APPLICATION NOTES – DEFINITIONS

NTC Thermistor 101

Thermistors – Thermally sensitive resistors whose primary function is to exhibit a change in electrical resistance with a change in its body temperature. They are passive electronic semiconductors whose electrical resistance varies with temperature and lies between that of conductors and insulators. An important characteristic of thermistors is their extreme sensitivity to relatively minute temperature changes.

While most metals have small positive temperature coefficients of resistance, thermistors exhibit a wide range of negative and positive temperature coefficients. The large coefficients and the non-linear resistance temperature characteristics of thermistors enable them to perform many unique functions.

NTC Thermistors – The resistance of an NTC (Negative Temperature Coefficient) thermistor decreases as its temperature increases. This characteristic gives rise to many uses in electronic design, as a temperature sensor and in applications where temperature can be used to control circuit operation.

NTCs are made from various material grades of manganese, nickel, cobalt and other metallic oxides. After these raw materials are milled and mixed in accurate proportions, suitable binders are added and the units are pressed or extruded to the desired shape. Thermistor elements are then sintered at temperatures above 1000°C under carefully controlled atmospheric and temperature conditions to produce hard ceramic material. Various electrode materials can then be attached and the ceramic can be machined into various geometries.

Alpha (α) – is used to express the slope of the R-T curve at any given point. It is a measure of the rate of change in resistance of the thermistor at a specific temperature. Alpha is expressed in -%/°C. Since the R-T curve is not linear, alpha is greater at lower temperatures than at higher temperatures. For example, the alpha of a typical NTC at -50°C might be as high as –8%/°C whereas its alpha at 150°C might be less than –2%/°C.

Alpha is useful in determining what tolerances are required for a particular application. For example, say the alpha value at 25°C for a particular NTC was –4.4%/°C. If the application requires a temperature accuracy of ±0.5°C, then the tolerance would need to specified as ±2.2%, (4.4%*0.5).

Beta – A constant, expressed in °K, which describes the resistance-temperature characteristics of an NTC thermistor. The beta of a thermistor depends on its physical composition. It is a ratio of resistances at two given temperatures and is defined as:

β = ln(R1/R2)/(1/T1-1/T2) where R1 is the resistance at temperature #1 and R2 is the resistance at temperature #2. Resistance is measured in Ohms and temperature is measured in Kelvin (°K).

This is a somewhat antiquated concept used to describe the resistance vs. temperature slope. The number is dependent on the two temperatures selected. In summary, the higher the Beta, the steeper the resistance vs. temperature slope.

It is important to note that the value for beta is dependent on the two temperatures used to calculate it. This is important to know because there is no industry standard for these two temperatures – every manufacturer uses a different set of numbers. So it may be possible that although the beta values from two manufacturers are different, they may be describing the same R-T characteristics because the two temperatures used to calculate the beta numbers are different.

For example, Therm-O-Disc's 'Grade 1' material has a beta value of 3965 for 25/75°C, 3905 for 0/50°C, 3934.4 for 25/50°C and 3977.5 for 25/85°C.

Beta used to be used to calculate R-T characteristics over a relatively narrow band using the following formula:

β = 2076.02 ln(R25°C/R75°C) using a beta based on 25/75°C.

The concept of using beta to calculate R-T values has given way to the Steinhart-Hart equation, which gives very accurate results over a much wider range of temperature.

NTC Thermistor Resistance vs. Temperature Curve
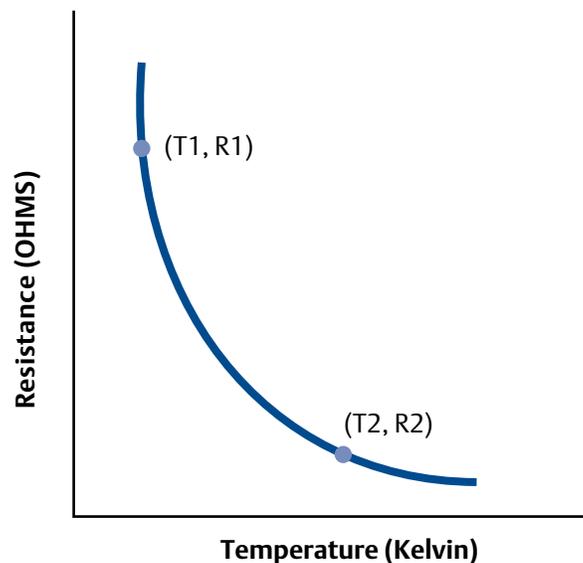
Dissipation Constant – The amount of power required to raise the temperature of the thermistor, in still air, 1°C over the ambient. For example, if a part has a dissipation constant of 4mW/C and the part is dissipating 2mW, then the thermistor's resistance will read 0.5°C above the ambient temperature. The lower the dissipation constant, the more susceptible a part is to self-heating. Similarly, the lower the power dissipated through the thermistor, the closer it will read to the actual ambient temperature.

