BetaTHERM Sensors
TEMPERATURE SOLUTIONS

NTC Thermistor theory

TABLE OF CONTENTS

Thermistors:

The term *"Thermistor"* is used to describe a range of electronic components whose principle characteristic is that their electrical resistance changes in response to changes in their temperature.

The word **"Thermistor"** derives from the description **"thermally sensitive resistor"**.

Thermistors are further classified as "Positive Temperature Coefficient" devices **(PTC devices)** or "Negative Temperature Coefficient" devices **(NTC devices)**.

PTC devices are devices whose resistance increases as their temperature increases.

NTC devices are devices whose resistance decreases as their temperature increases.

NTC thermistors are manufactured from proprietary formulations of ceramic materials based on transition metal oxides. A brief outline of the manufacturing process for the production of **chip thermistors** at BetaTHERM is shown inside the front cover of this catalog.

A discrete thermistor such as a chip, disc or rod is a fundamental electrical component.

BetaTHERM's **"chip"** thermistor elements are the foundation of a major proportion of BetaTHERM's products.

To understand the applications of thermistors and the selection of thermistor components in the design of thermistor circuits it is necessary to be aware of some basic concepts and definitions that are used in the thermistor industry. The next sections of the catalog cover some of these topics with reference to chip-based NTC products to provide some background to thermistor theory and to assist in the selection of products for applications. Product specifications are given in a separate section of the catalog.

The topics to be considered in this discussion on thermistors are:

- **Chip Configuration.**
- **Volume Resistivity of material.**
- **Electrical Resistance.**
- **Slope (Resistance Ratio).**
- **Modelling relationship between Temperature and Resistance.**
- **Thermal Time Constant, Dissipation Constant.**
- **Resistance-Temperature Characteristics.**
- **Voltage-Current Characteristics.**
- **Precision, Tolerance and Stability of Thermistors**
- **Current-Time Characteristics.**
- **Application notes .**
- **Circuit Guidelines.**

Chip Configuration:

The basic configuration of "chip" thermistor elements is shown in Figure #1. The thermistor material is metalized on the top and bottom surfaces for electrical contact. Metalization of the thermistor material is performed by dipping or screen printing with conductive ink based on materials such as silver or gold. The ink is fired to the wafers of the thermistor material. The wafers are then diced by mechanical saw or by laser scribing to produce chips of specific sizes. The length, width and thickness are controlled dimensions for specific chip element products. Typical chip dimensions are 1mm x 1mm x 0.25mm thick.

BetaTHERM supplies leadless "chip" thermistor elements for applications where die bonding and wire bonding assembly techniques are used for circuit connections. The elements can be supplied in vials or "waffle" packs.

TYPICAL CHIP THERMISTOR

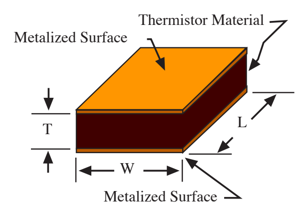


Figure # 1

Figure # 1

BetaTHERM's chip elements are used to produce components with wire leads which are coated with thermally conductive epoxy as illustrated in Figure # 2.

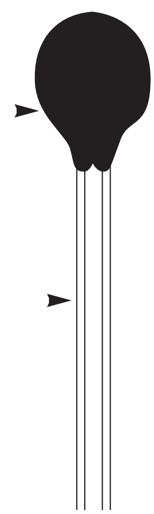


Figure # 2

Volume Resistivity:

The volume resistivity *of a material is a parameter that indicates the electrical resistance of a piece of the material.* ***It is defined*** *in a manner that allows the calculation of the resistance in* ***Ohms*** *of a piece of material when the* ***physical dimensions*** *are known.*

Resistivity is specified in units of resistance (ohms) multiplied by units of length (usually cm). Resistivity is then expressed in units of ohm-cm.(Ω-cm). Resistivity is usually represented by the Greek Letter ρ, (rho).

At first, the units of resistivity (ohm-cm) may not seem convenient. To develop the concept and improve understanding, it is essential to relate the material parameter **resistivity** with the actual resistance in **ohms** of a piece of material. The relationship between them is:

$$R\ (\text{ohms}) = \frac{\rho\ (\text{ohm-cm}) \times \text{thickness(cm)}}{\text{cross-sectional area (cm}^2)} = \frac{\rho \times T}{L \times W}\ \text{ohms}$$

(Equation #1)

where: ρ is material resistivity in ohm-cm,
T is the thickness of the conductor (chip) (cm)
L is the length of the conductor (chip) (cm)
W is the width of the conductor (chip) (cm)

Resistance is proportional to thickness (length of current path) because for a uniform cross-sectional area, increasing the thickness of a conductor is similar to combining resistors in series. Likewise, the resistance is inversely proportional to the cross-sectional area as increasing the cross-sectional area is similar to combining resistors in parallel, which reduces the overall resistance.

Resistivity is essentially an engineering parameter and it is an extremely important. It is useful because when it is known for a particular material, the resistance of a piece of that material can be calculated if the dimensions of the piece are known also. These calculations are demonstrated in a numerical example, but first, the concept of volume resistivity of materials is developed further.

The resistivity of thermistor material is treated as a **constant** for standard materials. The resistivity varies with temperature, so it is specified at particular temperatures (usually 25^{O}C). Thermistor manufacturers produce many different thermistor materials to cover an extensive range of resistance values (100 ohms to 1 Mega-ohm) for chips of various sizes.

A simple representation of the manufacturing process for *BetaTHERM* thermistors is shown on the inside of the front cover of this catalog.

When the metallization stage is complete, the thermistor material is in the form of a ceramic sheet or wafer of typical dimensions 50mm x 50mm x 0.25mm which is metallized on both sides. The resistivity of a piece of the material can be calculated by dicing a chip of regular shape (square or rectangular faces), measuring the resistance of that chip at the relevant temperature (usually 25 ^{O}C) and applying the definition of resistivity as follows:

Volume resistivity formula:

$$\rho = \frac{L \times W}{T} \times R_{25}\ (\text{ohm-cm})$$

(Equation #2)

Where: ρ = volume resistivity (ohm-cm)
L = length of chip element cm
W = width of chip element cm
T = thickness of chip element (cm)
R_{25} = measured resistance @ 25^{O}C (ohms)

A typical calculation based on resistivity is illustrated in the following example. In such calculations it is important to **observe consistency of measurement units and dimensions** especially where some dimensions are given in inches and others are in centimetres. For instance in the thermistor industry it is common to express resistivity in units of ohm-cm, but to give chip dimensions in inches.

Example: Calculate the volume resistivity for BetaTHERM Curve 3 Material with dimensions of 0.04" x 0.04" and thickness 0.01" with measured resistance value 8120 ohms at 25^{O}C.

$$\rho = \frac{0.04(\text{inches}) \times 2.54(\text{cm/inch}) \times 0.04(\text{inches}) \times 2.54(\text{cm/inch}) \times 8120\ (\text{ohms})}{0.01(\text{inches}) \times 2.54\ (\text{cm/inch})}$$

$$\rho = \mathbf{3299.96\ ohm\text{-}cm.}$$

When resistivity is specified in **ohm-cm** and the other dimensions are in **inches** then the equation can be written as :

$$\rho\ (\text{ohm-cm}) = \frac{L(\text{inches}) \times W(\text{inches}) \times 2.54}{T(\text{inches})} \times R_{25}(\text{ohms})$$

(2.54 is the conversion factor to relate cm and inches)

The concept of material resistivity is extremely important in the selection of thermistor material in relation to chip size in applications. The equations indicate that for material of the same resistivity, required resistance values can be achieved with different chip sizes, within the constraints of the equations relating resistance and resistivity. This provides flexibility for developing custom solutions in relation to chip sizes in applications.

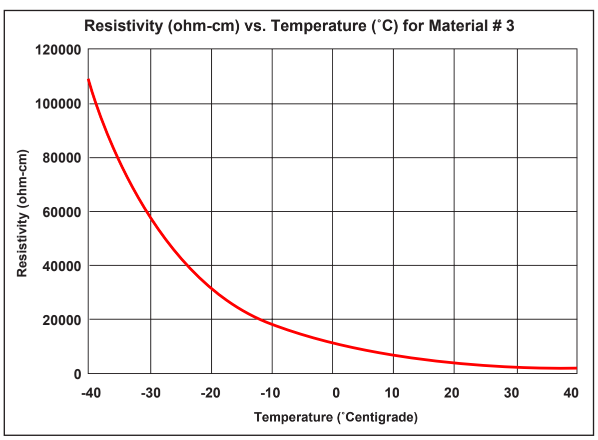
Material resistivities of BetaTHERM thermistors at 25 ^{O}C are listed in Table #1 below. The use of resistivity values in calculating the resistance of thermistor elements is of major importance in the thermistor industry. These values have been determined by accurate measurements.

BetaTHERM Standard Material Resistivities at 25^{O}C.

Material Curve	Resistivity (ohm-cm)
1	65
2	50
3	3300
4	3500
5	5500
6	18000
7LoRo	300
7HiRo	3000
9	325000

Table # 1:

Since a thermistor is a component whose resistance varies with temperature, the variation of resistivity with temperature is a critical material property. This relationship is indicated graphically below for Betatherm Material #3 over a limited temperature range (-40^{O}C to +40 ^{O}C).



Resistance:

Thermistors are devices that obey ***Ohms Law****, which relates the current through a resistor to the voltage across it.* ***Ohms law is usually stated as: V=IR,***

where ***V*** *is the voltage across the resistor in units of* ***Volts,***
I *is the current through the resistor in units of* ***Amps,***
R *is the resistance of the resistor in units of* ***Ohms.***

The word Thermistor is derived from the term Thermally sensitive resistor. The resistance of the thermistor depends on the temperature of the thermistor, **and at temperature points in it's useful range, the thermistor obeys Ohms Law.**

Thermistors exhibit a relatively large negative change in resistance with a change in body temperature, typically -3% to -6% per ^{O}C. This sensitivity is a major advantage of thermistors over other electrical temperature sensing devices.

