High-accuracy Temperature Measurement

Understanding the Temperature Measurement Application

Basic Problem Definition

There are many different approaches and techniques for measuring temperature, but one of the most fundamental issues involves understanding the application at hand. A basic evaluation of the application would include:

- **Physical environment**
- **Test sample physical constraints**
- **Temperature range**
- **Required accuracies**

This list may seem trivial, but the answers to these questions will help determine the type of transducer, the measurement instruments, and the approach that must be taken to physically interface to the test article.

Measurement Alternatives

The most common temperature measurement transducers available are:

- **Thermocouple**
- **RTD**
- **Thermistor**
- **IC sensor**

Each of these devices has been designed to address specific application spaces, and therefore it may not be appropriate to use these devices interchangeably. The fundamental operation of these devices varies significantly, and may limit the hardware that can be used for the measurement.

Thermistors and RTDs, for example, rely on the fact that the resistance of the material will change as the temperature that the transducer is in contact with changes. Like any resistance measurement, however, these devices require an external excitation current permitting the instrument to measure the voltage drop across the device. Additionally, some of these devices are manufactured in three- and four-wire configurations to increase accuracies. RTD devices generate the resistance change based on a metal junction and tend to be relatively linear in nature. The thermistor relies upon a ceramic semiconductor device to generate the resistance changes, and the response is nonlinear.

Transducer	Advantages	Disadvantages
Thermocouple	Very Inexpensive Rugged Easy to use Many sources Wide temperature range Many styles	Non-linear Microvolt-level response External reference voltage required Low sensitivity Slow response Low stability
Thermistor	Extremely fast Moderately stable High output level Resistance measurement Small size	Non-linear Fragile Narrow temperature range External current source required Inherently self heating
RTD	Extremely accurate Extremely stable Moderate linearity Many configurations	Slow response Expensive External current source required 3/4-wire measurement
I.C. Sensor	Extemely Linear Low cost High output	Slow response Limited temperature range External source required Inherently self heating

High-accuracy Temperature Measurement

ADC Type	Properties
Flash	Ultra-high speed, high input bandwidth
Pipeline	High throughput rate, medium bandwidth
Successive-Approximation-Register	Medium resolution, medium speed
Delta-Sigma	High resolution, medium speed
Integrating	Extremely high resolution

Table 2

Thermocouple and IC sensors generate a voltage (or possibly a current with the IC sensor) proportional to a specific temperature. Thermocouple devices rely on the principle that when two dissimilar metals are placed in contact with one another, a thermal electromotive force (EMF) will be generated. This is generated relative to the temperature, and it is nonlinear in nature. We will explore this phenomenon in much greater detail in the following sections.

Selection of the proper transducer to perform most efficiently for an application requires knowledge of certain key functional characteristics. A thermistor, for example, is designed for speed and accuracy, but it is not very robust and is susceptible to breakage. The thermocouple, on the other hand, is capable of withstanding a considerable amount of physical abuse, but it is the least accurate.

Table 1 lists the various transducer types, and indicates the advantages and disadvantages of each.

Instrumentation Essentials

ADC Selection

Temperature measurement shares many of the same challenges faced by other measurement devices, in addition to several challenges unique to this application area. Whether the measurement involves an RTD, thermistor, or thermocouple the instrument will ultimately measure a voltage.

The transducer voltage is measured with an A/D converter. There are many choices available to the designer, as can be seen in the Table 2, but the unique characteristics of the thermocouple narrow the choice. Table 2 lists the most common ADC types and their characteristics.

An ideal choice thermocouple voltage conversion is the successive-approximation-register (SAR) analog-to-digital converter. SAR devices are designed for use when sampling rates are below 5 MSa/s and they provide medium to high resolution conversion. The need to sample thermocouples higher than a few hundred samples per second does not exist, primarily because the thermocouple device is not capable of responding to changes fast enough to make this necessary. Other attractive characteristics of the SAR include small size and low power consumption.

Signal Multiplexing

The Concern

The physical environment that a thermocouple is used in is inherently noisy and susceptible to interference from a wide range of sources. It is not uncommon for the device under test to be producing significant electrical noise above that of the ambient environment.

