TEMPERATURE MEASUREMENT

TTE TRAINING LIMITED

INSTRUMENT COURSE

SECTION 8

TEMPERATURE MEASUREMENT

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TEMPERATURE MEASUREMENT.

8.1 Introduction.

Just as in the home we use heating systems to create a pleasant environment in which to live in, so to for the successful operation of chemical plant operations and manufacturing processes it is essential that the operating temperatures need to be monitored, and were necessary controlled or maintained within predetermined limits to ensure safe and economic operation of the plant.

Just as we are aware that water changes state from solid to liquid to gas the same applies in chemical manufacture, additionally we also know that some chemicals or substances have low ‘flash points’ or ignition temperatures, so therefore it is of utmost importance that we maintain and monitor process temperatures.

In practical terms, temperature related processes, tend to be slow re-acting processes, as compared to say pressure or flow.

8.2 Heat transfer and Temperature scales

In basic terms *Heat is a form of energy*, thermal energy, caused by the continuous movement of the minute particles or molecules of which the substance is made colliding into each other. Heat can be transferred in 3 main ways, these are ***conduction***, ***convection*** and ***radiation***. Conduction being heat transfer through a solid, convection being a method of transferring heat through gases, and radiation being the only method of transferring heat were there is vacuum or no air, ie;- from outside the earth’s atmosphere the sun heats the earth’s surface.

Temperature on the other hand is often referred to as a measurement of heat, however with heat being a form of energy, and energy units being in joules, then the literal definition of *temperature is an expression used to describe the ‘degree of hotness or coldness’* of a substance, be it liquid, gas or solid. There have been several attempts to standardise the units of temperature and as a result several temperature scales have been devised, the most common of these being Celsius or Centigrade, Fahrenheit, Kelvin and Rankine. The following table shows the relationship between the scales:-

Celsius/ centigrade °C	Fahrenheit °F	Kelvin °K	Rankine °R
-273	-459.6	0	0
0	32	273	459.6
100	212		

The most modern scale of Celsius (centigrade) takes the steam point and ice point of water, and divides these into 100 equal units. This specific temperature range is also referred to as the ***fundamental interval***.

Occasions will arise were we need to convert from one scale to another, for example if the indication device uses a scale that we are not familiar with, there are however times when we do this naturally and probably without realising it, such as when we talk about the weather or air temperature. For example when it is particularly cold we normally talk about the temperature as being near 0, degrees C, whereas, when on holiday we might say "it was in its 90's", degrees fahrenheit. The phrase '*Ambient temperature'* is often used to describe the current local surrounding air temperature, although a standard figure of 20°C is also used as a reference for ambient, others have called this 'room temperature'.

Another factor relating to air temperature is height above sea level. The higher you go, the air temperature starts to fall. The table below shows this:-

Height (m)	Height (Ft)	Temperature (approx)
0	0	15°C
3000	10000	-4°C
5000	16000	-17°C
9000	30000	-43°C
15000	50000	-56°C

From the table above the fall in temperature is also related to a reduction in pressure, this can be seen in the table below:-

Temperature(approx)	Pressure (mBar)
15°C	1013
-4°C	700
-17°C	500
-43°C	300
-56°C	120

In order to convert from one scale to another the following formula's may be used:-

°C to °F = temperature x 9/5 (1.8) + 32, 20°C = 68 °F

°F to °C = temperature - 32 x 5/9 (.5555555), 90°F = 32°C

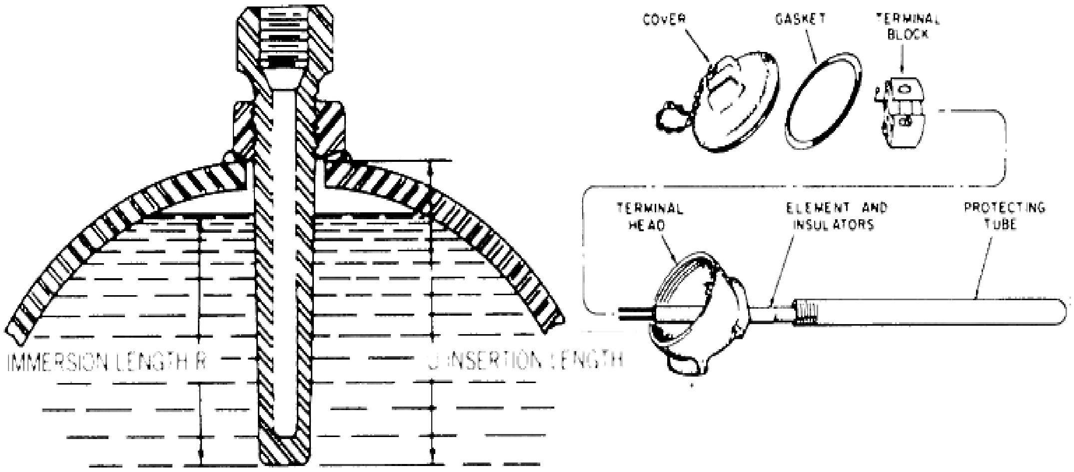
It is believed that as early as 1592 Galileo invented the liquid-in-glass thermometer, whilst resistance based thermometers were not developed until the 1930's.

For measurement purpose temperature detectors can be split into categories, these are liquid, solid and vapour expansion, thermo-electric and radiation types.

8.3 Temperature element installation

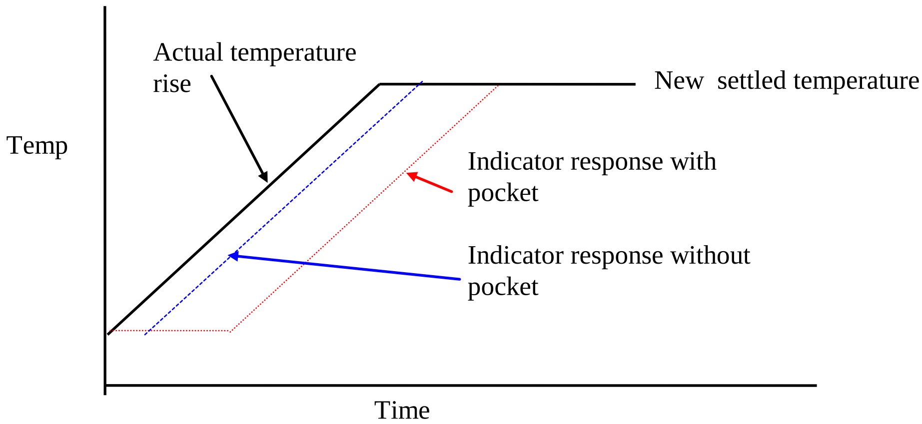
The phrase temperature element can be applied to any temperature detecting device, however no matter what the element is, its function is to measure temperature of the process fluid, be it liquid, gas or vapour. As such there needs to be a suitable method of installing these into the pipeline or vessel. Probably the most commonly used device for this purpose is the thermowell, or as they are commonly called ‘thermopockets’.