The amount of heat energy a thermistor dissipates is dependent on its surface area, insulation and ambient medium, among other factors.

Interchangeability – Refers to the ability to substitute a thermistor into an electronic circuit without recalibrating, and then predict the maximum change in temperature measurement. It also means the temperature tolerance of the NTC.

Steinhart-Hart Equation – The basis for much of the terminology is used throughout the industry to describe thermistor characteristics. Every NTC thermistor with a different base resistance and beta value has a unique Resistance vs. Temperature Curve. The curve is best defined as a polynomial equation. The more terms used in the polynomial, the more accuracy is achieved. However, for practical purposes, the Steinhart-Hart equation is extremely accurate for most applications.

$1/T = a + b(\ln R) + c(\ln R)^3$ – where T is in °K (°C+273.15)

Some of the more popular Therm-O-Disc part number constants:

'Grade 1', 10KΩ (1H103 parts, WC/WU92NA103 parts)
$a = 1.125190920 \times 10^{-3}$
$b = 2.347363293 \times 10^{-4}$
$c = 8.551343472 \times 10^{-8}$

'Grade 1', 50KΩ (1H503 parts)
$a = 7.602330993 \times 10^{-4}$
$b = 2.313331379 \times 10^{-4}$
$c = 7.172007260 \times 10^{-8}$

'Grade 1', 100KΩ (1H104 parts)
$a = 6.053377486 \times 10^{-4}$
$b = 2.298626288 \times 10^{-4}$
$c = 6.706142562 \times 10^{-8}$

Thermal Time Constant – The amount of time required for a thermistor to change 63.2% of the temperature difference between its initial and final sensing temperature in a step-function change of temperature. This value is dependent on the sensing medium – air, oil, etc. The part will respond faster in a liquid ambient compared to an air environment. Also, a part will respond to moving air faster than still air as moving air has the ability to move more heat towards or away from the part.

Tolerance on Resistance – A method of gauging precision in NTC thermistors. Tolerance is the percentage of variation in resistance from nominal that can be expected from a thermistor at a specific temperature. Since the tolerance of a thermistor varies with temperature, tolerance is always stated as a percentage at a specified temperature. The industry standard is to use 25°C as the base temperature, unless another temperature is specified.

In temperature measurement applications, it is generally more appropriate to determine the temperature tolerance than the tolerance on resistance. This is a difficult concept for many electrical engineers who are accustomed only to resistance tolerance for resistive elements. The results are usually an over-specifying of the thermistor's tolerance, which adds unnecessary cost to the thermistor.

Temperature tolerance is calculated using the alpha value as previously mentioned.

Temperature Tolerance = Resistance tolerance/α

Zero-Power Resistance – Refers to the resistance of a thermistor, at a specific temperature, with zero electrical power applied. Thermistor reference resistances are always given at zero-power. In practice, zero-power is not truly possible, as some small amount (albeit very minute) of current must flow through the thermistor to measure the resistance. The trick is to use a current so significantly low (compared to the thermistor's dissipation constant) that it essentially becomes zero-power.

Important Notice

The user must determine the suitability of our products for the application and assumes all risk and liability associated therewith.

# APPLICATION NOTES

NTC Thermistor 102

Temperature Measurement

The NTC thermistor offers a practical, low-cost solution to most temperature measurement and control applications. High sensitivity and accuracy can be obtained by placing a thermistor in contact with the material that one wishes to measure the temperature of. Sensing circuitry can use the thermistor as one leg of a Wheatstone bridge for linear voltage outputs, or as a single, simple voltage divider. In the voltage divider, if the resistance of the fixed resistor is chosen to equal the thermistor's resistance at the mid-point of a temperature range, the output voltage is fairly well linearized for temperature ranges under 50°C.

