



Industrial Temperature Primer

Article written by Tim Montgomery of Wilkerson Instrument Co., Inc.

Introduction

Approximately 16% of all process instrumentation measures, indicates, or controls temperature. According to a Frost and Sullivan survey, industrial temperature measurement is growing at a rate of 3.6% annually. This Temperature Primer is written with the intention of giving the reader a broad overview of the history of this important phase of measurement and the theory and hardware used in applications found in contemporary process control and measurement fields.

Sir Humphrey Davy was a brilliant scientist who made many important discoveries in his rather short lifetime. Among his many discoveries and inventions were the use of nitrous oxide (laughing gas) as the first anesthetic, the discovery of the elements sodium, potassium and boron, electric arc welding, and the invention of the miner's safety lamp, an oil lamp with a flame encased in metal gauze allowing light and air to pass through but preventing the heat from the flame starting an explosion by conducting the heat away. The flame of the lamp changes color in the presence of explosive gas. This lamp is still in use today as a backup to more advanced forms of gas detection.

In the year 1799, Sir Humphrey Davy (1778-1829) melted two pieces of ice by rubbing them together. This act proved for the first time that heat is a form of energy. Before this time, heat had been considered to be a weightless fluid called Caloric. This discovery allowed heat to be viewed in a completely different way and opened the way for advancement in temperature measurement technology which had been limited to simple thermometers before this time.

We've come a long way since that day in 1799! Today, temperature is the most measured process variable in industry. In this article we will briefly review some of the aspects of the field of industrial temperature measurement and control.

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Chapter 1. Temperature Measurement Devices:

Thermometers -

The first thermometer was invented by Galileo (1564-1642). It was an air thermometer consisting of a glass bulb with a long tube attached. The tube was dipped into a cooled liquid, then the bulb was warmed, expanding the air inside. As the air continued to expand, some of it escaped. When the heat was removed, the remaining air contracted causing the liquid to rise in the tube indicating a change in temperature. This type of thermometer is quite sensitive, but not too practical since it can be affected by the slightest change in atmospheric pressure.

In 1714 a gentleman by the name of Gabriel D. Fahrenheit invented both the mercury and the alcohol thermometer with which we are all quite familiar. Fahrenheit's mercury thermometer consists of a capillary tube which after being filled with mercury is heated to expand the mercury and expel the air from the tube. The tube is then sealed, leaving the mercury free to expand and contract with temperature changes. Although the mercury thermometer is not as sensitive as the air thermometer, it is not affected by the atmospheric pressure changes.

The mercury thermometer has a serious drawback, however. Mercury freezes at -39° Celsius, so it cannot be used to measure temperature below this point. Alcohol, on the other hand, freezes at -113° Celsius. Therefore, by substituting alcohol for mercury, much lower temperatures may be measured.

Many industrial thermometers register temperature by means of a pointer on a calibrated dial. These thermometers contain no liquid but do operate on the principle of unequal expansion. Since different metals expand at different rates, we can bond one metal to another and see that when heated, the bonded metal will bend in one direction and when cooled it will bend in the opposite direction (therefore the term "Bimetallic Thermometer"). This bending motion is transmitted by a suitable mechanical linkage to a pointer that moves across a calibrated scale. Although not as accurate as liquid in glass thermometers, BiMets are much more rugged, easy to read, and have a wider span making them ideal for many industrial applications. (Figure 1)

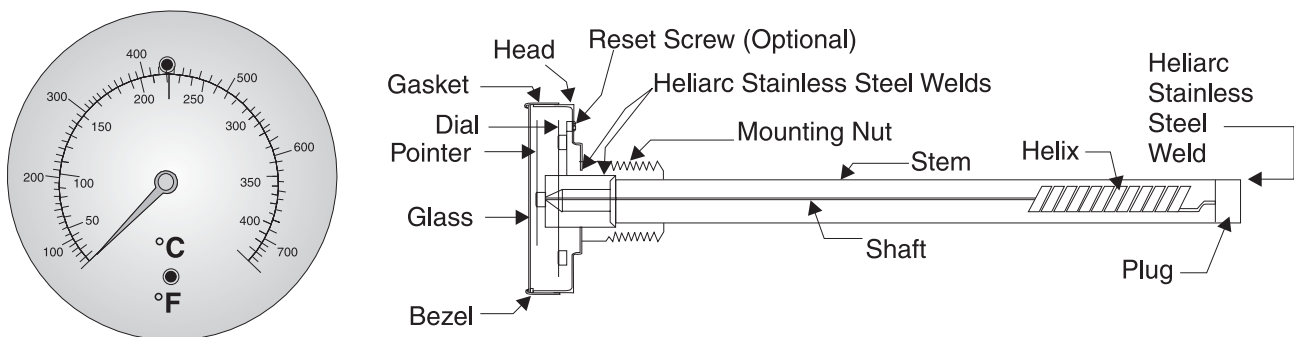
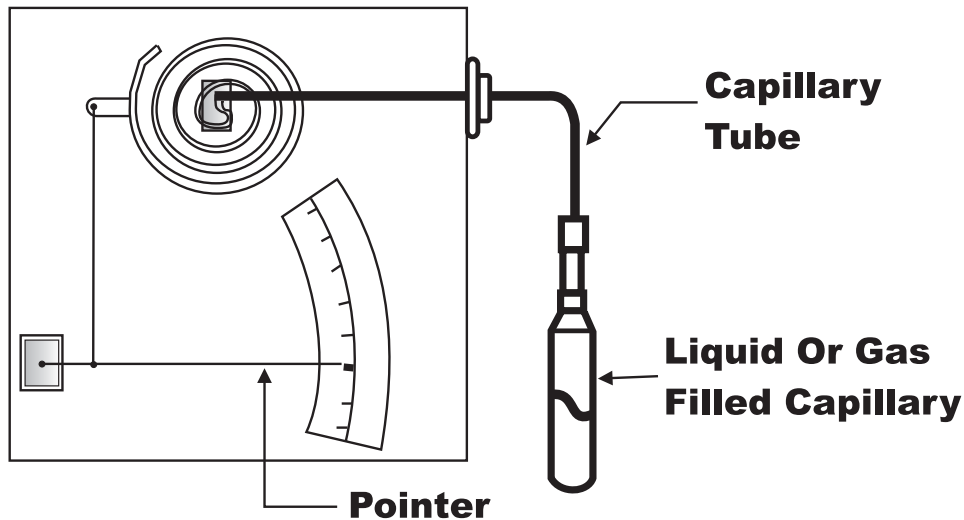


Figure 1

The filled system type of thermometer works on the same basic principle as the bimetallic thermometer. The sensing element is a capillary tube filled with a liquid or gas which expands with an increase in temperature. This sensing element delivers a motion of physical change that is applied to the control element which either indicates, records, or by comparing the signal to a setpoint can be used to control the temperature of a process.

The filled system thermometer differs from other thermometer types in that it can be used in some simple control situations. (Figure 2)



**Liquid Or Gas Filled Capillary Thermometer
(Filled System Thermometer)**

Figure 2

Thermocouples - History and Theory of Operation

In the year 1821, a very important discovery in the field of Thermometry was made. T. J. Seebeck observed that if two dissimilar metals are joined together to form a closed loop, and if one junction is kept at a different temperature from the other, an electromotive force is generated (called the Seebeck emf in honor of its discoverer) and electric current will flow in the closed loop. Experiments by Seebeck and others have shown that the amount of electric current flowing in the loop is relative in a predictable manner to the difference in temperature between the two junctions. So, if the temperature of one junction is kept at a known value, the temperature of the other junction can be determined by the amount of voltage produced. This discovery resulted in the temperature sensor that we know as the thermocouple. (Figure 3)

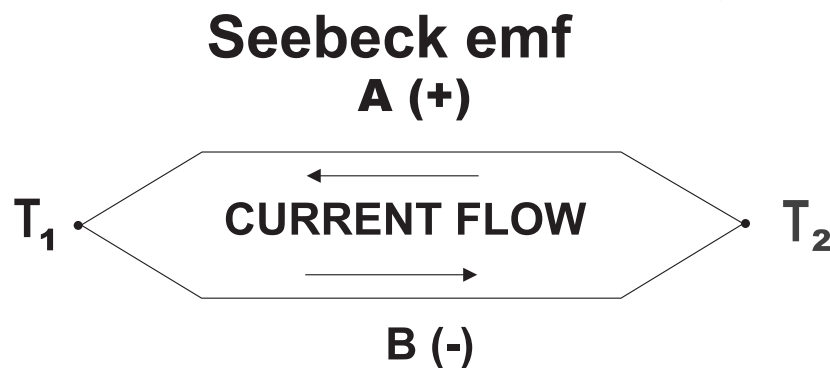
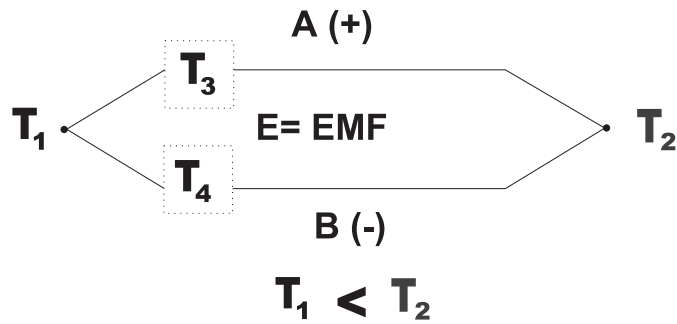


