method, determine graphically the value and direction of the resultant force with respect to the 200 N force.

1.9 Two forces of 28 N and 170 N act at right angles to each other. What is the resultant value of force being exerted?

1.10 Two forces 90° apart and each of 35 N act outwards at a point. Find the resultant force and the angle at which it acts.

1.11 Using the polygon method, find graphically the resultant of the following three forces, acting at 120° from each other at a single point:

$F_1 = 180$ N; $F_2 = 400$ N; $F_3 = 25$ N

1.12 With the aid of trigonometry, solve the missing components in the right-angled triangles listed below:

- hypotenuse 3.4 m; one angle 36.4°—find the other two sides
- angle 44°; adjacent side 26.8 N—find the other two sides
- adjacent side 285 m; opposite side 68 m—find all angles.

1.13 Using a zero-reference axis in the conventional position, find the rectangular components for 240 V at the following angles:

0°, 60°, 93°, 175°, 265°, 340°

1.14 Using the rectangular component method, find the resultant value of the following three forces:

$F_1 = 280$ N at 15°; $F_2 = 130$ N at 235°; $F_3 = 300$ N at 110°

1.15 If a steering wheel on a car requires a force of 15 N to turn it, what force would be required to turn the wheel if its diameter was reduced from 450 to 300 mm?

1.16 A 5 kW motor rotates at 960 r/min on full load.

(a) What torque is being exerted?

(b) If the motor has a pulley of 200 mm diameter, what force is being exerted at the circumference of the pulley?

1.17 What would be the efficiency of the motor in problem 1.16 if the input power was 5.3 kW?

1.18 Plot the graph using the figures in Table 1.9.

(a) Is this a linear graph?

(b) What is the spring extension at a force of 35 N?

(c) Are all results accurate?

1.19 A generator on test gave the results shown in Table 1.10.

(a) Plot a curve of these results and state whether it is a linear or non-linear curve.

(b) Are all results accurate?

(c) What is the maximum possible current?

1.20 A 50 kg body hangs at rest from a rope wrapped around a pulley 150 mm in diameter. What is the torque about the axis of the pulley?

1.21 What is the angular speed of each of the three hands of a twelve-hour clock?

1.22 An electric motor running at 1200 r.p.m. is supplying a torque of 5 N m. What power is the motor consuming from the mains at 78 per cent efficiency?

1.23 A 5 kW motor has an operating efficiency of 71 per cent. What is the input power requirement?

1.24 A 300 kg weight is lifted with a block and tackle to a height of 4 m in 1 minute and 30 seconds.

(a) Neglecting friction, calculate the power used.

(b) What is the efficiency if the actual power used is 24 W?

1.25 The sides of a right-angled triangle are in the ratio 9:12:15. Calculate the values of the other two angles.

1.26 In a right-angled triangle, the adjacent sides are 11 and 27 units long. Calculate the values of the other two angles.

1.27 Draw the graph of the equation $y = x^2 + 3$ for the values of x from –4 to +4. On the same axes, for the same values of x, draw a graph of $y = x^2 - 3$.

1.28 Two vectors of 10 N and 5 N respectively act on a point at an angle of 60° to each other. Find the value of the resultant force. If the angle was reduced to 45°, what would be the new value of the resultant force?

Table 1.9

Forces in newtons	0	4	8.5	13.5	19	26	30	32	39	45
Spring extension in millimetres	0	6	11	16.5	24	32.5	38	41	33	57

Table 1.10

Load in amperes	0	10	20	25	30	35	40	42	43	40	30	27
Volts		45	44	33	41.5	39.5	37	32	28	20	11	2	0

Chapter 2

Fundamentals of electricity

2.1 INTRODUCTION

Electrical energy is an accepted fact of life but little thought is given to the time and effort put in by early scientists to develop it to the standard we accept today.

Electrical energy has been a subject of experimentation and perseverance for centuries.

It must be understood that many experimenters were working simultaneously and often in concert. While some names have been recognised and given credit for either discoveries or developments, many names have been either ignored or forgotten.

The equipment used was primitive and limited in scope. Much of the time it was incapable of doing what was wanted by the experimenter. To illustrate this point, people tend to think of the transistor as a modern 'invention'. It is not appreciated that it was first proposed as a concept in the late 1800s. Then there was no equipment capable of making one for experimentation purposes. It was only with later developments and more modern techniques and equipment that a transistor could be made at all.

2.2 HISTORICAL PERSPECTIVE

The following are only a few of the names of people who have given the modern world such a widely used energy source. The list is of necessity short and many notable experimenters are omitted. The list is by year of birth in an attempt to put them and the progress of their work in historical order.

William Gilbert 1544–1603

Gilbert experimented with iron ore and its inherent magnetic properties. He wrote a lengthy treatise in Latin called (in brief) 'The Magnet' in 1603. It was not published in English until 1900.

Gilbert proposed a theory that the Earth was a giant magnet and that all materials were either 'electrics' or 'non-electrics'. Today we say all materials are either conductors or insulators. The theory was correct but his ideas of conductors and non-conductors were the reverse of the correct interpretation.

To put this man's version of magnetism into perspective, it has to be appreciated that it had not long been proved and accepted that the world was round and not flat. He was a physician and was often asked to entertain the court of Queen Elizabeth 1 of England with his 'parlour tricks' on electrostatics.

Stephen Gray 1697–1736

Gray corrected Gilbert by defining conducting materials and non-conducting materials as they are known today.