The Results

Most temperature measurement instrumentation, due to the relatively slow sampling requirements, will not incorporate a separate ADC on a per-channel basis. The instrument will utilize a multiplexer configuration connected to a single ADC; typical channel configurations are 16, 32, 48, and 64 channels. Many temperature related tests have been known to execute for extended periods of time, from days to weeks, therefore mechanical relays would not be appropriate due to the finite life span involved. High-speed solid state multiplexer circuits are therefore typically specified.

The very nature of the microvolt level thermocouple signals can create system level issues when used with less capable hardware designs. A high level, or over-load condition, applied to a channel adjacent to a thermocouple channel, can generate an error when the thermocouple channel is measured; a condition that may not be known to the user. This error can be due to stray capacitance and charges on the line. Some hardware designs that are unable to deal with these typical occurrences require the user to remain on a channel for an excessive period of time and over-sample and average to obtain a result.

The Best Approach

A high quality thermocouple measurement instrument will not depend on over-sampling and software averaging to obtain a marginally acceptable result. Each channel should be designed with independent filtering and amplification to isolate channel-to-channel operation. The signal sent to the ADC from the multiplexers will, therefore, not generate interference. Designs such as this will ensure that the data converted by the ADC is valid for each channel, regardless of an over-voltage or loading condition that might occur on adjacent channels.

High-accuracy Temperature Measurement

Analog Filtering

The Concern

Thermocouple voltages, being of microvolt level, often require significant bandwidth limiting to reject the effects of 50/60 Hz interference. This is particularly important in industrial environments where the thermocouple is exposed to significant electrical noise from motors, generators, welding devices, lighting, etc.

The Results

Many thermocouple measurement devices, such as DMM based systems, provide some level of programmable 50/60 Hz rejection. However, this bandwidth limiting is achieved through the setting of the ADC's integration rate. Specifically, 50/60 Hz rejection is improved by integrating over an integer number of power line cycles (PLC). This approach may reduce the effects of 50/60 Hz noise, but it results in substantially slower channel sampling rates. Furthermore, because this is a global setting, all channels in the system must scan at the reduced rate, even if only one channel requires it.

PC based relay multiplexer devices, in an apparent effort to reduce costs, typically do not offer any analog filtering and rely on averaging or other software techniques to manipulate the data. This can present difficulties when accurate, clean data is required across the measurement spectrum. It may become necessary to add additional external filtering circuits in an effort to improve the signal integrity. Clearly, the apparent lower cost solution does not turn out to be so.

The Best Approach

Leading edge instrumentation designers do not rely on the ADC to provide bandwidth limiting, nor do they rely on software over-sampling and averaging techniques. Bandwidth limiting is instead done in each channel's signal conditioning path; the approach permits each channel to be independently set to a specific cutoff frequency. A flexible approach would allow for multiple cutoff frequency ranges; a selection of 4 Hz or 1 kHz bandwidth would be appropriate. 4 Hz is suitable for most thermocouple/low voltage measurements and maximizes the (50/60) Hz rejection. The 1 kHz selection is suitable for fine gage thermocouples and higher speed voltage measurements.

The Critical CJC Circuit

The Concern

The cold junction compensation (CJC) circuit is arguably at the heart of a truly accurate thermocouple measurement engine. Even an isothermal block with significant thermal mass will slowly change temperature in phase with the ambient surroundings. Therefore, measurement errors will be guaranteed if these effects are underestimated, or not correctly addressed.

The Results

The accuracy of typical multiplexer card PC and DMM based system is, in general, about 1.0 ˚C - 1.5 ˚C. The reasons for this vary, and include issues such as low thermal mass isothermal blocks, incorrect or insufficient CJC sensor placement, or poor location of the terminal blocks in respect to adjacent sources of heat such as power supplies and displays. The bulk of the error in most implementations can be attributed to poorly designed CJC sensor circuits, and the input-to-CJC thermal coupling mechanisms.

