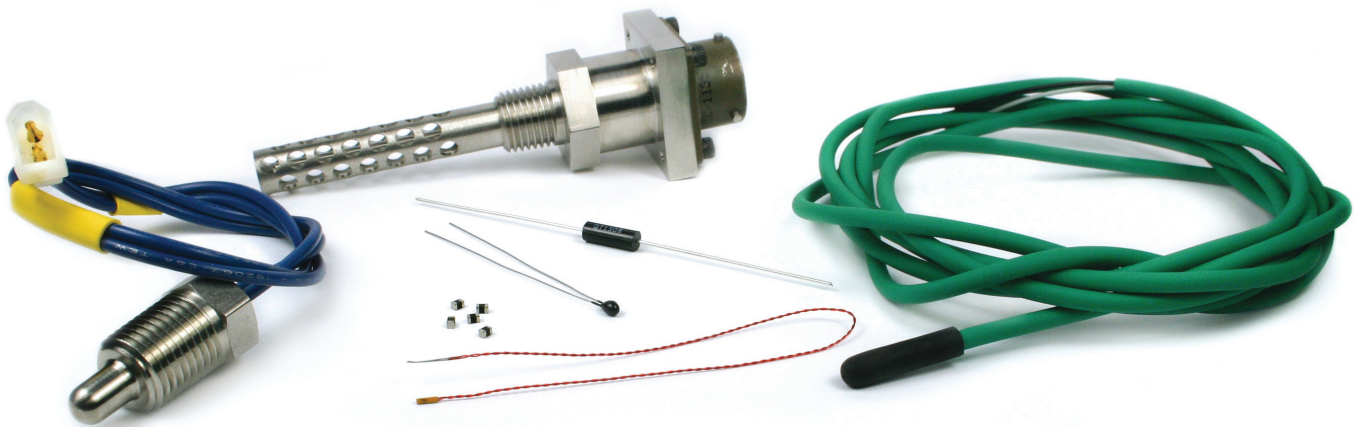


NEGATIVE TEMPERATURE COEFFICIENT THERMISTORS

Gregg Lavenuta, QTI Engineering Department



CHARACTERISTICS, MATERIALS AND CONFIGURATIONS

After time, temperature is the variable most frequently measured. The three most common types of contact electronic temperature sensors in use today are thermocouples, resistance temperature detectors (RTDs), and thermistors. This article will examine the negative temperature coefficient (NTC) thermistor.

GENERAL PROPERTIES AND FEATURES

NTC thermistors offer many desirable features for temperature measurement and control within their operating temperature range. Although the word thermistor is derived from THERMally sensitive resISTOR, the NTC thermistor can be more accurately classified as a ceramic semiconductor. The most prevalent types of thermistors are glass bead, disc, and chip configurations (see Figure 1), and the following discussion focuses primarily on those technologies.

Temperature Ranges and Resistance Values. NTC thermistors exhibit a decrease in electrical resistance with increasing temperature. Depending on the materials and methods of fabrication, they are generally used in the temperature range of -50°C to 150°C, and up to 300°C for some glass-encapsulated units. The resistance value of a thermistor is typically referenced at 25°C (abbreviated as R25). For most applications, the R25 values are between 100 Ω and 100k Ω. Other R25 values as low as 10 Ω and as high as 40M Ω can be produced, and resistance values at temperature points other than 25°C can be specified.

Accurate and Repeatable R/T Characteristic. The resistance vs. temperature (R/T) characteristic (also known as R/T curve) of the NTC thermistor forms the "scale" that allows its use as a temperature sensor. Although this characteristic is a nonlinear, negative exponential function, several interpolation equations are available that very accurately describe the R/T curve [1,2,3]. The most well known is the Steinhart-Hart equation: $1/T = A + B(\ln R) + C(\ln R)^3$

where: T = kelvin temperature R = resistance at temperature T

Coefficients A, B, and C are derived by calibrating at three temperature points and then solving the three simultaneous equations. The uncertainty associated with the use of the Steinhart-Hart equation is less than ±0.005°C for 50°C temperature spans within the 0°C-260°C range, so using the appropriate interpolation equation or lookup table in conjunction with a microprocessor can eliminate the potential nonlinearity problem.

Sensitivity to Changes in Temperature. The NTC thermistor's relatively large change in resistance vs. temperature, typically on the order of -3%/°C to -6%/°C, provides an order of magnitude greater sensitivity or signal response than other temperature sensors such as thermocouples and RTDs. On the other hand, the less sensitive thermocouples and RTDs are a good choice for applications requiring temperature spans >260°C and/or operating temperatures beyond the limits for thermistors.

Interchangeability. Another important feature of the NTC thermistor is the degree of interchangeability that can be offered at a relatively low cost, particularly for disc and chip devices. Interchangeability describes the degree of accuracy or tolerance to which a thermistor is specified and produced, and is normally expressed as a temperature tolerance over a temperature range. For example, disc and chip thermistors are commonly specified to tolerances



Figure 1. NTC thermistors are manufactured in a variety of sizes and configurations. The chips at the top of the photo can be used as surface mount devices or attached to different types of insulated or uninsulated wire leads. The thermistor element is usually coated with a phenolic or epoxy material that provides protection from environmental conditions. For applications requiring sensing tip dimensions with part-to-part uniformity and/or smaller size, the devices can be encapsulated in PVC cups or polyimide tubes.

