Application Note 043

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# Measuring Temperature with Thermocouples – a Tutorial

**David Potter**

## Introduction

One of the most frequently used temperature transducers is the *thermocouple*. Thermocouples are very rugged and inexpensive and can operate over a wide temperature range. A thermocouple is created whenever two dissimilar metals touch and the contact point produces a small open-circuit voltage as a function of temperature. This thermoelectric voltage is known as the *Seebeck voltage*, named after Thomas Seebeck, who discovered it in 1821. The voltage is nonlinear with respect to temperature. However, for small changes in temperature, the voltage is approximately linear, or

$$\Delta V \approx S\Delta T \qquad (1)$$

where $\Delta V$ is the change in voltage, S is the Seebeck coefficient, and $\Delta T$ is the change in temperature.

S varies with changes in temperature, however, causing the output voltages of thermocouples to be nonlinear over their operating ranges. Several types of thermocouples are available; these thermocouples are designated by capital letters that indicate their composition according to American National Standards Institute (ANSI) conventions. For example, a J-type thermocouple has one iron conductor and one constantan (a copper-nickel alloy) conductor. You can monitor thermocouples with versatile PC-based data acquisition systems. Thermocouples have some special signal conditioning requirements, which this note describes. The Signal Conditioning eXtensions for Instrumentation (SCXI) system, depicted in Figure 1, is a signal conditioning front end for plug-in data acquisition (DAQ) boards. SCXI systems are ideal for amplifying, filtering, and even isolating the very low-level voltages that thermocouples generate.

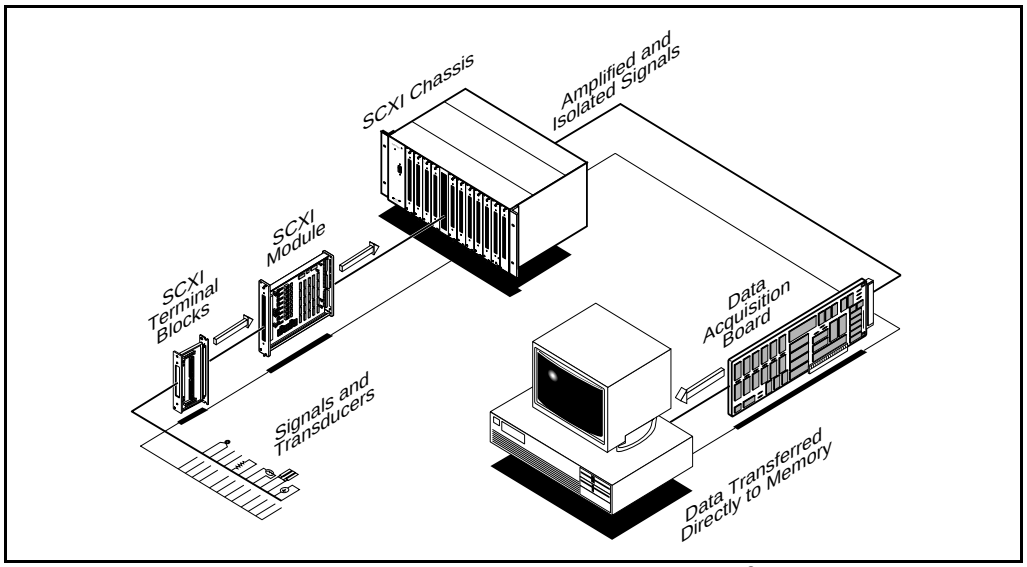



Figure 1. The SCXI Signal Conditioning Front-End System for Plug-In DAQ Boards

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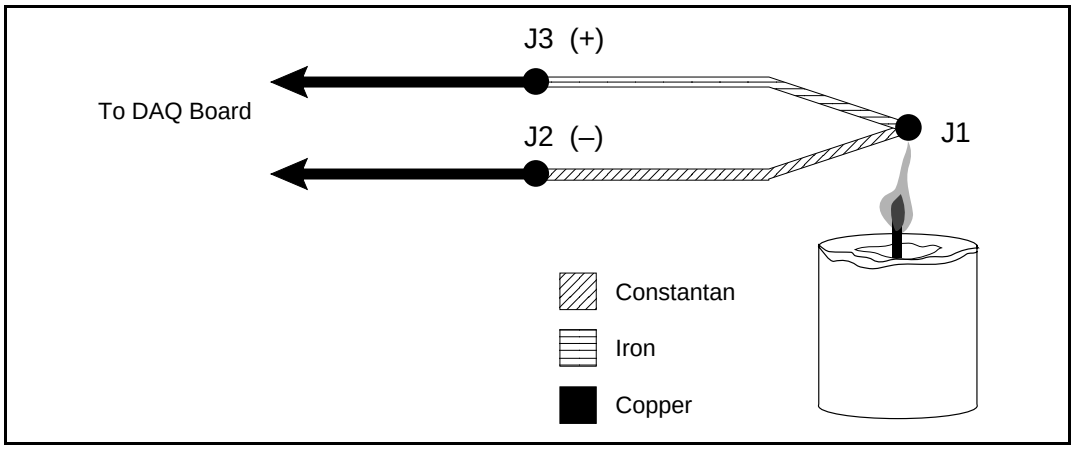


Figure 2. J-Type Thermocouple

# Thermocouple Circuits

## General Case

To measure a thermocouple Seebeck voltage, you cannot simply connect the thermocouple to a voltmeter or other measurement system, because connecting the thermocouple wires to the measurement system creates additional thermoelectric circuits.

Consider the circuit illustrated in Figure 2, in which a J-type thermocouple is in a candle flame that has a temperature you want to measure. The two thermocouple wires are connected to the copper leads of a DAQ board. Notice that the circuit contains three dissimilar metal junctions–J1, J2, and J3. J1, the thermocouple junction, generates a Seebeck voltage proportional to the temperature of the candle flame. J2 and J3 each have their own Seebeck coefficient and generate their own thermoelectric voltage proportional to the temperature at the DAQ terminals. To determine the voltage contribution from J1, you need to know the temperatures of junctions J2 and J3 as well as the voltage-to-temperature relationships for these junctions. You can then subtract the contributions of the parasitic thermocouples at J2 and J3 from the measured voltage.

# Cold-Junction Compensation

Thermocouples require some form of temperature reference to compensate for these unwanted parasitic thermocouples. The term *cold junction* comes from the traditional practice of holding this reference junction at 0° C in an ice bath. The National Institute of Standards and Technology (NIST) thermocouple reference tables are created with this setup, illustrated in Figure 3.

