Application Note

A Basic Guide to Thermocouple Measurements

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ABSTRACT

Thermocouples are common temperature sensors used in a wide variety of commercial and industrial applications. While slightly less accurate than resistance temperature detectors (RTDs), thermocouples cover a wide temperature range, are self-powered, and have a fast response time. Their simple construction make them inexpensive and durable. Because of the small sensor voltage and low noise requirements, delta-sigma analog-to-digital converters (ADCs) are ideal data converters for measuring thermocouples. This application report gives an overview of thermocouples, discussing theory of operation, functionality, and methods in temperature measurement. Many circuits are presented showing thermocouple connections to precision ADCs. Different topologies focus on biasing thermocouples for the ADC input and for burn-out measurements.

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1 Thermocouple Overview

Thermocouples are temperature measurement sensors that generate a voltage that changes over temperature. Thermocouples are constructed from two wire leads made from different metals. The wire leads are welded together to create a junction. As the temperature changes from the junction to the ends of the wire leads, a voltage develops across the junction.

Combinations of different metals create a variety of voltage responses. This leads to different types of thermocouples used for different temperature ranges and accuracies. Choosing a thermocouple often is a function of the measurement temperature range required in the application. Other considerations include the temperature accuracy, durability, conditions of use, and the expected service life.

1.1 Seebeck Voltage

In 1820, Thomas Johann Seebeck discovered that when a metal bar is heated on one end, a voltage (known as the Seebeck voltage) develops across the length of the bar. This voltage varies with temperature and is different depending on the type of metal used in the bar. By joining dissimilar metals that have different Seebeck voltages at a temperature sensing junction, a thermocouple voltage (V_{TC}) is generated.

The dissimilar metals are joined at a temperature sensing junction (T_{TC}) to create a thermocouple. The voltage is measured at a reference temperature (T_{CJ}) through the two metals. The leads of the thermocouple are required to be at the same temperature and are often connected to the ADC through an isothermal block. Figure 1-1 shows a thermocouple constructed from two dissimilar metals with the thermocouple leads connected to an isothermal block.

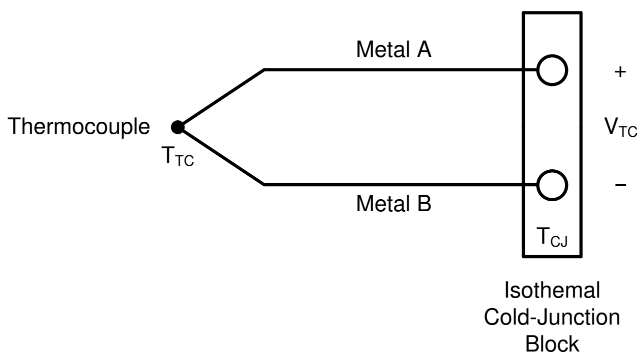

Figure 1-1. Thermocouple Voltage

The connection of the thermocouple to an isothermal block is important for the temperature measurement. For an accurate thermocouple measurement, the return leads of different metals must be at the same known temperature.

Any connection between two different metals creates a thermocouple junction. Connections from the thermocouple to the ADC should be simple and symmetric to avoid unintentional thermocouple junctions. These additional junctions cause measurement errors.

As the thermocouple signal connects to the ADC integrated circuit, each step along the path can encounter several additional thermocouples. This becomes a measurement problem if there is a temperature gradient across the circuit. Each connection from wire terminal, to solder, to copper trace, to IC pin, to bond wire, to chip contact creates a new junction. However, if the signal is differential, and each of the thermocouple pairs are at the same temperature, then the thermocouple voltages cancel and have no net effect on the measurement. For high-precision applications, the user must ensure that these assumptions are correct. Measurement with differential inputs include unintentional thermocouple voltages that do not cancel if the thermocouples are not located close together, or if there is a thermal gradient on the board or device.

1.2 Thermocouple Types

1.2.1 Common Thermocouple Metals

All dissimilar metals used to construct a thermocouple display a change in voltage from the Seebeck effect, but several specific combinations are used to make thermocouples. The thermocouples can be classified into two different construction types: base metal thermocouples and noble metal thermocouples.

Base metal thermocouples are the most common thermocouples. Noble metal thermocouples are composed of precious metals such as platinum and rhodium. Noble metal thermocouples are more expensive, and are used in higher temperature applications.

Regardless of metal lead, each thermocouple type is designated a single letter to indicate the two metals used. For example, a J-type thermocouple is constructed from iron and constantan. With each type, the thermoelectric properties are standardized so that temperature measurements are repeatable. Thermocouple leads and connectors are standardized with color plugs and jacks, indicating the type of thermocouple. Different colors for insulation and lead wires also indicate the thermocouple grade and extension grade. Table 1-1 lists several common thermocouple types and their characteristics.

Table 1-1. Common Thermocouple Types

Thermocouple Type	Lead Metal A (+)	Lead Metal B (–)	Temperature Range (°C)	EMF over Temperature Range (mV)	Seebeck Coefficient (µV/°C at 0°C)
J	Iron	Constantan	–210 to 1200	–8.095 to 69.553	50.37
K	Chromel	Alumel	–270 to 1370	–6.458 to 54.886	39.48
T	Copper	Constantan	–200 to 400	–6.258 to 20.872	38.74
E	Chromel	Constantan	–270 to 1000	–9.385 to 76.373	58.70
S	Platinum and 10% Rhodium	Platinum	–50 to 1768	–0.236 to 18.693	10.19

1.2.2 Thermocouple Measurement Sensitivity

The National Institute of Standards and Technology (NIST) has analyzed the output voltage versus temperature for the various types of thermocouples. Figure 1-2 illustrates the typical responses for these same thermocouple types.

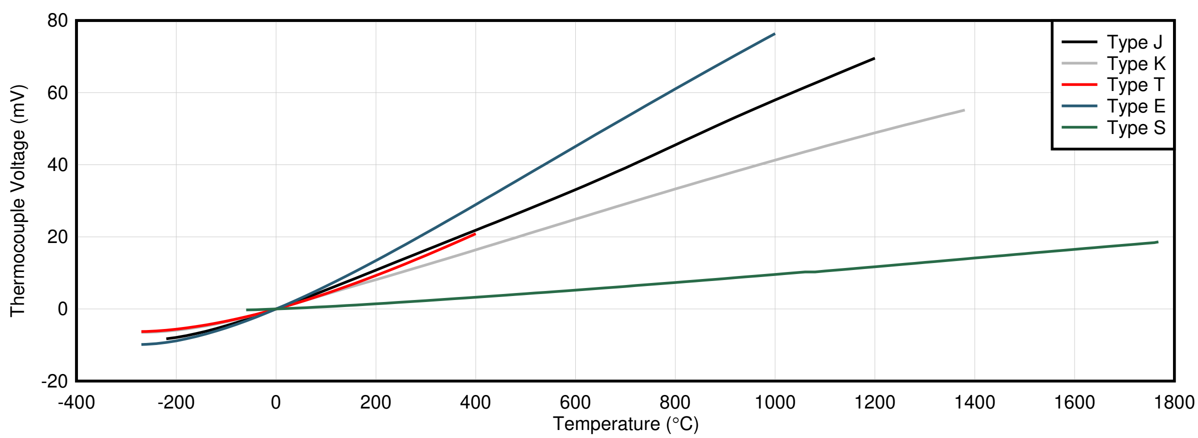

Figure 1-2. Thermocouple Responses

Several polynomial equations are defined by the International Temperature Scale of 1990 (ITS-90) standard that correlate the temperature and voltage output. This data is found on the NIST website at http://srdata.nist.gov/its90/main/. These equations are used to calculate the thermoelectric voltage from temperature or to calculate temperature from the thermoelectric voltage

1.2.2.1 Calculating Thermoelectric Voltage from Temperature

Direct polynomials construct the equations to calculate the thermoelectric voltage from a known temperature. These equations have a form shown in Equation 1.

$$E = \sum_{i=0}^{n} c_i (t_{90})^i \quad (1)$$

where

- E is in microVolts and t_{90} is in degrees Celsius

Table 1-2 summarizes the polynomial orders and the respective temperature ranges for the types of thermocouples.

Table 1-2. Characteristics of ITS-90 Thermocouple Direct Polynomials to Determine Voltage from Temperature

Thermocouple Type	Temperature Range (°C) for Polynomials	Polynomial Order(1)
J	–210 to 760, 760 to 1200	8th, 5th
K	–270 to 0, 0 to 1370	10th, 9th, + a $e^{b(t-c)^2}$
T	–200 to 0, 0 to 400	7th, 6th
E	–270 to 0, 0 to 1000	13th, 10th
S	–50 to 1064.18, 1064.18 to 1664.5, 1664.5 to 1768.1	8th, 4th, 4th

(1) For type K thermocouples above 0 °C, there is an additional term to account for a magnetic ordering effect

1.2.2.2 Calculating Temperature From Thermoelectric Voltage

Making the reverse conversion, Inverse polynomial functions calculate the temperature based on the thermocouple voltage. The equations for inverse polynomial functions are of the form shown in Equation 2.

$$t_{90} = d_0 + d_1 E + d_2 E^2 + \ldots + d_i E^i \quad (2)$$

where

- E is in microVolts and t_{90} is in degrees Celsius

As an example, the inverse function for a K-type thermocouple is shown in Table 1-3. Polynomials are constructed over three smaller ranges of the full temperature range. For each range, the temperature is described with a high order polynomial.

Table 1-3. ITS-90 Temperature Coefficients for a K-Type Thermocouple

Temperature Range:	−200°C to 0°C	0°C to 500°C	500°C to 1372°C
Voltage Range	**−5891 µV to 0 µV**	**0 µV to 20644 µV**	**20644 µV to 54886 µV**
d_0	0.000 000 0	0.000 000 0	$-1.318\ 058 \times 10^{2}$
d_1	$2.517\ 346\ 2 \times 10^{-2}$	$508\ 355 \times 10^{-2}$	$4.830\ 222 \times 10^{-2}$
d_2	$-1.166\ 287\ 8 \times 10^{-6}$	$7.860\ 106 \times 10^{-8}$	$-1.646\ 031 \times 10^{-6}$
d_3	$-1.083\ 363\ 8 \times 10^{-9}$	$-2.503\ 131 \times 10^{-10}$	$5.464\ 731 \times 10^{-11}$
d_4	$-8.977\ 354\ 0 \times 10^{-13}$	$8.315\ 270 \times 10^{-14}$	$-9.650\ 715 \times 10^{-16}$
d_5	$-3.734\ 237\ 7 \times 10^{-16}$	$-1.228\ 034 \times 10^{-17}$	$8.802\ 193 \times 10^{-21}$
d_6	$-8.663\ 264\ 3 \times 10^{-20}$	$9.804\ 036 \times 10^{-22}$	$-3.110\ 810 \times 10^{-26}$
d_7	$-1.045\ 059\ 8 \times 10^{-23}$	$-4.413\ 030 \times 10^{-26}$	
d_8	$-5.192\ 057\ 7 \times 10^{-29}$	$1.057\ 734 \times 10^{-30}$	
d_9		$-1.052\ 755 \times 10^{-35}$	
Error Range	0.04°C to –0.02°C	0.04°C to –0.05°C	0.06°C to –0.05°C

Table 1-2 and Table 1-3 show the complexity of direct and inverse polynomial equations. The mathematical operations used to calculate these high order equations without loss of precision can take a significant amount of computational processing with high resolution, floating-point numbers. This type of computation is generally not suited for embedded processing or microcontrollers. In many cases, it is far more efficient to determine the temperature through interpolation using a lookup table.

1.2.3 Thermocouple Construction

Thermocouples come in several different construction types as shown in Figure 1-3. Thermocouple leads are protected by a layer of insulation and often have a protective sheath at the thermocouple junction tip to protect the sensor element.