Figure 3

There are a couple of important laws governing the operation of Thermocouples. First, the Law of Homogeneous Circuits states that if thermocouple conductors are homogeneous, they are unaffected by intermediate temperatures. If a junction of two dissimilar metals is maintained at T_1 while the other is at T_2 , the thermal emf developed is independent and unaffected by any temperature distribution along the wires T_3 and T_4 . This law forms the basis for the use of thermocouple grade extension wire. (Figure 4)

Law of Homogeneous Circuits

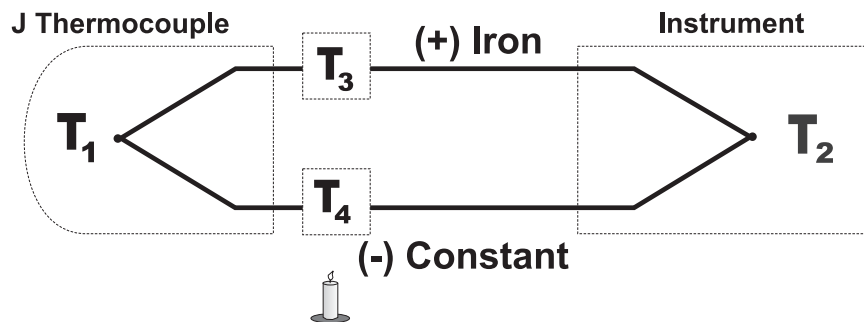


E Unaffected By T3 and T4

Figure 4

In figure 5. we see that because of the Law of Homogeneous Circuits, if the thermocouple wire is homogeneous, and if junctions T3 and T4 is less than or greater than T1, no affect in the measurement output emf will be seen. (Figure 5)

Law of Homogeneous Circuits Example



**If Thermocouple Wire Is Homogeneous
And T3 & T4 is < or > T1
No Affect In EMF Will Be Seen**

Figure 5

The second important law in thermocouple temperature measurement is the Law of Intermediate Metals. The Law of Intermediate Metals states that a third metal can be introduced into the circuit without creating errors if the junctions of the third metal to the thermocouple conductors are at the same temperature. When using thermocouples, it is usually necessary somewhere in the loop to introduce additional metals into the circuit. This happens when an instrument is used to measure the output of the thermocouple and the instrument input terminals are of a different metal (usually brass or gold) and when the junction is brazed or welded. It would seem that this introduction of other metals would change the emf output of the thermocouple and add error to the signal. However, as long as the junction of the third metal with the other two metals are at the same temperature, no error signal is produced. (Figure 6)

Law of Intermediate Metals

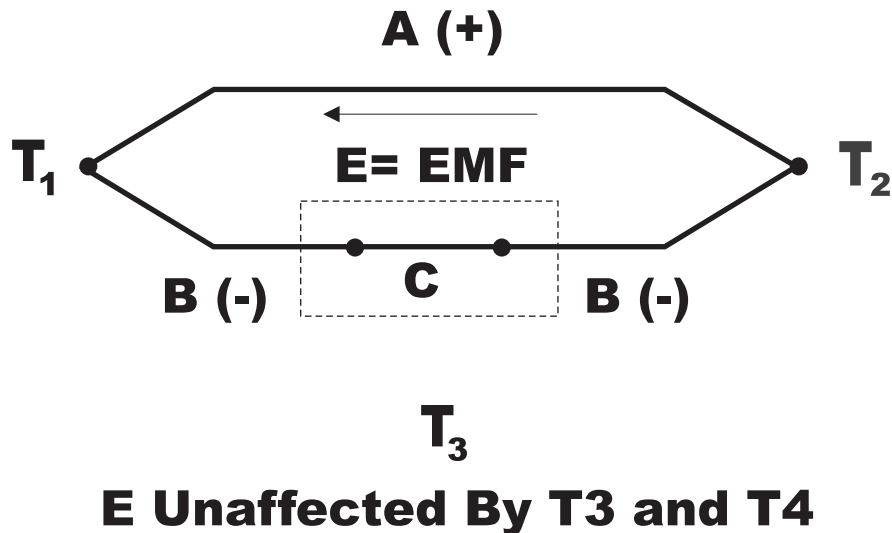


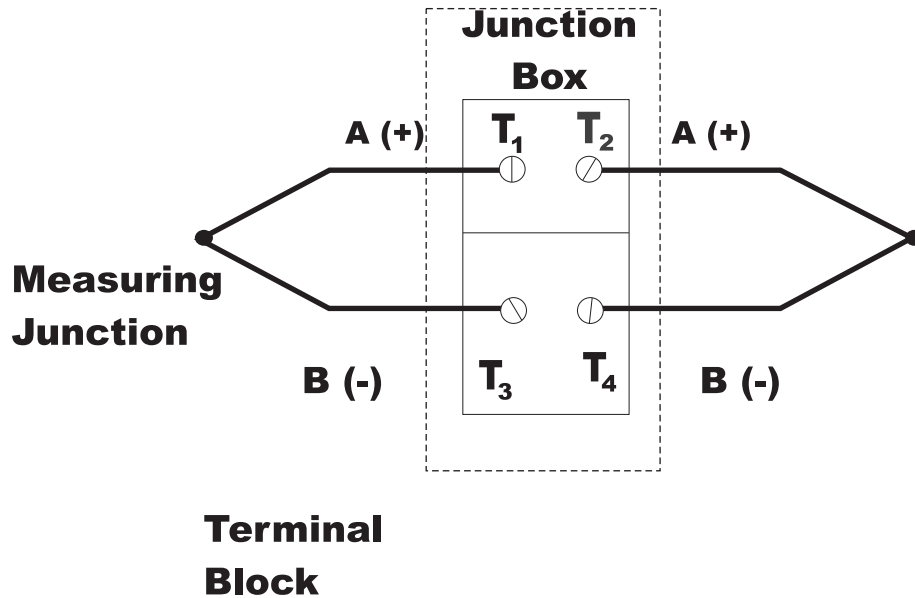
Figure 6

The law of intermediate metals comes into play when, for example, one uses a thermocouple with a brass terminal block in the connection head. The wires from the thermocouple element are attached to the terminal block to connect to the wires to the instrument. As long as there is no temperature gradient across the terminal block, no error will be introduced and the emf in the circuit will remain unaffected.

In figure 6 we see two dissimilar metals A and B with their junctions at T_1 and T_2 and a third metal C. joined on one leg. If C is kept at a uniform temperature along its length, the total emf in the circuit will not be affected.

A good example of the practical use of the Law of Intermediate Metals is shown in figure 7. In industrial applications, thermocouples are often terminated in a junction box where they are joined to thermocouple extension wire which extends back to the instrumentation in the control room. The terminal blocks used in the junction box are often constructed of a metal such as brass or nickel plated copper. Either of these metals represents an intermediate metal. According to the Law of Intermediate metals, as long as there is no difference in temperature between terminals T_1 and T_2 and between terminals T_3 and T_4 , there will be no error introduced into the circuit by the intermediate metals. (Figure 7)

Law of Intermediate Metals Example



If $T_1 = T_2$ and $T_3 = T_4$ Then No Affect To EMF

Figure 7

Thermocouple Types

Any two dissimilar metals can in theory be made into thermocouples. However, certain metals have been selected over time that make ideal thermocouples for various applications. These metals have been chosen for their emf output and their ability to operate under various conditions. There are several types of these "standard" thermocouples in use today.

As you can see from the chart on the next few pages, particular ISA calibrations of thermocouples are more suited to specific applications and temperature ranges than others.

One advantage thermocouples have over some other sensors is the ability to construct the sensor so as to suit most any application. From the simplest bare wire thermocouple, to protected sensors housed in protection tubes and thermowells with any number of different mounting arrangements. The fact that thermocouples are typically rugged, inexpensive, highly responsive and have a very broad temperature range makes them the temperature sensor of choice in many applications. Another important advantage is that since thermocouples measure temperature at the junction of the two dissimilar metals which are usually in the form of fine wire, they are naturally quite "tip sensitive". This means that you can measure temperature at a very small point of reference. One of the disadvantages of the thermocouple is that their outputs are quite non linear. Therefore, instruments used to measure temperature by thermocouples must include linearization circuitry. Also since the accuracy of the thermocouples is dependent upon the control of the alloy used in their manufacture, accuracy is somewhat limited.

