UNDERSTANDING TEMPERATURE MEASUREMENT

THE TEMPERATURE SCALE

Although temperature was one of the first variables to be measured in industry the first formal international temperature scale was not adopted until 1927. The scale started at -200°C and went beyond the freezing point of gold (1063°C) and was based on fixed points such as the boiling point of oxygen and sulphur. Today, the internationally recognised temperature scale is referred to as ITS90 and is defined by the following table:-

ITS90

Temperature deg C	Substance	State
-270.15 to -268.15	Helium	Vapour pressure point
-259.3467	Hydrogen	Triple Point
~-256.15	Hydrogen at 10192 Pa	Vapour pressure point
-252.85	Hydrogen at 33321.3 Pa	Vapour pressure point
-248.5939	Neon	Triple Point
-218.7916	Oxygen	Triple Point
-189.3442	Argon	Triple Point
-38.8344	Mercury	Triple Point
0.01	Water	Triple Point
29.7646	Gallium	Melting Point
156.5985	Indium	Freezing Point
231.928	Tin	Freezing Point
419.527	Zinc	Freezing Point
660.323	Aluminum	Freezing Point
961.78	Silver	Freezing Point
1064.18	Gold	Freezing Point
1084.62	Copper	Freezing Point

In recent years temperature measurement has become much more widespread throughout industry, commerce and in the home. This is largely due to the increasing variety of sensors and instruments, which have become available.

Sensors have developed into small devices with fast response, far removed from the bulky probes of some time ago.

However, in selecting a suitable sensor, we are often faced with a compromise between such factors as size, speed of response, ruggedness and price. To assist in the selection process it is helpful to have an understanding of the basic technology and the factors that influence measurement and interpretation of temperature readings.

TYPES OF SENSOR

Various types of sensors can be used for temperature measurement and control and the most common ones are:

- Thermocouples (T/C)
- Platinum sensors
- Thermistors
- Infra red pyrometers
- Solid state sensors (silicon or germanium)
- Liquid-in-glass (such as mercury thermometers)
- Bimetal (using differential expansion of metals)

The most common of all these, and most numerous in the Hawco Direct catalogue are thermocouples, platinum resistance sensors (also referred to as RTD's, or resistance temperature detectors), thermistors and infra red pyrometers.

PLATINUM SENSORS

(RTD/Resistance Temperature Detectors)

Platinum is currently used in all primary resistance thermometers because of its excellent stability and good linearity. Temperature measurement using platinum depends on the fact that its resistance increases linearly with temperature. The purer the metal, the more constant and precise the increase.

Mainly two types of RTD sensors are used, namely Platinum (Pt) and Nickel (Ni) sensors. Looking at them against thermocouples:

Advantages

- very stable
- higher accuracy than thermocouples
- better linearity than thermocouples

Disadvantages

- higher cost
- power supply is required
- low resistance value
- self-heating effect.

PLATINUM SENSORS

As described above, the most commonly used RTD sensors are platinum sensors, which are distinguished by their high accuracy and stability. Today's manufacturing technology has reduced the costs and made it possible to produce vibration resistant platinum sensors, which are also small in size. (Typically 2 mm wide x 4 mm long x 0.5 mm thick)

PLATINUM SENSOR TYPES

The most frequently used type is the Pt100Ω sensor which has resistance of 100Ω at 0°C, 138.5Ω at 100°C. Similarly it is possible to have Pt1000Ω sensors with resistance 1000Ω at 0°C etc. These higher ohmic value sensors are used to avoid resistance effects due to connection cables and contact junctions. Its resistance/temperature characteristics are exactly defined in equations, which differ slightly between various standards.

Other types of platinum sensors are : Pt250, Pt500 and Pt1000. These types have exactly the same characteristics as the Pt100, but the resistance values are 2.5, 5 and 10 times the Pt100 values for the same temperatures.

STANDARDS

Platinum sensors are manufactured according to different standards, though the European standard IEC 751 has become the most used. Other standards are the Japanese JIS 1604 and some American ANSI standards.

TOLERANCES

The standards mentioned above also define the allowed tolerances. IEC 751 has two tolerance classes for Platinum sensors: Class A and Class B, where Class A is the more accurate (with smaller tolerances).

