Fundamentals of Temperature Measurement
Using the DeltaV Resistance Temperature
Device and Thermocouple I/O Cards

1 Introduction

The purpose of this document is to provide a basic understanding of temperature measurement as it relates to the Delta V KJ3002X1-BF1 (VE4003S6B1 including terminal block) Resistance Temperature Device and KJ3002X1-BG1 (VE4003S5B1 including terminal block) Thermocouple Cards. The intent of conveying this information is to facilitate accurate temperature measurements using these products.

2 DeltaV System Theory of Operation

A DeltaV system consists of controller nodes and workstation nodes connected together with an Ethernet network. A controller node consist of a controller that performs local control, manages data, communicates to the rest of the control network on Ethernet, and sends commands and information to the I/O system associated with the controller node. The communication between the controller and its I/O system uses the SPI communication protocol. There can be up to 64 I/O cards with each controller node.

3 Common Topics to both Cards

Proper configuration of the wiring and software will ensure quality results. This section provides information about the set up of the data filters and guidelines for installing the sense wires.

3.1 Software Filtering

The DeltaV system provides a way to filter analog input signals using a first order filter algorithm implemented in software. The filter algorithm is executed in the I/O card. Since the control algorithm that is using the sampled I/O data is operating asynchronously with the sampling of this data, the I/O data is filtered in order to prevent aliasing of the sampled signal. The Thermocouple & RTD Input card uses a first order software filter that executes at the card scan rate and has a time constant based on the period of the sampled signal to prevent aliasing. The default filter time constants are 5 sec for the Thermocouple inputs and disabled for the RTD inputs in DeltaV version v6.3.2. (Both RTD and Thermocouple channel filters default to 5 sec in DeltaV v5.3.2. This filter supports a limited set of filter selections, which are matched with control algorithm execution rates. The equation for the digital filter supported by the module is as follows:

$$Yn = C*Xn - C*Y(n-1) + Y(n-1)$$

$$C = (P / (P + Tc))$$

$$Tc = 1.3 * Tca$$

P =

- **RTD = 1 Sec**
- **Thermocouple = 1 Sec**

$$Tca = 5000 \mid 10000 \mid 30000 \mid 60000 \text{ msec}$$

where:

Y_n = new filter output

Y_{n-1} = last filter output

X_n = new sampled data to be filtered

P = period of executing filter algorithm

Tc = filter time constant

Tca = period of consuming control algorithm

Filtering is also available in the AI block for the linearized input value by using the PV_FTIME parameter. Filtering should not be used in both places as it may lead to sluggish response.

3.2 Wiring Practices

Although it is stated repeatedly, good wiring practice is a topic that justifies reiteration. Thermocouple and Resistance Temperature Device signal levels are low-level signals. As such, they are susceptible to electrically noisy environments. With good wiring practices and the use of shielded sensor lines reasonable distances can be achieved. However, with long sensor leads, that is, greater than 100 meters, in electrically noisy environments signal degradation may affect the measurement quality. Therefore, for temperature critical measurements, that is, control of less than 5 degrees C, it may be prudent to place a temperature transmitter near the sensor element and return a 4-20 ma current signal. 4-20 ma current signals are significantly less affected by environmental noises. Additionally, if the environment is excessively noisy and the run is exceedingly long, the use of a temperature transmitter returning a 4-20mA signal may be more appropriate.

The two most significant recommendations regarding wiring are the use of shielded lead lines and separating low-level signals from all other lines. There is additional information at the end of this document regarding field wiring practices and noise sources.

4 Resistance Temperature Device (RTD)

This section describes the operating parameters pertaining to principals and techniques to perform Resistance and Temperature measurements.

4.1 Resistance Temperature Device - Theory of Operation

The fundamental principle for measuring temperature using Resistance Temperature Devices (RTD) capitalizes on the fact that the device resistance varies proportional to their sensed temperature. Although RTD resistive elements come in many types, sizes, ranges and accuracies, they all share two attributes. They all have a specified resistance at a known temperature and have a defined positive temperature coefficient (positive change in resistance for a positive change in temperature). This directly allows their sensed-temperature to be determined. To determine the temperature of the RTD, an excitation current is passed through the resistive element, and the voltage across the resistive element is measured. Because the resistance vs. temperature slope is non-linear, a polynomial is used to convert the resistance into a temperature.

Generally the RTD method is more stable and accurate than the thermocouple method of temperature measurement. Conversely, the thermocouple method may be more cost-effective, may have a broader range, does not self heat and is more rugged than the resistive-device method. Following is a brief discussion of RTD parameters and measuring techniques.

4.1.1 Theory of operation specific to DeltaV

The DeltaV RTD card uses two A/D converters to measure the eight channels, the lead-compensation and the excitation-current. Sensors connected to channels 1 through 4 are multiplexed to one A/D converter, while channels 5 through 8 are multiplexed to the other A/D converter. The two A/D converters are referenced to ground and provide no isolation. The RTD card uses a terminal block that provides a means of connecting 2-wire, 3-wire and 4-wire sensors. Each of the wire inputs has a separation-diode that is internal to the card. Therefore, no jumpers are required on the terminal block to 'mix-and-match' the channel inputs as required.