Comparative Resistance Graph
Thermistor vs. RTD

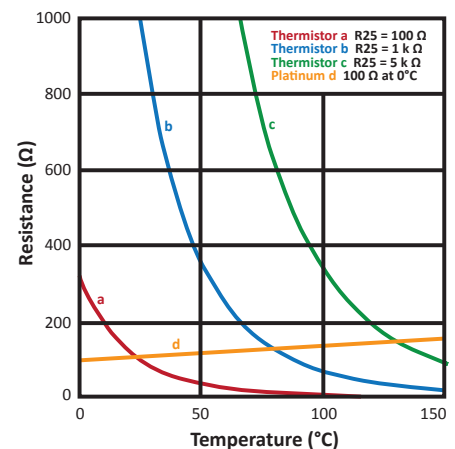


Figure 2. Over the range of -50°C to 150°C, NTC thermistors offer a distinct advantage in sensitivity to temperature changes compared to other temperature sensors. This graph illustrates the R/T characteristics of some typical NTC thermistors and a platinum RTD.

of $\pm 0.1^{\circ}\text{C}$ and $\pm 0.2^{\circ}\text{C}$ over the temperature ranges of 0°C to 70°C and 0°C to 100°C . Interchangeability helps the systems manufacturer or thermistor user to reduce labor costs by not having to calibrate each instrument/system with each thermistor during fabrication or while being used in the field. A health care professional, for instance, can use a thermistor temperature probe on one patient, discard it, and connect a new probe of the same specification for use on another patient—without recalibration. The same holds true for other applications requiring reusable probes.

Small Size. The small dimensions of most bead, disc, and chip thermistors used for resistance thermometry make for a very rapid response to temperature changes. This feature is particularly useful for temperature monitoring and control systems requiring quick feedback.

Remote Temperature Sensing Capability. Thermistors are well suited for sensing temperature at remote locations via long, two-wire cable because the resistance of the long wires is insignificant compared to the relatively high resistance of the thermistor.

Ruggedness, Stability, and Reliability. As a result of improvements in technology, NTC bead, disc, and chip thermistor configurations are typically more rugged and better able to handle mechanical and thermal shock and vibration than other temperature sensors.

MATERIALS AND CONFIGURATIONS

Most NTC thermistors are made from various compositions of the metal oxides of manganese, nickel, cobalt, copper, and/or iron. A thermistor's R/T characteristic and R25 value are determined by the particular formulation of oxides. Over the past 10 years, better raw materials and advances in ceramics processing technology have contributed to overall improvements in the reliability, interchangeability, and cost-effectiveness of thermistors.

Of the thermistors shown in Figure 3, beads, discs, and chips are the most widely used for precise temperature measurements. Although each configuration is produced by a unique method, some general ceramics processing techniques apply to most thermistors: formulation and preparation of the metal oxide powders; milling and blending with a binder; forming into a "green" body; heat-treating to produce a ceramic material; addition of electrical contacts (for discs and chips); and, for discrete components, assembly into a usable device with wire leads and a protective coating.

Bead thermistors, which have lead wires that are embedded in the ceramic material, are made by combining the metal oxide powders with a suitable binder to form a slurry. A small amount of slurry is applied to a pair of platinum alloy wires held parallel in a fixture. Several beads can be spaced evenly along the wires, depending on wire length. After the beads have been dried, the strand is fired in a furnace at 1100°C – 1400°C to initiate sintering. During sintering, the ceramic body becomes denser as the metal oxide particles bond together and shrink down around the platinum alloy leads to form an intimate physical and electrical bond. After sintering, the wires are cut to create individual devices. A glass coating is applied to provide strain relief to the lead-ceramic interface and to give the device a protective hermetic seal for long-term stability. Typical glass bead thermistors range from 0.01 in. to 0.06 in. (0.25 mm to 1.5 mm) in diameter.

Disc thermistors are made by preparing the various metal oxide powders, blending them with a suitable binder, and then compressing small amounts of the mixture in a die under several tons of pressure. The discs are then fired at high temperatures to form solid ceramic bodies. A thick film electrode material, typically silver, is applied to the opposite sides of the disc to provide the contacts for the attachment of lead wires. A coating of epoxy, phenolic, or glass is applied to each device to provide protection from mechanical and environmental stresses. Typical uncoated disc sizes range from 0.05 in. to 0.10 in. (1.3 mm to 2.5 mm) in diameter; coated disc thermistors generally measure 0.10 in. to 0.15 in. (2.5 mm to 3.8 mm) in diameter.

Chip thermistors are manufactured by tape casting, a more recent technique borrowed from the ceramic chip capacitor and ceramic substrate industries. An oxide-binder slurry similar to that used in making bead thermistors is poured into a fixture that allows a very tightly controlled thickness of material

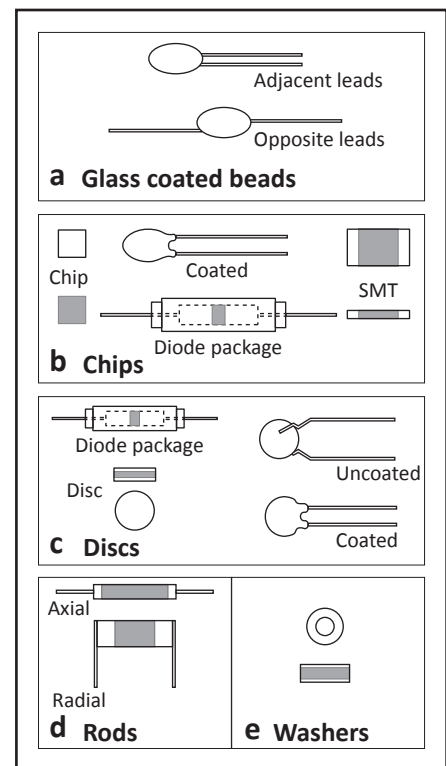


Figure 3. A variety of manufacturing processes are used to make NTC thermistors configured as beads (a), chips (b), discs (c), rods (d), and washers (e).

to be cast onto a belt or movable carrier. The cast material is allowed to dry into a flexible ceramic tape, which is cut into smaller sections and sintered at high temperatures into wafers 0.01 in. to 0.03 in. (0.25 mm to 0.80 mm) thick. After a thick film electrode material is applied, the wafers are diced into chips.