LIMITING DEVIATIONS FOR PT100 THERMOMETERS

Temperature °C	Limiting Deviations			
	Classification A		Classification B	
	°C	Ohm	°C	Ohm
-200	±0.55	±0.24	±1.3	±0.56
-100	±0.35	±0.14	±0.8	±0.32
0	±0.15	±0.06	±0.3	±0.12
100	±0.35	±0.13	±0.08	±0.30
200	±0.55	±0.20	±1.3	±0.48
300	±0.75	±0.27	±1.8	±0.64
400	±0.95	±0.33	±2.3	±0.79
500	±1.15	±0.38	±2.8	±0.93
600	±1.35	±0.43	±3.3	±1.06
650	-	-	±3.6	±1.13
700	-	-	±3.8	±1.17
800	-	-	±4.3	±1.28
850	-	-	±4.6	±1.34

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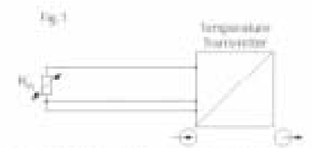
CONNECTIONS TO MEASURING INSTRUMENTS

RTDs are connected to instruments such as temperature transmitters using two, three or four leads; three or four leads are used to eliminate effects due to resistance of the leads themselves where high accuracy is desired. See Figure 1.



Example of a Platinum RTD in 3wire connection with a transmitter

Resistance v Temperature Table for PT100Ω Sensors

°C	Ω	Ω/°C	°C	Ω	Ω/°C	°C	Ω	Ω/°C	°C	Ω	Ω/°C
-200	18.52	0.432	70	127.08	0.383	340	226.21	0.352	610	316.92	0.320
-190	22.83	0.429	80	130.90	0.382	350	229.72	0.350	620	320.12	0.319
-180	27.10	0.425	90	134.71	0.380	360	233.21	0.349	630	323.30	0.318
-170	31.34	0.422	100	138.51	0.379	370	236.70	0.348	640	326.45	0.317
-160	35.34	0.419	110	142.29	0.378	380	240.18	0.347	650	329.64	0.316
-150	39.72	0.417	120	146.07	0.377	390	243.64	0.346	650	332.79	0.315
-140	43.88	0.414	130	149.83	0.376	400	247.09	0.345	670	335.93	0.313
-130	45.00	0.412	140	153.58	0.375	410	250.53	0.343	680	339.06	0.312
-120	52.11	0.409	150	157.33	0.374	420	253.96	0.342	690	342.18	0.311
-110	56.19	0.407	160	161.05	0.372	430	257.38	0.341	700	345.28	0.310
-100	60.26	0.405	170	164.77	0.371	440	260.78	0.340	710	348.38	0.309
-90	64.30	0.403	180	168.48	0.370	450	264.18	0.339	720	351.46	0.308
-80	68.33	0.402	190	172.17	0.369	460	267.56	0.338	730	354.53	0.307
-70	72.33	0.400	200	175.88	0.368	470	270.93	0.337	740	357.59	0.305
-60	76.33	0.399	210	179.53	0.367	480	274.29	0.335	750	360.64	0.304
-50	80.31	0.397	220	183.19	0.365	490	277.64	0.334	760	363.67	0.303
-40	84.27	0.396	230	186.84	0.364	500	280.98	0.333	770	366.70	0.302
-30	88.22	0.394	240	190.47	0.363	510	284.30	0.332	780	369.71	0.301
-20	92.16	0.393	250	194.10	0.362	520	287.82	0.331	790	372.71	0.300
-10	96.09	0.392	260	197.71	0.361	530	290.92	0.330	800	375.70	0.298
0	100.00	0.391	270	201.31	0.360	540	294.21	0.328	810	378.68	0.297
10	103.90	0.390	280	204.90	0.358	550	297.49	0.327	820	381.65	0.296
20	107.79	0.389	290	208.48	0.357	560	300.75	0.326	830	384.60	0.295
30	111.67	0.387	300	212.05	0.356	570	304.01	0.325	840	387.55	0.294
40	115.54	0.386	310	215.61	0.355	580	307.25	0.324	850	390.48	0.293
50	119.40	0.385	320	219.15	0.354	590	310.49	0.323			
60	123.24	0.384	330	222.68	0.353	600	313.71	0.322			

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NICKEL SENSORS

Compared to platinum sensors, nickel sensors are less expensive, less accurate and not so stable.

One small advantage could be that the resistance increases faster with temperature, which makes it easier to design measuring instruments for nickel sensors compared with platinum sensors.

