22
CHAPTER

Electric Welding

22.1. Introduction

Process of welding consists in joining together two or more pieces of metal, of similar or dissimilar composition, by heating to suitably high temperature with or without application of pressure and application of a so called *filler* material. Welding may be plastic welding or fusion welding.

Plastic Welding. In plastic welding, the metal parts to be joined are heated to a plastic state and then joined under application of pressure.

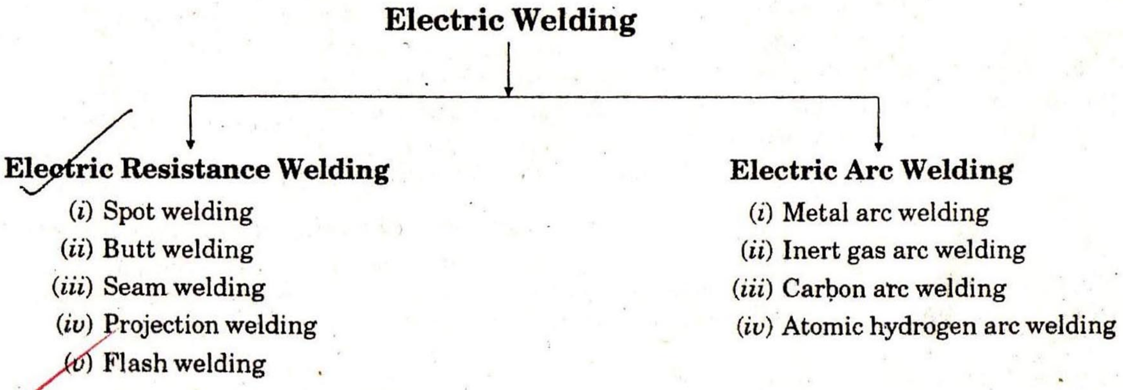
Fusion Welding. In fusion welding, the metal parts to be joined are heated to molten state and then allowed to solidify forming a localized homogeneous union of the two parts.

Plastic welding is further divided into three groups : (*i*) electric resistance welding (*ii*) forge welding and (*iii*) thermite welding with pressure.

Similarly fusion welding may be of three types : (*i*) electric arc welding (*ii*) gas welding and (*iii*) thermite welding without pressure.

We here consider only electric welding methods namely (*a*) electric resistance welding and electric arc welding.

22.2. Classification of Electric Welding Methods



22.3. Electric Resistance Welding

Electric resistance welding consists in joining together two or more metal pieces by passing short duration heavy dc or ac current through the areas of contact to be welded. The duration of current may be from a few milli-seconds to several seconds depending on the job requirement. Electric control of the duration and magnitude of the welding current has made possible precise welding of even such materials as aluminium and stainless steel.

The welding process is based on the resistance to current flow through two metal pieces where weld heat is produced.

The welding thermal energy w produced is given by,

$$w = \int_0^{t_w} i^2 . r \, dt \qquad ...(22.1)$$

where r is the resistance between the pieces to be welded (ohms) t_w is the time during which welding current flows (seconds) i is the instantaneous current (amperes)

Current i may be either alternating current or short pulses of unidirectional current.

22.4. Basic Circuit Arrangement of AC Electric Resistance Welding

Fig. 22.1 gives the block diagram of basic circuit. The main constituents are :

(i) Power transformer feeding 50 Hz supply
(ii) Circuit breakers
(iii) SCR contactor or Ignitron contactor
(iv) Weld timer
(v) Welding transformer
(vi) Welding electrode and welding assembly.

Alumnus –
Alumni

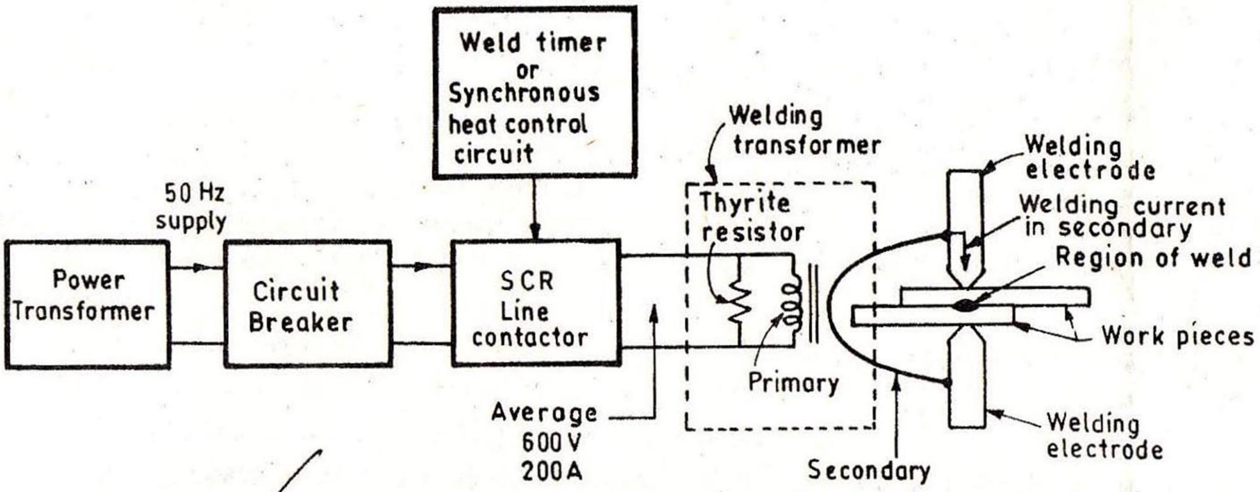


Fig. 22.1. Block diagram of a.c. electric resistance welding system.

Power transformer feeds to ac (50 Hz) power a suitably high voltage to the machine. The circuit breaker controls this ac power and feeds it to the contactor. The nature of line contactor depends on the nature of job. For metals which can be easily welded, the contactor may be simply a magnetically controlled contactor or even a manual switch. On the other hand, in case of metals requiring critical timing of operation, SCR (or ignitron) contactor is used. Earlier ignitron contactors were used exclusively but currently these have been largely replaced by SCR (thyristors) contactors. The function of the contactor is to connect the primary of the welding transformer to the ac supply during the desired welding interval only. The welding transformer is a step down transformer. The secondary of the welding transformer has relatively small number of turns typically only one and is rated for several volts, 10 to 15 volts typically but hundreds or thousands of amperes for heavy welds. In order to handle this large current, the secondary is in the form of a thick conductor. The secondary winding is connected to the winding electrodes through which the welding current passes into the job to be welded.

Ideally the complete heat energy w should be produced and concentrated at the spot to be welded *i.e.* the entire resistance should occur at this place. Hence the tips of the welding electrodes must be kept clean for making good electric contacts. Unfortunately, however, a part of the resistance and the corresponding temperature rise occurs (*i*) throughout the sheets (*ii*) in the contacts between the sheets and the electrodes and (*iii*) in the two electrodes themselves. Hence there exists a possibility that the electrodes themselves may weld to the material or a hole may be caused in the material.

In order to avoid welding of the electrode to the sheet, the electrodes are made of metals having high electrical and thermal conductivity and at the same time they are properly cooled by flow of water. As a result, the electrodes produce less heat and at the same time the heat is removed away by the flow of water. Hence maximum temperature rise takes place at the weld. For the purpose of water cooling, the spot welding electrodes are generally made hollow with provision for circulation of cooling water as shown in Fig. 22.2. A hard copper alloy is generally used for electrodes. This can stand the electrode pressure and can keep the temperature low to prevent deformation of electrode tip.

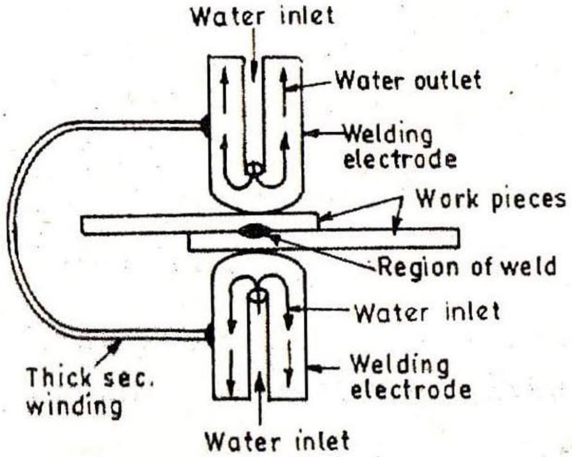


Fig. 22.2. Water cooled welding electrode.

Difficulty is sometimes created by high transient voltage across the transformer caused by very rapid rate of change of current in the primary of the welding transformer resulting in high voltage $\left(v = L\dfrac{di}{dt}\right)$. Such a high voltage may endanger the insulation of the transformer. To overcome this difficulty, a thyrite resistor is usually connected across the primary as shown in Fig. 22.1. The impedance of the thyrite reduces with the increase of voltage across it. Hence a properly designed thyrite resistor connected across the primary damps the transient voltage to a low value thereby eliminating the possibility of breakdown of insulation.

The metal pieces are forced together by the electrodes with high pressure resulting in decreased resistance between the metal pieces to ensure proper weld. The welding current is made to flow for only a fraction of a second with the help of the contactor. The contactor closes several times to make a number of welds.

By proper choice of electrode pressure and magnitude and duration of current, it is possible to spot weld satisfactorily metal sheets of thickness varying from about 10^{-3} cm to several cms. Further a large number of metals may be spot welded readily.

The quantum of welding heat needed depends on the metal to be welded. Thus for steel having high resistance, welding heat is easily produced. On the other hand, aluminium has low resistance and hence the welding heat is difficult to get. Further, in the case of aluminium, the heat is required to be produced in a very short duration because of its high conductivity and this has a tendency to get welded to the electrodes.

Operation times involved in Welding

Squeeze Time. To make a weld, a push button or fast switch is pressed to actuate a solenoid. This applies pneumatic pressure to an air cylinder causing the upper electrode to move down to press the work piece. This operation is called the *squeeze operation* and its time period is called the *squeeze time*, t_s.

Weld Time. The timer circuit actuates the contactor which supplies power to the welding transformer for the desired time period called the *weld time* t_w.

Hold Time. On completion of welding, the job is held still under pressure for a duration called *hold time* t_h to permit weld to harden. No welding current flows.

Off Time. Once the weld has hardened, pressure is released, the electrodes separate and welded material job is removed.

Merits of Electric Resistance Welding. (*i*) quick welding (*ii*) very little waste of metal (*iii*) process may be accurately controlled (*iv*) consistently uniform weld.

22.5. Types of Electric Resistance Welding

Resistance welding may be classified as below : (*i*) Spot welding (*ii*) Butt welding (*iii*) Seam welding (*iv*) Projection welding and (*v*) Flash welding.

(A) **Spot Welding.** This is the simplest and the most widely used method of making lap welds in thin metal sheets of thickness upto maximum of about half inch (12.7 mm). Basically it uses a step down transformer to produce a high current at low voltage. Spot welding is done by clamping together between the two pointed welding electrodes, two or more sheets or pieces of metal. The pointed electrodes ensure proper localisation of current. The block diagram of the equipment is as shown in Fig. 22.1 while Fig. 22.3 (a) gives the basic arrangement of electrodes. Fig. 22.3 (*b*) shows the spot welds along a line.

(*a*) Electrode arrangement (*b*) Spot welds along a line

Fig. 22.3. Basic electrode arrangement of spot welding.

Apart from high thermal conductivity, the electrode material should have very high strength to minimise the wear and tear at the tips of the electrodes. Electrodes are made of special copper alloy. The diameter of the electrode tip is equal to $\sqrt{t}$ where t is the sheet thickness.

The time period of flow of current varies with the thickness of sheets and the kind of metal. For thin sheets, the time period is about 20 ms for sheet thickness of about 0.3 mm.

Applications. Spot welding is used mainly for :

(*i*) fabricating all types of sheet metal structures where mechanical strength rather than water or air tightness is needed.

(*ii*) welding of sheets

(*iii*) fabrication of boxes, cores and enclosing cases.

(B) **Butt Welding.** In butt welding, the ends of the two bars, rods or tubes to be welded are firmly butted together under axial pressure as shown in Fig. 22.4. A heavy current flowing through the butt generates heat in the high contact resistance or the joint raising its temperature. The faces of the work pieces should be edge prepared. When the desired temperature is reached, the two work pieces are rammed together either manually or automatically resulting in a bulged weld. Butt welding may be used to weld together bars of diameter upto several centimetres.

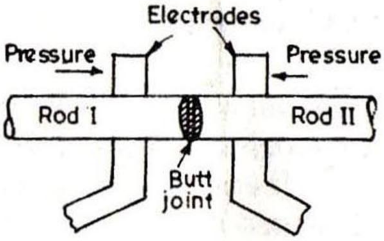


Fig. 22.4. Butt welding.

