute values, is recommended for measurements of the highest accuracy. A ratio table sets the R_0 value to 1, and uses A, B, and C coefficients to calculate ratios from this value. The absolute resistance at any given temperature is the product of R_0 and the ratio. Resistance ratios are preferred for their stability. Simple periodic checks of ice point resistance, with most recent R_0 used to calculate absolute resistances, will reduce or eliminate the need for complete recalibration and table generation.

Temperature coefficient of resistance

Temperature Coefficient of Resistance (TCR) has many definitions. For resistance thermometers, TCR is normally defined as the average resistance change per °C over the range 0 to 100°C, divided by $R_{0^\circ\text{C}}$:

$$TCR(\Omega / \Omega / ^\circ\text{C}) = \frac{(R_{100^\circ\text{C}} - R_{0^\circ\text{C}}) / R_{0^\circ\text{C}}}{(100^\circ\text{C} - 0^\circ\text{C})}$$

TCR values for the common elements are:

$$\text{Copper: } \frac{(12.897 - 9.035) / 9.035}{100} = 0.00427 \Omega / \Omega / ^\circ\text{C}$$

$$\text{Nickel: } \frac{(200.64 - 120) / 120}{100} = 0.00672 \Omega / \Omega / ^\circ\text{C}$$

$$\text{Nickel-iron: } \frac{(917.33 - 604) / 604}{100} = 0.00518 \Omega / \Omega / ^\circ\text{C}$$

$$\text{or } \frac{(1387.21 - 908.4) / 908.4}{100} = 0.00527 \Omega / \Omega / ^\circ\text{C}$$

$$\text{Platinum: } \frac{(138.50 - 100) / 100}{100} = 0.003850 \Omega / \Omega / ^\circ\text{C}$$

$$\text{or } \frac{(139.11 - 100) / 100}{100} = 0.003911 \Omega / \Omega / ^\circ\text{C}$$

$$\text{or } \frac{(139.26 - 100) / 100}{100} = 0.003926 \Omega / \Omega / ^\circ\text{C}$$

In one sense, TCR expresses the sensitivity of the resistive wire used in the element, as it defines the average temperature change of a hypothetical 1 Ω thermometer. But specifiers normally use TCR to distinguish between different resistance/temperature curves of the same element material, such as the three curves platinum. Because all of these curves see widespread use, platinum TCR's must be properly specified to maintain compatibility between thermometers and instruments.

There are four primary curves specified for platinum:

1. 0.003926 $\Omega / \Omega / ^\circ\text{C}$: Standard platinum resistance thermometers are the only PRT's that can achieve this TCR. They must have high purity platinum wire (99.999% or better) wound in a strain-free configuration. The stresses introduced in manufacturing lower the TCR of ordinary industrial models. Several manufacturers offer industrial platinum thermometers with nominal TCR of 0.00392; TCR's around 0.003923 are achieved regularly.
2. 0.003911 $\Omega / \Omega / ^\circ\text{C}$: This TCR is sometimes called the "U.S. Industrial Standard." It is lower than laboratory standards as the typical construction of high temperature ceramic elements impose strain on platinum wire.
3. 0.00385 $\Omega / \Omega / ^\circ\text{C}$: This is mandated by DIN 43760, IEC 751, and other national and international specifications.
4. 0.00375 $\Omega / \Omega / ^\circ\text{C}$: At least one manufacturer now offers thin-film 1000 Ω elements with 0.00375 TCR, intended for low-cost applications.

There are few inherent advantages in specifying any particular TCR over another. Laboratory systems traditionally use reference standards with the highest grade platinum, but industrial specifiers may aim instead for the greatest degree of standardization. In this case, 0.00385 TCR will be compatible with the greatest number of manufacturers.

Resistance Thermometers

Comparison of element types

Platinum, with its wide temperature range and stability, has become the preferred element material for resistance thermometers. Furthermore, advances in element construction have narrowed the price difference between platinum

and base metal thermometers. Nevertheless, nickel, copper, and nickel-iron do have benefits for many applications and should be considered. The primary advantages of the four element types are compared in Table 1.

Element type	Temperature range	Resistivity (Ω / circular mil foot at 20°C)	Benefits	Base resistance	TCR ($\Omega/\Omega/^\circ\text{C}$)	Sensitivity (avg. $\Omega/^\circ\text{C}$, 0 to 100°C)
Platinum	-259 to 1235°C (-434 to 2255°F)	63.8	<ul style="list-style-type: none"> Greatest range Best stability Good linearity 	100 Ω at 0°C	0.003926	0.392
	-259 to 630°C (-434 to 1166°F)			100 Ω at 0°C	0.00391	0.391
	-200 to 850°C (-328 to 1562°F)			100 Ω at 0°C	0.00385	0.385
	-200 to 850°C (-328 to 1562°F)			1000 Ω at 0°C	0.00385	3.85
Copper	-100 to 260°C	10.7	<ul style="list-style-type: none"> Best linearity 	10 Ω at 25°C	0.00427	0.039
Nickel	-100 to 260°C	41.5	<ul style="list-style-type: none"> Low cost High sensitivity 	120 Ω at 0°C	0.00672	0.806
Nickel-iron	-100 to 204°C	120.0	<ul style="list-style-type: none"> Low cost Highest sensitivity 	604 Ω at 0°C	0.00518	3.133
				1000 Ω at 70°F	0.00527	4.788
				2000 Ω at 70°F	0.00527	9.576

Table 1: Comparison of resistance thermometer element types

Effects of leadwire resistance and bridge design

Because an RTD is a resistance type sensor, any resistance in the extension wires between the RTD and control instrument will add to readings. In some cases, one can compensate for this extra resistance with adjustments at the instrument. However, this only compensates when the leads are at a constant temperature since variations in ambient temperature alter copper leadwire resistance.