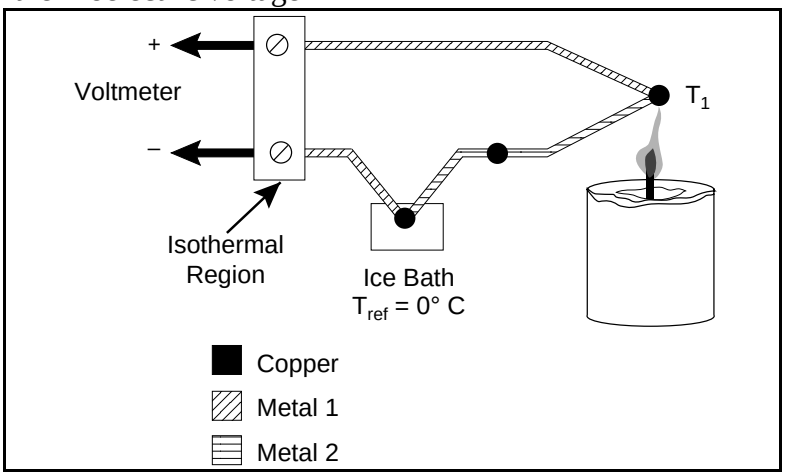


Figure 3. Traditional Temperature Measurement with Reference Junction Held at 0° C

In Figure 3, the measured voltage depends on the difference in temperatures $T_1$ and $T_{ref}$; in this case, $T_{ref}$ is 0° C. Notice that because the voltmeter lead connections are the same temperature, or *isothermal* (this term is described in detail later in this note), the voltages generated at these two points are equal and opposing. Therefore, the net voltage error added by these connections is zero.

Under these conditions, if the measurement temperature is above 0° C, a thermocouple has a positive output; if below 0° C, the output is negative. When the reference junction and the measurement junction are the same temperature, the net voltage is zero.

Although an ice bath reference is accurate, it is not always practical. A more practical approach is to measure the temperature of the reference junction with a direct-reading temperature sensor and subtract the parasitic thermocouple thermoelectric voltage contributions. This process is called *cold-junction compensation*. You can simplify computing cold-junction compensation by taking advantage of some thermocouple characteristics.

By using the Thermocouple Law of Intermediate Metals and making some simple assumptions, you can see that the voltage the DAQ board measures in Figure 2 depends only on the thermocouple type, the thermocouple voltage, and the cold-junction temperature. The measured voltage is in fact independent of the composition of the measurement leads and the cold junctions, J2 and J3.

According to the Thermocouple Law of Intermediate Metals, illustrated in Figure 4, inserting any type of wire into a thermocouple circuit has no effect on the output as long as both ends of that wire are the same temperature, or isothermal.

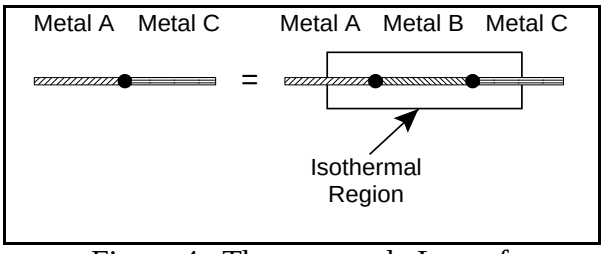



Figure 4. Thermocouple Law of Intermediate Metals

Consider the circuit in Figure 5. This circuit is similar to the previouly described circuit in Figure 2, but a short length of constantan wire has been inserted just before junction J3 and the junctions are assumed to be held at identical temperatures. Assuming that junctions J3 and J4 are the same temperature, the Thermocouple Law of Intermediate Metals indicates that the circuit in Figure 5 is electrically equivalent to the circuit in Figure 2. Consequently, any result taken from the circuit in Figure 5 also applies to the circuit illustrated in Figure 2.

In Figure 5, junctions J2 and J4 are the same type (copper-constantan); because both are in the isothermal region, J2 and J4 are also the same temperature. The junctions occur in opposite directions, however, so their total contribution to the measured voltage is zero. Junctions J1 and J3 are both iron-constantan junctions and also point in opposite directions, but may be different temperatures. Therefore, junctions J1 and J3 are the only two junctions with outputs that have any effect on the total voltage measured.

Using the notation $V_{Jx}(T_y)$ to indicate the voltage generated by the junction J*x* at temperature $T_y$, the

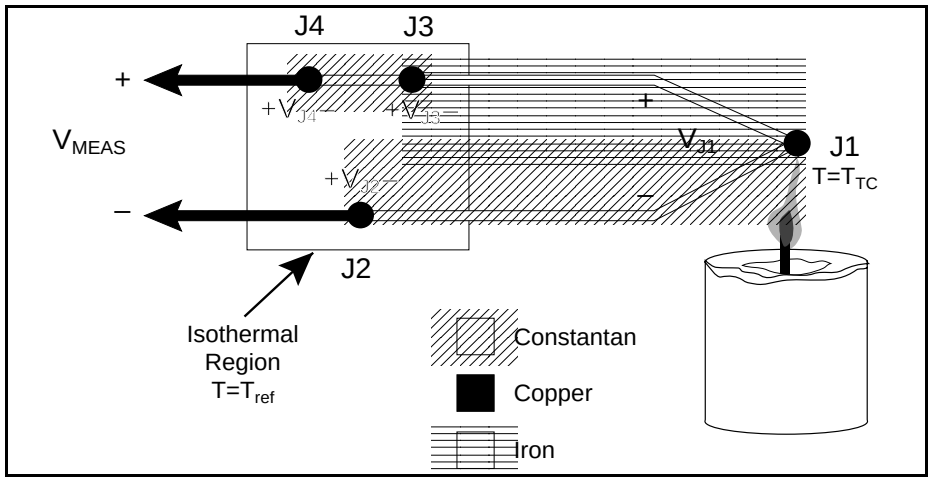



Figure 5. Inserting an Extra Lead in the Isothermal Region

general thermocouple problem is reduced to the following equation:

$$V_{MEAS} = V_{J1}(T_{TC}) + V_{J3}(T_{ref}) \quad (2)$$

where $V_{MEAS}$ is the voltage the DAQ board measures, $T_{TC}$ is the temperature of the thermocouple at J1, and $T_{ref}$ is the temperature of the reference junction.

Notice that in equation 2, $V_{Jx}(T_y)$ is a voltage generated at temperature $T_y$ with respect to some reference temperature. As long as both $V_{J1}$ and $V_{J3}$ are functions of temperature relative to the same reference temperature, equation 2 is valid. As stated earlier, for example, NIST thermocouple reference tables are generated with the reference junction held at 0° C.