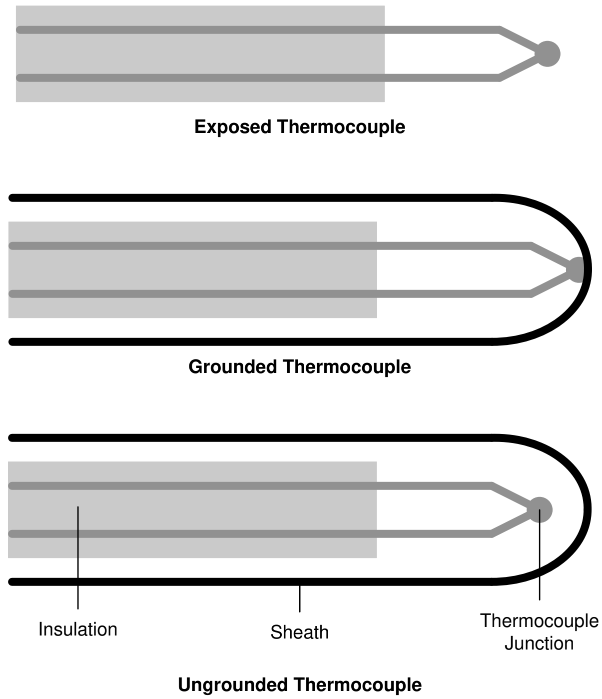

Figure 1-3. Thermocouple Construction Types

A thermocouple without a protective sheath is known as an exposed thermocouple. This allows for a small sensor, with direct heat transfer from the measured object. This type of thermocouple gives a fast sensor response.

In a grounded thermocouple, the sensor is welded to the sheath. Often this sheath is composed of metal, which also allows for heat transfer, but adds an extra protection for harsh and difficult environments. However, because the thermocouple is welded to the metal sheath, there is electrical contact. This makes the measurement susceptible to noise from ground loops.

An ungrounded thermocouple is isolated from the sheath, adding a layer of insulation between the thermocouple the measured object. This type of thermocouple has the slowest of the temperature responses because there is an isolation layer.

As mentioned, both grounded and exposed thermocouples have faster temperature responses because of the excellent heat transfer of metal contact. However, with direct metal contact there is electrical contact between the measurement circuit and anything the thermocouple contacts. This may cause ground loop problems with the measurement.

If the ground of the circuit is at a different electrical potential than the contact from the thermocouple, then the measurement circuit may be disrupted. As an example, a grounded or exposed thermocouple may contact earth ground, which may not be the same as the ADC ground. This can cause a variety of problems, including bad measurement data or even damage to the circuit. Even if the earth ground and ADC ground are identical, the thermocouple may not be in the range of the PGA. When using an exposed or grounded thermocouple, ensure that the thermocouple contact does not disrupt signal or measurement integrity.

1.2.4 Tolerance Standards

Temperature measurement accuracy and range depend on the type of the thermocouple used and the standard followed by the manufacturer. The International Electrotechnical Commission standard outlined in IEC-EN 60584 contains the manufacturing tolerances for base metal and noble metal thermocouples. A parallel standard used in the United States from the American Society for Testing and Materials is described by ASTM E230. Table 1-4 shows the tolerance of different thermocouples based on different standards and tolerance classes.

Table 1-4. Thermocouple Tolerance Class Information

Thermocouple Type	Tolerance Class		Temperature Range (°C)	Thermocouple Error (°C) (Larger between two columns)	
J	IEC-EN 60584-2	Class 1	–40 < T < 750	±1.5°C	±(0.004 · |T|)
		Class 2	–40 < T < 750	±2.5°C	±(0.0075 · |T|)
		Class 3	–	–	–
	ASTM E230 ANSI MC96.1	Special	0 < T < 750	±1.1°C	±(0.004 · |T|)
		Standard	0 < T < 750	±2.2°C	±(0.0075 · |T|)
K	IEC-EN 60584-2	Class 1	–40 < T < 1000	±1.5°C	±(0.004 · |T|)
		Class 2	–40 < T < 1200	±2.5°C	±(0.0075 · |T|)
		Class 3	–200 < T < 40	±2.5°C	±(0.015 · |T|)
	ASTM E230 ANSI MC96.1	Special	0 < T < 1250	±1.1°C	±(0.004 · |T|)
		Standard	–200 < T < 0 0 < T < 1250	±2.2°C ±2.2°C	±(0.02 · |T|) ±(0.0075 · |T|)
T	IEC-EN 60584-2	Class 1	–40 < T < 350	±0.5°C	±(0.004 · |T|)
		Class 2	–40 < T < 350	±1.0°C	±(0.0075 · |T|)
		Class 3	–200 < T < 40	±1.0°C	±(0.015 · |T|)
	ASTM E230 ANSI MC96.1	Special	–200 < T < 0 0 < T < 350	±0.5°C ±0.5°C	±(0.008 · |T|) ±(0.004 · |T|)
		Standard	–200 < T < 0 0 < T < 350	±1.0°C ±1.0°C	±(0.015 · |T|) ±(0.0075 · |T|)
E	IEC-EN 60584-2	Class 1	–40 < T < 800	±1.5°C	±(0.004 · |T|)
		Class 2	–40 < T < 900	±2.5°C	±(0.0075 · |T|)
		Class 3	–200 < T < 40	±2.5°C	±(0.015 · |T|)
	ASTM E230 ANSI MC96.1	Special	–200 < T < 0 0 < T < 900	±1.0°C ±1.0°C	±(0.005 · |T|) ±(0.004 · |T|)
		Standard	–200 < T < 0 0 < T < 900	±1.7°C ±1.7°C	±(0.01 · |T|) ±(0.005 · |T|)
S	IEC-EN 60584-2	Class 1	0 < T < 1600	±1.0°C	±[1 + 0.003 · (|T| – 1100)]
		Class 2	–40 < T < 1600	±1.5°C	±(0.0025 · |T|)
		Class 3	–	–	–
	ASTM E230 ANSI MC96.1	Special	0 < T < 1450	±0.6°C	±(0.001 · |T|)
		Standard	0 < T < 1450	±1.5°C	±(0.0025 · |T|)

As an example, Figure 1-4 graphically shows the error of a type-K thermocouple with the IEC-EN 60584-2 tolerance classes. At higher temperatures, the thermocouple error becomes significantly greater.

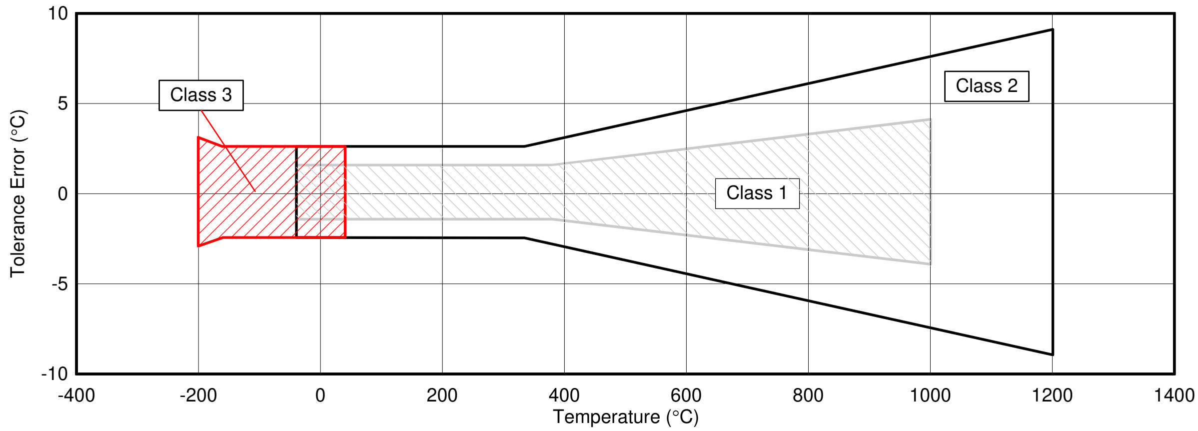

Figure 1-4. Type-K IEC-EN 60584-2 Tolerance Class Errors

Thermocouples show a wide range of error dependent on the tolerance class. However, few of these thermocouples have error tolerances better than ±1°C. For this reason, RTDs are preferred for applications requiring higher precision and accuracy. It common to use 16-bit ADCs for thermocouple measurements and 24-bit ADCs for RTD measurements.

1.3 Thermocouple Measurement and Cold-Junction Compensation (CJC)

As discussed earlier, the thermocouple generates a voltage related to the temperature difference between the thermocouple junction and the leads to attached to the cold junction at the isothermal block (see Figure 1-1). However, the voltage created from the thermocouple is non-linear depending on the temperature of the cold junction. Cold-junction compensation is required to accurately determine the thermocouple junction temperature based on the cold junction temperature.

With cold-junction compensation, the leads of the thermocouple must be at the same known temperature. In thermocouple measurement systems, there is a cold-junction block which connects the thermocouple lead to the ADC measurement. This block holds both thermocouple leads at the same temperature and is often a connector made from a large metal mass, with thermal capacitance. In some applications, it may be sufficient to maximize the copper fill around the junctions of the PCB, layering the connection between metal fill between top and bottom layers. Because air currents may affect the temperature, an enclosure around the block may be necessary.

An accurate measurement of the cold junction block acts as the reference temperature of the cold-junction. This reference measurement is often made through a diode, thermistor, or RTD. If the reference temperature at T_{CJ} is known, then the thermocouple temperature at T_{TC} is computed based on the thermocouple voltage. The process of accounting for T_{CJ} is called cold junction compensation because it is generally assumed that T_{CJ} is the cold temperature.

In the classical method of setting the cold-junction temperature the leads of the thermocouple are placed in an ice bath, ensuring that the reference temperature is 0°C. However, in most systems the cold-junction temperature is measured separately with a device such as an RTD or thermistor.

Once the reference temperature is measured, the thermocouple voltage for that temperature (relative to 0°C) can be determined and added to the measured voltage on the thermocouple leads. This compensation gives the voltage that would have been developed if T_{CJ} had been at 0°C. Note that this voltage is required when referencing the NIST charts, since the chart values are specified relative to 0°C.

Thermocouple voltages are non-linear with temperature. Therefore you cannot simply add the temperature of the cold-junction to the temperature computed from the thermocouple voltage. To accurately determine the thermocouple temperature, the proper method is to:

1. Convert the cold-junction temperature (T_{CJ}) to a voltage (V_{CJ})
2. Add the cold-junction voltage to the measured thermocouple voltage (V_{CJ} + V_{TC})
3. Convert the summed cold-junction voltage and thermocouple voltage to the thermocouple temperature (T_{TC})

Conversion tables and polynomial equations used to determine thermocouple temperature from the thermoelectric voltage is found at the NIST website at http://srdata.nist.gov/its90/menu/menu.html.

1.4 Design Notes

The following sections describe different considerations for designing a thermocouple measurement with a precision ADC. The discussion starts with the operational range of the ADC, setting up the circuit, making measurement conversions, and performing cold-junction compensation. Each section describes different considerations that help make a more accurate measurement.

1.4.1 Identify the Range of Thermocouple Operation

The thermocouple voltage is very small and requires a low-noise precision ADC for measurement. Referring back to Figure 1-2, different thermocouples have different output voltage ranges. Using a K-type thermocouple operating from –270°C to 1370°C as an example, the thermocouple voltage would range from about –6.5 mV to 55 mV.

Because many precision ADCs have onboard programmable gain amplifiers (PGAs), this measurement signal can be amplified for a more precise measurement. Using this thermocouple output voltage range and the reference voltage, calculate the maximum gain allowed without over-ranging the PGA. Many precision ADCs have an onboard PGA with gain settings in factors of 2. Many precision ADCs also have a precision voltage reference. Voltage measurements for thermocouples require precision references with low noise. Reference error directly impacts the measurement accuracy. The reference voltage, combined with the PGA determine the input range of the measurement.

As an example, with a maximum input of 55 mV, the PGA gain can be set to 32. This results in an equivalent input signal of 1.76 V. Using a 2.048-V internal reference voltage, this maximizes the ADC input range without over-ranging the PGA.

1.4.2 Biasing the Thermocouple

After calculating the PGA gain, consider the PGA common-mode input range. Many PGAs are implemented similar to the front end of an instrumentation amplifier. This requires that the common-mode voltage of the input must be within the PGA range of operation. With increasing PGA gain, the common-mode input voltage is limited so that the amplifier output does not go into either the positive or negative supply rails. Consult the device data sheet for specific absolute or common-mode input voltage ranges. In most cases, setting the input to the mid-point of the analog supply voltages ensures the thermocouple is within the range of the PGA.

Thermocouples require biasing to set the sensor voltage DC operating point. There are a number of ways to bias the thermocouple. The most common method for thermocouple biasing is using large resistors tied to either end of the thermocouple as shown in Figure 1-5. The opposite end of the resistors are then tied to either supply. This method sets the thermocouple operating voltage at mid-supply assuming that the resistors are equal, and that the thermocouple voltage is relatively small.