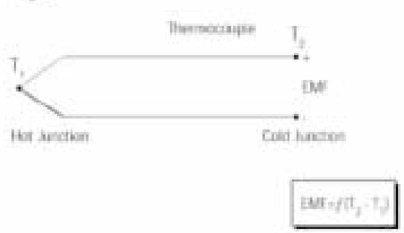
Nickel sensors are mainly produced in two types: Ni 100 and Ni1000, having a resistance of 100 and 1000 ohms respectively at 0°C.

Nickel sensors are normally manufactured according to European standard DIN 43760. They are standardized over the temperature range -60 to +180°C, and only one tolerance class is used.

THERMOCOUPLES (T/C)

In 1821 Seebeck discovered that if two wires composed of different metals are connected together in a loop, when one of the joints is heated, current will flow. The two leads are connected at one end, known as the Hot Junction, which is also the measuring point of the T/C. The other end of the leads, the Cold Junction, is normally connected to a temperature transmitter or some other measuring instrument. (See Figure 2).

Fig 2



The output from the T/C is a mV signal, also called EMF (Electromotive Force). The EMF is a function of the difference in temperature between the Hot Junction (T1) and the Cold Junction (T2).

The relation between EMF and temperature difference depends on the materials used for the two T/C leads. Because we want the T/C to measure the temperature T1, and it is normally not possible to keep the temperature T2 at 0°C, it is necessary to compensate for the deviation from 0°C.

This so called Cold Junction Compensation (CJC) can be performed in a temperature transmitter. The transmitter measures the terminal temperature and performs the compensation automatically. Besides the CJC, the temperature transmitter will measure the EMF, and create an output signal, which is proportional to the temperature T1.

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Advantages

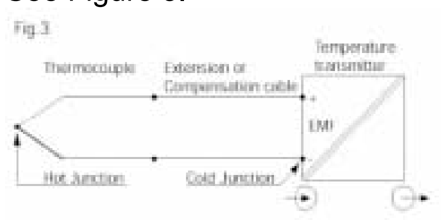
- needs no power supply (generates a millivolt signal)
- simple construction
- sturdy and physically adaptable
- relatively inexpensive
- wide measuring range

Disadvantages

- non-linear over its range
- emf is very low in some cases
- reference point (junction) required
- lower sensitivity
- long term drift

CONNECTIONS TO MEASURING INSTRUMENTS

If a T/C is not connected directly to a measuring instrument, e.g. a temperature transmitter, the T/C has to be "extended" up to the transmitter by means of an extension or compensation cable. These cables have the same effect, behaving as if the T/C reached all the way to the transmitter, thus transferring the cold junction to the terminals of the transmitter, where the cold junction compensation is performed. See Figure 3.



EXTENSION AND COMPENSATION CABLES

Extension Cables

These are made from the same materials as the T/C and can be regarded as a direct extension of the T/C with only a very small effect on the accuracy.

Compensation Cables

These are used together with T/C's of more expensive materials such as Pt and Rh. The characteristics of compensation cables are very similar to the corresponding T/C. The tolerances are higher, so compensation cables should not be used overcertain temperatures, typically 200°C

T/C TYPES

There are a number of standardized T/C types available on the market. They all have different characteristics, making them more or less suitable for different applications. The following T/C types are well known and standardized according to the European standard IEC 584 1 (some also according to American standards):

- Type B, Pt30%Rh Pt6%Rh
- Type E, NiCr CuNi
- Type J, Fe CuNi
- Type K, NiCr Ni
- Type N, NiCrSi NiSi
- Type T, Cu CuNi
- Type R, Pt13%Rh Pt
- Type S, Pt10%Rh Pt

COLOUR CODES FOR THERMOCOUPLE PRODUCTS

T/C Type	Conductor +	Conductor -	T/C Junction Continous Temp.Range °C	New Int'l. IEC 584-3:1989 BS4937Pt30:1993	Former British BS1843:1952	French to NFE-18001	German to DIN 43714	Japanese to JIS C 1610-1981	American to ANSI MC 96.1	Cable Code
K	Ni-Cr	Ni-Al	0 to +1000							KX
J	Fe	Cu-Ni Constantan	+20 to +700							JX
T	Cu	Cu-Ni Constantan	-185 to +300							TX
N	Ni-Cr-Si Nicrosil	Ni-Si-Mg Nisil	0 to +1100							NX NC
E	Ni-Cr	Cu-Ni Constantan	0 to +800							EX
B	PT-30Rh	PT-6Rn	+100 to +1600							BX
R	PT-13Rh	Pt	0 to +1600							RCA
S	PT-10Rh	Pt	0 to +1550							SCA
U	Cu	Cu-Ni Constantan	Compensating Cable to Types R and S 0 to +50							RCA SCA
W	W	W-26Re	+20 to +2000		No standard (use US codes)					
W3	W-3Re	W-25Re	+20 to +2000		No standard (use US codes)					
W5	W-5Re	W-26Re	+20 to +2300		No standard (use US codes)					
Vx	Cu	Cu-Ni	Compensating Cable for Type K 0 to +80							KCB