STANDARD ISA THERMOCOUPLE CALIBRATION INFORMATION

LETTER DESIGNATION ANSI CODES	CONDUCTOR MATERIAL	COLOR CODE	MAGNETIC	TEMPERATURE RANGE (°F)	LIMITS OF ERROR STANDARD SPECIAL (% OR °F)		APPLICATIONS
J	IRON	+WHITE	YES	32 to 530	± 4°	± 2	May be used in vacuum, oxidizing, reducing, and inert atmospheres. Since iron oxidizes rapidly, use heavy gauge wire above 1000°F. This calibration is the most used because of its versatility and low cost.
	CONSTANTAN	- RED	NO	530 to 1400	± 3/4%	± 3/8%	
K	CHROMEL®	+YELLOW	NO	32 to 530	± 4°	± 2	Use in oxidizing atmospheres above 1000°F. Cycling above and below 1800°F should be avoided due to alterations in EMF caused by aging of alloys. "Pre-aging" of thermocouples prevents the action. Avoid using this calibration in reducing atmospheres. Preferential oxidation of chromium takes place in reducing atmosphere (commonly called "green rot"). This causes a large negative shift of EMF and rapid deterioration of the thermoelement.
	ALUMEL®	- RED	YES	530 to 2300	± 3/4%	± 3/8%	
T	COPPER	+BLUE	NO	-300 to -75	± 2%	± 1%	Resistant to corrosion in oxidizing / reducing atmospheres (avoid Chlorine). Best for Cryogenic applications. Do not use above 700°F due to poor oxidation resistance of copper.
	CONSTANTAN	-RED	NO	-75 to +200 200 to 700	± 1.5% ± 3/4%	± 3/4% ± 3/8%	
E	CHROMEL®	+PURPLE	NO	-300 to +600	± 3°	N/A	Has the Highest EMF per degree of any standard thermocouple. Since one leg of this thermocouple is CHROMEL®, the same precautions, used with type K should be taken.
	CONSTANTAN	- RED	NO	600 to 1600	± 1/2%	N/A	
N	NICROSIL	+ORANGE	NO	32 to 2300	± 4°	± 3/8%	Replaces K. Does not exhibit preferential oxidation problem found with K. Longer life and better stability than type K.
	NISIL	- RED	NO		± 3/4%		
S	PLATINUM 10% RHODIUM	+BLACK	NO	32 to 1000	± 1/4%	N/A	Avoid reducing atmospheres. Will cause excessive grain growth resulting in calibration drift (up to -2 mv).
	PLATINUM	- RED	NO	1000 to 2700		N/A	
R	PLATINUM 13% RHODIUM	+GREEN	NO	32 to 1000	± 1/4%	N/A	Avoid reducing atmospheres. Will cause excessive grain growth resulting in calibration drift (up to -2 mv).
	PLATINUM	- RED	NO	1000 to 2700		N/A	
B	PLATINUM 30% RHODIUM	+GRAY	NO	1000 to 3100	± 1/2%	N/A	Avoid reducing atmospheres. Will cause excessive grain growth resulting in calibration drift (up to -2 mv).
	PLATINUM 6% RHODIUM	- RED	NO				

NO ANSI CODES

W	TUNGSTEN	+WHITE	NO	32 to 4208	± 1%	N/A	Vacuum or inert atmospheres only. Very high temperature applications only.
	TUNGSTEN 26% RHENIUM	- RED	NO				
C(W5)	TUNGSTEN 5% RHENIUM	+WHITE	NO	32 to 4208	± 1%	N/A	Somewhat less brittle than W.
	TUNGSTEN 26% RHENIUM	- RED	NO				
19 ALLOY/ 20 ALLOY	Ni-18Mo	+N/A	YES	32 to 2300	± 3/4%	N/A	Developed for measuring temperatures in hydrogen or reducing atmospheres. Should not be used in oxidizing atmospheres.
	Ni-1Co	-N/A	YES				

OTHER TYPES OF THERMOCOUPLES USED PRIMARILY FOR SPECIAL APPLICATIONS

PLATINEL II	Approximates the type K curve. Can be used unprotected in air for extended periods of time. Has less drift than type K if aged in hydrogen for 1000 hrs. at 1000°C. Cannot be used in sulfur, phosphorus, or silicon atmospheres.
IRIDIUM / RHODIUM	Can be used for short periods of time up to 2180°C. Can be used in inert atmospheres and in vacuum. Cannot be used in reducing atmospheres.
PLATINUM - MOLYBDENUM	Used for measuring temperatures from 1100 to 1500° C. Under neutron radiation. You cannot use Platinum thermocouples containing Rhodium in neutron radiation due to rhodium being transmuted into palladium under neutron bombardment.

The Type “J” or iron-constantan thermocouple is the most widely used calibration of thermocouple. Over two hundred tons of iron and constantan materials are used in the manufacture of this calibration each year in the United States alone.

This popularity is in spite of the fact that the use of iron as a thermocouple material was vigorously opposed by many in the field of thermometry. Burgess and Le Chatelier, in their book on “Measurement of High Temperature” (1912), are emphatic on this point, basing their objections on the inhomogeneity of iron wires, and the consequent large parasitic emfs developed where a temperature gradient exists in the wire. However, the relatively high emf output, a comparatively low cost, and the adaptability to both oxidizing and reducing atmospheres justify iron-constantan’s wide use. Also, the iron used in today’s thermocouples are not appreciably less homogeneous than the constantan with which it is paired. When used under conditions where the temperature gradient along the wire is not subject to rapid fluctuations, the parasitic emfs seldom result in errors larger than one or two degrees F in measured temperature.

Constantan is an alloy of copper and nickel with a typical composition Cu57Ni43 plus the addition of small percentages of Mn and Fe. The precise composition of the alloy is not specifically defined and depends on whether it is to be used with iron for type J thermocouples, CHROMEL® for type E thermocouples, or with copper for type T thermocouples.

The type “T” thermocouple (copper constantan) is used in applications down to 11 degrees Kelvin (K) (-262° C). Copper of high electrical conductivity and low oxygen content gives a highly reproducible thermoelectric output. Since copper is available in near pure form, it need not be specially selected for thermocouple use as long as it conforms to ASTM specs for soft or annealed bare copper wire. The constantan used with the type J thermocouple cannot be used with the type T thermocouple because of different voltage requirements. A specially formulated constantan must be used. This alloy is commonly known as the “Adams Constantan” alloy. It is a copper-nickel alloy that combined with copper matches the Adams Copper-Constantan Table. The limits of error of the type T thermocouple are totally dependent upon the degree of reproducibility of constantan from melt to melt. Adams constantan is acceptable if it gives emfs against a platinum standard within the limits of error of $\pm 1.5^\circ$ F. between -75° and 200° F.

The type “T” thermocouple should not be used above 350° C since the copper will oxidize rapidly above this limit. The type “K” thermocouple designates any thermocouple which exhibits, within specified limits, the thermal emf characteristics as given in the CHROMEL®-ALUMEL® tables over the range of temperatures from -253 to 2505° F. The CHROMEL®-ALUMEL® thermocouple is the most common used to meet this criteria.

CHROMEL® is an alloy having the composition Ni90Cr10. Its thermoelectric power against platinum is higher than that of any other commonly used alloy, reaching a maximum of 35 microvolts per degree C. As a nickel-chromium alloy it is resistant to oxidation at high temperature.

The manufacturing processes involved with industrial thermocouple sensors is almost as varied as the applications for which they are intended. Basically speaking, however, industrial thermocouples are made by first forming the measuring (hot) junction by welding the two dissimilar metal wire conductors together. Welding in an inert gas atmosphere prevents oxidation and is highly recommended if the thermocouple is to be used at temperatures exceeding 1000 degrees F. For lower temperature applications, junctions may be silver brazed using a borax flux. The thermocouple wire may be either bare wire conductors or wire conductors housed in metallic sheath material with hard packed powder insulating material usually made of magnesium oxide (MgO). When using the mineral insulated type tube or sheath of metal or ceramic after thermocouple material, the sheath is usually welded over at the same time the junction is welded thereby forming a sealed junction. The bare wire type thermocouple

may be housed in a closed end the junction is welded. Before insertion into the well or protection tube, ceramic insulators are placed over the bare thermocouple wires to prevent the shorting of the wire together or to the wall of the tube. The thermocouple assembly is then fitted with the required termination (connectors, connection heads, lead wire, etc.) to complete the assembly.

Resistance Temperature Detectors - History and Theory of Operation

Another widely used device for measuring temperature is the Resistance Temperature Detector or RTD. Fifty years after Seebeck made his discovery concerning thermoelectricity, Sir William Siemens, using research done by Sir Humphrey Davy that determined that the resistivity of metals showed a distinct relationship to temperature change, established the use of platinum as the element of a resistance thermometer or RTD. Platinum RTDs as well as RTDs made from various other metals operate under the principle that the electrical resistance of certain metals increase / decrease in a repeatable manner as temperature increases / decreases.

Resistance temperature detectors are rapidly becoming today's temperature sensor of choice. In fact, there are currently over seventy five manufacturers of industrial RTD sensor assemblies in the United States alone.

Even though RTD sensors tend to be relatively slower in response than thermocouples, Resistance Temperature Detectors offer several advantages over thermocouples as temperature sensors in industrial applications. Typically, at temperatures over 850° C, thermocouples must be used, but for temperatures not exceeding 850° C, RTDs offer a definite alternative. RTDs are usually selected over thermocouples because of their inherent stability. A typical Platinum RTD can be thermally shocked from boiling water to liquid Nitrogen (-195° C) 50 times with a resulting error of less than 2/100's of a degree C. Typical stability is rated at $\pm 0.5^\circ \text{C}$ per year.

Another advantage over thermocouples is that no special compensating leadwire or cold junction compensation is needed.

Briefly, an RTD works like this: Electrical resistance of certain metals increases and decreases in a predictable manner as the temperature increases or decreases. The most commonly used metals for RTDs are Platinum, Copper, and Nickel. There are basically three reasons for selecting these metals over others. First of all, these three metals are available in near pure form. This is important to insure consistency in the manufacturing process. Secondly, these metals offer a very predictable temperature versus resistance relationship. While not perfectly linear, they are much more linear than thermocouples. Also, all three of these metals offer the ability to be processed into extremely fine wire. This is important especially in "wire wound" elements, which are the most common types in use today.

RTD Types

Among the three metals mentioned above, Platinum is the most commonly used due to its having the best temperature to resistance relationship, its ability to withstand high temperatures, its limited susceptibility to contamination, as well as the best stability. Platinum RTD elements are also the most repeatable and have the broadest measuring range (typically from -200 to +850 degrees Celsius).

