

# The use of NTC Thermistors as sensing devices for TEC controllers and temperature control Integrated Circuits

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**Abstract**—Description providing general guidelines and best practice for the use of Thermistors as the temperature sensor for input to temperature sensor integrated circuits.

**Index Terms**—Thermistor, NTC, TEC, Thermoelectric Cooler, Peltier Cell, System Temperature monitors, Temperature controller, Dense Wave Division Multiplexing, Telecommunications components.

## I. INTRODUCTION

This document provides technical support to designers of temperature control systems that utilize sensor components and integrated circuits (IC's). It will provide guidance in the selection and use of the most suitable type of Negative Temperature Coefficient (NTC) Thermistor for a specific application.

This technical paper contains detailed sections on the background, type and ohmic range of NTC thermistors available today. There is also a section in the paper that explains how to deal with the non-linearity effects of NTC thermistors as input devices.

## II. BACKGROUND

With the increasing availability of integrated circuits, the demand for high-resolution temperature measurement is now greater than ever. More and more designers are now looking both for better measurement and associated temperature control. Some IC manufacturers include a p-n junction embedded in the IC package for use as a local sensor. Other manufacturers allow the use of a p-n junction in a discrete package for remote temperature sensing. The usual resolution that can be achieved using a p-n type semiconductor sensor is in the region of  $\pm 1$  to  $\pm 2^\circ\text{C}$ . However, the use of an NTC thermistor device as a temperature sensor allows resolutions of  $\pm 0.1$  to  $\pm 0.2^\circ\text{C}$  to be easily achieved. The high sensitivity of NTC thermistor sensors combined with the availability of tight resistance tolerances make them the ideal choice when designing temperature control systems.

This paper describes thermistor devices that are suited to temperature sensing for various applications including ThermoElectric Coolers (TEC). Commonly used sensors for such applications are devices whose electrical resistance is dependent on their body temperature. Such devices are known as Resistance Thermometer Devices or RTD's. The family of devices known as RTD's includes metal element devices, such as Platinum sensors of type Pt100 or Pt1000, and ceramic devices which are commonly referred to as "Thermistors".

The term "Thermistor" is derived from the expression "**Thermally Sensitive Resistor**", and could be used to refer to any RTD type sensor. However, in common engineering usage, the term "thermistor" is usually reserved for devices produced from bulk ceramic materials. These ceramic-based devices are semiconductors whose characteristics can be varied through the use of different constituent metal oxides in the base material. The ceramic thermistor devices can be further subdivided into two categories. The first consists of components whose resistance decreases as their temperature increases; i.e. thermistor components with a Negative Temperature Coefficient, known as NTC Thermistors. The second category consists of components whose resistance increases as their temperature increases, i.e. thermistor components with a Positive Temperature Coefficient, known as PTC Thermistors.

PTC thermistors are typically used for circuit protection applications rather than for temperature sensing applications. NTC thermistors are ideally suited for temperature sensing applications over a temperature range of  $-80^\circ\text{C}$  to  $+250^\circ\text{C}$ .

A variety of NTC thermistor material types are fabricated using proprietary formulations and processes.

The temperature sensitivity of a temperature sensor is usually expressed as "percentage change per degree", and can be expressed in units of "% /  $^\circ\text{C}$ ". For NTC thermistors the temperature sensitivity is of the order of  $-3\%$  to  $-6\%$  per  $^\circ\text{C}$ . Typical values of temperature sensitivities for various Betatherm thermistor material types are indicated in Table 1.

It is also useful to express temperature sensitivity in terms of ohms per  $^\circ\text{C}$ . ( $\Omega/^\circ\text{C}$ ) for comparisons between NTC thermistors and other RTD's.

TABLE 1  
TYPICAL TEMPERATURE SENSITIVITY (%/ °C) AT SELECTED  
TEMPERATURES FOR BETATHERM THERMISTOR MATERIALS

Material System #	0°C	25°C	50°C	100°C
Material 1	4.1%	3.5%	3.1%	2.3%
Material 3	5.2%	4.4%	3.8%	2.8%
Material 4	4.7%	4.1%	3.5%	2.7%
Material 6	5.5%	4.7%	4.1%	3.2%

Metal element RTD's are defined in terms of their resistance values at 0°C. A standard Pt100 device has a resistance of 100 ohms at 0°C. The temperature sensitivity for such a device is 0.39 %/°C, which corresponds to **0.39 ohms per °C** at 0°C.

