
Measuring Temperature with Thermistors – a Tutorial

David Potter

Introduction

Thermistors are *thermally sensitive resistors* used in a variety of applications, including temperature measurement. This application note discusses this application of thermistors, including basic theory and how to interface thermistors to modern data acquisition systems.

Thermistor Overview

A thermistor is a piece of semiconductor made from metal oxides, pressed into a small bead, disk, wafer, or other shape, sintered at high temperatures, and finally coated with epoxy or glass. The resulting device exhibits an electrical resistance that varies with temperature.

There are two types of thermistors – negative temperature coefficient (NTC) thermistors, whose resistance decreases with increasing temperature, and positive temperature coefficient (PTC) thermistors, whose resistance increases with increasing temperature. NTC thermistors are much more commonly used than PTC thermistors, especially for temperature measurement applications.

A main advantage of thermistors for temperature measurement is their extremely high sensitivity. For example, a 2252 Ω thermistor has a sensitivity of $-100 \Omega/^\circ\text{C}$ at room temperature. Higher resistance thermistors can exhibit temperature coefficients of $-10 \text{ k}\Omega/^\circ\text{C}$ or more. In comparison, a 100 Ω platinum RTD has a sensitivity of only $0.4 \Omega/^\circ\text{C}$. The physically small size of the thermistor bead also yields a very fast response to temperature changes.

Another advantage of the thermistor is its relatively high resistance. Thermistors are available with base resistances (at 25°C) ranging from hundreds to millions of ohms. This high resistance diminishes the effect of inherent resistances in the lead wires, which can cause significant errors with low resistance devices such as RTDs. For example, while RTD measurements typically require 3-wire or 4-wire connections to reduce errors caused by lead wire resistances, 2-wire connections to thermistors are usually adequate.

The major tradeoff for the high resistance and sensitivity of the thermistor is its highly nonlinear output and relatively limited operating range. Depending on the type of thermistors, upper ranges are typically limited to around 300°C . Figure 1 shows the resistance-temperature curve for a 2252 Ω thermistor. The curve of a 100 Ω RTD is also shown for comparison.

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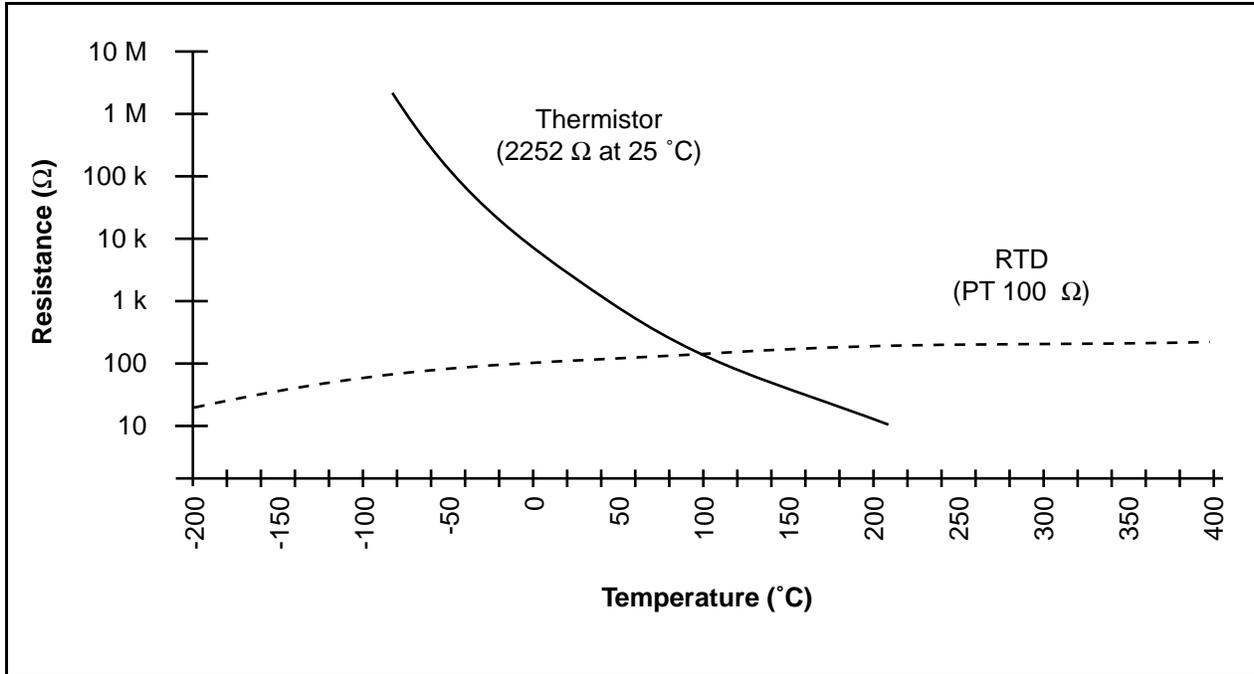