The concept of **electrical resistivity** and the material resistivity constants that were introduced in the previous section can be used to calculate the **resistance** of thermistor components. The physical dimensions of the thermistor and the material resistivity at the relevant temperature are required. The reference temperature is usually taken to be 25^{O}C. Referring to **Equation #1** and the definition of resistivity, the resistance **(R)** of the thermistor at the reference temperature of 25^{O}C is calculated from **Equation # 1** which is repeated below:

$$\mathbf{R} = \frac{\rho \times T}{L \times W} \quad \textbf{ohms}$$

Equation #1: ***(Resistance formula repeated)***

Where: **R** is the resistance of the component in ohms.
ρ is the material resistivity in ohm-cm
T is the thickness of the component (cm). (This dimension represents the current path through the thermistor.).
L is the length of the metalized surface of the thermistor (cm).
W is the width of the metalized surface of the thermistor (cm).

While the equation represents a common calculation in general electronic applications, it is a very important one in the Thermistor industry, in particular where the dimensions of the component are critical. It can be used to determine the dimensional options available to produce the required thermistor. It is very important in the use of equation 1 to maintain consistency of measurement units.

Example: Calculate the resistance at 25^{O}C of a thermistor chip made from *BetaTHERM's* Curve 3 Material. The resistivity of the material is 3300 ohm-cm (at 25^{O}C) and the chip dimensions are 0.04" x 0.04" x 0.01" thick.

$$\mathbf{R} = \frac{3300(\text{ohm-cm}) \times 0.01(\text{inches}) \times 2.54\ (\text{cm/inch})}{(0.04\ (\text{inches}) \times 2.54\ (\text{cm/inch}) \times 0.04\ (\text{inches}) \times 2.54\ (\text{cm/inch}))}$$

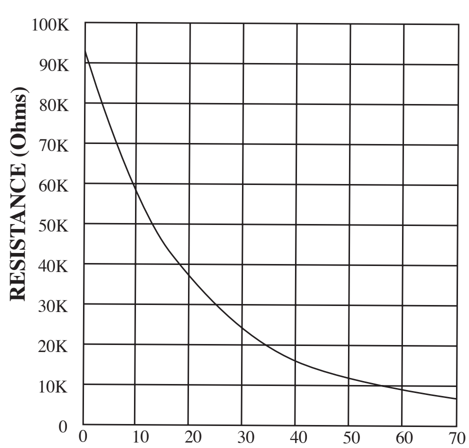
$$\mathbf{R} = \frac{33}{0.004064} = \mathbf{8120\ ohms}$$

The required resistance and resistivity for a given material dictate the realistic size of the finished product. For instance, a thermistor made from *BetaTHERM's* material curve # 3 can have a practical resistance range, at 25^{O}C, from 2000 ohms to 100000 ohms. Values outside this resistance range are not practical to produce because of the calculated size of the thermistor element.

The 2000 ohm thermistor has a calculated size of approximately (0.070" x 0.050" x 0.006" thick) and the 100000 ohm thermistor has a calculated size of approximately (0.014" x 0.014" x 0.015" thick). The sizes are feasible to manufacture, but are at the limits where chip handling becomes difficult.

The discussion so far has effectively considered the resistance of thermistors at a **single temperature point.** The next stage in understanding thermistor operation is to consider the electrical behaviour over an **extensive temperature range.**

The Resistance-Temperature Characteristics for a common thermistor (30K5) are displayed in ***Graph 1*** below over a range from **0^{O}C to 70^{O}C**.



Graph # 1

Slope: (Resistance Ratio)

*In considering the relationship between **resistance** and **temperature** of thermistors there are some important concepts that are used in the thermistor industry. One such concept is **slope**, which is an indication of the rate of change of the resistance of the component with temperature.*

The slope or resistance ratio for thermistors is defined as the ratio of resistance at one temperature (usually 0^{O}C) to the resistance at a second and higher temperature (usually 70^{O}C).

Specified slope (resistance ratio) information for *BetaTHERM* standard thermistor materials at temperatures 0/50^{O}C, 0/70^{O}C and 25/125^{O}C are listed on page 50.

The concept of resistance / slope is demonstrated in **Graph # 2,** (next page), where the 0/70^{O}C slope line connects the resistance value at 0^{O}C to the resistance value at 70^{O}C. This provides an indication of the rate of change of resistance with temperature and the potential thermal sensitivity of the component.

Slope measurements are used as a qualification step in the process of manufacturing "chip" thermistors. This is a monitoring step at an early stage of the process to ensure that that the thermistor material will meet required specifications.

The following example illustrates how the slope value of a thermistor can be calculated using the Resistance versus Temperature tables provided in the catalog.

Slope: (Resistance Ratio) Example of calculations:

For BetaTHERM's 30K5 thermistors (which have a nominal resistance of 30000 ohms at 25^{O}C) (Curve 5 Material) the nominal R_0/R_{70} ratio will equal 17.73

Per the R-T tables on pages 43 to 47 the nominal 30K5 resistance at 0^{O}C = 94980 ohms and the nominal resistance at 70^{O}C = 5358 ohms:

$$\frac{R_0}{R_{70}} = \frac{94980\ \text{ohms}}{5358\ \text{ohms}} = 17.7267 = 17.73$$

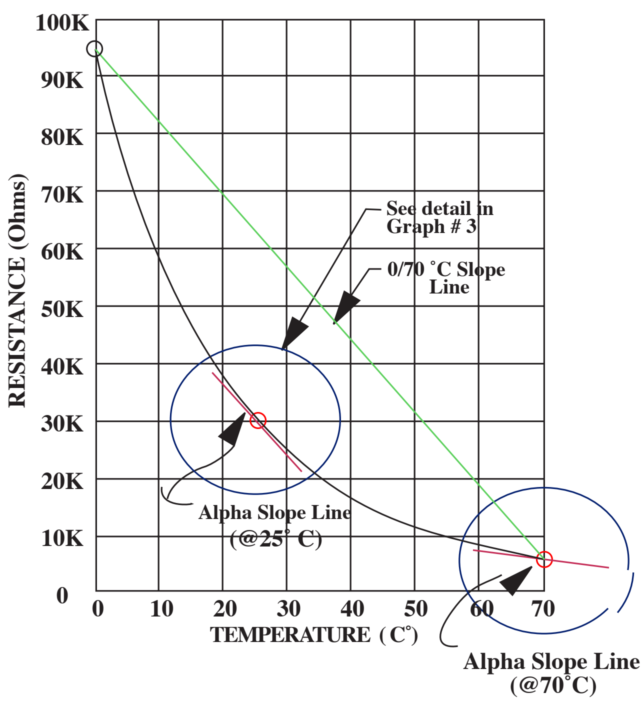
Slope or resistance ratio provides an introduction to the concept of rate of change of resistance with temperature and the sensitivity of the resistance of thermistors to temperature change. This concept is developed further by considering the more general case of thermal sensitivity in terms of percentage resistance change of a component per degree centigrade increase in temperature.

In the thermistor industry, this topic is dealt with by the definition of a material parameter known as **Alpha (α)**

Alpha (α) (Temperature coefficient): ***Alpha, a material characteristic, is defined as the percentage resistance change per degree Centigrade. Alpha is also referred to as the temperature coefficient.*** *For Negative Temperature Coefficient (NTC) Thermistors, typical values of alpha are in the range -3%/^{O}C to -6%/^{O}C. The temperature coefficient is a basic concept in thermistor calculations.*

Because the resistance of NTC thermistors is a nonlinear function of temperature, the alpha value of a particular thermistor material is also nonlinear across the relevant temperature range, as illustrated in **graph # 2** below.

Curve for 30K5 Thermistor
0^{O}C to 70^{O}C Range with Slope and Alpha details.



Graph # 2

For example, *BetaTHERM's* Standard Curve 5 thermistor material has an alpha of -4.30%/^{O}C at 25^{O}C, and an alpha of -3.42%/^{O}C at 70^{O}C. The alpha value is a material constant and is independent of the resistance of the component at that temperature.

Calculation of alpha values:

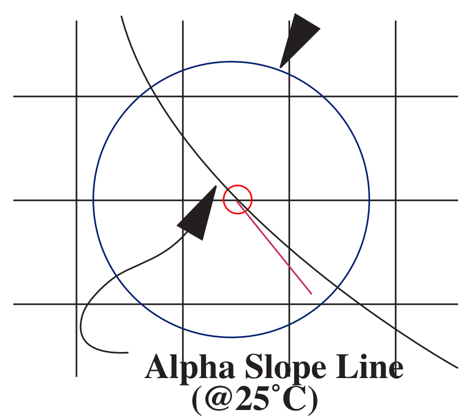
The relevance of alpha values to the Resistance vs Temperature curve of particular material is illustrated in **Graph # 3**. In this graph, a tangent line is drawn along the R-T curve at 25^{O}C. This line represents the gradient or "steepness" of the curve at 25^{O}C. From the definition of Alpha given above, it may be calculated as follows :

$$\alpha = \frac{1}{R_T} \times \frac{dR}{dT} \times 100 \ (\% / {}^{O}C).$$

(Equation # 3) ***Definition of Alpha:***

Where $\mathbf{R_T}$ is the resistance of the component at the relevant temperature **T** (^{O}C), **dR/dt** is the gradient of the Resistance vs Temperature curve at that temperature point, and **alpha** is expressed in units of "percentage change per degree Centigrade". (***Note:*** In some texts the "100" term is omitted from the equation, but it is understood or implied in the units in which alpha values are specified.)