4.2 Attributes of the RTD

This section provides the user with specific details and parameters about materials and equipment used in making the temperature and resistance measurements.

4.2.1 RTD Resistive Element Material

Several metals are used as the resistive element of the RTD. The most common are Platinum (Pt), Nickel (Ni), Nickel-Iron, and Copper (Cu). Platinum is the most popular element metal because of its linearity, noble metal properties and over all signal integrity. The nickel and copper elements are generally more cost-effective than the platinum elements.

4.2.2 Nominal Resistance

The nominal resistance is the specified resistance at a reference temperature. The standard value for the Pt RTD is 100 ohms; however, 200, 500 and 1000 ohms are readily available. The most common specified reference temperature is 0 degrees C. A noted exception to this is for 10-ohm copper that has a reference temperature of 25 degrees C.

4.2.3 Temperature Coefficient

The term temperature coefficient (TC) describes the average resistance change from the ice point to the boiling point of water. This is the average change; do not infer that the resistance vs. temperature slope is linear through this region. Following is a brief explanation of how the TC of a Pt100 with a TC (alpha) of 0.00385 ohms per ohm-degree centigrade is derived:

- Resistance at the ice point of water (0 degrees C): 100.00 ohms
- Resistance at the boiling point of water (100 degrees C): 138.50 ohms
- Delta from 0 degrees C to 100 degrees C: 38.50 ohms

Divide the delta (38.50 ohms) by the change (100 degrees C) then divide by the nominal resistance (100 ohms) and the result is the mean TC of 0.00385 ohms per ohm-degree centigrade. The TC is referred to as the alpha value. In general, the 100-ohm Platinum RTD with an alpha of 0.00385 (called the European curve) is the accepted standard. However, other alpha-values do exist (namely the American curve with an alpha of 0.00392). Often the alpha value is not stated and is assumed to be 0.00385. Regardless, the alpha value should be verified because the resistances vs. temperature slopes diverge and significant errors will result at higher temperatures.

DeltaV uses the 0.00385 alpha for its interpretation of the input resistances for temperature values. If a 100 ohm RTD with an American alpha is used, the resulting temperature must be multiplied by (0.00385/0.00392).

4.2.4 Accuracy

Most elements are constructed to have a nominal resistance of 100 ohms at 0 degrees C. International standards such as IEC751 have defined tolerance requirements for accuracy. Class A and Class B elements are depicted in the following formula. Class A tolerance does not apply at temperatures above 650 degrees C or to elements with only two measuring wires connected. Tighter tolerance devices are available.

Tolerance Class	Tolerance degree C
A	$0.15+0.002|t|$
B	$0.3 +0.005|t|$

Where $|t|$ = modulus of temperature in degree C without regard to sign

Temperature Tolerance

Degrees	Class A		Class B	
(C)	(+/- C)	(+/- R)	(+/- C)	(+/- R)
-200	0.55	0.24	1.3	0.56

-100	**0.35**	**0.14**	**0.8**	**0.32**
0	**0.15**	**0.06**	**0.3**	**0.12**
100	**0.35**	**0.13**	**0.8**	**0.30**
200	**0.55**	**0.20**	**1.3**	**0.48**
300	**0.75**	**0.27**	**1.8**	**0.64**
400	**0.95**	**0.33**	**2.3**	**0.79**
500	**1.15**	**0.38**	**2.8**	**0.93**
600	**1.35**	**0.43**	**3.3**	**1.06**
650	**1.45**	**0.46**	**3.6**	**1.13**
700	**-----**	**-----**	**3.8**	**1.17**
800	**-----**	**-----**	**4.3**	**1.28**
850	**-----**	**-----**	**4.6**	**1.34**

4.2.5 Self-Heating

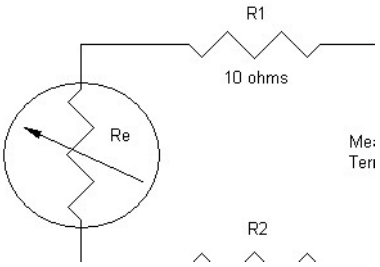
Self-heating is a condition where the temperature of the RTD element rises because the element is dissipating power due to the measuring current. Usually this effect is minimal, however, when the RTD is immersed in flowing gasses and liquids. Steps have been taken concerning the Delta V system to greatly reduce this heat-rise of the element due to the measurement current.

4.3 Lead Wire Configuration and Measurement

The single-element RTD is available in a 2-wire, 3-wire, or 4-wire arrangement. Each of these configurations is discussed in the following paragraphs.

4.3.1 2-Wire Configuration

The following diagram illustrates a 2-wire RTD lead arrangement with the measuring-leads and their associated resistances. 'Re' represents the resistance of the element; R1 and R2 represent the lead-resistance. For this example the lead-resistance will be 10 ohms per lead. This value represents approximately 75 meters or 250 feet of 26 AWG copper wire. With an accurate measurement of 'Re', an accurate determination of the temperature can be made. In the simplistic 2-wire measurement arrangement shown following graphic it should be obvious that Re can not be accurately determined because the element resistance 'Re' is in series with the lead-resistance of R1 and R2. If the lead-resistance is neglected and added to 'Re' this would represent an error of approximately 52 decrees C (20/0.385=51.9) for a Pt100.