It is noteworthy to mention that Platinum RTDs are used to define the International Practical Temperature Scale (IPTS) from the triple point of Hydrogen (-259.34° C) to the freezing point of Silver (+961.78° C).

Since Platinum RTDs are already used as temperature standards in laboratories throughout the world, advancements in manufacturing techniques that make RTDs more rugged are making RTDs the sensor of choice in many industrial applications.

The typical RTD is constructed by winding a very fine wire of one of the metals mentioned above around an inert substrate such as glass or ceramic material. Most elements are then encapsulated in glass or ceramics to protect them from damage due to vibration, moisture, dust, and migration of foreign metals. The wires from the RTD extend through the encapsulation material where they can then be joined to lead wires by brazing, welding, or soldering. From this point, the RTD element can be housed in tubes or thermowells to match the applications much like thermocouples. (Figure 8)

Two Types Of RTD's

Wire Wound RTD

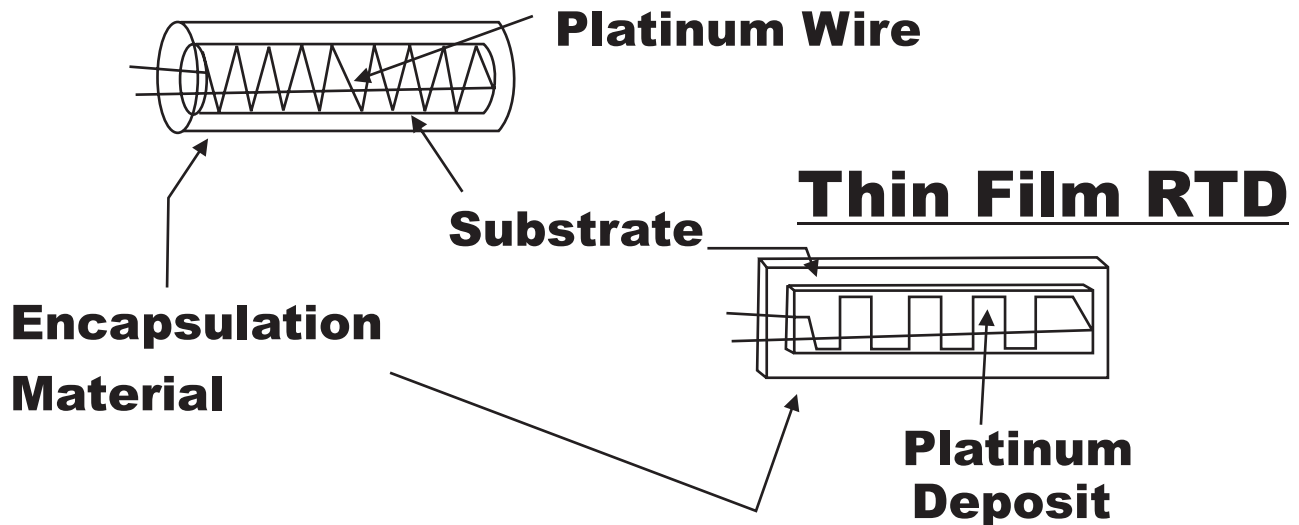


Figure 8

Most recently introduced to the RTD market has been the “Thin Film” RTD element. This type of element, rather than being “wire wound”, is produced through a process known as Thin Film Technology. Developed by the semiconductor industry, this process deposits a thin film of Platinum onto a substrate usually of ceramic material through cathodic atomization or “sputtering”. Cathodic atomization works like this: A ceramic substrate made of high purity aluminum oxide is placed in a vacuum opposite a platinum disk. The platinum disk serves as a cathode (carries a negative charge). After the vacuum container is evacuated, a noble gas is introduced and a discharge is fired by means of a high frequency electric field generator. A plasma forms between the ceramic substrate and the platinum cathode. The gas atoms exist in the ionized state in the plasma. The positively charged noble gas ions are accelerated through the electric field toward the platinum cathode. When they strike the surface of the platinum they knock platinum particles off through the force of impact. These particles come off at such a high velocity that they deposit on the surface of the ceramic substrate. Over a calculated period of time, the platinum “sputters” to a layer of defined thickness over the substrate. The layer of Platinum may be as thin as 1 micron. After the deposition is made, a laser is used to trim the platinum layer to a precise resistance. Another even newer technology for producing thin film RTDs is called Thin Film Lithography. In this process, after the substrate has been coated with platinum, a photosensitive lacquer is applied to the platinum layer. The lacquer is then illuminated through a mask with light of a defined wavelength, and then developed. After developing the non illuminated parts of the lacquer are left behind and represent the final design of the RTD conductor. Using a dry etching process, the non covered parts of the platinum coating are removed by bombardment with atoms. The platinum layer beneath the lacquer remains behind on the ceramic substrate. The remaining lacquer is then removed. Finally, the platinum conductors

are again laser trimmed to reach the required nominal resistance value. Because of this relatively new technology, RTDs can now be produced in more versatile shapes and designs. They can also be made much smaller than their wire wound counterparts. In fact, it is now possible to manufacture an RTD element the size of a pencil point! You might ask “why make such a small element?” By making the element as small as possible, we can now make an RTD assembly more responsive and “tip” sensitive. The “tip sensitive” nature of a thermocouple has always been an advantage over the RTD. Now this advantage has been all but eliminated. (Figure 8.)

RTDs, unlike thermocouples, are passive devices. They operate as one leg of a bridge network and therefore require a small amount of current, typically one mA, to produce a measurable resistance change proportional to temperature change. It is important, of course, that the power supply generating the excitation current be stable and that the other legs of the bridge network remain constant with any change in temperature.

There are two popular calibrations of Platinum RTD's in use today. With thermocouples, we work with ISA standards for thermocouple alloys. With RTDs we work with temperature coefficients or “Alphas”. The most popular and most used alpha for Platinum RTDs throughout the world is the 100 ohm international or DIN 43760 coefficient of .00385 ohms / ohm / degree Celsius. This means that the element at 0 degrees Celsius has a resistance of 100 ohms while at 100 degrees Celsius the resistance is 138.5 ohms. The other somewhat common but much less popular alpha is the sometimes called American Standard alpha of .003926 ohms / ohm / degree Celsius. The essential difference in the two alphas is that due to a slightly more pure Platinum used in the .003926 alpha, absolute accuracy is slightly better.

A word of warning. Since we are dealing with two alphas, it is most important that our instrumentation be matched to the correct alpha. Just as you would not use a type “J” thermocouple with an instrument calibrated for type “K” thermocouples, you would not use a DIN RTD with an instrument calibrated for a .003926 alpha. Doing so would introduce significant errors into the system.

Care must be taken in ordering both RTDs and the instrumentation associated with them. Just as you cannot assume that because it is a platinum RTD, it has an alpha of .00385, neither can you assume that a specification that calls for an instrument with input for a Platinum RTD requires calibration for the DIN .00385 coefficient.

Although there are advantages to using RTDs over thermocouples, there are some concerns as well. I call them concerns, not problems, because if we understand the applications, the concerns will not become problems.

First of all, there is the concern with “lead resistance”. As mentioned earlier, RTDs work as one leg of a bridge. Where RTDs are mounted some distance from the instrument, the most frequently encountered cause for error is with the lead resistance effect. Since the copper conductor in the lead wire can change resistance with temperature, and since these lead wires are in series with the RTD element, an error can be introduced. In order to compensate for these errors, RTDs are often supplied in three or four wire versions. (Figure 9) The extra wire or wires are used to offset the error by balancing the bridge. Because of lead resistance error, three wire RTDs have become the most common RTD in industry with four wire RTDs becoming more and more popular. The only apparent disadvantage of three or four wire RTDs is the need to run extra leads back to the instrumentation. This problem can be avoided if 2 wire transmitters are used.

Another concern is the phenomenon of “self heating”. Since current must flow through the sensor, there must be a certain amount of heat energy produced. This additional heat will of course elevate the temperature measurement erroneously. Self heating is expressed as the amount of electrical energy required to raise the output of the sensor by one degree Celsius. It is usually measured in milliwatts. The self heating is usually minimal if the excitation current is kept in the range of one to two milliamps.

An additional concern is the fact that RTD elements are not as rugged as thermocouples. Where necessary (in areas of high vibration or shock), this concern can be lessened by the use of thin film RTDs.

**Two, Three, or Four Wires,
That is...**

A 2-wire RTD in a typical “Wheatstone Bridge” circuit.

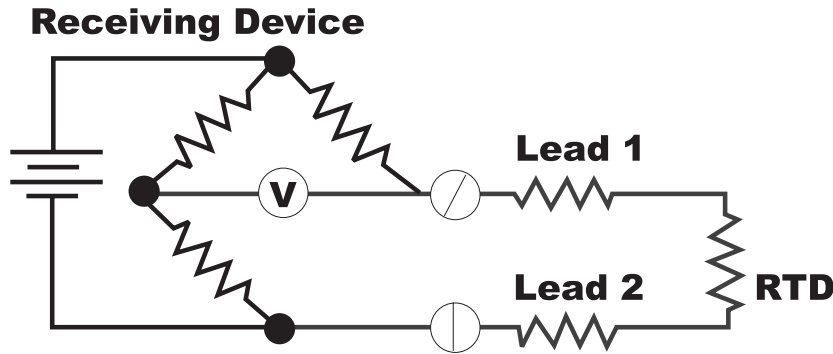


Figure 9a

Unlike a 2 wire RTD, a 3-wire RTD will compensate for lead length resistance. An accurate measurement will result only if the length, and resistance of each lead matches exactly (shown; a “Wheatstone Bridge” circuit).