Detail from Graph # 2 showing Alpha Slope Line of the 30K5 Thermistor @ 25^{O}C.



Graph # 3

The purpose of the concepts that have been introduced and discussed so far is to enable some basic calculations to be performed. The most important calculations required in the thermistor industry are those that relate the resistance of thermistor components to their temperature. An example illustrating typical use of alpha value to do this is given next:

Example:

A thermistor made from BetaTHERM material 3 has a resistance of 10000 ohms at 25^{O}C. The alpha value for this material at 25^{O}C is listed in the catalog to be –4.39 %/^{O}C. If *the resistance of the device in a stable environment at ideal measurement conditions (discussed later) is measured as 10200 ohms, what temperature is the device at ?*

By re-writing Equation 3 in the form:

$$\alpha = \frac{1}{RT} \times \frac{\Delta R}{\Delta T} \times 100$$

where $\Delta R/\Delta T$ *is used as an approximation for the true derivative* dR/dt *, the reference temperature is* $25^{o}C$*, on re-arranging, the equation becomes:*

$$\Delta T = \frac{\Delta R}{RT} \times \frac{100}{\alpha}$$

Inserting the numerical values given above, the value for ΔT*, the temperature difference from* $25^{o}C$*, is given by :*

$$\Delta T = \frac{200}{10000} \times \frac{100}{-4.39} = -0.456^{o}C$$

so that the temperature of the thermistor is:
$(25^{o}C - 0.456^{o}C) = \mathbf{24.554^{o}C}$

The example is applicable for certain thermistor resistance and temperature calculations. In particular, because of the approximation used for the differential of the R / T curve, it is **of relevance for small percentage changes in resistance around the temperature value for which the particular alpha value is quoted.**

The alpha value is a very useful parameter provided it is used in a logical way and that it is applied with the constraints in mind.

Limitations in the use of temperature coefficients:

The approach of using temperature coefficient values is adequate provided that accurate alpha values and resistance values are available for a range of temperature points for the thermistor materials. Tables of alpha values for various temperature points for various *BetaTHERM* NTC thermistor materials are given in this catalog. The use of such look-up tables and substitution in equation 3 are useful for initial selection of thermistors for applications. The method is somewhat slow and highlights the need for a **mathematical model** that can be used to relate the resistance and temperature of thermistors by a single equation. The need for such a model is especially relevant to allow computation of R/T values using modern calculators, computers or microcontrollers.

To discuss the issue further it is instructive to look at a typical NTC thermistor R/T curve, as shown in graph #1 on page 8. The curve is non-linear, and that presents certain difficulties in developing a useful model. Modelling of the R/T curve is discussed in the next section of the catalog.

Modelling of Conduction in Thermistors:

A plot of Resistance vs Temperature for a typical NTC Thermistor is shown in ***graph # 1***, on page 8. The relationship between Resistance and Temperature is non-linear so modelling this relationship physically and mathematically can be a complex procedure.

In considering **modelling** the Resistance versus Temperature characteristics of NTC thermistor devices it is useful to briefly review some of the principles of **solid state physics** associated with NTC thermistor materials. At this stage the reader may proceed directly to **page 13** where modelling equations are listed if an overview of the modelling process is not required.

Detailed descriptions of the electrical conduction mechanism for metal-oxide thermistor materials are beyond the scope of this catalog, but a brief overview is adequate to outline some concepts here.

The exact conduction mechanisms are not fully understood. The metal oxide NTC thermistors behave like **semiconductors**, as shown in the decrease in resistance as temperature increases.

The **physical models** of electrical conduction in the major NTC thermistor materials are generally based on one of two theories. Detailed treatment of these models can be found in reference books on ceramic materials. Brief summaries of these theories are outlined below.

A model of conduction called **"hopping"** is relevant for some materials, especially ferrites and manganites that have a spinel crystal structure. It is a form of Ionic conductivity where ions (oxygen ions) "hop" between point defect sites in a spinel crystal structure. The probability of point defects in the crystal lattice increases as temperature increases, hence the "hopping" is more likely to occur and so material resistivity decreases as temperature increases.

A second model of conduction is based **on the band gap model of solid state physics**. This model is of particular relevance in the semiconductor industry for materials like Silicon and Gallium-Arsenide. This model describes the availability of charge carriers in terms of the distribution of physical impurities in the crystal lattice. This model works very well for materials like Silicon which can be produced in monocrystalline structures with a high degree of purity. The silicon can then be "doped" with required impurities like Boron or Phosphorous to produce materials with characteristics that can be modelled mathematically, from basic theoretical principles, with accuracy.

For metal oxide thermistors the crystal structure is much more complex. The material structure is polycrystalline and granular. The materials are composed of several metal oxide components and are generally very difficult to model from basic principles.

The approach that is used for predicting the behaviour of thermistor materials, is to make accurate measurements of Resistance and Temperature of components and to apply curve fitting techniques to model the relationship between them. The physical models of conduction are used in conjunction with this approach to provide direction in developing the mathematical models.

Mathematical Modelling of Thermistors:

One of the core physical assumptions of the band gap theory of solid state physics is that charge carrier concentration has an exponential dependence on absolute temperature. The charge carriers can be either negatively charged (n-type) electrons, or positively charged (p-type) holes. The p-type conduction mechanism is the trapping of electrons by fixed positively charged sites. The electrons move between these sites so that the **net effect** is that of mobile positively charged carriers moving in an electric field, in the opposite direction to negatively charged electrons.

It can be demonstrated theoretically from the chemical composition of the components and experimentally from Hall effect measurements that the metal oxide thermistor materials are p-type semiconductors. More details on the determination of carrier types can be found in reference text books on ceramic materials.

The expression for the density of carriers available in "ideal" semiconductor material can be derived directly from application of **Quantum Mechanics** to Solid State theory. This involves applying the **Fermi-Dirac** distribution to the calculation of energy states for charge carriers in the material. The process leads to an equation that describes the intrinsic carrier density in terms of some material constants and physical constants. The results derived in this way are expressed in an equation of the form:

$$n_i \propto \exp(-{}^1/(2kT))$$

Where : n_i is the intrinsic carrier density in appropriate units
T is the absolute temperature in Kelvin.
k is Boltzmann's constant (1.38066 x 10-23) J/K

Further analysis of "ideal" semiconductor materials using principles of solid state physics relates the electrical resistivity of the material to the carrier density. The resulting expression is in the form of :

$$\rho \propto {}^1/n_i \quad \Rightarrow \quad \rho \propto \exp({}^1/(2kT))$$

Where ρ is the material resistivity, in appropriate units, such as ohm-cm.

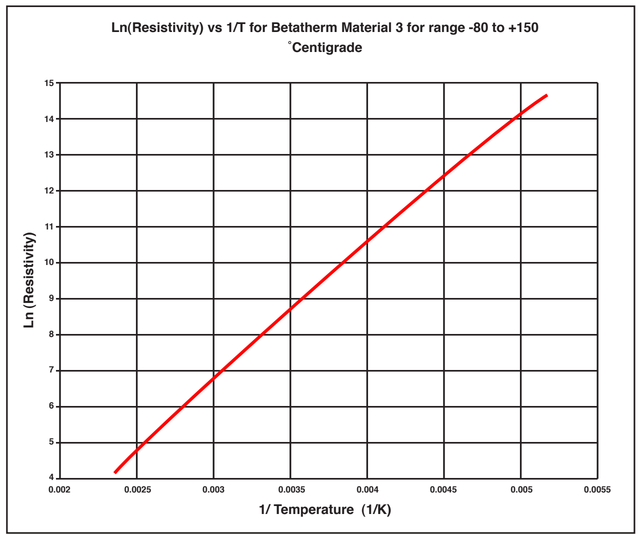
The equation can be reduced to a simpler format by writing it as:

$$\rho \propto \exp({}^1/T)$$

This equation relates the resistivity of semiconductor material to the exponential of the reciprocal of absolute temperature, directly from fundamental principles of solid state physics.

As stated previously, an equation of this form is relevant for an "ideal" material with a regular crystal structure. Although the metal oxide thermistor materials are not "ideal", intuition based on the foregoing discussion would suggest that there should be an **exponential** aspect to the relationship between **material resistivity and the reciprocal of absolute temperature**.

Inspection of a graph of the natural log of measured Resistivity values versus the reciprocal of absolute temperature for thermistor materials, indicate that such a model is appropriate.



Graph # 4

The Resistance (R) of a piece of material of resistivity ρ (ohm-cm) is proportional to this resistivity value.

R = ρ x (t/A)

where: **R** is the resistance in ohms,
t is thickness of the material (length of current path),
A is the cross-sectional area.

It follows that the expression for resistance as a function of temperature can be stated as:

$$R_T \propto \exp(^1/T)$$

Where $\mathbf{R_T}$ denotes Resistance in ohms at temperature **T** Kelvin.

Exponential Model of NTC Thermistors: 0/50 Beta Value (β) or Sensitivity Index:

As outlined in the previous section, a simple approximation for the relationship between Resistance and Temperature for an NTC thermistor assumes an exponential relationship between them. This approximation is based on simple curve fitting to experimental data and also on an intuitive feel for electrical behaviour of semiconductor devices.

The exponential approximation is a mathematical model that applies an equation that can be expressed in the form:

$$R_T = A \exp(^\beta/T) \quad \text{...........} \quad \text{(equation \# 4)}$$

Where:

R_T is the Resistance in ohms at temperature T
T is the absolute Temperature in Kelvin
A is a linear factor
"exp" is the exponential function
β is the exponential factor known as "beta" value or sensitivity index of the thermistor material.