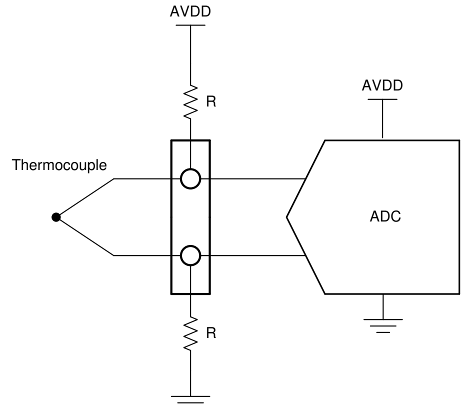

Figure 1-5. Resistor Biasing of a Thermocouple

Resistor values are generally chosen to be from 500 kΩ to 10 MΩ depending on the input current. Different ADCs have different magnitudes of input current. If the resistance is too high, the biasing current becomes too small compared to the ADC input current of the resistors. Consider the ADC input current when selecting resistor values as this may offset the bias point.

If the thermocouple leads are long, then resistor biasing may create additional error. Long resistive leads will react with the bias current to develop a voltage error in the measurement. In another biasing method, the negative thermocouple lead is connected to a known voltage source, as shown in Figure 1-6. Using a voltage source removes the bias current passing through the thermocouple. Only the ADC input current remains, which is usually orders of magnitude lower. In many cases, the ADC reference or an external reference may be used for biasing. Similarly, many ADCs have a VBIAS line that can be used to attach a specific analog input to a voltage generator through the input multiplexer of the ADC.

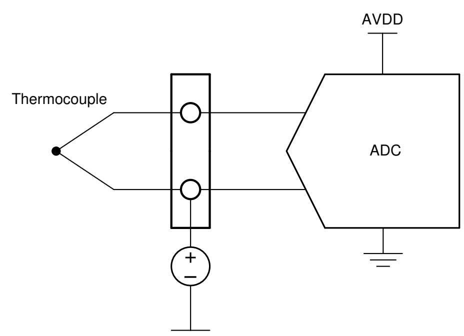

Figure 1-6. Voltage Biasing of a Thermocouple

Similarly, if the ADC uses a bipolar supply, the negative thermocouple input can be tied to ground. Using the ground establishes the input at the mid-point of the supply and sets the bias point within the PGA input range.

Regardless, all of these methods establish a DC operating point for the thermocouple measurement. Many of the later sections of this application note discuss different circuit topologies for biasing the thermocouple.

1.4.3 Thermocouple Voltage Measurement

After setting the gain and putting the thermocouple in the input range of the PGA, measure the thermocouple voltage with the ADC. If you have a 16-bit bipolar ADC and a set PGA gain, calculate the thermocouple measurement voltage with Equation 3. Typically, the reference voltage is the equivalent to the positive full scale.

$$V_{TC} = (\text{Output Code} \bullet V_{REF}) / (\text{Gain} \bullet 2^{15}) \quad (3)$$

Start with this example as a K-type thermocouple. Also assume the system settings are V_{REF} = 2.048 V, PGA gain = 32, and a 16-bit bipolar ADC. If the ADC reports back a data reading of 31CFh (12751d), the thermocouple voltage can be calculated from Equation 4.

$$V_{TC} = (12751 \text{ codes} \cdot 2.048 \text{ V}) / (32 \cdot 32768 \text{ codes}) = 24.904 \text{ mV} \quad (4)$$

Using a conversion table, this voltage would be determined to be 600°C. However, this is the correct value only if the cold-junction temperature is known to be 0°C. To get the actual thermocouple temperature you need to determine the cold-junction temperature and make the conversion to the voltage.

1.4.4 Cold-Junction Compensation

There are many ways to determine the cold junction temperature. RTD measurements are often used to get a more accurate temperature reading for the cold-junction measurement. There are also thermistors and other semiconductor temperature sensors that can be used to get a cold junction measurement. Regardless of how it is done, the cold-junction measurement must be accurate. Any error in the cold-junction measurement directly adds to the error in the thermocouple measurement.

Returning to the original example, assume the cold junction is measured to be 25°C. Using the K-type thermocouple table, this is the equivalent to 1.000 mV of thermoelectric voltage. To get an accurate temperature measurement of the thermocouple voltage, you would add the thermocouple voltage to the equivalent cold-junction voltage.

$$V = V_{TC} + V_{CJ} = 24.904 \text{ mV} + 1.000 \text{ mV} = 25.904 \text{ mV} \quad (5)$$

Now that the equivalent thermoelectric voltages have been added together, return to the table and find the equivalent temperature. With some interpolation, the resulting temperature of the thermocouple is about 623.5°C. The thermocouple voltage is non-linear and depends on the cold-junction voltage.

For accuracy, cold-junction compensation requires that the junction temperature is converted to the thermoelectric voltage for the measurement. The tables and equations start with an assumption of a 0°C cold junction. Calculation requires a specific conversion when the cold-junction is not at that temperature. As mentioned in the previous section, the proper method to calculate the thermocouple temperature follows.

A simple addition between the equivalent thermocouple temperature and the cold-junction temperature would have resulted in 625°C. This would have produced a 1.5°C error because of the thermocouple non-linearity over temperature. The only way to compensate for the non-linearity of the thermocouple curve is to convert the cold-junction temperature to the equivalent voltage, sum the thermocouple measurement voltage and cold-junction equivalent voltage, and convert the result back to temperature.

As noted earlier, if the cold-junction is held at 0°C (as if held at the temperature by an ice bath), then the equivalent cold-junction thermoelectric voltage is 0 mV. This allows for a direct conversion of the thermocouple voltage to temperature.

1.4.5 Conversion to Temperature

Conversion of data from the ADC requires both measurements of the thermocouple voltage and the cold-junction temperature. Often measurements of each are interleaved to ensure an accurate measurement of both. The flow diagram in Figure 1-7 shows the conversion method to determine the actual temperature of the thermocouple based on the ADC measurements.

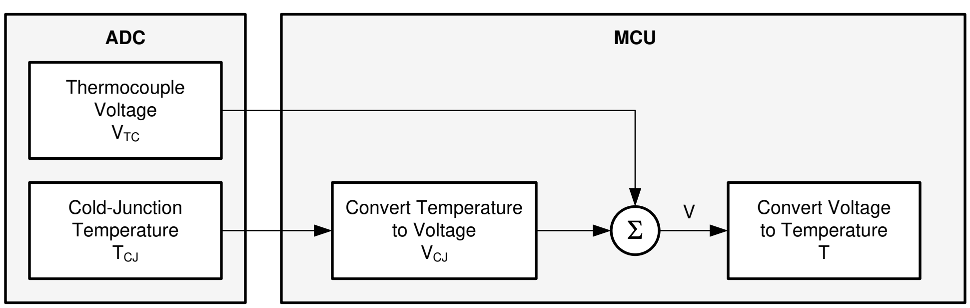

Figure 1-7. Thermocouple and Cold-Junction Measurement Conversion to Temperature

As previously mentioned the cold-junction temperature (T_{CJ}) is first converted to a thermoelectric voltage (V_{CJ}). This voltage is then added to the ADC measurement of the thermocouple voltage where

$V = V_{CJ} + V_{TC}$. This voltage sum is converted to temperature to determine the temperature of the thermocouple sensor.

Conversions from temperature to voltage or from voltage to temperature may be calculated though the polynomial equations explained in Section 1.2.2. Coefficients may be stored in the microcontroller to make these calculations for each ADC conversion.

An alternative to processor-intensive calculations is to use lookup tables for a simple linear interpolation of these polynomials. Temperature and voltage ranges may be evenly broken up for making conversions. *Precision Thermocouple Measurement with the ADS1118* describes using lookup tables with different numbers of table entries to calculate the thermocouple temperature. Figure 1-8 shows the conversion error that can be expected from linear interpolation using a lookup table for a K-type thermocouple from 0°C to +500°C. As the number of lookup table entries exceeds 16, the improvement in accuracy become smaller and smaller.

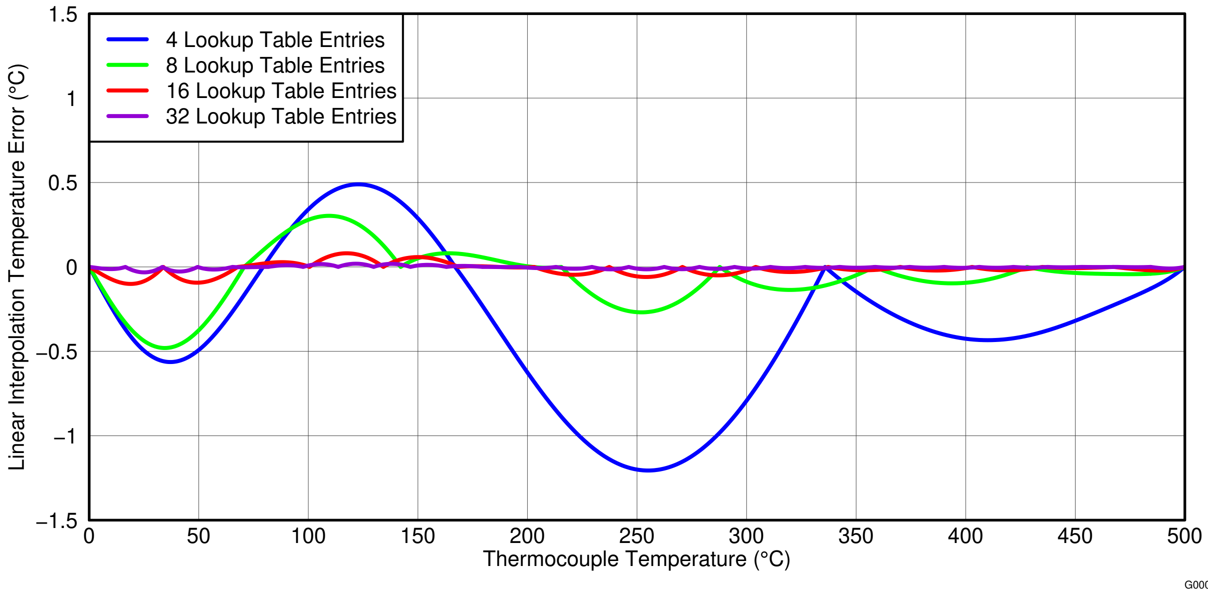

Figure 1-8. Comparison of Interpolation Errors Using Various Lookup Tables

1.4.6 Burn-out Detection

If a thermocouple has failed or burned out, system designers may want to some indication that this has occurred. A full-scale ADC reading for an opened sensor can be used to help make this determination. This measurement may be part of a normal measurement or the system may require an interim measurement as a periodic check.

Methods of thermocouple biasing can allow for automatic burn-out detection. As an example, when the thermocouple is biased through resistors attached from each thermocouple lead to either supply shown in Figure 1-9. The small resistor currents hold the thermocouple at a DC bias point if the thermocouple is intact and produces a small voltage. If the thermocouple has burned out and become high impedance, the resistors pull the voltage of each lead to either rail. This would cause the ADC input to be greater than the full-scale range and cause the ADC to give a full-scale reading (7FFFh for a 16-bit ADC). Again, the resistors should be small enough to overcome the input bias current of the ADC.

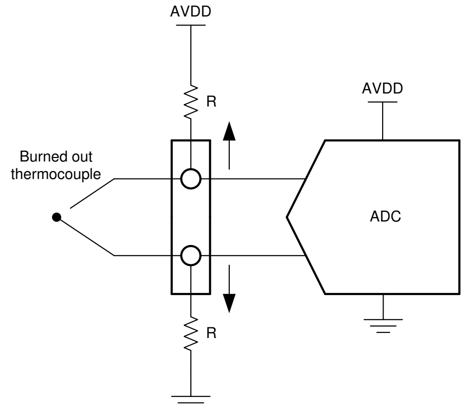

Figure 1-9. Burn-out Detection Using Resistor Biasing

In different methods of thermocouple biasing, there may be no pullup resistor to enable a burn-out measurement. Many precision ADCs include burn-out current sources (BOCS), where a current source is used to pull up on the positive analog input and a current sink pulls down on the negative analog input as shown in Figure 1-10. These current sources are used to pull apart the positive and negative leads of a thermocouple during a burn-out condition. This is useful even if the thermocouple is biased from only one end by a DC source, such as a reference voltage or VBIAS line. The positive burn-out current source pulls the positive lead high enough so that the ADC reads a positive full-scale reading.