The purpose of this device is twofold, (1) to protect the element from chemical attack, and (2) to allow the element to be inserted into the process, and also allow element removal without having to go through complex and time consuming plant shutdown. The most common form of thermopockets are either screwed or flange fitted into the pipe or vessel wall, it is essential that the temperature at the insert point gives a true reflection of the process condition, and so the length of the element and thus the pocket is important, it is also important to ensure that the construction material and thickness are more than adequate to protect against prolonged chemical attack. The next diagram shows the construction and installation of a pocket:-



The result of using the thermopocket will have no effect on the temperature indication however it may be noted that the speed of response is slower due to heat transfer between the pocket and the element, in some cases the pocket may be oil filled to minimise the delay, however this will not eliminate delay totally. Also, the location of the pocket is important, as a flowing fluid will transfer heat more rapidly than a slow moving one

The graph that follows shows the time delay in response:-



8.4 Expansion thermometers.

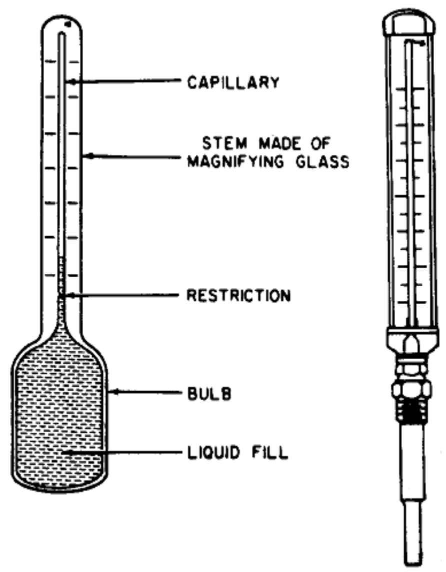
The devices in the section work on the principle that Liquids, gases(vapours) or solids expand with rise in temperature.

Liquid expansion thermometers

.

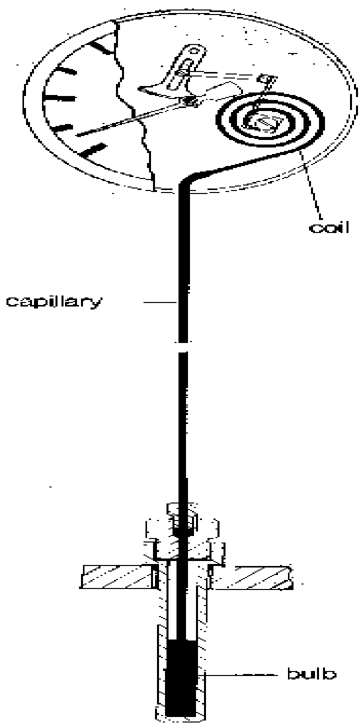
Probably the simplest form of temperature detector is based on the principle that Liquid expands with rise in temperature, the simplest device in this range being the common glass thermometer.

The glass thermometer consists of a glass bulb connected to a thin capillary tube, with the glass bulb being filled with a liquid, depending on the temperature range required either mercury or alcohol is used, you may have seen alcohol filled thermometers with either a red or blue liquid in them. As the bulb temperature is increased the liquid expands and rises up the capillary. Along the capillary length is a scale made up of markings (graduations) that indicate the temperature to which the bulb is exposed. As can be seen from most thermometers the relationship between the expansion rate of the liquid and temperature is linear, and hence have linear scales.



The diagram left shows a simple glass thermometer:-

The primary limitation of this device is its construction material, which makes it difficult for industrial use. Its temperature range (with mercury) is from around -40°C to around 540°C, with low temperature devices containing alcohol or other hydrocarbon based product, dyes are often add to these to enhance visibility (commonly red or blue). With some of the earlier types a metallic thermowell would have been constructed around the bulb and capillary section to make the device more rugged, this thermowell would have no effect on the temperature reading by may slow down the response time. For industrial use these are now very limited particularly due to the toxic nature of mercury. The basic device has no method of transmitting signals although some versions of this include reed switches to create temperature alarms, again more modern efficient and safer equipment is available for this purpose. As a positive these are relatively inexpensive.



Filled system thermometers.

Liquid filled thermometers

The filled system thermometer is derived from the basic principles associated to the glass thermometer, however the bulb and capillary sections are metal rather than glass, hence the derived name of ‘liquid in steel’.

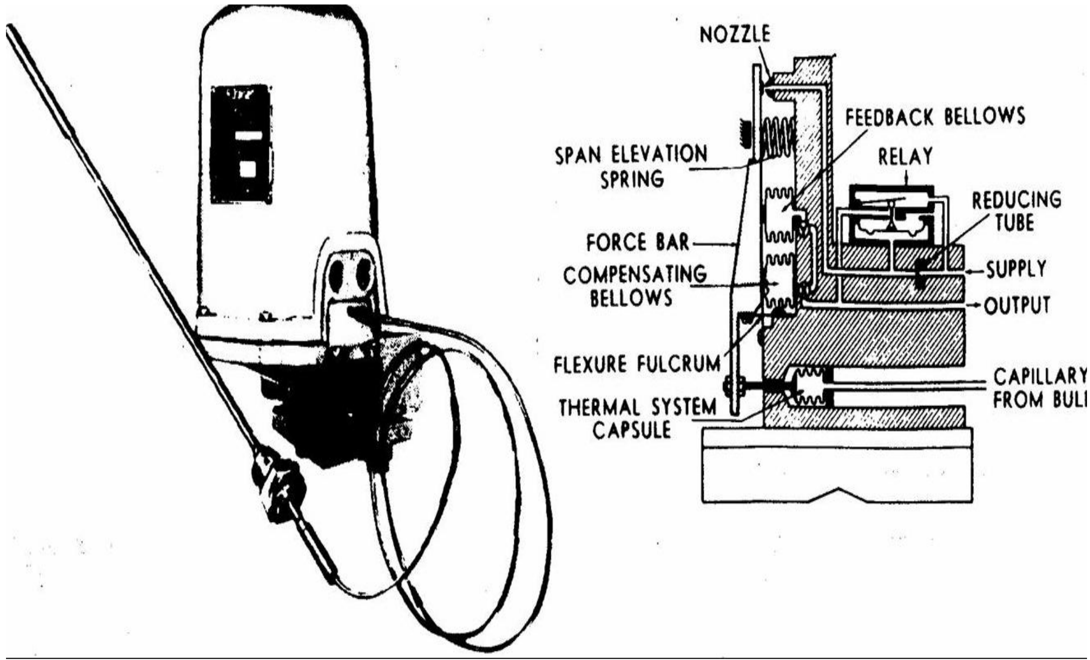
The major change is that the capillary is used to connect to a bourdon tube, and the complete system being filled with mercury. So now, as the bulb temperature rises the expanding liquid has nowhere to go and thus the pressure of the liquid increases thus causing movement of the bourdon tube,