Benjamin Franklin 1706–1790

Franklin developed the concept of positive and negative charges. For his experiments he used a kite to 'bleed off' large electrical charges from clouds in stormy weather. He took suitable precautions when doing so. Some other experimenters did not and this led to a number of fatalities.

His experiments led to a mechanical device being developed to produce large charges of static electricity. The present-day version of this machine is called a Wimshurst machine.

Charles Coulomb 1736–1806

Coulomb was a mechanical engineer who developed instruments for measuring quantities of electricity, which could now be quantified and compared with other experimental results.

Luigi Galvani 1737–1798

Galvani developed the concept of dynamic electricity.

Aliesandro Volta 1745–1851

Volta developed the concept of current flow and corrected Galvani's ideas on dynamic electricity. He produced the voltaic pile and later the voltaic cell for continuous current flow. The principle behind both was that of placing two dissimilar metals in a conducting solution.

André Ampère 1775–1836

Ampère showed that parallel conductors carrying a current could attract or repel each other. He introduced the solenoid to the electrical world, and developed the solenoid to the electromagnet stage.

Hans Oersted 1777–1851

Oersted developed the concept of an electric current flow creating a magnetic effect around a conductor. His work was enhanced by Ampère and Faraday.

Georg Ohm 1789–1854

Ohm proposed and published the theory 'The Galvanic Circuit Mathematically Considered'. Ridiculed at first, it was later proved correct and is now known as Ohm's law. Ohm also worked on the theory of resistance of conductors and how to calculate values of resistance. This was developed from work by Henry Cavendish (1771–1810).

Michael Faraday 1791–1867

Faraday was not the father of electromagnetism as often claimed, but he considerably advanced knowledge of electromagnetism. He discovered the concept of induction, where a conductor in moving through a magnetic field has electricity induced in it.

2.3 STRUCTURE OF MATTER

Everything around us occupies space and has mass. All matter—whether solid, liquid, or gas—is built up of numbers of small and distinct particles called molecules. The available data suggest that these particles can be broken down into something like 100 different elementary substances.

By combining these elementary particles in various proportions, all the different materials in the world can be formed. These elementary substances are called elements.

2.3.1 Molecules

The smallest particle into which any one particular material can be divided without changing the characteristics of that matter is called a molecule of that material. The molecules of various substances are different from each other, but all molecules of the same substance are similar. Dividing a molecule causes it to change its characteristics and exhibit those of a different type of material. For example, water is composed of two parts of hydrogen and one part of oxygen. A molecule of water exhibits all the

characteristics of water, just as though it were a litre of water instead of a very small particle. Subdividing a molecule of water reduces it to hydrogen and oxygen, each with completely different characteristics from those of water.

2.3.2 Elements

Subdividing the water molecule produces two different materials called elements. In this example, the particle of water is broken down into two gases, each of which is an element. The smallest part of an element is called an atom.

2.3.3 Atoms

The atom itself can be further subdivided into smaller parts that no longer have the properties of the element that they make up. These parts consist of electrical charges and are common to all elements. They are relatively unstable in the sense that they are constantly trying to cancel each other.

An atom has never been seen directly by the human eye, but certain similarities between different elements indicate similarities in their structure. A mental concept called a model has gradually been developed to indicate the structure of an atom. The most adequate theories of atomic structure are mathematical, but a useful model is given by the orbiting electron picture of the atom shown in Figure 2.1(a). Although electrons are shown here in only a two-dimensional picture, they are assumed to be orbiting in a three-dimensional shell totally enclosing the nucleus of the atoms as shown in Figure 2.1(b).

The nucleus contains protons, which are positively charged, and it may also contain a number of neutrons, which effectively have no charge. In orbit around the nucleus are electrons, which have a negative charge. Under normal conditions the number of electrons and the number of protons are equal.

It is assumed that the attraction between the positively charged nucleus and the negatively charged electrons provides the force necessary to keep the electrons adjacent to the nucleus, while the motion keeps the electrons from plunging into the nucleus. In any particular atom, the actual number of positive charges is equal to the atomic number of the element. The actual number of neutrons in the nucleus is not necessarily equal to the number of protons or electrons. At the end of this book in the appendix section is a list of the elements. The element number indicates the number of protons and the number of electrons in the atom of that element. To find the number of neutrons in the nucleus, the number of the element must be subtracted from the atomic weight as an integer.

For example, copper has the atomic number 29 and an atomic weight of 63. This means that an atom of copper holds 29 electrons and $(63 - 29) = 34$ neutrons in the nucleus, together with 29 protons. Similarly, aluminium, with an atomic number of 13 and an atomic weight of 27, has 13 electrons in orbit around the nucleus and 13 protons and 14 neutrons $(27 - 13)$ in the nucleus. The roughly equal numbers of protons and electrons ensure electrical neutrality, while the number and arrangement of electrons around the nucleus play a part in determining the properties of an atom.

Orbits are sometimes referred to as energy levels and any electron that changes its orbit must gain or lose energy. This energy change affects the atom as a whole and causes it to behave in a different manner to normal. The electron orbits are divided into shells that can be further subdivided into sub-shells. In Table 2.1 there are five shells listed, showing the number of electrons required to fill each.

Each stable combination of electrons and protons makes one particular type of atom. In Figure 2.1(a), the K shell is filled and the third electron is in the L shell, which is capable of holding 7 more electrons. Because the atom has 3 electrons, it also has 3 protons and has an element number of 3.