NTC thermistors devices are produced from a variety of material types. The base materials have high resistivity values and so devices with high resistance values can be produced. NTC thermistor devices are usually defined in terms of their resistance value at 25 °C. A thermistor made from Betatherm material system #3, with a resistance value of 10,000 ohms at +25 °C, has a resistance value of 32,651 ohms at 0 °C. The temperature sensitivity of such a device at 0°C, is -5.2 %/ °C, so the sensitivity in ohms is **1698.8 ohms per °C** at 0°C.

The principal advantages that NTC thermistors have over metal element RTD's are due to their large temperature sensitivity and include the following points:

- Lead wire resistance is usually negligible in comparison to NTC thermistor resistance. Two wire connections are adequate for connecting NTC thermistors to circuits in most situations. Metal element RTD's often require three or four wire connections.
- Small temperature changes can be resolved easily with NTC thermistors.
- Signal conditioning and amplification requirements are less critical for NTC thermistors than for metal element RTD's.
- There is considerable scope for customization in the design of NTC thermistor sensors and assemblies. Metal element RTD's are more constrained in mechanical and electrical option

### III. RESISTANCE VERSUS TEMPERATURE CHARACTERISTICS OF NTC THERMISTORS.

A perceived disadvantage of NTC thermistors compared to metal element RTD's is the non-linear nature of their Resistance versus Temperature (R / T) characteristics. The non-linear characteristics are not necessarily a limiting factor in using NTC thermistors as temperature sensors in modern electronic systems.

Typical (R / T) characteristics for a Betatherm NTC thermistor with a resistance value of 10,000 ohms at 25 °C made from Betatherm material system #3 are shown in Figure 1.

In the nomenclature used by Betatherm, such a device is referred to as a **10K3** device, indicating that it has a resistance value of **10 K-ohm** at 25 °C and that it is made from Betatherm material system # **3**.

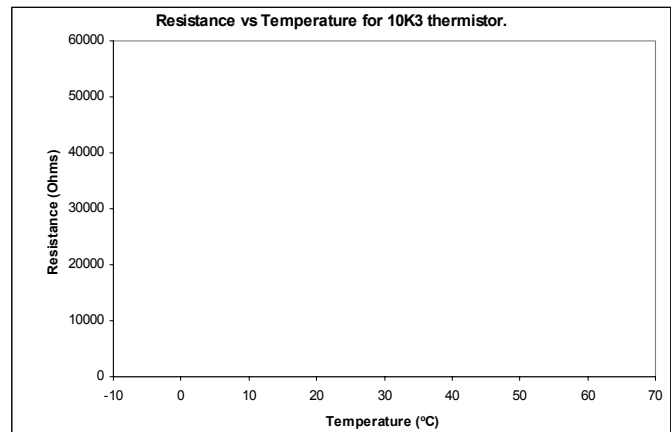


Figure 1. Resistance vs. Temperature characteristics of Betatherm 10K3 NTC Thermistor.

In considering the characteristics of any electronic component it is useful to have a mathematical model that can be used to relate the relevant parameters. The general use of thermistors as sensors requires the measurement of the resistance value of the thermistor and the use of this measured value to calculate it's body temperature.

The R / T characteristics of an NTC thermistor have an exponential trend. The resistance of the thermistor at a particular temperature,  $R_T$ , can be considered to be approximately proportional to the exponential of the reciprocal of absolute temperature,  $T$  (Kelvin). This relationship can be expressed as:

$$R_T \propto \exp(1/T) \quad \text{or} \quad 1/T \propto \ln(R_T)$$

From the general application of using a measured resistance value of a thermistor to calculate the temperature it is useful to consider the graph of  $1/T$  versus  $\ln(R_T)$ .