and again because the pressure relationship to liquid expansion and temperature is linear, the scale on the front of the gauge is in units of temperature around a linear scale. There are two common versions of this thermometer one of which has a solid thermowell built around the capillary whereas the other keeps the capillary flexible, these tend to have various lengths of capillary and can be upto 45metres in length. These devices are often referred to as dial thermometers. The next diagram shows a typical example:-

The operating temperatures of these devices, is now determined by the type of metal used and the operating limits of the filling liquid. Typical overall range ,being around -35 to 650°C, although devices are available with specific ranges ie; 0 - 100°C. For safety the name of the system filling liquid is often displayed on the indicator gauge front. Because the system is normally under pressure to start the length of the capillary tends to have no affect creating static pressure. Although still in common use mercury filled systems are currently being phased out, new filling liquids include xylene or other inert hydrocarbons.

Whilst dial thermometers have their uses, they still have the restriction of not being able to generate or transmit signals. As with all gauge style instruments, the simple addition of an alarm front transforms the device into one which can now display temperature, but also create the alarm contacts used to initiate plant warning and shutdown systems.

With a little bit of thought, by using the pressure from the capillary, to expand a unit called the 'thermal system capsule', it is not too difficult to see how this forms the basis for the design of the pneumatic pressure transmitter, derived from a pressure transmitter. The Foxboro 12a temperature transmitter is shown in the next diagram.



Vapour filled systems.

These devices look and work the same as the liquid filled counterpart, with the exception the filling material is vapour, there are various filling vapours currently in use, but methyl chloride, ethyl alcohol and sulphur dioxide are the names of a few. The major difference with this type of filling is its non-linear response characteristic, however the top end response is more sensitive than the liquid versions. This characteristic is seen on the scale front, and can be seen in the diagram opposite:-

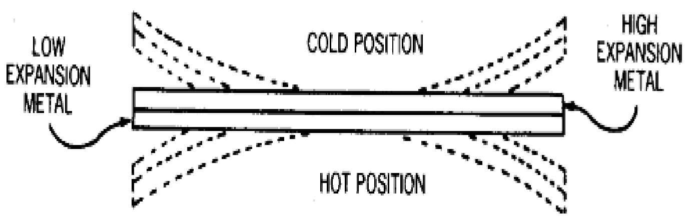
Temperature range is again determined by the filling vapour, but typical range is from -80 to 40°C, or upto 250°C.

The following table compares Liquid, Gas and Vapour filled thermometers

	Mercury in steel	Gas filled	Vapour filled
Scale	Evenly divided	Evenly divided	Non-linear
Temp .Limits	-35 to +650°C continuous limit 500°C min range 50°C	-60 to +700°C min range 80°C	-40 to +175°C not suitable for ambient temp'
Capillary limit's	Distance between bulb and indicator does not produce significant error	No error caused by capillary length	Distances above 2m can cause errors
Capillary length	Up to 45m	Up to 20m	Up to 10m
Accuracy	+/- 1% full scale	+/- 1% full scale	+/- 1.5% full scale
Excess temp'	Can withstand excess temp's	Not suitable for excess temp's	Not suitable for excess temp's

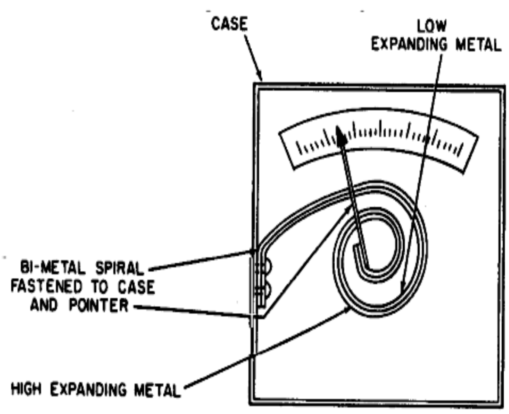
Solid Expansion thermometers.

These devices operate on the fundamental principles: (1) that metals change volume with temperature, and (2) that the coefficient of change is not the same for all metals.

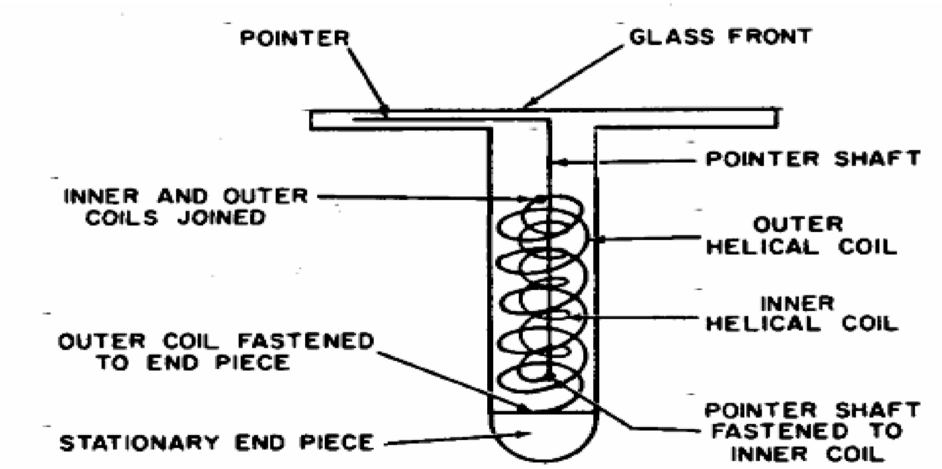


Therefore if two different metals are bonded together to form a strip and heated, the result would be that the strip will bend towards the side with the lowest expansion rate. These devices are more commonly known as bimetallic strips. By restricting one end and allowing the other to move, we have the basis for a simple temperature indicator.