Table 2.1 • Grouping of electron orbits

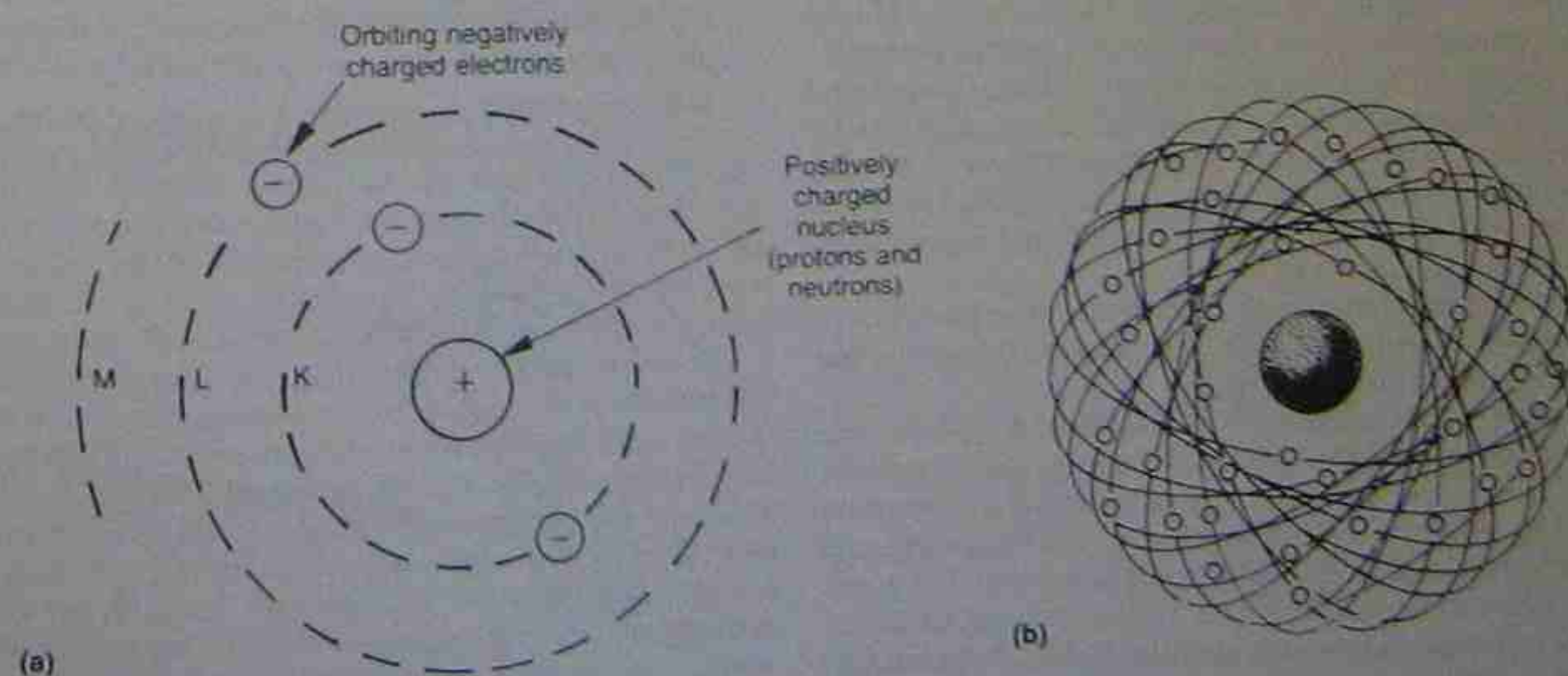| Shell or ring	1	2	3	4	5
Number of electrons	2	8	18	32	32
Designation	K	L	M	N	O

inner ring

Figure 2.1 • Model of atomic structure

number of shells... The distribution of electrons in the shells also determines an atom's electrical stability. Of special importance is the number of electrons in the shell farthest from the nucleus. Normally this outermost shell requires 8 electrons for stability (except where there is only one ring). The outer shell is often called the valency ring and the valency expressed as a number indicates the ease with which electrons can be removed from the valency shell. Copper has an atomic number of 29 i.e. 29 protons in the nucleus balanced by 29 orbiting electrons. The K shell is filled with 2 electrons, the L shell with 8 electrons, and the M shell with 18 electrons. The last electron fits into the N shell and, because of 'shielding' from the nucleus, is fairly easily removed and attached to the other atoms.

Sulphur, on the other hand, with an atomic number of 16, has 2 electrons in the K shell, 8 in the L and 6 in the M ring. With this greater number, higher electrical forces are required to shift electrons from a sulphur atom. For these reasons, copper is said to be a good conductor of electrons and sulphur a poor conductor.

2.3.4   Ionisation

Once an electron has been removed from a copper atom, the atom is no longer electrically neutral. It has 28 electrons and 29 protons and this means there is a net positive charge of 1 unit. On the other hand, the addition of an electron in the outer orbit will give a net negative charge of 1 unit. The process by which an originally neutral atom becomes charged by the removal of electrons is called ionisation and the atom itself becomes an ion. In order to provide a conducting path for electrical charges it is essential that there are electrons and ions.

Atoms in solid conductors are fixed in a regular arrangement characteristic of the conductor material, and are unable to move about. A current flow through a solid is actually brought about by the electrons attaching themselves first to one atom and then to another as they move towards the positive polarity of the applied potential.

Gas atoms, while structurally similar to solid atoms are, by the very nature of a gas, free to move about as molecules of gas in a random fashion. Owing to their movement they are able to gain and lose energy. If a potential difference is applied to a gas, the molecules are placed under an electrical stress, and electrons may receive sufficient energy to leave the nucleus and migrate towards the electrode of positive polarity. Such an atom, deficient by one electron, has a net positive charge and, as in a solid, is also called a positive ion. Because the positive ion is still part of a gas, it is free to move towards the supply electrode of negative polarity.