The output of either the Wheatstone bridge or voltage divider can be routed to an A/D pin on any microprocessor equipped for extremely accurate temperature measurement.

In temperature measuring applications, the current through the NTC is limited to a value so that appreciable self-heating does not occur. The device may be calibrated to read directly as a thermometer or used in a control circuit. The high resistance of a thermistor, as compared to the resistance of long runs of wire, makes possible accurate temperature measurements and control from remote locations.

An example of temperature measurement is in battery charging applications. Despite many claims from various silicon semiconductor manufacturers, NTC thermistors remain one of the most economical, simple and reliable methods used to determine termination of the fast-charge cycle for rechargeable batteries.
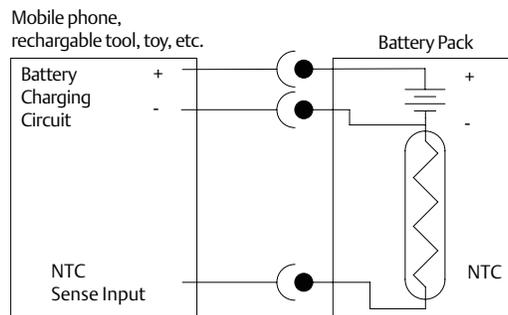

*Battery NTC*

Temperature Compensation

NTC thermistors are effective in offsetting the effect of temperature on other circuit components. Unlike the NTC thermistor, the resistance of most circuit components increases as the circuit heats up. Thermistor temperature compensation improves the performance of these thermally sensitive circuits and extends their useful operating range. Thermistors can be used to stabilize the gain of a solid state amplifier or to provide temperature compensation in circuits where copper coils are used.

Thermistors used in compensation circuits typically will have fixed resistors used in parallel and series combinations with the NTC. Note that the resulting R-T curve is much shallower and linear than the non-networked NTC.

Rp

Rntc   Rs

Rs = (resistor series)
Rp = (resistor parallel)
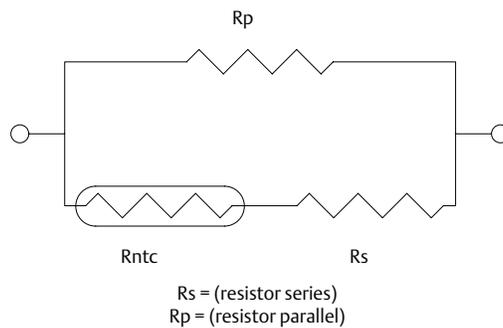
NTC Net

Thermistors can be used to accomplish temperature compensation of transistor circuits. Use of an NTC thermistor in shunt with R2 in the following circuit is an example of this application.

R1   R3

E in

E out

R2   R4
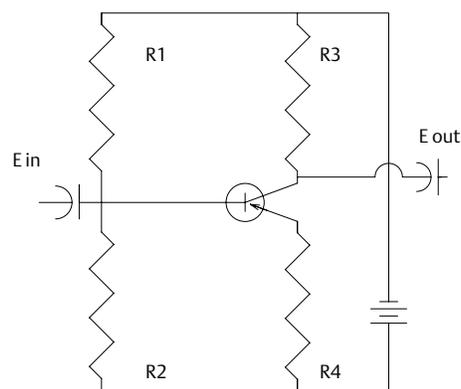
NTC Compensator

Airflow and Liquid-Level Sensing

The small size and fast response of NTC thermistors make them ideal for liquid and airflow detection circuitry. A thermistor dissipates significantly more heat in a liquid or in an air stream than it does in still air. A liquid-level or airflow circuit can use the difference in the voltage drop across an exposed thermistor. A liquid-level or airflow circuit can use the difference in the voltage drop across an exposed thermistor as input to a comparator or to actuate a signal.

Another design uses a Wheatstone bridge with a thermistor in opposing legs, where the input voltage keeps both thermistors in their self-heating range. The bridge is balanced when both thermistors are in identical environments. When liquid covers the sensing thermistor's housing, or the air begins to flow past it, the bridge becomes unbalanced.

Design Assistance

Temperature Accuracy – Because the resistance of the thermistor changes at a fairly large amount compared to the temperature, it is possible to achieve fairly high temperature accuracy with fairly loose resistance tolerances. For example, the 'Grade 1' NTC sensors change at a rate of approximately -4.4%/C at 25°C. Therefore, a +/-5% part has an accuracy of about +/-1.1°C at 25°C. Similarly, a +/-1% part has an accuracy of about +/-0.2°C at 25°C.