Table 2 shows resistance values of common copper leadwire sizes. To approximate error in an uncompensated system, multiply the total length (in feet) of extension leads by the appropriate value in the table. Then divide by the sensitivity of the RTD element from Table 1 to obtain an error figure in $^\circ\text{C}$. For example, assume a 100 Ω platinum element with 0.00385 TCR and 22 AWG leads, 100 feet long:

$$\text{Total resistance} = 200 \text{ ft} \times 0.0165 \Omega/\text{ft} = 3.3 \Omega$$

$$\text{Approx. error} = 3.3 \Omega / (0.385 \Omega/^\circ\text{C}) = 8.6^\circ\text{C}$$

Leadwire AWG	Ohms/foot at 25°C
12	0.0016
14	0.0026
16	0.0041
18	0.0065
20	0.0103
22	0.0165
24	0.0262
26	0.0418
28	0.0666
30	0.1058

Table 2: Resistance of common copper leadwire sizes

Leadwire error can be significant, especially with small diameter leads or low sensitivity elements. Fortunately, the use of a 3-lead system will reduce errors to a negligible level in most applications.

Figure 2 shows a 2-lead RTD connected to a typical Wheatstone bridge circuit. The bridge, a resistive network, translates the RTD's resistance into an electrical signal used by the monitoring or controlling instrument. In this figure, E_s is the supply voltage; E_o is the output voltage; R_1 , R_2 , and R_3 are fixed resistors; and R_t is the sensing element of resistance thermometer. L_1 and L_2 are the resistances of the two leads.

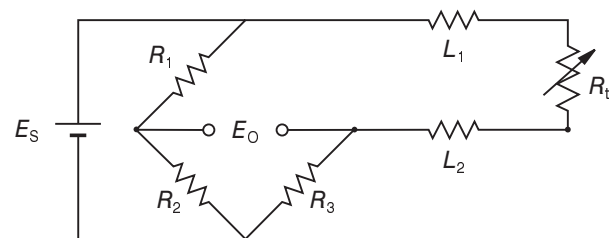


Figure 2: Uncompensated 2-lead bridge circuit

With a balanced bridge, the voltage drops across the two upper arms, (1) R_1 and (2) $R_t + L_1 + L_2$, are equal and E_o is zero. The fixed resistors R_1 , R_2 , and R_3 are specified so that the bridge ratios are equal at balanced condition:

$$\frac{R_1}{R_2} = \frac{R_t + L_1 + L_2}{R_3}$$

Maximum bridge sensitivity is realized if

$$R_1 = R_2 = R_3 = R_t + L_1 + L_2$$

Resistance Thermometers

Effects of leadwire resistance and bridge design

This sensitivity is desirable, however, only in laboratory systems where the bridge is constantly rebalanced. Typical industrial circuits will have unequal resistors.

The value of R_t at the temperature point of most interest will influence the selection of the bridge arm resistors. Values should also be chosen to limit bridge currents and consequent self-heating in the thermometer. Bridge resistors must be stable and insensitive to ambient temperature variations for best accuracy.

In a 2-lead bridge, the leadwire resistance $L_1 + L_2$ adds directly to readings. If leads are short enough or sensitivity high enough, the offset may be acceptable. When long extension runs are required between the sensor and instrument, or sensitivity is low, the specifier should consider a 3-lead system. All resistance thermometers with copper elements must have three leads to offset their low sensitivity.

Figure 3 shows a 3-lead compensating bridge circuit. L_1 and L_2 are now in two separate arms of the bridge, so the measuring currents and voltage drops across them are identical. The third lead L_3 forms part of the output circuit and does not affect the bridge ratios or balance. In fact, no current flows through L_3 when the bridge is in balance.

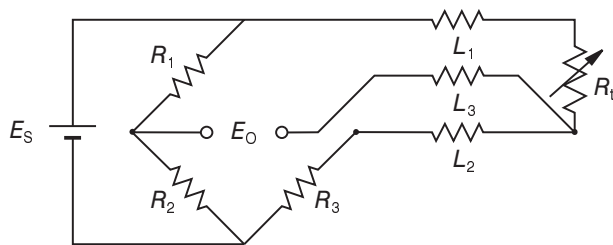


Figure 3: 3-lead compensating bridge circuit

Proper compensation with the 3-lead system depends on these conditions:

1. Lead resistances L_1 and L_2 should be equal. Most manufacturers match leads within $\pm 5\%$. In most cases, therefore, error with a 3-lead system is less than 5% of the error with a similar 2-wire system.
2. Leadwires should stay bundled together to ensure that ambient temperature changes act equally on all leads.