The β value is a very important parameter in the description and specification of thermistor materials and thermistor components. When the natural log of both sides of the equation is taken, the relationship becomes:

$$\ln(R_T) = C + (^\beta/T) \quad \text{.................} \quad \text{(equation \# 5)}$$

Where **C** is a constant factor, (C = ln(A)) from the equation above.

If $\ln(R_T)$ is plotted versus 1/T, (as in graph #4) then the **slope** of the resulting curve will be equal to **beta, β.**

This equation provides a reasonable approximation to measured data, but as mentioned in the previous section, the thermistor materials are not ideal materials. For the exponential model to apply over a large temperature range (greater than 50 ^{O}C) the beta value has to vary, therefore the beta value is not constant over extensive ranges. In fact, **the beta value is also temperature dependent and it decreases with temperature.**

Although this simple exponential model for the relationship between Resistance and Temperature of a thermistor is limited over large temperature spans, concepts derived from it are of importance in the thermistor industry and in the specification of NTC thermistors. Some of these concepts are developed in the following sections with the intention of explaining some of the basic calculations and specifications used in the industry.

Practical application of the beta value:

It is common practice to specify thermistor materials in terms of beta value over a particular temperature span.

For a temperature T_1 and thermistor resistance R1 at this temperature T_1: $\mathbf{R_1 = A \exp (\beta / T_1)}$.

For a temperature T_2 and thermistor resistance R_2 at this temperature T_2 : $\mathbf{R2 = A \exp ((\beta / T2)}$

Taking the ratio: $\mathbf{R_1 / R_2 = \exp(\beta (1/ T_1 - 1/ T_2))}$

The expression for β then becomes:

$$\beta = \frac{1}{^1/T_1 - {}^1/T_2} \times \ln(R_1 / R_2) \quad \text{.. .....} \quad \text{(equation \# 6)}$$

Where:
β has units of temperature (Kelvin)
"ln" represents the natural logarithm (log base e) inverse of the exponential function.

In this form, published beta values can be used to calculate resistance or temperature values when other items in the equation are known.

The beta value can then be regarded a quantitative value of thermistor materials that is assigned as a material constant and that indicates the relationship of material resistivity to temperature.

Application of the beta value is demonstrated in a numerical example at the end of this section.

The general information on sensitivity of material resistivity to temperature that can be interpreted from the beta value is indicated in ***Graph # 5***. This shows the resistivities of *BetaTHERM's* Standard Thermistor Materials versus their 0/50 ^{O}C Beta Values.

The beta value is derived from a mathematical approximation. For this mathematical approximation to apply over a large temperature range, beta has to vary with temperature. This variation of beta value with temperature is indicated in **Graph # 6.** The variation is greater at the low temperature end of the curve. This variation should be borne in mind when using beta values for calculations over temperature ranges.

Because the beta value is an indication of the relationship between the resistivity of thermistor material and temperature, it can also be used to calculate alpha (α) value (temperature coefficient) for a thermistor made from the same material. *Recalling the definition of the alpha value as the percentage change in resistance per ^{O}C, given by* **equation # 3**

$$\alpha = \frac{1}{R_T} \times \frac{dR_T}{dT} \times 100 \ \ (\text{\% per } ^{O}C).$$

and, expressing R as a function of T using the exponential model, it can be shown that a good approximation for the temperature coefficient or alpha value, at a temperature T Kelvin, in terms of beta is :

$$\alpha = \frac{-\beta}{T^2} \times 100 \quad (\text{\% per } ^{O}C). \quad \text{....... (equation \# 7)}$$

The beta value is a single expression that can be regarded as a **material** constant. It depends on basic material properties, and beta values derived from measurements provide an indication of general thermistor material quality.

Although deviations in beta value from nominal values affect the tolerance of thermistors and are indicative of material quality, such deviations are not widely published by thermistor manufacturers. Typically, manufacturers will list the nominal Beta Value only or will list the nominal Beta Value with a tolerance expressed in K.

BetaTHERM provide information on beta value deviations for the range of thermistor materials that it produces. This information is contained in **Table # 2**. This lists the beta values and deviations for high precision BetaCURVE thermistors and includes data for low precision tolerance BetaCHIP thermistors also.

Graphs of Material resistivity versus Beta value, and Beta Value versus temperature are included also to illustrate how Beta is regarded as a material characteristic that is related to resistivity. The relationship between Beta value and temperature shows the temperature regions for which Beta value is approximately constant for different materials.

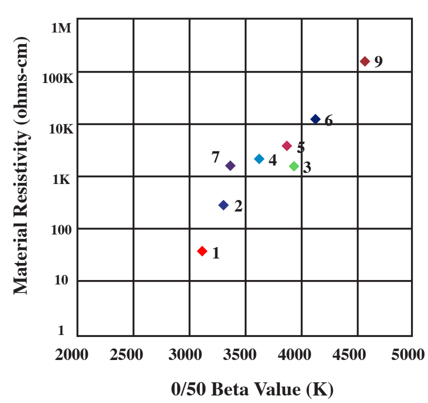
Sample calculations are included in this section also to illustrate some typical engineering uses of beta values.

Beta Values and tolerances for BetaCURVE and BetaCHIP series Thermistors.

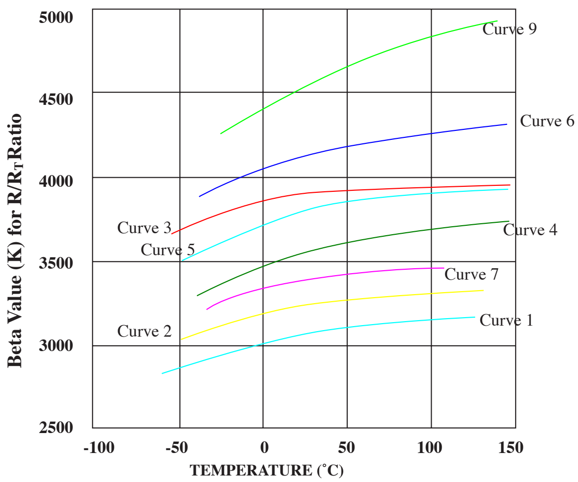
Material Curve #	0/50 Beta Value (K) BetaCURVE	BetaCHIP
1	3108 +/-0.40%	3108 +/-1.7%
2	3263 +/-0.38%	3263 +/-0.9%
3	3892 +/-0.32%	3892 +/-1.0%
4	3575 +/-0.30%	3575 +/-1.0%
5	3811 +/-0.33%	3811 +/-0.9%
6	4143 +/-0.30%	4143 +/-1.3%
7	3422 +/-0.36%	3422 +/-1.0%
9	4582 +/-0.63%	4582 +/-1.9%

Table # 2

Material Resistivity vs. Beta Value for BetaTHERM Thermistor Materials (Curves)



Graph # 5



Beta Values vs. temperature for Betatherm Materials

Graph # 6

Examples of calculations using Beta values:

(The 0/50 Beta value means a Beta value calculated from resistance data at 0^{O}C and at 50^{O}C)

Example: Calculate the 0/50 Beta value for BetaTHERM's 30K5A1 thermistor, given the following information:

R_1 is resistance value measured at T_1, 0^{O}C = 94980 ohms
R_2 is resistance value measured at T_2, 50^{O}C= 10969 ohms

The relevant formula for calculating the beta value is:

$$\beta = \frac{1}{1/T_1 - 1/T_2} \times \ln(R_1 / R_2)$$

Where:
β has units of temperature (Kelvin)
ln represents the natural logarithm (log base e) inverse of the exponential function.
Temperatures are expressed in Kelvin.

This can then be written as:

$$\beta_{0\text{-}50} = \frac{1}{1/273.15 - 1/323.15} \times \ln(94980 / 10969)$$

$= 1765.36847706 \times 2.1587611778$
$\Rightarrow \beta_{0\text{-}50} = \mathbf{3811\ K}$

Since the Beta value of a thermistor material is derived from an exponential model, it can also be used to calculate resistance values of a thermistor at a particular temperature when the resistance at another temperature is known. This is demonstrated in the following example:

Example: Calculate the resistance of a BetaTHERM 10K3 thermistor at 33^{O}C using the following information:

The resistance of the thermistor at 25 ^{O}C is 10000 ohms, the 0-50 Beta value is 3892 K

Using the equation:

$$\mathbf{R_1 / R_2 = \exp(\beta\ (1/ T_1 - 1/ T_2))}$$

and writing it in the form:

$$\mathbf{R_2 = R_1 / (\exp(\beta\ (1/ T_1 - 1/ T_2)))}$$

where **T_1 = 25^{O}C = 298.15 K, R_1 = 10000 ohms.**
T_2 = 33^{O}C = 306.15 K, β= 3892 K

Using these values, the value of R2 is calculated as:

R_2 = 10000 / (exp(0.3411094421367))

Resistance at 33^{O}C calculated using Beta value:
R_2 = 7109.81ohms.

The value of resistance of a 10K3 device that is published in the R / T tables in this catalog is **7097.2** ohms. The sensitivity of the resistance of the device to temperature in this region is 304 ohms per ^{O}C. The difference between the published resistance value and the resistance value that is calculated using the beta value is equivalent to **.04 ^{O}C** .

Using the Beta 0-50 value in the range 0-50 ^{O}C, the maximum errors are at the ends of the range, and are of the order of **0.22 ^{O}C**.

When the **tolerance of the Beta value** is taken into account, then the errors at the ends of the range for **material 3 BetaCHIP** products are of the order of **0.45 ^{O}C**, while the errors at the ends of the range for **material 3 BetaCURVE** products are of the order of **0.29 ^{O}C**.