As the rate of resistance change varies with temperature, the tolerance required to achieve a certain accuracy of temperature also varies. For instance, to achieve a +/- 1°C accuracy at 100°C, a resistance tolerance of about +/-2.8% is required, while a +/-5% tolerance at 0°C will also achieve the same precision.

Working Example: Suppose a 10K-ohm part with a +/-1°C accuracy at 50°C is required. Through either the multiplier tables or the R-T formula, we determine the resistances at 49°, 50° and 51°C (50+/- 1°C):
49°C = 3743 ohms nom.
50°C = 3603 ohms nom.
51°C = 3469 ohms nom.

For an accuracy of +/-1°C, we would want a minimum of 3469 ohms and a maximum of 3743 ohms, or 3603 ohms +3.9%/-3.7%.

A deviation of +1.2% is possible on the tolerance at 50°C. If we subtract 1.2% from 3.7%, we find we would need a guard-banded part of at least +/-2.5% at 25°C. The closest standard 10KΩ part would be the 1H10301T, which offers a +/-2% tolerance at 25°C. If a large volume of parts are required and cost is of the essence, it would probably be worthwhile to have a special part number with a +/- 2.5% tolerance not listed here to be selected by a Therm-O-Disc sales engineer.

Resistance Tolerance Over Temperature – As the temperature deviates from 25°C, the tolerance increases. If a specific tolerance at a temperature other than 25°C is required, parts can be either "guard band" selected for a tighter tolerance at 25°C that will allow parts to fall within specifications at the desired temperature, or they can be selected by Therm-O-Disc specifically at that temperature.

Explanation of Thermal Time Constant
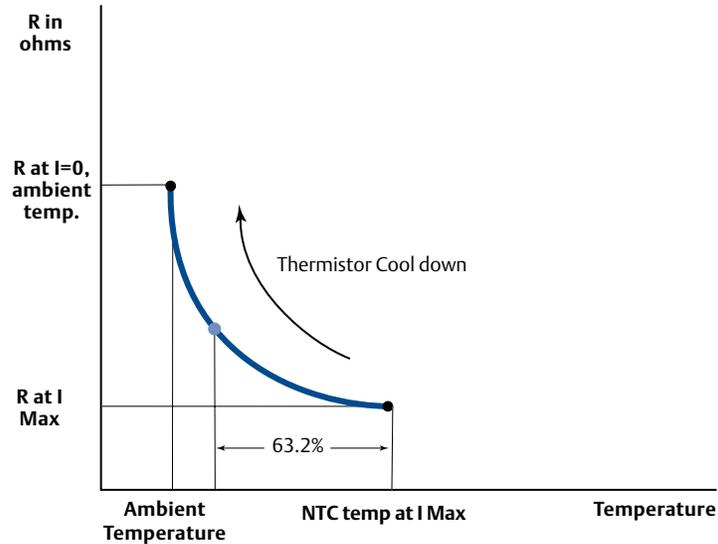
Thermal Time Constant – This is not how fast a thermistor will respond to a change in temperature. It is a method of comparing the relative speeds of thermistors with each other. By definition, the thermal time constant is the amount of time required for a thermistor to change 63.2% of the temperature difference between its initial and final sensing temperatures in a step-function change in temperature. This value is dependent on the sensing medium – still air, moving air, liquid, etc.

Working with Dissipation Constants – For this example, we will use Therm-O-Disc part number 1H103T, which has a published dissipation constant of 2mW/°C. For this example we will use a temperature range of 0° to 100°C and a desired temperature error of 0.1°C. To determine the maximum voltage applied to the circuit, we need to know the minimum resistance of the NTC. For the 1H103T, it would be 680Ω at the upper limit of 100°C. This means the series resistance of the NTC and R1 would be 4280Ω. And since $P=E^2/R$ and $E=\sqrt{PR}$ and if P=0.2mW=0.1°C self-heating, then $E= \sqrt{0.0002*4280}=0.925$ volts.
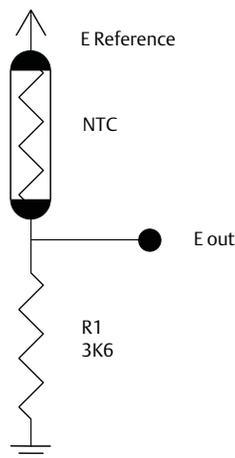
NTC Divider

Interfacing NTC Thermistors – Thermistors require control circuitry to act on a power circuit. To replace a bimetal thermostat, a thermistor requires a few fixed resistors and a transistor/power semiconductor as a minimum. Since thermistors are solid state, they are much less prone to fatigue and can last hundreds of thousands of cycles with minimal change in characteristics, providing very high system reliability.