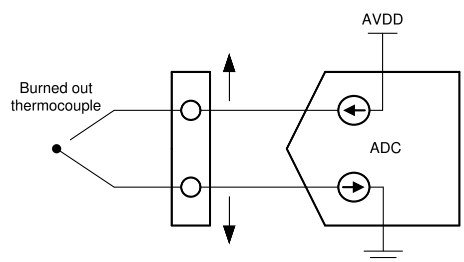

Figure 1-10. Burn-out Detection Using BOCS

In general, the burn-out measurement using BOCS should be a separate measurement than the normal temperature measurement. Using the BOCS may induce error when the thermocouple is not burned out. Extra current may lead to self-heating of the sensor. Additionally, there are often RC filters at the front end of the ADC. Because the BOCS are sourced from the device, additional current flowing from BOCS creates an error voltage as they pass through the series filter resistors.

When enabling the BOCS for a burn-out measurement, ensure that there is additional time for voltage setting between measurements. Filter capacitance may require time for voltage settling in both the burn-out and temperature measurement.

2 Thermocouple Measurement Circuits

Note

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes. Customers should validate and test their design implementation to confirm system functionality.

The following sections describe thermocouple circuit topologies with delta-sigma ADCs. Because thermocouple measurements are primarily simple voltage measurements, these circuit examples focus mainly on different circuit topologies for biasing the thermocouple and burn-out detection. The *Design Notes* section may be used to guide the design with the following system topologies. For each topology, determine the PGA setting based on the thermocouple operating range, consider the necessary biasing and PGA input range, and determine the cold-junction compensation. Burn-out detection is also described with the following system topologies. Cold-junction measurements are discussed at the end of the application note.

Conversion results are shown with a generic 16-bit bipolar ADC, using the positive full-scale range of the device. Conversions with 24-bit ADCs are similar in calculation. Results are shown as functions of the reference voltage and gain of the PGA. Conversion to temperature depends on the linearity and error of the individual thermocouple sensor, and the cold-junction compensation.

As mentioned in previous sections, conversion tables to determine thermocouple temperature from the thermoelectric voltage is found at the NIST web site at http://srdata.nist.gov/its90/menu/menu.html.

2.1 Thermocouple Measurement With Pullup and Pulldown Bias Resistors

In this topology, the thermocouple DC voltage is biased using matched pullup and pulldown resistors. This is a common method for biasing and allows for burn-out detection.

2.1.1 Schematic

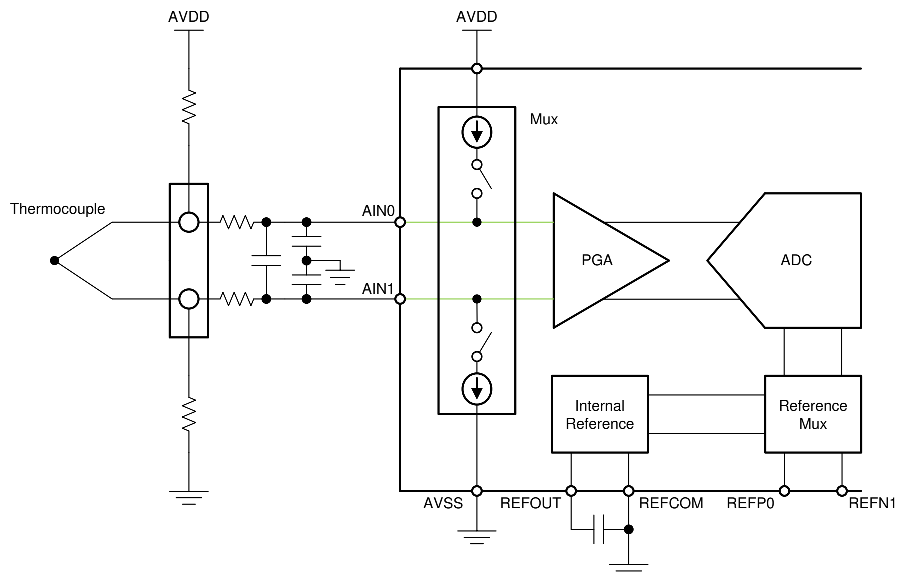

Figure 2-1. Thermocouple Measurement Circuit With Pullup and Pulldown Resistors

2.1.2 Pros and Cons

Pros:

- Simple biasing
- Biasing resistors allow for burn-out detection without separate measurement

Cons:

- Requires two external resistors for biasing
- Biasing current flows through the thermocouple and resistive leads, creating additional error

2.1.3 Design Notes

The measurement circuit requires:

- Pullup and pulldown resistors
- AINP and AINN inputs
- Internal reference or an external voltage reference
- Isothermal cold-junction connection and measurement

Figure 2-1 shows the most common method of thermocouple biasing. Matched resistors are attached to either lead of the thermocouple to set the DC biasing for the input signal. A first resistor pulls the positive lead of the thermocouple to AVDD, and a second resistor pulls the negative lead of the thermocouple to AVSS. Because the measured thermocouple voltage is small, the bias current can be approximated as the supply voltage divided by the two biasing resistors. If the resistors are matched, the thermocouple voltage is biased to the mid-point of the analog supply. Setting the biasing near the mid-point of the supply ensures that the input voltage is within the input range of the PGA. Consult the ADC data sheet for specific PGA common-mode and absolute input ranges.

Resistor values are large to reduce the amount of current passing through the thermocouple and the thermocouple leads. Bias current reacting with long resistive leads create an additional voltage which is measured by the ADC as an error voltage. However, the bias current must be large enough so that the resistor current is significantly larger than the input current of the ADC. If the bias current is small or close to the level of the ADC input current, the DC bias of the thermocouple is offset from the mid-point of the supply. Biasing resistor values are typically from 500 kΩ to 10 MΩ.

An additional error in the measurement comes from the input current of the ADC. An extra voltage error is seen as the ADC input current reacts with the series input filter resistors and any series resistance associated with the input multiplexer. Because this current cannot be removed, it is important to select an ADC with a low input current and calculate the contribution of this error to the measurement.

The biasing resistors are also used for burn-out measurement. In the case of a burned out thermocouple, the positive input is pulled to AVDD while the negative input is pulled to AVSS. This creates a large voltage across the analog inputs, over-ranging the ADC. If the ADC is over-ranged, the ADC value would read 7FFFh (assuming a 16-bit bipolar ADC), showing a full-scale reading to indicate a burned out thermocouple. To ensure that the ADC reports a full-scale reading, verify that the biasing resistors are low enough so that they can pull against the input biasing current of ADC and yield a voltage larger than the input full-scale voltage. Because the biasing resistors are always in place, a separate burn-out measurement is not needed.

Unless the cold junction is at 0°C, there should be a separate cold-junction measurement. This measurement can be done through several different methods, using either an RTD, calibrated thermistor, or a variety of integrated circuit temperature sensors.

2.1.4 Measurement Conversion

Using the ADC internal voltage reference or external voltage reference, the output code is converted to the measured thermocouple voltage. An output code of 7FFFh may indicate a open sensor.

$$V_{TC} = (V_{REF} \cdot \text{Code}) / (2^{15} \cdot \text{Gain}) \tag{6}$$

Measure the cold-junction temperature and convert the temperature to the equivalent cold-junction thermoelectric voltage. Add the thermocouple voltage to the equivalent cold-junction voltage.

$$V = V_{TC} + V_{CJ} \tag{7}$$

Convert the resulting voltage (V) to temperature determine the exact thermocouple temperature.

2.1.5 Generic Register Settings

- Enable the internal reference or use an external reference, set ADC reference
- Select multiplexer settings for AINP and AINN to measure the leads of the thermocouple
- Enable the PGA, set gain to desired value
- Select data rate and digital filter settings
- Settings for cold-junction compensation measurement

2.2 Thermocouple Measurement With Biasing Resistors Attached to the Negative Lead

Another topology for biasing the thermocouple would be to attach the biasing resistors to a single end of the thermocouple. This removes any biasing current through long resistive thermocouple leads, reducing any added voltage error, but requires a separate burn-out sensor measurement.

2.2.1 Schematic

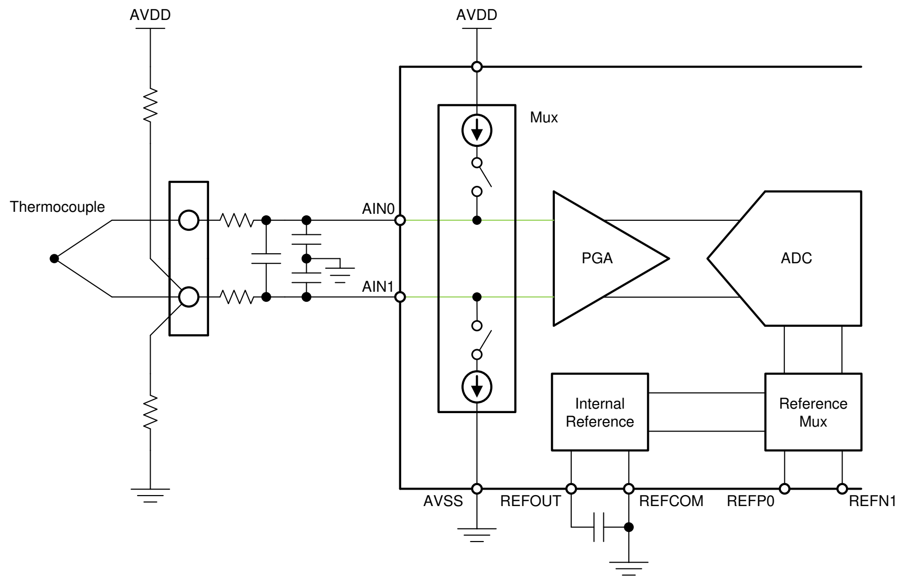

Figure 2-2. Thermocouple Measurement Circuit With Biasing Resistors Attached to the Negative Lead

2.2.2 Pros and Cons

Pros:

- Removes the voltage error from biasing current with long resistive thermocouple leads

Cons:

- Requires enabling of burn-out current sources and separate measurement for burn-out detection

2.2.3 Design Notes

The measurement circuit requires:

- Biasing resistors attached to the negative lead of the thermocouple
- AINP and AINN inputs
- Internal reference or an external voltage reference
- Burn-out current sources for a separate sensor burn-out measurement
- Isothermal cold-junction connection and measurement

Similar to the first design, this topology uses matched resistors to set the biasing for the thermocouple. In this example, matched resistors are used to bias only the negative end of the thermocouple. As long as the current through the resistors is significantly larger than the ADC input current, the resistor biasing places the negative input near mid-supply. Setting the biasing near mid-supply ensures that the input voltage is in the range of the PGA.

Attaching the bias resistors to only the negative thermocouple lead eliminates the bias current flowing through the thermocouple. This removes the error that comes from the bias current reacting with the resistive leads of the thermocouple.

Removing the bias current flowing through resistive thermocouple leads does not eliminate all errors. As in the previous topology, there is still error as the ADC input current reacts with the series input filter resistors and any series resistance associated with the input multiplexer of the ADC. Because this current cannot be removed, it is important to select an ADC with a low input current and calculate the contribution of this error to the measurement.

In the previous design, biasing resistors pulled apart the inputs in the case of a burned out thermocouple. In this design, one lead is still set to mid-supply, while the second lead is left unconnected. Because there us no current to pull up on the positive thermocouple lead, burn-out detection requires a second measurement with a change in setup for the ADC. To detect a burned out or open thermocouple, the burn-out current sources in the ADC are enabled for a separate burn-out current measurement. The burn-out current sources should not remain on for the normal measurement. These current sources, reacting with the series input filtering resistors and series resistance in the multiplexer add a large additional error.

Burn-out current sources may be set to various levels, depending on the ADC being used. Verify that the burn-out current level is high enough so that an open input creates a full-scale reading (7FFFh, assuming a 16-bit bipolar ADC) for burn-out detection.

Unless the cold junction is at 0°C, there should be a separate cold-junction measurement. This measurement can be done through several different methods, using either an RTD, calibrated thermistor, or a variety of integrated circuit temperature sensors.