Applications of Butt Welding. The main applications of butt welding are :

(*i*) for end-to-end or edge-to-edge joint

(*ii*) for welding pipes, tubes, wires and rods.

(C) **Seam Welding.** In seam welding, two overlapping sheets of metals are welded together through a series of spots along a continuous line by moving the sheets between two wheel shaped electrodes through which the welding currents flow at short intervals. Fig. 22.5 illustrates the general principle. In slow speed seam welding, general practice consists in allowing welding current of 6 cycles and permitting break of 6 cycles. In high speed seam welding, on the other hand, with rate of rolling of the order of about half a metre/second, the *off* period becomes zero and half cycles of current produce welds that overlap each other.

The main object of overlapping spots is to produce gas and liquid leak-proof lap joints. The weld may be cooled by splashing water over it. The intermittent overlap weld technique is used for metals which are critical to heat treatment.

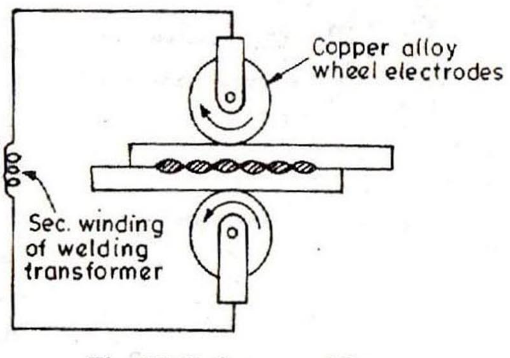


Fig. 22.5. Seam welding.

Applications of Seam Welding

(*i*) For making lap and butt welds

(*ii*) For pressure tight and leak-proof tanks for various purposes, circular or radial containers, car body sections and transformer radiator units.

(D) **Projection Welding.** In projection welding, instead of using pointed electrodes, slight projections are formed on one or both of the work pieces at a location where welding is desired as shown in Fig. 22.6. Projections are made by a special set of dies.

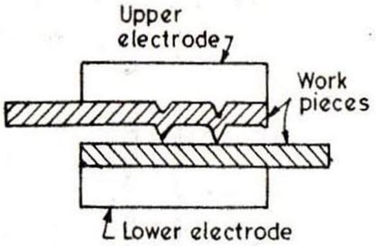


Fig. 22.6. Projection welding.

Merits of Projection Weld

(*i*) Welding may be done at more than one spot simultaneously.

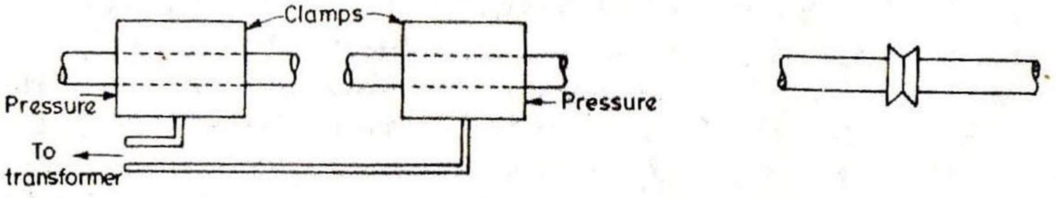
(*ii*) It needs low current density and low pressure. Hence the life of electrodes is increased.

(*iii*) Better finished appearance is obtained.

(*iv*) Locations of welds are automatically fixed at the desired points of projections.

Applications. Projection welding is specifically used in assembling parts made by punching or stamping and for welding studs, nuts to plates etc.

(E) **Flash Welding.** It is similar to butt welding but for the difference that in this case welding current is applied to the parts before they are brought together with the result that when they meet, arc or flash takes place. The two work pieces are clamped strongly in a flash winding machine. As the points are brought together, the resistance to the current heats the contact surfaces. Once the temperature reaches the optimum melting point, the current is shut off and the pieces are quickly brought together under considerable pressure. Fig. 22.7 gives the general arrangement. Due to higher pressure, the squeezed molten metal gives off sparks



(*a*) Basic arrangement (*b*) Welded pieces

Fig. 22.7. Flash welding.

or flashes and the work pieces are heated to their plastic state and they fuse together and also slag out of the joint making a good weld as shown in Fig. 22.7 (*b*).

Applications. Flash welding is widely used in production works specially in welding together rods, pipes etc.

22.6. Electric Arc Welding

Electric arc welding utilizes the fact that when electricity passes through an air gap from one electric conductor to another, a very intense and concentrated heat is produced with temperature between the two conductors being approximately 3500° to 4000°C. At this high temperature, intense heat in the arc at the point of welding melts a small portion of metal in the work piece. Further welding electrodes also melt slightly and the molten material gets deposited in the small pool of molten work metal. Subsequently the metal pool cools down under a protective cover of slag left by the electrodes. On cooling, a perfect joint gets formed between the two molten pieces. Fig. 22.8 gives the general circuit arrangement.

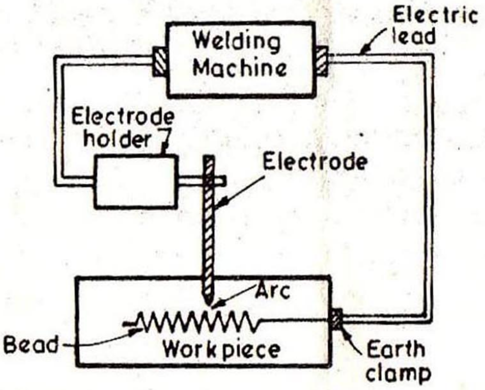


Fig. 22.8. Electric arc welding.

An electric arc may be defined as the flow of electric energy through a gas accompanied by generation of heat and bright light. Thus an electric arc gets created on first short circuiting two electrodes and then suddenly withdrawing them apart. During this withdrawal of the electrodes, the area of contact of electrodes first reduces increasing the resistance. Hence on actual separation of electrodes, the tips of electrodes get red hot. The electrons leave the cathode, move under the accelerating force due to potential gradient existing between the electrodes and on their way collide with the atoms and molecules in the air ionizing the same. Hence air or gas in between the electrodes provides the conducting path for the arc.

Arc welding may use either ac current or dc voltage. The ac supply voltage requirement is between 70 V and 100 V while that for dc is between 50 V and 60 V. Once the arc strikes, the voltage requirement reduces to 20 V and 30 V for ac and dc respectively.

DC Welding Set. A dc generator with drooping characteristic is needed. This may be achieved by using shunt and series fields opposing each other. Welding current may be obtained by varying either the shunt or both shunt and series fields. A constant potential is used obtained through using compound generator.

In case only ac supply is available, then a motor generator is used, the motor being a squirrel cage induction motor.

AC Welding Set. Here the normal mains voltage is stepped down to the value equal to the striking voltage. Drooping characteristic can be achieved by using suitable resistance and reactance. Resistance so used, reduces the efficiency while the reactance reduces the power factor. Harmonics may be prevented by designing reactor to operate under saturation point on its magnetic circuit.

22.7. Types of Electric Arc Welding

Electric arc welding may be of the following types : (*i*) Metal arc welding (*ii*) Inert gas arc welding (*iii*) Carbon arc welding and (*iv*) Atomic hydrogen arc welding.

(A) **Metal Arc Welding.** This uses an electrode of the same metal as the job being welded. The electrode also serves the function of filler *i.e.* provide molten metal to the point of the job. At the high temperature of the arc, the job metal as well as the electrode melt. Metal arc welding may use either ac or dc supply. In case of dc supply, arc characteristic is controlled by changing the polarity of the electrode. Principal drawback of dc metal arc welding is the occurrence of arc blow many times under certain conditions. Arc blow is the distortion of arc stream from desired path caused by any nonuniform magnetic field. Arc blow makes welding difficult and further increases consumption of energy. Arc blow is quite low in ac arc welding.

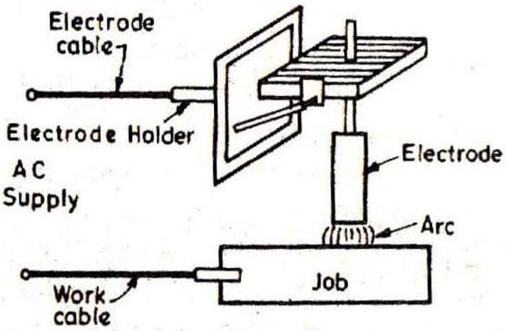
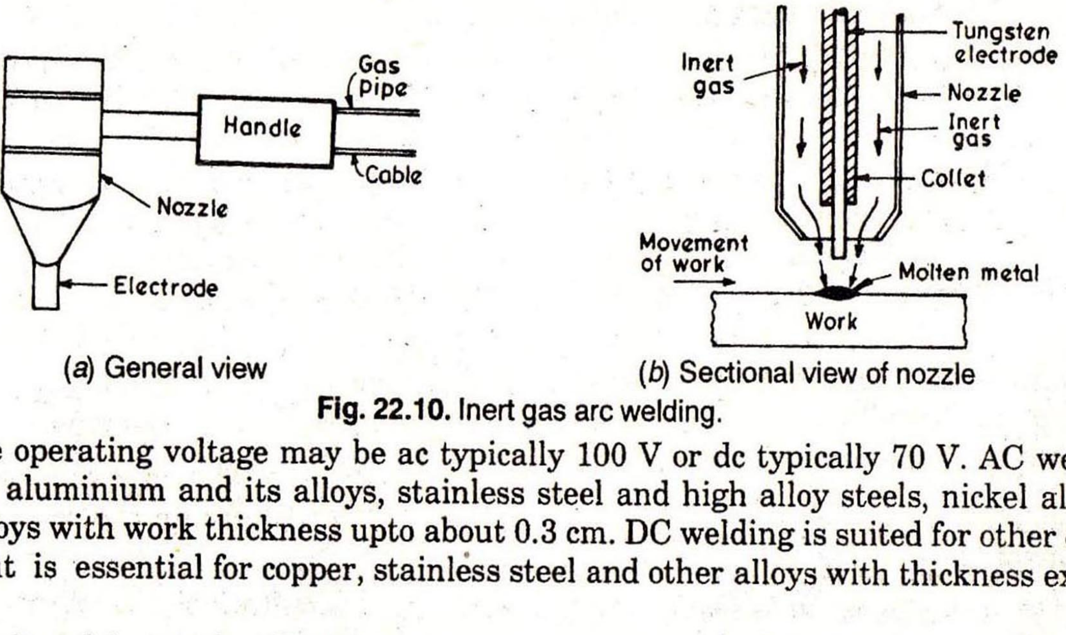


Fig. 22.9. Metal arc welding.

The electrode is fitted into a holder as shown in Fig. 22.9. Electric power is fed to the holder through a cable while the return lead is connected to the job piece. A switch (usually hand operated) feeds the power and arc is struck between the work and the metal rod. The arc so produced melts the rod and the surfaces get welded. Voltage needed for arc lies in the range 50 V to 60 V for dc arc welding and 80 V to 90 V for ac arc welding.

For good weld, reaction of oxygen and nitrogen over the molten metal is prevented. Further fluxing and slagging ingradients are used for removing impurities.

(B) **Inert Gas Arc Welding.** This method of welding is used for welding aluminium and its alloys, magnesium and its alloys. The arc is produced between tungsten electrode and the work piece in an inert atmosphere of helium or argon to prevent oxidation of the welded joint. Fig. 22.10 (*a*) gives the general view of hand held machine while Fig. 22.10 (*b*) gives a section of the nozzle for holding the electrode and passage of inert gas.



(*a*) General view (*b*) Sectional view of nozzle

Fig. 22.10. Inert gas arc welding.

The operating voltage may be ac typically 100 V or dc typically 70 V. AC welding is suited for aluminium and its alloys, stainless steel and high alloy steels, nickel alloy, and copper alloys with work thickness upto about 0.3 cm. DC welding is suited for other common metals but is essential for copper, stainless steel and other alloys with thickness exceeding 1 cm.

Merits of Argon Arc Welding

(*i*) Because of use of inert gas, flux is not formed.

(*ii*) It is possible to concentrate heat and thereby reduce distortion.

(C) **Carbon Arc Welding.** It uses only dc supply. Initially arc is struck between the work piece and the electrode made of graphite or carbon. The work or job to be welded fuses. To complete the weld, a metal filler rod is melted and it flows into the gap in the work completing the deficiency of metal. The filter rod, however, does not form a part of the electrode, and no current flows through it. Carbon electrode when used, is placed on the negative side of the arc to ensure stability of arc and to avoid the weld from getting brittle due to absorption of carbon monoxide from the vapour of the electrode. Graphite electrodes have longer life than carbon electrodes.