Because junction J3 is the same type as J1 but in the opposite direction, $V_{J3}(T_{ref}) = -V_{J1}(T_{ref})$. Because $V_{J1}$ is the voltage that the thermocouple type undergoing testing generates, this voltage can be renamed $V_{TC}$. Therefore, formula 2 is rewritten as follows:

$$V_{MEAS} = V_{TC}(T_{TC}) - V_{TC}(T_{ref}) \quad (3)$$

Therefore, by measuring $V_{MEAS}$ and $T_{ref}$, and knowing the voltage-to-temperature relationship of the thermocouple, you can determine the temperature of the thermocouple.

There are two techniques for implementing cold-junction compensation–hardware compensation and software compensation. Both techniques require that the temperature at the reference junction be sensed with a direct-reading sensor. A direct-reading sensor has an output that depends only on the temperature of the measurement point. Semiconductor sensors, thermistors, or RTDs are commonly used to measure the reference-junction temperature. For example, several SCXI terminal blocks include thermistors that are located near the screw terminals to which thermocouple wires are connected.

## Hardware Compensation

With hardware compensation, a variable voltage source is inserted into the circuit to

cancel the parasitic thermoelectric voltages. The variable voltage source generates a compensation voltage according to the ambient temperature, and thus adds the correct voltage to cancel the unwanted thermoelectric signals. When these parasitic signals are canceled, the only signal the DAQ system measures is the voltage from the thermocouple junction. With hardware compensation, the temperature at the DAQ system terminals is irrelevant because the parasitic thermocouple voltages have been canceled. The major disadvantage of hardware compensation is that each thermocouple type must have a separate compensation circuit that can add the correct compensation voltage, which makes the circuit fairly expensive. Also, hardware compensation is generally less accurate than software compensation.

## Software Compensation

Alternatively, you can use software for cold-junction compensation. After a direct-reading sensor measures the reference-junction temperature, software can add the appropriate voltage value to the measured voltage to eliminate the parasitic thermocouple effects. Recall formula 3, which states that the measured voltage, $V_{MEAS}$, is equal to the difference between the thermocouple voltages at the thermocouple temperature and at the reference-junction temperature.

**Note:** ***The National Instruments LabVIEW®, LabWindows®, and NI-DAQ® software packages include routines that perform the required software compensation steps.***

There are two ways to determine the thermocouple temperature when given the measured voltage, $V_{MEAS}$, and the temperature at the reference junction, $T_{ref}$. The first method is more accurate, but the second method requires fewer computational steps.

### Procedure 1–Direct Voltage Addition Method for Software Cold-Junction Compensation

The more accurate compensation method uses two voltage-to-temperature conversion steps. From formula 3, you can find the true open-circuit voltage that the thermocouple would produce with a reference junction at 0° C, as shown in the following equation:

$$V_{TC}(T_{TC}) = V_{MEAS} + V_{TC}(T_{ref}) \quad (4)$$

Therefore, this method requires the following steps:

1. Measure the reference-junction temperature, $T_{ref}$.
2. Convert this temperature into an equivalent *voltage* for the thermocouple type undergoing testing, $V_{TC}(T_{ref})$. You can use either the NIST reference tables or polynomials that assume a reference junction at 0° C.
3. Add this equivalent voltage to the measured voltage, $V_{MEAS}$, to obtain the true open-circuit voltage that the thermocouple would produce with a reference junction at 0° C, $V_{TC}(T_{TC})$.
4. Convert the resulting voltage into a temperature; this value is the thermocouple temperature, $T_{TC}$. This compensation method requires a translation of the junction temperature into a thermocouple voltage followed by a translation of a new voltage into a temperature. Each of these translation steps requires either a polynomial calculation or a look-up table. It is, however, more accurate than the following method.

### Procedure 2–Temperature Addition Method for Software Cold-Junction Compensation

A second, easier software compensation approach makes use of the fact that thermocouple output voltages are approximately linear over small deviations in

temperature. Therefore, for small deviations in temperature, you can use the following equation:

$$V_{TC}(T_1) - V_{TC}(T_2) \approx V_{TC}(T_1 - T_2) \quad (5)$$

This assumption is true if $T_1$ is fairly close to $T_2$ because the thermocouple voltage-versus-temperature curve is approximately linear for small temperature variations. Assuming that the thermocouple temperature is relatively close to the reference temperature, you can rewrite formula 3 as shown in the following equation:

$$V_{MEAS} = V_{TC}(T_{TC} - T_{ref}) \quad (6)$$

Remember that if you are using standard NIST thermocouple reference tables or equations, the voltage $V_{TC}$ is a function of temperature relative to a reference temperature of 0° C. By assuming linearity and using equation 6, assume that the voltage-versus-temperature curves with a reference temperature of 0° C are identical to curves with a reference temperature of $T_{ref}$. Therefore, you can convert the measured voltage into a temperature using the NIST reference tables. This temperature is the difference between temperatures $T_{TC}$ and $T_{ref}$. This simplified compensation method is as follows:

1. Measure the reference-junction temperature, $T_{ref}$.
2. Convert the measured voltage, $V_{MEAS}$, into a temperature using the voltage-to-temperature relationship of the thermocouple. This temperature is approximately the difference between the thermocouple and the cold-junction reference, $T_{TC} - T_{ref}$.
3. Add the temperature of the reference junction, $T_{ref}$, to this value. This is the thermocouple temperature.

This method saves a computation step over the first method of software compensation but is less accurate. A comparison of the accuracy of these two methods is included in the application examples later in this note.

# Linearizing the Data

Thermocouple output voltages are highly nonlinear. The Seebeck coefficient can vary by a factor of three or more over the operating temperature range of some thermocouples. For this reason, you must either approximate the thermocouple voltage-versus-temperature curve using polynomials, or use a look-up table. The polynomials are in the following form:

$$T = a_0 + a_1 v + a_2 v^2 + ... + a_n v^n \quad (7)$$

where *v* is the thermocouple voltage in *volts*, T is the temperature in degrees Celsius, and $a_0$ through $a_n$ are coefficients that are specific to each thermocouple type. Table 1 lists NIST polynomial coefficients for several popular thermocouple types over a selected range of temperature.