Comparing NTC Thermistors with other sensors – Thermistors still provide a very versatile and economical means of temperature sensing for electronic circuits. Automotive, appliance, electronic and industrial markets continue to increase their usage of these devices despite the numerous options available for temperature sensing.

A summary of the most popular temperature sensing options:

Sensor Type	Features	Disadvantages
Bimetal Thermostat	Able to sense temperature and provide circuit control	Limited to one or two temperatures
Thermocouple	Capable of high temperatures	Requires special thermocouple wire back to pcboard, low sensitivity
RTD	Capable of high temperatures and high accuracy	Can be expensive, low sensitivity
IC's(special temperature sensing types)	Linear voltage outputs or digital outputs are easy to interface and program	Can be expensive, low sensitivity, limited temperature range,difficult to sense temperatures away from a pcboard
NTC Thermistors	High sensitivity, low cost, wide temperature range, easiest to interface with a pcboard from a remote location	Nonlinear output without using additional components or software correction

The "Wind Chill" Factor – Because many people are concerned with weather, the wind chill index is a very familiar concept. Many engineers using thermistors are concerned that moving air will effect the temperature reading of the thermistors.

The question is: "Does the wind chill factor effect thermistors in sensing the correct ambient temperature?" The answer is no—at least not the way most people would believe.

For a working example, consider a car with a thermistor mounted to the outside to sense temperature outside the car. This is a fairly standard automotive application. Let's say the car has a digital display that converts the thermistor's resistance to read directly in °C. Now pretend this car is in a heated garage where the temperature is 12°C and the temperature outside the garage and surrounding area is 0°C. Inside the garage, the digital display reads 12°C. Now if the car is driven outside the garage and parked in the 0°C ambient, the gauge will slowly change from 12°C to 0°C, as we would expect.

Now consider what would happen if this was repeated except that the car kept moving once outside. This movement creates an artificial wind over the thermistor. This 0°C wind cools the once 12°C thermistor down to 0°C much quicker than still air and the gauge would change from 12°C to 0°C that much faster. In fact, the faster the car was moving, the quicker the 12°C to 0°C transition would take place.

Does the temperature gauge ever go below 0°C? No, because the ambient temperature never goes below 0°C and therefore no ΔT is ever created which is necessary to change the readout. To lower the temperature of the thermistor, a ΔT must be created. Simply moving the same temperature of air across the thermistor does not create the necessary ΔT. The only difference the moving air makes is the rate at which the display changes.

So the wind chill factor is at work in getting the thermistor to its final temperature quicker, but it does not allow a mis-reading of temperature due to it.

Wind chill is the effect of a cooler wind blowing on a heated object such as the human body or a house. Because cooler-moving air is able to move more heat away from a heated object than in still air, it can act in the same manner as colder, yet still air. The key factors are a ΔT between the air and the human body and the fact that the body is heated and warmer to the surrounding air. In the thermistor, the still air has the same temperature as the moving air (no ΔT) and the fact that the thermistor is not heated artificially above the ambient temperature.

Important Notice

The user must determine the suitability of thermistors for the application and assumes all risk and liability associated therewith.

TEMPERATURE MEASUREMENT
WITH MICROPROCESSORS

Many individuals designing temperature-measuring circuits are apprehensive to use thermistors because they have a non-linear resistance versus temperature curve. There are three basic methods of temperature measurement using NTC thermistors and microprocessors. Two methods involve software linearization and minimal circuitry (usually a single resistor voltage divider into the ADC). The third method involves hardware linearization and minimal software.

1. **Software linearization using the Steinhart equation NTC Thermistors resistance vs. temperature characteristics track the following equation:** $1/_T = a + b (ln R) + c (ln R)^3$ where T is in °K (°K = 273.15 + °C) and a, b, c are constants particular to an individual thermistor R-T curve and resistance at 25°C.