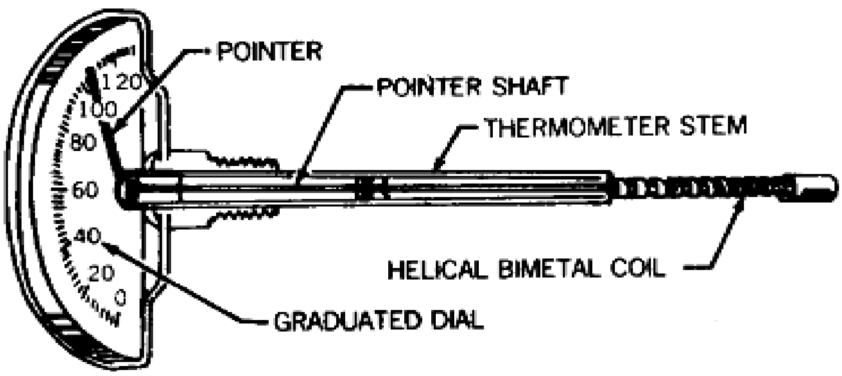
These can be preset to produce predictable responses to set temperatures, and form the basis of temperature switches in various household appliances.



For practical industrial use, the movement of the strip is to small and maybe amplified by winding the strip into a spiral, helix, or coil thus forming the basis of the bimetallic thermometer, with one end fixed and the other free to move, a pointer is fixed to the centre of the free end and as the strip is heated the resulting deflection of the pointer is directly proportional to the temperature.



Knowing the coefficients of expansion a calibrated scale may be used under the pointer and thus can be used as a indicator of temperature. For practical use the spiral strip is contained inside a metal tube. One of the most common manufacturers of these devices is the Rototherm company.



One of the major advantages of this type of indicator is its rugged construction, they can also be modified to move a pen on a chart recorder. In terms of range and accuracy, the minimum span is approx 50°C, and the range of use being around -50 to 550°C. On the negative side these can be upto 10° inaccurate. Some versions of these temperature indicators have added alarm contacts for high and low temperature alarm initiation. Stem lengths are available upto 24 inches and dial size upto 5 inches.

8.5 Radiation thermometers.

Particularly in combustion processes were there are known high temperatures, one of the ways to measure the temperature is to measure the amount of radiation emitted by the hot object, devices that operate in this way are called radiation pyrometers. Other radiation devices particularly the infra-red type measure the wavelength of the emitted radiation. The temperature range of these devices is around 0 - 4000°C.

These devices are available in either portable or permanent system form, with costs from £200 - £3000.

8.6 Quartz crystal thermometers

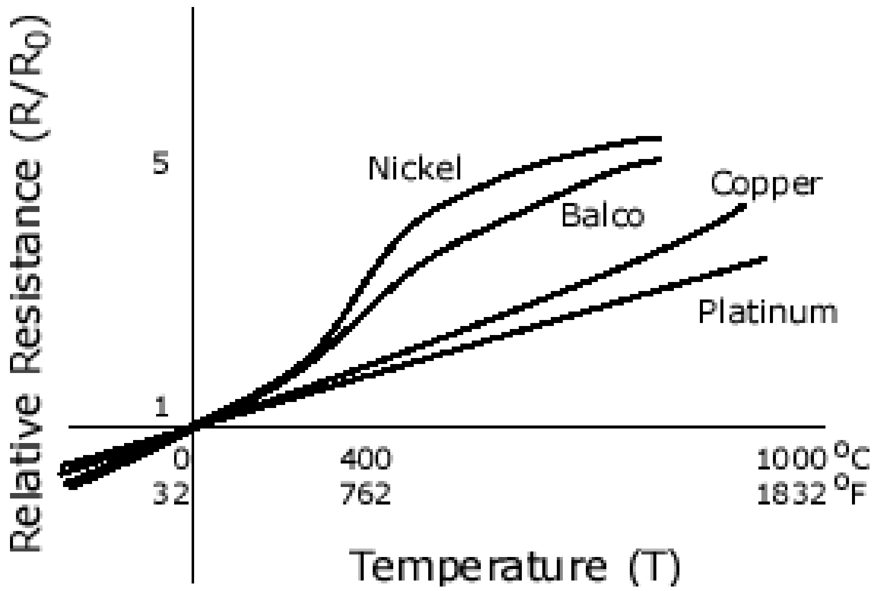
These thermometer types tend only to be available as probes which are connected into an electronic circuit. The sensor operation is based on the principle that the resonant frequency of quartz varies with temperature, the amount of resonant change is equivalent to around 500 cycles per °C, therefore making these sensitive to within 0.0005°C. The overall range of these is quite small in the region of -80 to 250°C.

8.7 Thermo-Electric thermometers – (RTD's and Thermistors).

The two main devices to be discussed in his section are the Resistance Temperature Detector, or RTD for short, and the Thermocouple (T/c). Another device in this section is the thermistor which we will discuss briefly.

RTD.

The basis of operation of these detectors is that the resistivity of metals is dependent on their temperature. Resistance thermometers work on the basis of increasing resistance with increase of temperature.

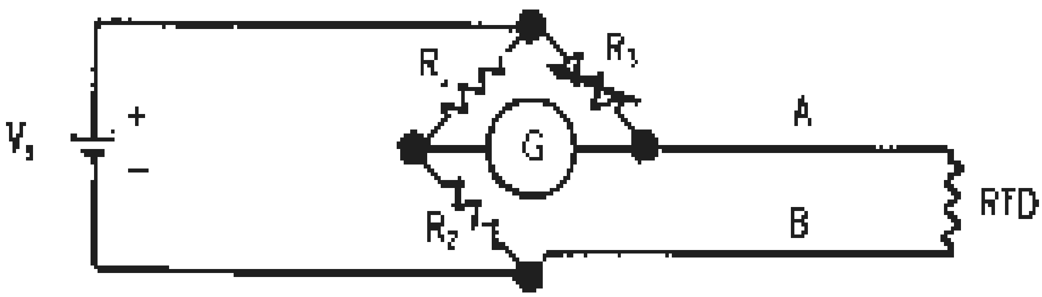


The most commonly used metal for this purpose being platinum whose temperature range is -220 to 900°C, or -200 to 320°C for nickel based elements. Use of platinum for this purpose offers the best overall performance in stability, repeatability over a wide temperature range. The standard platinum element responds in a predictable fashion, with the now standard PT100 element, producing 0.385Ω/°C, or 100Ω @ 0°C and 138.5Ω @100°C this temperature range is also referred to as the 'fundamental interval'.