A provision exists in the Delta V system with which to enter a value of the lead-resistance into the configuration to automatically subtract the lead-resistance for 2-wire configurations. However, as the temperature of the leads fluctuates, inaccuracies will be introduced into the measurement. Remember that the temperature coefficient of copper is 0.004 ohms per ohm-degree C. Therefore the fluctuation of temperature would equate to a 1.6-ohm increase for a 20 degrees C increase in lead-temperature. 1.6 ohms represent a 4.1-degree error for a Pt100 due to the lead-temperature changing.

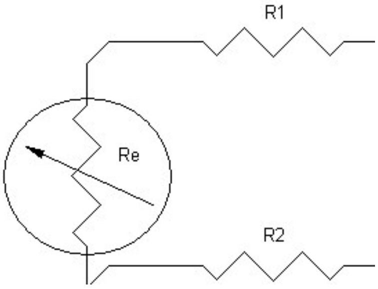
4.3.1.1 Using 10-ohm copper in 2-wire mode

The 10-ohm copper RTD when used in 2-wire mode should be used for indicative purposes only. If a 10-ohm copper RTD was used in the previous examples, errors of 0.1 ohms will occur while measuring the lead- resistance. This resistance will produce an error of approximately 3 degrees C. If the leads were the same as the previous example, the 1.6-ohm increase, due to lead-temperature changes, would result in an error of 40 degrees C. To improve the accuracy of the Delta V RTD card while using a 10-ohm copper RTD in 2-wire mode, add 0.2 ohms to the value of the lead resistance. This is approximately the value that the terminal block adds to the lead-resistance that is not accounted for. The channel parameter COMPENSATION is used to input the lead resistance factor in ohms.

4.3.2 3-Wire Configuration

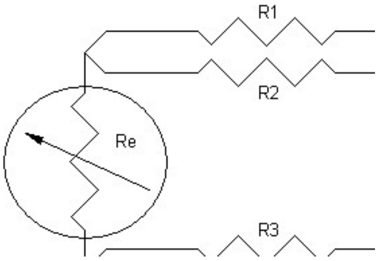
To overcome the limitations of 2-wire measurements a third measurement wire is added to facilitate continuous lead-resistance compensation. By using 3-wire compensation the lead-resistance measurement is automatically performed and errors due to temperature change are eliminated. To understand the concepts of the 3-wire compensation refer to the next diagram. The use of 3-wire compensation assumes that the three lead-resistances are the same; that is R1=R2=R3. To obtain an accurate temperature measurement the total resistance between terminals T1 and T3 is measured. Then the lead-resistance from T2 to T3 is measured. Finally, the lead-resistance is subtracted from the total resistance and the element-resistance 'Re' is obtained.

Note it is important that the resistances of the three wires are equal. If R1 is 10.3 ohms, R2 is 9.7 ohms and R3 is 10 ohms the total resistance equals 'Re' + 20.3 ohms. The value for the lead-resistance is equal to 19.7 ohms. When the 19.7 ohms is subtracted from the total resistance the calculated value of 'Re' is 'Re' + 0.6 ohms. This value, 0.6 ohms produces a 1.5-degree C error for a Pt100. Because there are two resistance measurements made for the 3-wire configuration, the reported temperature may appear to be less stable than the 2-wire and 4-wire readings (when the scale has been reduced to a window of only several degrees).



4.3.3 4-Wire Configuration

For measurements of the highest accuracy a 4-wire configuration should be used. In this configuration the sensor excitation-current is passed through the element using terminals T1 and T4. The voltage-measurement across the element is made at terminals T2 and T3. Since negligible current flows in the measurement-leads only the voltage drop across the element is observed. In the 4-wire configuration the lead-wire resistance does not need to be perfectly matched.



5 Thermocouples

This section discusses basic thermocouples, their operation and it shows examples and techniques for performing the thermocouple measurements.

5.1 Thermocouples - Theory of Operation[1]

When two wires composed of dissimilar metals are joined, a voltage, that is dependent on temperature and the composition of the two metals is produced. All junctions made up of dissimilar metals exhibit this effect. The voltage produced by the joining of two metals is called the Seebeck voltage. Figure 1 shows the equivalent circuit.

Figure 1

It is not possible to measure the Seebeck voltage directly because we must first connect a measurement device (voltmeter) to the thermocouple. The measurement device leads can create stray junctions that will contribute to a reading that is erroneous. Several techniques will be discussed that can be used to overcome this problem.

As an example, connect a voltmeter across a Copper-Constantan (Type - T) thermocouple and look at the voltage output in figure 2.