The main purposes of these examples were :

- To show some typical uses of Beta values in calculations.
- To demonstrate the difference between BetaCHIP and *BetaCURVE* product. In particular to show that the tighter tolerance *BetaCURVE* product has lower errors than the *BetaCHIP* product in converting from Resistance to temperature using the exponential model.
- To establish the relevance of Beta as a material characteristic.
- To show some of the limitations of the exponential model so that **further modelling** of the R / T characteristics of thermistors can be considered.

Further Modelling of NTC Thermistor R/T Characteristics:

The concepts introduced so far to relate the resistance of a thermistor to the temperature have been primarily based on the characterization and specification of **materials** and on the use of material parameters rather than on **component** parameters.

While the **temperature coefficient or alpha value** can be used to calculate the temperatures corresponding to various resistance values of a thermistor, the method is rather limited. A look-up table of Resistance versus Temperature values for the thermistor is required and details of alpha values at various points are needed also. It is very useful and relevant in certain situations.

The use of **Beta Values or sensitivity index**, and the associated exponential model are useful for material specification, and for the comparison of the sensitivity of bulk materials. The method is somewhat limited for general use in relating the resistance of a thermistor to temperature over extensive ranges mainly because of the temperature dependence of the Beta Value itself.

In general applications NTC thermistors are used to measure temperature, and this is accomplished by measuring the resistance of the thermistor and then using that resistance value to make an estimate of temperature. The various means of relating resistance of a thermistor to the temperature that have been discussed so far are not ideally suited to this, as outlined above. **The requirement is for a single equation that can be used easily to relate resistance and temperature of thermistors**. The requirement is all the more important to optimize the use of programmable calculators, computer spreadsheets and microcontrollers.

Because the conduction mechanism in metal oxide semiconductors is a complex one, it is difficult to explain accurately by applying mathematics to a physical model. **The method used for accurate mathematical modelling of the Resistance versus Temperature characteristic of a thermistor is to obtain accurate measurements of Resistance and Temperature of components and to apply curve fitting techniques to model the relationship between them.**

The next section of this catalog describes the mathematical model, which is in general use throughout the industry, to give a single equation that relates the Resistance and Temperature of an NTC thermistor component. The equation is called the **Steinhart-Hart Equation**, and it is used by all thermistor manufacturers .

The Steinhart-Hart Thermistor Equation:

The Steinhart-Hart thermistor equation is named for two oceanographers associated with Woods Hole Oceanographic Institute on Cape Cod, Massachusetts.

The first publication of the equation was by **I.S. Steinhart & S.R. Hart in "Deep Sea Research" vol. 15 p. 497 (1968).**

The equation is derived from mathematical curve-fitting techniques and examination of the Resistance versus Temperature characteristic of thermistor devices.

In particular, using the plot of the natural log of resistance value, **ln(R)** versus **(1/T)** for a thermistor component to consider **(1/T)** to be a polynomial in **ln(R)**, an equation of the following form is developed:

$$\frac{1}{T} = A_0 + A_1(\ln(R) + \text{.........} + A_N(\ln(R))^N$$

(where T is the temperature in Kelvin, and A_0 ....A_N are polynomial coefficients that are mathematical constants.)

The order of the polynomial to be used to model the relationship between R and T depends on the accuracy of the model that is required and on the non-linearity of the relationship for a particular thermistor.

It is generally accepted that use of a third order polynomial gives a very good correlation with measured data, and that the "squared" term is not significant.

The equation then is reduced to a simpler form, and it is generally written as:

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

Equation # 8

where: A, B, and C are constant factors for the thermistor that is being modelled.

This is the Steinhart-Hart equation, with Temperature as the main variable.

The equation is presented explicitly in resistance on page 19, which is a summary page of information on the Steinhart-Hart equation. Before summarizing the situation, some general points of relevance in understanding the practical issues associated with it are discussed:

The equation is relevant for the complete useful temperature range of a thermistor.

The coefficients A, B, and C are constants for the **individual** thermistors. Unlike Alpha and Beta they should **not be regarded as material constants**.

The A, B, and C constants are established for individual thermistors in a particular temperature range as follows:

The equation is considered for three temperature points in the range – usually at the low end, the middle and the high end of the range. This ensures best fit along the full range. (The smaller the temperature range, the better the calculations will match measured data.) The temperature values are usually taken to be 0^{O}C, 25 ^{O}C and 70 ^{O}C therefore these values are used to illustrate the principle.

Precisely controlled measurements of temperature and associated resistance value of the thermistor are made in a temperature controlled medium at these three calibration points.

These accurately measured values of Resistance and Temperature are inserted into the equation to form three simultaneous equations as follows: **(note: 0^{O}C = 273.15K)**

$$\frac{1}{T_0} = \frac{1}{273.15} = A + B(\ln(R_0)) + C(\ln(R_0))^3$$

$$\frac{1}{T_{25}} = \frac{1}{298.15} = A + B(\ln(R_{25})) + C(\ln(R_{25}))^3$$

$$\frac{1}{T_{70}} = \frac{1}{343.15} = A + B(\ln(R_{70})) + C(\ln(R_{70}))^3$$

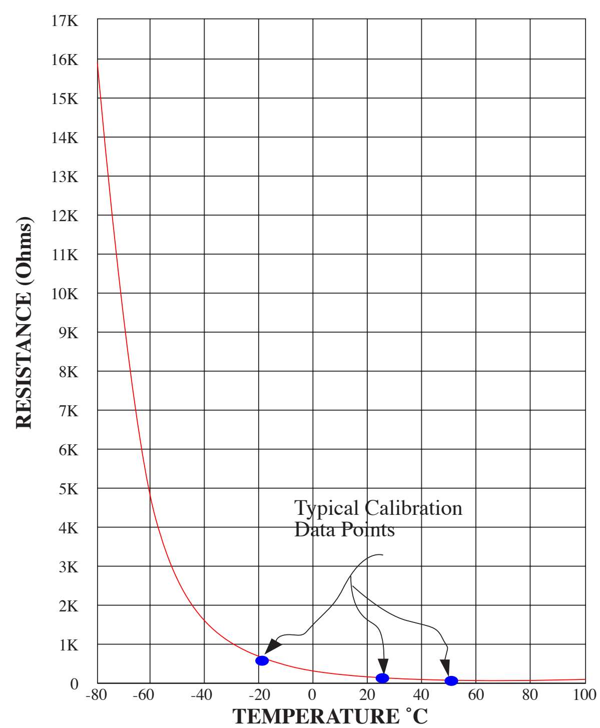
Since the resistance values are measured numerical quantities, the equations are a system of three simultaneous equations in three unknowns namely A, B and C. The values for A, B and C can be found by standard mathematical techniques for solving simultaneous equations, or by use of analytical software tools.

This is a brief summary of the origins and techniques used to derive the A, B and C coefficients for thermistor components. These values are sometimes referred to as the "Steinhart Coefficients" for a thermistor. Thermistor manufacturers publish data for these coefficients for their thermistor products. Values of the Steinhart Coefficients for *BetaTHERM* products are listed on page 19 of this catalog.

Software is available at *BetaTHERM* to calculate the Steinhart coefficients for thermistors measured at calibration points other than the standard ones used in the example. This is useful when modelling thermistors over limited ranges or when using customized thermistor components.

It should be noted that the Steinhart-Hart equation produces a good approximation to the relationship between T and R for the complete range of a thermistor based on data from just three calibration points.

R-T Graph for BetaTHERM part # 0.1K1A Thermistors. Full Temperature range from -80 ^{O}C to +100 ^{O}C Maximum.



Graph # 7

Because the Steinhart-Hart equation is a mathematical approximation, it is instructive to do some calculations using the equation for a thermistor and to compare the resulting temperature or resistance values with the published R / T data in the catalog. The published R /T tables are based on actual measurements, but the difference between values calculated from the Steinhart-Hart equation and the published data should typically be less than +/- 0.01 ^{O}C.

This is illustrated for a 10K3 device over a limited range in the table on this page. The table was generated by using the published Resistance versus Temperature data for this device, and inserting the Resistance values into the Steinhart-Hart equation to calculate the Temperature. This calculated Temperature can then be compared with the reference Temperatures at which the resistance was measured.

Relevant information for the practical use of the Steinhart-Hart equation to model thermistors is given on page 19. This includes a statement of the equation explicitly in resistance form and a listing of the Steinhart coefficients for a range of *BetaTHERM* components.

It should be noted that Steinhart-Hart coefficients that are in the summary table on page 19 were not all derived from measurements at 0 ^{O}C, 25 ^{O}C and 70 ^{O}C. For devices with higher resistance values (for example 1M9A1), which are generally used at higher temperatures, the Steinhart-Hart coefficients were derived from measurements at 25 ^{O}C, 100 ^{O}C and 150 ^{O}C. These temperature values are more representative of the temperature range where these thermistors are used. The values of the calibration temperatures are included in the table.

The Steinhart-Hart equation is a very useful means of modelling the Resistance versus Temperature characteristics of a Thermistor but it should be remembered that it provides good correlation with actual measurements for a thermistor in ideal measurement conditions. This concept of "ideal" measurement conditions and factors that affect the measured value of resistance of a thermistor is explained in the sections of the catalog that follow the summary page relating to the Steinhart-Hart equation.