Therefore by measuring the resistance change of the element it is possible to measure the process temperature by inserting the element into the process via the use of a thermopocket and connecting them via lead wires to a measuring circuit and indicator.

Other resistance elements exist, using other than the temperature/ resistance ranges mentioned so far. For simplicity this section will deal only with the standard PT100. For other information you would need to consult manufacturers information, the operating principles would be the same.

The measuring circuit for the RTD element is based around the wheatstone bridge network, and is shown on the next diagram:-



With the RTD connected as the unknown resistance, the output on the DVM or galvanometer is equal to 0 (zero), when:-

R1 + R3 = R2 +(A + B + RTD)

R3 = A + B + RTD

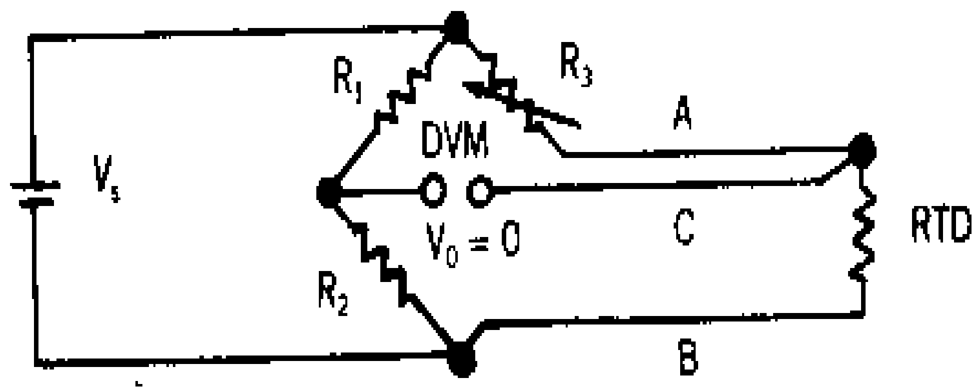
From the above formula, for the circuit to be 'in balance', all the resistances need to be at the same value. Assuming that the resistance of the RTD (resistance element) is at 0°C and therefore at 100Ω, ideally the resistances R1, R3 and R2 would also need to be 100Ω for the circuit to be in balance, this effect means that the volt drop and current flow through each resistance arm would be equal, however when the temperature of the RTD element increases, so to the resistance of the element will increase thus forcing the circuit 'out of balance'. The effect of this causes a to current flow through the centre arm, this out of balance can be displayed on an indicator, and for ease is displayed in units of temperature rather than current or resistance.

Unfortunately because the element is located away from the measuring circuit extra resistance is introduced as a result of the resistance of the wire, this could be as much as 10Ω or more (on the basis of 10Ω/ 150m of wire), in terms of temperature this would appear as though the temperature was 26°C higher than normal.

Another problem with this set-up is, that if the wire was to pass additional heat sources between the element and measuring circuit this could also introduce extra resistance. Whilst this method is practical provided the distance between element and measuring circuit is short (ie; less than a few inches), if there is significant lead length a significant resistance would be introduced (significant in this type of measurement circuit needs only to be a couple of ohms). This is not practical and there would then have to be an inbuilt method for compensating for this problem, this is achieved using the 3 wire connection method.

3 wire RTD systems.

This is probably the most common set-up for RTD systems, whilst it remains relatively inexpensive it also creates a compensation network for the lead resistance to the element. The next diagram shows this set-up:-

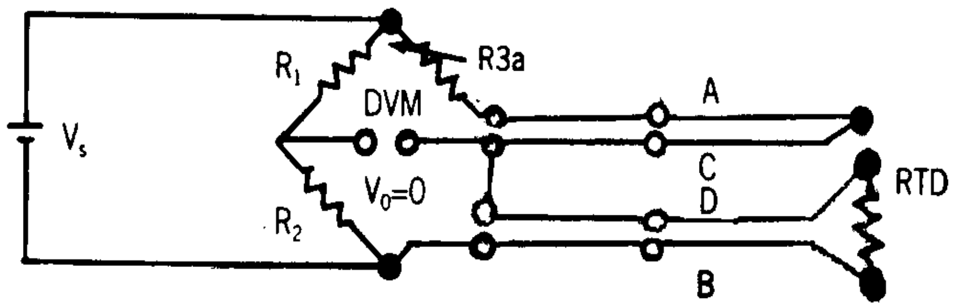


In the above diagram lead 'C' acts as a sensing wire being in both halves of the bridge and therefore cancelling out the lead resistances, with the lead wires A and B being in different halves of the circuit, at balance the formula for the circuit would be:-

R3 = B - A + RTD, on the indicating scale this would represent 0°C.
If this system was to be used for low temperature applications it would be fine, however total compensation is only guaranteed to within 10% tolerance and rely on all the lead wires being identical in length. A small inaccuracy of 1Ω for example would as a result create a reading 2.6°C higher if using a

PT100 element, with high temperature systems in terms of percentage this might end up being to much of an error. If this is the case and total compensation is required the 4 wire connection method would be required.

4 Wire RTD connection system.



In this connection method 2 extra lead wires (a and c) are run from the other arm of the bridge to the RTD to form a loop back to the measuring circuit and thus cancel the resistance of the RTD connection wires (d and b) completely, leaving only the resistance of the RTD element as the effective resistance.

RTD Installation.

As with most temperature detection devices, the use of a thermopocket would be well advised for installation of the element, the top part of the element to were the lead wires would be connected is normally contained inside a small ceramic, plastic or galvanised steel housing.

It is also important to keep these installations away from sources of moisture as this would eventually short out the terminals on the element causing low readings.

Another important factor to ensure is that the terminals are tight and corrosion free, as both of these would introduce resistance into the circuit making the readings higher than they should be.

The important consideration is to replace like for like, this means making sure that the RTD elements have the same fundamental interval, or resistance change from 0 to 100°C. This information is often available on an information plate on the underside of the connection head. Also noted would be the connection detail, the element should have its resistor wires clearly marked, some use red and white wire sheathing while others use letters.

RTD Calibration.