Table 1. NIST Polynomial Coefficients for Voltage-to-Temperature Conversion ($T = a_0 + a_1 v + a_2 v^2 + ... + a_n v^n$)

| | Thermocouple Type | | | | | |
|---|---|---|---|---|---|---|
| | **E** | **J** | **K** | **R** | **S** | **T** |
| **Range** | **0° to 1,000 °C** | **0° to 760 °C** | **0° to 500 °C** | **-50° to 250 °C** | **-50° to 250 °C** | **0° to 400 °C** |
| $a_0$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $a_1$ | 1.7057035E -2 | 1.978425E -2 | 2.508355E -2 | 1.8891380 E-1 | 1.84949460E -1 | 2.592800E -2 |
| $a_2$ | -2.3301759E -7 | -2.001204E -7 | 7.860106E -8 | -9.3835290E -5 | -8.00504062E -5 | -7.602961E -7 |
| $a_3$ | 6.5435585E -12 | 1.036969E -11 | -2.503131E -10 | 1.3068619E -7 | 1.02237430E -7 | 4.637791E -11 |
| $a_4$ | -7.3562749E -17 | -2.549687E -16 | 8.315270E -14 | -2.2703580E -10 | -1.52248592E -10 | -2.165394E -15 |
| $a_5$ | -1.7896001E -21 | 3.585153E -21 | -1.228034E -17 | 3.5145659E -13 | 1.88821343E -13 | 6.048144E -20 |
| $a_6$ | 8.4036165E -26 | -5.344285E -26 | 9.804036E -22 | -3.8953900E -16 | -1.59085941E -16 | -7.293422E -25 |
| $a_7$ | -1.3735879E -30 | 5.099890E -31 | -4.413030E -26 | 2.8239471E -19 | 8.23027880E -20 | |
| $a_8$ | 1.0629823E -35 | | 1.057734E -30 | -1.2607281E -22 | -2.34181944E -23 | |
| $a_9$ | -3.2447087E -41 | | -1.052755E -35 | 3.1353611E -26 | 2.79786260E -27 | |
| $a_{10}$ | | | | -3.3187769E -30 | | |
| **Error** | ±0.02° C | ±0.05° C | ±0.05° C | ±0.02° C | ±0.02° C | ±0.03° C |

The errors listed in Table 1 apply only to the polynomial calculation, and do not take into account errors introduced by the measurement system or thermocouple itself.

Recall that Procedure 1 for software cold-junction compensation also requires a temperature-to-voltage step to convert the cold-junction temperature into the equivalent voltage for the specific thermocouple type. Again, you can use either thermocouple reference tables, or approximate the curve with a polynomial. NIST also specifies a set of polynomials for the thermocouple voltage as a function of temperature,

$$v = c_0 + c_1 T + c_2 T^2 + ... + c_n T^n \quad (8)$$

where $c_0$ through $c_n$ are coefficents that are specific to each thermocouple type. Table 2 lists NIST polynomials for temperature-to-voltage conversion for several popular thermocouple types.

NIST also specifies sets of polynomials that cover temperature ranges other than those lited in Tables 1 and 2. More examples of polynomials, including wider temperature ranges, are listed in the National Bureau of Standards Monograph 175 (see *References*).

To speed computation time, a polynomial can be computed in nested form. Consider the fourth order polynomial:

$$T = a_0 + a_1 v + a_2 v^2 + a_3 v^3 + a_4 v^4 \quad (9)$$

If this polynomial is evaluated as written, several unnecessary multiplications will be performed to raise *v* to the various powers. If the polynomial is written and evaluated instead as shown in the following formula, no powers are calculated and computation executes much faster:

$$T = a_0 + v(a_1 + v(a_2 + v(a_3 + v a_4))) \quad (10)$$

These NIST polynomials are implemented in functions included with LabVIEW, LabWindows/CVI, and NI-DAQ software from National Instruments.

**Note:** ***As a precaution, check the units specified for the voltages. For the formulas in Tables 1 and 2, the voltages are in microvolts. For some other thermocouple tables and linearization polynomials, the voltages may be in millivolts or volts. Using the incorrect unit yields erroneous results.***

# Thermocouple Measurements with a DAQ System

Thermocouples are commonly used to monitor temperature with PC-based DAQ systems. For example, the National Instruments SCXI product line is especially well-suited for thermocouple measurements.

SCXI is a front-end instrumentation system for plug-in DAQ boards. A shielded, rugged chassis houses signal conditioning modules that amplify, filter, isolate, and multiplex analog signals from thermocouples or other transducers. The amplified analog signal is then cabled to the plug-in digitizing DAQ board, or passed to a local SCXI digitizing DAQ module. Figure 6 shows some of the hardware in the SCXI product line.

For some applications, you may be able simply to use a plug-in DAQ board with termination accessories equipped with temperature sensors for cold-junction compensation, such as the AMUX-64T multiplexer board and the SC-207X Series termination panels.

Table 2. NIST Polynomial Coefficients for Temperature-to-Voltage Conversion ($v = c_0 + c_1T + c_2T^2 + ... + c_nT^n$)

| | **Thermocouple Type** | | | | | |
|---|---|---|---|---|---|---|
| | **E** | **J** | **K** | **R** | **S** | **T** |
| **Range** | **0° to 1,000 °C** | **-210° to 760 °C** | **0° to 1372°C** | **-50° to 1,064 °C** | **-50° to 1,064 °C** | **0° to 400 °C** |
| $c_0$ | 0.0 | 0.0 | -17.600413686 | 0.0 | 0.0 | 0.0 |
| $c_1$ | 58.665508710 | 50.38118782 | 38.921204975 | 5.28961729765 | 5.40313308631 | 38.748106364 |
| $c_2$ | 4.503227558E -2 | 3.047583693E -2 | 1.85587700E -2 | 1.3916658978E -2 | 1.2593428974E -2 | 3.32922279E -2 |
| $c_3$ | 2.890840721E -5 | -8.56810657E -5 | -9.9457593E -5 | -2.388556930E -5 | -2.324779687E -5 | 2.06182434E -4 |
| $c_4$ | -3.30568967E -7 | 1.322819530E -7 | 3.18409457E -7 | 3.5691600106E -8 | 3.2202882304E -8 | -2.18822568E -6 |
| $c_5$ | 6.50244033E -10 | -1.7052958E -10 | -5.607284E -10 | -4.62347666E -11 | -3.314651964 -11 | 1.09968809E -8 |
| $c_6$ | -1.9197496E -13 | 2.09480907E -13 | 5.6075059E -13 | 5.007774410E -14 | 2.557442518E -14 | -3.0815759E -11 |
| $c_7$ | -1.2536600E -15 | -1.2538395E -16 | -3.202072E -16 | -3.73105886E -17 | -1.25068871E -17 | 4.54791353E -14 |
| $c_8$ | 2.14892176E -18 | 1.56317257E -20 | 9.7151147E -20 | 1.577164824E -20 | 2.714431761E -21 | -2.7512902E -17 |
| $c_9$ | -1.4388042E -21 | | -1.210472E -23 | -2.81038625E -24 | | |
| $c_{10}$ | 3.59608995E -25 | | **NOTE A** | | | |

**NOTE A:** The equation for type K is $v = c_0 + c_1T + c_2T^2 + ... + c_9T^n + 118.5976e^{(-1.183432E-4)(T- 126.9686)^2}$