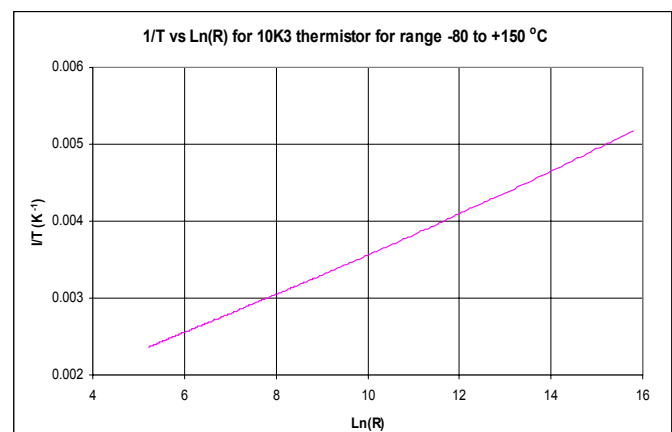


Figure 2.  $1/T$  vs.  $\ln(R)$  for Betatherm 10K3 NTC Thermistor.

Using mathematical curve fitting techniques it is possible to consider  $(1/T)$  to be a polynomial in  $\ln(R)$ . An equation of the following form can be developed:

$$1/T = A_0 + A_1(\ln(R)) + \dots + A_N(\ln(R))^N$$

where  $T$  is the temperature of the NTC thermistor in Kelvin, and  $A_0, A_1 \dots A_N$  are polynomial coefficients that are mathematical constants. It is generally accepted that the use of a third order polynomial gives a very good correlation with measured data and the " $(\ln(R))^2$ " term is negligible. The equation then is reduced to a simpler form and is generally written as:

$$\frac{1}{T} = A + B(\ln(R)) + C(\ln(R))^3$$

Equation 1

This equation is known as the "**Steinhart-Hart thermistor equation**" and is used by most thermistor manufacturers. The coefficients  $A, B$  and  $C$  are known as the Steinhart-Hart coefficients and the temperature value is in Kelvin.

Thermistor manufacturers typically supply values for the Steinhart-Hart coefficients and also supply tables of Resistance versus Temperature data for various thermistor components.

The equation is presented in this form with Temperature as the main variable. When the requirement is to calculate Resistance values of a thermistor at particular temperatures, the equation can be solved to have resistance as the main variable as follows:

$$R_T = \exp \left[ \left( -\frac{X}{2} + \left( \frac{X^2}{4} + \frac{Y^3}{27} \right)^{1/2} \right)^{1/3} + \left( -\frac{X}{2} - \left( \frac{X^2}{4} + \frac{Y^3}{27} \right)^{1/2} \right)^{1/3} \right]$$

Where

$$X = \frac{A - 1/T}{C} \quad Y = \frac{B}{C}$$

Equation 2

The equation in this form uses the same  $A, B$  and  $C$  coefficients as the equation above and is amenable for use in computer spreadsheets or programmable calculators. It can be employed in microprocessor systems for the generation of  $R/T$  look-up tables.

The equations outlined above are useful in interfacing NTC thermistor temperature sensors to temperature monitoring and control systems.

#### IV. INTERFACING NTC THERMISTORS TO INSTRUMENTATION.

While there are many types of instrumentation systems available for implementing temperature measurement and control functions, it is useful to consider such systems in two broad categories.

The first category covers the situation where the system has significant digital processing capability available.

The second category deals with the situation where there may not be digital or computational power available.

##### Interfacing NTC thermistors to systems with digital processing capability:

Digital processing capability is available in many electronic systems at reasonable cost. The basic principle of such systems is the Micro-Converter, ( $\mu C$ ) IC concept. Such devices have an Analog to Digital Converter (ADC), microprocessor and output stages integrated in a single module or chip. They have the capability to be programmed by the user to perform various mathematical functions. In systems based on such devices, the NTC thermistor can typically be interfaced to the ADC stage in a potential divider configuration. Other configurations may also be suggested in the application notes supplied with the ADC or  $\mu C$ . The choice of resistance value of the series resistor is determined by considerations such as the current levels in the thermistor and power consumption in the circuit. Limiting the current in the thermistor is advisable to minimize power dissipation in the thermistor, which can cause undesirable self-heating effects. Typically the power dissipation in the thermistor should be lower than  $100 \mu W$ .