Figure 1. Resistance-Temperature Curve of a Thermistor

The thermistor has been used primarily for high-resolution measurements over limited temperature ranges. The classic example of this type of application is medical thermometry. However, continuing improvements in thermistor stability, accuracy, and interchangeability have prompted increased usage of thermistors in all types of industries.

Resistance/Temperature Characteristic of Thermistors

The resistance-temperature behavior of thermistors is highly dependent upon the manufacturing process. Therefore, thermistor manufacturers have not standardized thermistor curves to the extent that thermocouple or RTD curves have been standardized. Typically, thermistor manufacturers supply the resistance-versus-temperature curves or tables for their particular devices. The thermistor curve, however, can be approximated relatively accurately with the Steinhart-Hart equation :

$$T(^{\circ}\text{K}) = \frac{1}{a_0 + a_1 \ln(R_T) + a_2 [\ln(R_T)]^3}$$

Where $T(^{\circ}\text{K})$ is the temperature in degrees Kelvin, equal to $T(^{\circ}\text{C}) + 273.15$, and R_T is the resistance of the thermistor. The coefficients a_0 , a_1 , and a_2 can be provided by the thermistor manufacturer, or calculated from the resistance-versus-temperature curve.

Thermistor Measurement Circuits

Because the thermistor is a resistive device, you must pass a current through the thermistor to produce a voltage that can be sensed by a data acquisition system. The high resistance and high sensitivity of the thermistor simplify the necessary measurement circuitry and signal conditioning. Special 3-wire, 4-wire, or Wheatstone bridge connections are not necessary. The most common technique is to use a constant current

source, and measure the voltage developed across the thermistor. As shown in Figure 2a, the measured voltage V_0 will be equal to $R_T * I_{EX}$.

Alternatively, you can supply a constant voltage source, V_{EX} , and a reference resistor, R_R , and configure the thermistor in a simple voltage divider. In this configuration, shown in Figure 2b, the output voltage V_0 will be equal to $V_{EX} * R_T / (R_T + R_0)$.