21

Cathode Ray Oscilloscope (CRO)

21.1. Introduction. The cathode ray oscilloscope (CRO) is a very useful and versatile laboratory instrument used for display, measurement and analysis of waveforms and other phenomena in electrical and electronic circuits. CROs are in fact very fast $X - Y$ plotters, displaying an input signal versus another signal or versus time. The "stylus" of this " plotter" is a luminous spot which moves over the display area in response to an input voltage. The luminous spot is produced by a beam of electrons striking a fluorescent screen. The extremely low inertia effects associated with a beam of electrons anables such a beam to be used for following the changes in instantaneous values of rapidly varying voltages. The extremely low inertia of electrons as compared to metallic conductors used in an electromechanical Duddell's oscilloscope enables a CRO to be used at frequencies much above the highest on which the Duddell's oscilloscope can be used.

The normal form of a CRO uses a horizontal input voltage which is an internally generated ramp voltage called "**Time Base**". This horizontal voltage moves the luminous spot periodically in a horizontal direction from left to right over the display area or screen. The vertical input to the CRO is the voltage under investigation. The vertical input voltage moves the luminous spot up and down in accordance with the instantaneous value of the voltage. The luminous spot thus traces the waveform of the input voltage with respect to time. When the input voltage repeats itself at a fast rate, the trace (display) on the screen appears stationary on the screen. The CRO thus provides a means of visualizing time varying voltages. As such, the CRO has become a universal tool in all kinds of electrical and electronic investigations.

CROs operate on voltages. However, it is possible to convert current, strain, acceleration, pressure and other physical quantities into voltages with the help of transducers and thus to present visual representations of a wide variety of dynamic phenomena on CROs.

CROs are also used to investigate waveforms, transient phenomena, and other time varying quantities from a very low frequency range to the radio frequencies.

Oscilloscopes have been evolved continuously, and they are now available which can measure frequencies upto 1 GHz, and observer events as small as 20 Hz in duration.

Many additional features are available with some oscilloscopes and these include built in digital multimeters and counters. The oscilloscopes are progressively getting smarter, and many are microprocessor controlled. They have the ability to calculate several features, such as rise time or pulse width of the measured waveform, and to display these values along with the display of waveforms. They are easier to use and internal routines often act as a guide for the user, and display a warning if there is any error in setting.

Many oscilloscopes are now available with IEEE 488 bus capabilities, so that they can be used as a part of measurement test bed, with the instrument's controls set at a remote location, and the readings digitised and retreived for the purposes of recording and analysis.

Although, most oscilloscopes are monochromatic, colour oscilloscopes are finding increasing applications in computers and in television

The applications of oscilloscopes have been enhanced on account of many recent developments. Most present day oscilloscopes are capable of accepting two or more inputs displaying them simultaneously. This may be achieved through using a split beam or by using a multiple beam tube. Sampling oscilloscopes are used for high speed applications. These oscilloscopes employ time sampling and through their use it is possibe to measure signals of about 20 GHz. They can only detect a repetitive waveform, and work on the principle of taking a sample once every cycle, over several cycles, each sample point being shifted from the previous point. The complete picture of the waveform is stored, and can be displayed as a stantionary signal.

Storage oscilloscopes can be used for capturing transient signals, and then display them for periods which may vary from a few minutes to several years. An analog ocilloscope uses a modified form of a conventional cathode ray tube to store the trace. The digital storage oscilloscope first converts the analog signal to a digital form and stores it in digital memory. The signal can then be recalled for display as and when required.

21.2. Cathode Ray Tube (CRT). A cathode ray oscilloscope consists of a cathode ray tube (CRT), which is the heart of the tube, and some additional circuitry to operate the CRT. The main parts of a CRT are :

(*i*) Electron gun assembly, (*ii*) Deflection plate assembly, (*iii*) Fluorescent screen, (*iv*) Glass envelope, (*v*) Base, through which connections are made to various parts.

The main parts of a CRT are shown in Fig. 21.1. Before going into details of working of various parts of a CRT, a summary of functions of the different parts is given below :

The "**Electron gun assembly** " produces a sharply focused beam of electrons which are accelerated to high velocity. This focused beam of electrons strikes the fluorescent screen with sufficient energy to cause a luminous spot on the screen.

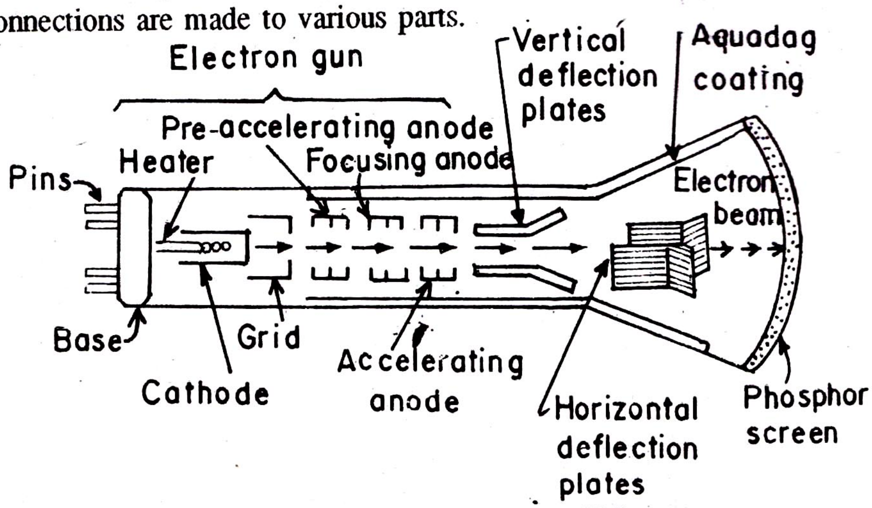


Fig. 21.1. Internal structure of a CRT.

After leaving the electron gun, the electron beam passes through two pairs of "**Electrostatic deflection plates**". Voltages applied to these plates deflect the beam. Voltages applied to one pair of plates move the beam vertically up and down and the voltages applied to the other pair of plates move the beam horizontally form one side to another. These two movements *i.e.* horizontal and vertical are independent of each other and thus the beam may be positioned anywhere on the screen.

The working parts of a CRT are enclosed in an evacuated glass envelope so that the emitted electrons are able to move about freely from one end of the tube to the other.

21.3. Electron Gun. The source of focused and accelerated electron beam is the electron gun. The electron gun, which emits electrons and forms them into a beam consists of a heater, a cathode, a grid, a pre-accelerating anode, a focusing anode and an accelerating anode.

In smaller CRTs, connections to the various electrodes are brought out through pins in the base of the tube as shown in Fig. 21.1. Large and medium sized high performance tubes operate at very high voltages, and these leads are usually brought out through the sides of the glass envelope.

Electrons are emitted from the indirectly heated cathode. A layer of barium and strontium oxide is deposited on the end of the cathode–which is a cylinder–to obtain high emission of electrons at moderate temperatures. The typical values of current and voltage required by an indirectedly heated cathode are 600 mA at 6.3 V. High efficiency systems use 300 mA at 6.3 V. The special low power designs use 140 mA at 1.5 V. These electrons pass through a small hole in the "**control grid**". This control grid is usually a nickel cylinder, with a centrally located hole, co-axial with the CRT axis. This is usually a metal cup of low permeability steel, about 15 mm in diameter and 15 mm long. An aperture of about 0.25 mm is drilled in the cap of the grid for the electrons to flow through. The intensity of electron beam depends upon the number of electrons emitted from the cathode. The grid with its negative bias controls the number of electrons emitted from the cathode and hence the **intensity** is controlled by the grid.

The electrons, emitted from the cathode and passing through the hole in the control grid are accelerated by the high positive potential which is applied to the "**pre-accelerating**" and "**accelerating anodes**".

Application of CRO

10. Astigmatism. In most modern oscilloscopes there is an additional focusing control marked **Astigmatism.** This is used to correct an effect which exactly is analogous to astigmatism in optical lenses. To focus the spot correctly, it is necessary to stop it near the centre of the screen by switching off the time base and adjusting the X and Y positioning controls. The spot is then made as sharp as possible by successive adjustment of focus and astigmatism controls.

21.18. Observation of Waveform on CRO. In order to observe waveform on a CRO, the waveform of voltage under test is applied to Y plates and a voltage obtained from a sawtooth generator is applied to X plates. Let us assume that the sawtooth waveform has an idealized waveshape.

When simultaneously with the horizontal sawtooth (ramp) voltage, an input voltage is applied to vertical deflection (Y) plates, the beam is under the influence of two forces : (*i*) one in the horizontal direction moving the beam at a linear rate from left to right, and (*ii*) second in the vertical direction moving the beam up and down. Since the deflection is proportional to the voltage applied to the deflection plates, the horizontal movement is proportional to the voltage applied to X plates at any instant and since the ramp voltage is linear it traces a straight line on the CRT screen. The vertical deflection is proportional to the voltage applied to the Y plates at any instant and thus the beam moves up and down according to the magnitude and polarity of the input voltage. Fig. 21.29 shows the waveform displayed on a CRT tube due to an input sinusoidal voltage.

At the end of one sweep cycle, the sweep voltage abruptly drops down and the spot is immediately transferred to its original position. The process is then repeated again, with the result, that a stationary image is seen on the screen.

For the case shown the frequency of the input voltage is twice that of sawtooth (sweep) voltage. To observe more than one cycle of the input voltage, the sweep voltage frequency has to be a submultiple of the input voltage frequency.

21.19. Measurement of Voltages and Currents. The expression for electrostatic deflection, given in Eqn. 21.16, shows that the deflection is proportional to the deflection-plate voltage. Thus the cathode-ray tube will measure voltage. It is usual to calibrate the tube under the given operating conditions by observing the deflection produced by a known voltage. Direct voltages may be obtained from the static deflection of the spot, alternating voltages from the length of the line produced when the voltage is applied to Y plates while no voltage is applied to X plates. The length of this line corresponds to the peak-to-peak voltage. When dealing with sinusoidal voltages, the rms value is given by dividing the peak-to-peak voltage by $2\sqrt{2}$.

Laboratory oscillographs frequently incorporate voltage-measurement facilities by including constant-gain amplifiers and calibrated shift controls. The Y-shift control is adjusted so that positive peak of the test voltage coincides with some datum line on the screen ; the shift control is then operated until the negative peak coincides with the datum. The movement of the control is arranged to read directly the peak-to-peak voltage. The value of a current can be obtained by measuring the voltage drop across a known resistance connected in the circuit.

21.20. Measurement of Phase and Frequency (Lissajous Patterns). It is interesting to consider the characteristics of patterns that appear on the screen of a CRT when sinusoidal voltages are simultaneously applied to horizontal and vertical plates. These patterns are called **'Lissajous Patterns'.**

When two sinusoidal voltages of equal frequency which are in phase with each other are applied to the horizontal and vertical deflection plates, the pattern appearing on the screen is a straight line as is clear from Fig. 21.30.

Thus when two equal voltages of equal frequency but with 90° phase displacement are applied to a CRO, the trace on the screen is a circle. This is shown in Fig. 21.31.

or
$$\frac{dQ}{Q} = 2.5\ \frac{dH}{H}$$

or
$$dQ = \pm\ 2.5 \times 0.2506 \times 0.01/0.5 = \pm\ 0.0153\ \text{m}^3/\text{s}.$$

Hence, the discharge can be written as $0.2506 \pm 0.0153\ \text{m}^3/\text{s}$.

25.6. Transducers. An electronic instrumentation system consists of a number of components to perform a measurement and record its results. As explained earlier a generalized measurement system consists of three major components.

(*i*) an input device,
(*ii*) a signal conditioning or processing device,
and (*iii*) an output device.

The input device receives the measurand or the quantity under measurement and delivers a proportional or analogous electrical signal to the signal conditioning device. Here the signal is amplified, attenuated, filtered, modulated, or otherwise modified in format acceptable to the output device.

The input quantity for most insrumentation systems is a *''non-electrical quantity''*. In order to use electrical methods and techniques for measurement, manipulation or control, the non-electrical quantity is generally converted into an electrical form by a device called a *''transducer'*. We can define a **transducer** as a device which, when actuated transforms energy from one form to another.

The broad definition of a **transducer** includes, for example, devices which convert *mechanical force* into an electrical signal. These devices form a very large and important group of transducers commonly used in industrial instrumentation area. The instrumentation engineers and technologists are therefore primarily concerned with this area of instrumentation. Many other *physical* parameters such as heat, intensity of light, flow rate, liquid level, humidity and pH value may also be converted into electrical form by means of transducers. These transducers provide an output signal when stimulated by a mechanical or a non-mechanical input : a photoconductor converts light intensity into change of resistance, a thermocouple converts heat energy into electrical voltage, a force produces a change of resistance in a strain gauge, an acceleration produces a voltage in a piezo-electrical crystal and so on. In all cases, however, the electrical output is measured by *standard* methods, giving the magnitude of the input quantity in terms of an analogous output.