When the positive ions recombine with the electrons to form neutral atoms, the ionisation energy acquired by the atoms is released as radiation.

Whether this radiation is visible to the human eye depends on the nature of the gas and the pressure under which it is operating. With careful selection of gases and operating pressures, suitable radiation can be created and used to advantage in electrical appliances such as fluorescent tubes and advertising signs. In the first case radiation is used to cause a powder lining the inside of the tube to fluoresce, while in the second case the actual radiation is

emitted directly as light. While the gas in the tube is ionised, electrons flow one way, ionised atoms the other, and recombinations of ions and electrons cause radiation to be emitted continuously. If the power source is removed from the gas, the electrons and positive ions recombine to form neutral atoms. This recombination takes approximately one ten-millionth of a second for some gases, while for other gases such as those derived from metals, the time may be as long as one-thousandth of a second.

Ionisation in a liquid is somewhat similar to that of a gas. Ions are created with both positive and negative charges and these progress through the liquid, causing a current flow. The effects are different to those created in a gas and are discussed in greater detail in section 2.13.

2.4   STATIC ELECTRICITY

2.4.1   Production of an electrical charge

The ancient Greeks observed that amber, when rubbed with cloth, attracted light bodies. Dr Gilbert, an English physicist, published a book in 1603 in which he revealed that resin, sulphur and other materials behaved in a similar way. The Greek word elektron (amber) was used to name this phenomenon and it is from this word that the present term electricity is derived.

It is found that glass rubbed with silk, sealing wax and flannel, and volcanite with fur, seem to behave in a similar way to the amber originally used. The external agent which is the cause of this action is termed electricity (fig. 2.2). An electrified body is said to be 'charged' with electricity.

The following experiments help to explain something of the charges of electricity on rods of glass and ebonite.

1. If an ebonite rod which has been rubbed with fur or flannel is suspended by a dry silk thread, and a second, similarly rubbed ebonite rod is brought near the first, the suspended rod will move away from the second rod and is said to be repelled (fig. 2.3(a)). A glass rod rubbed with silk will attract the suspended ebonite rod (fig. 2.3(b)).

2. If an electrified glass rod is suspended from the thread, a second glass rod first rubbed with silk will repel it when brought near, while the ebonite rod previously rubbed with fur will attract it.

3. If the suspended electrified rod is replaced by an uncharged rod, it will be attracted to either the
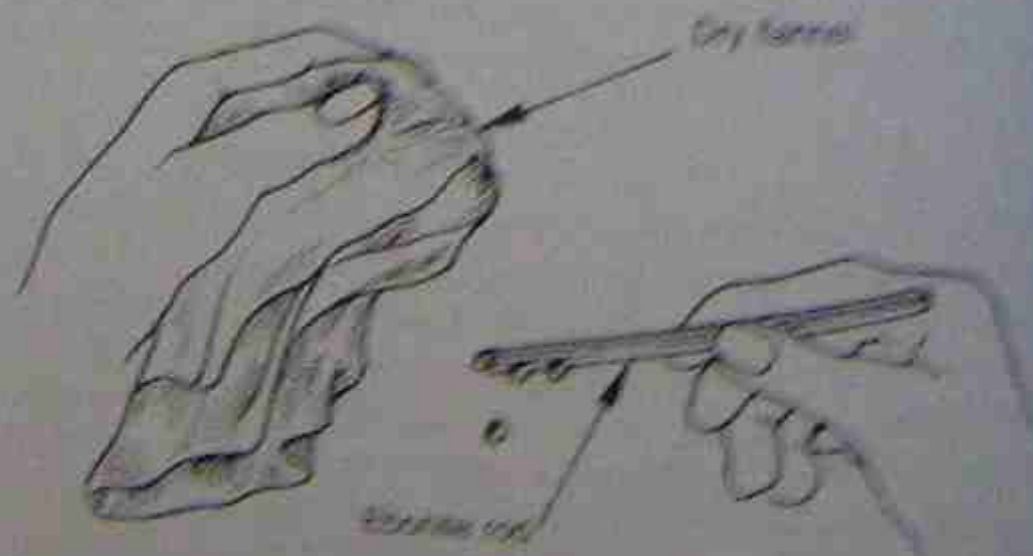

Figure 2.2 • Electrification by friction

electrified glass or the electrified ebonite rod when either is brought near it.

From these experiments it appears that there are two kinds of electrification.

The state of electrification exhibited by glass or similar materials when rubbed with silk is called positive i.e. the glass is positively charged, and the state of electrification of ebonite or resinous materials when rubbed with fur is negative i.e. the ebonite is negatively charged. Several charges of the kind indicated by the electrification of the rods are termed static electrical charges.