3. Electronic circuitry connected to E_o should have sufficient input impedance to prevent appreciable current drain through L_3 . L_3 normally acts only as a potential-carrying lead. Any current through it will cause errors when the bridge is out of balance.

3-lead systems represent a practical compromise between accuracy over distance and the cost of extra leads. Although well suited to most industrial areas, they may be affected by electrical noise and contact resistance at the junction points.

4-lead circuits provide the same resistance compensation as 3-lead systems, but also relieve problems with unmatched leads, contact resistances, and thermal EMF's. Thermal EMF's are spurious voltages introduced by the thermocouple effect where two dissimilar metals make contact. Laboratory systems, used for the highest precision measurements, are often variants of the Mueller bridge. The Mueller bridge is basically a switched three-wire system requiring two readings which are averaged to yield a true reading.

The need to throw switches and calculate the mean of readings excludes Mueller bridges from use in automated readout or control. An alternative, still using 4-lead RTD's, is the constant current circuit of Figure 4. Here a constant current source drives I_s through L_1 and L_4 , and the potential produced by R_t appears across L_2 and L_3 . Circuitry connected to E_o must have an impedance high enough to prevent appreciable current flow through L_2 and L_3 . In this circuit, the measured potential is unaffected by lead and contact resistance. Use of an AC current source nullifies EMF's.

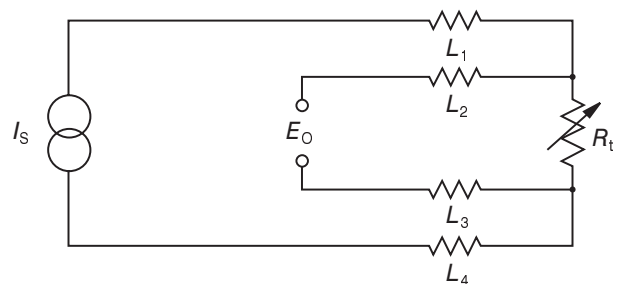


Figure 4: 4-lead system with constant current source

Resistance Thermometers

Two-wire temperature transmitters

Resistive networks like the Wheatstone bridge represent a passive solution to the problem of leadwire resistance. The 2-wire temperature transmitter, in contrast, actively amplifies and conditions the RTD signal.

A transmitter, which mounts at or near the RTD location, converts the resistance reading to a current signal proportional to temperature. This current travels over two extension wires to the control instrument. Unlike voltage or resistance, current must be the same at both ends of a signal loop. This means that temperature signals can be sent thousands of feet over two wires with no loss of accuracy from leadwire resistance or electrical noise.

The standard process control transmitter produces a 4 to 20 mA signal proportional to temperature over a specified range. The signal current also provides power for the transmitter's electronics. Allowable resistance in

the signal loop depends on the voltage required by the transmitter at the 20 mA level. Hundreds of ohms—thousands of feet of wire—are usually no problem.

The disadvantages of transmitters are price—typically about twice that of a resistance thermometer alone—and the need to periodically recalibrate zero and span. On the other hand, cost savings result from the use of inexpensive twisted-pair signal wires over long distances. Also, the linear current signal easily interfaces to voltage input instruments through the use of a load resistor.

Most transmitters mount in a connection head attached to the resistance thermometer or in an instrument rack nearby. Some types of transmitters mount in the same enclosure as the thermometer. This arrangement requires careful attention to the problem of temperature rises induced by heat from the transmitter.

Potential sources of error with resistance thermometers

Resistance thermometer systems are susceptible to three types of errors: The inherent tolerances built into the thermometers, gradients between the thermometer and the medium to be sensed, and errors introduced along the path between the sensor and readout or control instrument. Some sources of error are electrical; others result from the mechanical construction of the thermometer.

Potential sources of error include:

Interchangeability/Conformity: Conformity specifies the amount of resistance a thermometer is allowed to deviate from a standard curve (such as the curve produced by the Callendar-Van Dusen equation). Conformity has two components: a tolerance at the reference temperature, usually 0°C, and a tolerance on the slope or TCR. Figure 5 shows that a resistance thermometer conforms most closely to its curve at the reference temperature, while the resistance fans out above and below this reference. For example, IEC 751, Class B, requires calibration within 0.12 Ω (0.3°C) at 0°C, but allows TCR to deviate from nominal 0.00385 by $\pm 0.000012 \Omega/\Omega/^\circ\text{C}$. Thus, tolerance spreads to 0.8°C at 100°C, 1.3°C at 200°C, and on up to 3.8°C at 700°C. Interchangeability between two thermometers is no more than twice the value of their conformity.