25.7. Electric Transducers. The art of electrical measurements has been chiefly used for measurement of electrical quantities but its value in making measurements of non-electrical quantities in this new era of automation is rapidly growing. In order to measure non-electrical quantities a detector is used which usually converts the physical quantity into a displacement. This displacement actuates an **electric transducer,** which acting as a secondary transducer, gives an output that is electrical in nature. The electrical quantity so produced is measured by standard methods used for electrical measurements. The result (electrical output) gives the magnitude of the physical quantity or condition being measured.

The electrical signal may be a current or a voltage or a frequency and production of these signals is based upon electrical effects which may be resistive, capacitive, inductive etc. in nature

The first stage of a measurement system may simply be called a **transducer stage** instead of **detector transducer stage** by redefining a **transducer.** A **transducer**, in general form, may be defined as a device which converts energy from one form to another. However, this definition has to be restricted, many a time especially in the field of **electrical instrumentation.** Keeping this restriction in view, a **transducer** may be defined as a device which converts a physical quantity or a physical condition into an electrical signal. Another name for a transducer is **pick up.**

25.7.1. Advantages of Electrical Trandducers. There are a number of transducers which transform a variety of physical quantities and phenomena into electrical signals. The reasons for transforming a physical phenomenon into electrical form are numerous. The advantages of converting physical quantities into analogous electrical quantities are :

(*i*) Electrical amplification and attenuation can be done easily and that too with static devices.

(*ii*) The mass-inertia effects are minimized. In fact, when dealing with electrical or electronic signals, the inertia effects are due to electrons which have negligible mass. In many situations, we do not come across mass or inertia problems at all.

(*iii*) The effects of friction are minimized.

(*iv*) The electrical or electronic systems can be controlled with a very small power level.

(*v*) The electrical output can be easily used, transmitted and processed for the purpose of measurement.

(*vi*) Telemetry is used in almost all sophisticated measurement systems. The entire aerospace research and development is based upon telemetry and remote control. The ever enlarging field of radio monitoring in space research has left us with no alternative but to resort to electronic means. This completely eliminates the data transmission through mechanical means and hence electrical and electronic principles have to be employed for these conditions. The remote indication or recording is an essential part of modern day instrumentation technology.

(*vii*) There has been an explosive development in the field of electronic components and devices. This development is on account of the fact that electronic devices are very amenable to miniaturization. Components which are compact, have always an, advantage. **Miniaturization** on account of use of **ICs** (integrated Circuits) has completely revolutionised the field of instrumentation.

In short, it can be said that the reasons for transforming a physical phenomenon into electrical form is that the electrical output can be easily used, transmitted and processed for the purposes of measurement. Modern digital computers make the use of these transducers absolutely essential.

When the definition of **transducer** is confined to a device that covers the entire **detector transducer stage,** wherein the transducer converts a non-electrical quantity into an analogous electrical signal, the transducer may be thought of consisting of two important and closely related parts. These two parts are :

(*i*) Sensing Element, and (*ii*) Transduction Element.

In addition there may be many other auxiliary parts, such as amplifiers and other signal processing equipment, power supplies, calibrating and reference sources, and mechanical mounting features.

1. Sensing or Detector Element. A detector or a sensing element is that part of a transducer which responds to a physical phenomenon or a change in a physical phenomenon. The response of the sensing element must be closely related to the physical phenomenon. .

2. Tranduction element. A transduction element transforms the output of a sensing element to an electrical output. The **transduction element,** in a way, acts as a **secondary transducer.**

25.8. Classification of Transducers.

The transducers can be classified

(*i*) on the basis of transduction form used,
(*ii*) as primary and secondary transducers,
(*iii*) as passive and active transducers,
(*iv*) as analog and digital transducers,
and (*v*) as transducers and inverse transducers.

25.8.1. Classification based upon Principle of Transduction. The transducers can be classified on the basis of principle of transduction as resistive, inductive, capacitive etc. depending upon how they convert the input quantity into resistance, inductance or capacitance respectively. They can be classified as piezoelectric, thermoelectric, magnetorestrictive, electrokinetic and optical. Table 25.2 lists the classification of transducers based upon principle of transduction.

25.8.2. Primary and Secondary Transducers. Let us consider the case of a Bourdon's tube as shown in Fig. 25.26. The Bourdon tube acting as a primary detector senses the pressure and converts the pressure into a displacement of its free end. The displacement of the free end moves the core of a linear variable differential transformer, (L.V.D.T.) which produces an output voltage which is proportional to the movement of the core, which is proportional to the displacement of the free end which in turn is proportional to the pressure. Thus, there are two stages of transduction, firstly the pressure is converted into a displacement

Table 25.2
Types of Electrical Transducers

Electrical parameter and class of transducer	*Principle of Operation*	*Typical applications*
	Passive transducers (externally powered)	
Resistance		
Potentiometer device	Positioning of the slider by an external force varies the resistance in a potentiometer or a bridge circuit.	Pressure, displacement.
Resistance strain gauge	Resistance of a wire or semiconductor is changed by elongation or compression due to externally applied stress.	Force, torque, displacement.
Pirani gauge or hot wire meter	Resistance of a heating element is varied by convection cooling of a stream of gas.	Gas flow, gas pressure.
Resistance thermometer	Resistance of pure metal wire with a large positive temperature co-efficient of resistance varies with temperature.	Temperature, radiant heat
Thermistor	Resistance of certian metal oxides with negative temperature coefficient of resistance varies with temperature.	Temperature, flow
Resistance hygeometer	Resistance of a conductive strip changes with moisture content.	Relative humidity.
Photoconductive cell	Resistance of the cell as a circuit element varies with incedent light.	Photosensitive relay.
Capacitance		
Variable capacitance pressure gauge	Distance between two parallel plates is varied by an externally applied force.	Displacement, pressure.
Capacitor microphone	Sound pressure varies the capacitance between a fixed plate and a movable diaphragm.	Speech, music, noise.
Dielectric gauge	Variation in capacitance by changes in the dielectric or dielectric constant.	Liquid level, thickness.
Inductance		
Magnetic circuit transducer	Self-inductance or mutual inductance of a.c. excited coil is varied by changes in the magnetic circuit.	Pressure, displacement.
Reluctance pick up	Reluctance of the magnetic circuits is varied by changing the position of the iron core of coil.	Pressure, displacement, vibrations, position.
Differential transformer	The differential voltage of two secondary windings of a transformer is varied by positioning the magnetic core through an externally applied force.	Pressure, force, displacement, position.

Electrical parameter and class of transducer	*Principle of Operation*	*Typical applications*
Eddy current gauge	Inductance of a coil is varied by the proximity of an eddy current plate.	Displacement, thickness.
Magnetostriction gauge	Magnetic properties are varied by pressure and stress.	Force, pressure, sound.
Voltage and Current		
Hall effect pickup	A potential difference is generated across a semiconductor plate (germanium) when magnetic flux interacts with an applied current.	Magnetic flux, current, power
Ionization chamber	Electron flow induced by ionization of gas due to radio-active radiation.	Particle counting, radiation.
Photoemissive cell	Electron emission due to incident radiation upon photoemissive surface.	Light and radiation.
Photomultiplier tube	Secondary electron emission due to incident radiation on photosensitive cathode.	Light and radiation, photosensitive relays.
Self-generating transducers (no external power)		
Thermocouple and thermopile	An emf is generated across the junction of two dissimilar metals or semiconductors when that junction is heated.	Temperature, heat flow, radiation.
Moving coil generator	Motion of a coil in a magnetic field generates a voltage.	Velocity, vibrations.
Piezoelectric pickup	An emf is generated when an external force is applied to certain crystalline materials, such as quartz.	Sound, vibrations, acceleration, pressure changes.
Photovoltaic	A voltage is generated in a semiconductor junction device when radiant energy stimulates the cell.	Light meter, solar cell

by Bourdon tube then the displacement, is converted into an analogous voltage by L.V.D.T. The Bourdon tube is called a **"Primary Transducer"** while the L.V.D.T. is called a **'Secondary Transducer'**.

Let us take the another example which is the case of measurement of a compressive force with the help of a load cell in conjunction with strain gauges as shown in Fig. 25.27. (Load cells and strain gauges are explained later in this chapter).

The load cell is a short column or a strut with resistance wire strain gauges bonded to it. The measurand, in this case, is a force and is applied to the column thereby producing strain. The force is first detected by the column and is converted into strain which is a mechanical displacement. The higher the force, the higher is the strain and thus the input signal (force) is converted into an analogous output (strain). This strain changes the resistance of the strain gauges. Thus we have an output which is a change in the value of resistance *i.e.*, electrical in form. Hence, in this case, it takes two processes to convert an input into an analogous output. The first process involves conversion of force into mechanical displacement which is done by the column,

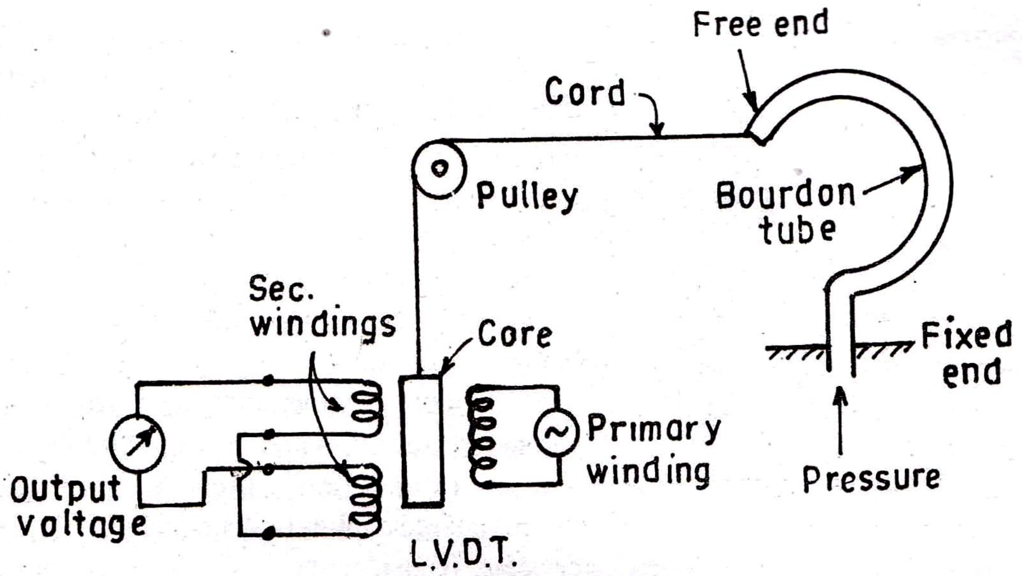


Fig. 25.26. Measurement of pressure using Bourdon tube an L.V.D.T. (Example of primary and Secondary transducers).

while the second process involves conversion of mechanical displacement into change of resistance which is done by strain gauges.

Thus we see that the force is *detected* by the column in the first stage and hence it is called a **Primary Transducer**. The output signal from the primary transducer is converted subsequently into a usable output by the strain gauges and therefore they are known as **Secondary Transducers.**

In most of measurement systems, there is a suitable working combination wherein a **Mechanical device** acts as a **primary detector transducer** and the **electrical device** acts as the **secondary transducer** with **mechanical displacement** serving as the **intermediate signal.**

25.8.3. Passive and Active Transducers.

Transducers may be classified according to whether they are *passive* or *active*

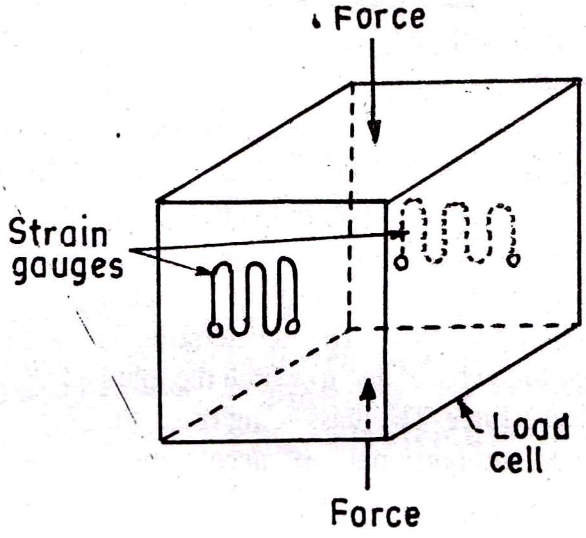


Fig. 25.27. Force measurement with load cell and strain gauges.

1. Passive Transducers. Passive transducers derive the power required for transduction from an auxiliary power source. They also derive part of the power required for conversion from the physical quantity under measurement. They are also known as *"externally powered transducers"* Typical examples of passive transducers are resistive, inductive and capacitive transducers.

A typical example of a passive transducer is a 'POT' which is used for measurement of displacement. A 'POT' is a resistive transducer powered by a source voltage e_i as shown in Fig. 25.28. This 'POT' is used for measurement of linear displacement x_i.

Suppose L is the total length of potentiometer whose total resistance R_t. The input displacement is x_i.