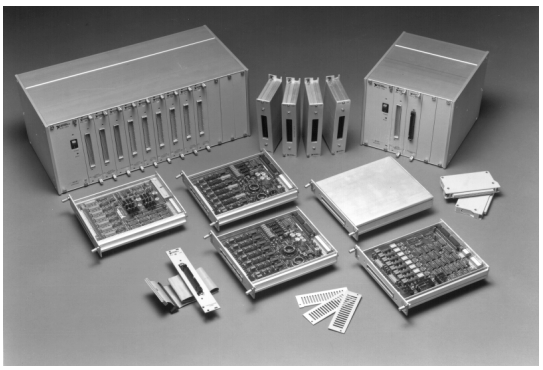


Figure 6. SCXI Signal Conditioning and Data Acquisition System

## Thermocouple Measurements with SCXI

The SCXI product line includes a variety of analog and digital signal conditioning modules for various types of signals, including thermocouples, RTDs, thermistors, strain gauges, voltage, and current sources. The SCXI-1102, SCXI-1120, and SCXI-1122 modules in particular are well suited for use with thermocouples. The SCXI-1120, SCXI-1121, and SCXI-1122

provide isolated measurements, which prevents problems caused by ground loops, high common-mode voltages, and high voltages in general.

The SCXI-1102 is a nonisolated thermocouple amplifier module. Table 3 summarizes the capabilites of these input modules.

## Signal Conditioning for Thermocouples

The following sections describe some general measurement system capabilities that can be important when measuring thermocouples.

### Low-Noise System

Low-level thermocouple signals are very susceptible to noise corruption. Therefore, it is very important that the signal conditioning and DAQ hardware are well shielded with very low-noise performance. For example, the SCXI chassis and modules are fully shielded. The backplane analog bus, the SCXIbus, is optimized for low-noise performance and avoids noise corruption caused by high-speed digital signals. In addition, the cable connecting the SCXI system to the plug-in DAQ board uses shielded, twisted-pair cable for the best possible noise performance.

You can also improve the noise performance of your system significantly by amplifying the low-level thermocouple voltages at as short a distance as possible from the actual thermocouple. Thermocouple wire can act like an antenna and pick up unwanted noise from the environment. Because thermocouple voltages are extremely small, typical electrical noise levels can seriously corrupt the measurement.

SCXI modules, however, amplify the thermocouple voltage near the thermocouple before the signal is passed over the cabling through a potentially noisy environment, and into the noisy computer chassis. Because the thermocouple signal has been amplified to a higher level, the noise that is picked up in the wiring and in the computer has much less of an effect and causes a relatively smaller measurement error.

Table 3. SCXI Signal Conditioning Modules for Thermocouples

| | **SCXI-1102** | **SCXI-1120/1121** | **SCXI-1122** |
|---|---|---|---|
| Number of inputs | 32 | 8 (SCXI-1120)<br>4 (SCXI-1121) | 16 |
| Amplifier gains | 1 or 100<br>– software-programmable<br>– selectable per channel | 1 to 2,000<br>– jumper-selectable<br>– selectable per channel | 0.1 to 2,000<br>– software-programmable<br>– selectable per module |
| Filtering options | 1 Hz | 4 Hz or 10 kHz | 4 Hz[1] or 10 kHz |
| Isolation | N/A | 250 Vrms | 450 Vrms |
| Recommended terminal block for thermocouples | SCXI-1303 or TBX-1303 | SCXI-1328 or TBX-1328 | SCXI-1322 |

[1] This filter setting requires slower acquisition rate; check product data sheet for full details.

## High Amplification

Because thermocouple output voltage levels are very low, you should use as large a gain as possible for the best resolution and noise performance. Amplification, together with the input range of your analog-to-digital converter (ADC), determines the usable input range of your system. Therefore, you should carefully select your amplification so that the thermocouple signal does not exceed this range at elevated temperatures.

Table 4 lists the voltage ranges from several standard thermocouple types; you can use this table as a guide for determining the best gain and input range settings to use.

For example, a J-type thermocouple outputs -8 mV at -210° C and 33 mV at 600° C. If you are using a J-type thermocouple over this temperature range with SCXI and an AT-MIO-16E-2 board, set your SCXI module gain to 100. In this configuration, the effective input range of the system is ±5 V/100 = ±50 mV. Because the AT-MIO-16E-2 uses a 12bit ADC with $2^{12}$ binary levels, the resolution of this system with a total gain of 100 is 10 V/(100 x 4,096) = 24 µV. If you are using the thermocouple over a more limited temperature range, you can use a higher gain to obtain higher resolution.

## Input Filtering

To further reduce noise, the SCXI-1102, SCXI-1120, and SCXI-1121 include a lowpass resistor-capacitor (RC) filter for each input channel. The SCXI-1102 includes a fixed 1 Hz filter on each channel. The SCXI-1120 and SCXI-1121 filters are jumper-selectable for 4 Hz or 10 kHz. These filters are useful for removing the 60 Hz power line noise that is prevalent in most laboratory and plant settings. The SCXI-1122 module includes a single lowpass filter that can be enabled or disabled. Because this filter is applied to the output of the module, after the multiplexer, the filter should be used only for very low scanning rate applications.

## Broken Thermocouple Detection

It is useful to be able to detect a break, or open circuit, in the thermocouple circuit. You can use the characteristics of SCXI amplifiers to detect broken thermocouples. A differential amplifier saturates to either full-scale positive or full-scale negative output if the input leads are open circuit. Therefore, when a thermocouple is broken, the SCXI amplifier saturates and produces a full-scale output in either direction. You can check for this saturation condition with software and take the necessary actions.

## Temperature Sensor for Cold-Junction Compensation

As discussed earlier, thermocouple measurements require sensing of the cold-junction, or reference, temperature at the point where the thermocouple wire is connected to the measurement system. Therefore, signal connection accessories should include an accurate cold-junction sensor, and should be designed to minimize any temperature gradients between the cold-junction sensor and thermocouple wire connections.

Shielded terminal blocks connect thermocouples to the SCXI signal conditioning modules. Table 3 lists which terminal blocks provide the most accurate cold-junction sensing. These terminal blocks use a high-precision thermistor to measure the cold-junction temperature. These terminal blocks also use an isothermal design to minimize temperature gradients across the screw terminals. For example, the SCXI-1328 uses screw terminals embedded in an aluminum isothermal plate that helps maintain all the screw terminals and the temperature sensor at the same temperature. With these terminal blocks, you can measure the reference temperature with 0.5° C accuracy. Other general purpose terminal blocks, as well as the AMUX-64T multiplexer board and SC-207X Series termination boards, use the National Semiconductor LM-35CAZ temperature sensor. The LM-35CAZ temperature sensor produces a linear voltage output of 10 mV/°C.