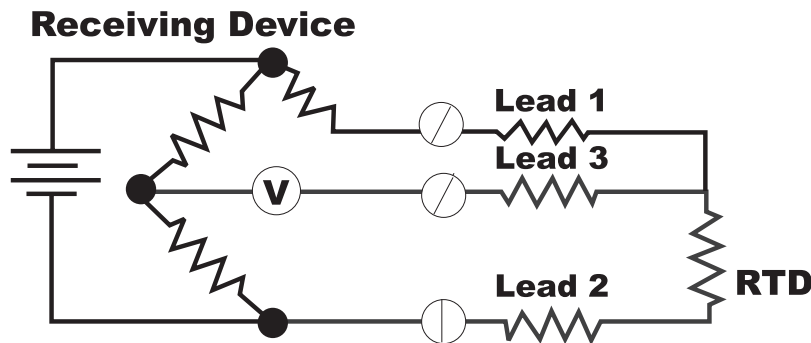


Figure 9b

A 4-wire RTD compensates for all resistance imbalances between the leads (shown: a circuit with a constant current source).

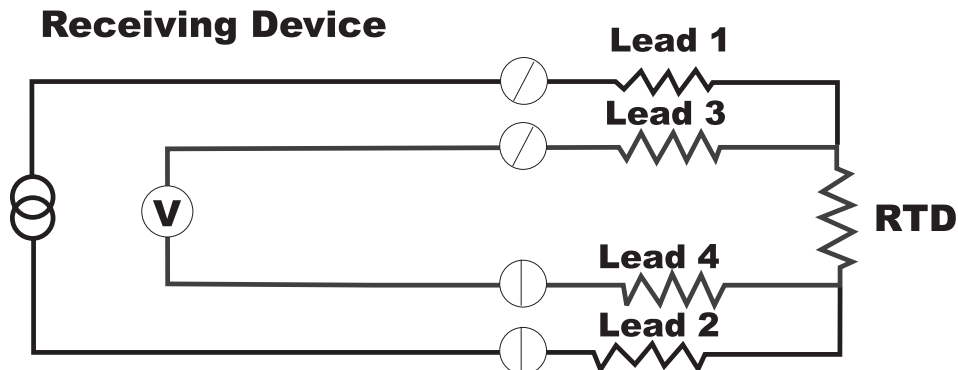


Figure 9c

Thermistors -

Another resistance based temperature sensor is the Thermistor. Unlike the RTD, the typical thermistor has a negative temperature coefficient. This means that with an increase in temperature, the resistance of the thermistor decreases. Since the per degree resistance change in a thermistor is much greater than with an RTD, a thermistor is quite sensitive to minute changes in temperature. Although the thermistor is a more sensitive device, it is also very non-linear and usually used over a very small temperature span. Thermistors have not gained nearly the popularity of RTDs or even thermocouples in industry due to their limited span as well as other disadvantages. Since thermistors are semiconductor devices, they are quite susceptible to permanent decalibration when exposed to high temperatures. In addition, thermistors are quite fragile and great care must be taken to mount them so that they are not exposed to shock or vibration.

IC Sensors -

Integrated Circuit Temperature Sensors are one of the latest innovations in temperature sensing. The main advantage to this type of sensor is that it is a naturally linear device which provides an output that is proportional to absolute temperature. The output of IC sensors is typically stated in microamps per degree Kelvin. The most common IC sensor in use today is the AD590 manufactured by Analog Devices.

The AD590 acts as a high-impedance, constant current regulator passing 1 micro-amp per degree Kelvin. It uses a supply voltage of between 4 and 30 V.

The IC temperature sensor uses a fundamental property of silicon and germanium transistors, from which it is made, to realize its temperature proportional characteristic. If two identical transistors are operated at a constant ratio of collector circuit densities (r), then the difference in their base-emitter voltages will be (kT/q) linear. Since both k (Boltzmann's constant) and q (the charge of an electron) are constant, the resulting voltage is directly proportional to absolute temperature. This voltage is converted to a current by a low-temperature-coefficient thin-film resistor.

Another popular IC temperature sensor is the LM134/234/334 series from National Semiconductor. This series of ICs make ideal remote temperature sensors due to the fact that they operate on a current output that is unaffected by long wire runs. The output current is directly proportional to absolute temperature in degrees Kelvin. The typical output is 1 microamp per degree Kelvin. Another advantage of this sensor is that it operates on any voltage from 1 to 40 volts DC.

The disadvantages of IC sensors are all of those expressed with RTD's plus a very limited temperature range usually limited to 150° C maximum.

Radiation Sensors -

All of the sensors we have discussed so far have their advantages in certain applications. However, they also share one distinct disadvantage. They must come in contact with the medium whose temperature we desire to monitor. That fact eliminates their usage in very high temperature applications found in many industrial applications. Radiation sensors often offer a solution to this problem.

The radiation sensor can typically measure temperatures up to 3500° C without contact with the measured medium.

Radiation sensors work on the principle that the temperature of a target determines the wavelength of the

COMPARISON THERMOCOUPLES VS. RTDS VS. IC SENSORS			
	THERMOCOUPLES	RTDS	IC SENSORS
ACCURACY	Limits of error wider than RTD or IC Sensor	Better accuracy than thermocouple	Best Accuracy
RUGGEDNESS	Excellent	Sensitive to strain and shock	Sensitive to Shock
TEMPERATURE DRIFT	-400 to 4200° F Higher than RTD	-200 to 1475° F Lower than TC	-70 to 300° F
LINEARITY CJC	Very non-linear Required	Slightly non-linear No	Very Linear No
RESPONSE	Fast dependent on size	Slow due to thermal mass	Faster than RTD
COST	Rather inexpensive unless Noble metal. Noble metal tc's very expensive	More Expensive	Low Cost

Table 2

emitted radiation. The simplest of the radiation sensors is the optical pyrometer, which simply requires the operator to match the color of an incandescent target to a color scale in his line of sight. Other systems are both more complex and accurate. The accuracy of a radiation sensor depends on relative stability in colors, incandescent lighting, ambient temperature of the detector head, detector angle relative to the measured surface, and surface emissivity changes. All of these variables can contribute to system errors. However, progress is being made in the area of radiation sensors. It is now possible by using long wavelength detectors and filters and by using digital sensor head transmitters which output a linear signal, to avoid electrical interference and maintain an accuracy to within a few degrees which is usually adequate in very high temperature applications.

Emissivity is a term for the amount of energy emitting characteristics of different materials. It is the function of wavelength, temperature, and angle of view. Emissivity is defined as the ratio of the energy radiated by an object at a given temperature to the energy emitted by a "blackbody" or perfect IR radiator at the same temperature. Theoretically, a blackbody neither transmits nor reflects energy. The emissivity of a blackbody is represented by "1.0". Blackbodies absorb and re-emit all energy incident upon them and are therefore ideal surfaces for IR measurement. Therefore, blackbodies are used to calibrate IR measuring devices. All objects other than blackbodies have an emissivity of less than 1.0. For example, an object may have an emissivity of .85. That means that the object emits only 85% of the energy emitted by a blackbody. Correction factors and adjustments are usually built in to IR sensors so that they may be calibrated for specific emissivities. If the correction factors are not applied, the temperature reading will be lower than the actual temperature of the object being monitored.

Radiation sensors have their biggest advantage in measuring high temperatures. However, there are many lower temperature applications where non contact temperature measurement is desired.

Small targets and moving objects can be monitored more accurately since IR sensors measure only the energy emitted by the object, not the surrounding area.

Infrared measurements are much faster, allowing several measurements to be made in less than a second. Contact methods require much longer due to slower response times.

Chapter 2. Temperature Signal Conditioning

Now that we have a very broad overview of available industrial temperature sensors, let's discuss briefly the instrumentation typically used with temperature sensors. Since liquid in glass thermometers use the graduation on the glass tube as the indicator and bimetallic and filled system dial thermometers use an analog scale built into the sensor assembly as the indicator, we will not spend further time on these types of sensors. The other types of sensors, however, have a broad array of instrumentation that may be associated with them. We will attempt to give an overview of each type starting with Temperature Transmitters.

The first instrument in line after the sensor is often some type of signal conditioning instrument. Most often it is a device called a temperature transmitter. Temperature transmitters are used to convert the signal produced by the sensor to an electrical signal recognizable to the processing instrumentation. Temperature transmitters may be of two basic types, four wire and two wire.

Four wire transmitters use a power input that is separate from the signal transmitting wiring. Two wire transmitters use a DC power supply that supplies power to the transmitter over the same two wires that are used to transmit the signal. (Figure 10).