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THERMISTORS
(Thermally sensitive resistors)

Thermistors, derived from Thermally sensitive resistors, are solid state devices that exhibit a high coefficient of resistivity. They are used to measure temperature typically in the range –50 to 200°C, as well as being incorporated into electrical circuits as protection and compensation devices.

Thermistors are manufactured from complex metal oxides such as cobalt, magnesium, manganese or nickel.

There are two types of Thermistor; an NTC (negative temperature coefficient), whose resistance changes inversely with temperature, and a PTC (positive temperature coefficient) whose resistance changes proportionally to temperature. There are no industry standard Thermistors consequently each manufacturer produces devices with unique characteristics in various formats such as bead, disc, washer or chip.

Advantages

- cost effective in volume
- stable
- better accuracy than thermocouples

Disadvantages

- linear only over a limited temperature range
- no industry standard
- Not always interchangeable

Because of the limited temperature range of Thermistor devices, the temperature probes are predominantly used in applications such as HVAC and refrigeration where they are connected directly to the measurement or control instruments or panel meters.

INFRA RED RADIATION PYROMETERS

These devices are particularly useful for measuring temperatures of moving objects or rotating surfaces where contact is not possible or is undesirable.

Radiation pyrometers measure the temperature of an object by measuring the amount of radiation that the object emits. All objects emit radiant energy but the intensity and wavelength of this energy depends on the object's temperature and its emissivity (its ability to send out radiant energy). The wavelength of this radiant energy is from the visible light area, 0.35 to 0.75 microns, to the infrared area of 0.75 to 20 microns.

Therefore some hot objects will emit visible radiation e.g. red-hot steel, tungsten filament etc., but there is much more radiation emitted in the infrared area of the spectrum. The emissivity of an object is measured relative to a perfect emitter or a blackbody, which is an object that absorbs all heat to which it is exposed and emits that heat as radiant energy.

Infra red pyrometers comprise two main component parts; the optical component that collects the radiant energy emitted by the target object and the radiation detector that converts the energy into an electrical signal.

Advantages

non-contact temperature measurement
wide temperature range –20 to 3500°C
fast response
adjustable for long term drift

Disadvantages

expensive
bulky
needs to be adjusted for precise emissivity

TEMPERATURE TRANSMITTERS

This section describes the following basic facts about temperature transmitters:

What Is A Temperature Transmitter?
Why Do We Use Temperature Transmitters?
Why Use Isolated Transmitters?
Where To Mount The Transmitters?

A temperature transmitter is generally recognized as a device, which on the input side is connected to some sort of temperature sensor and on the output side generates a signal that is amplified and conditioned in various ways. Normally the output signal is directly proportional to the measured temperature within a defined measurement range. Many additional features can be added depending on the type of transmitter being used. The features of temperature transmitters are often described using slightly different terms with respect to technology, mounting method, functions etc. The following is a short summary of the terms used.

TECHNOLOGY

Analogue Transmitters

These transmitters are designed with analogue circuit technology. They normally offer basic functions such as temperature linearisation and sensor break detection. Sometimes they are adjustable for different measuring ranges.

Digital Transmitters

This transmitter type is microprocessor based. They are often called intelligent transmitters, because they normally offer many extra features, which are not possible with analogue transmitters.

MOUNTING METHOD

In-head transmitters are designed for mounting in the connection heads of temperature sensors. All Hawco in-head transmitters fit into DIN B heads or larger. Special care has to be devoted to durability because of the harsh conditions that sometimes exist. DIN rail transmitters are designed to snap on to 35mm rail according to DIN EN 50022.

INPUT TYPE

RTD transmitters are used only with RTD sensors i.e. Pt100, Pt1000, Ni100 etc. Normally they can handle only one RTD type at any one time. Hawco RTD transmitters are designed for Pt100 input and are either fix-range or adjustable. They all have a temperature linear output.

THERMOCOUPLE

Transmitter measures a mV-signal from the T/C and compensates for the temperature of the cold junction. This cold junction compensation (CJC), is normally performed by measuring the terminal temperature.
Alternatively some transmitters can be adjusted to compensate for an external fixed cold junction temperature.