The chips can be used as surface mount devices or made into discrete units by attaching leads and applying a protective coating of epoxy, phenolic, or glass. Typical chip sizes range from 0.04 in. by 0.04 in. (1 mm by 1 mm) to 0.10 in. by 0.10 in. (2.5 mm by 2.5 mm) in square or rectangular shapes. Coated chip thermistors commonly measure from 0.08 in. to 0.10 in. (2.0 mm to 2.5 mm) in diameter. Very small coated chip thermistors 0.02 in. to 0.06 in. (0.5 mm to 1.5 mm) in diameter are available for applications requiring small size, fast response, tight tolerance, and interchangeability.

Washer-shaped thermistors are essentially a variation of the disc type except for having a hole in the middle, and are usually leadless for use as surface mount devices or as part of an assembly. Rod-shaped thermistors are made by extruding a viscous oxide-binder mixture through a die, heat-treating it to form a ceramic material, applying electrodes, and attaching leads. Rod thermistors are used primarily for applications requiring very high resistance and/or high power dissipation.

COMPARISON OF THERMISTOR CONFIGURATIONS

One of the problems the thermistor industry has faced over the years is that some manufacturers have claimed their particular style or configuration of thermistor is better than other configurations made by their competitors, without regard to other, more pertinent factors. These thermistor "politics," more harmful than beneficial to the industry, can confuse engineers and purchasing agents who are looking for reliable information to help them choose the appropriate product for their application. Although some thermistor qualities or capabilities, including interchangeability, repeatability, size, responsiveness, and stability, can either be enhanced or limited by style or geometry, these characteristics are much more dependent on a manufacturer's ability to understand the ceramics technology being used and to maintain control of the manufacturing process.

Glass-coated beads feature excellent long-term stability and reliability for operation at temperatures up to 300°C. Studies at the National Institute of Standards and Technology (NIST) and other laboratories indicate that some special bead-in-glass probes have measurement uncertainties and stabilities (better than $\pm 0.003^\circ\text{C}$ for temperatures between 0°C and 100°C) that approach those of some standard platinum resistance thermometers [3,4,5]. The relatively small size of glass bead thermistors gives them a quick response to temperature changes, but for some applications this small size can make the devices hard to handle during assembly and have the

HISTORICAL NOTE ON THE THERMISTOR

Michael Faraday (1791-1867), the British chemist and physicist, is best known for his work in electromagnetic induction and electrochemistry. Less familiar is his 1833 report on the semiconducting behavior of Ag_2S (silver sulfide), which can be considered the first recorded NTC thermistor [9].

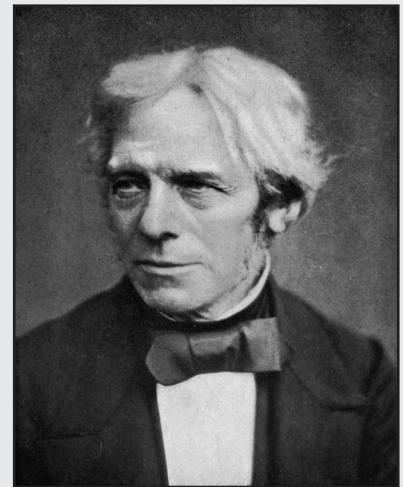


Figure 4. Michael Faraday.

Because the early thermistors were difficult to produce and applications for the technology were limited, commercial manufacture and use of thermistors did not begin until 100 years later. During the early 1940s, Bell Telephone Laboratories developed techniques to improve the consistency and repeatability of the manufacturing process [10]. Some of the first commercial thermistors were the disc type, and by today's standards, their tolerances were quite broad. These devices were used primarily for regulation, protection, and temperature compensation of electronic circuits.

In the 1950s and 1960s, the expanding aerospace industry's requirement for more accurate and stable devices led to several improvements in the materials used to manufacture glass bead and disc thermistors. During the 1960s and 1970s, the demand for tight-tolerance devices in high volumes at a lower cost led to the development of the chip thermistor [11].

As the reliability of these devices improved during the 1980s, the use of electronic thermometers in the health care industry increased. The rising costs of sterilization and concerns about cross-infection among patients led to the demand for low-cost disposable temperature probes, for which chip thermistors were well suited. Throughout the 1980s and 1990s, the use of NTC thermistors has continued to grow in the automotive, food processing, medical, HVAC, and telecommunications markets.

effect of limiting their power dissipation. It is also more difficult and more expensive to produce glass beads with close tolerances and interchangeability. Individual calibration and R/T characterization, resistor network padding, or use of matched pairs are among the methods used to achieve interchangeability.

Chip and disc thermistors are noted for their tight tolerances and interchangeability at a relatively low cost compared to bead thermistors. These qualities are inherent in the manufacturing processes. The thermistors' larger size permits power dissipation higher than that of beads, although at some expense of response times. Larger size can be a disadvantage in some applications. Because of their geometry, disc thermistors normally have larger coated diameters and higher power dissipation capabilities than chip thermistors. On the other hand, chip thermistors typically can be produced to smaller coated diameters and are better suited for applications requiring smaller size and faster response times. More recent designs of chip thermistors allow the production of sizes and response times approaching those of glass beads. In some cases, chip and disc thermistors with equivalent physical and electrical characteristics can be used in the same applications without any noticeable difference in performance.