The Best Approach

A quality temperature measurement instrument will incorporate a high-precision CJC mechanism, significant thermal mass, careful placement of parts that generate internal temperature gradients, and self-calibration functionality. The CJC sensor is typically a precision thermistor device and it is not uncommon for several of these devices to be located at strategic points on the isothermal block. A system level measurement accuracy of 0.2 ˚C - 0.4 ˚C is possible when focusing on these details. This would result in one of the most accurate thermocouple instruments available.

Open Thermocouple Detection

The Concern

Open thermocouple detection is one of the most important features of any thermocouple measurement instrument, as it safeguards the user from invalid data that would occur from an open sensor connection. However, the implementation of this feature will truly determine its effectiveness and the amount of faith that the user can place in the results. Many thermocouple multiplexer cards offer open TC detection upon command; however, this is performed outside the temperature scanning process. Specifically, the system performs a resistance measurement between the two input terminals and reports an open if the resistance exceeds a pre-determined threshold. This is an acceptable approach for checking for opens before a test is started, but does nothing to ensure that the integrity of the measurement is maintained during a temperature test of very long duration. Consequently, an open connection that occurs during a test will often result in a reading that looks very normal, as evidenced by this scenario.

High-accuracy Temperature Measurement

The Results

Assume that there is a broken (open) channel that is preceded by a valid channel. During the connection and measurement of the valid channel, the front end of the instrument will be sitting stable at some valid voltage. When the scanner switches to the broken channel, the front end of the instrument, being high impedance, will start to slowly drift away. However, the time spent on this open channel will usually not be long enough to allow the DMM to drift very far.

Accordingly, the instrument will compute a valid temperature value that is very close to the value reported on the preceding channel, but totally unrepresentative of the actual temperature of that channel. The user will receive incorrect data and have no way of knowing it!

The Best Approach

The best philosophy for monitoring thermocouple is when each channel has its own independent amplifier path that is biased by a very small current. In the case of a valid connection, this current will flow in the thermocouple leads, but is so small that it causes insignificant voltage drop. However, if a lead breaks, this current serves to quickly drive the high impedance amplifier into saturation, creating a reliable overload measurement condition.

With this architecture, open TC detection is embedded in the signal conditioning operation, instead of being disjointed from it. The detection is not dependent on sampling rate and all the channels are completely independent. Another aspect of the architecture is that there is a bias current on both leads. This is important for thermocouples that are electrically connected to ground at the DUT. By biasing both leads, an open condition will be reported even if only one of the wires is open and the other is grounded.

Calibration

Calibration of any measurement device is essential in order to generate published accuracies, but many mission critical applications require accuracies that an annual metrology schedule cannot guarantee. High-quality temperature measurement instrumentation will be designed to include an integrated internal calibration subsystem specifically designed to meet this need.

In essence, a thermocouple measurement instrument is a high precision, low voltage measurement device. Therefore, the calibration of such instruments will follow that of a typical voltmeter. Specifically, it must contain a stable precision voltage source that can be set to produce nominal values, for example ±95 mV, ±45 mV, and 0 mV. During calibration, the input amplifiers are disconnected from their normal input path and are connected to this voltage source. Calibration then involves the determination of gain and offset constants for each possible input path configuration, on a per-channel basis. This calibration is a complete end-to-end calibration from input amplifiers through to the ADC. Additionally, accurate self-calibration, such as this, will be most effective if the voltage source is applied prior to any input filtering or gain circuits; therefore, any errors generated by drift, aging, or temperature variations in the complete analog input path will be included.

While the voltage measurement circuitry will tend to be very stable with time and temperature, the inherently high sensitivity of thermocouple measurements, to even voltage drift on the microvolt level, makes maintaining high accuracy levels over a wide range of ambient temperature conditions a challenge. The internal calibration source, however, affords the ability to conduct a self-calibration at any time, without removal of the user input connections.

The self-calibration sequence performs the same steps as factory calibration, except for the data created. Self-calibration does not generate gain and offset constants that replace the factory constants, but constants that slightly modify the underlying factory constants. The greatest benefit of self-calibration is the zero-step, because offset errors have the most influence on the thermocouple accuracy.