The accuracy of the element may be checked at various temperatures in its operating range by inserting it into a temperature simulator or container of heated water and then measuring the resistance at various points, the corresponding information may be checked against recognised temperature/ resistance tables. If the element resistance is incorrect against temperature it would normally require replacement as they tend not to be repairable.

In order to check the measuring circuit from the element, firstly this must be disconnected, an in its place connect a resistance (decade box) keeping the wiring connection the same. With 100Ω resistance applied the indicator should read 0°C. Using the resistance/ temperature tables now inject various resistances through the range to check the highest point and also the linearity of the system. Once complete, reconnect the element, and the system should work accurately.

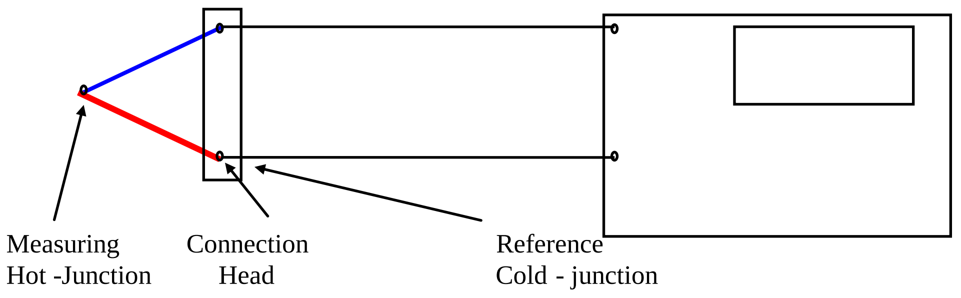
Thermistors.

Thermistors are semiconductors made from pure oxides of nickel, manganese, copper and cobalt amongst others. These have high temperature coefficients and are good for narrow span applications. Thermistors were also known as thermally sensitive resistors. The range of use is limited to applications below 320°C as beyond this temperature they can be prone to drift. The use of thermistors can be applied to voltage regulation, flowmeters, power level controls and gas analysers were temperature compensation or measurement is an important feature of operation. These can also be used for thermal switches and have use in circuitry or micro processors

8.8 Thermo-Electric thermometers – (Thermocouples).

A thermocouple (T/C) is the joining of 2 dissimilar metals to form a junction, which when heated create a small continuous emf. This simple device was developed in 1821 when T.J Seebeck put his name to this phenomena, now known as the Seebeck effect. Since then this is probably the most widely used temperature sensor.

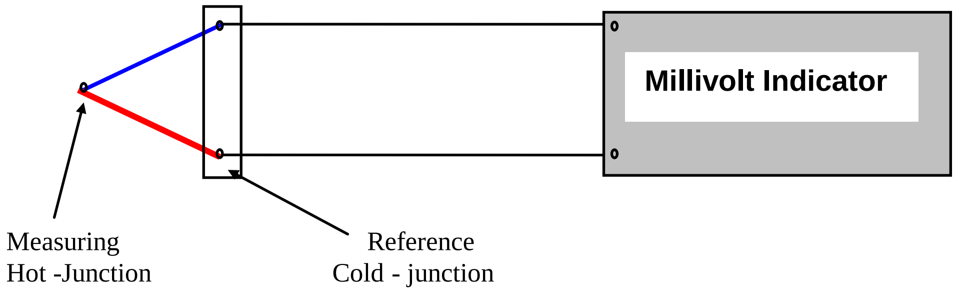
The thermocouple consists of two different metals, which are fastened together to form a measuring junction, this is normally referred to as the hot junction, since most measurements are normally made above ambient temperature.



The most common combinations are shown in the list below with the type code:-

Type	Leg 1	Leg 2	Range
J	Constantan	Iron	0 to 700°C
T	Copper	Constantan	-150 to 400°C
K	Chromel	Alumel	0 to 1100°C
R	Platinum	13%Rhodium	-50 to 1600°C
S	Platinum	10%Rhodium	-50 to 1700°C
W	Tungsten	26%Rhenium	0 to 2600°C

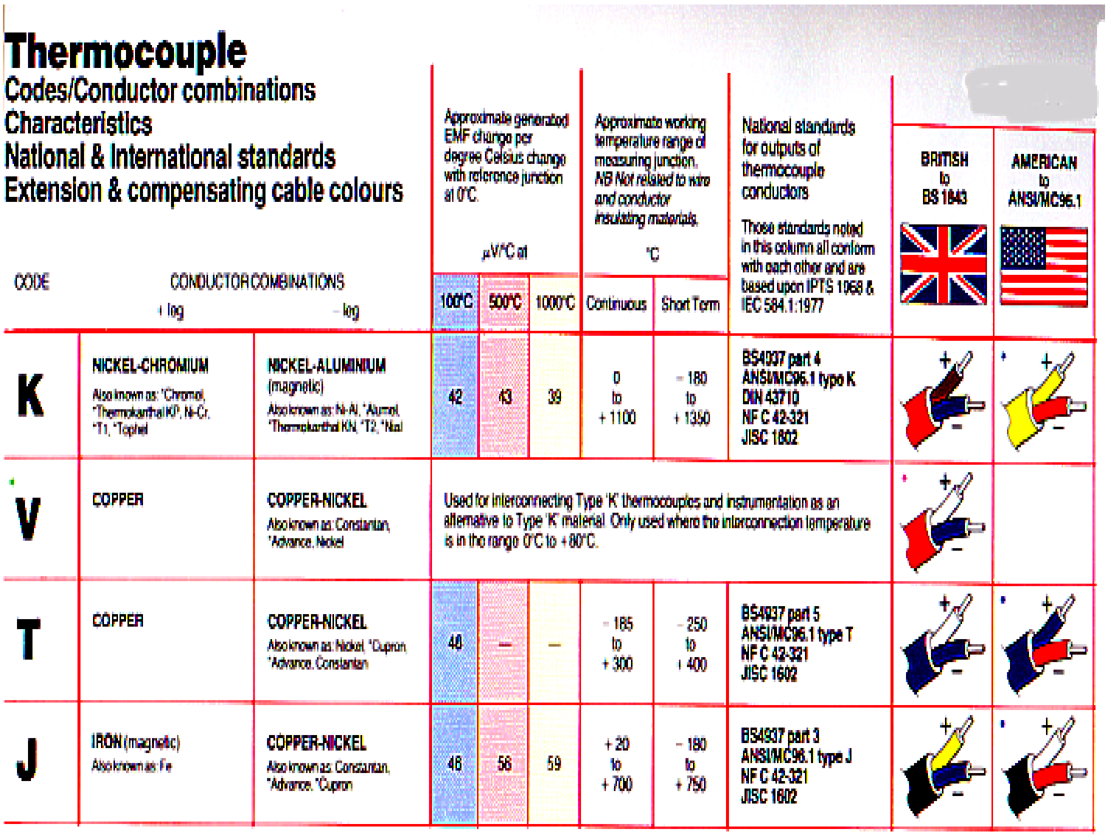
The free ends are connected to a connection head and then to a Millivolt measuring device to complete the circuit. This is shown below:-



The millivoltage created by the thermocouple is actually a product of the '***difference'*** between the temperature of the hot junction and the temperature of the cold (reference) junction. If we know what the reference junction temperature is then we can measure the process temperature by measuring the millivoltage generated by the thermocouple. The thermocouple indicator will therefore require a measurement of ambient temperature in order to make effective compensation.