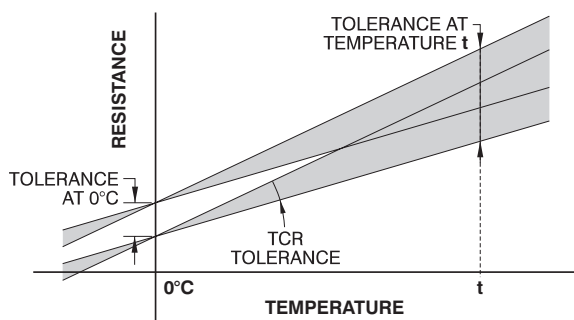


Figure 5: Effects of R_0 and slope tolerance on total tolerance.

Commercial platinum resistance thermometer elements are available with extremely tight tolerances, to within 0.01 Ω (0.026°C) in some cases. When interchangeability is an overriding consideration, the specifier may consider other means to achieve it. For example, manufacturers may alter their calibration procedures to fix the reference temperature—and tightest tolerance—at a point other than 0°C. Or if the difference between two thermometers is more important than absolute temperature, matched pairs—measured to agree within a certain tolerance—may be less expensive than calibrating each thermometer within a small range of nominal.

It is important to note that conformity/interchangeability specifications only denote the relative accuracy of two otherwise identical thermometers mounted side by side in the same environment. They do not include errors acting equally upon both thermometers.

Sensitivity: The resistance change per degree change in temperature is a function of base resistance and TCR (Temperature Coefficient of Resistance). Although a thermometer with higher sensitivity is not necessarily more accurate, a larger signal simplifies output electronics and is less susceptible to leadwire effects and electrical noise. In addition, a larger resistance produces the same voltage output with less measuring current, which helps to limit self-heating of the thermometer element.

Insulation Resistance: If the sensing element and leads are not completely insulated from the case, a shunting effect occurs in which the case becomes a parallel resistor and lowers apparent readings. In most industrial thermometers, with specified insulation resistances in the 100 megohm range, error approaches zero. The manufacturer must take care to seal water-absorbing materials.

The shunting effect decreases with low-resistance elements, which accounts for the use of 25.5 Ω PRT's in laboratory measurements.

Resistance Thermometers

Potential sources of error with resistance thermometers (cont.)

Self-Heating: A resistance thermometer is a passive resistance sensor; it requires a measuring current to produce a useful signal. Because this measuring current heats the element wire above the true ambient temperature, errors will result unless the extra heat is dissipated.

Self-heating is most often expressed in mW/°C, which is the power in milliwatts ($1000 I^2 R$) required to raise the thermometer's internal temperature by 1°C. The higher the mW/°C figure, the lower the self-heating. As an example, assume a 5 mA measuring current is driven through a 100 Ω platinum RTD at 100°C. Self-heating is specified as 50 mW/°C in water moving at 3 ft/sec. The amount of heat generated is:

$$1000 \text{ mW} \times (0.005 \text{ A})^2 \times (138.5 \text{ } \Omega) = 3.5 \text{ mW}$$

The self-heating error is:

$$(3.5 \text{ mW}) / (50 \text{ mW/}^\circ\text{C}) = 0.07^\circ\text{C}$$

The generated heat increases with higher sensor element resistance (when a constant current measurement device is used), or with increasing measuring current. The resulting error is inversely proportional to the ability of the thermometer to shed extra heat; which, in turn, depends on thermometer materials, construction, and environment. The worst self-heating occurs when a high resistance is packed into a small body. Thin film elements, with little surface area to dissipate heat, are an example. Self-heating also depends on the medium in which the thermometer is immersed. Error in still air may be over 100 times greater than in moving water.

Time Constant: A time constant indicates the responsiveness of a resistance thermometer to temperature change. A common expression is the time it takes a thermometer to reflect 63.2% of a step temperature change in moving water. Response speed depends on the mass of the thermometer and the rate at which heat transfers from the outer surface to the sensing element. A rapid time constant reduces errors in a system subject to rapid temperature changes.

Repeatability: The degree of accord between two successive readings with a thermometer is its repeatability. Loss of repeatability results from permanent or temporary changes to the resistance characteristics of the ele-

ment and may be caused by exposing the thermometer to temperatures at or beyond the endpoints of its specified range. A repeatability test cycles the thermometer between low and high temperatures; any changes to $R_{0^\circ\text{C}}$ are noted. A typical repeatability rating for an industrial platinum resistance thermometers is $\pm 0.1^\circ\text{C}$.

Stability: Stability is long term drift in thermometer readings. A typical specification would limit drift to 0.1°C per year for rated operation. Normal service at points well within the temperature rating typically cause much less drift. Drift is a consequence of the element material, with platinum being the most stable; encapsulating materials which could contaminate the element; and mechanical stress placed on the element by expansion of winding bobbins or other supporting structures.

Shock and Vibration: Mechanical shock and vibration can alter thermometer readings or cause complete failure. In fact, stability and ruggedness are somewhat exclusive. A laboratory thermometer designed for maximum stability contains an unsupported element which is far too fragile for industrial use.

The elements of most industrial resistance thermometers are fully supported by a bobbin or packing material, and therefore stand up quite well to extreme environments. More likely to suffer are leadwire transition points, which should be properly immobilized. A typical RTD will meet a specification allowing shock of 100 G's of 8 milliseconds duration and vibration of 10 to 2000 Hz at 20 G's.