In other words, the self-calibration process links the accuracy of the input path to the internal calibration source. Generally, the calculation modifications made by the self-calibration step are saved for as long as power is maintained to the unit, but are lost when power is cycled. This is done so that the unit always powers up with its factory calibration. The self-calibration is designed to be easy and quick to run, affording the user the ability to conduct it often, without inconvenience.

Factory calibration involves the extra step of connecting these source outputs to a NIST-traceable voltmeter. Additionally, there is accuracy verification of the instrument for voltage and temperature inputs. While a thermocouple measurement is composed of a voltage measurement and a CJC measurement, only the voltage measurement component is calibrated. The CJC mechanism is absolutely accurate to an acceptable level without additional adjustment. Its accuracy is then verified with temperature accuracy verification.

Practical Considerations

Noise

One of the major issues concerning accurate and repeatable thermocouple measurements is ambient noise. Most applications are located in hostile environments, with numerous electrical noise sources that might include basic fluorescent lighting, welding machines, and high current ac and dc motors. These sources are capable of generating powerful electromagnetic fields that vary in intensity and in frequency. The majority of the noise sources are indeed (50/60) Hz; however, other higher frequency sources cannot be ignored.

We have already discussed several areas in the instrumentation that can greatly reduce the ill effects from external noise sources. Among these were the proper implementation of signal multiplexing, analog filtering, and the correct ADC selection. There are, however, other steps that can be taken to ensure that the complete system is as immune to noise sources as possible.

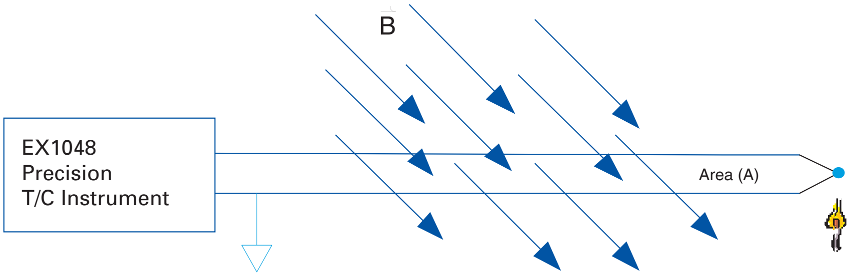
Thermocouple Wire and Shielding

Noise reduction in cabling can be achieved by making the proper choices during the system design phase. Since typical installations will span from several meters to hundreds of meters, the properties of the cable become critical. The performance of longer cable runs can be improved by using larger diameter thermocouple cable, and ensuring that the cable is in the twisted pair configuration. The magnetic fields discussed above will induce a voltage proportional to the rate of change of the magnetic field, as well as the area that the wires enclose. These fundamental principles of physics can be described using the following equation:

$V_B = df / dt$; where f is the magnetic flux.

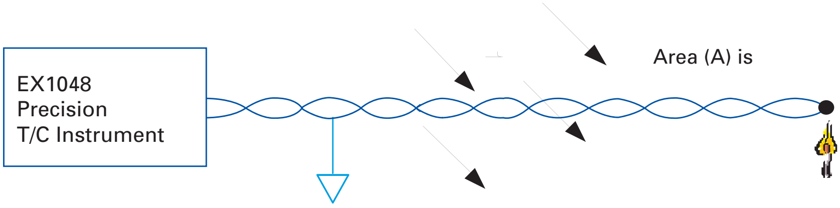
Figures 1 and 2 illustrate the difference between the two configurations. Clearly, the interference seen at the instrument will be reduced by the selection of twisted pair wires.

Figure 1



System without twisted pair wiring.

Figure 2



System twisted pair wiring.