$\therefore$ Output voltage
$$e_0 = \frac{x_i}{L}\, e_i$$

or
$$x_i = \left(\frac{e_0}{e_i}\right) L$$

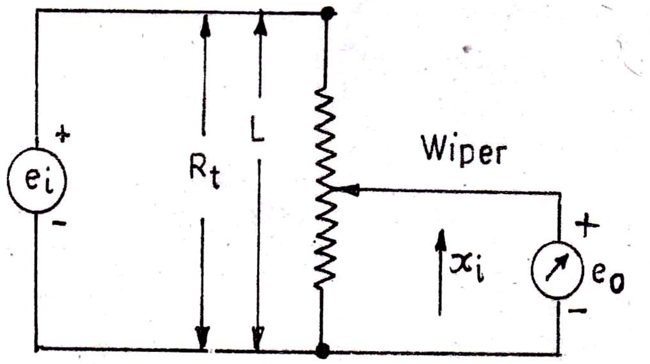


Fig. 25.28. Linear potentiometer (POT), a passive transducer.

In the absence of external power, the transducer cannot work and it hence is called a *passive transducer.*

2. Active Transducers. Active transducers are those which do not require an auxiliary power source to produce their output. They are also known as *self generating type* since they develop their own voltage or current output. The energy required for production of output signal is obtained from the physical quantity being measured.

Velocity, temperature, light intensity and force can be transduced with the help of active transducers. These transducers include tachogenerators, thermocouples, photovoltaic cells and piezoelectric crystals. Consider the case of a piezoelectric crystal used for measurement of acceleration as shown in Fig. 25.29. The crystal is sandwiched between two metallic electrodes, and the entire sandwich is fastened to a base which may be the floor of a rocket. A fixed mass is placed on the top of the sandwich.

The property of the piezo-electric crystals is that when a force is applied to them, they produce an output voltage. The mass exerts a certain force on account of acceleration on the crystal due to which a voltage is generated. The acceleration is applied to the base, due to which the mass produces a force. The mass being fixed, the force is proportional to acceleration. The voltage output is proportional force and hence is proportional to acceleration (the mass being fixed).

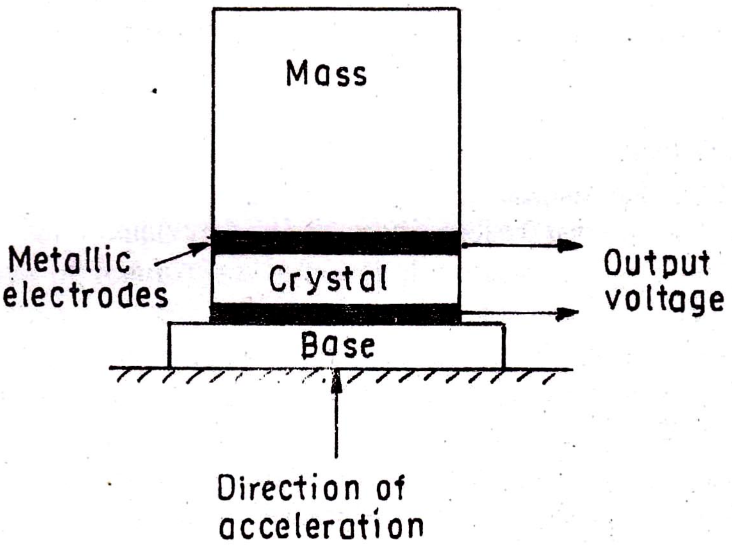


Fig. 25.29. Piezo-electric crystal measuring acceleration—an active transducer.

It should be noted from above that this transducer called *"accelerometer"* which converts acceleration into electrical voltage does not need any auxiliary power source to convert a physical phenomenon (acceleration in this case) to an electrical output (voltage in this case) and therefore is an *active transducer.*

25.8.4. Analog and Digital Transducers. The transducers can be classified on the basis of the output which may a continuous function of time or the output may be in discrete steps.

1. Analog Transducers. These transducers convert the input quantity into an analog output which is a continuous function of time. Thus a strain gauge, an L.V.D.T., a thermocouple or a thermistor may be called as *"Analog Transducers"* as they give an output which is a continuous function of time.

2. Digital Transducers. These transducers convert the input quantity into an electrical output which is in the form of pulses.

As the binary system uses only two symbols 0 and 1 it can be easily represented by opaque and transparent areas on a *glass scale* or non-conducting and conducting areas on a *metal scale.* A scale constructed to show the linear position on a movable object and having five digits is shown in Fig. 25.30. The complete binary number denoting position is obtained by scanning the pattern across the scale at a stationary index mark.

Glass scales can be read optically by means of a light source, an optical system and photocells. Metal scales are scanned by brushes making electrical contact with individual tracks.

The resolution depends upon the digits comprising the binary number and is 1/2n of full scale where n is the number of digits.

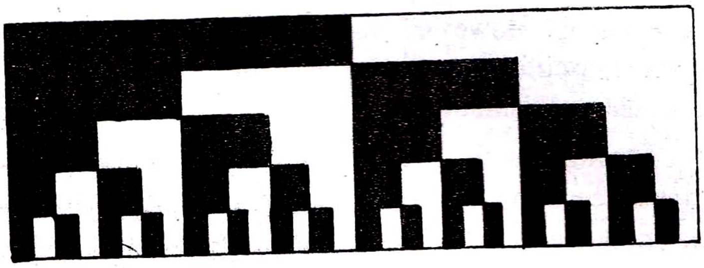


Fig. 25.30. 5-digit scale for digital indication of linear position of a movable object.

25.8.5. Transducers and Inverse Transducers. There is a strong association of control with measurement. The basic requirement for control of physical quantities such as position, speed, temperature, pressure and flow rate in an industrial plant is the ability to measure these quantities. The control action is only possible if the physical quantity can be measured. For example, in a position control system called *"servomechanism"*, it is desired to control the position of a shaft. This requires an accurate method for measurement of the shaft position in order that its position be accurately controlled. Further, if it is desired that the shaft be accelerated in a controlled manner, then the position measuring device must be able to measure shaft position for rapid changes *i.e.* the device must have a fast dynamic response.

Fig. 25.31 shows the block diagram of closed loop control system. The controlled (output) quantity is usually a non electrical quantity. The control action is through an input quantity that corresponds to the desired output (non electrical quantity). The input quantity called reference input is usually an electrical quantity. The controlled quantity is measured and converted into an analogous quantity by transducers which form the feedback loop. The loop input quantity (electrical in nature) is compared with the electrical quantity proportinal to the output in a *comparator*. In case, the two are not equal an error signal is produced. This error signal is amplified and applied to an *actuator* in the forward path, which corrects the output quantity till the output quantity reaches the desired level.

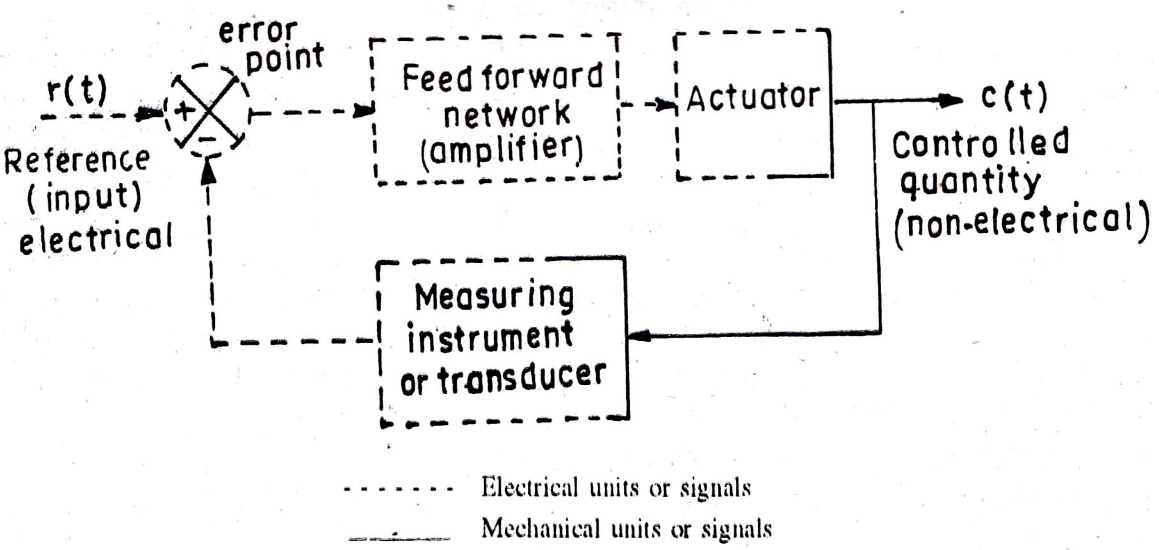


Fig. 25.31. Feedback control system for control of non-electrical quantities.

1. Transducers. A transducer can be broadly defined as a device which converts a non-electrical quantity into an electrical quantity.

2. Inverse Transducers. An *inverse transducer* is defined as a device which converts an electrical quantity into a non-electrical quantity. It is a precision actuator which has an electrical input and a low power non-electrical output. A piezoelectric crystal acts as an inverse transducer because when a voltage is applied across its surfaces, it changes its dimensions causing a mechanical displacement.

A current carrying coil moving in a magnetic field is also an inverse transducer because current carried by it is converted into a force which causes transational or rotational diaplcement. Many data indicating and recording devices are inverse transducers. An analog ammeter or voltmeter converts current into mechanical

THERMISTOR

Solution. The value of resistance in case the temperature is not to exceed 150°C can be calculated as under.

$$R_{150} = 10\,[1 + 0.00393\,(150 - 20)]$$
$$= 15.11\ \Omega.$$

Example 25.25. A temperature alarm unit with a time constant of 120 s is subjected to a sudden rise of temperature of 50°C because of fire. If an increase of 30°C is required to actuate the alarm, what will be the delay in sudden temperature increase ?

Solution. Assume the termometer be a first order system, the variation of indicated temperature θ, to a step input temperature θ_0 is,

$$\theta = \theta_0\,[1 - \exp\,(-\,t/\tau)]$$
$$30 = 50\,[1 - \exp\,(-\,t/120)]$$

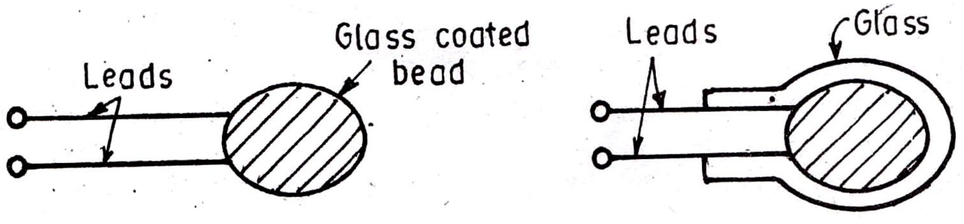
or $$t = 110\ \text{s}.$$

The alarm would be delayed by 110 s.

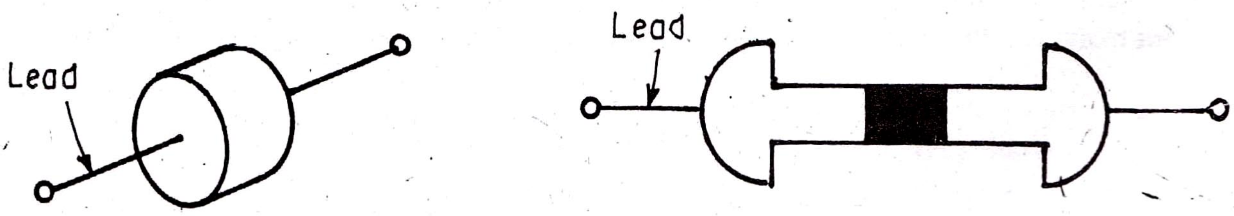
25.20. Thermistors : Thermistor is a contraction of a term **"thermal resistors"**. Thermistors are generally composed of semi-conductor materials. Although positive temperature co-efficient of units (which exhibit an increase in the value of resistance with increase in temperature) are available, most thermistors have a negative coefficient of temperature resistance *i.e.* their resistance decreases with increase of temperature. The negative temperature coefficient of resistance can be as large as several percent per degree celcius. This allows the thermistor circuits to detect very small changes in temperature which could not be observed with an RTD or a thermocouple. In some cases the resistance of thermistor at room temperature may decrease as much as 5 percent for each 1°C rise in temperature. This high sensitivity to temperature changes makes thermistors extremely useful for precision temperature measurements control and compensation.

Thermistors are widely used in applications which involve measurements in the range of – 60°C to 15°C. The resistance of thermistors ranges from 0.5 Ω to 0.75 MΩ. Thermistof is a highly sensitive device. The price to be paid off for the high sensitivity is in terms of linearity. The thermistor exhibits a highly non linear characteristic of resistance versus temperature.