Analogue T/C transmitters are often not temperature linearized because of the complicated non-linearity of the T/C's.

Universal transmitters are normally of the intelligent (microprocessor based) type. They are programmable for different input types and ranges and have accurate temperature linearisation. The Hawco transmitters in the IPAQ family are all universal with input types such as RTD's, T/C's, resistance, voltage and current.

OUTPUT TYPE

The majority of field mounting transmitters today produces the industry standard 4-20mA output signal. The signal is proportional to its temperature input and scaled specifically to the desired temperature range of the process. Field mounting devices in particular, are generally loop powered or 2 wire transmitters whose 4-20mA output is passive. The voltage to power these transmitters is derived from the loop whose 10 to 36 Volts DC supply (typically 24VDC), is generated at the instrument end of the 4-20mA loop and quite often incorporated within the controller, panel indicator or PLC.

In addition to 4-20mA, other standard output signals such as 0-5VDC and 0-10VDC are available with DIN rail mounting transmitters. These devices require a separate power supply e.g. 230VAC or 24VDC, and are termed 4 wire transmitters producing an active and programmable output to suit the associated instrumentation.

Recent developments in field instrumentation have seen the introduction of network transmitters within process control and automation systems. These network transmitters convert the signal from the sensor to a digital signal in the form of a standard serial format such as RS485 and other standard fieldbus protocols including Profibus, Modbus, Interbus, CANbus etc.

WHAT IS A TEMPERATURE TRANSMITTER?

Output / Power Supply Connection

2-wire transmitters:	Two leads are used in common for power supply and output signal.
3-wire transmitters:	Three leads are used for power supply and output signal. One lead is common.
4-wire transmitters:	Four leads are used, two for the power supply and two for the output signal.

Isolation

Non-isolated transmitters have internal connections between, for instance, input and output circuits. They should be used with care.

Isolated transmitters have no internal connections between circuits that are isolated from each other. The isolation effectively eliminates the risk of circulating currents and facilitates the connection of transmitters to control systems with grounded inputs.

WHY DO WE USE TEMPERATURE TRANSMITTERS?

To Convert A Low-Level Sensor Output To An Amplified Signal.

The amplified signal is much less sensitive to electrical disturbances. This is particularly important if the sensor is located remote from the receiving instrumentation. Long cables and low signal levels increase the risk of significant disturbances in the measurement.

To Convert A Non-Linear Sensor Output To A Temperature Linear Standard Signal.

Typical standard signals are 0-20 or 4-20 mA, 0-5 or 1-5 V and 0-10 or 2-10 V. Thanks to these standard signals, which are proportional to temperature, it is possible to use standard instruments for indication, recording etc. and standard input modules in PLCs or DCSs. This greatly simplifies plant engineering.

To Reduce The Costs Of Cabling And Other Instrumentation.

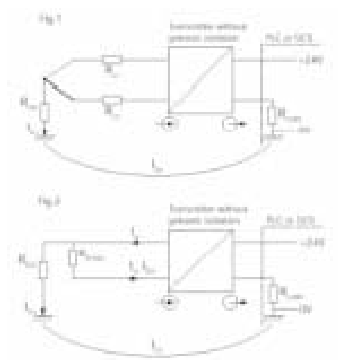
If field mounted transmitters are used, cable costs can be reduced. Only two leads are required if a 2- wire transmitter is used, compared with three or four for RTDs. Standard signal cables can be used instead of more expensive compensation or extension cables for T/cs. Normally all the required instrumentation is less expensive if using standard input signals like for instance 4-20 mA.

To Improve Safety/Integrity Of Temperature Measurement.
Safety/ integrity can be improved by letting the transmitter monitor the sensor leads. The Sensor break protection feature will indicate broken sensor leads and force the output to a user defined level.

WHY USE ISOLATED TRANSMITTERS?

Measurements With Thermocouples

Figure 1 shows a typical situation, when using T/Cs connected to a PLC or DCS through a non-isolated transmitter.



The isolation to ground R ISO is sometimes rather low, e.g. at high temperatures and/or with a small sized T/C. An undesired "ground current" I_{Err} of variable magnitude, depending on the actual situation, will arise. This ground loop will flow through the T/C and cause voltage drops over the resistances R L1 and R L2 in the T/C leads. These voltage drops will interact with the EMF generated by the T/C and can cause significant measuring errors. It is sometimes difficult to predict and calculate these errors, but it is not unusual for them to reach 5-10 % of the measuring range. If the transmitter is galvanically isolated between the input and output circuit, the ground loop will be cut off, and the ground current will be stopped. No errors will arise due to low isolation between T/C and ground.