The friction of fur on the ebonite rod causes a transfer of electrons from the fur to the surface atoms of the rod. The rod is then negatively charged because it now contains a larger number of electrons than its normal number. In the presence of the fur the rod becomes positively charged because it has lost electrons. The electrons acquired or the neutral state from the outermost electron orbits of the atoms and leave the atoms temporarily ionised, in an attempt to return to the electrically neutral, stable state. The zero nett attracting force on electrons in orbit around adjacent atoms. The charges on the rod remain there (static) because the rods used are very poor conductors of electrical charges.
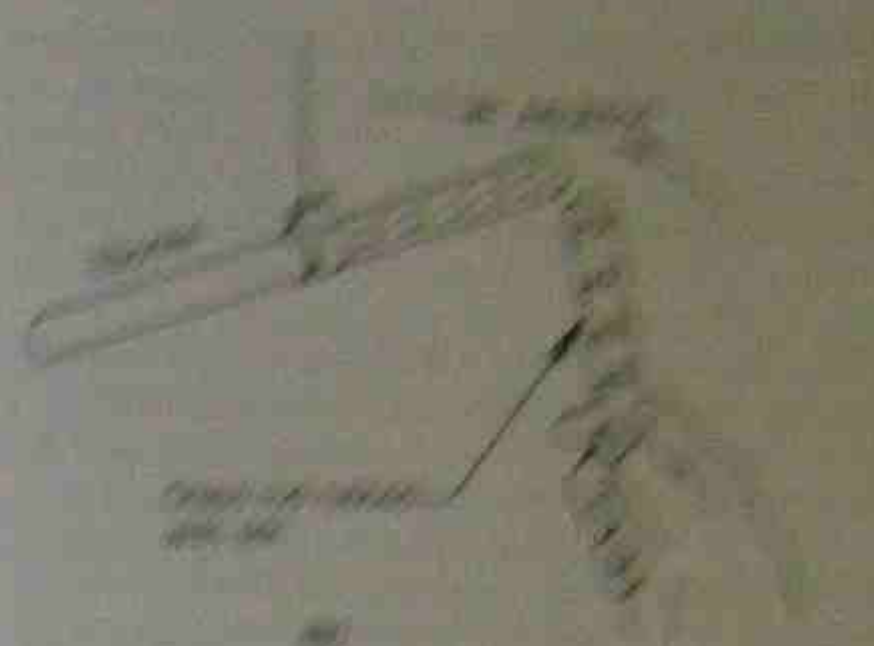
Conclusions

Like charges repel each other. Unlike charges attract. A rod with no charge is attracted by both positively and negatively charged rods.

2.4.2   Electrical potential

When two different substances are rubbed together, the electrons from the surface of one are transferred to the surface of the other. Experimentation has proved that the number of electrons transferred depends upon the substances used. That is, the intensity of the electric charge is different for different combinations of substances.

The unbalancing of the electric forces due to electrifying creates a strain, or electric pressure, which tends to restore the balance. The greater the intensity of the charge, the greater is the electric pressure, and therefore the greater is the potential ability to cause a flow of electrons and restore the balance. An electrified body is said to possess an electric potential, and the difference in electric pressure between two bodies is referred to as the potential difference (p.d.).

Figure 2.3 • Attraction and repulsion between charged bodies

The flow of negative charges is maintained from one body to another when the bodies are brought into contact. This flow from one body occurs because the potential between the two bodies is adjusted to zero. The flow of electrons is dependent on the electric potential i.e. a constant flow of electrons, a constant difference must be provided. The electron flow from one body to another can be maintained as long as a potential difference can be provided. Two electrostatic effects due to a constant potential difference are provided in section 2.4.4.

2.4.3   Movement of electrons

Figure 2.4(a) illustrates a neutral rod, a particle rod. The neutral body has equal quantities of charge and electrons. This positively charged atom has a scarcity of electrons. The p.d. between them is several volts.

If these bodies are connected by a conducting medium, as in figure 2.4(b), electrons will migrate away from the neutral body to the point of the electrons that positively charged rod, until they share the same charge.
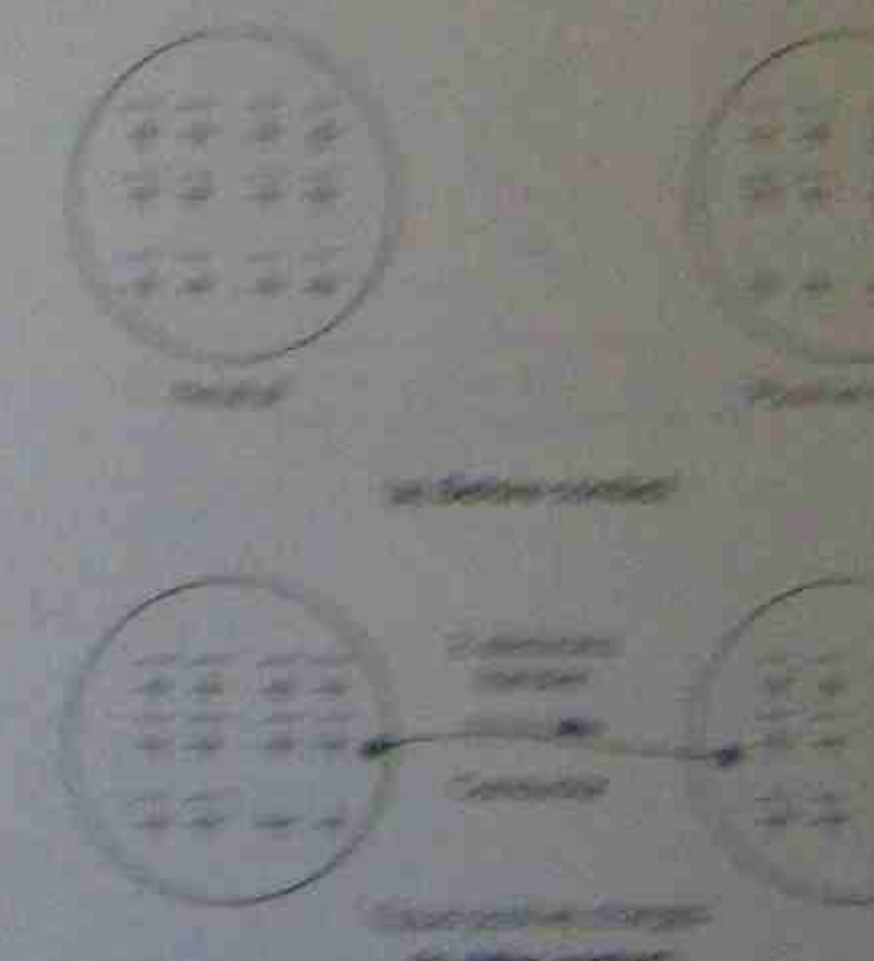