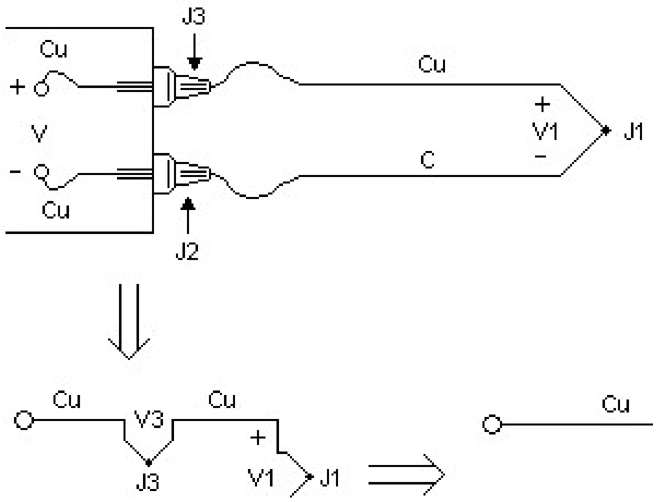


Figure 2

We are primarily interested in the voltage V1; however, by connecting the voltmeter in a configuration to measure the output of J1, we have created two new metallic junctions: J2 and J3. Since J3 is a copper-to-copper-junction, it creates no thermal EMF (V3 = 0). Conversely, J2 is a copper-to-constantan-junction that adds an EMF (V2) in opposition to V1. The resultant voltage reading V will be proportional the temperature differences between J1 and J2. This means that we can not find the temperature at J1 unless we first find the temperature at J2.

One way to determine the temperature of J2 is to physically put the junction in an ice bath, forcing its temperature to be zero degree C and establishing J2 as the reference junction. Since both voltmeter terminal junctions are now copper-to-copper, no thermal EMF is created and the V reading on the voltmeter is proportional to the temperature difference between J1 and J2. Now the voltmeter reading is:

$$\mathbf{V = (V1 - V2) \cong \alpha\ (t_{J1} - t_{J2})}$$

Where α is the Seebeck coefficient.

If we specify T_{J1} in degrees Celsius:

$$\mathbf{T_{J1}\ (^{\circ}C) + 273.15 = t_{J1}}$$

Then V becomes:

$$\mathbf{V = V1 - V2 = \alpha\ [(T_{J1} + 273.15) - (T_{J2} + 273.15)]}$$

$$\mathbf{= \alpha\ (T_{J1} - T_{J2}) = \alpha\ (T_{J1} - 0)}$$

$$\mathbf{V = \alpha\ T_{J1}}$$

The protracted derivation is used to emphasize that the ice bath junction output is not zero volts, but a function of absolute temperature. By placing J2 in the ice bath, we have referenced the reading V to zero degree C.

The Copper - Constantan thermocouple used in the previous example is unique because the copper wire is the same metal as the voltmeter terminals. Since the copper wire in the thermocouple is replaced with an iron wire, the number of dissimilar metal junctions has increased as both voltmeter terminals becomes Cu - Fe thermocouple junctions. Figure 3 shows the circuit for a J-type thermocouple connected to a voltmeter.

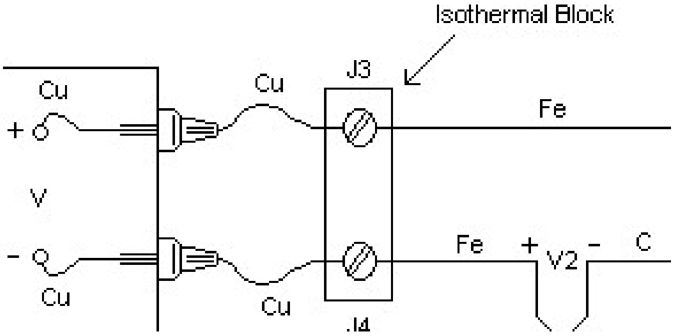


Figure 3

An isothermal block is used to keep the two junctions J3 and J4 at the same temperature. The actual temperature of the isothermal block does not matter because the two Cu - Fe junctions act in opposition. As long as J3 and J4 are held at the same temperature the measured voltage will still be:

$$\mathbf{V = \alpha\ (T1 - T_{ref})}$$

Now the reference junction can be placed on the same Isothermal bloc as junction J3 and J4. The resulting circuit is shown in figure 4:

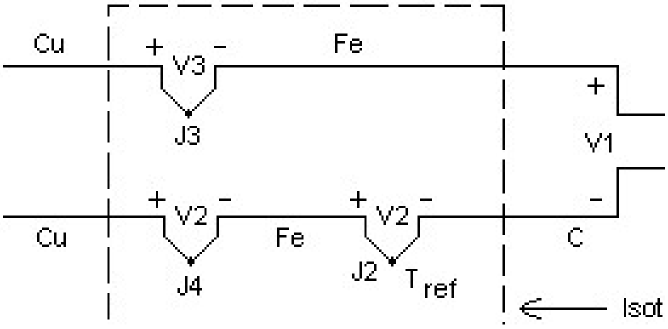


Figure 4

The law of intermediate metals can now be used to eliminate the reference junction. The "law" of intermediate metals is an empirical "law". It states that a third metal (in this case, iron) inserted between the two dissimilar metals of a thermocouple junction will have no effect upon the output voltage as long as the two junctions formed by the additional metal are at the same temperature. Figure 5 illustrates the law of intermediate metals:

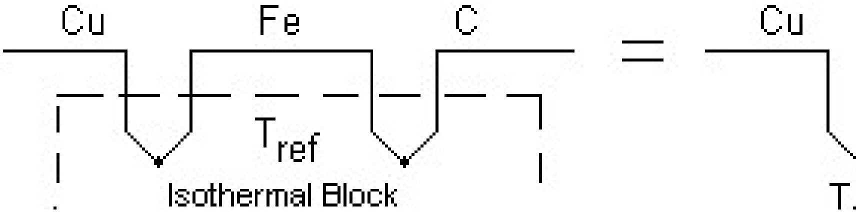


Figure 5

This means that in our example with the Iron - Constantan thermocouples, we can eliminate the need for the iron (Fe) wire in the negative lead of the thermocouple circuit. The simplified circuit is shown in figure 6.