Packaging and Thermal Transfer: Sheaths and other structures surrounding resistive elements should maximize heat transfer from the sensed medium, minimize heat transfer from ambients which can alter readings, and provide necessary protection of the elements. Proper materials and construction can dramatically improve reading accuracy.

One strategy practicable only with wire-wound resistance thermometers—versus thermistors, thermocouples, and solid-state devices—is temperature averaging. An element may be wound to average temperature over lengths of up to 100 feet.

Resistance thermometer types

Examples of commonly available resistance thermometer types, with an emphasis on the design features which take advantage of the benefits listed above, and which avoid the sources of error, are presented in the following paragraphs.

Standard Platinum Resistance Thermometers for Laboratory Use

NIST specifies the standard platinum resistance thermometer (SPRT) as the standard interpolating instrument used to define temperatures from -259.35 to 961.78°C. According to the ITS-90, a standard platinum

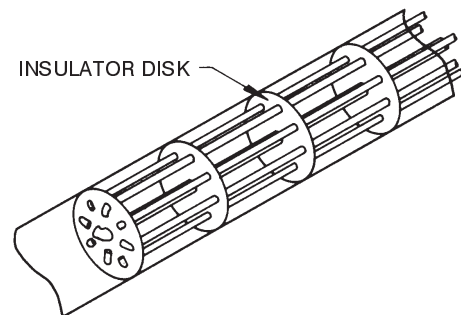


Figure 6: "Bird-cage" platinum element

Resistance Thermometers

Resistance thermometer types (cont.)

resistance thermometer must meet one of the following criteria:

$$R_{29.7646^{\circ}\text{C}}/R_{0.01^{\circ}\text{C}} \geq 1.11807, \text{ or } R_{-38.8344^{\circ}\text{C}}/R_{0.01^{\circ}\text{C}} \leq 0.844235$$

This requires very high purity platinum wound in a nearly strain-free manner.

Figure 6 shows a classic “bird cage” strain-free element, in which the element wire is supported by insulating disks. Figure 7 shows a less expensive helical wind. The highest accuracy primary standards encapsulate the element within a glass or quartz sheath, although stainless steel or Inconel may be substituted for secondary, or transfer, standards. The element area must be hermetically sealed to exclude oxidizing agents and helium-filled if used at cryogenic ranges.

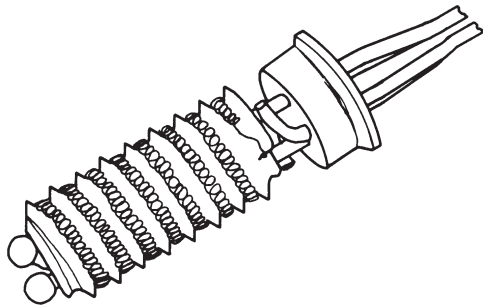


Figure 7: Helical-wound strain-free element

The unsupported coils of a strain-free element are quite susceptible to damage from shock and vibration. Even a slight tap on a table can invalidate an expensive calibration.

Industrial Resistance Thermometer Elements

Resistance thermometers could not have migrated from the laboratory to the industrial plant without the invention of rugged, low-cost elements. The need to encapsulate the resistive element for protection from shock and corrosive environments, without unduly straining the element, have led to a variety of technologies for constructing elements.

Figure 8 diagrams a common ceramic element. The element wire, commonly platinum, is wound around a ceramic bobbin, welded to leadwires, and coated with glass. The manufacturer must carefully match materials to prevent thermal expansion strains on the wire.



Figure 8: Industrial resistance thermometer element

Higher temperatures are possible with the element construction of Figure 9. Here, a coil of platinum wire is passed through bores in a ceramic tube. The bores are then filled with a ceramic or alumina powder to cushion the coils.

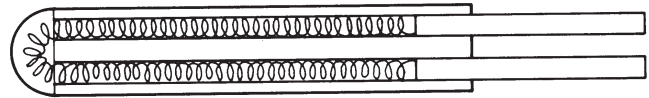


Figure 9: High temperature element

Copper, nickel, and nickel-iron may replace platinum as element materials for lower temperatures, generally below 260°C. Moderate temperatures also allow the use of organic materials in element construction, enabling a wide variety of styles. Resulting benefits include lower cost and faster time response.

Thin-film elements (Figure 10) have arrived within the last ten years and are now comparable to wire-wound ceramic elements in performance, but lower in price. They consist of a flat substrate with a thin film of deposited platinum, laser-trimmed to proper resistance. Thin-films can have high resistances, commonly 1000 ohms, without the expense of extra platinum wire. Naked elements exhibit very fast time responses, although they will respond more slowly in probes because of difficulties transferring heat to the flat element. Also, the user should be careful to limit measuring current as the small size and high resistance of thin films invite self-heating. Thin-films tend to be more fragile than wire-wound elements as well.