The algorithm required in the programmable stage system to obtain a temperature value from the thermistor would typically include the following steps:

- Measurement of the voltage across the thermistor via the ADC.
- Calculation of the resistance of the thermistor from this voltage value.
- Calculation of the temperature using the Steinhart-Hart equation as presented in Equation 1.

Alternatively, when the system processing power is limited, the system could be programmed with a look-up table of Temperature and corresponding thermistor voltage or resistance values. The algorithm to obtain a temperature value from the thermistor would then typically include the following steps:

- Measurement of the voltage across the thermistor via the ADC.
- Relating the measured voltage value to the temperature by using the programmed look-up table.

The temperature resolution in such systems, using tight tolerance thermistors and resistors can be in the order of  $\pm 0.01^\circ C$ .

Further notes on interfacing thermistors to ADC's are included in Appendix I.

### Interfacing NTC thermistors to systems without digital processing capability:

Many temperature measurement and control applications are based on functional blocks that operate in the Analog domain. A particular example is the control of Thermoelectric Coolers for use in optical communications systems.

A leading supplier of thermoelectric coolers (TEC) controllers is Analog Devices. The ADN8830 is a TEC controller that is configured to use an NTC thermistor element and details can be found at [www.analog.com/adn8830](http://www.analog.com/adn8830).

NTC thermistors are often interfaced to such systems using potential divider configurations. In such systems the non-linear R/T characteristics of the thermistor can be regarded as a disadvantage. However it is possible to configure potential dividers so that the disadvantages of the non-linear characteristics of the NTC thermistor are minimized while still availing of the ease of connection and high temperature sensitivity.

For potential divider configurations such as that shown in Figure 3 it is useful to consider the transfer function or "standard" function of the system.

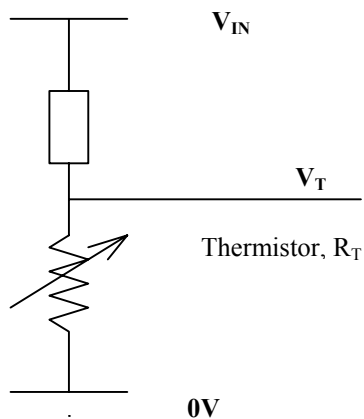


Figure 3. Constant Voltage Potential Divider

This is usually considered to be an expression of the output voltage, normalized with respect to the input voltage, in terms of circuit parameters.

In this case, the regular potential divider equations can be applied and the standard function can be expressed as:

$$\frac{V_T}{V_{IN}} = \frac{R_T}{R_1 + R_T}$$

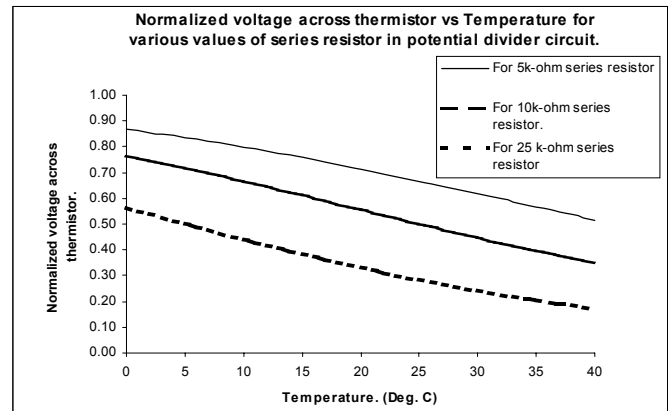
It is useful to consider this standard function over a temperature range for various values of  $R_1$ .

Figure 4 shows a graph data for a Betatherm 10K3 thermistor for various values of series resistor over the range from 0 °C to 40 °C. From the graph it can be seen that the normalized voltage across the thermistor is an approximately linear function of the

thermistor temperature. It can be seen that the value of the series resistor affects the degree of linearity in this relationship. The linearity can be optimized by suitable choice of resistor value.