Table 4. Thermocouple Voltage Output Extremes (mV)

| Thermocouple Type | Conductor | | Temperature Range (°C) | Voltage Range (mV) | Seebeck Coefficient (μV/°C) |
|---|---|---|---|---|---|
| | Positive | Negative | | | |
| E | Chromel | Constantan | -270° to 1,000° | -9.835 to 76.358 | 58.70 at 0° C |
| J | Iron | Constantan | -210° to 1,200° | -8.096 to 69.536 | 50.37 at 0° C |
| K | Chromel | Alumel | -270° to 1,372° | -6.548 to 54.874 | 39.48 at 0° C |
| T | Copper | Constantan | -270° to 400° | -6.258 to 20.869 | 38.74 at 0° C |
| S | Platinum-10% Rhodium | Platinum | -50° to 1,768° | -0.236 to 18.698 | 10.19 at 600° C |
| R | Platinum-13% Rhodium | Platinum | -50° to 1,768° | -0.226 to 21.108 | 11.35 at 600° C |

## High-Performance Scanning

Although thermocouples are generally used for low-bandwidth applications, you may need to use high scanning rates to minimize sampling delays between channels and for applications involving large numbers of channels. For example, a 10 Hz scanner monitoring 300 thermocouples can sample each thermocouple only once every 30 s. An SCXI system with the AT-MIO-16E-2 DAQ board, on the other hand, can scan input channels at up to 3 μs per channel. Therefore, an SCXI system can sample each of the 300 thermocouples every 0.9 ms. Also, higher scanning rates minimize the sampling delay from channel to channel.

## Differential Measurements

If you are using any thermocouples that are grounded, a differential measurement is important. With differential measurements, each channel uses two signal leads; only the voltage difference between the leads is measured. The differential amplifier rejects ground-loop noise and common-mode noise, which therefore do not corrupt the measurement. With single-ended measurements, on the other hand, the negative leads of all the input signals are connected to a common ground. SCXI analog input modules use differential input measurements.

If you are connecting thermocouples directly to your DAQ board and are not using SCXI, use the differential input mode of the board, if possible. You can configure the MIO Series boards, Lab Series boards, and DAQPad units for differential inputs.

# Thermocouple Examples

The following section includes some examples to assist you in making your own thermocouple measurements.

## Example 1–Monitoring 64 Thermocouples with SCXI-1102s

For this example, assume that you want to use 64 K-type thermocouples to measure the temperature of a high-pressure boiler system with a known maximum temperature of 250° C. Assuming that electrical isolation is not important for this application, you can use two SCXI-1102 modules to monitor the 64 thermocouples. Figure 7 diagrams the complete DAQ system.

The AT-MIO-16E-2 board is used to acquire the readings because the board has a higher scan rate, self-calibration, and high-performance direct-memory access (DMA) capabilities. The two SCXI-1102 modules are housed in an SCXI-1000 four-slot chassis and connected to the AT-MIO-16E-2 board with one SCXI-1349 shielded cable assembly. This SCXI-1349 cable assembly is available in lengths up to 10 m.

An IBM PC/XT/AT or compatible computer running Windows controls the temperature monitoring system. Therefore, application software choices for controlling the system include LabVIEW, LabWindows/CVI, or ComponentWorks. Alternatively, you can use a standard programming language in Windows, such as C, Pascal, or Visual Basic, and control the DAQ hardware with the NI-DAQ driver software that is included with National Instruments plug-in DAQ boards.

You connect the thermocouples to the SCXI-1102 modules with SCXI-1303 or TBX-1303 terminal blocks. Each terminal block includes an accurate sensor for cold-junction compensation. In addition, you can configure the SCXI-1303 and TBX-1303

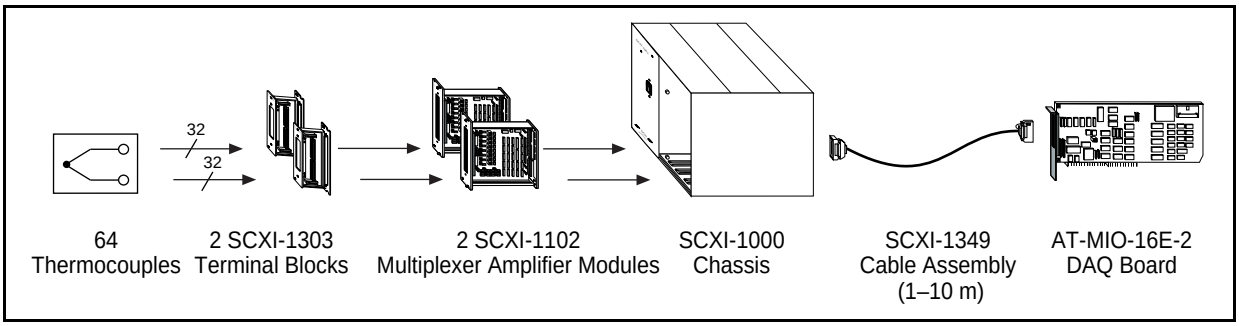



Figure 7. SCXI System for Monitoring 64 Thermocouples

terminal blocks with a high-impedance ground reference on each channel. In this configuration, you can connect either floating or ground-referenced thermocouples.

A thermocouple reference table shows that the output voltage for temperatures less than 250° C never exceeds 10 mV (recall that the voltage measured is a function of the reference temperature as well as the temperature being measured). Therefore, a ±5 V input range with a total system gain of 500 (±10 mV maximum signal) accommodates the maximum expected signal from the thermocouple. With this gain setting, the resolution is 10 V/(500 x 4,096) = 4.9 μV, or 0.12° at 250° C.

Both the AT-MIO-16E-2 board and SCXI-1102 module include amplifiers that you configure via software. Because using the largest gain possible near the signal source yields the best noise performance, configure the SCXI-1102 module for a gain of 100 and the AT-MIO-16E-2 board for a gain of 5. With LabVIEW, you can simply indicate the high and low input limits (±10 mV in this example), and the driver software calculates the necessary gain for both the plug-in board and the SCXI module.

The following sections detail two software compensation procedures for this example. The first method is more accurate, but the second method is faster. Consult your software reference manual to determine the actual functions you need. For example, LabVIEW, LabWindows, ComponentWorks, and NI-DAQ implement thermocouple conversion routines that convert measured voltage values into temperatures for different thermocouple types and perform cold-junction compensation.