Figure 5. NTC thermistors can be attached to extension leads or jacketed cable and assembled into various types of housings. The optimum materials, dimensions, and configuration for a probe assembly are determined by careful review of the application requirements.

Thermistors, thermocouples, RTDs, and other sensors and electronic components exhibit a phenomenon called drift, a gradual, predictable change in certain properties over time. For a thermistor, drift results in a change in resistance from its initial value, typically after being continuously exposed to or cycled to an elevated temperature. Thermistor drift is expressed as a percent change in resistance and/or as a change in temperature that occurs at a given exposure temperature for a certain length of time. As the exposure temperature increases, so do the drift and the drift rate [4,5,6].

Chip and disc thermistors with soldered leads and an epoxy or phenolic coating have potential limitations in their maximum operating temperatures, typically 150°C for short-term exposures (1-24 hours) and 105°C for long-term exposures (1-12 months). When subjected to environmental conditions above their recommended maximum operating temperatures, epoxy- or phenolic-coated chips and discs can begin to exhibit an undesirable, excessive amount of drift. When such thermistors are used at temperatures below the specified maximum operating temperatures, drift is minimal, on the order of 0.02°C to 0.15°C after 12 months of continuous exposure to temperatures between 25°C and 100°C, respectively. Recent advances in the techniques used to manufacture chip and disc thermistors with a glass coating have produced devices that combine the interchangeability advantage of chips and discs with the stability of glass beads [5,6]. For applications that require operating temperatures up to 200°C, these new devices offer a lower cost alternative to the conventional glass bead thermistors.

These comparisons can help determine whether a thermistor supplier is objectively evaluating an application in terms of the appropriate thermistor, or simply promoting the configuration it manufactures. For an example of the latter approach, see [7], where a manufacturer of disc thermistors stated that "Loose-tolerance thermistors are usually mass-produced by tape casting," and that "These devices . . . are designed for applications requiring neither interchangeability nor a high degree of accuracy," implying that all chip thermistors are loose tolerance. On the contrary, millions of precision chip thermistors with superior long-term stability are produced annually to an interchangeable tolerance of $\pm 0.1^\circ\text{C}$, and they are available with an interchangeability of $\pm 0.05^\circ\text{C}$. In reality, broad-tolerance and tight-tolerance thermistors are available in each of the three major thermistor configurations discussed above.

After determining the appropriate specifications, the engineer and purchasing agent need to evaluate which configuration and supplier will best meet the requirements for process control, quality, on-time delivery, and value at a reasonable price. An important part of the evaluation process is to perform some basic tests on the design and quality of the thermistor and, wherever possible, include simulation of the actual environmental conditions of the intended application. To achieve optimum performance, thermistors are usually mounted into protective housings or probe assemblies (see Figure 5). For additional information on sensor assembly design, see [8]. An informed decision can then be made as to which product and supplier will provide the best value for the application requirement. The next section of this article will examine the ways to perform these tests.

DETERMINING THE LEVEL OF UNCERTAINTY

Determining the level of uncertainty is an important part of the process used for setting up a thermistor testing system. The National Institute of Standards and Technology (NIST) [12], other national standards laboratories, and the International Organization for Standardization [13] have formed an international consensus to adopt the guidelines recommended by the International Committee for Weights and Measures (CIPM) to provide a uniform approach to expressing uncertainty in measurement. In these guidelines, terms such as accuracy, repeatability, and reproducibility have definitions that may differ from those used by some equipment manufacturers. In the NIST guidelines, for example, accuracy is defined as a qualitative concept and should not be used quantitatively. The current approach is to report a measurement result accompanied by a quantitative statement of its uncertainty [12]. Some equipment manufacturers use accuracy and others use uncertainty in their specifications, so it will probably take some time before all companies adopt the current guidelines.

DETERMINING THE LEVEL OF UNCERTAINTY

The first step in setting up a thermistor test system is to determine the level of uncertainty allowable for the application. Because the cost of equipment increases as the level of uncertainty decreases, it is important not to overspecify the equipment. Generally speaking, test system uncertainty should be 4 to 10 times better than that of the device to be tested. A 4:1 ratio is adequate for most applications; for more stringent requirements, a 10:1 ratio may be necessary and will probably result in a more costly system [14,15]. For example, using the 4:1 ratio, a thermistor with a tolerance of $\pm 0.2^\circ\text{C}$ should be tested on a system with an overall uncertainty of $(\pm 0.2^\circ\text{C})/4$ or $\pm 0.05^\circ\text{C}$. If a 10:1 ratio were required, the overall system uncertainty would need to be $\pm 0.02^\circ\text{C}$.

To calculate the uncertainty of the overall test system, the uncertainties of the individual components are combined using a statistical approach [12-15]. Each component is represented as an estimated standard deviation, or the *standard uncertainty*. The two statistical methods most commonly used by NIST are the *combined standard uncertainty* and the *expanded uncertainty* [12].

The combined standard uncertainty (NIST suggested symbol u_c) is obtained by combining the individual standard uncertainties using the usual method for combining standard deviations. This method is called the *law of propagation of uncertainty*, commonly known as the *root-sum-of-squares* (square root of the sum of the squares).

The expanded uncertainty, suggested symbol U , is obtained by multiplying the combined standard uncertainty by a coverage factor, suggested symbol k , which typically has a value between 2 and 3 (i.e., $U = ku_c$). For a normal distribution and $k = 2$ or 3, the expanded uncertainty defines an interval having a level of confidence of 95.45% or 99.73%, respectively. The stated NIST policy is to use the expanded uncertainty method with the coverage factor $k = 2$ for all measurements other than those to which the combined uncertainty method traditionally has been applied.