2.2.4 Measurement Conversion

Using the ADC internal voltage reference or external voltage reference, the output code is converted to the measured thermocouple voltage.

$$V_{TC} = (V_{REF} \cdot \text{Code}) / (2^{15} \cdot \text{Gain}) \quad (8)$$

Measure the cold-junction temperature and convert the temperature to the equivalent cold-junction thermoelectric voltage. Add the thermocouple voltage to the equivalent cold-junction voltage.

$$V = V_{TC} + V_{CJ} \quad (9)$$

Convert the resulting voltage (V) to temperature determine the exact thermocouple temperature.

Burn-out detection requires BOCS to be enabled and a separate measurement. An output code of 7FFFh may indicate a open sensor.

2.2.5 Generic Register Settings

- Enable the internal reference or use an external reference, set ADC reference
- Select multiplexer settings for AINP and AINN to measure the leads of the thermocouple
- Enable the PGA, set gain to desired value
- Select data rate and digital filter settings
- Enable burn-out current sources for a separate burn-out measurement (optional)
- Settings for cold-junction compensation measurement

2.3 Thermocouple Measurement With VBIAS for Sensor Biasing and Pullup Resistor

Another topology for biasing the thermocouple requires enabling the VBIAS generator in the multiplexer of the ADC. The VBIAS is attached to the negative lead of the thermocouple, setting the thermocouple to a mid-supply voltage. A pullup resistor is attached from the positive lead of the thermocouple to AVDD. This pulls the positive input away from VBIAS during a burn-out condition, yielding a positive full-scale ADC reading.

2.3.1 Schematic

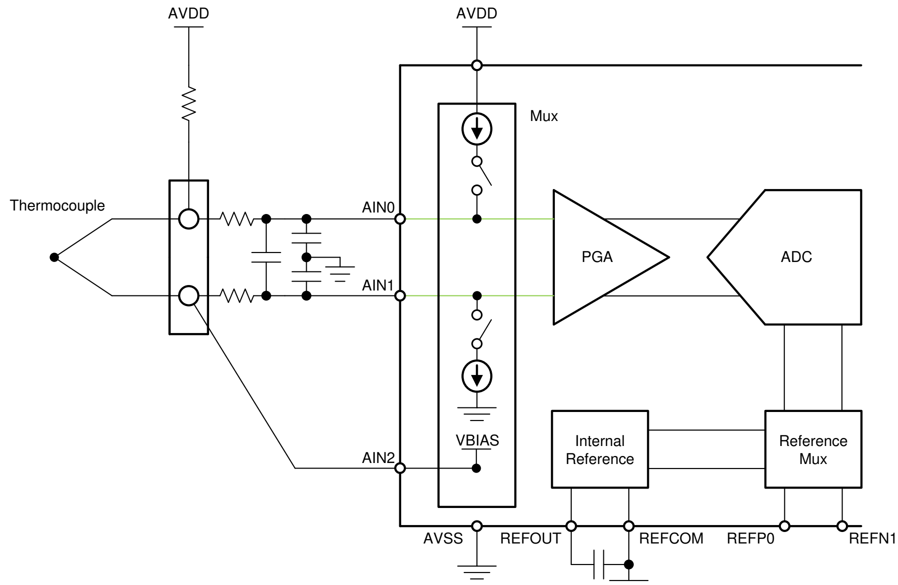

Figure 2-3. Thermocouple Measurement Circuit Using VBIAS For Sensor Biasing and Pullup Resistor

2.3.2 Pros and Cons

Pros:

- Uses VBIAS to set up the sensor DC voltage
- Pullup resistor to AVDD allows for burn-out detection without separate measurement

Cons:

- Requires an extra resistor as a pullup for burn-out detection
- Biasing current flows through the thermocouple and resistive leads, creating additional error
- Requires an extra input multiplexer line for connection to VBIAS

2.3.3 Design Notes

The measurement circuit requires:

- A single pullup resistor attached to the positive lead of the thermocouple
- Enabled VBIAS voltage attached to the negative lead of the thermocouple
- AINP and AINN inputs, and an AINx connection for the VBIAS connection
- Internal reference or an external voltage reference
- Isothermal cold-junction connection and measurement

In many precision ADCs, a bias voltage generator provides a DC input voltage for unbiased sensors such as thermocouples. This VBIAS voltage may be connected to the sensor through the multiplexer to the ADC input pins. For most devices, this VBIAS may be set to a voltage of (AVDD – AVSS) / 2. This provides a mid-supply voltage used to set the sensor bias in the middle of the input range of the PGA.

A single pullup resistor may be attached to the positive thermocouple lead for burn-out detection. In the case of a burned-out thermocouple, negative lead is still set to mid-supply, while positive lead is pulled up to AVDD. As in the previous designs, the pullup resistor is generally large to keep the bias current low. Any bias current reacting with the lead resistance of the thermocouple becomes an error in the measurement. However, the biasing current must be large enough to overcome the ADC input current. If a burn-out condition exists, the pullup resistor must be able pull the positive analog input high enough above VBIAS to give an ADC full-scale reading (7FFFh, assuming a 16-bit bipolar ADC).

As in the previous topologies, the biasing resistor must be high to keep the bias current low. Bias current reacting with the resistive leads of the thermocouple is measured as an error voltage. Also, the ADC input current reacts with the series input filter resistance and multiplexer resistance to add another measurement error.

While it is possible to connect VBIAS directly to the measurement negative input (AIN1 through the ADC multiplexer), that particular configuration may not yield precise results. The biasing current flows from the pullup resistor, through the thermocouple, into the input, and finally is sunk into the VBIAS connection. The bias current reacting with the series filter resistor (and any series resistance in the input multiplexer) causes a significant error in the measurement. In the configuration shown in Figure 2-3, the VBIAS drives the thermocouple lead from an external pin, allowing the bias current to bypass the input filter resistance.

Unless the cold junction is at 0°C, there should be a separate cold-junction measurement. This measurement can be done through several different methods, using either an RTD, calibrated thermistor, or a variety of integrated circuit temperature sensors.

2.3.4 Measurement Conversion

Using the ADC internal voltage reference or external voltage reference, the output code is converted to the measured thermocouple voltage. An output code of 7FFFh may indicate a open sensor.

$$V_{TC} = (V_{REF} \cdot \text{Code}) / (2^{15} \cdot \text{Gain}) \quad (10)$$

Measure the cold-junction temperature and convert the temperature to the equivalent cold-junction thermoelectric voltage. Add the thermocouple voltage to the equivalent cold-junction voltage.

$$V = V_{TC} + V_{CJ} \quad (11)$$

Convert the resulting voltage (V) to temperature determine the exact thermocouple temperature.

2.3.5 Generic Register Settings

- Enable the internal reference or use an external reference, set ADC reference
- Select multiplexer settings for AINP and AINN to measure the leads of the thermocouple
- Enable VBIAS on a separate analog input pin attach to the negative lead of the thermocouple
- Enable the PGA, set gain to desired value
- Select data rate and digital filter settings
- Settings for cold-junction compensation measurement

2.4 Thermocouple Measurement With VBIAS For Sensor Biasing and BOCS

Similar to the circuit in Section 2.3, this design uses the VBIAS for the sensor biasing. However, external resistors are not used for the burn-out measurement. A separate burn-out measurement is made after enabling the burn-out current sources in the ADC. Without the external biasing resistor, there is no additional voltage error from the biasing current passing through the thermocouple, filter resistors, and any resistance in the ADC multiplexer.

2.4.1 Schematic

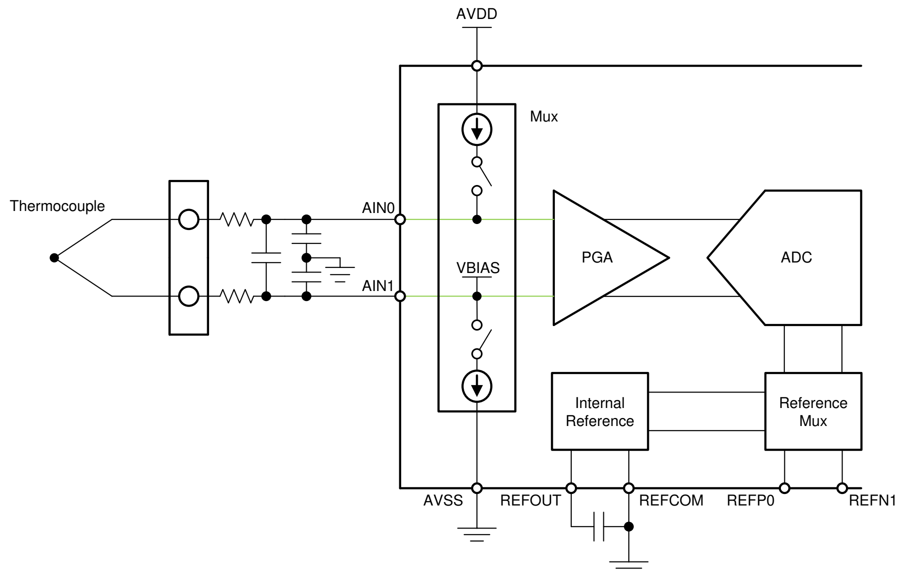

Figure 2-4. Thermocouple Measurement Circuit With VBIAS for Sensor Biasing and BOCS

2.4.2 Pros and Cons

Pros:

- Uses VBIAS to set up the sensor DC voltage
- Does not require an external VBIAS connection through the ADC multiplexer
- Does not require external components for biasing or burn-out measurements

Cons:

- Requires enabling of burn-out current sources and separate measurement for burn-out detection

2.4.3 Design Notes

The measurement circuit requires:

- Enabled VBIAS voltage attached to the negative lead of the thermocouple
- AINP and AINN inputs
- Internal reference or an external voltage reference
- Burn-out current sources for a separate sensor burn-out measurement
- Isothermal cold-junction connection and measurement

As in the previous design VBIAS provides a DC input voltage for unbiased sensors. This VBIAS voltage may be connected to the thermocouple negative input through the multiplexer and is typically set to a voltage of (AVDD - AVSS) / 2. As mentioned previously, there is no additional voltage error from the biasing current passing through the thermocouple, and any series input resistance. However, there may be some small error from the ADC input current reacting with the same elements. Consult the device data sheet for information about ADC input current.

Because there is no current to pull up on the positive thermocouple lead, burn-out detection requires a second measurement with a change in setup for the ADC. To detect a burned out or open thermocouple, the burn-out current sources in the ADC are enabled for a separate burn-out current measurement. The burnout current sources should not remain on for the normal measurement. These current sources, reacting with the series input filtering resistors and series resistance in the multiplexer add a large additional error.

Burn-out current sources may be set to various levels, depending on the ADC being used. Verify that the burn-out current level is high enough so that an open input creates a full-scale reading (7FFFh, assuming a 16-bit bipolar ADC) for burn-out detection.

Unless the cold junction is at 0°C, there should be a separate cold-junction measurement. This measurement can be done through several different methods, using either an RTD, calibrated thermistor, or a variety of integrated circuit temperature sensors.

2.4.4 Measurement Conversion

Using the ADC internal voltage reference or external voltage reference, the output code is converted to the measured thermocouple voltage.

$$V_{TC} = (V_{REF} \bullet Code) / (2^{15} \bullet Gain) \quad (12)$$

Measure the cold-junction temperature and convert the temperature to the equivalent cold-junction thermoelectric voltage. Add the thermocouple voltage to the equivalent cold-junction voltage.

$$V = V_{TC} + V_{CJ} \quad (13)$$

Convert the resulting voltage (V) to temperature determine the exact thermocouple temperature.

Burn-out detection requires BOCS to be enabled and a separate measurement. An output code of 7FFFh may indicate a open sensor.

2.4.5 Generic Register Settings

- Enable the internal reference or use an external reference, set ADC reference
- Select multiplexer settings for AINP and AINN to measure the leads of the thermocouple
- Enable VBIAS and attach to the negative lead of the thermocouple
- Enable the PGA, set gain to desired value
- Select data rate and digital filter settings
- Enable burn-out current sources for a separate burn-out measurement (optional)
- Settings for cold-junction compensation measurement

2.5 Thermocouple Measurement With REFOUT Biasing and Pullup Resistor

Similar to the Section 2.3 circuit, this design uses the internal reference to bias the thermocouple instead of the VBIAS connection. While this voltage may not be exactly at mid-supply, it should be close enough to set the sensor common-mode voltage to within the input range of the PGA.