Figure 3

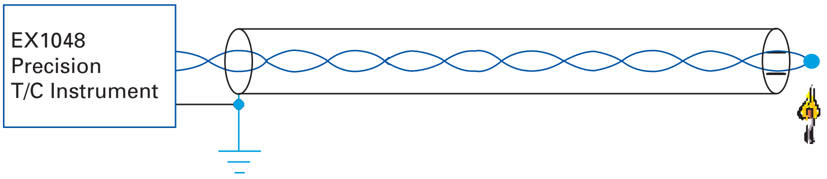


Table 3

Type	Composition (+/-)	Color (+/-)	Temperature Range (˚C)
B	Platinum - (30%) Rhodium / Platinum - (6%) Rhodium	Grey / Red	0 to 1700
E	Nickel - (10%) Chromium / Constantan	Violet/Red	-200 to 900
J	Iron / Constantan	White/Red	0 to 750
K	Nickel - (10%) Chromium / Nickel - (5%) AlSi	Yellow/Red	-200 to1250
N	Nicrosil / Nisil	Orange/Red	-270 to 1250
R	Platinum - (13%) Rhodium / Platinum	Black/Red	0 to 1450
S	Platinum - (10%) Rhodium / Platinum	Black/Red	0 to 1450
T	Copper/Constantan	Blue/Red	-200 to 350

The effects of noise can also be reduced by the use of shielded twisted pair wiring. The shielding provides a low impedance path for noise to travel to ground, rather than into the instrument via the signal connections. The shield should only be terminated at one end to avoid the creation of ground loops, and this is typically performed at the instrument ground. Note that the drawing (Figure 3) illustrates the shield floating at the sensor end.

Thermocouple Calibration

The thermocouple manufacturing process will invariably result in subtle differences in cabling from lot to lot, and even from spool to spool. Other variables such as the connection weld and actual path of the wire can also have minor effects on the signal. Therefore, the voltage output from consecutive cable sections will vary slightly as a result of these differences.

For the accuracy of the measurements to be as great as possible, the recommended approach would involve calibrating the entire system including all cabling and interconnection points. This approach may require some additional steps external to the instrument, but it will provide the most accurate system level measurements.

Thermocouple Fundamentals

The most common temperature transducer for most typical data acquisition applications, ranging from aircraft engine test to automotive relays, is the thermocouple. The thermocouple provides a good level of temperature accuracy at a very economical price. Our understanding of the thermocouples thus far would lead one to believe that measuring these devices is a simple matter of connecting a voltmeter to the open leads and converting the voltage to a temperature. However, delving into the theory behind making an accurate thermocouple measurement will clearly show that this is not as trivial as it may seem.

Thermal EMF

As mentioned previously, thermocouples generate a thermal EMF when two dissimilar metal alloys are connected at one end and measured at the other. A list of the most popular thermocouple types and their compositions can be seen in Table 3

Thomas Seebeck discovered that when two dissimilar metals are connected, a current will flow when one of the junctions is heated (see Figure 4).

Any dissimilar metal combination will exhibit this effect, but several combinations have become industry standards based upon their performance across specific temperature bands and the durability that the alloy exhibits.

The open circuit voltage produced by this junction is also referred to as the Seebeck voltage, and can be seen in Figure 5.