A useful method of selecting the resistor value that will provide the best linear relationship between voltage across the thermistor and temperature is as follows:

Figure 4. Normalized Voltages Across Thermistor and Series Resistors



- Determine the relevant temperature range.
- Find the resistance of the thermistor at the end-points and mid-point of this temperature range. These values can usually be found from the thermistor manufacturers data or from measurement.
- These resistance values of the thermistor are designated as follows:

$R_{T1}$  = Resistance of thermistor at the lowest temperature in the range.

$R_{T2}$  = Resistance of thermistor at the mid-point temperature in the range.

$R_{T3}$  = Resistance of thermistor at the highest temperature in the range.

The value of series resistor,  $R_X$ , to optimize the linearity can then be calculated using the following formula:

$$R_X = \frac{R_{T1}R_{T2} + R_{T2}R_{T3} - 2R_{T1}R_{T3}}{R_{T1} + R_{T3} - 2R_{T2}}$$

For best accuracy  $R_X$  should be a 0.1% tolerance resistor.

In this configuration, the smaller the temperature range, the more linear the output of the potential divider will be with respect to temperature. The scale of errors associated with this method of selection of series resistor are of the order of +/- 0.01°C over a 10 °C range, +/- 0.05 °C over a 30 °C range and +/- 2.0 °C over a 60 °C range.

If linearity is required over a more extensive range, Betatherm can supply a range of linear thermistor networks that consist of a combination of thermistors and resistors. Such linear networks are beyond the scope of this paper, but details can be found on the Betatherm web site at [www.betatherm.com](http://www.betatherm.com) or from the Betatherm Applications Engineering department.

*Note: A complete listing of the Resistance /Temperature (R/T) tables are available from Engineering at Betatherm Thermistors or via the Internet.*

## V. THERMISTOR SELECTION / PHYSICAL FORMS

When selecting an NTC thermistor for a particular application it is important to consider a number of key design areas. These areas would need to include environmental, mechanical and electrical requirements. Both custom and applications specific designs are available from the manufacturer. This section of the technical paper outlines some examples of different NTC thermistor types that are available.

The first area to consider will be the environment in which the thermistor will be expected to perform. If the thermistor is to be embedded into or onto some other substrate it may be possible to use BetaChip Gold terminated leadless thermistor (See Fig. 5). With metalization on both the top and bottom surfaces, attachment to hybrid, IC or printed circuits is accomplished using industry standard die attach and wire bonding techniques. Chip thermistors may be soldered directly to the substrate or conductive epoxy technologies used to mount them. Chip thermistors offer a number of advantages where space is at a premium. As they can be also mounted in direct contact with a heat source, they exhibit extremely fast time responses.

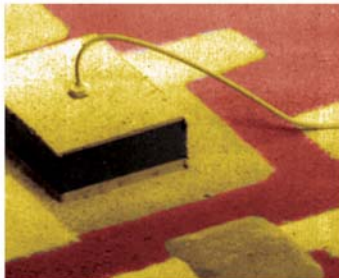


Fig 5. Betatherm BetaChip Gold Terminated Chip Thermistor

A typical example of a telecommunications laser diode sub-assembly can be seen in Fig. 6. This type of arrangement is typically found controlling the system cooling of Erbium-doped fiber-optical amplifiers (EDFA) and Raman laser pumps. The temperature stability expected from these components will be  $\pm 0.001^{\circ}\text{C}$ . Typical chip sizes used ( $1\text{mm} \times 1\text{mm} \times 0.25\text{mm}$ ) allow for accurate robotic placement.



Fig 6. Laser Diode Sub-assembly including Betatherm BetaChip Thermistor

If the thermistor is to be printed circuit board mounted then Betatherm Thermistors manufacture a range of BetaCurve Interchangeable Thermistors. (See Fig. 7). These components are offered in a wide range of resistance values with temperature tolerances as low as  $\pm 0.05^{\circ}\text{C}$  (single point) and  $\pm 0.1^{\circ}\text{C}$  across a temperature range from  $0^{\circ}\text{C}$  to  $+70^{\circ}\text{C}$ . The thermistors are encapsulated in a thermally conductive epoxy that provides mechanical protection and fast time responses ( $\sim 1$  second in liquids). This type of discrete thermistor component is available with either insulated or non-insulated lead to suit the particular application.