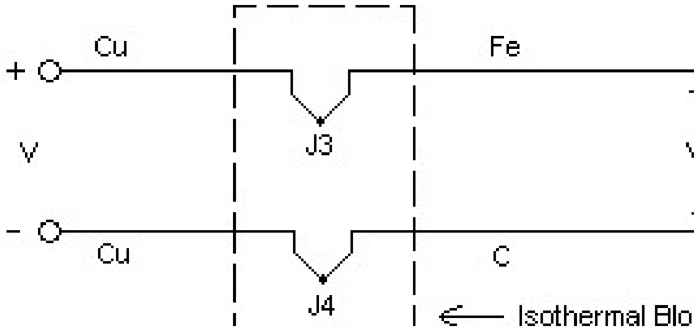


Figure 6

Again we have $V = \alpha (T_1 - T_{ref})$, where α is the Seebeck constant for an Fe - C (type J) thermocouple. Now, instead of holding the temperature T_{ref} at a constant, known temperature, we can let T_{ref} vary and use a device like an RTD to measure the absolute temperature of T_{ref}. In the example, junctions J3 and J4 are assumed to be at the same temperature due to the design of the Isothermal block.

When doing the voltage-to-temperature conversion, it is important to remember that a thermocouple is a nonlinear device. Different thermocouples have different Seebeck coefficient, and the coefficient changes with temperature. By examining the variations in Seebeck coefficient for various thermocouples over the temperature range, we can easily see that using a constant α would limit the range of the thermocouple measurement, and limit the accuracy of the system. To get better accuracy over a broader temperature range, a polynomial can be used to calculate the mV to Temperature conversion. The polynomial has the general form:

T = a0 + a1V + a2V2 + a3V3 + ...+ anVn

Where:

T = Temperature

V = Thermocouple voltage

a = Polynomial coefficient unique to each thermocouple type.

n = Maximum order of the polynomial.

5.1.1 Theory of operation specific to DeltaV

The DeltaV Thermocouple card uses the terminal block as the Isothermal block. The reference temperature is measured using an RTD mounted inside the thermocouple terminal block. The reference temperature is referred to as the Cold Junction Temperature (CJT). DeltaV uses a 5th order polynomial to convert the measured voltage to temperature. In addition, the range of the thermocouples is divided into 5 zones and different coefficients are used for different zones.

When measuring temperature with the DeltaV thermocouple card keep in mind that the response of the junction that is made up by the screw terminal and the thermocouple wire is relatively fast compared to the response time of the RTD that makes up the CJT. This means that fast temperature swings in the ambient temperature of the thermocouple terminal block can result in temporary errors in the thermocouple readings.

The DeltaV thermocouple card uses two A/D converters to measure the thermocouples and to measure the reference temperature of the terminal block. Thermocouples connected to channels 1 through 4 are multiplexed to one A/D converter, while channels 5 through 8, and the CJT are multiplexed to the other A/D converter.

5.1.2 Open Loop detect

In order for the DeltaV system to detect open loop conditions of a channel (known as burnout), a small current is switched on to the thermocouple while that channel is selected by the multiplexer. If the thermocouple is open, the input filter of that channel will charge up resulting in a reading that is out of range for the A/D converter. When the A/D converter goes out-of-range, the PV is incorrectly set to the maximum possible value for the thermocouple type and the message "sensor out of range" is sent to DeltaV Diagnostics. This eliminates the need to configure the burnout to high or low.

5.1.3 Remote CJT Measurement

As mentioned in earlier sections of this document, DeltaV is performing Cold Junction Temperature (CJT) measurement at the DeltaV terminal block. This is referred to as a local CJT reading. However, it is possible to configure DeltaV to perform a remote CJT reading. In this configuration, the thermocouples are connected to a reference junction in the field, and regular copper wires are used to connect between the reference junction and the thermocouple terminal block. One of the thermocouples is then used to measure the temperature of the remote reference junction. Figure 7 illustrates the remote compensation.

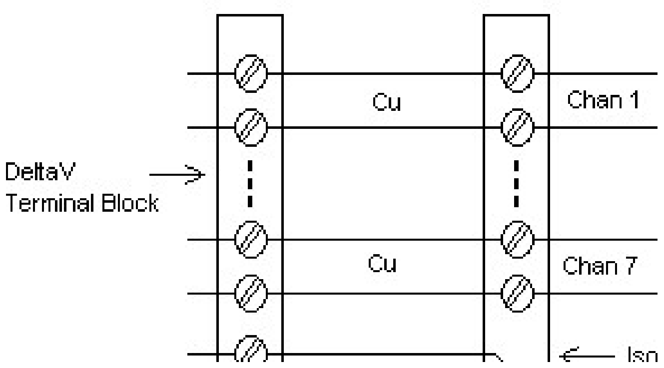


Figure 7

When the thermocouple card is configured for remote cold junction compensation, one of the channels is used to measure the remote CJT temperature. This thermocouple uses the local CJT for its compensation measurement. Any one of the thermocouple channels can be used to do the remote cold junction compensation measurement by modifying the thermocouple card parameter CJT_CHAN.