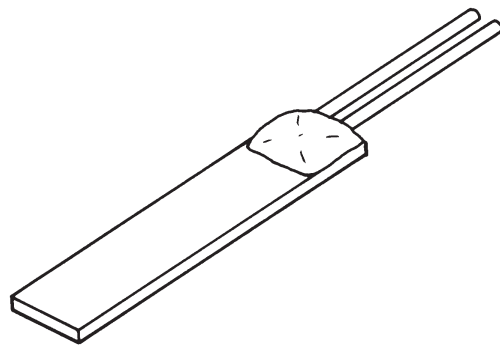


Figure 10: Thin-film element

Resistance Thermometers

Resistance thermometer types (cont.)

Industrial RTD Probes

The encased probe is the standard resistance thermometer configuration for industrial process control and machinery protection. Most probe cases are stainless steel or Inconel to withstand high temperatures, although other materials offer advantages at intermediate ranges. For example, the tip-sensitive probe of Figure 11 has a copper-alloy tip which conducts heat 20 times better than stainless steel. This design improves thermal contact with sensed surfaces and reduces errors from conduction along the sheath.



Figure 11: Tip-sensitive probe

Standard probe diameters range from 0.125" to 0.250". Smaller probes respond faster when directly immersed, but larger probes may fit more snugly in standard thermowells. Probe lengths range from a few inches to ten feet or more.

Figure 12 shows the construction of a high temperature probe. The element fits in the tip, surrounded by high temperature powder or cement. Extension leads, normally uninsulated, extend back from the element and are encapsulated by powder, cement, or bored ceramic spacers. External leads, often insulated with Teflon or glass braid, are potted with cement at the entry point to seal against moisture.

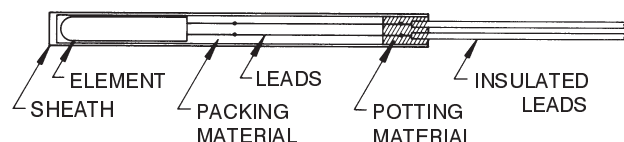


Figure 12: High temperature probe

The alternative construction of Figure 13 places the element, potting, and lead transitions within a module at the tip of the probe. This design allows the user to cut the probe to required lengths. Temperature is limited to the rating of the external leadwire insulation: 260°C (500°F) for Teflon, up to 550°C (1022°F) for insulations such as woven mica/glass.

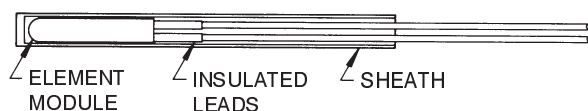


Figure 13: Cut-to-length probe

Probe Assemblies

A wide variety of mounting fittings and accessories aid probe installation. Selection depends on the nature of the medium being sensed and cost requirements.

Direct immersion of a probe into a liquid requires a fitting with a pipe thread, which may be adjustable or welded on the probe. Figure 14 shows a typical assembly, with one thread for mounting the probe and another for a connection head. Connection heads provide a transition between probe leads and external signal wires.

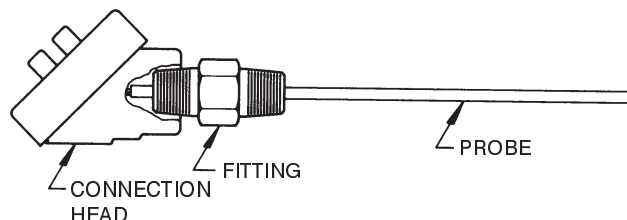


Figure 14: Typical probe assembly

Mounting in a solid material is best accomplished with a spring-loaded holder, which may be fixed or adjustable. Spring loading provides good contact of the probe tip against the bottom of the hole and dampens potentially damaging vibration.

When liquids are particularly corrosive, under high pressure, or fast-flowing, a thermowell may be necessary. A thermowell is a tube, closed at one end, which protects the probe and allows its removal without breaking the liquid seal. Many materials and styles are available to match application requirements. Thermowells drilled from solid bar stock provide the highest pressure ratings, but welded models cost much less. Figure 15 shows a typical thermowell assembly, including a spring-loaded holder for enhanced thermal response and reliability.

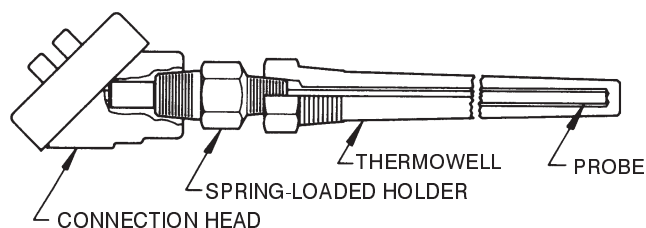


Figure 15: Thermowell assembly

Flexible Resistance Thermometers

The encased probes described above do not adapt well to sensing flat surfaces. Unlike thermocouple junctions, which can be welded directly to metal surfaces, resistance thermometers present a certain amount of bulk; and heat losses to ambient air may affect readings. Small flat elements, such as thin films, may mount on

Resistance Thermometers

Resistance thermometer types (cont.)

surfaces, but fragile element and leadwire connections make installation difficult.

Figure 16 shows a flexible resistance thermometer with a wire-wound sensing element sandwiched between insulating layers. It conforms closely to sensed surfaces, and has thin insulation to readily transmit heat to the sensing element. The wire element may be wound to nearly any size to average out temperature gradients, and the flexible construction can withstand extreme shock and vibration.