Figure 2.4 • Transfer of electrons from an electrified charged rod

This means that, because there are insufficient electrons to bring either body to a neutral state of charge, both will be slightly deficient in electrons. Note that each of the bodies has a small positive charge, a potential equal to 2 units of positive charge and there is no potential difference between the two bodies after contact.

If a positively charged body is connected to a negatively charged body, the electron flow will be from the negative to the positive body. The potential difference between the bodies will be zero when the electron flow ceases.

Before they are connected, the p.d. between them is numerically equal to the algebraic difference between their potentials (i.e. the p.d. is equal to the sum of the surplus and deficient electrons in both bodies).

Figure 2.5(a) shows a body with a surplus of 6 electrons and a body with a deficiency of 2 electrons. The p.d. between these bodies is 6 + 2, which equals 8 electron units.

After they have been joined together, the potential of each body will be 2 units of negative charge and both bodies will have zero p.d. (see Fig. 2.5(b)).

Note that a transfer of 4 electrons occurs: 2 to neutralise the positive charge and 2 more to make it 2 units of negative potential.

In both the above examples, the number of protons in a body did not alter when contact was made, only the number of electrons transferred.

Conclusions

1. Matter is composed of molecules made up of different atoms.

2. These molecules can be subdivided to produce the elements of which they are made.

3. There are almost 100 separate elements, each with its own characteristics.

4. The smallest part of an element is an atom.

Negative charge   Positive charge

(a) Before contact

4 electrons transfer

Conductor

Equal negative charges

(b) After contact
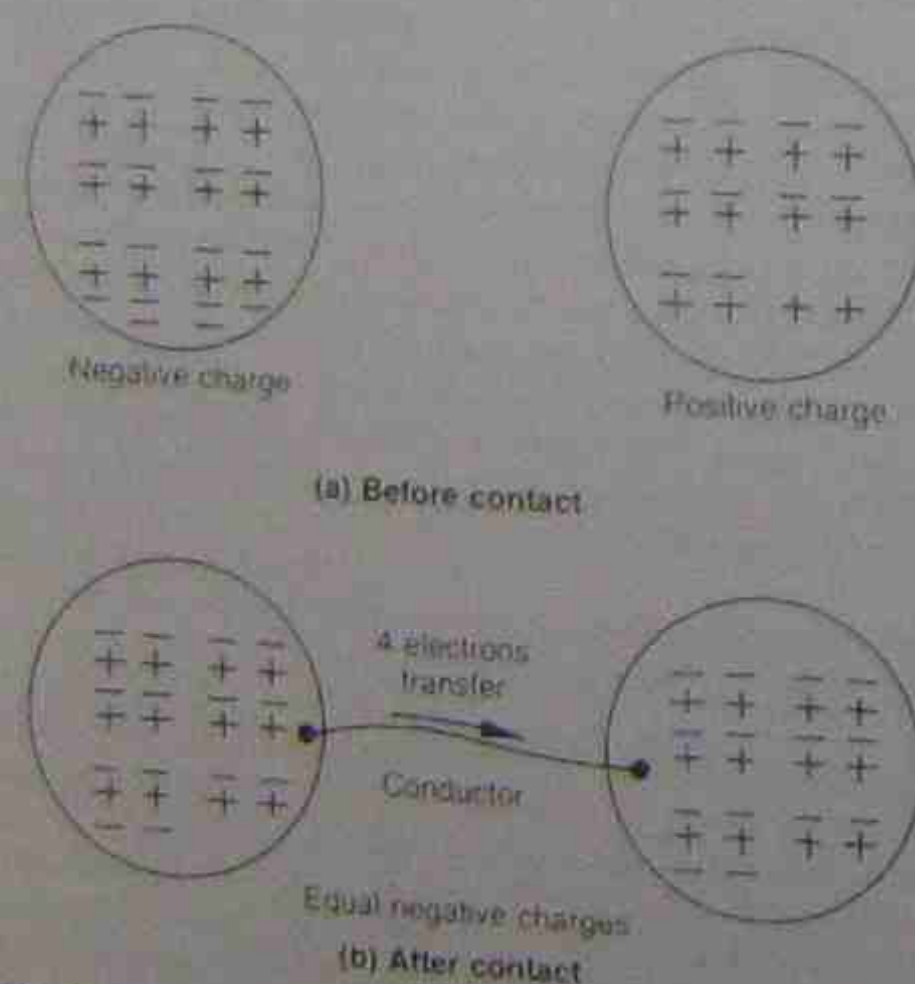
Figure 2.5 • Transfer of electrons from a negatively charged body to a positively charged one

5. If an atom is ionised there are negative charges produced called electrons. The remainder of the atom is left positively charged, that is, it becomes a positive ion.

6. All atoms can be ionised to produce positive and negative charges. For example, an electron from an atom of sodium produces an identical negative charge to the electron from an atom of chlorine or an atom of copper.