## Procedure 1–Direct Voltage Addition Method of Software Compensation for Example 1

1. Read the voltage from the temperature sensors (MTEMP) located on each SCXI-1303 terminal block. The thermistor used for cold-junction sensing in the SCXI-1303 will output a voltage ranging from 0.58 V to 1.91 V. Therefore, the gain on the AT-MIO-16E-2 should be either 1 or 2 (2 for the best resolution). After measuring the voltage output of the thermistor, use the thermistor conversion routine provided with LabVIEW and NI-DAQ to convert this voltage to temperature. For example, an MTEMP thermistor reading of 1.25 V from the SCXI-1303 corresponds to a cold-junction temperature of 25˚ C.
2. Translate this cold-junction temperature reading into the corresponding voltage for a K-type thermocouple at that temperature using either a look-up table or an NIST polynomial. Notice that the

polynomials required here are the *inverses* of those given in Table 1. Using a look-up table, or temperature to voltage conversion routine (such as the one provided with LabVIEW), your reading of 25˚ C translates to a K-type thermocouple voltage of 1.000 mV.

3. Read the voltages on the thermocouple channels. For the example given, assume that you get a reading of 2.930 mV on Channel 1.
4. Add the voltage from step 2 to the voltage measured in step 3. You then have

   1.000 + 2.930 = 3.930 mV
5. Translate the result into a temperature using either a look-up table or a polynomial such as one from Table 1. For the reading from the K-type thermocouple of 3.930 mV, for example, you can calculate that the temperature is 96.15° C.

## Procedure 2–Temperature Addition Method of Software Compensation for Example 1

1. Read the voltage from the temperature sensors (MTEMP) located on each SCXI-1303 terminal block. The thermistor used for cold-junction sensing in the SCXI-1303 will output a voltage ranging from 0.58 V to 1.91 V. Therefore, the gain on the AT-MIO-16E-2 should be either 1 or 2 (2 for the best resolution). For example, an MTEMP thermistor reading of 1.25 V from the SCXI-1303 corresponds to a cold-junction temperature of 25˚ C.
2. Read the voltages on any thermocouple channels. For the example given, the gain is at 500 for Channel 1.
3. Translate the reading into a temperature using either a look-up table or a polynomial such as one from Table 1; you get a reading of 2.930 mV. By applying formula 3 and the coefficients from Table 1, you can calculate that the temperature is 71.6° C.
4. Add the cold-junction temperature from step 1 to the temperature obtained in step 3. The result is the temperature at the measuring end of the thermocouple. For the example given, the temperature of the boiler system is 71.6° + 25° = 96.6° C. In this case, the error introduced by using this faster method is 0.45° C.

**Comments**

Procedure 1 is more accurate but requires two temperature-to-voltage conversions. Procedure 2 is faster but introduces an error of 0.45° C. To determine if the error from procedure 2 is acceptable in your application, you can work through some examples both ways. Use a thermocouple reference table and consider voltages and temperatures close to those in your application.

## Example 2–Temperature Control with SCXI-1120

Consider another application that uses a Macintosh computer with SCXI to control the temperature of 16 environmental chambers in a testing facility. A J-type thermocouple in each chamber monitors the temperature, which never exceeds 200° C. Each chamber includes a heater that turns on and off to maintain the temperature at the desired setpoint.

Another requirement for this application is that the controlled systems be electrically isolated from the computer that is monitoring and controlling the station. This protects the computer and DAQ hardware from large voltage spikes and prevents the ground-loop voltages that can occur.

Figure 8 shows the complete system for this application. Because isolation is required, you should use the SCXI-1120 isolated amplifier module. This module includes eight isolation amplifier channels, which can operate with a common-mode voltage of 240 Vrms between channel and earth or between channels. The 16 thermocouples are connected to the two SCXI-1120 modules

using two SCXI-1320 terminal blocks. This terminal block includes a temperature sensor for cold-junction compensation.

For more accuracy, you can substitute the SCXI-1328 terminal block, which includes a high-precision thermistor and an isothermal aluminum plate to minimize temperature gradients.

To control the heaters, you can use the SCXI-1160 single-pole double-throw (SPDT) relay module. This module includes 16 independent SPDT latching relays that can switch up to 2 A at 250 VAC or 30 VDC. You can use this module with an SCXI-1324 terminal block to control the on-off state of the 16 heaters.

In this example, an NB-MIO-16L-9 multifunction plug-in DAQ board controls the two SCXI-1120 isolation amplifier modules and the SCXI-1160 relay module. The modules are housed in an SCXI-1000 chassis and cabled to the NB-MIO-16L-9 board with an SCXI-1345 shielded cable assembly.

You can control the DAQ hardware of this example using LabVIEW on the Macintosh. Alternatively, you can use traditional programming languages with the NI-DAQ driver software included with National Instruments plug-in DAQ boards for the Macintosh.

Again, you must first determine the configuration of the SCXI-1120 modules and NB-MIO-16L-9 board that yields the maximum resolution possible. Because the chamber temperature will never exceed 200˚, configure the jumpers of the SCXI-1120 modules for a gain of 500. This yields an input range of ±10 mV forthe system. Next, configure the NB-MIO-16L-9 for an input range of ±5 V and a gain of 1.

The steps for measuring and compensating the thermocouple readings are identical to those of example 1.

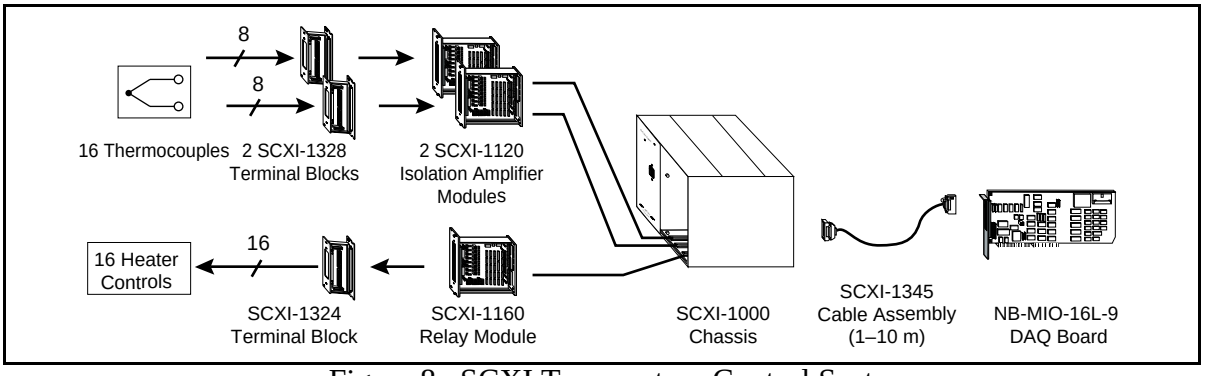



Figure 8. SCXI Temperature Control System

# Sources of Error

When making thermocouple measurements, the possible sources of error include compensation, linearization, measurement, thermocouple wire, and experimental errors.