Measurements With Rtds.

Figure 2 shows an RTD sensor connected to a PLC or DCS through a nonisolated transmitter. Isolation to ground R ISO is normally very high in a "healthy" RTD, typically 50 to 500 Mohm. However, under certain conditions the internal isolation of an RTD can be significantly reduced. Reasons might be wear or damage causing moisture to penetrate into the RTD. Depending on the value of R ISO a certain proportion, I_{Err}, of the measuring current I_m will pass through the ground and not through the RTD sensor. This will cause a measuring error. If the transmitter is galvanically isolated between the input and output circuit, the ground loop will be cut off, and the ground current will be prevented. No errors will arise due to low isolation between RTD and ground.

Conclusion To be sure of good results, use isolated transmitters!

WHERE TO MOUNT THE TRANSMITTERS?

In an industrial plant, where there are normally long distances between the measuring points and the receiving instrumentation, correct location of the transmitters can be important.

There are basically three alternatives for mounting temperature transmitters:

1. In-head mounting - inside the temperature sensors' connection head.
2. Field mounting - close to the temperature sensors.
3. Central mounting - in the vicinity of the control room.

IN-HEAD MOUNTING

The transmitters are mounted directly inside the connection head and normally replace the terminal block. All Inor's In-head transmitters fit in a DIN B head or larger. They are designed and tested for the harsh conditions that In-head transmitters will often meet. This method of mounting normally offers the biggest advantages. However it is necessary to be aware of the environmental influence (mainly the temperature) on the measurement accuracy.

Advantages

- Maximum safety in signal transmission. The amplified signal, e.g. 4- 20 mA, is very insensitive to electrical disturbances induced along the transmission cable.
- Cost savings for the transmission cables. Only two leads are required if a 2- wire transmitter is used.
- Cost savings on installation. No extra connection points needed.
- Cost and space savings. No extra housings or cabinets are needed.
- Field instruments, e.g. indicators, can easily be installed and at a later stage, without redesigning the measuring circuits. For instance, if using Inor IPAQ-H PLUS or IPAQ-HX PLUS transmitters, an Inor digital display can be connected, or loop powered indicators can be installed in the 4-20 mA loop.

Disadvantages

- Ambient temperatures can be outside the allowed limits for the transmitters.
- The ambient temperature effect on accuracy has to be considered. If temperature is expected to deviate strongly from normal room temperature, and if the highest possible accuracy is required, we recommend using Inor's high-performance transmitters IPAQ-H PLUS or IPAQ-HX PLUS because of their extreme temperature stability.
- Extreme vibrations might cause malfunction of the transmitters.
- The location of the temperature sensor can give maintenance problems.

FIELD MOUNTING

Transmitters are either mounted directly beside the temperature sensors or in their vicinity. Often more than one transmitter is mounted in the same field box. This method is more expensive than In-head mounting, but otherwise a good alternative offering most of the advantages of In-head mounting without the disadvantages mentioned above.

Advantages

- High integrity for signal transmission. The main transmission is made with an amplified signal.
- No extreme temperatures or vibrations exist. This facilitates accurate and safe measurements.
- Cost savings for transmission cables.
- A wider selection of transmitters is available. DIN rail transmitters can also be used.
- Field instruments can often be installed easily.
- Maintenance can normally be carried out without problems.

Disadvantages

- Higher installation costs compared with In-head mounting.
- Costs and space requirements for transmitter boxes or cabinets.

CENTRAL MOUNTING

In this case transmitters are placed in the vicinity of the control room or in another central part of the plant. They are often mounted inside cabinets, and/or closed rooms with good and stable ambient conditions. This method offers the most convenient conditions for maintenance and the best possible environment for the transmitters. There are on the other hand some disadvantages that should be considered.

Advantages

- Convenient for installation, commissioning & maintenance.
- Minimum risk of environmental influences (e.g. temperature effect).

Disadvantages

- Reduced integrity of signal transmission. The low-level sensor signal is rather sensitive to electrical disturbances being induced along the transmission cable.
- Relatively high costs for cabling. T/C measurements require compensation or extension cables all the way to the transmitters. RTD measurements with high accuracy should be done as a 4-wire connection to nullify lead resistance
- Costs and space requirements for cabinets etc.
- Rather complicated and expensive to connect field instruments, e.g. indicators.