7. An excess or a deficiency of electrons causes a potential difference to be built up between two bodies and, if a conducting path is provided, the electrons flow along it, thereby equalising the charge and reducing the potential difference to zero. The electron flow then stops.

2.4.4   Applications for static electricity

1. Electrostatic precipitation

A precipitator unit consists of a central electrode connected to the negative polarity of a high voltage source. A surrounding cylinder that normally comprises part of the final flue is connected to the positive polarity. By passing emissions through the unit the air or gas is ionised and the ions attach themselves to the foreign bodies present in the flue emissions. These being negatively charged are attracted to the outer cylindrical unit and are neutralized on coming into contact with an opposite charge. The undesirable components then fall back and are collected and disposed of in a manner less harmful to the atmosphere. This method for limiting air pollution is common in power generating stations still operating with fossil fuels where the emissions consist of ash particles and large quantities of sulphur and other acidic components.

2. Paint spraying

This method is more common in industries where painting is used extensively as part of the manufacturing process. It also applies to powder coating procedures. Uses are in the white goods industry to coat refrigerators and washing machines. The method is also used in the car manufacturing industry. The unit to be painted is suspended on a travelling overhead rail and raised to a high voltage. When sprayed with either paint or powder the paint particles are attracted to the unit and become firmly attached. In economic terms much less paint is used for the same amount of spraying and with far less waste. In the case of powder coating the overspray can largely be recovered and used again.

2.5   DYNAMIC ELECTRICITY

It was stated earlier that when two bodies are at different potentials an electric force exists between them. This force can cause an electron flow between the bodies if a conducting path exists between them.

The electric force or pressure is termed an electromotive force (e.m.f.). It is measured by the potential difference in volts between two points.

If points of different potential are joined by an electrical conductor, the electrons will be forced from the point where there is a surplus of electrons to a point where there

is a deficiency. That is, electrons will flow from a point of higher electron potential to one of lower electron potential whenever a conducting path exists between those points. These issues give rise to three factors:

1. Potential difference

Once the potential difference between two points has been reduced to zero, the flow of electrons stops. For practical purposes this irregular flow of electrons is unsatisfactory. To ensure a continuous flow of electricity a continuous source of electromotive force is required.

2. Electrical materials

Electrical energy needs to be guided to where it can be used effectively. This is done with materials that exhibit specific characteristics. One type of material conducts the electrical energy to where it can be used (a conductor), while another type prevents any unwanted flow from other parts of an electrical circuit (an insulator).

3. Electron flow

The rate of flow of electricity is governed by the above two factors. That is, a high potential difference tends to increase the flow and a poor conductor tends to decrease the flow.

2.5.1   Sources of electromotive force

The great bulk of electrical energy is still generated in the same manner as it was one hundred years ago. Fossil fuel is burned to obtain heat, which converts water to steam to move mechanical devices that drive electrical generators. The major concern now is that there will be depleted supplies of fossil fuels to continue the process in the future, or the replacement of fossil fuels by nuclear fuels to generate steam. There are many other methods for producing electricity, but none is at the stage of development to produce anything like the quantities presently available from the rotating generator.

The generator employs the principle of forcing conductors through a magnetic field to generate a voltage. Depending on the type of machine, the resulting current may be alternating (a.c.) or direct (d.c.). The generation of alternating voltages is discussed in Chapter 8, and that of direct current in Chapter 12.

The only real variations are in the type of prime mover required. The driving unit may be a steam turbine, water turbine, gas turbine or diesel engine, each having particular advantages. The electromechanical method is used wherever large quantities of electrical power are supplied from a common source for large cities and their associated industries. A typical operating efficiency could be 40 per cent, although this figure is highly variable.

2.5.2   Development of the generator

Faraday's experiments with induction led to the development of rotating machinery to produce dynamic electricity. Initially rotating machinery was of open construction and primitive by today's standards.