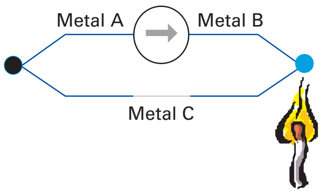


Figure 4

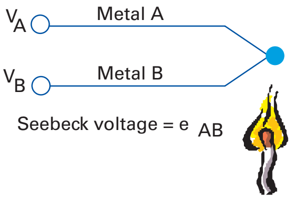


Figure 5

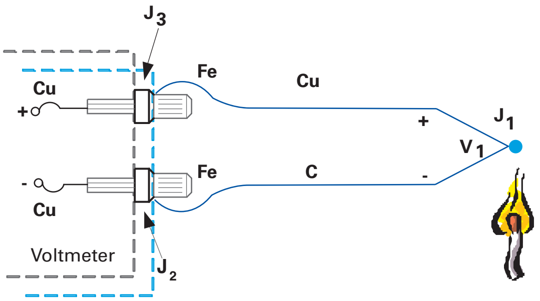


Figure 6

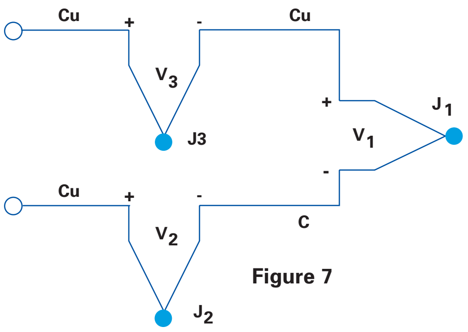


Figure 7

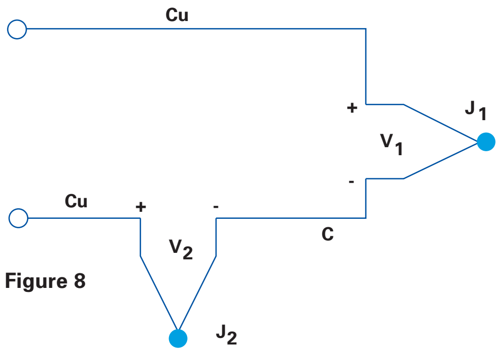


Figure 8

High-accuracy Temperature Measurement

One of the difficulties that one encounters when measuring the voltage from a thermocouple is that the voltage cannot be measured directly. If the thermocouple is connected directly to a voltmeter or ADC, the connection point is also a thermoelectric circuit and will result in an inaccurate measurement. Figure 6 shows an example of a Type T thermocouple (copper-constantan) connected to a measurement device.

Figures 7 and 8 provide a schematic representation of the thermoelectric junction points from the previous drawing. Recall that the only time a thermal EMF is generated is when two dissimilar metals are joined; therefore, the Cu-Cu junction does not generate a voltage. The equivalent circuit only contains the two junctions. Even with this simplification we are still faced with a dilemma; how can we find the temperature at J_1 without first knowing the temperature at J_2.

Reference Junction

One approach would be to place the junction at J_2 at a known temperature, for example in an ice bath. The ice bath establishes a known Reference Junction at 0 ˚C. The known value of the reference junction now results in the instrument reading a value which is proportional to the difference between J_1 and J_2. It is important to realize that the value measured at V_2 is not zero volts, but rather a voltage value proportional to 0 ˚C.

The process of using an ice bath provides a very accurate reference point; additionally, this point can be accurately controlled. The National Bureau of Standards utilizes the ice bath point as the reference for their published thermocouple tables, therefore, these tables can now be used to convert the voltage at V_1 to the temperature at J_1.

The above example provides a somewhat simplified connection in that one of the thermocouple leads is copper, resulting in only one dissimilar metal junction. A more common problem arises when a different thermocouple type is used, Type J for example, where both terminals of the instrument will generate a thermal EMF. This can be seen in Figure 9 and 10.

A measurement error will be generated if both of these points (J3 and J4) are not at the same temperature. One might think that these differences are insignificant, but recall that the output from a thermocouple is measured in microvolts; a slight variation in temperature between the two connections will introduce additional error (See Figure 11 and 12).

We must provide a means to keep the two termination points at the same temperature. The most common approach is to use an isothermal block; an isothermal block is ideally designed with a large thermal mass to minimize any rapid changes in temperature due to changes in the ambient environment. The block also provides electrical isolation for physical connection to the thermocouple (see Figure 13).

Figures 14 and 15 illustrate the equivalent diagram, but the number of required connections would still make

Figure 9

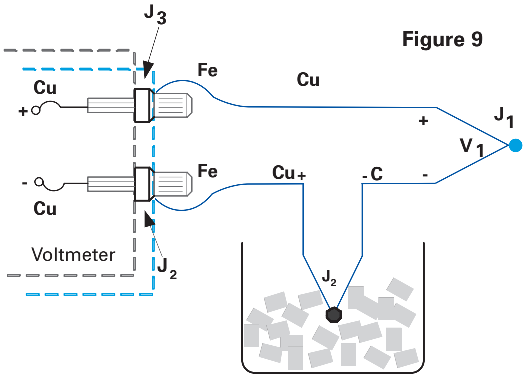
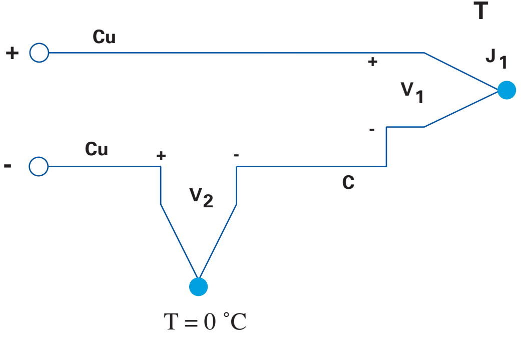