25.20.1 Construction of Thermistors. Thermistors are composed of sintered mixture of metallic oxides such as manganese, nickel, cobalt, copper, iron and uranium. They are available in variety of sizes and shapes. The thermistors may be in the form of beads, rods and discs. Some of the commercial forms are shown in Fig. 25.65.



(*a*) Bead (*b*)Probe



(*c*) Disc (*d*) Rod

Fig. 25.65. Different forms of construction of thermistors.

A thermistor in the form of a bead is smallest in size and the bead may have a diameter of 0.015 mm to 1.25 mm. Beads may be sealed in the tips of solid glass rods to form probes which may be easier to mount than the beads. Glass probes have a diameter of about 2.5 mm and a length which varies from 6 mm to 50 mm. Discs are made by pressing material under high pressure into cylindrical flat shapes with diameters ranging from 2.5 mm to 25 mm.

25.20.2. Resistance-Temperature Characteristics of Thermistors. The mathematical expression for the relationship between the resistance of a thermistor and absolute temperature of thermistor is :

$$R_{T1} = R_{T2} \exp\left[\beta\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \qquad \text{...(25.76)}$$

where R_{T1} = resistance of the thermistor at absolute temperature T_1 ; °k,

R_{T2} = resistance of the thermistor at absolute temperature T_2 ; °k

and β = a constant depending upon the material of thermistor, typically 3500 to 4500 °k

The resistance temperature characteristics of a typical thermistor are given in Fig. 25.66. The resistance temperature characteristics of Fig. 25.66 show that a thermistor has a very high negative temperature co-efficient of resistance, making it an ideal **temperature transducer.**

Fig. 25.66 also shows the resistance-temperature characteristics of platinum which is a commonly used material for resistance thermometers. Let us compare the characteristics of the two materials. Between —100°C and 400°C, the thermistor changes its resistivity from 10^5 to 10^{-2} Ωm, a factor of 10^7, while platinum changes its resistivity by a factor of about 10 within the same temperature range. This explains the high sensitivity of thermistors for measurement of temperature.

The characteristics of thermistors are no doubt non-linear but a linear approximation of the resistance-temperature curve can be obtained over a small range of temperatures. Thus, for a limited range of temperature, the resistance of a thermistor varies as given by Eqn. 25.77.

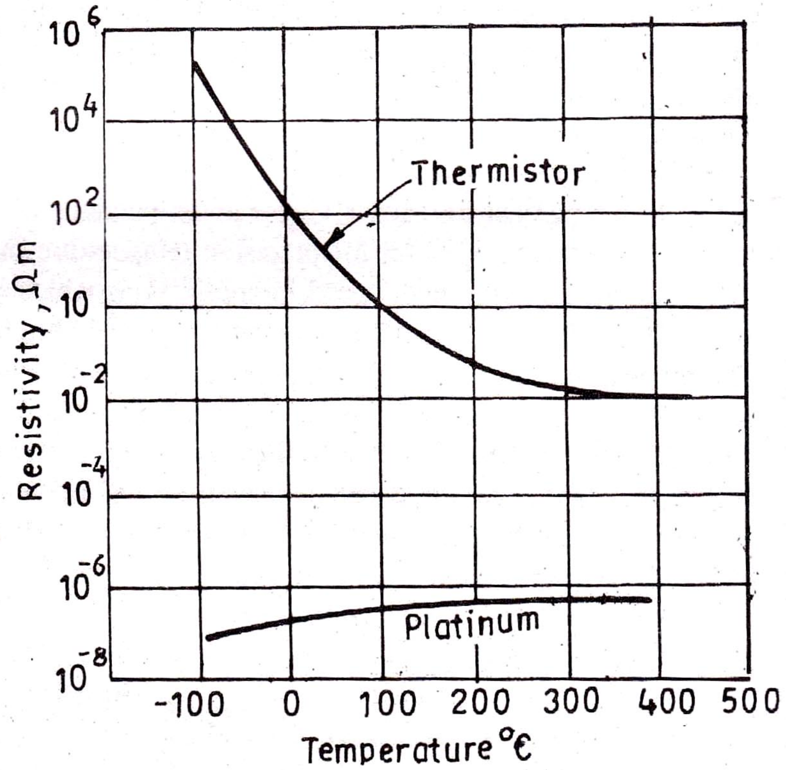


Fig. 25.66. Resistance-temperature characteristics of a typical thermistor and platinum.

$$R_\theta = R_{\theta_0}\,[1 + \alpha_{\theta_0}\,\Delta\theta] \qquad \text{...(25.77)}$$

A thermistor exhibits a negative resistance temperature co-efficient which is typically about 0.05/°C.

An individual thermistor curve can be closely approximated through the **Steinhart-Hart equation** :

$$\frac{1}{T} = A + B \log_e R + C (\log_e R)^3 \qquad \text{...(25.78)}$$

where T = temperature ; °k,

R = resistance of thermistor ; Ω,

A, B, C = curve fitting constants.

A, *B* and *C* are found by selecting three data points on the published data curve and solving the three simultaneous equations. When the data points are chosen to span no more than 100°C within the nominal centre of thermistors temperature range, this equation approaches a remarkable ± 0.2°C curve fit.

A simpler equation is :

$$T = \frac{B}{\log_e R - A} - C \qquad \text{...(25.79)}$$

where *A*, *B* and *C* are found by selecting three (*R*, *T*) data points and solving three resultant simultaneous equations. Eqn. 25.79 must be applied over a narrower temperature range in order to approach the accuracy achieved by Steinhart-Hart Equation. Another, relationship that can be conveniently used for resistance-temperature curve of thermistors is :

$$R_T = aR_o \exp\,(b/T) \qquad \text{...(25.80)}$$

where, R_T, R_o = resistance of thermistor at temperature T°k and ice point respectively.

25.20.3. Voltage-Current and Current-Time Characteristics of Thermistors. Three important characteristics of thermistor make them extremely useful in measurement and control applications. These are :

(*i*) the *resistance–temperature* characteristics,

(*ii*) the *voltage current* characteristics.

(*iii*) the *current–time* characteristics.

1. Resistance Temperature Characteristics. The resistance-temperature characteristics have already been described in Art. 25.20.2. The other two characteristics are described below.

2. Voltage – Current Characteristics. These characteristics are shown in Fig. 25.67. Fig. 25.67 shows that the voltage drop across a thermistor increases with increasing current until is reaches a peak value beyond which the voltage drop decreases as the current increases. In this portion of the curve, the thermistor exhibits a *negative resistance* characteristic. If a very small voltage is applied to the thermistor, the resulting small current does not produce sufficient heat to raise the temperature of the thermistor above ambient. Under this condition, Ohm's law is followed and the current is proportional to the applied voltage. Larger currents, at larger applied voltages, produce enough heat to raise the thermistor temperature above the ambient temperature and its resistance then decreases. As a result, more current is then drawn and the resistance decreases further. The current continues to increase until the heat dissipation of the thermistor equals the power supplied to it. Therefore, under any fixed ambient conditions, the resistance of a thermistor is largely a function of the power being dissipated within itself, provided that there is enough power available to raise its temperature above ambient. Under such operating conditions, the temperature of the thermistor may rise 100°C or 200°C and its resistance may drop to one-thousandth of its value at low current.

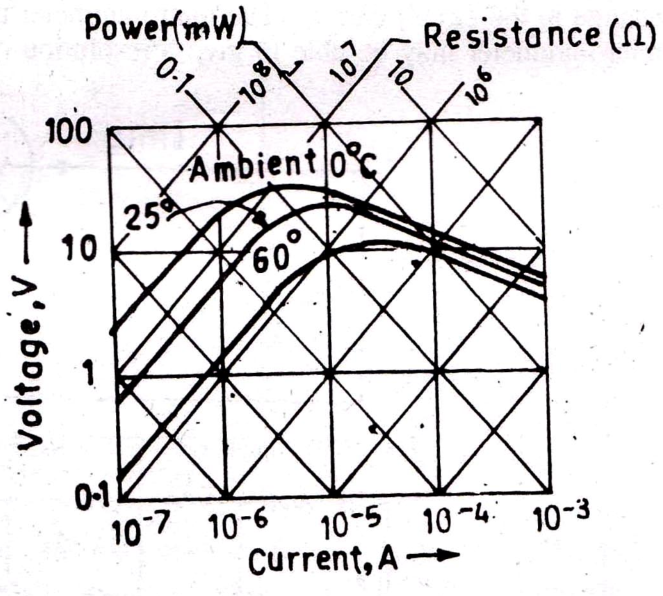


Fig. 25.67. Voltage-currents characteristics of thermistors.

This characteristic of *self-heat* provides an entirely new field of uses for the thermistor. In the self-heat state, the thermistor is sensitive to anything that changes the *rate* at which heat is conduced away from it. It can so be used to measure *flow, pressure, liquid level, composition of gases,* etc. If, on the other hand, the rate of heat removal is fixed, then the thermistor is sensitive to power input and can be used for *voltage* or *power-level* control.

3. Current Time Characteristics. The current-time characteristics shown in Fig. 25.68 indicate the time delay to reach maximum current as a function of the applied voltage. When the heating effect just described occurs in a thermistor network, a certain finite time is required for the thermistor to heat and the current to build up to a maximum steady-state value. This time, although fixed for a given set of circuit parameters, may easily be varied by changing the applied voltage or the series resistance of the circuit. This time-current effect provides a simple and accurate means of achieving time delays from milliseconds to many minutes.

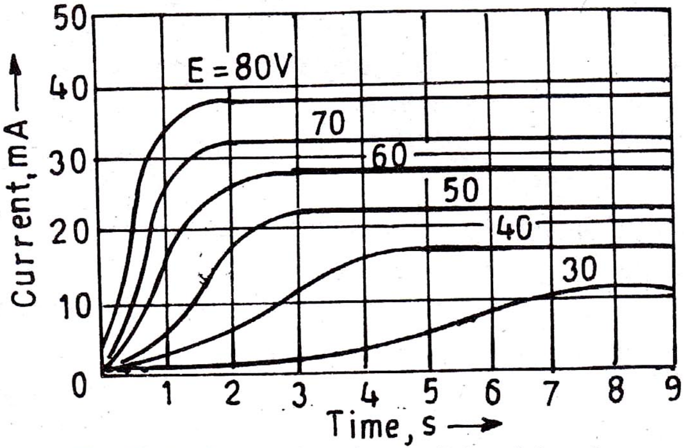


Fig. 25.68. Current time characteristics of thermistors.

25.20.4. Applications of Thermistors. Although major applications of thermistors are measurement and control of temperature, they may be used for a number of other applications. The various applications of thermistors are :

1. Measurement of Temperature : A thermistor produces a large change of resistance with a small change in the temperature being measured. This large sensitivity of thermistor provides good accuracy and resolution. A typical industrial-type thermistor with a 2000 Ω resistance at 25°C and a resistance temperature co-efficient of 3.9 percent per °C exhibits a change of 78 Ω per degree °C change is temperature. When this thermistor is connected in a simple series circuit consisting of a battery and micro-ammeter as shown in Fig. 25.69, any change in temperature causes a change in the resistance of thermistor and corresponding change in the circuit current. The micro-ammeter may be directly calibrated in terms of temperature. The micro-ammeter may be able to give a resolution of 0.1°C.

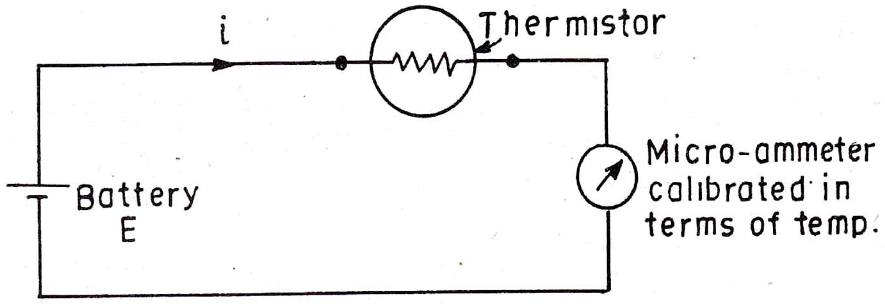


Fig. 25.69. Simple series circuit for measurement of temperature using a thermistor.