From the diagram, the reference junction can be seen referred to as the cold junction. If the wires connecting the element to the indicator are different to those making up the thermocouple, secondary thermocouples will be created as a consequence, so it is therefore important that the connecting wires are the same as the element or that they have the same thermoelectric properties. These interconnecting wires are known as '**extension' cable** (if it is the same), or '**compensating' cable** if it has the same thermoelectric properties but not necessarily the same wire. Compensating cable is used were the cost of extension cable would be uneconomical.

In order to aid type selection there is also an International colour coding chart, so for example type K would be Red outer sheath, Brown +ve and Blue -ve. Probably the most widely used being type k. The only problem with colour coding is that different countries had different colour codes, however there have been recent attempts to standardise colour coding, however the effects of implementing these changes in full across the industry would prove a very costly exercise., as such you may still find old colour coding still in use.



Thermocouple
Codes/Conductor combinations
Characteristics
National & International standards
Extension & compensating cable colours

CODE	CONDUCTOR COMBINATIONS + leg	CONDUCTOR COMBINATIONS − leg	Approximate generated EMF change per degree Celsius change with reference junction at 0°C. µV/°C at 100°C	500°C	1000°C	Approximate working temperature range of measuring junction. *NB Not related to wire and conductor insulating materials.* °C Continuous	Short Term	National standards for outputs of thermocouple conductors. Those standards noted in this column all conform with each other and are based upon IPTS 1968 & IEC 584.1:1977	BRITISH to BS 1843	AMERICAN to ANSI/MC96.1
K	NICKEL-CHROMIUM Also known as: 'Chromel, 'Thermokanthal KP', Ni-Cr, 'T1, 'Tophel	NICKEL-ALUMINIUM (magnetic) Also known as: Ni-Al, 'Alumel, 'Thermokanthal KN, 'T2, 'Nial	42	43	39	0 to + 1100	− 180 to + 1350	BS4937 part 4 ANSI/MC96.1 type K DIN 43710 NF C 42-321 JISC 1602	+ −	+ −
V	COPPER	COPPER-NICKEL Also known as: Constantan, 'Advance, Nickel	Used for interconnecting Type 'K' thermocouples and instrumentation as an alternative to Type 'K' material. Only used where the interconnection temperature is in the range 0°C to +80°C.						+ −	
T	COPPER	COPPER-NICKEL Also known as: Nickel, 'Cupron, 'Advance, Constantan	46	—	—	− 185 to + 300	− 250 to + 400	BS4937 part 5 ANSI/MC96.1 type T NF C 42-321 JISC 1602	+ −	+ −
J	IRON (magnetic) Also known as: Fe	COPPER-NICKEL Also known as: Constantan, 'Advance, 'Cupron	46	56	59	+ 20 to + 700	− 180 to + 750	BS4937 part 3 ANSI/MC96.1 type J NF C 42-321 JISC 1602	+ −	+ −

Calibration of thermocouple systems.

Similar to the RTD, the thermocouple output may be measured by inserting the thermocouple into a temperature calibrator and raising and lowering the temperature and measuring the emf at set temperatures. Then by checking these against Thermocouple tables conversion can be made into temperature. However thermocouple tables take the reference temperature at 0°C, therefore you would need to find the millivoltage for the ambient temperature of the cold junction and add this to the measured voltage. The combination of this would equate to the actual temperature.

If you wanted to check the thermocouple system, you would need to disconnect the element and connect in an accurate Millivolt source. Then inject the appropriate millivoltage to give the indication of temperature required. Using the thermocouple tables remembering the reference temperature of 0°C, you would need to find the appropriate millivoltage remembering to subtract the millivoltage for ambient temperature. A typical millivoltage range or fundamental interval for the type K thermocouple is 0 - 4.1mV.

For example, A ‘type K’ temperature element is put into a temperature calibrator which is set at 100°C, approximately 3.2mV is measured from the device. In-order that the device may be proved to be working, ‘ambient temperature compensation’ needs to be applied (the cold junction is at ambient temperature)

Calibrator temperature = measured mV (temperature) + ambient temperature

Therefore, since from tables the mV is referenced to 0°C, then

Calibrator temperature = (3.2mV or 80°C) + ambient temperature (.798mV or 20°C)

Since for a Type K thermocouple, 3.288mV = 80°C

Calibrator temperature = 3.288mV + .798mV or 20°C + 80°C

= 4.086 or 100°C

As a quick summary when measuring what the T/C is giving out, add ambient. And when you want inject into the system, take ambient off the tabled millivoltage.

T/C installation.

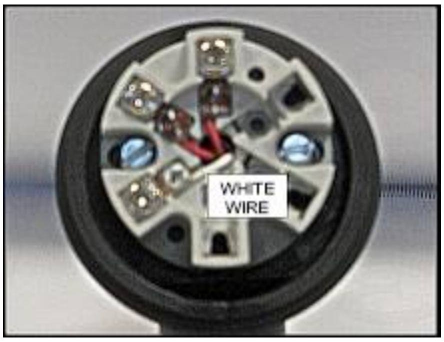
Like the RTD the installation of the thermocouple element is via a thermopocket.

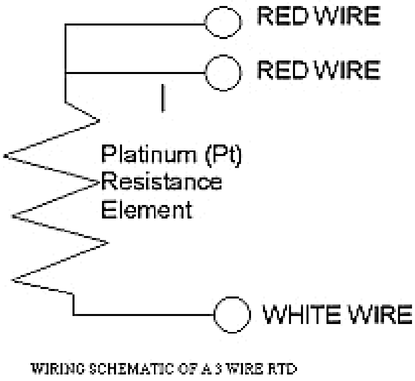
It is important to ensure fitting like for like, this is referred to by the fundamental interval or millivoltage change to give 0 to 100°C. On some connection heads the material inside the t/c leads can be identified by the colour coding of the wires, or from information on a plate on the underside of the head.