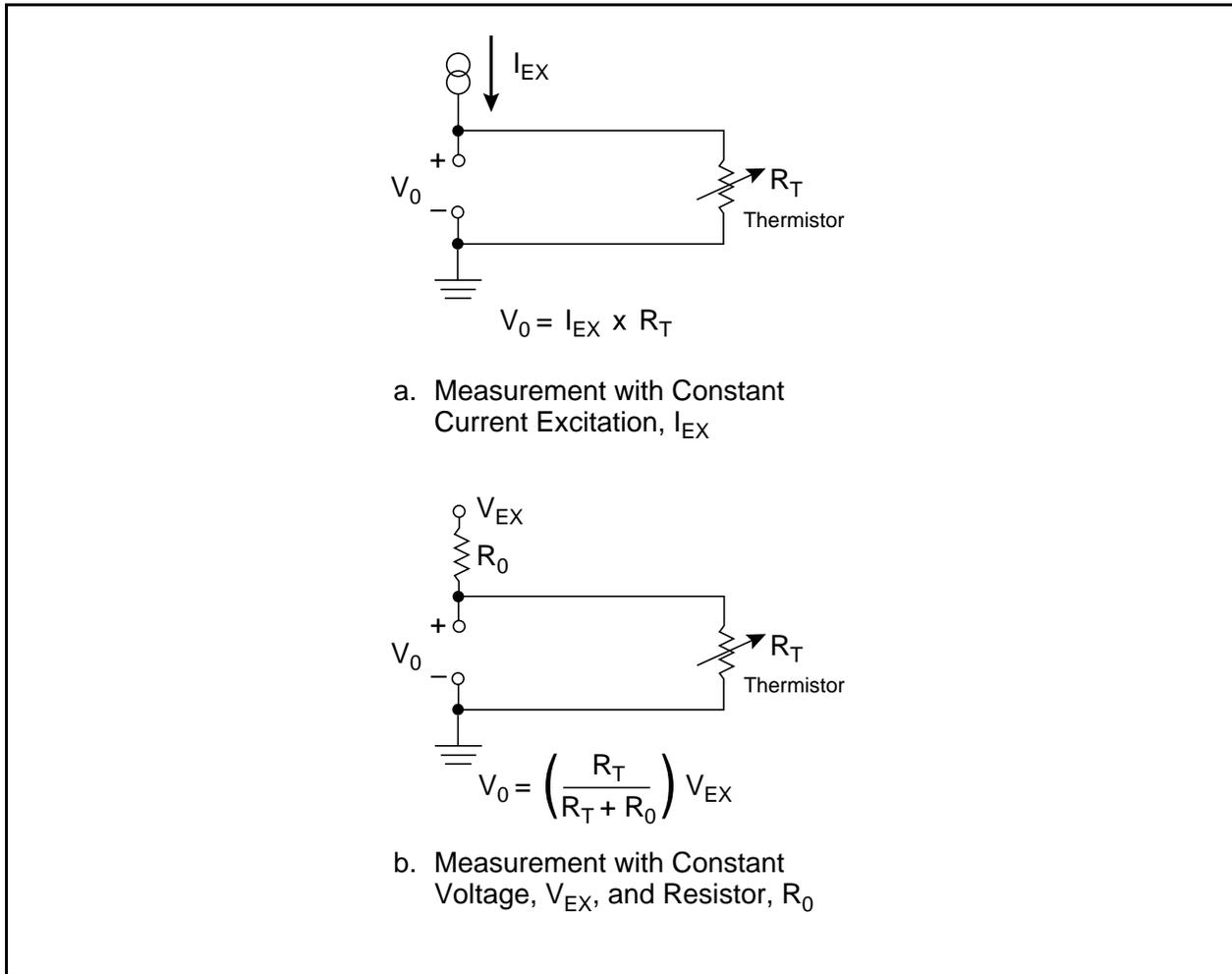


Figure 2. Thermistor measurements using a.) constant current source and b.) constant voltage source in voltage divider circuit.

The level of the voltage output signal will depend directly on the thermistor resistance and magnitude of the current or voltage excitation source. Therefore, you may be tempted to use a higher level of current or voltage excitation in order to produce a higher level output signal. This can be very detrimental because the current causes the thermistor to heat internally, which appears as an error. This phenomena is called self-heating, and is typically specified by manufacturers as the amount of power that will raise the temperature of the thermistor by 1°C .