Figure 10



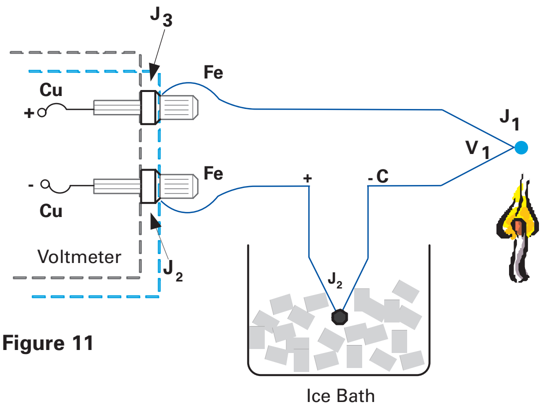
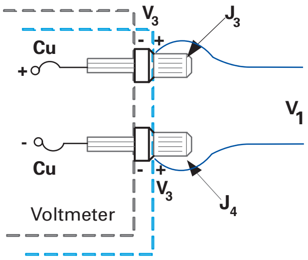


Figure 11



V_1= V only if V_2=V_4
i.e., only if T_{J3}= T_{J4}

Figure 12

High-accuracy Temperature Measurement

Figure 13

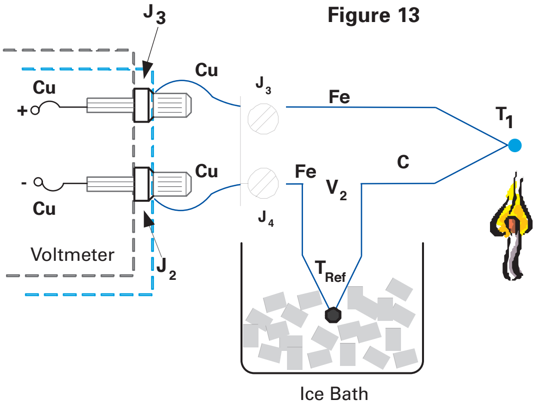


Figure 14

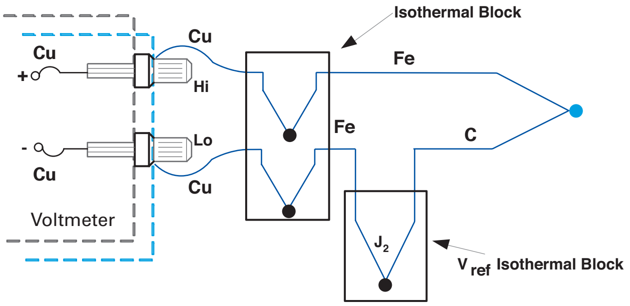


Figure 15

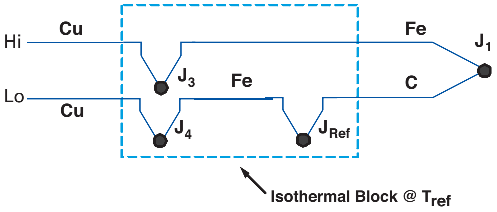


Figure 16

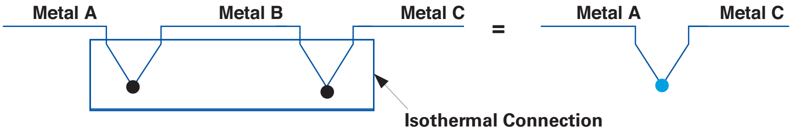
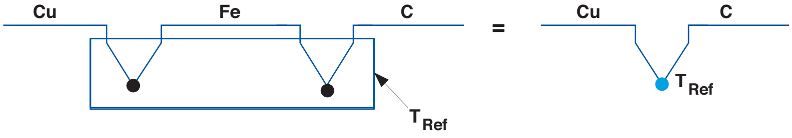