Typical 2 - Wire Transmitter Hookup

2 - Wire Transmitter

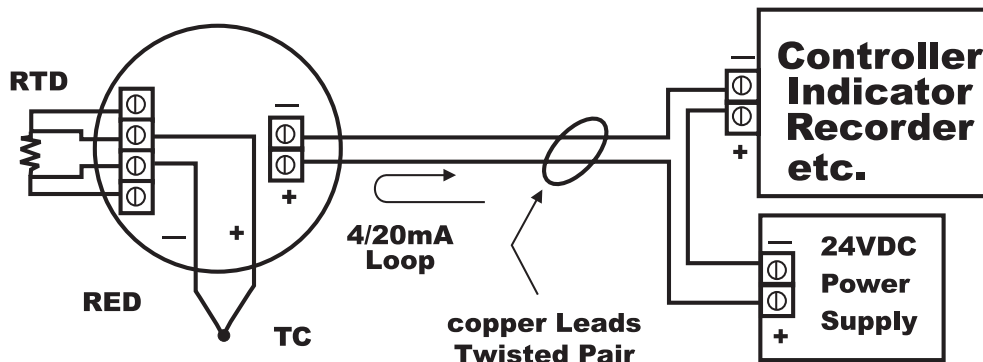


Figure 10

In fact, more than one two wire transmitter may be powered by the same DC power supply as long as the total possible current draw of the transmitters does not exceed the specifications of the power supply. (Figure 11)

Multiple Two - Wire Transmitters Single Power Supply Wiring Diagram

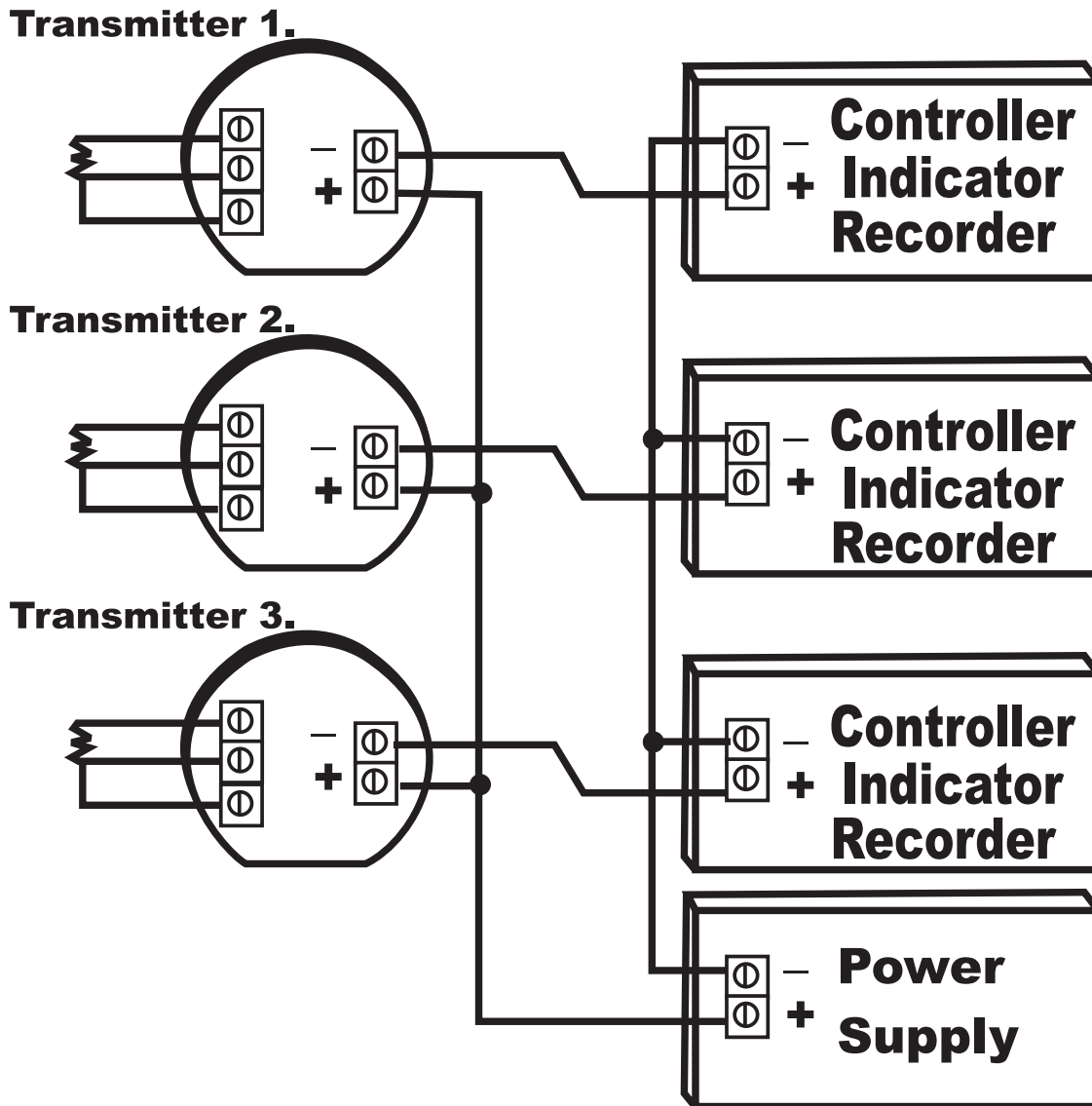


Figure 11

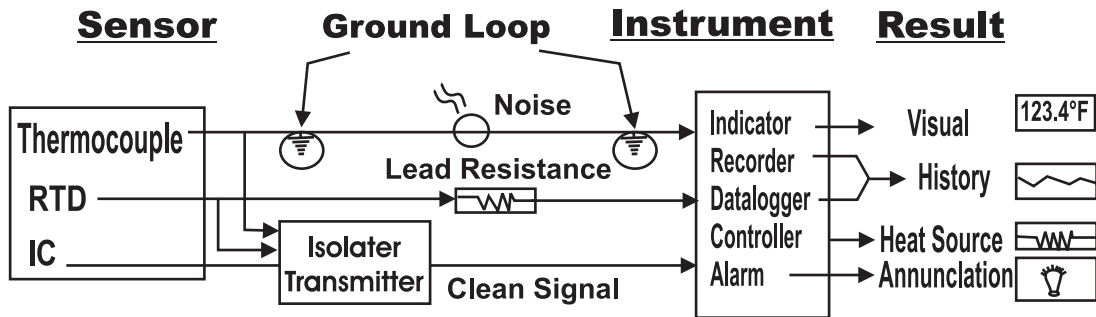
Thermocouple and RTD transmitters offer a some unique advantages over transmitting the sensor signal directly to the receiving instrument by means of thermocouple extension wire, in the case of thermocouples, and regular copper wire, in the case of RTDs.

First of all, we must remember that with thermocouples, we are dealing with a very low level emf measured in millivolts. When these small millivolt signals are transmitted by way of thermocouple extension wire over long distances, they are very susceptible to outside interference from electrical noise generated by surrounding machinery. This electrical noise can render the thermocouple signal useless. Thermocouple circuits are also prone to ground loop problems which can result in erroneous readings.

Thermocouple transmitters convert the small millivolt output of a thermocouple to a current signal (typically 4-20 mA DC) which is immune to noise and voltage drops over a long distance. Isolated thermocouple transmitters eliminate the ground loop problems by isolating the transmitter input from the transmitter output.

RTD transmitters convert the RTD resistance measurement to a current signal and thereby eliminate the problems inherent in RTD signal transmission via leadwire which is lead resistance. Errors in RTD circuits (especially two and three wire RTDs) are often caused by the added resistance of the leadwire between the sensor and the instrument. (Figure 12)

Why Transmitters



Ground Loops = Errors
Noise = Errors
Lead Resistance = Errors
Clean Signal = no Problems

Figure 12

Another fact that often makes the use of transmitters in thermocouple and RTD circuits advantageous is cost. Thermocouple extension wire is very expensive because its conductors are constructed of the same alloys as the element itself (refer to the Law of Homogeneous Circuits in chapter 1). Also, if lead lengths are long, a heavy gage (typically 16 awg) must be used to resist voltage drop in the circuit. This not only increases the cost of the extension wire but it makes it more difficult to install as well. If the distance between the sensor and the receiving instrument is substantial, then the difference in cost between thermocouple extension wire and the copper wire used with a transmitter can more than pay for the addition of a transmitter to the circuit. Pretty much the same holds true in RTD circuits. The extension wire used is copper but most often three conductors must be run instead of two. Also larger gage size is required to lessen the lead resistance effect.

Another reason that transmitters must often be used is that many instruments will not accept the signals produced by thermocouples and RTDs directly. Much of today's temperature instrumentation consists of computer based systems and programmable logic controllers (PLC). These systems normally handle the current input from a transmitter with no problem. Thermocouple and RTD signals often cannot be inputted directly to these devices. Even when they can, it often requires the addition of expensive electronic circuitry to convert the thermocouple and RTD signals to one that is usable by the system.

Chapter 3. Single Loop Temperature Controllers

A single loop temperature controller is an instrument that takes the signal from a sensor, compares it to a setpoint signal, and adjusts the output to the heating device to maintain, as close as possible, equilibrium between the measured temperature and the setpoint temperature. The key phrase here is “as close as possible”. There are several types of control methods used to accomplish this. We will attempt to briefly explain the most common.

On-Off Control

Selection of the right temperature controller for the application depends on the degree of control required by the application. The simplest of applications may only require what is called “On-Off” control. On-Off control operates much in the same manner as the thermostat on our home heating systems. In other words, the output of the controller is either 100% on or 100% off. The sensitivity of the On-Off control (sometimes called “hysteresis” or “dead-band”) is designed into the control action between the points at which the control output switches from “off” to “on”. This designed in hysteresis prevents the output from switching from off to on too rapidly. If the hysteresis is set too “narrow”, rapid switching will occur and often result in what is known as output “chattering”. This “chattering” can result in poor lifetime of output relays and heating components. Therefore, the hysteresis should be set so that there is sufficient time delay between the “on” and “off” modes of the outputs. Due to the hysteresis needed in the output of the on-off controller, there will always be a certain “undershoot” and “overshoot” in the control action. The amount of under shoot and overshoot is dependent upon the characteristics of the entire thermal system of a particular application. (Figure 13A..)