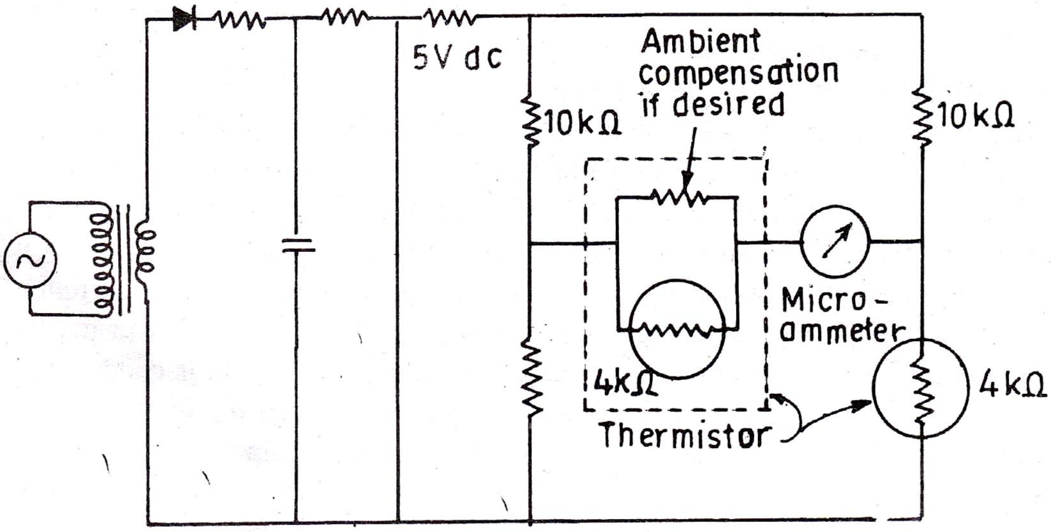


Fig. 25.70. Measurement of temperature using a thermistor and a bridge circuit for getting higher sensitivities.

The use of a bridge circuit as shown in Fig. 25.70 gives higher sensitivities. The 4 kΩ thermistor used will readily indicate as small changes as 0.005°C in temperature.

The high sensitivity together with high thermistor resistance which may about 100 kΩ, makes the thermistor ideal for *remote* measurement or control, as the changes in contact or transmission line resistances due to change in the ambient temperature have almost a negligible effect on the accuracy of measurement or control. For example a 150 m long transmission line made of copper when subjected to change of 25°C will affect the accuracy of measurement or control by approximately 0.05°C.

3. Control of Temperature. A simple temperature control circuit may be constructed by replacing the micro-ammeter shown in the typical thermistor temperatue control circuit of 25.70 with a relay. This is shown in the typical thermistor temperature control circuit of Fig. 25.71. It uses a 4 kΩ thermistor connected in an a.c. excited bridge. The unbalance voltage is fed to an a.c. amplifier whose output excites a relay coil. The relay contacts are used to control the current in the circuit which generates the heat. These circuits can be controlled to a precision of 0.00005°C.

Thermistor control systems are inherently sensitive, stable and fast acting and require relatively simple circuitry. The voltage output of the standard bridge circuit at 25°C is about 18 mV/°C using a 4 kΩ thermistor in the configuration of Fig. 25.70.

4. Temperature Compensation. Because thermistors have a negative temperature coefficient of resistance—opposite to the positive coefficient of most electrical conductors and semiconductors—they are widely used to compensate for the effects of temperature on both component and circuit performance. Disk-type thermistors are used for this purpose where the maximum temperature does not exceed 125°C. A properly selected thermistor, mounted against or near a circuit element, such as a copper meter coil, and experiencing the same ambient temperature changes, can be connected in such a way that the total circuit resistance is constant over a wide range of temperatures. This is shown in the curves of Fig. 25.72, which illustrates the effect of a compensation network.

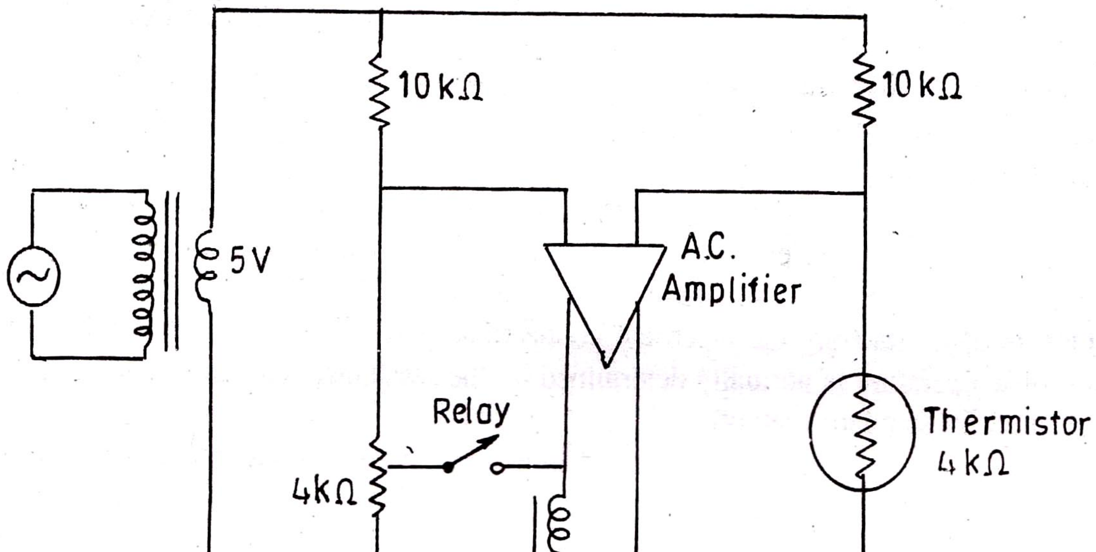


Fig. 25.71. Typical thermistor temperature control circuit.

The compensator consists of a thermistor, shunted by a resistor. The negative temperature coefficient of this combination equals the positive coefficient of the copper coil. The coil resistance of 5,000 Ω at 25°C, varies from approximately 4,500 Ω at 0°C to 5,700 Ω at 60°C, representing a change of about ± 12 per cent. With a single thermistor compensation network, this variation is reduced to about ± 15 Ω or ± $\frac{1}{4}$ per cent. With double or triple compensation networks, variations can be reduced even further.

THERMOCOUPLE

(*ii*) Resistance of thermistor at 25°C = 10,000 Ω.

$$\therefore \text{ Frequency of oscillations} = \frac{1}{2\pi \times 7500 \times 500 \times 10^{-12}} \text{ Hz} = 31.83 \text{ kHz.}$$

(*iii*) Resistance of thermistor at 30°C = 10,000 [1 – 0.05 (30 – 25)] = 7500 Ω.

$$\therefore \text{ Frequency of oscillations} = \frac{1}{2\pi \times 5700 \times 500 \times 10^{-12}} \text{ Hz} = 42.44 \text{ kHz.}$$

25.21. Thermocouples. The operation of thermocouples has been explained in Chapter 9 (see page 340). The emf produced in a thermocouple circuit is given by :

$$E = a\,(\Delta\theta) + b\,(\Delta\theta)^2 \qquad \text{(Eqn. 9.71 or page 340)}$$

where $\Delta\theta$ = difference in temperature betwen the hot thermocouple junction and the reference junction of the thermocouple ; °C,

and a, b = constants.

a is usually very large as compared with b and therefore emf thermocouple is $E \simeq a\,(\Delta\theta)$ or $\Delta\theta \simeq E/a$.

In a thermocouple temperature measuring circuit, the emf set up is measured by sending a current through a moving coil instrument, the deflection being directly proportional to the emf. Since emf is a function of temperature difference $\Delta\theta$, the instrument can be calibrated to read the temperature. The emf may also be measured by a potentiometer.

Fig. 25.74 shows a typical circuit of an iron constantan themocouple.

Since the thermo-electric emf depends upon the difference in temperature between the hot junction and the reference junction, the temperature of the latter should remain absolutely constant in order that the calibration holds good and there are no errors on account of change in ambient temperature. The temperature of the reference junction is controlled for this purpose. The reference junction temperature is usually 0°C. Thermocouples are used for measurement of temperature upto 1400°C. The common types of thermocouples are given in Table 25.7 together with useful temperature range. It should be mentioned here that the combination of metals be so chosen that a rise in temperature should always produce a linear rise in emf *i.e.* the value of 'b' (Eqn. 9.71) should be negligible.

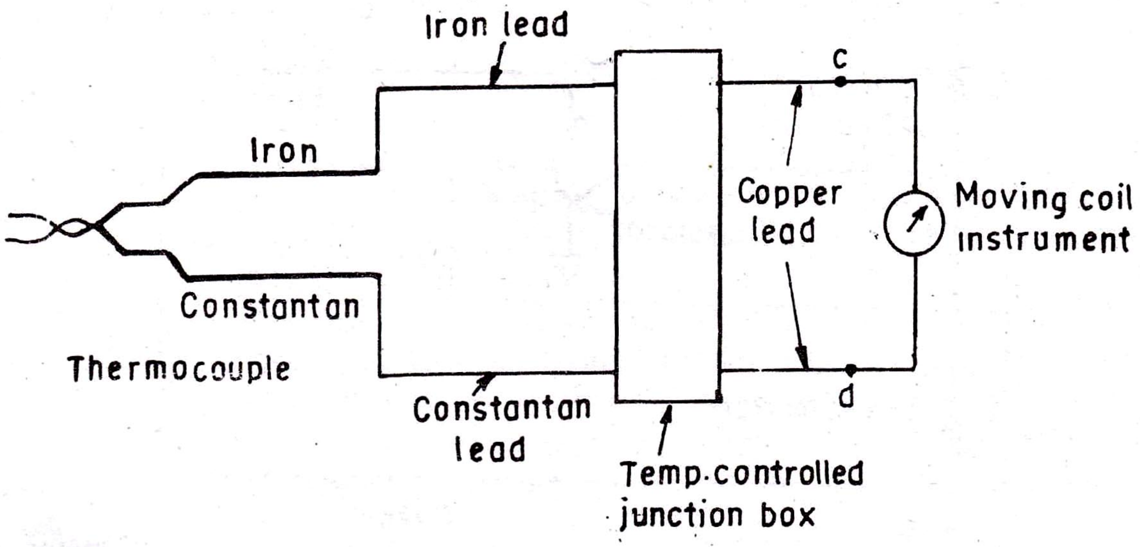


Fig. 25. . Measurement of temperature with thermocouple.

The emf of many thermocouples follows the quadratic relationship given by Eqn. 9.71. Fig. 25.75 shows curves for several combinations of metals, when one of the junctions, **reference junction,** is kept at a temperature 0°C and the temperature of the other junction, the **detecting junction,** is the variable temperature (*i.e.* the temperature to be measured).

It should be borne in mind that thermocouples are **active transducers** unlike RTD and thermistors which are **passive transducers.**

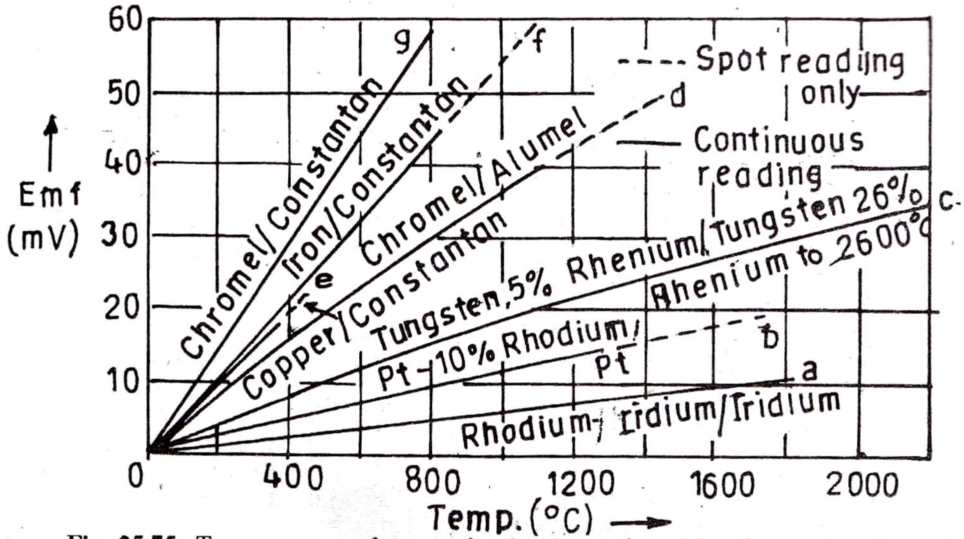


Fig. 25.75. Temperature emf curves for thermocouples with reference junction at 0°C.