Comparison of actual (measured) data and calculated temperature values using measured resistances in Steinhart-Hart equation for BetaTHERM 10K3 device:

Measured Resistance (Ohms)	Actual Temperature (^{O}C)	Temperature Calculated (^{O}C)
49633.00	-8	-7.999
47047.00	-7	-6.999
44610.00	-6	-5.999
42314.60	-5	-5.000
40149.50	-4	-4.000
38108.50	-3	-3.000
36182.80	-2	-2.000
34366.10	-1	-1.000
32650.80	0	-0.001
31030.40	1	1.000
29500.10	2	2.000
28054.20	3	3.000
26687.60	4	3.999
25395.50	5	4.999
24172.70	6	5.999
23016.00	7	7.000
21921.70	8	7.999
20885.20	9	8.999
19903.50	10	9.999
18973.60	11	10.999
18092.60	12	11.999
17257.40	13	12.999
16465.10	14	13.999
15714.00	15	14.999
15001.20	16	15.999
14324.60	17	17.000
13682.60	18	17.999
13052.80	19	19.033
12493.70	20	19.999
11943.30	21	20.999
11420.00	22	22.000
10922.70	23	23.000
10449.90	24	24.000
10000.00	25	25.000

Summary of Steinhart-Hart equation for modelling Resistance vs. Temperature characteristics of thermistors:

(In the listings below A, B, and C are constant factors for the thermistor, R is resistance in ohms, T is temperature in Kelvin.)

Steinhart-Hart Equation with temperature as main variable:

$$\frac{1}{T} = A + B(\ln(R)) + C(\ln(R))^3 \qquad \text{...............} \qquad \textbf{Equation \# 8 (repeated)}$$

Steinhart-Hart Equation in terms of Resistance, suitable for programmable computation.

$$R = \exp\left[\sqrt[3]{-\left[\frac{\frac{(A-T^{-1})}{C}}{2}\right]+\sqrt[2]{\left[\frac{\left[\frac{(A-T^{-1})}{C}\right]^2}{4}+\frac{\left(\frac{B}{C}\right)^3}{27}\right]}}+\sqrt[3]{-\left[\frac{\frac{(A-T^{-1})}{C}}{2}\right]-\sqrt[2]{\left[\frac{\left[\frac{(A-T^{-1})}{C}\right]^2}{4}+\frac{\left(\frac{B}{C}\right)^3}{27}\right]}}\right]$$

Equation # 9

BetaTHERM Steinhart Coefficients , A, B and C constants for Standard Part Numbers.

Part No.	"A" Constant	"B" Constant	"C" Constant	Temperature reference points °C
0.1K1A	1.942952×10^{-3}	2.989769×10^{-4}	3.504383×10^{-7}	-20°C, 25 °C and 50 °C
0.3K1A	1.627660×10^{-3}	2.933316×10^{-4}	2.870016×10^{-7}	-20°C, 25 °C and 50 °C
1K2A	1.373168×10^{-3}	2.772261×10^{-4}	1.997412×10^{-7}	-20°C, 25 °C and 50 °C
1K7A	1.446059×10^{-3}	2.683626×10^{-4}	1.643561×10^{-7}	-20°C, 25 °C and 50 °C
2K3A	1.498872×10^{-3}	2.379047×10^{-4}	1.066953×10^{-7}	0°C, 25 °C and 70 °C
2.2K3A	1.471388×10^{-3}	2.376138×10^{-4}	1.051058×10^{-7}	0°C, 25 °C and 70 °C
3K3A	1.405027×10^{-3}	2.369386×10^{-4}	1.012660×10^{-7}	0°C, 25 °C and 70 °C
5K3A	1.287450×10^{-3}	2.357394×10^{-4}	9.505200×10^{-8}	0°C, 25 °C and 70 °C
10K3A	1.129241×10^{-3}	2.341077×10^{-4}	8.775468×10^{-8}	0°C, 25 °C and 70 °C
10K4A	1.028444×10^{-3}	2.392435×10^{-4}	1.562216×10^{-7}	0°C, 25 °C and 70 °C
30K5A	9.331754×10^{-4}	2.213978×10^{-4}	1.263817×10^{-7}	0°C, 25 °C and 70 °C
30K6A	1.068981×10^{-4}	2.120700×10^{-4}	9.019537×10^{-8}	0°C, 25 °C and 70 oC
50K6A	9.657154×10^{-4}	2.106840×10^{-4}	8.585481×10^{-8}	0°C, 25 °C and 70 °C
100K6A	8.271111×10^{-4}	2.088020×10^{-4}	8.059200×10^{-8}	0°C, 25 °C and 70 °C
1M9A	7.402387×10^{-4}	1.760865×10^{-4}	6.865999×10^{-8}	25°C, 100°C and 150°C

Table # 3

Factors affecting measured resistance values of Thermistors:

In the notes relating to the use of published data tables for resistance versus temperature of Thermistors and to the use of the Steinhart-Hart equation, reference was made to "ideal" measurement conditions for determining the resistance of a thermistor. The following section discusses factors that affect the measured resistance value of a thermistor. These factors are associated with thermistor properties or characteristics that are the basis of general thermistor applications.

It is essential that developers of thermistor circuits have an understanding of these characteristics to exploit relevant thermistor properties in a particular application and to minimize the influence of other properties that could adversely affect thermistor performance in the application.

Self Heating effect of Thermistors:

To fully avail of the information in the published tables of Resistance versus temperature for thermistors and to optimize the accuracy of the Steinhart-Hart Equation it is essential to consider the **electrical power levels** in the thermistor during measurements. When the resistance of a thermistor is being measured there is a voltage across it and a current passing through it (from Ohm's Law).

Ohms Law states that for a resistive component: **V = IxR**
where, **V** is the voltage across the component in Volts,
I is the current through the component in Amps
R is the resistance of the component in Ohms.
The power in the component is defined as the product of the current and voltage: **P = I x V**
where **P** is the **power** in **Watts**, I is in Amps,V is in Volts.

This power is dissipated in the component, and for a thermistor the power causes heating of the thermistor. The heating effect in turn causes the resistance of the thermistor to decrease. **This power dissipation is known as <u>self-heating</u> of the thermistor.**

If the power levels are moderate (of the order of several milli-Watts (mW), the self-heating will not continue indefinitely, because the thermistor will reach thermal equilibrium with it's environment. The stage at which this equilibrium is reached depends on the thermal characteristics of the system.

It should be noted that when this "steady" state is reached, the resistance of the thermistor will not accurately represent the temperature of it's environment. Instead, the resistance of the thermistor will be lower than expected, because of the self heating effect. To obtain a resistance reading from the thermistor that accurately represents the temperature of it's environment it is critical that the power levels (essentially the current levels) associated with the measurement are low enough not to cause appreciable self heating.

The self heating effect should be considered in all thermistor applications and even in basic resistance measurements using a digital ohm-meter (multi-meter). Most manufactures of measuring instruments specify the magnitude of current used on the various resistance measuring ranges and it is important to be aware of these values in performing resistance measurements on thermistors.

The self-heating effect is a disadvantage in attempting to make accurate resistance measurements, but it is the basis of other applications. These applications are discussed in a later section of the catalog.

Because the self-heating effect can influence the measured resistance value of a thermistor it is important to quantify it in some manner. This is done by using the concept of **"Zero-power resistance characteristic."**

Zero-power resistance characteristic

The "zero-power resistance characteristic" is a description of "ideal" conditions for resistance measurement - it can be defined as follows:

<u>The Zero-Power Resistance</u> (Ro) at a specific temperature T, is the measured DC (Direct Current) resistance when the power dissipation is negligible.

Mil-T-23648 considers the power to be negligible when "any further decrease in power will result in not more than a 0.1% change in resistance".

In practical terms, a thermistor is generally considered to be dissipating Zero-power when the current through it is less than **100 micro-Amps (μA).** On modern multimeters resistance measurements in the kilo-Ohm range can be performed with adequate resolution (+/- 0.1 Ohm) with measuring currents of the order of tens of micro-amps. There is generally a compromise in measuring instruments or measurement circuits between resolution and magnitude of measuring current, but for thermistor measurements the self-heating effect must be considered also.

Zero-power sensing refers to applications that use thermistors in such a way that the resistance of the thermistor will reflect the temperature of the medium. Zero-power sensing can be based on the published R/T data for a thermistor, or on the use of the Steinhart-Hart equation to relate Resistance to Temperature.

The measured resistance value of a thermistor in a medium is affected by the **thermal characteristics** of the **system** which is comprised of the thermistor coupled with the medium being measured. This topic is discussed next:

Thermal Time Constant (T.C.):

When a thermistor is being used to monitor the temperature of it's environment then the accuracy of measurement of the resistance of the thermistor is critical.

While the power dissipated in the thermistor is an important factor in this measurement as discussed in the previous section, the thermal characteristics of the system and the thermistor are important also. This is especially relevant in systems where the temperature is changing with time. The **dynamic thermal response** of the thermistor must be considered in these situations. To quantify this dynamic response, the concept of a **Thermal Time Constant (T.C.)** is used in the thermistor industry and it is defined as follows:

The Thermal Time Constant for a thermistor is the time required for a thermistor to change its body temperature by 63.2% of a specific temperature span when the measurements are made under zero-power conditions in thermally stable environments.

This concept is illustrated in the example below:

Example: A thermistor is placed in an oil bath at 25^{o}C and allowed to reach equilibrium temperature. The thermistor is then rapidly moved to an oil bath at 75^{o}C.
The T.C. is the time required for the thermistor to reach 56.6^{o}C (63.2% of the temperature span).