2.5.1 Schematic

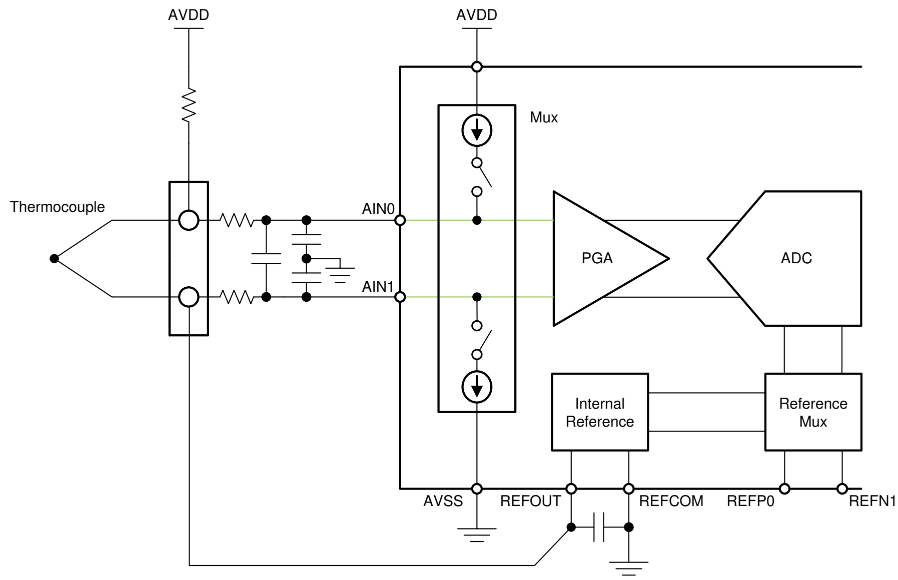

Figure 2-5. Thermocouple Measurement Circuit With REFOUT Biasing and Pullup Resistor

2.5.2 Pros and Cons

Pros:

- Uses the internal reference to set up the sensor DC voltage
- Pullup resistor to AVDD allows for burn-out detection without separate measurement

Cons:

- Requires an extra resistor as a pullup for measuring a burn-out
- Biasing current flows through the thermocouple and resistive leads, creating additional error

2.5.3 Design Notes

The measurement circuit requires:

- A single pullup resistor attached to the positive lead of the thermocouple
- Enabled internal reference voltage attached from the reference output pin (REFOUT) to the negative lead of the thermocouple
- AINP and AINN inputs
- Isothermal cold-junction connection and measurement

Another feature of many precision ADCs is an internal reference. The internal reference is often used as only the ADC reference. However, if the reference is buffered and brought out of the device to a pin, it can be used to bias a thermocouple. While this reference voltage may not be at exactly the mid-supply voltage, it is likely in the input range of the PGA. Consult the ADC data sheet for specific PGA common-mode and absolute input ranges.

First, enable the internal reference voltage. The REFOUT line is then attached to the thermocouple negative input, while a resistor is used to pull up the thermocouple positive input to AVDD. As in the similar design using VBIAS, the large pullup resistor is used for burn-out detection. If the thermocouple has burned out and become high impedance, the ADC over-ranges and gives a full-scale reading.

A single pullup resistor may be attached to the positive thermocouple lead for burn-out detection. In the case of a burned-out thermocouple, the negative lead is still set to mid-supply, while the positive lead is pulled up to AVDD. As in the previous designs, the pullup resistor is generally large to keep the bias current low. Any bias current reacting with the lead resistance of the thermocouple becomes an error in the measurement. However, the biasing current must be large enough to overcome the ADC input current. If a burn-out condition exists, the pullup resistor must be able pull the positive analog input high enough above VBIAS to give an ADC full-scale reading (7FFFh, assuming a 16-bit bipolar ADC).

As in the previous topologies, the biasing resistor must be high to keep the bias current low. Bias current reacting with the resistive leads of the thermocouple is measured as an error voltage. Also, the ADC input current reacts with the series input filter resistance and multiplexer resistance to add another measurement error.

Unless the cold junction is at 0°C, there should be a separate cold-junction measurement. This measurement can be done through several different methods, using either an RTD, calibrated thermistor, or a variety of integrated circuit temperature sensors.

2.5.4 Measurement Conversion

Using the ADC internal voltage reference or external voltage reference, the output code is converted to the measured thermocouple voltage. An output code of 7FFFh may indicate a open sensor.

$$V_{TC} = (V_{REF} \cdot \text{Code}) / (2^{15} \cdot \text{Gain}) \quad (14)$$

Measure the cold-junction temperature and convert the temperature to the equivalent cold-junction thermoelectric voltage. Add the thermocouple voltage to the equivalent cold-junction voltage.

$$V = V_{TC} + V_{CJ} \quad (15)$$

Convert the resulting voltage (V) to temperature determine the exact thermocouple temperature.

2.5.5 Generic Register Settings

- Enable the internal reference, set as ADC reference
- Select multiplexer settings for AINP and AINN to measure the leads of the thermocouple
- Enable the PGA, set gain to desired value
- Select data rate and digital filter settings
- Settings for cold-junction compensation measurement

2.6 Thermocouple Measurement With REFOUT Biasing and BOCS

Similar to the previous design, the thermocouple is biased with an external connection to the internal reference from the ADC. However, the burn-out detection is made through a second measurement with the burn-out current sources enabled.

2.6.1 Schematic

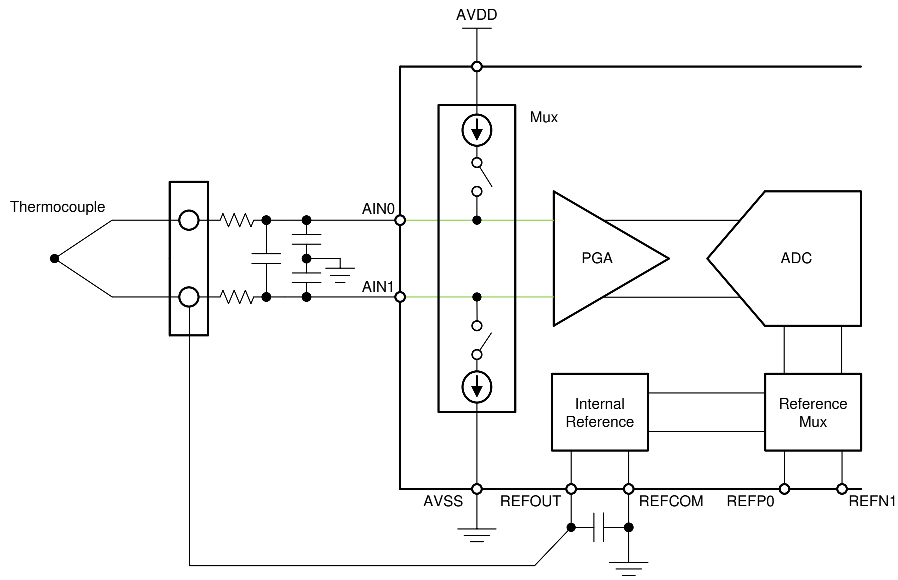

Figure 2-6. Thermocouple Measurement Circuit With REFOUT Biasing and BOCS

2.6.2 Pros and Cons

Pros:

- Uses the internal reference to set up the sensor DC voltage
- Does not require extra components for burn-out measurement

Cons:

- Requires enabling of burn-out current sources and separate measurement for burn-out detection

2.6.3 Design Notes

The measurement circuit requires:

- Enabled internal reference voltage attached from the reference output pin (REFOUT) to the negative lead of the thermocouple
- AINP and AINN inputs
- Burn-out current sources for a separate sensor burn-out measurement
- Isothermal cold-junction connection and measurement

As in the previous topology, the REFOUT line is attached to the thermocouple negative input for sensor biasing. However, instead of using a resistor connected from the positive lead to AVDD, the burn-out current sources are enabled only during a burn-out sensor measurement.

There is still error as the ADC input current reacts with the series input filter resistors and any series resistance associated with the input multiplexer of the ADC. Because this current cannot be removed, it is important to select an ADC with a low input current and calculate the contribution of this error to the measurement.

To detect a burned out or open thermocouple, the burn-out current sources in the ADC are enabled for a separate burn-out current measurement. The burnout current sources should not remain on for the normal measurement. These current sources, reacting with the series input filtering resistors and series resistance in the multiplexer add a large additional error.

Burn-out current sources may be set to various levels, depending on the ADC being used. Verify that the burn-out current level is high enough so that an open input creates a full-scale reading (7FFFh, assuming a 16-bit bipolar ADC) for burn-out detection.

Unless the cold junction is at 0°C, there should be a separate cold-junction measurement. This measurement can be done through several different methods, using either an RTD, calibrated thermistor, or a variety of integrated circuit temperature sensors.

2.6.4 Measurement Conversion

Using the ADC internal voltage reference or external voltage reference, the output code is converted to the measured thermocouple voltage.

$$V_{TC} = (V_{REF} \cdot Code) / (2^{15} \cdot Gain) \quad (16)$$

Measure the cold-junction temperature and convert the temperature to the equivalent cold-junction thermoelectric voltage. Add the thermocouple voltage to the equivalent cold-junction voltage.

$$V = V_{TC} + V_{CJ} \quad (17)$$

Convert the resulting voltage (V) to temperature determine the exact thermocouple temperature.

Burn-out detection requires BOCS to be enabled and a separate measurement. An output code of 7FFFh may indicate a open sensor.

2.6.5 Generic Register Settings

- Enable the internal reference, set ADC reference
- Select multiplexer settings for AINP and AINN to measure the leads of the thermocouple
- Enable the PGA, set gain to desired value
- Select data rate and digital filter settings
- Enable burn-out current sources for separate burn-out measurements (optional)
- Settings for cold-junction compensation measurement

2.7 Thermocouple Measurement With Bipolar Supplies And Ground Biasing

Similar to biasing the thermocouple with an external voltage source, biasing can be done by connecting the negative lead of the thermocouple to the ground, while using bipolar supplies for the ADC.

2.7.1 Schematic

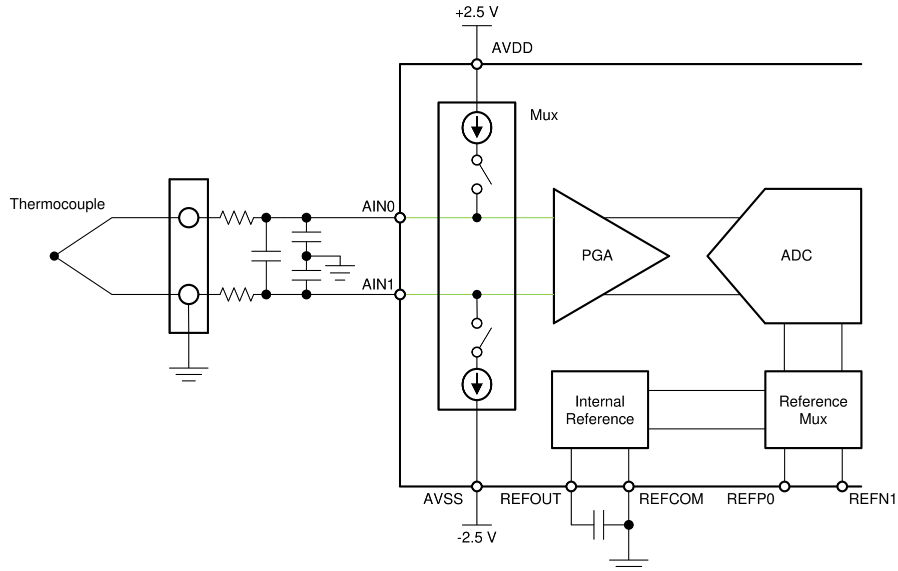

Figure 2-7. Thermocouple Measurement Circuit With Bipolar Supplies and Ground Biasing

2.7.2 Pros and Cons

Pros:

- Uses the ground line to set up the sensor DC voltage
- Does not require extra components for burn-out measurement

Cons:

- Requires bipolar analog supplies
- Requires enabling of burn-out current sources and separate measurement for burn-out detection

2.7.3 Design Notes

The measurement circuit requires:

- Bipolar supplies, with a ground node connected to the negative lead of the thermocouple
- AINP and AINN inputs
- Internal reference or an external voltage reference
- Burn-out current sources for a separate sensor burn-out measurement
- Isothermal cold-junction connection and measurement

In this topology, the negative lead of the thermocouple is connected to ground. However, the supplies are bipolar supplies, which puts ground inherently at mid-supply. This is very similar to using VBIAS to bias the thermocouple, because the ground is inherently mid-supply. Because the input is set to mid-supply, the input range is within the range of the PGA.