5.2 Thermocouple Installation[1]

When implementing a system that utilizes thermocouples, it is important to remember that the signal from a thermocouple is a very low voltage. Because of this low signal, it is very important that the thermocouples and the associated equipment are properly installed. The thermocouple signal becomes especially susceptible to inference if the signal is required to travel a long distance. This section will discuss some of the things that will affect the stability and accuracy of the thermocouple reading. Aside from the specified accuracy of the DeltaV card, measurement errors may be attributed to one or more of these primary sources:

- Noise and Electro Magnetic Interference (EMI)
- Poor calibration of thermocouple wire
- Shunt impedance and galvanic action
- Thermocouple specifications

5.2.1 Electro Magnetic Interference

Since the signal from a thermocouple is very small, it is susceptible to Electro-Magnetic Interference (EMI). It is therefore important to use twisted, shielded thermocouple wire between the thermocouple and the measurement equipment. It is also good practice not to run wires carrying such low level signals together with cables that emit a lot of EMI such as cables carrying power. If the required length of travel for the signal is long, and the environment is electrically noisy, a temperature transmitter to convert the temperature reading to a 4-20mA signal might be required.

The DeltaV thermocouple card can be used with either grounded or ungrounded thermocouples. However, since the thermocouples are connected through the same multiplexer in-groups of four (channels 1 through 4, and 5 through 8) it is important that the potential between the thermocouples does not exceed 0.7 volts. This means that if one thermocouple in the group is referenced in the field (for example, grounded), all the other thermocouples in that group should be referenced to the same potential. Even between groups of four it is advisable not to have more than 0.7 volts difference in potential. The preferred type to use is the ungrounded thermocouple.

It is also important to use the largest gauge possible for the thermocouple extension wire. This will minimize the series resistance and the effect of any stray currents. As a rule of thumb, the wire-resistance should be kept below 100 ohms.

5.2.2 Thermocouple Wire that is not calibrated

Not calibrated describes the process of unintentionally altering the physical makeup of the thermocouple wire so that it no longer conforms to specification. This condition can be caused by diffusion of atmospheric particles into the thermocouple wire metal. Diffusion is typically caused by high temperature annealing or by cold-working the metal. Cold-working of the metal can occur when the wire is drawn through a conduit or strained by rough handling or vibration. Annealing can occur with the section of the wire that undergoes a temperature gradient. Since it is actually a temperature gradient in the thermocouple wire that produces the thermocouple voltage and not necessarily the junction itself, it is important to avoid steep temperature gradients in the thermocouple wire. Figure 8 illustrates this point.

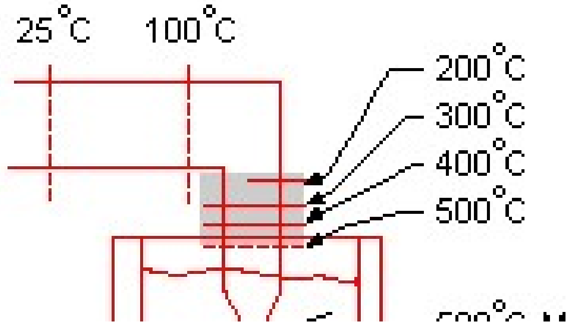


Figure 8

In figure 8, two regions are virtually isothermal and one has a large gradient. The shaded region is the region with the large gradient that produces virtually the whole signal from the thermocouple. Thermocouple wire obviously can not be manufactured perfectly; there will be some regions of the thermocouple wire that will be different. These inhomogeneities can be especially disruptive if they occur in a region of steep temperature gradient. Since it is not known where an imperfection will occur within a wire, the best thing to do is to avoid creating steep gradients in the thermocouple extension wire.

5.2.3 Shunt Impedance and Galvanic Action

High temperature or vibration can also take its toll on thermocouple wire insulation. Insulation resistance decreases exponentially with temperature, even to the point where it creates a virtual junction. If the thermocouple wire resistance is fairly large, the virtual junction can result in an erroneous reading. The insulation also contains impurities that can diffuse into the thermocouple wire, causing the wire to deviate from its specifications.

The galvanic action results from the fact that some thermocouple insulation is made with dyes that will form an electrolyte in the presence of water. This creates a galvanic action, with an output hundreds of times greater than the Seebeck effect. Care should be taken to shield thermocouple wires from all harsh atmospheres and liquids.

5.2.4 Thermocouple Specification

As discussed earlier, the voltage produced by a thermocouple varies with temperature; the voltage reading is then converted into a temperature reading by the measuring device. Unfortunately the voltage output does not vary linearly with temperature. Different types of thermocouples are more linear over different temperature ranges. When selecting a thermocouple, care should be taken to select the right type for the intended temperature range.