When current is passed through the thermistor, power dissipated by the thermistor, equal to I^2R , will heat the thermistor. Thermistors, with their small size and high resistance, are particularly prone to these self-heating errors. Manufacturers typically specify this as the dissipation constant, which is the power required to heat the

thermistor 1°C from ambient temperature ($\text{mW}/^\circ\text{C}$). The dissipation constant depends heavily on how easily heat is transferred away from the thermistor, so the dissipation constant may be specified for different media – in still air, water, or oil bath. Typical dissipation constants range anywhere from less than $0.5\text{ mW}/^\circ\text{C}$ for still air to $10\text{ mW}/^\circ\text{C}$ or higher for a thermistor immersed in water. A $2,252\ \Omega$ thermistor powered by a 1 mA excitation current will dissipate $I^2R = (1\text{ mA})(2,252\ \Omega) = 2.25\text{ mW}$. If this thermistor has a dissipation constant of $10\text{ mW}/^\circ\text{C}$, the thermistor will self-heat 0.225°C . Therefore, carefully read self-heating specifications of your thermistors and choose your excitation current or voltage accordingly. If your thermistors have a small dissipation constant, then you should minimize the level of your excitation current to minimize the self-heating errors.

Signal Conditioning Systems for Thermistors

The use of thermistors for temperature measurement with a PC-based DAQ system requires some signal conditioning hardware to interface the thermistor to the measurement device, such as a plug-in DAQ board. Signal conditioning is defined here as any conditioning required to interface the thermistor and its output signal to a DAQ board or module. The DAQ board or module performs the actual analog-to-digital (A/D) conversion. Briefly, signal conditioning for thermistors should include the following functionality.

Excitation current or voltage source – As explained in the previous section, a constant current or voltage (with reference resistor) converts the thermistor resistance into a measurable voltage output. A higher level excitation source will generate a higher-level voltage output, but will also increase the self-heating of the thermistor.

Signal amplification – Most signal conditioners include voltage signal amplifiers. Amplification of the thermistor voltage yields a high-level voltage signal that is less susceptible to noise corruption and more precisely digitized.

Lowpass filtering – Lowpass filters reject unwanted noise in the thermistor signal. The temperature information contained in the thermistor voltage is relatively low bandwidth, or slowly changing. The measurement circuit, however, is likely to pick up higher frequency noise from the environment. The most common is 50 or 60 Hz noise from power lines and machinery. Lowpass noise filters are designed to remove this noise by attenuating any signal components with frequencies above some defined bandwidth.

Isolation – Signal conditioning hardware with isolation serve to electrically isolate the thermistor and other sensors from the measurement system. Isolation prevents ground loops, rejects large common-mode voltages, and in general protects the data acquisition system from high voltages.

Multiplexing – A typical plug-in DAQ board has eight to 16 analog input channels. However, you can use external multiplexing systems, included in some signal conditioning systems, to expand the number of input channels that you can connect to a DAQ board. The multiplexing system sequentially switches multiple channels to a single-input channel of the DAQ board.

SCXI Signal Conditioning Systems

One example of a signal conditioning system for PC-based DAQ is Signal Conditioning eXtensions for Instrumentation (SCXI). SCXI is an instrumentation front end that connects either to a plug-in DAQ board, to a long-distance RS-232 or RS-485 network, or directly to the parallel port of the PC. SCXI modules condition signals from a variety of signal sources, such as thermistors, RTDs, thermocouples, and strain gauges. The conditioned signals are passed to a plug-in DAQ board that acquires the signals directly into PC memory. Alternatively, the signals can be digitized locally in the SCXI unit and communicated to the PC via the parallel port or serial communications.

The SCXI product line has a variety of analog and digital I/O modules for various types of sensors and signals. In particular, the SCXI-1121 and SCXI-1122 are well suited for thermistors (see Table 1). The SCXI-1121 is an isolated amplifier and multiplexer module with four isolated input channels. Each of the four channels has an amplifier with jumper-selectable gain (from 1 to 2,000) and a lowpass filter (4 Hz or 10 kHz). The SCXI-1121 also has four channels of isolated voltage or current excitation.

The SCXI-1122 is multiplexer input module that can be configured for 16 two-wire inputs or 8 four-wire thermistor inputs. The inputs are multiplexed into one isolation amplifier, which is programmable for a gain of 0.01 (for high voltages) to 2,000. The module includes one isolated voltage and one isolated current source.