Figure 16: Flexible resistance thermometer

Specification of the covering insulation depends on the environment seen by the sensor. Kapton™ is popular for aerospace and medical use, as it withstands both chemicals and vacuums. Silicone rubber features a higher temperature rating, to 220°C (428°F).

Special Purpose Resistance Thermometers

Resistance thermometers readily adapt to most process control and thermal equipment designs. The user may specify cases with axial leads for circuit board mounting, flat packages for clamping to surfaces, miniature cases for embedment into metal blocks, and any sheaths and fittings which can be produced by a machine shop. In addition, wire windings may be configured to sense over large areas.

Where to use resistance thermometers

In summary, resistance thermometers offer the greatest benefits relative to other thermometer types in these situations:

- Accuracy and stability are the foremost goals of the application
- Accuracy must extend over a wide temperature range
- Area, rather than point, sensing improves control
- A high degree of standardization is desirable

Thermistors

A thermistor operates through electrical resistance changes in semiconductors rather than pure metal. The base material is a mixture of metal oxides pressed into a bead, rod, disk, wafer, or other shape. The bead, with leadwires embedded, is sintered at high temperatures and are often coated with epoxy or glass. Beads may be quite small—down to 0.01" (0.25 mm) diameter in some cases.

The design, construction, and characteristics of thermistors vary widely among manufacturers. Typical properties are:

1. Thermistors exhibit very large resistance changes, but usually in a direction opposite to resistance thermometers; resistance drops as temperature rises. This is called negative temperature coefficient of resistance (NTC).
2. Base resistances, commonly specified at 25°C, range from thousands to millions of ohms. Thermistor sensitivity dwarfs that of resistance thermometers.
3. Trimming thermistors into a specified resistance tolerance is not easily accomplished. The user must individually calibrate circuits when thermistors are interchanged.
4. Resistance/temperature curves deviate widely from linearity, except over narrow ranges.
5. Thermistors tend to drift more than resistance thermometers, although they stabilize over time.

6. Temperature ranges are moderate, with 300°C (572°F) the common upper limit.

The combination of nonlinearity, high sensitivity, and instability has generally limited thermistors to high-resolution measurements over limited ranges. A classic example is medical thermometry. Physicians are only concerned with a small range around 37°C (98.6°F) and thermistors can be chosen to provide a large, fairly linear signal in this area. One-point calibration is simple and sufficient.

Some manufacturers of thermistors offer special models with these characteristics:

1. Positive temperature coefficient (PTC) models, which are used more for current limiting in electronic circuits than for temperature measurement; as current increases through the bead, self-heating drives up resistance dramatically, throttling the current.
2. Thermistors which are closely matched, and therefore interchangeable, over a specified range.
3. Linearized thermistors or thermistor sets which produce a highly linear output over a limited range.
4. Glass-coated thermistors, specially aged, which may maintain excellent stabilities over moderate temperatures, e.g. $\pm 0.005^\circ\text{C}$ per year over the range 0 to 100°C.

Thermistors

As a general rule, a thermistor acts as a single-purpose sensing device. The designer must relate temperature ranges, resistance/temperature characteristics, and out-

put circuits for each application. The reward is a high degree of resolution and accuracy with a relatively inexpensive systems.

Resistance/temperature characteristics of thermistors

Figure 17 traces the resistance curve of a typical thermistor, referenced to a platinum resistance thermometer. The thermistor's resistance/temperature change is far more dramatic, although less linear and with a negative slope. In general, the log of a thermistor's resistance is proportional to the inverse of its temperature. The following equation, called the Steinhart and Hart equation, is valid for ranges up to 100°C in size:

$1/T = a_0 + a_1 \log_e(R_T) + a_3 \log_e(R_T)^3$, where
 T is the absolute temperature in K ($t_c + 273.15$),
 R_T is the zero-power resistance at temperature T , and
 a_0 , a_1 , and a_3 are coefficients which describe a given thermistor.

The particular coefficients of the equation depend solely on the composition of the thermistor material and vary widely. There are no published standards to guarantee compatibility, although some popular types may be available from more than one source.

Thermistor output circuits

The lack of linearity in thermistor curves has spurred the development of many types of compensating circuits. Two of the simpler ones—to linearize voltage and to linearize resistance—are described below.

Figure 18 shows a simple voltage divider circuit. The output voltage is given by:

$$\frac{e_o(t)}{e_s} = \frac{1}{1 + sr(t)} = F(t), \text{ where}$$

$e_o(t)$ = output voltage at temperature t ,
 e_s = source resistance,
 R = a fixed resistance,
 $R(t_0)$ = reference, or base, resistance of the thermistor,
 $s = R(t_0)/R$, and
 $r(t) = R(t)/R(t_0)$ (resistance at temperature t referenced to base resistance).

$F(t)$ is approximately linear over a selected temperature range. The user should specify base resistance $R(t_0)$ and fixed resistance R so that the curve for s is centered over the temperature of interest. The output voltage tracks temperature in a reasonably linear fashion over a limited range.