5.2.5 Configuration of Thermocouple Channels

The Thermocouple card is also used as a Millivolt Input card. It configures itself automatically to be a Thermocouple card or a Millivolt Input card depending upon which terminal block it is plugged into when booting. If the Thermocouple card is plugged into a regular DeltaV terminal block, or plugged into the backplane with no terminal block installed, the card will automatically configure itself as a Millivolt Input card. Only when the Thermocouple card is plugged into a Thermocouple terminal block will it be configured as a Thermocouple card. After the Thermocouple card is installed in the system, the thermocouple type for each channel can be configured from the channel property dialog window. DeltaV uses the Analog Input function block to read a thermocouple channel. For more information on how to configure the AI function block, please see DeltaV Books on Line.

6 Additional Information

This final section recommends certain procedures and provides information about coupling, noise, and interference that apply to RTD and thermocouple measurements.

6.1 Field Wiring Practice Recommendations

The following wiring practices are strongly recommended for installing field wiring. Wiring recommendations regards AC and DC power distribution are discussed in other FRS publications.

1. Ground all shields at one point only, normally at the signal source. When a multi-pair cable is split into shielded single-pair leads at a junction box, connect all shields at the junction box, and ground the multi-pair cable shield at the system.

2. Cable shields should extend to within one inch of the terminations. Shields must be insulated except at the ground point.

3. Ground all unused signal leads in a multi-pair cable at one point only, typically at the same point that the cable shield is grounded.

4. Each multi-pair cable should contain at least one pair of spare leads. Good design practices suggest that at least 10 percent of the leads be spares.

5. High-level analog signals are generally safe to route in multi-pair cable. However, in areas that are extremely noisy electrically, shielded twisted-pair wiring is recommended.

6. Use individually shielded twisted-pair cables to protect millivolt signals that are extremely susceptible to electrically induced noise. Devices such as thermocouples, strain gauges, resistance- temperature detectors (RTD), oxidation-reduction potential electrodes, and pH electrodes generate millivolt signals. Each signal has characteristics that must be taken into consideration when selecting the signal wire. Refer to the manufacturer's recommendations for the wire types to be used with a particular device.

7. Pulse count signals contain fast rise-time components that make them both noisy and susceptible to external noise. Pulse count signals should be routed in individually shielded, twisted-pair cables.

8. Discrete signals in the 5-volt or 20-milliamp range can be safely cabled with high-level analog signals. Higher-level dc signals and 120-volt ac signals, however, should be cabled separately to avoid coupling the signal noise.

9. Route motor control outputs and other high-energy device signals (typically any signals derived from relay contact closures) separately from all other lower-level signals.

10. Field wiring connects to the field termination assembly for each input unit at the screw terminals. Each screw terminal uses a captive wire clamp or collar to securely attach the wires from the external devices. Route the incoming field wires into the horizontal and vertical cable trays of a system cabinet, using lacing as required by local electrical codes or standards. Neat wiring runs, brought directly from the horizontal cable trays, simplifies any modifications and additions or changes that may be required at a later date.

11. The use of twisted-pair leads results in less loop area for inductive pickup because the inductance per foot is lower.

12. Cable used for the transmission of digital data should consist of twisted conductors.

13. Multiple conductor cables should have an overall electrostatic shield.

14. Unused conductors and shields should be terminated. If multiple conductor cables are involved, half of the unused conductors and shields should be terminated at one end and the remainder at the other end.

15. Signals transmitted through multiple conductor cables should have similar characteristics.

16. For transmission of signals that must be noise free, use cable specifically designed for that purpose. Three-conductor, twisted, shielded cable is available for three-wire signals such as potentiometer signals and dc power to amplifiers.

17. Power leads should be kept close together to maximize cancellation of conductor magnetic fields.

18. Conductors carrying alternating currents should be twisted with their returns.

19. Shields should be insulated from ground and each other along their lengths.

20. Where twisted, shielded leads must be broken, keep the unshielded length to a minimum.

21. Low level signal lines should be run unbroken from signal source to receiver.

22. Low level signal lines should not be run parallel to high-current or high-voltage wires.

23. Signal lines that are run in close proximity to switch gear may require special precautions (that is, use of localized magnetic barriers).

24. Conduit should not be buried beneath high-voltage power transmission lines or near known ground currents.

25. Solid-state switches require the same noise considerations as digital logic devices.

26. Difference signals such as those used in error correction require special attention.

27. Cable routing requires special attention. Route cables around rather than through high-noise areas. Cables carrying signals of different classifications should cross at right angles rather than run parallel for a distance before crossing.

28. Cables carrying signals of different classifications should be kept physically separated.

29. Cables carrying signals of like classification can be run adjacent to each other if twisted wiring is used to minimize crosstalk.

30. Documentation for system wiring should be complete and up-to-date to support maintenance and expansion of the system.

6.2 Electrical Noise sources

Electrical noise can be induced on signal wiring by power lines, Radio Frequency transmissions, power-switching circuits, transformers, dc motors, arc welders, lightning, and other sources. These noise-producing sources can have an adverse effect on the signals used by both analog and digital equipment. In the case of the analog equipment, the effect is generally transitory; however, in the case of digital equipment, the noise can be interpreted as data and erroneously stored in memory, thus producing a long-term effect. The most common types of electrically-induced noise are Electromagnetic Interference (EMI) and directly-coupled noise. Electric and magnetic fields outside the signal circuits cause electromagnetic Interference. Directly-coupled noise is caused when two or more signals share a common path such as a ground return. The following paragraphs provide general methods used to avoid problems produced by these noise sources.