Table 1. SCXI Module Specifications

	SCXI-1121	SCXI-1122
Number of input channels	4 isolated two-wire or four-wire	16 two-wire/8 four-wire
Number of excitation sources	4 independent current/voltage sources	1 voltage and 1 current source
Excitation levels	Current: 0.15 mA, 0.45 mA Voltage: 3.33 V, 10.0 V	Current: 1.0 mA Voltage: 3.33 V
Gains	1 to 2,000	0.01 to 2,000
Filtering:	4 Hz or 10 kHz, lowpass	4 Hz or 4 kHz, lowpass
Isolation	250 Vrms channel to channel and channel to earth	450 Vrms channel to earth
Input channel scanning rate	Up to 333 kS/s	100 S/s

Application Example 1 – Monitoring 16 Thermistors with the SCXI-1122

Consider a production test system that requires the ability to monitor and record the temperature at 16 test points as part of a functionality test. Under normal operating conditions, the unit under test will exhibit temperatures over a limited range (10° to 100° C), and your test requires maximum sensitivity and fast response. Therefore, you decide to use 2252 Ω thermistors.

You can monitor all 16 thermistors with two SCXI-1122 modules installed in a four-slot SCXI-1000 chassis. The modules and chassis are connected to a plug-in PC DAQ board, the AT-MIO-16E-2, which acquires the analog signals from all four modules and stores the digitized readings into PC memory. Figure 3 is a diagram of the system.

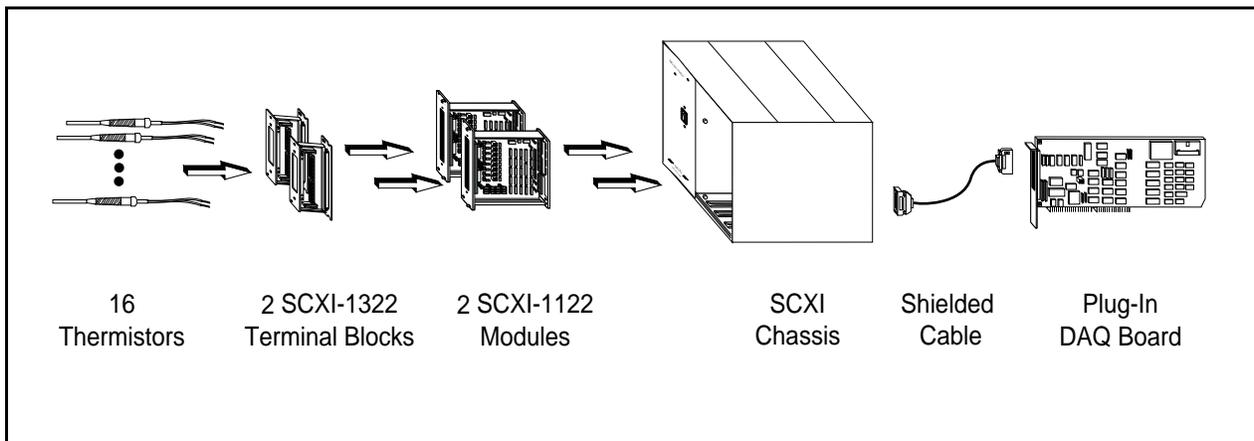


Figure 3. SCXI-1122 System for Monitoring 16 Thermistors

The SCXI-1122 supplies a constant current excitation for the thermistors, isolation for high common-mode voltages and protection, optional lowpass filtering, and multiplexing. The SCXI-1122, when configured for thermistors, operates as an 8-channel four-wire scanner. In this mode, the constant current source is multiplexed sequentially to each thermistor, synchronized with the multiplexing of the thermistor input voltage. Therefore, at any one time, the current source is applied only to the thermistor being measured. Otherwise, the single current source does not have the power to drive eight 2252 Ω thermistors at the same time.