Without the pullup resistors, there is no error created from the bias current flowing through the resistive leads of the thermocouple. However, there is still error as the ADC input current reacts with the series input filter resistors and any series resistance associated with the input multiplexer of the ADC. Because this current cannot be removed, it is important to select an ADC with a low input current and calculate the contribution of this error to the measurement.

In this design, one lead is still set to mid-supply, while the second lead is left unconnected. Because there no current to pull up on the positive thermocouple lead, burn-out detection requires a second measurement with a change in setup for the ADC. To detect a burned out or open thermocouple, the burn-out current sources in the ADC are enabled for a separate burn-out current measurement. The burnout current sources should not remain on for the normal measurement. These current sources, reacting with the series input filtering resistors and series resistance in the multiplexer add a large additional error.

Burn-out current sources may be set to various levels, depending on the ADC being used. Verify that the burn-out current level is high enough so that an open input creates a full-scale reading (7FFFh, assuming a 16-bit bipolar ADC) for burn-out detection.

Unless the cold junction is at 0°C, there should be a separate cold-junction measurement. This measurement can be done through several different methods, using either an RTD, calibrated thermistor, or a variety of integrated circuit temperature sensors.

2.7.4 Measurement Conversion

Using the ADC internal voltage reference or external voltage reference, the output code is converted to the measured thermocouple voltage.

$$V_{TC} = (V_{REF} \cdot Code) / (2^{15} \cdot Gain) \quad (18)$$

Measure the cold-junction temperature and convert the temperature to the equivalent cold-junction thermoelectric voltage. Add the thermocouple voltage to the equivalent cold-junction voltage.

$$V = V_{TC} + V_{CJ} \quad (19)$$

Convert the resulting voltage (V) to temperature determine the exact thermocouple temperature.

Burn-out detection requires BOCS to be enabled and a separate measurement. An output code of 7FFFh may indicate a open sensor.

2.7.5 Generic Register Settings

- Enable the internal reference or use an external reference, set ADC reference
- Select multiplexer settings for AINP and AINN to measure the leads of the thermocouple
- Enable the PGA, set gain to desired value
- Select data rate and digital filter settings
- Enable burn-out current sources for burn-out measurements (optional)
- Settings for cold-junction compensation measurement

2.8 Cold-Junction Compensation Circuits

In the previous thermocouple circuits, cold-junction compensation was not discussed. The following sections show several examples of cold-junction temperature measurements using other input channels for the ADC. Several different temperature sensors are shown in different circuit topologies.

Regardless of the temperature sensor being used, ensure that the cold-junction measurement accurately measures the temperature of the isothermal block connecting the leads of the thermocouple.

2.8.1 RTD Cold-Junction Compensation

As presented in other application notes, the RTD temperature measurement can be used for cold-junction compensation. There are several different configurations for the RTD, but the one presented in Figure 2-8 is for a two-wire RTD. In most cases, RTD measurements potentially have the best accuracy.

2.8.1.1 Schematic

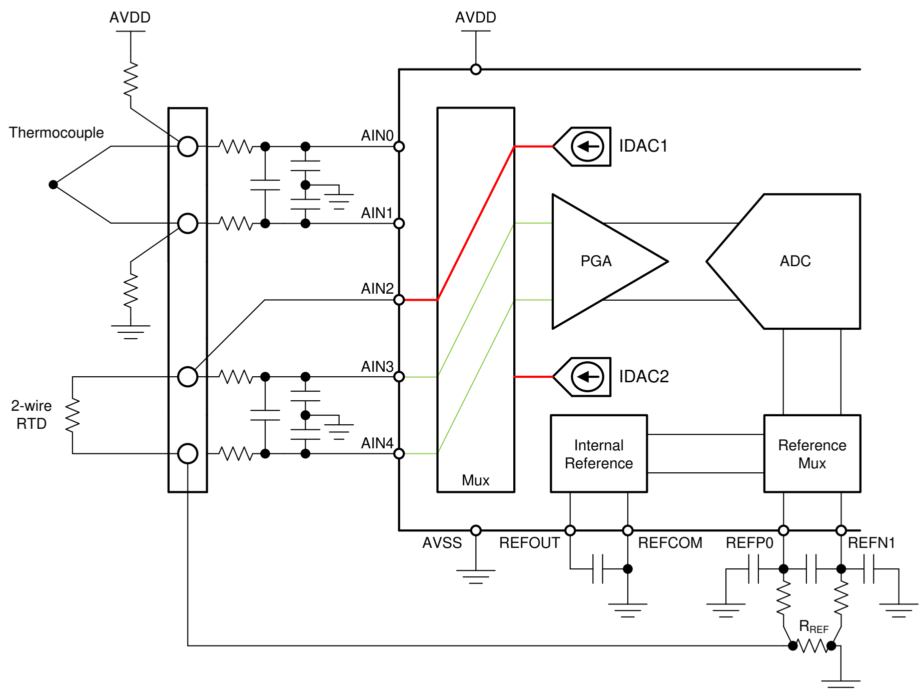

Figure 2-8. Thermocouple Measurement Circuit With Two-Wire RTD Cold-Junction Compensation

2.8.1.1.1 Design Notes

The RTD is a temperature sensor that changes resistance over temperature. There are several different types of RTD construction, but the resistance for any given temperature is well characterized. RTDs are often used to make precision temperature measurements. Figure 2-8 shows a 2-wire RTD circuit topology for making a temperature measurement used for cold-junction compensation.

The measurement circuit requires:

- Single dedicated IDAC output pin
- AINP and AINN inputs
- External reference input
- Precision reference resistor

An IDAC current source drives both the RTD and the reference resistor, R_{REF}. Because the same current drives both elements, the ADC measurement is a ratiometric measurement. Calculation for the RTD resistance does not require a conversion to a voltage, but does require a precision reference resistor with high accuracy and low drift.

With IDAC1, the ADC measures the voltage across the RTD using the voltage across R_{REF} as the reference. This provides an output code that is proportional to the ratio of the RTD voltage and the reference voltage as shown in Equation 20. Ratiometric measurements only produce positive output data, assuming zero offset error. For a fully-differential measurement, this is only the positive half of the full-scale range of the ADC, reducing the measurement resolution by one bit. The following equations assume a 16-bit bipolar ADC, with ±VREF as the full-scale range of the ADC.

$$\text{Output code} = 2^{15} \cdot V_{RTD} / V_{REF} = 2^{15} \cdot I_{IDAC1} \cdot R_{RTD} / (I_{IDAC1} \cdot R_{REF}) \quad (20)$$

The currents cancel so that the equation reduces to Equation 21.

$$\text{Output code} = 2^{15} \cdot R_{RTD} / R_{REF} \quad (21)$$

In the end, the RTD resistance can be represented from the code as a function of the reference resistance.

$$R_{RTD} = \text{Output code} \cdot R_{REF} / 2^{15} \quad (22)$$

The measurement depends on the resistive value of the RTD and the reference resistor R_{REF}, but not on the IDAC1 current value. Therefore, the absolute accuracy and temperature drift of the excitation current does not matter. In a ratiometric measurement, as long as there is no current leakage from IDAC1 outside of this circuit, the measurement depends only on R_{RTD} and R_{REF}. ADC conversions do not need to be translated to voltage. Assuming the ADC has a low gain error, R_{REF} is often the largest source of error. The reference resistor must be a high accuracy precision resistor with low drift. Any error in the reference resistance becomes a gain error in the measurement.

There are many different types of RTDs and several different construction forms. For more detailed information about RTD measurement, see *A Basic Guide to RTD Measurements*.

2.8.1.1.2 Measurement Conversion

$$\text{Output Code} = 2^{15} \cdot \text{Gain} \cdot V_{RTD} / V_{REF} = 2^{15} \cdot \text{Gain} \cdot (I_{IDAC1} \cdot R_{RTD}) / (I_{IDAC1} \cdot R_{REF}) = 2^{15} \cdot \text{Gain} \cdot R_{RTD} / R_{REF} \quad (23)$$

$$R_{RTD} = R_{REF} \cdot \text{Output Code} / (2^{15} \cdot \text{Gain}) \quad (24)$$

2.8.1.1.3 Generic Register Settings

- Select multiplexer settings for AINP and AINN to measure the RTD
- Enable the PGA, set gain to desired value
- Select data rate and digital filter settings
- Select reference input to measure R_{REF} for ratiometric measurement
- Enable the internal reference (the IDAC requires an enabled internal reference)
- Set IDAC magnitude and select IDAC1 output pin to drive the RTD

2.8.2 Thermistor Cold-Junction Compensation

The thermistor is another temperature measurement element often for the cold-junction compensation. In general, thermistors have a more limited range of temperature measurement and have a response that is non-linear. Linearization techniques are often used to get more accurate readings over an even more limited temperature range.

2.8.2.1 Schematic

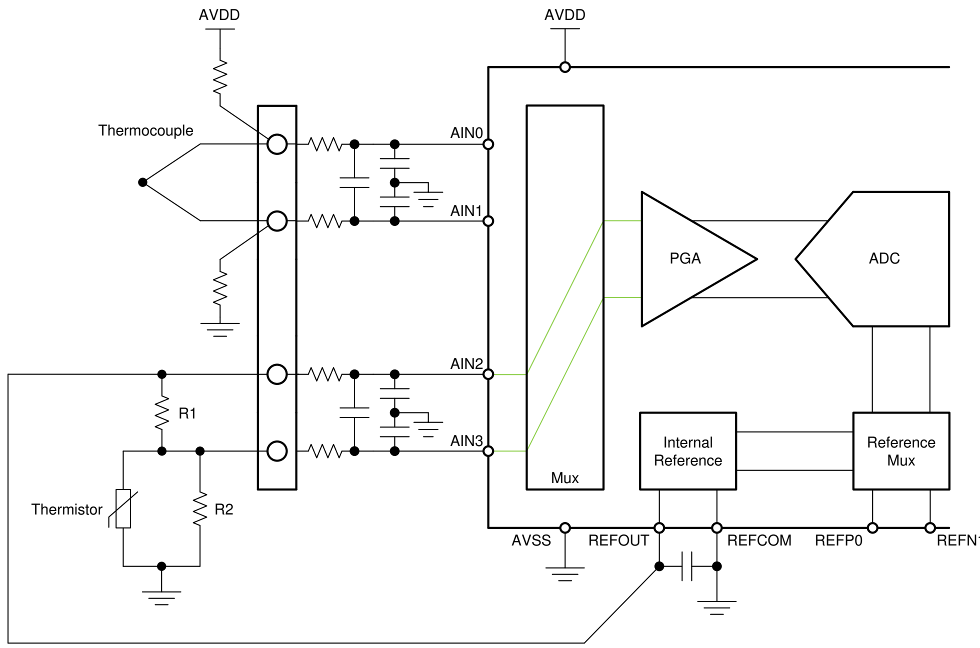

Figure 2-9. Thermocouple Measurement Circuit With Thermistor Cold-Junction Compensation

2.8.2.2 Design Notes

Similar to the RTD, thermistors are sensors that have a resistance that vary with temperature. The thermistor may be a PTC type (positive temperature coefficient) or an NTC type (negative temperature coefficient). The resistance varies significantly with temperature and are far more non-linear than the RTD, but are used for a more limited temperature range. Figure 2-10 shows an NTC thermistor measurement used for cold-junction compensation. This example thermistor has a resistance of 5 kΩ at 25°C. Two resistors are added to the circuit for linearizing the measurement at a cold-junction temperature near room temperature.

The measurement circuit requires:

- AINP and AINN inputs
- Enabled internal reference for the ADC and driving the thermistor circuit
- Precision resistors for thermistor linearization circuit

For the topology shown in Figure 2-9, the thermistor circuit is driven by the ADC internal reference. R_2 is added in parallel with the thermistor resistance to give a more linear response near room temperature. Figure 2-10 shows a plot of the resistance versus temperature for the linearization.