The expanded uncertainty of a system thus can be determined once the uncertainties of the bath, the temperature standard, and the resistance measuring instrument are known. The following is an example of the process used for calculating the U of a system with these equipment specifications.

bath uniformity = $\pm 0.01^\circ\text{C}$

bath stability = $\pm 0.01^\circ\text{C}$

uncertainty of the temperature standard = $\pm 0.01^\circ\text{C}$

uncertainty of the resistance measuring instrument = $\pm 0.01\%$ or $\pm 0.003^\circ\text{C}$

$$U = 2\{(\pm 0.01^\circ\text{C})^2 + (\pm 0.01^\circ\text{C})^2 + (\pm 0.01^\circ\text{C})^2 + (\pm 0.003^\circ\text{C})^2\}^{1/2}$$

$$U = \pm 0.035^\circ\text{C}$$

Therefore, if an application allows the use of the 4:1 uncertainty ratio, the system illustrated above could measure a thermistor requiring an estimated expanded uncertainty specification no tighter than or equal to $4(\pm 0.035^\circ\text{C})$ or $\pm 0.14^\circ\text{C}$. If an application required a thermistor measurement capability with a tighter expanded uncertainty, equipment with reduced uncertainties would be necessary. For example, if a system had a bath uniformity of $\pm 0.005^\circ\text{C}$, a bath stability of $\pm 0.005^\circ\text{C}$, a temperature standard with a standard uncertainty of $\pm 0.005^\circ\text{C}$, and a resistance measuring instrument standard uncertainty of $\pm 0.003^\circ\text{C}$, the expanded uncertainty of the system would be $\pm 0.018^\circ\text{C}$. The system described in the latter example would be capable of testing thermistors requiring an estimated expanded uncertainty of $4(\pm 0.018^\circ\text{C})$ or $\pm 0.07^\circ\text{C}$. These two examples illustrate how the individual equipment uncertainties affect the overall system uncertainty.

THERMISTOR TESTING EQUIPMENT AND GUIDELINES

The guidelines presented here on equipment and methods typically used for thermistor testing will help users accurately identify their application requirements and evaluate a supplier's capabilities. These recommendations are neither exhaustive nor meant to imply that every thermistor user should set up a complete temperature calibration laboratory. In many cases, such an exercise would be impractical and unnecessarily costly, and the services of an outside lab might be a better choice. Even when taking this route, though, the user can profit from knowing how to evaluate the capabilities of candidate labs.

A thermistor testing system typically includes a temperature-controlled bath (see Figure 6), a temperature calibration standard, and an instrument to measure electrical resistance. Each must be initially evaluated to determine its fit in the entire system.

THE TEMPERATURE CONTROLLED BATH

Evaluating the temperature-controlled bath, usually the most costly piece of equipment in the system, can be one of the most time-consuming steps. Without the instrumentation or test capability necessary to verify that the bath's performance matches the manufacturer's specifications, it may be difficult to determine whether the bath will meet the requirements of the application.

Wherever possible, request a demonstration of the bath's capabilities, research the manufacturer's reputation for quality and service, and ask for references before making a purchase. For most test systems, the accuracy of the bath temperature set point specification listed by most manufacturers is less important than the set point resolution of the temperature, since a separate temperature standard will be used as the reference to set and monitor the bath temperature. More pertinent are the temperature stability and uniformity specifications. The relationship between stability/uniformity specifications and uncertainty is simple: the greater the stability and uniformity of the bath temperature, the better the estimated expanded uncertainty of the total system.

Stability/uniformity specifications derive from a number of factors, including design, intended use, and price. Typical specifications are $\pm 0.5^\circ\text{C}$ for low-cost baths; $\pm 0.05^\circ\text{C}$ for mid-priced baths; and $\pm 0.005^\circ\text{C}$ or better for high-end calibration lab baths.

A bath may need to be heated or cooled or both, depending on the test temperature range. Baths with heating and cooling capabilities are commonly used for thermistors in the -20°C to 120°C range. Baths with heat-only capability usually specify an operating temperature range from 10°C above ambient to 150°C . Baths capable of handling wider temperature ranges (e.g., -80°C to 110°C , 40°C - 300°C) and extremely low temperatures (down to -100°C) are available, but may cost significantly more.

Good bath design includes the proper combination of physical/mechanical features and the electronic temperature controls. The right type of heater and refrigeration will balance the heating and cooling systems, minimizing temperature gradients. The bath fluid must be stirred vigorously to promote even temperature without the formation of air bubbles or vortices in the fluid. The temperature control system, including the temperature sensor, must be responsive enough to maintain temperature uniformity and stability for long periods. Because thermistors exhibit a high degree of sensitivity and a quick response to temperature changes, thermistor-based temperature controllers typically provide the best results for baths requiring excellent temperature uniformity and stability.

Other features to be considered are bath volume and depth and the type of bath fluid. Bath volume is dictated by the size of the sensor(s) to be tested. A good general rule is to have the volume or mass of the bath fluid at least 1000 X the mass of the device to be tested. Most commercial baths are available in capacities ranging from 4 to 8 liters (~1 to 2 gallons), 2000-4000 X the mass of a typical thermistor. Proper bath depth permits the sensor to be sufficiently immersed without getting too close to the bath bottom or sidewalls where temperature gradients may exist. The baths described above normally have a depth of 15 - 25 cm (~6 in. to 10 in.), sufficient for testing most thermistors.