Over the temperature range of 10° to 100° C, the manufacturer's specification sheet tells us that the thermistor resistance will vary from 4.5 k Ω at 10° C to 153 Ω at 100° C. Because the SCXI-1122 excitation current source delivers 1 mA, the measured voltage will vary from 4.5 V at 10° C to 153 mV at 100° C. You should configure the SCXI-1122 modules for an amplifier gain of 2, since the input range of the module at a gain of 2 is ± 5 V.

The AT-MIO-16E-2 is a 12-bit multifunction I/O plug-in board for IBM PC AT and compatible computers. The AT-MIO-16E-2 will digitize the conditioned voltage output of the two SCXI-1122 modules. With the SCXI-1122 modules configured for an input range of ± 5 V, the resolution of the digitization will be equal to $10 \text{ V}/4,096 = 2.44 \text{ mV}$. With the 1 mA current source, this corresponds to 2.44 Ω change in thermistor resistance. For higher resolution, you could use the 16-bit AT-MIO-16XE-50 or AT-MIO-16X. With these boards, the resolution for this application will be $10 \text{ V}/65,536 = 153 \text{ }\mu\text{V}$, or 0.15 Ω . Similar 12-bit and 16-bit boards are also available for the Macintosh platform.

The SCXI chassis, which houses the two SCXI-1122 modules, is connected to the AT-MIO-16E-2 with the SCXI-1349 shielded cable assembly, available in lengths up to 10 m. The thermistors are wired into two SCXI-1322 terminal blocks, which have convenient screw terminals with strain relief.

An IBM PC/XT/AT or compatible computer controls the SCXI data acquisition system. Therefore, application software choices for controlling the system include LabVIEW[®] and LabWindows/CVI[®] for Windows, and LabWindows[®] for DOS. Alternatively, you can use a general-purpose programming language, such as C, Basic, or Pascal, under DOS or Windows, and control the DAQ hardware with the NI-DAQ[®] driver software that is included with National Instruments plug-in DAQ boards. Plug-in boards and software are also available for Macintosh computers.

Table 2 summarizes the configuration for the SCXI-1122 module for this thermistor application. With the exception of the excitation level, which is fixed at 1.0 mA, all of these parameters are software selectable. The module bandwidth, selectable for 4 Hz or 4 kHz, is configured for 4 kHz so the channels can be scanned at the full rate of 100 S/s.

Table 2. Typical Configuration for an SCXI-1122 Used with Thermistors

SCXI-1122 Parameter	Typical Setting for a Thermistor
Scanning mode	4-wire, with current excitation
Module gain	2*
Module Bandwidth	4 kHz
Excitation level	1.0 mA

*The appropriate module gain depends on the resistance range of the particular thermistor used.

Application Example 2 – Monitoring 16 Thermistors with the SCXI-1121

Consider the same test system requirements in the first application. Now, however, your system specification requires complete channel-to-channel safety isolation, selectable gain and filtering on every channel, and the ability to scan input channels at rates higher than 100 S/s. Therefore, you can use the SCXI-1121 isolation amplifier module with excitation. You can monitor all 16 thermistors with four SCXI-1121 modules installed in a four-slot SCXI-1000 chassis. Again, the modules and chassis are connected to a plug-in PC DAQ board that acquires the analog signals from all four modules and stores the digitized readings into PC memory. Figure 4 is a diagram of the system.

Each input channel of the SCXI-1121 includes isolation for high common-mode voltages and protection, lowpass filtering of 4 Hz or 10 kHz, programmable gain from 1 to 2,000, and an excitation channel that can source a voltage or current excitation.

Each excitation channel can be configured to source 0.15 mA or 0.45 mA. To minimize self-heating of the thermistor, you can set the excitation level to 0.15 mA. Over the temperature range of 10 ° to 100° C, the manufacturers specification sheet tells us that the thermistor resistance will vary from 4.5 k Ω at 10° C to 153 Ω at 100° C. With the 0.15 mA current excitation, the output voltage will vary from 0.675 V at 10° C to 23.0 mV at 100° C. Therefore, you should configure the SCXI-1121 channels for a gain of 5, which yields an input range of ± 1 V. To acquire the conditioned signals into the PC, you can use any one of a variety of plug-in DAQ boards, or the SCXI-1200 module that connects directly to the PC parallel port.