Figure 17



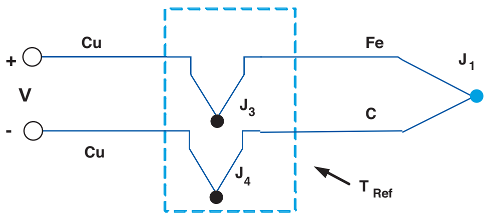


Figure 18

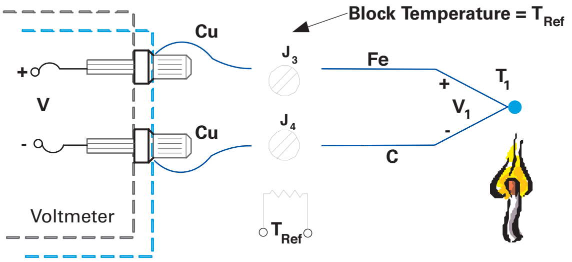


Figure 19

this approach difficult to use; therefore, we will combine the two isothermal blocks and eliminate the iron wire connecting the J_{Ref} and J4 junctions.

We can further simplify this configuration by utilizing the law of intermediate metals. This states that if a third metal is inserted between two dissimilar metals, there will be no effect on the output voltage, if the junctions are maintained at the same temperature (see Figure 16).

Therefore, we can use this principle to completely eliminate the iron wire in the low signal path. The equivalent circuit can be seen in Figures 17 and 18.

The final task that we are faced with is measuring the reference temperature of the isothermal block and using this information to determine the temperature at J1; however, this is not as trivial as it may sound (see Figure 19).

Polynomial Fit

As we mentioned before, the thermocouple is not a linear device, therefore a power series polynomial must be utilized to determine the temperature. As the order of the polynomial increases, the accuracy of the results will increase as well.

Below is a sample polynomial equation followed by a table illustrating representative values for Types J and K thermocouples.

$$T_{90} = c_0 + c_1x + c_2x^2 + c_3x^3 + c_4x^4 + c_5x^5 + \dots\dots\dots + c_nx^n$$

T_{90} = Temperature
x = Thermocouple voltage
c = Polynomial coefficients unique to each thermocouple type
n = Maximum order of polynomial

The table below illustrates a sample of the coefficients for Type J and K thermocouples over different temperature ranges. The polynomial fit will rapidly degrade once you exceed the ranges listed in the table, and should therefore not be extrapolated outside of the specified ranges.

NIST ITS-90 Polynomial Coefficients are shown in Table 4.

Table 4

Type	Type J		Type K	
Range Error Data	-210 ˚C to O ˚C ±0.05 ˚C 8th Order	0 ˚C to 760 ˚C ±0.04 ˚C 8th Order	-200 ˚C to 0 ˚C ±0.04 ˚C 8th Order	0 ˚C to 500 ˚C ±0.05 ˚C 8th Order
0	0	0	0	0
C_0	-1.2286185 x 10^{-6}	-2.001204 x 10^{-7}	-1.1662878 x 10^{-6}	7.860106 x 10^{-8}
C_1	1.9528268 x 10^{-2}	1.978425 x 10^{-2}	2.5173462 x 10^{-2}	2.508355 x 10^{-2}
C_2	-1.0752178 x 10^{-9}	1.036969 x 10^{-11}	-1.0833638 x 10^{-9}	-2.503131 x 10^{-10}
C_3	-5.9086933 x 10^{-13}	-2.549687 x 10^{-16}	-8.9773540 x 10^{-13}	8.315270 x 10^{-14}
C_4	-1.7256713 x 10^{-16}	3.585153 x 10^{-21}	-3.7342377 x 10^{-16}	-1.228034 x 10^{-17}
C_5	-2.8131513 x 10^{-20}	-5.344285 x 10^{-26}	-8.6632643 x 10^{-20}	9.804036 x 10^{-22}
C_6	-2.3963370 x 10^{-24}	5.099890 x 10^{-31}	-1.0450598 x 10^{-23}	-4.413030 x 10^{-26}
C	-8.3823321 x 10^{-29}	-5.1920577 x 10^{-28}		1.057734 x 10^{-30}
C				
C				