The dominant factors that affect the T.C. of a thermistor are:

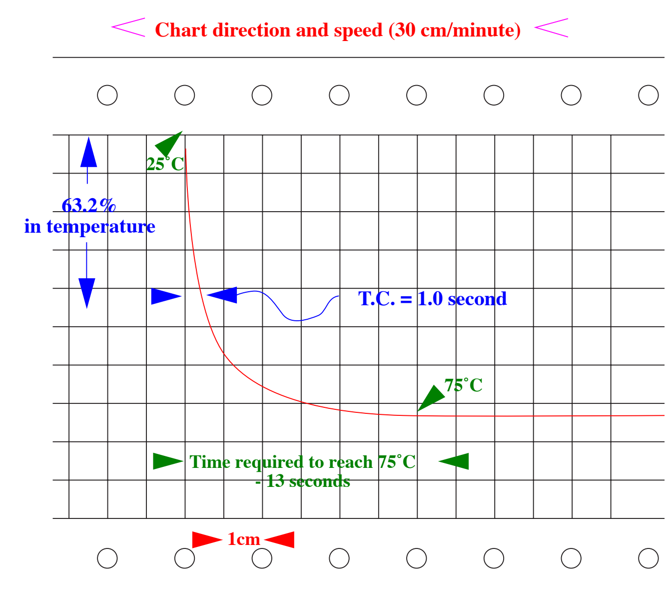
- The mass and the thermal mass of the thermistor itself.
- Custom assemblies and thermal coupling agents that couple the thermistor to the medium being monitored.
- Mounting configurations such as a probe assembly or surface mounting.
- Thermal conductivity of the materials used to assemble the thermistor in probe housings.
- The environment that the thermistor will be exposed to and the heat transfer characteristics of that environment. Typically, gases are less dense than liquids so that thermistors have greater time constants when monitoring temperature in a gaseous medium than in a liquid one.

The definition of Thermal Time Constant arises from the exponential nature of the rate of transfer of heat between the thermistor and the medium that it is monitoring. It is similar in principle to the definition of time constants in describing the responses of systems where physical effects have an exponential response with respect to time.

BetaTHERM offers a wide variety of thermistor devices with T.C.s ranging from 100 milli-seconds to 10 or even 20 seconds depending on test conditions.

Graph # 8 illustrates determination of T.C. for the thermistor of the previous example using a strip chart recorder. When the thermistor is transferred from a 25^{o}C oil bath to a 75^{o}C oil bath it's resistance will change and the voltage drop across it can be measured using the chart recorder. By measuring the graph and the speed of the chart recorder the T.C. for the device in a stable oil bath environment can be determined.

Time Constant recording of a thermistor element using a strip chart recorder.



Graph # 8

The value of resistance of a thermistor that is measured in a physical system depends on the power dissipated in the thermistor due to the measurement method and also on the thermal characteristics of a dynamic temperature system. It is important to consider both effects in implementing thermistor sensing systems.

It is useful to combine aspects of both effects in a single parameter and this can be achieved by definition of a **Thermal Dissipation Constant** as described in the next section:

Thermal Dissipation Constant (D.C.):

Because the measured resistance of a thermistor at a particular time depends on the power dissipated in the thermistor during measurement and on the thermal dynamics of the system being measured, it is useful to quantify the combined effect of these two factors. This leads to the concept of **Thermal Dissipation Constant (D.C.)**, which is defined as follows:

The Thermal Dissipation Constant of a thermistor is defined as the power required to raise the thermistor's body temperature by 1°C in a particular measurement medium. The D.C. is expressed in units of mW/°C (milliWatts per degree Centigrade).

BetaTHERM specify the D.C. for Epoxy Coated BetaCURVE and BetaCHIP Thermistor series (which are described later) as typically 0.5mW/°C to 1.0mW/°C in still air at 25°C, and 7mW/°C to 8mW/°C in a well stirred oil bath at 25°C.

The D.C. is a very important parameter in circuit design and application considerations. In practical applications the D.C. will be affected by:

- the mass or thermal mass of a thermistor.
- the mounting of the thermistor in a probe assembly.
- the thermal dynamics of the environment that the thermistor is to monitor.
- the "ranging" of measuring instruments that change current levels as measurement ranges change to track resistance changes of thermistors.

The D.C. is an important factor in applications that are based on the **self-heating effect** of thermistors. In particular, the resistance change of a thermistor due to change in D.C. can be used to monitor levels or flow rates of liquids or gasses. For example as flow rate increases, D.C. of a thermistor in a fluid path will increase and the resistance will change in a manner that can be correlated to flow rate.

The three factors, **zero-power resistance (Ro), time constant (T.C.), and dissipation constant (D.C.)** influence the measured value of the resistance of a thermistor which will affect temperature values that are calculated from the resistance measurements. An understanding of these factors is critical in developing thermistor applications and in measurement of thermistors.

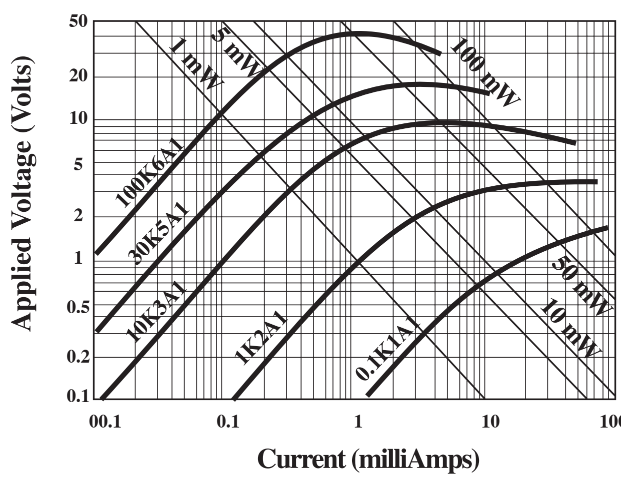
The importance of the three factors discussed previously can be understood more completely by studying the Voltage-Current characteristics of thermistors. This is discussed in the next section:

Voltage –Current Characteristics – (E.I. behaviour)

As stated previously, thermistors are devices that obey Ohm's law at temperature points within their useful range. Since Ohm's law relates Voltage and Current of a component, **(V = I x R)** it is useful to consider the voltage versus current characteristics of thermistor components.

Typical voltage-current characteristics for selected *BetaTHERM* thermistors are illustrated in ***Graph # 9***, below. The unique characteristic of thermistors where the body temperature increases as current passes through it can be seen by considering the power levels in the thermistor. This is the **"self-heat" mode**, and it is indicated by the inflection of the graph at higher power levels.

Voltage-Current Characteristics for Selected BetaTHERM Thermistors:



Graph # 9

For thermistors being used for temperature sensing, control or compensation, it is required that very low current levels be utilized. Typical values are less than 100 microamps. These are generally **"zero-power"** sensing applications.

Applications where thermistors are used in **self-heat mode** include Liquid Level Control, Air Flow Measurements, Voltage Control, Gas Chromatography and Time Delay. These applications are based on detecting changes in the Dissipation Constant (D.C.) of the system being measured.

The next section of the catalog discusses the specification of thermistors in terms of precision relative to nominal R/T characteristics, this relates to **tolerance of thermistors.**

Tolerance of Thermistors

Having considered some of the factors and conditions that affect the measured value of the resistance of a thermistor, it is important to consider inherent thermistor properties that affect the measured value of resistance of a thermistor at a particular temperature. In this respect, the concept of **tolerance** is essential in selecting and specifying thermistors for an application.

***Tolerance** for thermistors is the specified resistance percentage or temperature deviation from curve nominal values. Tolerance can be specified as a +/- percentage at a single temperature point or as a temperature value in degrees Centigrade over a particular temperature range.*

Standard low precision tolerance thermistors are typically specified as a percentage of resistance (+/-5% or +/-10%) at 25°C. **Standard high precision tolerance** thermistors are specified as a temperature tolerance of (+/-0.1°C or +/-0.2°C) over the temperature range 0°C to 70°C.

Because thermistors of Standard tolerances do not solve all application requirements, *BetaTHERM* will customize temperature tests at temperatures other than 25°C for single point measurements. *BetaTHERM* will also perform multiple temperature tests. For applications that require ranges other than the standard 0°C to 70°C range. Requirements for high precision tolerance thermistors specified as a percentage (+/-1%) at a single point at 25°C or at a temperature other than 25°C can be accommodated also.

It is most economical to use Standard thermistors when ever possible, but if requirements cannot be satisfied by standard thermistors then *BetaTHERM* Applications Engineering Group can assist in solving special temperature tolerance needs.

BetaCURVE and BetaCHIP product:

BetaTHERM use two designations in specifying tolerance of thermistor product. These designations are the ***BetaCURVE* series** and the ***BetaCHIP* series**.

***BetaCURVE* thermistors are standard "interchangeable" (high precision tolerance) devices with tolerance specified over a temperature range.**

To simplify ordering these thermistors BetaTHERM supply them in 4 temperature tolerance classifications, A, B, C and D.

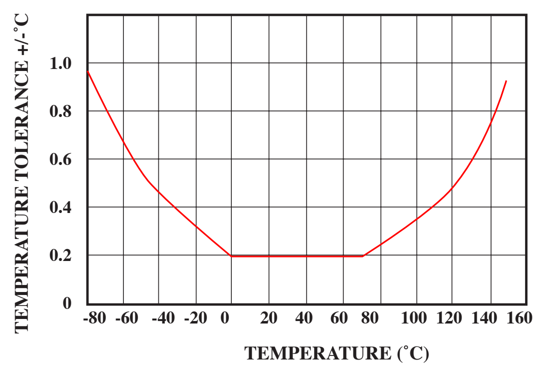
- Class A (+/-0.1°C from 0°C to 70°C);
- Class B (+/-0.2°C from 0°C to 70°C);
- Class C (+/-0.5°C from 0°C to 70°C);
- Class D (+/-1.0°C from 0°C to 70°C).

Graphs # 10 and # 11 represent the thermistor tolerance for BetaTHERM Curve # 3 *BetaCURVE* thermistors over the temperature range (-80°C to 150°C).