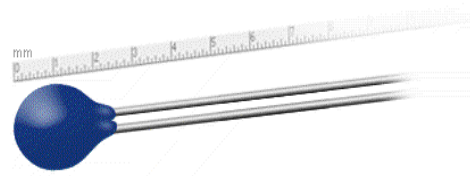


Fig 7. Discrete thermistor with insulated leads

If the NTC thermistor sensor is to be exposed to harsh environmental conditions then a Betatherm probe assembly should be considered. Thermistor probe assemblies are manufactured in a range of shapes and configurations depending on the requirements of the end-user. An example could be the heavy construction flange-mount stainless steel probe used in ovens or chambers. This type of probe is designed to withstand mechanical abuse.

NTC thermistors have also found use in the medical field where fast time responses and high accuracy are of great importance. One example of the configurations available is micro-probes for medical catheters. They are designed to have a Thermal Time Constant (T.C.) of less than 200ms and a diameter of less than 0.5mm. (See Fig. 8).



Fig 8. Microprobe assembly with a nominal diameter of  $< 0.5$  mm.

When selecting a thermistor the temperature to which the part will be exposed is of paramount importance. Betatherm, as a thermistor manufacturer, can offer devices to suit a range of temperatures from  $-80^{\circ}\text{C}$  to  $+300^{\circ}\text{C}$ .

## APPENDIX I – INTERFACING THERMISTORS WITH ANALOG TO DIGITAL CONVERTERS.

A typical circuit configuration for achieving high-resolution temperature measurements involves use of an NTC thermistor in conjunction with a dedicated ADC. It is possible to offer



the user this combination to cover the vast majority of different applications. For instance the typical 12-bit ADC using a 5 volt reference with a uni-polar input of 0-5V will have a resolution of 5 V divided by 12 bits (5/4096) equating to 1.2mV per count. A standard Betatherm 10K3A11A thermistor discrete component and series resistor of 5K ohms can be placed in series with the same 5v reference. At the low temperature of 0°C, the volt-drop across the 5K-ohm resistor will be 0.66v. At the high temperature of 50°C, the voltdrop across the 5Kohm series resistor will be 2.9v. The calculation shows that for every 1°C temperature change a difference of 44mV will be seen. This 44mV is equal to a count of 36 for the 12-bit converter. This configuration could easily achieve the quoted resolution of  $\pm 0.04^\circ\text{C}$  over the 50°C temperature span. The accuracy of this approach depends on the 5V reference used which may be either a voltage reference built into the dedicated ADC or from external circuitry.

Since the output of the ADC is a digital number, this value can simply be compared to a lookup table and the equivalent temperature can be established. The accuracy and resolution of the combined Integrated Circuit and Thermistor will have already have been fixed by the manufacturer and the list of available choices continues to grow. Another possible solution is to provide the ADC with some math capability. When a value equivalent to temperature is measured, the math formula can be applied and hence a value of temperature output.

This type of device can be manufactured to provide its output in many ways. The most useful outputs being an analogue output in Volts/°C; digital outputs either in standard communications form RS232 or I<sup>2</sup>C. (See Fig 9).

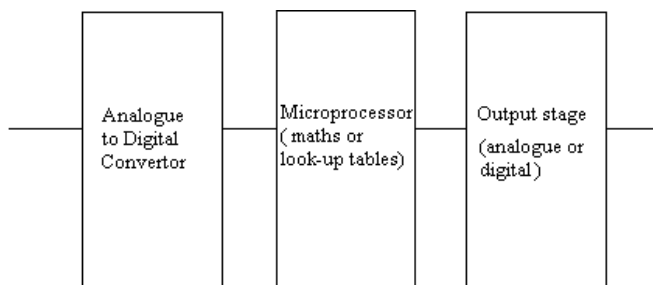


Fig 9. Block diagram of ADC with Microprocessor and Output Stage

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