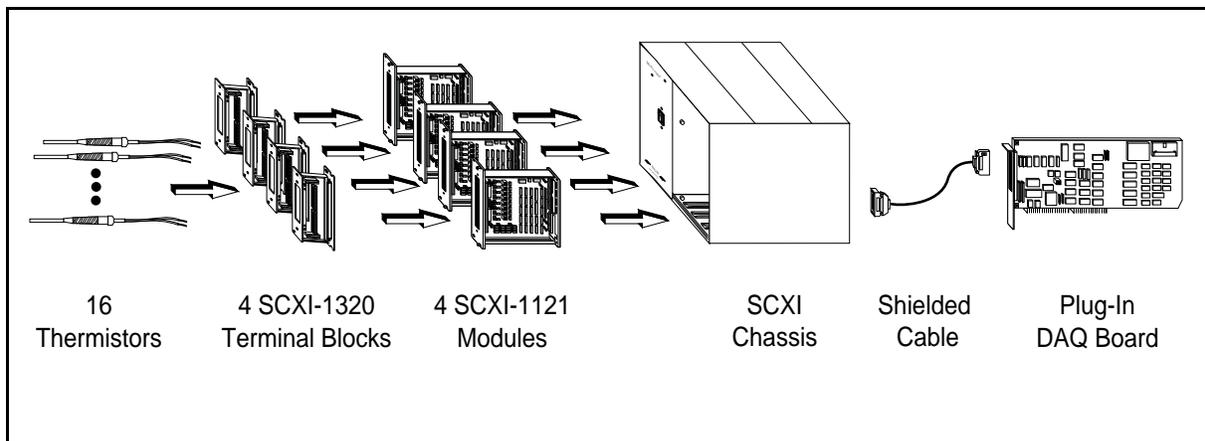


Figure 4. SCXI-1121 System for Monitoring 16 Thermistors

Table 3 summarizes the configuration for the SCXI-1121 modules used in this application with 2252 Ω thermistors. The SCXI-1121 module also includes bridge completion circuitry which can be enabled when using strain gauge transducers. All of the parameters listed in Table 3 are selectable on a per channel basis.

Table 3. Typical Configuration for an SCXI-1121 Used with Thermistors

SCXI-1121 Parameter	Typical Setting for a 100 Ω Four-Wire thermistor
Channel gain	5*
Bandwidth	4 Hz
Excitation mode	Current
Excitation level	0.15 mA
Bridge completion	Disabled

*The appropriate channel gain depends on the resistance range of the particular thermistor used.

For this application, we selected the 0.15 mA current excitation level to minimize self-heating of the thermistor. At room temperature, the thermistor resistance is 2,252 Ω and the dissipated power will be equal to $I^2R = (0.15 \text{ mA})^2 * 2,252 \Omega = 0.05 \text{ mW}$. If the thermistor has a dissipation constant of 3 mW/ $^{\circ}\text{C}$ in still air, then the self-heating error at room temperature will be $0.05/3 = 0.017^{\circ}\text{C}$.

Thermistor Unit Conversion Routines

After you have configured your SCXI system, wired your thermistors to the SCXI terminal blocks, and configured your NI-DAQ driver software, you are ready to start taking thermistor readings.

The NI-DAQ driver software, included free of charge with all National Instruments DAQ boards and the SCXI-1200, includes special high-level routines to acquire thermistor data using SCXI modules. The basic NI-DAQ measurement routines, which you can call from LabVIEW, LabWindows, LabWindows/CVI, or a traditional programming language, will return measured *voltages*. However, for thermistor applications, the NI-DAQ library includes special routines that implement the Steinhart-Hart equation to convert these measured voltages into thermistor temperatures.



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