In the graphic display of the temperature tolerance *(ΔT)* ***Graph # 10***, it can be seen that the deviation or tolerance which is (+/-0.2°C, from 0°C to 70°C) for BetaCURVE material # 3 is wider outside the 0° C to 70°C range.

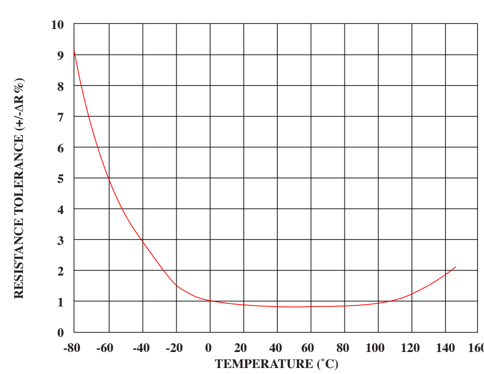
Graph # 11 also depicts *BetaCURVE* material # 3 with the deviation or tolerance expressed as a percentage *(ΔR %)* over the range -80°C to 150°C. The range and tolerance information for all of BetaTHERM's material curves is listed in the Temperature and Deviation Tolerance Tables on pages 48 and 49 of the catalog.

__Temperature Tolerance Curve__ (ΔT) for BetaTHERM Material Curve # 3 ***BetaCURVE*** *Thermistors.*
(Standard tolerance, +/-0.2°C from 0°C to 70°C)



Graph # 10

__Percent Tolerance Curve__ (ΔR %) for BetaTHERM Material Curve # 3 ***BetaCURVE*** *Thermistors.*
(Standard tolerance, +/-0.2°C from 0°C to 70°C)

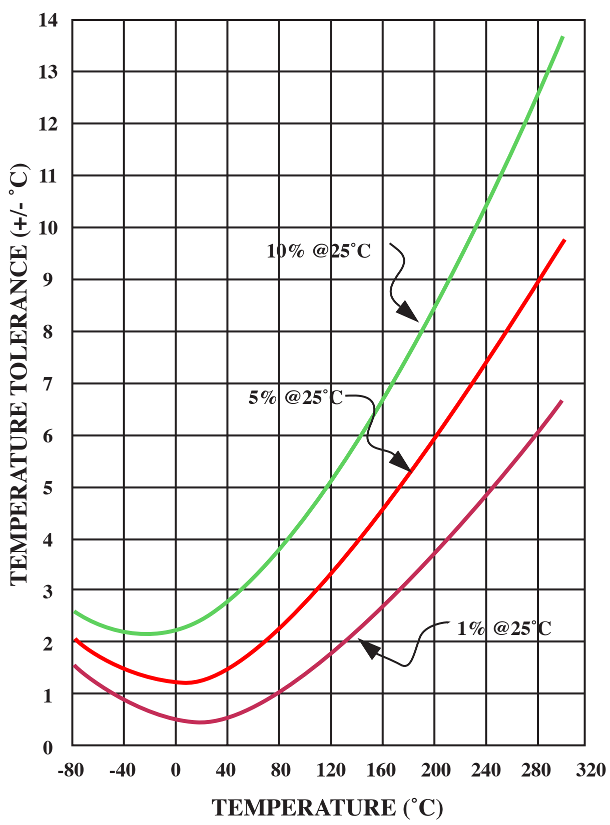


Graph # 11

BetaCHIP **thermistors are low precision tolerance thermistors with tolerance specified at a single point temperature and tolerance.** The "worst case" deviation or tolerance for temperatures -80^{O}C to +300^{O}C are depicted in **Graph # 12** for temperature deviation and in **Graph # 13** for percent deviation from curve nominal values for 1%, 5% and 10% @ 25^{O}C Material Curve # 3 thermistors. The scale of the Graphs extends to 300^{O}C to display the tolerance for high temperature (glass coated *BetaCHIP* and DO-35 packaged *BetaCHIP*) thermistors.

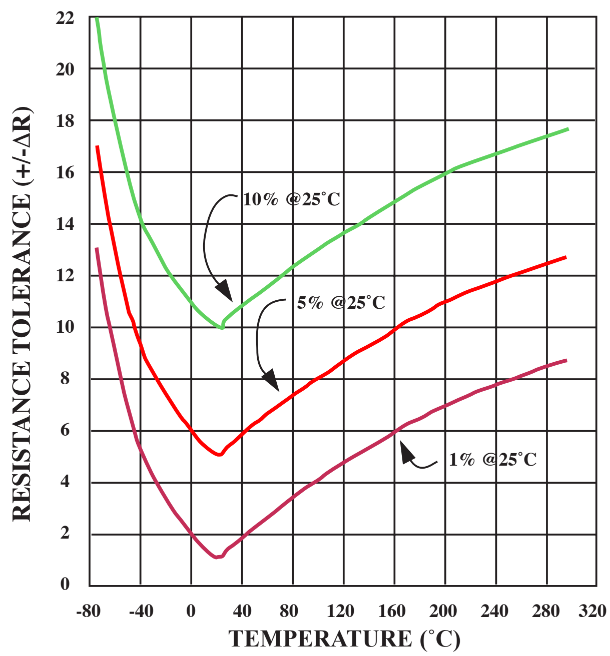
The values displayed in the graphs are also listed in the Temperature and Deviation Tolerance Tables on pages 48 and 49.

Temperature Tolerance Curve *(ΔT) for BetaTHERM Material Curve # 3* ***BetaCHIP*** *(Standard 1%, 5% and 10% tolerance @ 25^{O}C) Thermistors.*



Graph # 12

Percent Tolerance Curve *(ΔR %) for BetaTHERM Material Curve # 3* ***BetaCHIP*** *(Standard 1%, 5% and 10% tolerance @ 25^{O}C) thermistors.*



Graph # 13

Curve Matching Accuracy and Interchangeability:

The issue of tolerance of components becomes important where the interchangeability of components is being considered. One of the original motivations for having interchangeable devices was to be able to replace failed devices easily. With improvements in manufacturing techniques, thermistor products are now much more reliable, so replacement is not such a major issue.

While replacement of devices is still an important consideration, the issue of interchangeability is presently more likely to be concerned with using similar devices in individual units of large volume products where thermistors are interfaced to a control system. It is important in such cases that systems in individual product items will all behave in a similar manner.

BetaTHERM's BetaCURVE devices are available in volume quantities with curve matching accuracy of +/- 0.2 ^{O}C over a temperature range from 0 ^{O}C to + 70 ^{O}C, which makes them suitable for use in high volume production products.

Stability and Reliability of Thermistors:

The issue of Long Term Stability of components is a critical one in most temperature sensing applications. Systems Designers are usually concerned with developing circuitry and thermistor sensor specifications which assure accurate, long-term measurement capability. It is extremely important therefore that the Resistance versus Temperature characteristics of the thermistors used in such critical applications do not change or drift over time.

BetaTHERM's range of BetaCurve product exhibit very low drift in the R/T characteristic with respect to time at elevated temperatures. This is indicated in the table below.

The long-term stability is achieved by control of materials in the manufacturing process and by **"ageing"** the chips at elevated temperatures prior to assembly.

Information on stability with respect to time is included in the product section of the catalog for relevant products.

For customized applications, BetaTHERM can provide advice on aging methods and on the selection of products with optimum long term stability.

AgingTime (years) at 75^{o}C For Material # 3	Change in resistance value ΔR %	Change in temperature value ΔT %
(Initial) 0	0.00	0.000
1	+ 0.05	- 0.011
2	+ 0.10	- 0.022
3	+ 0.15	- 0.033
4	+ 0.20	- 0.044
5	+ 0.25	- 0.056
6	+ 0.30	- 0.067
7	+ 0.35	- 0.077
8	+ 0.40	- 0.087
9	+ 0.45	- 0.097

Table # 4

For applications where tolerance and stability are critical, BetaTHERM's BetaCURVE series of products are superior to the BetaCHIP range. Most manufacturers offer ranges of product that are classified as either high precision and high stability or low precision devices. It is generally more economical to use low precision components where possible, but for more critical applications it is advisable to use high precision devices.

Specification of thermistors for applications:

The preceding sections of the catalog have covered topics relating to the factors that affect the measured value of resistance of a thermistor and to issues that affect the correlation between this measured resistance value and temperature of the thermistor. The next major topics concern the **specification** of thermistors and the implementation of **applications** that use thermistors.

The **specification** of thermistors in terms of part numbers and product ranges is dealt with in the product section of the catalog. This section provides information on the specification of Material Curve number, nominal resistance value, tolerances, lead wire options and associated factors. All of these attributes affect the performance of a thermistor in an application.

For situations where the specification of a **component part-number** are not clear-cut, BetaTHERM applications engineering group can provide advice and customer support.

In terms of **applications**, thermistors represent a mature product range and there are many "standard" application methods in existence. However, it can be difficult to find information on specific aspects of thermistor applications, as the published literature on the topic is diverse and not well catalogued.

The application notes that are in the next sections of the catalog attempt to address this situation. While an in-depth discussion at text-book level is beyond the scope of the catalog, the application notes provide a general overview of methods of using thermistors and provide **key words** and **headings** that may serve as **pointers** towards more detailed sources of information.

The applications section concludes with some notes on interfacing thermistors to instrumentation. This section is also presented as an overview of some relevant topics, so that the key-words and headings can be used to source more detailed information on particular items.

Thermistor applications make use of the basic thermistor features, such as Resistance versus Temperature characteristics, zero-power characteristics, self heating effects and thermal characteristics like heat capacity and dissipation constant. It follows that a knowledge of these factors is important in understanding principles of thermistor applications.

Once the general principle of an applications is understood, then the concepts of tolerance and stability and product specification become relevant in selecting the actual component to be used in the application.