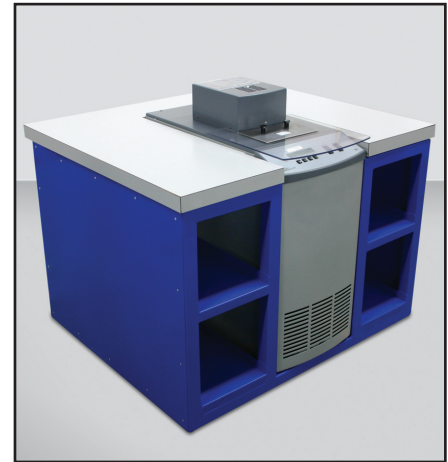


Figure 6. Baths are designed for precision thermistor calibrations because of their high stability and uniformity, typically less than $\pm 0.005^\circ\text{C}$.

The choice of bath fluid depends on the specifications recommended by the bath manufacturer, the configuration of the sensor, and the temperature range over which it will be tested. The most common bath fluids are oil and water. A variety of high-dielectric fluids are available for temperatures below 0°C and above 100°C, where the use of water would not be feasible. The fluid should have the right viscosity for the operating temperature range to permit proper stirring action. Some bath manufacturers recommend a fluid viscosity of ≤ 10 cSt; others can accommodate up to 50 cSt.

It is important to match the fluid to the bath's operating temperature range. For example, a high-temperature fluid in a cold bath would make the fluid excessively viscous, resulting in poor stirring and even damage to the stirring mechanism. Conversely, using a fluid at a temperature above its flash point is hazardous.

Thermistors with bare leads are usually tested in a high-dielectric oil. Substituting water would yield erratic results because the test current of the resistance-measuring instrument would electrically conduct through the water between the leads. Depending on the purity of the water, this condition would cause a short-circuit reading or the instrument would show an apparent reading much lower than the actual resistance value. However, distilled or deionized water can be used for thermistors with insulated leads and a water-resistant coating or those that are sealed in probe housings, as long as the bath is designed and built for use with water.

THE TEMPERATURE CALIBRATION STANDARD

The temperature calibration standard consists of a temperature probe and a readout instrument. Several types are available, but considerations of cost and ease of use limit this discussion to platinum resistance thermometers (PRTs) and super-stable thermistor probes (see Figure 7). The choice of a specific standard will depend on your specific requirements—overall test system uncertainty, temperature range, and capital expenditure budget. Keep in mind that the cost of the standard increases as the uncertainty decreases.

If your thermistor application calls for testing over a relatively wide temperature range, e.g., -40°C to 200°C, a good secondary reference grade PRT with a temperature coefficient of $0.003925 \Omega/\Omega/^\circ\text{C}$ may be necessary. This type of probe normally has a nominal resistance (R_0) of 100 Ω at 0°C; a usable temperature range of -200°C to 500°C; a standard uncertainty of $\pm 0.01^\circ\text{C}$; and a stability of $\pm 0.01^\circ\text{C}/\text{yr}$. The probes are usually supplied with calibration tables and range in price depending on the manufacturer and the type of calibration service provided. The readout instruments used with 100 Ω PRTs vary in cost depending on the uncertainty level specified. PRT probes are available with higher R_0 resistance values (500 Ω or 1000 Ω), which may allow use with a less expensive readout instrument but which will show a compromise in the uncertainty and stability specifications. PRT probes with lower R_0 values (25 Ω) may have better uncertainty and stability specifications than the 100 Ω PRT but require more expensive instruments.

The required expanded uncertainty of the total system will guide you in selecting a PRT/instrument combination. One way to improve the uncertainty of a temperature standard is to have the probe and the readout instrument calibrated together as a unit, instead of calibrating them separately and then combining the uncertainties mathematically. Some manufacturers and calibration labs will accommodate this type of calibration and others will not. The calibration lab's decision most likely would be based on its policies and procedures and the type of PRT and readout instrument to be calibrated. You should request this type of service during the equipment evaluation process, and it should be a matter to consider before deciding on a purchase.

Although PRTs are very useful standards for calibrating temperatures in the -200°C to 500°C range, their sensitivity to mechanical vibration and shock can be a serious limitation in some applications. Over the many years that PRTs and standard platinum resistance thermometers (SPRTs) have been used as thermometers, PRT manufacturers have developed and used various configurations of "strain-free" platinum wirewound elements [17]. This construction allows for thermal expansion and contraction of the platinum wire without constraint from its support. Because the element is loosely supported, however, mechanical shock or vibration can create a strain on the wire and increase the PRT's resistance. For many PRTs, simply tapping the probe on a table can shift it out of calibration by as much as 0.01°C - 0.02°C . The probe would afterward need to be annealed and recalibrated.

As previously noted, for most thermistor applications the requirements for testing are primarily for temperatures in the 0°C - 100°C range, and other applications may require testing down to -40°C or up to 120°C. For these, a super-stable



Figure 7. Thermometer readouts from entry-level systems to a primary standards model can achieve an accuracy of $\pm 0.001^\circ\text{C}$. Pictured above is a secondary platinum resistance thermometer (PRT), commonly used in calibration.

calibration standard probe offers several advantages over the PRT. For example, the thermistor sensor has an inherent high sensitivity that provides temperature resolution to 0.0001°C when used with the appropriate readout instrument. Thermistor temperature standards are available (see Figure 8) with standard uncertainties of $\pm 0.01^{\circ}\text{C}$ to $\pm 0.002^{\circ}\text{C}$ and stability specifications of better than $\pm 0.01^{\circ}\text{C}$ to $\pm 0.005^{\circ}\text{C}/\text{yr.}$, depending on the type of probe [3,4,5]. Furthermore, the way in which the thermistor element is constructed makes the thermistor probe virtually immune to normal mechanical shock and vibration.