25.21.1. Construction of Thermocouples. In industrial applications the choice of materials used to make up a thermocouple depends upon the temperature range to be measured, the kind of atmosphere to

Table 25.7. Industrial Thermocouples

	Base-metal couples				**Rare metal couples**		
Positive Wire	*Copper*	*Iron*	*Chromel 90% Cr. 10% Ni*	*Chromel*	*Platinum 90% rhodium 10%*	*Tungsten 95% rhenium 5%*	*Rhodium iridium*
Negative wire	*Constantan 40% Ni, 60% Cu approx.*	*Constantan*	*Alumel 94% Ni, 2% Al, + Si and Mn*	*Constantan*	*Platinum*	*Tungsten 72% rhenium 26%*	*iridium*
Temperature range (°C)	− 250 to + 400	− 200 to + 850	− 200 to + 1100	− 200 to + 850	0 to + 1400	0 to + 2600	0 to + 2100
Spot maximum (°C)	500	1100	1300	1100	1650		
Characteristics	Resists oxidising and reducing atmospheres up to 350°C. Requires protection from acid fumes.	Low cost. Corrodes in the presence of moisture oxygen, and sulphur-bearing gases. Suitable for reducing atmospheres.	Resistant to oxidising but not to reducing atmosphere. Susceptible to attack by carbon-bearing gases sulphur, and cyanide fumes.	Suitable for oxidising but not for reducing atmospheres, carbon-bearing gases and cyanide fumes. High emf.	Low emf. Good resistance to oxidising atmospheres, poor with reducing atmospheres. Calibration is affected by metallic vapours and contact with metallic oxides.	For use in non-oxidising atmospheres only. The 5% rhenium arm is brittle at room temperatures.	Similar to platinium rhodium-platinum.

has resulted from a temperature difference equal to the amount by which the reference junction is above 0°C. (This is because the thermocouples are calibrated with temperature of reference junction as 0°C).

Now $E_T = E_t + E_0$ where E_T is the total emf at temperature T, E_t is the emf on account of temperature difference between detecting (hot) and the reference junction and E_0 is the emf due to temperature of the reference junction being above 0°C. Since, there exists a non-linear relationship between the emf and the temperature, it is important that temperatures are determined by the above process rather than converting an emf to temperature and then adding it to ambient temperature.

25.21.5. Lead Compensation. In many applications it is desirable to place the reference junction at a point far removed from the measurement junction. The connecting wires from the thermocouple head to the meter are, therefore, very long and are usually not at the same temperature throughout their length. This causes errors, which can be avoided by using connecting wires made of the same material as the thermocouple wires. The implementation of this arrangement may not be possible in many cases due to cost and other consideration. Under these circumstances, materials are chosen such that the relationship between emf and temperature is the same or almost the same as that for thermocouple wires. These wires then called **Compensating Leads.**

25.21.6. Advantages and Disadvantages of Thermocouples

Advantages. 1. Thermocouples are cheaper than the resistance thermometers.

2. Thermocouples follow the temperature changes with a small time lag and as such are suitable for recording comparatively rapid changes in temperature.

Thermocouples are very convenient for measuring the temperature at one particular point in a piece of apparatus.

Disadvantages. 1. They have a lower accuracy and hence they cannot be used for precision work.

2. To ensure long life of thermocouples in their operating environments, they should be protected in an open or closed-end metal protecting tube or well. To prevent contamination of the thermo-couple, when precious metals like platimum or its alloys are being used, the protecting tube has to be made chemically inert and vacuum tight.

3. The thermocouple is placed remote from measuring devices. Connections are thus made by means of wires called extension wires. Maximum accuracy of measurement is assured only when compensating wires are of the same material as the thermocouple wires. The circuitry is, thus, very complex.

Example 25.30. Calculate the thermoelectric sensitivity of a device using bismuth and tellurium as the dissimilar metals. Estimate the maximum output voltage for a 100°C temperature difference at room temperature using one junction. The sensitivity of bismith is – 72 μV/°C and that of tellurium is 500 μV/°C.

Solution. Sensitivity of thermocouple = 500 – (– 72) = 572 μV/°C.

$\therefore$ Voltage output for a temperature difference of 100°C = $572 \times 10^{-6} \times 100 = 57.2$ mV.

Example 25.31. A chromel-alumel hot junction is connected to a potentiometer. This is at a temperature of 20°C and gives a reading of 27.07 mV. Determine the measured temperature assuming the thermocouple to conform to the values given in Fig. 25.75 which are based on reference junction at 0°C. The emf corresponding to a temperature of 20°C is 0.8 mV. Consult curves given in Fig. 25.74.

Solution. The measured emf is the algebraic sum of emfs at the hot and reference junctions.

$\therefore$ Required emf is $E_T = E_t + E_0 = 27.07 + 0.8 = 27.87$ mV.

Corresponding to this emf the temperature is 620°C.

Example 25.32. A thermocouple circuit uses a chromel-alumel thermocouple which gives an emf of 33.3 V when measuring a temperature of 800°C with reference temperature 0°C. The resistance of the meter coil, R_m is 50 Ω and a current of 0.1 mA gives full scale deflection. The resistance of junctions and leads, R_e, is 12 Ω. Calculate :

(*a*) Resistance of the series resistance if a temperature of 800°C is to give full scale deflection.

(*b*) the approximate error due to rise of 1 Ω in R_e.

(*c*) the approximate error due to a rise of 10°C in the copper coil of the meter. The resistance temperature co-efficient of coil is 0.00426/°C.

Solution. (*a*) Emf $E = i\,(R_m + R_s + R_e)$ or $33.3 \times 10^{-3} = 0.1 \times 10^{-3}\,(50 + R_s + 12)$ or series resistance $R_s = 271\ \Omega$.

(*b*) Current in the circuit with increased resistance $= \dfrac{33.3 \times 10^{-3}}{(50 + 271 + 1 + 12)} = 0.0997$ mA.

$\therefore$ Approximate error in temperature $= \dfrac{0.0997 - 0.1}{0.1} \times 800 = -\,2.4$°C.

(*c*) Change in resistance of coil with a temperature increase of 10°C $= 50 \times 0.00426 \times 10 = 2.13\ \Omega$.

Current in the circuit with increase resistance of coil $= \dfrac{33.33 \times 10^{-3}}{50 + 2.13 + 271 + 12}$ A $= 0.09936$ mA.

$\therefore$ Approximate error in temperature $= \dfrac{0.09936 - 0.1}{0.1} \times 800 = -\,5.12$°C.

Example 25.33. The simple potentiometer circuit of Fig. 25.80 is to work from a platinum/platinum rhodium 10 per cent thermocouple and have a measuring range of 900°C – 1200°C.

The scale readings are to be correct for a reference junction temperature of 20°C. The slide wire resistance is 2.5 Ω and the circuit is standardized to give 1.08V between *A* and *B*. Find the values of resistance R_1 and R_2. Data from thermocouple tables for platinum/platinum-rhodium 10 per cent with 0°C reference junction temperature is :

emf for 20°C = 0.112 mV,
emf for 900°C = 8.446 mV,
emf for 1200 ° = 11.946 mV.

Solution. The resultant emfs at the detecting junction temperature of θ_1 and reference junction temperature of $\theta_2 = 20$ °C, are

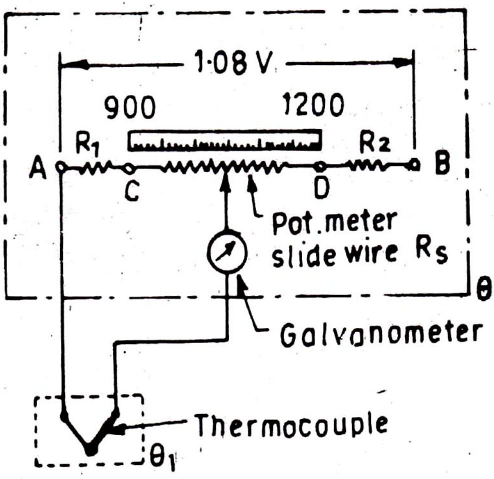


Fig. 25.80. Diagram of Example 25.33.

at 900 °C, $E_1 = 8.446 - 0.112 = 8.334$ mA
and at 1200°°C $E_2 = 11.946 - 0.112 = 11.834$ mV.

With the same standardising current, the emfs are :

$$E_{ac} = \frac{1.08}{R_1 + 2.5 + R_2} \times R_1 = 8.334 \times 10^{-3} \qquad \text{...}(i)$$

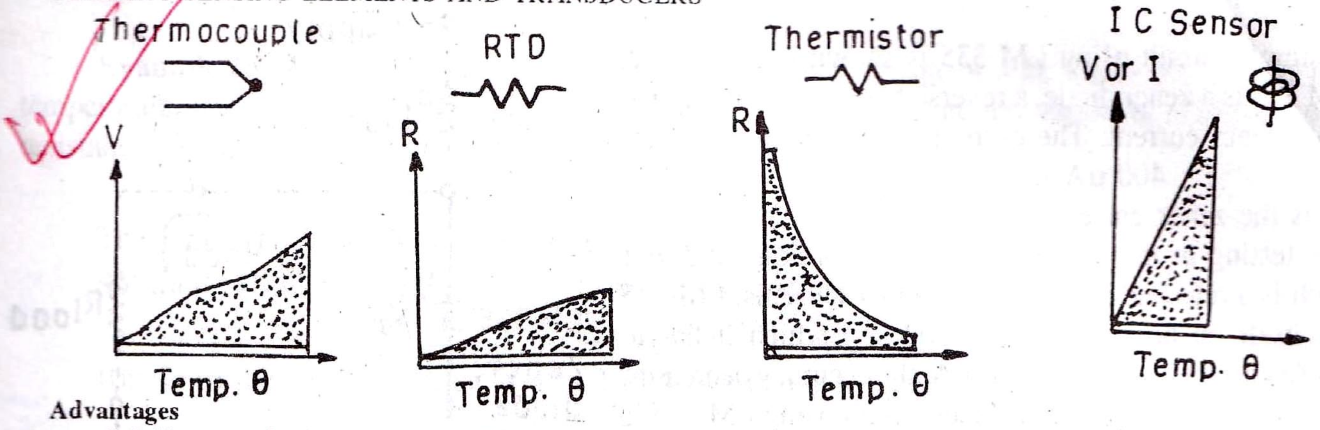
and

$$E_{ad} = \frac{1.08}{R_1 + 2.5 + R_2} \times (R_1 + 2.5) = 11.834 \times 10^{-3} \qquad \text{...}(ii)$$

Dividing (*ii*) by (*i*), we have $\dfrac{R_1 + 2.5}{R_1} = \dfrac{11.834}{8.334}$ or $R_1 = 5.95\ \Omega$

Substituting the value of R_1 in (*i*), we get $R_2 = 762.6\ \Omega$.

25.22. Integrated circuit Temperature Transducers. Each of the three temperature transducers described earlier, *i.e.* RTD, thermistors and thermocouples have some significant limitations. For example, thermocouples have a low output signal which varies non-linearly with temperature. Also they need some form of reference compensation with regards to ice point, RTDs are more linear than thermocouples but the changes in their resistance is very small even for large change in input temperatures *i.e.* they have low sensitivity. The thermistors have a large change in resistance with temperature and thus have a high sensitivity. However, they exhibit a highly non linear resistance-temperature characteristics. Their typical properties are shown in 25.81.



Advantages	* Self-powered * Simple * Rugged * Inexpensive * Wide variety * Wide temperature range	* Most stable * Most accurate * More linear than thermocouple	* High output * Fast * Two-wire ohms measurement	* Most linear * Highest output * Inexpensive
Disadvantages	* Non-linear * Low voltage * Reference required * Lest stable	* Expensive * Current source required * Small ΔR * Low absolute resistance resistance * Self-heating	* Non-linear * Limited temperature * Fragile * Current source required * Self-heating	* 0 < 200°C * Power supply required * Slow * Self-heating * Limited configuration

Fig. 25.81. Properties of temperature transducers.

For each of these transducers, electronic compensation circuits have to be used in order to overcome their shortcomings. Also, additional circuitry may be needed to increase their voltage or current outputs. Usually, this additional electronics circuitry takes the form of monolithic integrated circuits. Thus, it requires to combine the temperature sensing element with signal conditioning electronics to produce single monolithic integrated circuit package.

Three integrated circuit (IC) package are described in this section. They are :

(*i*) LM 335 – it provides an output of 10 mV/°k.

(*ii*) LM 34 – it provides an output of 10 mV/°F.

(*iii*) AD 592 – it provides a current output of 1 μA/°k.

1. LM 335 Series. The LM 335 is a temperature sensitive zener diode, which when reverse biased into its breakdown region, gives an output of :

$$V_z = \frac{10}{T}\,\theta \quad \text{mV} \qquad ...(25.81)$$

where

T = temperature ; °k

θ = temperature ; °C.

The size of degree kelvin and degree celsius are the same, and therefore there is 273° offset Hence Eqn. 25.81 can be written as :

$$V_z = 2.73 \times 10^3 + 10\theta \text{ mV} \qquad ...(25.82)$$

The three temperature ranges available are listed in Table 25.8. Notice that none of these ranges come closer to the temperature range of thermocouples or RTDs. This is inherent in the silicon material of integrated circuit.

Table 25.8. LM/135/235/2335 Temperature Ranges

Device	*Range (°C)*	*Use*
LM 135	– 55 to + 150	Defence
LM 235	– 45 to + 125	Industrial
LM 335	– 45 to + 100	Commercial