The a, b, c constants for most common Therm-O-Disc thermistors

	P1H103T	P1H503T	P1H104T
a =	$1.125190920 \times 10^{-3}$	$7.602330993 \times 10^{-4}$	$6.053377486 \times 10^{-4}$
b =	$2.347363293 \times 10^{-4}$	$2.313331379 \times 10^{-4}$	$2.298626288 \times 10^{-4}$
c =	$8.551343472 \times 10^{-8}$	$7.172007260 \times 10^{-8}$	$6.706142562 \times 10^{-8}$

The user may want to experiment with rounding these constants to less digits. As presented above, the accuracy is approximately less than 0.05°C accurate for 0-100°C.

2. **Software linearization using a look up table.** Rather than calculating temperature, a lookup table can be used to minimize calculation cycle time. This is very simple to program in assembly language, it is the most popular method with our customers and much less demanding on a microprocessor than calculating the Steinhart-Hart equation.

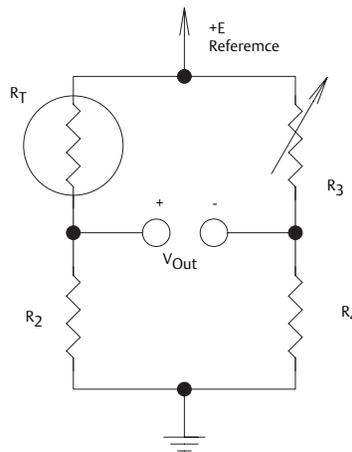### 3. Hardware Linearization using a basic bridge circuit *(see figure 1).*

Figure 1

Basic bridge circuit.

R_T is a Therm-O-Disc P1H103T, which has a resistance of 10K ohms ±2% at 25°C and an inter-changeability of 1°C. The P1H103T has the following R-T table:

°C	Resistance-ohms
0	32,654
10	19,903
20	12,493
30	8,056
40	5,327
50	3.603
70	1,752
100	680

Voltage into the bridge should be in the area of two volts to keep any self-heating of the thermistor to a minimum.

R_2 and R_4 in the bridge circuit should be of equal value and equal to R_T at its mid-point in the intended temperature range. For a 0° to 50°C range, (32° to 122°F), a 10K ohm resistor is chosen. A circuit reading 0° to 100°C (32° to 212°F), should use 3.6K ohm resistors for R_2 and R_4. Trimmer

R_3 should be set to yield a 0 volt output for 0°C. In both cases, this would be approximately 33K ohms. This can be calibrated with ice water and a thermometer. Care should be taken that the water does not short out the thermistor.

Analog to Digital Conversion

 Interfacing this circuit with a microprocessor requires an analog to digital converter. An ADC with an adjustable voltage reference and a differential analog voltage input is preferred. The support circuitry will vary with the microprocessor used. If this type of ADC is not available, the voltage output of the bridge may be fed into a 741-type op-amp as shown *(see figure 2)*.
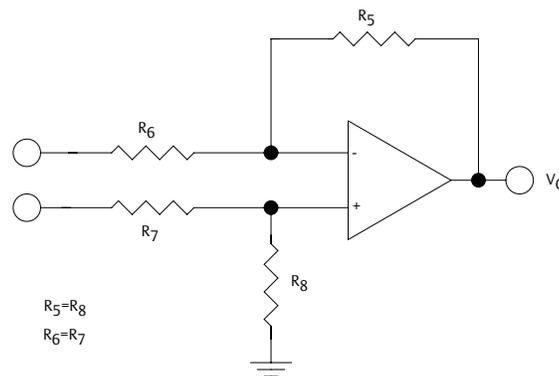

Figure 2

Analog and digital conversion.

A Programming Tip

One may notice the 0°C to 50°C circuit is more linear than the 0°C to 100°C circuit. Likewise, a short segment of 15°C on the 0°C to 50°C circuit is even more linear. Most applications call for reading temperatures between 10°C and 30°C (50°F to 86°F) or a similar interval. Under those conditions, the reading is very linear. Programs over wide ranges that require critical readings should be divided into four or five ranges with a different formula, however slight, to calculate actual temperature. It should be noted that self-heating of the thermistor may also give a false reading 0.1°C higher than the actual ambient temperature.

Another hardware trick to maximize voltage output in all three linearization methods is to pulse a 5V logic signal to the input of the bridge or voltage divider instead of a steady 2V input. With a short pulse, a reading can be made before self heating can effect the thermistor's resistance, thus reducing the amount of signal amplification required.