Thermistor temperature standards cost about the same as PRTs, but offer much better uncertainty and stability specifications. In the temperature range of 0°C to 100°C , some thermistor standards can actually approach the uncertainty levels of some SPRTs that are used as primary temperature standards. Thermistor probes normally can be used with readout instruments that cost about the same as those used with $100\ \Omega$ PRTs, but achieve better expanded uncertainties than the PRT systems.

Additional improvements to the expanded uncertainty of the temperature standard can be made by calibrating the thermistor probe and readout instrument as a unit. For less exacting test uncertainty requirements, lower cost thermistor probe/instrument combinations can be obtained, but with some compromise of stability ($\pm 0.02^{\circ}\text{C}/\text{yr.}$) and system uncertainty ($\pm 0.03^{\circ}\text{C}$).

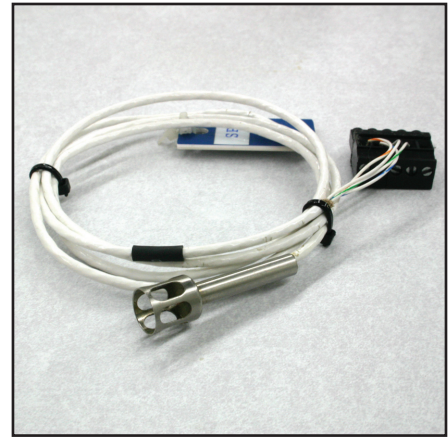


Figure 8. For the same price as an entry-level secondary PRT system, a thermistor standard can deliver accuracy to $\pm 0.005^{\circ}\text{C}$ over a narrow temperature range.

RESISTANCE MEASURING DEVICES AND THERMISTOR TEST METHODS

The final (and probably the easiest) piece of equipment to evaluate is the resistance measuring instrument. Both analog and digital instruments are available, although there are fewer analog resistance bridges to choose from and they tend to be more costly than digital multimeters (DMMs) with equivalent uncertainty specifications. During the past few years, advances in DMM technology have greatly improved the performance of these instruments, making them a more cost-effective solution for testing thermistors. In addition, many DMMs come with standard communications ports that allow their use with an automated test system (see Photo 6). The specifications outlined below are usually listed in the manufacturer's literature, and more detailed explanations of the terms are given in [16].

A DMM's resolution depends on the number of digits that can be displayed; the user's test uncertainty (accuracy) and sensitivity requirements, along with budget constraints, will be the deciding factors in selecting the appropriate level of resolution needed. For some applications, a $4\frac{1}{2}$ digit DMM may be adequate. A testing capability with lower uncertainty requirements may require a $5\frac{1}{2}$ or a $6\frac{1}{2}$ digit DMM. In general, the higher resolution DMMs have better uncertainty specifications.

Other areas to consider are the sensitivity and the test current. Because the DMM's resistance function is used to test thermistors, the sensitivity of the instrument is the smallest change in resistance it can detect. Sensitivity depends on the resolution and the lowest measurement range available on the DMM. For most thermistor applications, a $5\frac{1}{2}$ digit DMM is sufficient and provides the overall best, most cost-effective solution. However, resolution and sensitivity must be evaluated with consideration of the test current the DMM applies at each appropriate resistance range anticipated.

A thermistor can experience self-heating if the test current and the resultant power dissipated through the thermistor are too high, so it is important to limit the test current level. When a thermistor self-heats, the resistance reading becomes less than that of its true zero-power resistance. For some thermistors, self-heating by the DMM test current can cause resistance deviations of $2\text{--}5\ \Omega$ less than the zero-power readings, depending on the type of thermistor. Expressed in terms of temperature, these deviations increase the thermistor resistance measurement uncertainties by $0.03^{\circ}\text{C}\text{--}0.06^{\circ}\text{C}$, respectively.

The amount of power a thermistor can dissipate depends on a number of factors, including size, shape, resistance value, configuration, coating material, and test medium. In general, the larger the thermistor and the higher its resistance value, the more power it can dissipate. Note, too, that a thermistor can dissipate more power into a stirred fluid than into still air. A typical epoxy- or phenolic-coated thermistor with a $0.095\ \text{in. o.d.}$ and $0.010\ \text{in. dia.}$ leads exhibits dissipation constants of $1\ \text{mW}/^{\circ}\text{C}$ in still air and $8\ \text{mW}/^{\circ}\text{C}$ in stirred oil. If the user's test requirement specifies that the uncertainty in measurement due to self-heat should be 0.01°C , the maximum amount of power the thermistor should dissipate is $[(0.01^{\circ}\text{C})(1\ \text{mW}/^{\circ}\text{C})]$ or $10\ \mu\text{W}$ in still air and $80\ \mu\text{W}$ in stirred oil. These power levels correlate to test currents of $\sim 10\ \mu\text{A}$

to 100 μA , depending on the resistance value of the thermistor. When choosing a DMM for testing thermistors, carefully review its specifications to be certain that the test currents for the applicable resistance ranges do not exceed these amounts. Usually, the DMM with the lowest test current, $\sim 10 \mu\text{A}$, is the best choice for testing thermistors.

One of the most important specifications to analyze when evaluating a DMM's capability is the manufacturer's stated uncertainty (or accuracy) of its resistance-measuring function. The uncertainty can be stated as a plus or minus percentage of reading plus a number of counts of the least significant digit, or in terms of parts per million such as $\pm(\text{ppm of reading} + \text{ppm of range})$. The manufacturer usually states these specifications for periods ranging from 24 hours to one year. The one-year uncertainty specifications are particularly important because they give an indication of how well the instrument will stay within calibration over time. The measurement uncertainty expressed in terms of percentage of resistance or ppm of reading can be converted to temperature uncertainty by using the thermistor's NTC for each temperature at which the resistance readings will be taken.