Time Proportioning

Processes requiring a little more precise control than On-Off control usually require what is called Time Proportioning. A time proportioning control operates much the same way as an on-off control while the process temperature is outside of what is called the proportional band. The proportional band is that area around the setpoint in which time proportioning control takes places. When the process temperature enters the proportional band (approaching setpoint) the cycle time between time on and time off begins to vary. At the low end of the proportional band, the on time is much greater than the off time. As the process gets closer to the setpoint, the on time decreases and the off time increases. This changes the effective power to the heating load and causes a “throttling back” in the speed at which the temperature of the process is increased. This action continues until a stabilization takes place somewhere below the setpoint. At this point, control is achieved. The difference in the control point and the actual setpoint is called “droop”. (Figure 13B.)

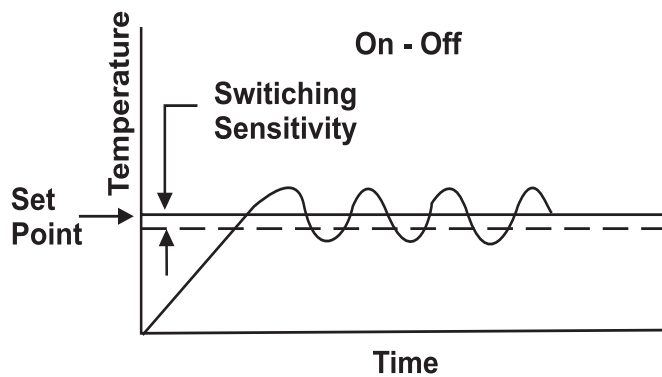


Figure 13a

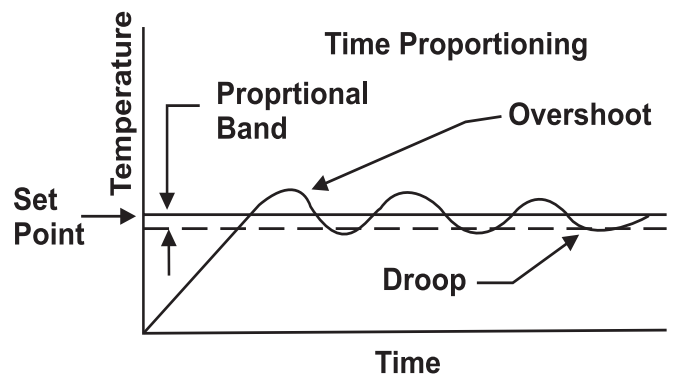


Figure 13b

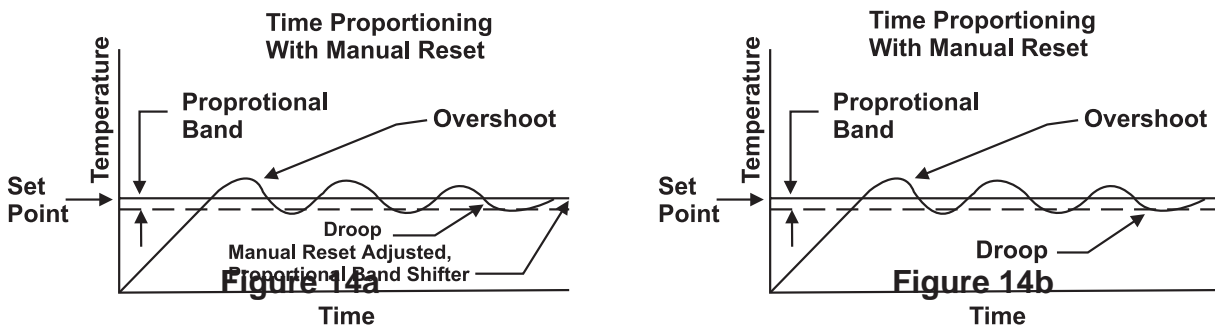
As long as there is no change in the process load, this condition will remain constant.

Integral or “Reset Action”

If the “droop” in the time proportioning form of control cannot be tolerated in the process, the Integral function of control must be added. The integral function found in “automatic reset” controllers uses a mathematical algorithm to calculate the amount of droop and then adjusts the output to “reset” the control result to setpoint. This is usually done by automatically shifting the proportion band slightly to compensate for the droop.

Automatic reset action can only take place within the proportional band. Should automatic reset be applied outside the proportional band, the result would be a condition of extreme overshoot of the setpoint. The process of eliminating the automatic reset outside of the proportional band is called “anti-reset windup” and is typically a standard feature of controls that include the automatic reset or “integrating” function.

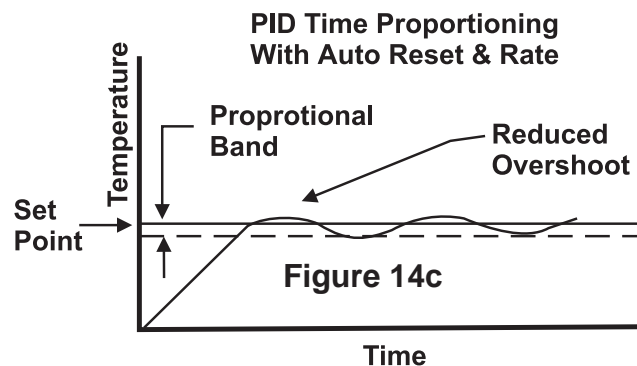
On many controls that do not offer “automatic” reset. This function is accomplished manually by a potentiometer adjustment that manually shifts the proportional band. (Figure 14A and 14B)



Derivative (Automatic Rate)

Temperature overshoot is when the process, during its cycling, exceeds setpoint. Overshoot can be small and insignificant or large enough to cause major problems with the process. In all the types of control discussed so far, overshoot occurs. Overshoot can be damaging in many processes and therefore must be avoided. The derivative function (also called “automatic rate”) can be used in control systems to prevent overshoot. The derivative function anticipates how quickly the setpoint will be reached. It does this by measuring the rate of change of process temperature and then by forcing the control into a proportioning action at a faster rate thereby slowing down the rate of process temperature change. This action allows the process temperature to “glide” into the setpoint and thereby prevent a large degree of overshoot on start-up and when system changes such as large load changes or the opening of a furnace door, etc. takes place.

Typically, the most precise of process control applications will require a control that has proportional, automatic reset, and automatic rate functions. This type of control is known as PID (Proportional, Integral, Derivative). (Figure 14C)



Control System Tuning

On-Off Control

Tuning an On-Off control system is usually accomplished by one simple manual adjustment. This adjustment basically controls the switching hysteresis by adjusting the points at which the control turns on and turns off.

(PID)

Proportional (P), Proportional plus Integral (PI), and Proportional plus Integral plus Derivative .

There are several methods for the proper tuning of P, PI, and PID controls. Most methods require a considerable amount of trial and error as well as a technician endowed with a lot of patience! The following is one of those methods.

The first step is the tuning of the proportional band. If the controller contains Integral and Derivative adjustments, tune them to zero before adjusting the proportional band. The proportional band adjustment selects the response speed (sometimes called gain) a proportional controller requires to achieve stability in the system. The proportional band must be wider in degrees than the normal oscillations of the system but not too wide so as to dampen the system response. Start out with the narrowest setting for the proportional band. If there are oscillations, slowly increase the proportional band in small increments allowing the system to settle out for a few minutes after each step adjustment until the point at which the offset droop begins to increase. At this point the process variable should be in a state of equilibrium at some point under the setpoint.

The next step is to tune the Integral or reset action. If the controller has a manual reset adjustment, simply adjust the reset until the process droop is eliminated. The problem with manual reset adjustments is that once the setpoint is changed to a value other than the original, the droop will probably return and the reset will once again need to be adjusted.

If the control has automatic reset , the reset adjustment adjusts the auto reset time constant (repeats per minute). The initial setting should be at the lowest number of repeats per minutes to allow for equilibrium in the system. In other words, adjust the auto reset in small steps, allowing the system to settle after each step, until minor oscillations begin to occur. Then back off on the adjustment to the point at where the oscillations stop and the equilibrium is reestablished. The system will then automatically adjust for offset errors (droop).

The last control parameter to adjust is the Rate or Derivative function. Always adjust this function last. Always! The reason I am so emphatic on this point is that if the rate adjustment is turned on before the reset adjustment is made, the reset will be pulled out of adjustment when the rate adjustment is turned on. Then you just have to start your tuning procedure over!

The function of the rate adjustment is to reduce as much as possible any overshoot. The rate adjustment is a time based adjustment measured in minutes which is tuned to work with the overall system response time. The initial rate adjustment should be the minimum number of minutes possible. Increase the adjustment in very small increments. After each adjustment let it settle out a few minutes. Then increase the setpoint a moderate amount. Watch the control action as the setpoint is reached. If an overshoot occurs, increase the rate adjustment another small amount and repeat the procedure until the overshoot is eliminated. Sometimes the system will become "sluggish" and never reach setpoint at all. If this occurs, decrease the rate adjustment until the process reaches setpoint. There may still be a slight overshoot but this is a trade-off situation.

Autotune

Tuning control parameters is no fun! Thank goodness for modern technology and the invention of “Autotune”. Most of today’s controller manufacturers offer single loop temperature controllers with the option of automatic parameter tuning which eliminates a lot of the drudgery of manual tuning. There are several methods of autotuning. Most operate on a system whereby the controller “looks” at the initial start-up cycle from start to the time the process reaches setpoint. Then by learning from the response characteristics of the first cycle it adjusts itself to optimum tuning parameters based on the history created in the first cycles. The auto-tune function continues to “learn” from subsequent cycles and readjusts parameters until the optimum settings for PID are reached. Since not all manufacturer’s auto-tune controllers function the same, it is advisable to consult the instruction manual before attempting to use the auto-tune feature for the first time.