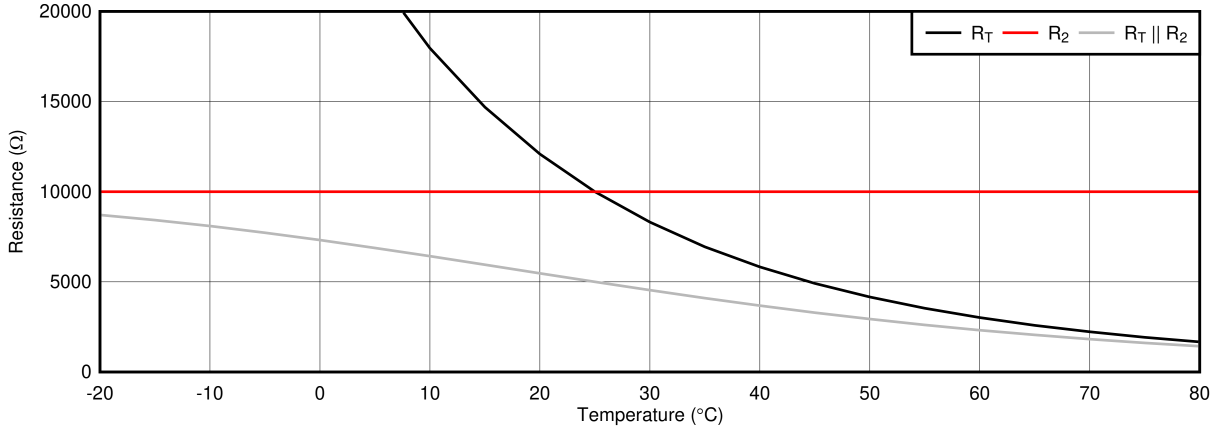

Figure 2-10. Thermistor and Linearization Responses Over Temperature

The NTC thermistor has a resistance (R_T) that is non-linear over temperature. At low temperatures, there is a large change in the resistance for a small change in temperature. At higher temperatures, there is a small change in resistance for a large change in temperature. As mentioned earlier, the thermistor has a resistance of 5 kΩ at a temperature of 25°C.

R_2 has a resistance of 10 kΩ that is constant over temperature. By adding R_2 in parallel, the resulting resistance is linear for a smaller range of operation. For this measurement it is acceptable because the cold-junction temperature is at a moderate value compared to the thermocouple measurement temperature.

Adding R_1 as a voltage divider to the parallel combination of R_2 and the thermistor resistance, measuring R_1 gives a positive temperature coefficient to the thermistor measurement (measuring across the thermistor and R_2 results in a negative temperature coefficient). Thermistor linearization is shown in Figure 2-11.

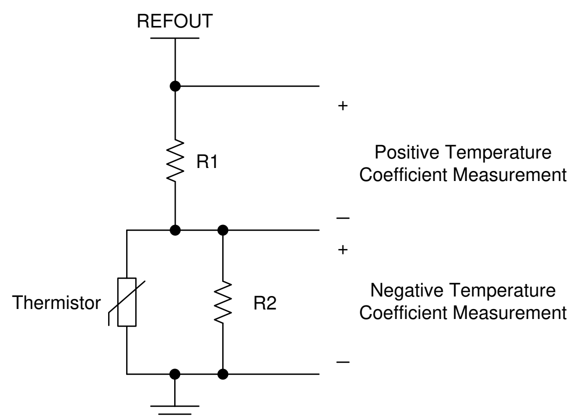

Figure 2-11. Linearization of Thermistor With Parallel Resistor and Voltage Divider

It is likely that this measurement does not require PGA amplification. If the PGA is enabled, ensure that this measurement over temperature is within the absolute and common-mode input ranges of the PGA. Note that many PGAs are not be able to measure the ground node. For this example, the ADC measured the positive temperature coefficient voltage across R_1. If the negative temperature coefficient measurement is required, then R_1 is placed at the bottom connected to the ground node and REFOUT drives the parallel combination of the thermistor and R_2.

Choosing R_1 to be a resistance of 5 kΩ, the output voltage (measured across R_1) be 1.024 V at a temperature of 25°C. This assumes that the reference voltage is 2.048 V. The output voltage measured from the thermistor circuit is shown in Figure 2-12.

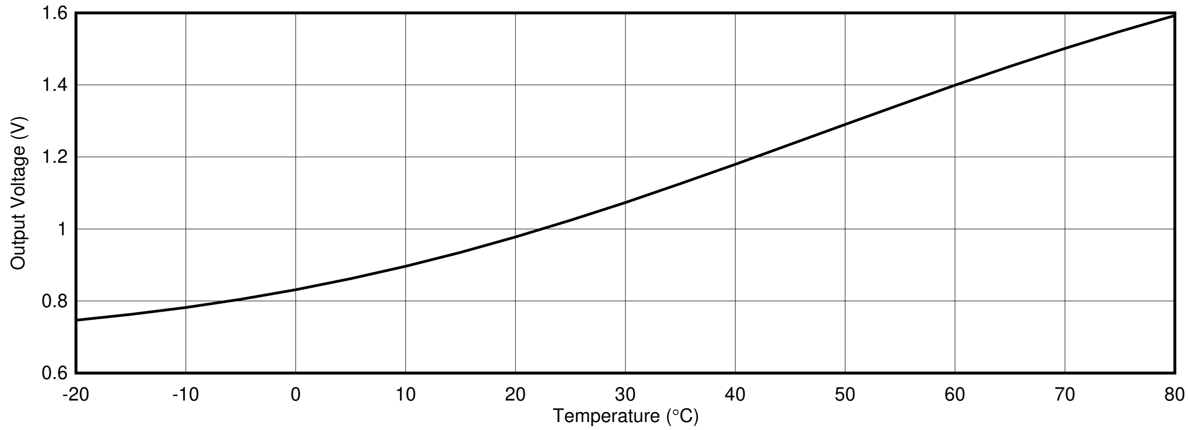

Figure 2-12. Linearized Output of Thermistor Circuit

The temperature response may be adjusted so that the result is more linear at different temperatures. Adjusting R_1 can set the best linearity for a higher or lower temperature for easy calculation with the best sensitivity of the cold-junction temperature. In this example, the measurement linearity is best from 40°C to 50°C, to center the non-linearity closer to room temperature, raise the value of R_1.

2.8.2.3 Measurement Conversion

The cold-junction compensation starts with a voltage measurement across R_1 as shown in Equation 25

$$V_{R1} = (V_{REF} \bullet \text{Code}) / (2^{15}) \qquad (25)$$

The measured voltage may be compared against the plot shown in Figure 2-12. Using the calculated result, the temperature of the cold-junction is determined.

2.8.2.4 Generic Register Settings

- Select multiplexer settings for AINP and AINN to measure the thermistor circuit
- Disable the PGA
- Select data rate and digital filter settings
- Enable the internal reference for use as the ADC reference

2.8.3 Temperature Sensor Cold-Junction Compensation

Another option for cold-junction temperature measurement is to use a semiconductor device temperature sensor. The following circuit shows a cold-junction measurement with an LMT70 device.

2.8.3.1 Schematic

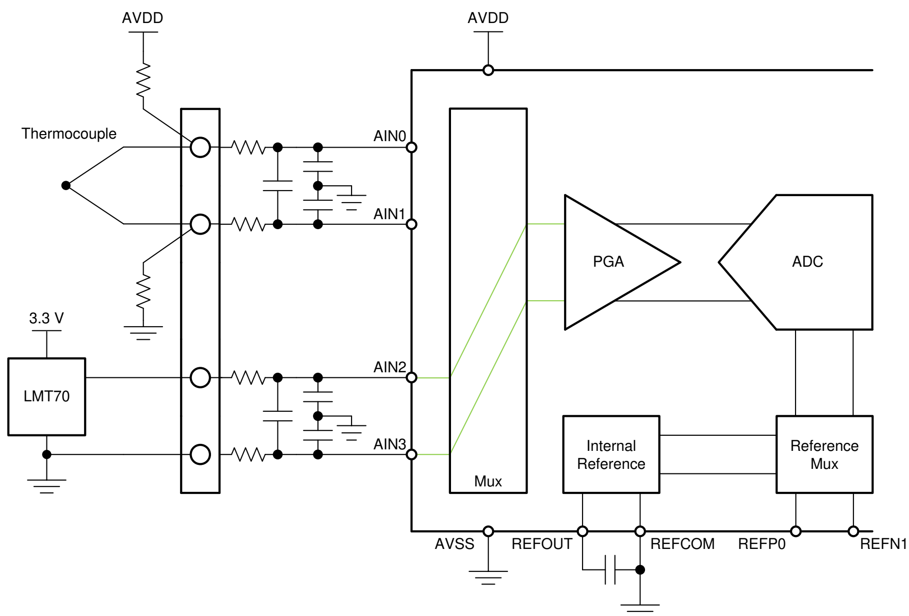

Figure 2-13. Thermocouple Measurement Circuit With Temperature Sensor Cold-Junction Compensation

2.8.3.2 Design Notes

Many semiconductor temperature sensors have temperature measurement accuracies below 1°C and can be used for cold-junction compensation. Figure 2-13 shows a circuit that uses the LMT70 for measurement.

The measurement circuit requires:

- ADC input range that extends to ground
- AINP and AINN inputs
- Internal reference for voltage measurement

This ADC measurement is a directly measures voltage and requires a known reference voltage. The output of the LMT70 gives an output voltage that can be used to calculate a temperature. Table 2-1 shows voltages that can be used to convert the LMT70 output to temperature.

One important consideration for this measurement is the input range of the PGA. The output of the LMT70 extends to the ground node and an accurate temperature measurement of the temperature may not be possible unless the PGA is disabled. Consult the ADC data sheet for PGA specifications and operation.

For more information about the LMT70, consult *LMT70, LMT70A ±0.05°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC*.

2.8.3.3 Measurement Conversion

The cold-junction compensation starts with a voltage measurement as shown in Equation 26.

$$V_{LMT70} = (V_{REF} \cdot Code) / 2^{15} \quad (26)$$

The resulting voltage is then converted to a temperature. Table 2-1 shows a table for temperature given the output voltage of LMT70. Use this table be used to construct a piece-wise linear plot of temperature versus output voltage of the device.

Table 2-1. Conversion From Voltage to Temperature for the LMT70

Temperature (°C)	V_{TAO} (mV)			Local Slope (mV/°C)
	MIN	TYP	MAX	
–55	1373.576	1375.219	1376.862	–4.958
–50	1348.99	1350.441	1351.892	–4.976
–40	1299.27	1300.593	1301.917	–5.002
–30	1249.242	1250.398	1251.555	–5.036
–20	1198.858	1199.884	1200.91	–5.066
–10	1148.145	1149.07	1149.995	–5.108
0	1097.151	1097.987	1098.823	–5.121
10	1045.9	1046.647	1047.394	–5.134
20	994.367	995.05	995.734	–5.171
30	942.547	943.227	943.902	–5.194
40	890.5	891.178	891.857	–5.217
50	838.097	838.882	839.668	–5.241
60	785.509	786.36	787.21	–5.264
70	732.696	733.608	734.52	–5.285
80	679.672	680.654	681.636	–5.306
90	626.435	627.49	628.545	–5.327
100	572.94	574.117	575.293	–5.347
110	519.312	520.551	521.789	–5.368
120	465.41	466.76	468.11	–5.391
130	411.288	412.739	414.189	–5.43
140	356.458	358.164	359.871	–5.498
150	300.815	302.785	304.756	–5.538

2.8.3.4 Generic Register Settings

- Select multiplexer settings for AINP and AINN to measure the LMT70
- Disable the PGA, ensure that the ADC is able to use ground as AINN
- Select data rate and digital filter settings
- Enable the internal reference for use as the ADC reference

3 Summary

Thermocouples are temperature sensors that are constructed from two dissimilar metals. The junction of these metals is used as the temperature sensing element, while the remaining two leads are connected to an isothermal block. Thermocouple measurements are made using precision ADCs, but still require considerations for biasing, burn-out detection, and cold-junction measurement for the isothermal block.

The circuits shown in this application note are a simple guide to how thermocouple measurements are made with precision ADCs. An overview was presented along with different thermocouple biasing topologies and different methods used for burn-out sensing. Additional circuits for cold-junction compensation were presented.

Topologies presented here are a sampling of different thermocouple topologies. Different methods of thermocouple biasing and burn-out detection can be expanded and combined to create larger systems with more channels. Alternate temperature measurement methods can be used for cold-junction temperature measurement.

4 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (September 2018) to Revision A (March 2023)	Page
• Updated the numbering format for tables, figures and cross-references throughout the document..................	1

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