6.2.1 Radio Frequency Interference

With Radio Frequency interference (RFI), a circuit acts as an antenna, picking up signals from nearby radio transmitters, other signal sources, and even nearby radar systems. Although the Delta V system is relatively immune to this form of interference, other external equipment and outside signal leads may be affected. Therefore, do not operate hand-held radio transceivers near the sensors, field-device transmitters, or unshielded signal wires. If a transceiver must be used and noise interference does develop, it may be necessary to shield the signal leads, the sensor, or the field transmitter.

6.2.2 Inductive Coupling

Inductive coupling induces interference on signal wires chiefly from continuously changing magnetic fields. This type of interference usually occurs when signal leads are routed close to power lines or other high-current ac cabling or equipment. The best way to reduce inductive coupling between power and signal cables is to keep them physically separated.

Table 2-1 indicates the recommended minimum separation distances between twisted-pair signal cables and ac power lines for up to parallel runs of approximately 20 feet (6 meters). For longer parallel runs, increase the separation by 12 inches for each additional 30-foot length (33 cm for each additional 10 meters of length).

Table 2-1 Minimum Separation Between signal Cables and AC Power Lines

Voltage	Current	Minimum Distance to Signal Cables
0 - 125	**0 - 10**	**12 inches (30 cm)**
125 - 250	**0 - 50**	**15 inches (38 cm)**
250 - 440	**0 - 200**	**18 inches (46 cm)**
Note These distances are applicable to twisted pair, shielded, signal cables.		

Route signal leads to avoid the strong fields surrounding large transformers, motors, generators, electric furnaces, and other high-current devices. The absolute minimum distance between the signal wires and these devices is 5 feet (1.5 meters), with the recommended minimum separation is 10 to 15 feet (3 to 4.5 meters).

In addition to keeping the signal leads away from interference sources, route the signals through twisted-pair wires. Twisted pairs are effective in reducing noise caused by magnetic fields because the voltages induced in the two wires are approximately of equal magnitude, but of opposite polarity, and thus tend to cancel out. Twisted pairs with about eight crossovers per foot (26 crossovers per meter) are five to six times more effective in reducing noise coupling than only shielding the cable.

When power lines are known to be a source of interference, they can also be twisted to reduce their own field. When signal and power leads must cross, they should do so at 90-degree angles, and both signal and power leads should have their wires twisted on both sides of the crossover for at least the distances given in Table 2-1.

6.2.3 Electrostatic Coupling

Electrostatic coupling (also known as capacitive coupling) is the main cause of noise on signal wiring. Electrostatic coupling usually occurs when long runs of signal leads are very close together. The leads act as capacitors and couple their signals to each other. The effect is especially severe when wires carrying signals of different types, high frequencies (such as used for digital communications), and high energy levels run close together.

Electrostatic coupling can be controlled. An effective way is to keep wires, which carry signals that are susceptible to this kind of coupling, shielded from each other. The wiring recommendations of this section generally indicate which types of signal wires may and may not be grouped together. The shield used can be a metal conduit, a covered tray or metal trough, or, more commonly, a shielded cable. An overlapping, multiple-folded, foil-shielded cable with a continuous drain wire in contact with the shield is the type recommended.

6.2.4 Direct Coupling of Noise

There are three basic causes of direct coupling of electrical noise onto signal leads:

1. Common signal return (common mode) lines
2. Leakage and loading (or shunting-effect) currents
3. Common-impedance coupling (ground loops)

Common signal return paths carry currents from all circuits on the path. Each current causes a voltage drop that appears as an unwanted voltage on all other circuits using the path. Providing separate return paths for each signal usually eliminates this type of problem. Common-mode signals are signals that simultaneously appear at both input terminals of a device. These signals must be rejected without disturbing the wanted signal. The Delta V system accomplishes this rejection through circuit design.

Leakage currents are generally caused by poor insulation on cables and between terminals, inadequate separation of exposed signal leads, and buildup of corrosion on terminal strips or circuit wiring components. Excessive moisture compounds these problems. Clean, dry, and well-insulated cables and terminal strips avoid most current-leakage problems. Loading or shunting-effect current noises occur when a signal source is connected to a device with low input impedance, which attenuates the signal voltage because of the shunting effect of the device on the signal source. Circuit design in the Delta V system provides proper matching of source and load impedances that generally eliminates a shunting-effect noise.

Common-impedance coupling (ground loops) occurs when a wire is connected to grounds at more than one point. If the grounds are at different voltages, a current flows in the grounded wire. If the wire is part of a signal return path, any voltage drop caused by the current flow adds or subtracts from the signal on the wire. If the wire is a shield, the spurious signal in the shield may couple to the signal leads by any of the EMI effects discussed above. Ground loop problems must be eliminated through both the grounding system design and the system installation method and techniques chosen.

[1] Portions taken from The Temperature Handbook published by OMEGA ENGINEERING INC.