Chapter 4. Datalogging

In many industrial applications it is often necessary to record temperatures for permanent records due to government or manufacturing requirements or to simply provide historical data that may later help determine problems within a system.

Data collection of temperature readings in industry vary from sophisticated DCS systems (Distributed Control Systems) which do both data logging and control usually of many process points simultaneously to simple manual systems using inexpensive portable indicators.

The most inexpensive portable indicators do not provide any “recording” or memory features. Readings from these instruments must be recorded by hand. Some portable indicators now are available with memory so that a number of measurements may be taken into memory and later downloaded into personal computers for permanent records.

Another popular way to record data from temperature sensors is by chart recorder. Chart recorders have been around for a long time and still have application in today’s process marketplace. Round chart recorders take thermocouple and RTD signals directly or analog process signals from sensors using a transmitter. The advantage of round chart recorders is that the charts are graduated into precise time periods for those who require records by the day, week, or hour on separate charts. Strip chart recorders, on the other hand, offer the ability to input many more inputs and read them by scanning and then printing. Many of today’s chart recorders are what is called “Hybrid” recorders. These recorders offer many more functions and abilities that the standard chart recorders can’t.

Hybrid recorders offer various recording modes such as analog trending where a pen or dotting mechanism “draws” a recorded input for each channel. Each channel, in most cases, can be charted in a different color. This is important when recording a number of different points as it allows simple identification of the point the technician is trying to read. Hybrid recorders also offer digital recording modes which alphanumerically list sensor measurement with time stamps, tag numbers, point numbers, etc. Hybrid recorders also offer the combination of digital and analog trend recording. In this mode, the recorder can be programmed to trend record for an adjustable time period and then automatically print out a chart of measurement readings at specified time intervals. These modern day recorders usually offer digital readouts as well that give a digital indication of the process temperature of selected points or of scanned points. Many additional features such as alarm outputs, change of print color in alarm condition, self diagnostics, etc. are available on Hybrid recorders.

Distributed control systems also offer datalogging as a part of their overall capabilities. Since these systems are computer based, the datalogging functions are programmable to almost any configuration you may need.

Chapter 5.

Final Control Devices

Up to this point, we have briefly discussed temperature sensors, temperature transmitters, temperature controls, and temperature recorders and dataloggers. One more area deserves our attention in the discussion of temperature and the application of temperature instrumentation products. That is the area of final control devices.

To complete the loop in a closed loop temperature control system, you must have some device that takes the output from the temperature control device and converts it into heating or cooling production.

For electrical heating in industry, that device usually must carry a high current due to the amount of power needed to heat a large process. These processes cannot be controlled directly by the output from a temperature controller since that output is usually limited to a load of no more than 5 amps. The final control device can cover a range from the simplest electromechanical relay to mercury relays, to solid state relays and solid state SCR power controllers.

Electromechanical relays are the lowest cost of the final control devices. The problem with electromechanical relays is the ever switching output of a temperature controller results in a short lifetime to the relay's mechanical contacts. This results in frequent contact replacement which will quickly eat away any cost savings on the initial relay purchase. Mercury displacement relays offer an alternative over the electromechanical relays in that the contacts are hermetically sealed from air so that little, if any, spark is present when contacts are closed due to the displacement of the mercury. Mercury containing devices, however, have come under close scrutiny lately due to mercury being listed as a "Hazardous Material".

Replacing mercury relays with solid state relays is often the answer. Solid state relays offer the distinct advantage of having no moving parts to wear out. Solid state relays are selected based on their particular application. Not only do you need to know the load current requirement, you must also identify how the solid state relay is to be operated. Solid state relays are available for both AC and DC input triggering devices. The AC input solid state relay may be operated directly by the output relay of a temperature controller. The DC input solid state relay is usually operated by a DC input signal (open collector) of between 3 and 32 VDC. Any DC voltage in this range will cause the solid state relay to "close the circuit" to operate the heating device. Electromechanical relays, mercury displacement relays, and solid state relays have one thing in common. They all switch the power to the heating load either full on or full off. Many applications that require extreme accuracy need what is called "true" proportioning control. True proportioning control requires what is typically called a "power controller". This device is operated by means of Silicon Controlled Rectifiers (SCR) which can be fired a number of ways to meet the requirements of specific applications. SCR Power Controllers normally take a proportional output from a temperature controller (normally 4-20 mADC) and convert it into a proportional control output to the heating device by means of either "Burst Firing", "Fixed Time Based Firing", "Variable Time Based Firing", or "Phase Angle Firing".

Zero Crossover or Burst Firing provides a proportional output to the heating device by turning "on" for a number of cycles of the AC input (either 50 or 60 Hz) and then turning off for a number of cycles. The proportion of "on" to "off" cycles is dependant upon the command signal from the temperature controller. In other words, if the controller has a 4-20 mA output and the output is at 12 mA, then the power controller would be on for 30 cycles and off for 30 cycles on a 60 Hz power system.

With variable time based controls, the on and off times are still proportional to the command control signal, but the time base changes as a function of the demand. Using the example of the 12 mADC output you would have power on for one full cycle and then power off for one full cycle (50% Demand). If you had a 20% demand, the power would be on for one cycle and off for four cycles, etc. One of the biggest advantages with zero crossover control is that since the SCR fires at only the zero point of the 50 or 60 cycle sine wave, the signal is virtually immune to electrical interference.

Phase angle fired SCR power controllers offer the truest form of proportional control because the power passing through the SCR can be controlled. When the SCR is turned “on” it stays on until the polarity changes (the sine wave passes through the zero point). The turn on point, however, can take place at any point in the sine wave. Therefore, since the turn on point is not zero, but delayed inside the sine wave, then the actual amount of power allowed through the SCR is controlled. Although very accurate temperature control may be achieved with phase angle firing, since the turn on point may be at any point in the sine wave, the signal is susceptible to electrical noise in some applications.

A couple of available features make phase angle fired SCR power controllers even more attractive. Some electrical heaters, such as silicon carbide heaters, change resistance with temperature to such an extent that rapid temperature change will shorten their lifetime. A feature called “Soft Start” in a phase angle fired SCR allows the heaters to warm up slowly by delaying the on time of the SCR and gradually increasing the on time by using less delay in each cycle.

Another important available feature is “current limiting”. Current limiting SCR power controllers have a current sensing transformer that will not allow more than a pre-established amount of current to pass through the SCR. This feature also lengthens the lifetime of many types of electrical heating elements. A note of warning here, however. If a short circuit in the heater occurs during the on time of a current limiting SCR controller, the high amount of current cannot be restrained from going through the SCR. For this reason, I2T fuses must be used in line with the SCRs so that they will blow at any time during the cycle.

Closed Loop Temperature Control

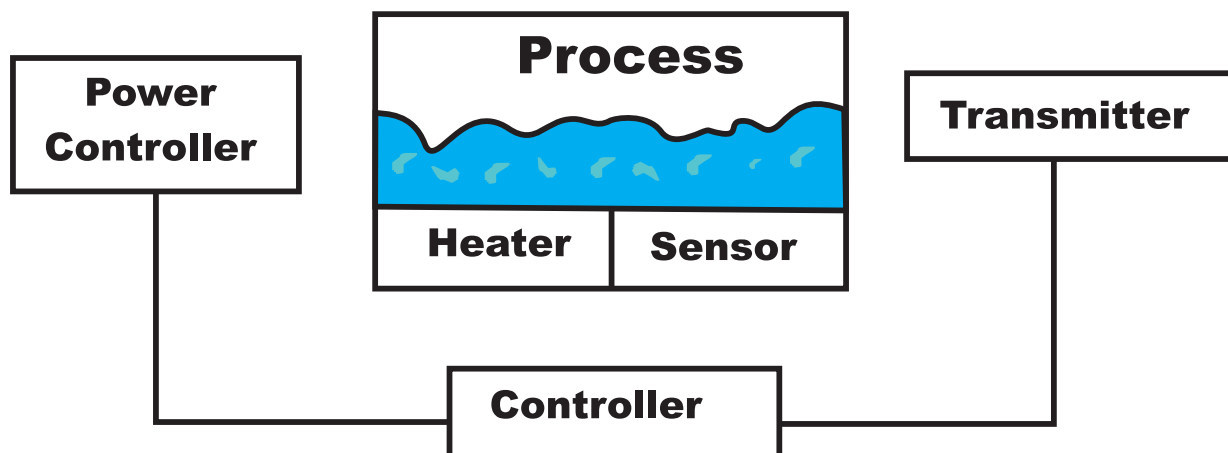


Figure 15

Chapter 6. Summary

In the preceding chapters, we have discussed the basic parts of a temperature control loop. The sensor, the signal conditioner / transmitter, the controller, and the final control device. Our discussion has been brief and intended only as a primer for those not experienced in temperature control systems. In other words, we have just scratched the surface of this important phase of process control.

For information in further detail you may want to consult the ISA Directory of Publications. Also, most manufacturers of the products discussed offer detailed information on their particular area of expertise and are happy to provide that information to you.

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2915 Parkway Street
Lakeland, FL 33811-1391 · USA

800-234-1343

Tel: 863-647-2000 · Fax: 863-644-5318
www.wici.com · Email: sales@wici.com