Cold-junction compensation errors can arise from two sources–inaccuracy of the temperature sensor and temperature differences between the sensor and the screw terminals. The LM-35CAZ sensor on the SCXI-1300, SCXI-1320, and SCXI-1321 terminal blocks has an effective accuracy of 0.9° C. In addition, temperature gradients between the sensor and the screw terminals can be as high as 0.5° C, for a total accuracy of 1.4° C. The SCXI-1303, SCXI-1322, SCXI-1328, TBX-1303, and TBX-1328 isothermal terminal blocks, however, limit temperature gradients and use a high-precision thermistor for better accuracy.

Table 5 lists the cold-junction sensing accuracy for the various terminal blocks.

Linearization error occurs because polynomials are approximations of the true thermocouple output. The linearization error depends on the degree of the polynomial used. Table 1 lists the linearization errors for the NIST polynomials.

Table 5. Cold-Junction Sensing Accuracy

| **Terminal Block** | **CJC Accuracy (15° to 35° C)** |
|---|---|
| SCXI-1303, TBX-1303 | 0.65° C |
| SCXI-1328, TBX-1328 | 0.50° C |
| SCXI-1322 | 0.8° C |
| SCXI-1300, SCXI-1320, SCXI-1321, SCXI-1327 | 1.3° C |

Measurement error is the result of inaccuracies in the DAQ board and signal conditioning modules. These include offset error, gain error, nonlinearities, and resolution of the ADC. Although SCXI modules are calibrated to minimize offset errors, you can completely remove the offset error of any module by grounding the input, taking a reading, and subtracting this offset error from subsequent readings.

Both the plug-in board and the SCXI module can also introduce gain error. For example, a calibrated AT-MIO-16XE-50 has a gain error of less than 0.01%, and the SCXI-1102 introduces a typical gain error of 0.02% at gain = 100. If the input range is ±5 V and the total system gain is 500, gain error contributes a maximum of (0.02% + 0.01%) x 20 mV, or 6 μV of error. However, you can use an external calibration source to completely remove this gain error.

Other sources of measurement error include the nonlinearity and resolution of the digitizing DAQ board or module. However, these errors are typically minimized by the high gain of the SCXI module. For example, the specified relative accuracy of the AT-MIO-16E-2, which includes resolution and nonlinearity, is ±0.5 least significant bits (LSB). Used with an SCXI module that provides a system gain of 500, however, this error is equivalent to only 0.5(20 mV/4,096) = 2.4 μV. With a J-type thermocouple, for example, this is equivalent to 0.05° C at room temperature.

Often, the major source of error is the thermocouple itself. Thermocouple wire error, for example, is caused by inhomogeneities in the thermocouple manufacturing process. These errors vary widely depending on the thermocouple type and even the gauge of wire used, but a value of ±2° C is typical. Check with the thermocouple manufacturer for exact accuracy specifications.

Another potential source of error is noise picked up by the thermocouple leads. Software averaging of the acquired data can remove noise from your measurements.

Table 6 lists the expected measurement error and resolution in degrees Celsius, subject to the following conditions:

- A calibrated SCXI-1102 , SCXI-1122, or SCXI-1120 module, configured for gains of 100 and 500.
- A calibrated AT-MIO-16XE-50 configured for a gain of 1 and an input range of ±10 V

The errors listed in Table 6 include the measurement error of a calibrated AT-MIO-16XE-50 and SCXI module, and the cold-junction sensor error of the SCXI-1303, SCXI-1328, or SCXI-1322 terminal block. The linearization errors of the NIST polynomials and thermocouple wire error is neglected because of dependence on several factors as previously listed..

The errors listed in Table 6 are of the format:

$$\pm(x\% \text{ of reading} + y\ ^\circ \text{C})$$

For example, an SCXI-1122 configured for a gain of 500 and used with an AT-MIO-16XE-50 has an accuracy of ±(0.02% of reading + 0.81° C). Therefore, at a temperature reading of 70° C, the accuracy is ±(0.02% of 70° C + 0.81° C) = ±0.82° C. This accuracy includes the potential error of the
cold-junction compensation reading.

# Conclusion

Thermocouples are inexpensive temperature sensing devices that are widely used with PC-based DAQ systems. Thermocouple measurement requires signal conditioning, including cold-junction compensation, amplification, and linearization. The National Instruments SCXI signal conditioning system is a low-noise front end for PC-based DAQ systems when you use thermocouples to measure temperature.

# Reference

G. W. Burns, M. G. Scroger, G. F. Strouse, et al. *Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the IPTS-90* NIST Monograph 175. Washington, D.C.: U.S. Department of Commerce, 1993.

Table 6. Thermocouple Measurement Accuracies with SCXI-1102, SCXI-1120, or SCXI-1122 with AT-MIO-16XE-50

| Amplifier Gain[1] | | Thermocouple Type | | | |
|---|---|---|---|---|---|
| | | **J** | **K** | **E** | **T** |
| 500 | **Temp. Range**[2] | -210° to 366° C | -270° to 485° C | -199° to 307° C | -270° to 406° C |
| | **Resolution** | 0.05° C | 0.06° C | 0.04° C | 0.06° C |
| | **Accuracy**[3] | | | | |
| | SCXI-1102 | 0.02% + 0.72 °C | 0.02% + 0.76 °C | 0.02% + 0.70 °C | 0.02% + 0.76 °C |
| | SCXI-1122 | 0.02% + 0.81 °C | 0.02% + 0.82 °C | 0.02% + 0.81 °C | 0.02% + 0.82 °C |
| | SCXI-1120 | 0.15% + 0.55 °C | 0.15% + 0.58 °C | 0.15% + 0.54 °C | 0.15% + 0.59 °C |
| 100 | **Temp. Range**[2] | -210° to 1,200° C | -270° to 1,254° C | -270° to 1,000° C | n/a |
| | **Resolution** | 0.24° C | 0.31° C | 0.21° C | n/a |
| | **Accuracy**[3] | | | | n/a |
| | SCXI-1102 | 0.02% + 0.75 °C | 0.02% + 0.81 °C | 0.02% + 0.73 °C | |
| | SCXI-1122 | 0.02% + 0.88 °C | 0.02% + 0.92°C | 0.02% + 0.86 °C | |
| | SCXI-1120 | 0.15% + 1.1 °C | 0.15% + 01.4°C | 0.15% + 1.0 °C | |

[1]With SCXI-1102, gain = 500 is achieved with gain of 100 on SCXI-1102 and gain of 5 on AT-MIO-16XE-50

[2]Assumes the cold junction temperature is 25° C.

[3]Includes the measurement error of the SCXI module, terminal block (0.65 ° max for SCXI-1303, 0.80 °C max for SCXI-1322 and 0.5° C for SCXI-1328). Does not include polynomial linearization error or thermocouple inaccuracy.