8.9 Temperature to current converters.

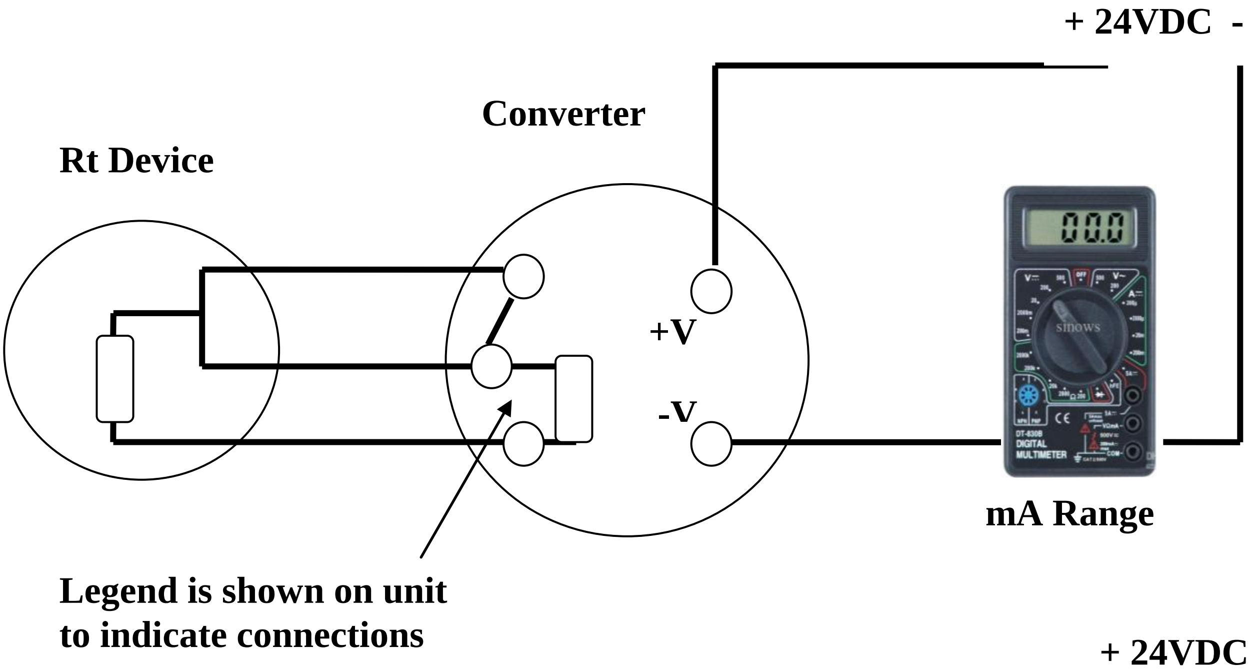
Temperature to current converters or transmitting heads as they are commonly referred are devices which take temperature related inputs and convert these to a 4 - 20mA output signal. The most common converters in this category are the RT/I and the TC/I with an Mv/I being used for similar purpose. There are various manufacturers of these devices, the most common being Rosemount and Honeywell, with both these companies offering smart technology transmitting heads.

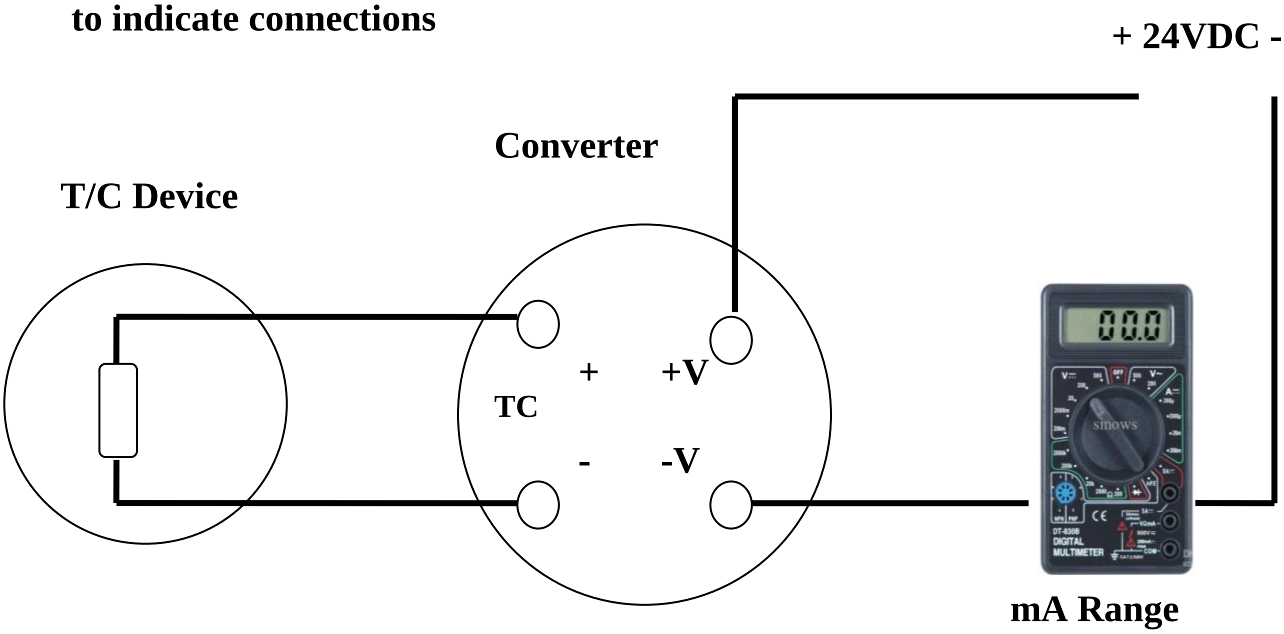
The advantage of the transmitting head is that the signal only has to travel the distance of the element before being connected into the converter which is normally mounted to the top of the element. The transmission signal is a more stable 4 - 20mA.





PHOTOGRAPH OF HEAD WIRING IN A TYPICAL THREE WIRE Pt100 RTD (showing the two red and one white wires)





Calibration Setup for convertors