If the test system's long-term uncertainty is especially crucial, consider purchasing stable resistance standards with values close to those of the thermistors to be tested and the temperature standard to be used for calibrating the bath. Pricing for these standards depends on the uncertainty specified. Resistance standards can be very helpful tools for verifying the uncertainties of the resistance measuring instruments between calibrations.

Typical Methods for Testing Thermistors

When the appropriate test equipment is in place and in proper working order, it's time to make some final preparations. By carefully designing the right test clips and fixtures for the type of thermistors to be tested, for example, you will maximize the efficiency of the process and the repeatability of the results. Forms for recording data should be planned in advance and ready for use. This practice will help ensure that the test information will be recorded in an orderly and accurate manner, facilitating data analysis after testing is complete. The generic test sequence below can be modified for your specific requirements.

- 1. Temperature-controlled bath setup.** The bath is set to the desired temperature, allowed to stabilize, and then calibrated. The time to complete these steps can be $\sim 1/2$ hour to 2 hours, depending on the bath temperature and its heating/cooling rates.
- 2. Resistance measuring instrument setup.** The test clips or fixtures are connected to the DMM. The instrument is set to the resistance range with the proper test current and resolution for the thermistors to be tested. Many $5\frac{1}{2}$ digit and $6\frac{1}{2}$ digit DMMs have 20 k Ω and 200 k Ω ranges with 10 μA test currents, which cover most thermistor testing requirements.
- 3. Testing thermistors and thermistor probes.** The thermistor leads are connected to the test clip and the thermistor is immersed in the bath fluid to a depth dictated by the type of thermistor being tested. A thermistor with bare leads is typically immersed 2–3 in. into the bath fluid, depending on the lead length and the test clip design. The proper immersion depth can be determined by trial and error until the best results are obtained. While testing, be careful not to immerse the test clip in the fluid because the added mass may disturb the bath's equilibrium temperature. The thermistor should be allowed to come into equilibrium with the bath temperature (typically 5–15 s). The test technician either records the resistance reading onto the data sheet or compares the reading to a predetermined acceptable resistance range if the reading need not be recorded.

When testing thermistors assembled into probe housings, the proper immersion depth becomes more critical for preventing resistance measurement errors due to a condition called *stem effect*, which is caused by heat transfer into or out of the probe. Such "thermal pipelines" create temperature gradients that distort the thermistor reading and must be compensated by using greater immersion depths. As a general rule, a starting point for immersion depth should be ~ 10 to $20 \times$ the diameter of the probe. Taking readings at various immersion depths should reveal the optimum depth for testing. Also, a thermistor probe with its greater mass will require more time (typically 1–2 min.) to attain equilibrium with the bath temperature than will a small thermistor with bare leads.



Figure 9. Digital multimeters offer a wide range of features.

4. Reviewing the data. Another simple but commonly overlooked step is to review the data while testing to see if the information seems reasonable. Making corrections or adjustments to the equipment before proceeding with the testing is much less time-consuming than having to completely repeat the testing sequence.

5. Other testing considerations. In Part I of this article, the drift characteristic of a thermistor was discussed. If the application requires an analysis of drift, extra care must be taken throughout the testing process to ensure that the resistance measurements have the best repeatability and lowest uncertainty possible. This extra effort will prevent the introduction of unwanted variables or errors that would distort the actual drift characteristic of the thermistor.

CONCLUSION

Technical advances have established the NTC thermistor as the optimum sensor for most applications within the -50°C to 150°C temperature range. The historical, theoretical, and practical information in this series of articles was intended to improve the reader's understanding of how to determine the appropriate temperature sensor for an application. The discussion of thermistor configurations highlighted the strengths and limitations of the three most common types used for resistance thermometry: glass bead, disc, and chip thermistors. Recommendations as to the setup and use of a thermistor test system should help the user evaluate thermistors for compliance with resistance/temperature specifications. As thermistor users and manufacturers strive to achieve a better working relationship, the result will be continued improvements in product design, quality, and service that ultimately will benefit the entire temperature measurement and control industry.

GLOSSARY

Accuracy. The closeness of the agreement between the result of a measurement and the value of the specific quantity subject to measurement, i.e., the measurand [12]. Although most equipment manufacturers still use the term as a tolerance in their specifications, NIST and other international standards bodies have classified it as a qualitative concept not to be used quantitatively. The current uniform approach is to report a measurement result accompanied by a quantitative statement of its uncertainty [12].

Error. The result of a measurement minus the value of the measurand [12].

Precision. The closeness of agreement between independent test results obtained under stipulated conditions [12]. Precision is a qualitative term used in the context of repeatability or reproducibility and should never be used interchangeably with accuracy.

Repeatability. The closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement [12].

Reproducibility. The closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement [12].

Resolution. A measure of the smallest portion of the signal that can be observed [16]. For example, a thermometer with a display that reads to three decimal places would have a resolution of 0.001°C . In general, the resolution of an instrument has a better rating than its accuracy.

Sensitivity. The smallest detectable change in a measurement. The ultimate sensitivity of a measuring instrument depends both on its resolution and the lowest measurement range [16].

Uncertainty. The estimated possible deviation of the result of measurement from its actual value [16]. The uncertainty of the result of a measurement generally consists of several components that may be grouped into two categories according to the method used to estimate their numerical values: A. those evaluated by statistical methods; B. those evaluated by other means [12]. Uncertainty and error are not to be used interchangeably.

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2108 Century Way Boise, Idaho 83709 USA
T: (208) 377-3373, 800-554-4784 | F: (208) 376-4754
qtisales@thermistor.com | www.thermistor.com