For a constant-current type circuit, in which a current source is driven through the thermistor and voltage drop measured, a linear **resistance** is necessary. An ordinary shunt resistor in parallel with sensing element, as in Figure 19, yields this formula:

$R = R_1[1 - F(t)]$, where
 R = overall resistance of the circuit,
 R_1 = a fixed resistance, and
 $F(t)$ is the function defined above.

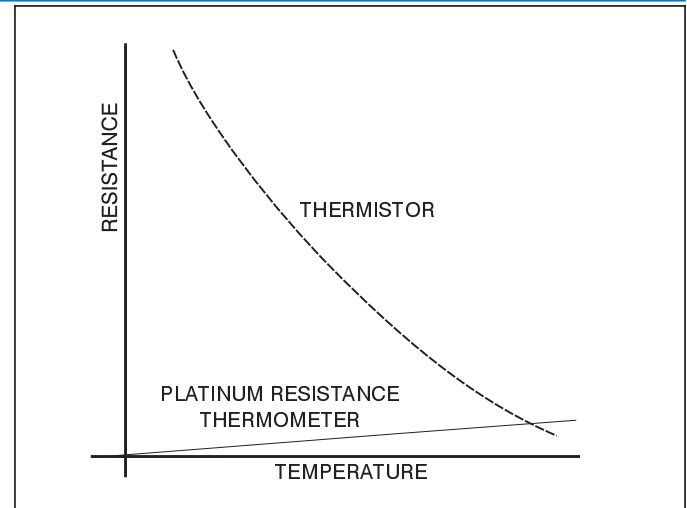


Figure 17: Resistance/temperature curve: thermistor vs. resistance thermometer

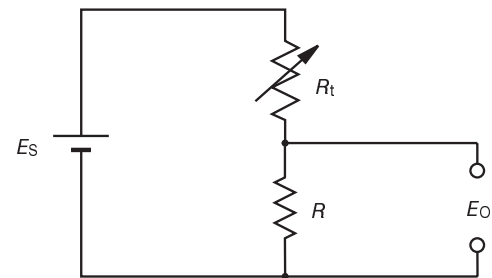


Figure 18: Voltage linearizing thermistor circuit (Courtesy Thermometrics, Inc.)

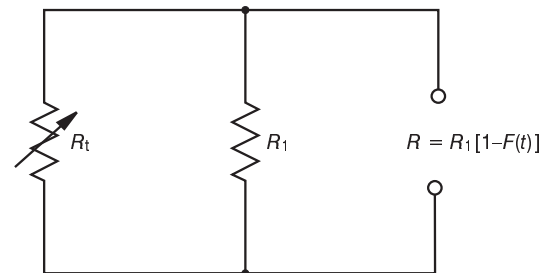


Figure 19: Resistance linearizing thermistor circuit (Courtesy Thermometrics, Inc.)

Again, response is fairly linear over limited spans.

Complex circuits, with Wheatstone bridges or other resistive networks, can further linearize thermistor output when necessary. Most employ matched sets of thermistor beads.

Thermistors

Potential sources of error with thermistors

Most of the sources of error listed for resistance thermometers apply as well to thermistors. Thermistors remove one worry: Leadwire resistance is normally negligible in relation to their high resistance. Three or four-wire circuits are rarely required for lead compensation, although they may be needed for linearization with matched sets.

Self-heating can present far more of a problem with thermistors. High resistance generates more internal heat and there is little surface area for dissipation. The same current through a thermistor and RTD will produce self-heating around 100 times greater in the thermistor. The user should carefully read self-heat specifications and limit current accordingly.

Because of self-heating error, the reference resistance of thermistors is specified at a "zero-power" value. This is an extrapolation from a series of measurements at different sensing currents. It gives the ideal resistance assuming no current and no consequent self-heating.

Where to use thermistors

Thermistors offer the greatest benefit in these situations:

- The application requires high resolution over a narrow span
- Probes are to be disposable, or may be frequently and easily recalibrated
- Low cost is a primary consideration
- The application is an OEM device produced in sufficient volume to justify the design of special linearizing circuits
- Point sensing or miniaturization is desirable

Thermistor types

Most manufacturers offer beads in the configurations of Figure 20: a bare bead, a glass-encapsulated bead, and an assembly with extension leads. These simple elements may be assembled into the same types of cases as RTD's. Bead thermistors are inherently point sensing devices and may fit very small areas, although most environments require some protection for the fragile bead and leadwire transitions.

Nearly all temperature sensing applications employ bead type thermistors. Others, such as rods, chips, or flakes, mount on circuit boards for temperature compensation or current limiting.

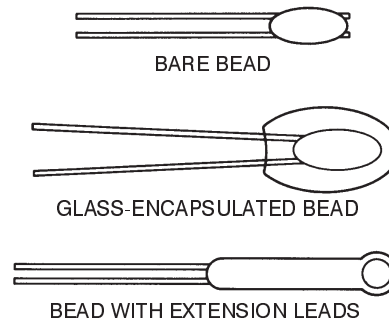


Figure 20: Thermistor types

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