Figure 2.6 shows early versions in the development of a direct current generator. It can be seen that there has been little obvious change in direct current generators during the last 60 years. However, there has been refinement of the internal construction and materials used.
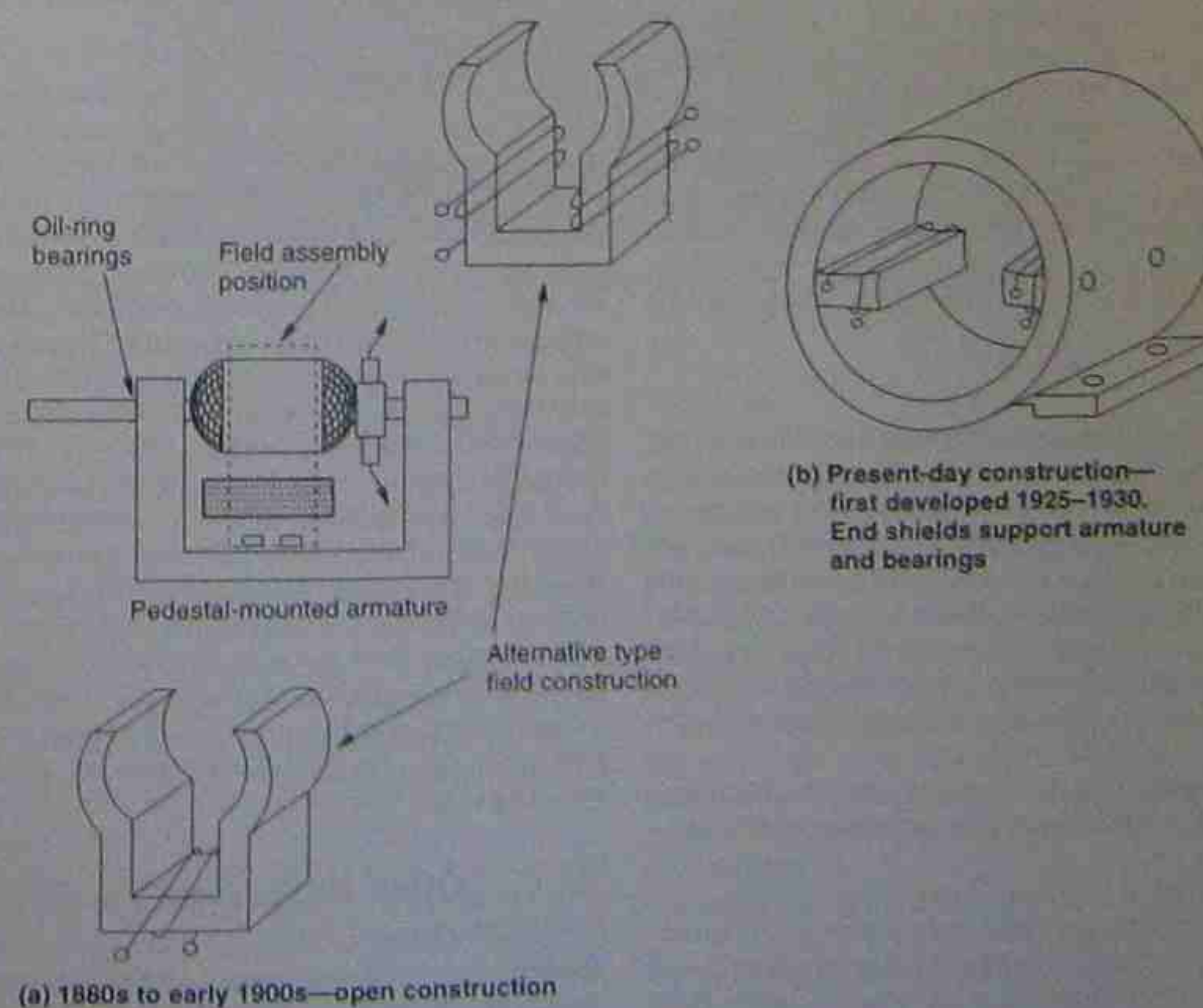

Oil-ring bearings   Field assembly position

Pedestal-mounted armature

Alternative type field construction

(a) 1880s to early 1900s—open construction

(b) Present-day construction—first developed 1925–1930. End shields support armature and bearings

Figure 2.6 • Construction of early electric motors and generators

2.5.3   Modern power generation methods

It was soon realised that alternating current offered many advantages in both the generation and transmission of electrical power. The changeover from direct current to alternating current power was a progressive one taking many years and meant that both systems were in use for a considerable time. Methods of generating electrical power were rather stable, in that steam-driven engines originally used to drive low-speed generators were instead used to drive alternating current generators.

Steam-driven turbines were a later development and alternators became larger and larger.

Steam turbines

The most common way of generating power in the mainland states of Australia is with steam turbines. In the majority of cases, steam is produced by burning either coal, oil or gas.

The methods for producing steam may vary from place to place and may be governed by local conditions. Steam-powered generating stations are often sited adjacent to large quantities of water for cooling and condensation purposes.

Gas-fired steam generators are noted for high efficiency and their ability to produce quantities of steam quickly. They have the ability to get alternators onto line for additional power supplies at peak times and make excellent standby plants for emergencies. The heat from the exhaust is returned to preheat water and air as well as driving the unit's air-compressors to force air into the steam generator.

Geothermal power

Italy has been generating electrical energy for many years by harnessing steam emerging from the earth. The steam is cleaned and fed to low-pressure turbines driving alternators. Precautions have to be taken to ensure that finely divided solids and 'wet' steam are prevented from reaching the turbines. Large volumes of steam are required, owing to the relatively lower temperature and pressure.

The United States and New Zealand have commenced using this method for power generation comparatively recently.

Nuclear power

France and other European countries have committed their future to nuclear energy for the generation of steam to drive turbines. They have no access to cheap supplies of oil, coal or gas, and so have to look to alternative means for the generation of electrical energy. Germany currently has approximately 20 nuclear power stations and Japan, which has a serious scarcity of materials for energy production, is developing a similar usage. The United States has many nuclear powered stations and is intending to install more.

The nuclear energy is used to produce steam which is then fed to turbines as in steam-powered generating stations.

Tidal movements

France and England have done innovative work in collecting sea water by tidal movement for generating power with hydroelectric turbines. In some coastal areas these two countries have tidal movements of between 6 m and

9 m. On the north-west coastal regions of Australia there are similar variations in sea level. However, because of low population densities it is currently not an economic proposition in Australia.

The principle is to contain as much water as possible at high tide and release it at low tide through turbines. Generating electrical power this way is of course somewhat limited to times of low tide levels.

Hydroelectric power

In Scandinavia, Canada, Tasmania, and the Snowy Mountains in mainland Australia, hydroelectric power is generated by running large volumes of water through low-speed turbines. The water is collected at as high a level as possible in reservoirs. A power station is then built at a lower level.

As the water 'falls' down to the power station it gains sufficient energy to drive the turbines. Tasmania has ample supplies of water (most of the time) but no easy access to coal, oil or gas. The water run-off from the power station can be channelled to power stations at lower levels, used for irrigation, or fed into the water supply of adjacent towns (see Fig. 2.7).

Engine-driven generators

In remote areas, diesel-driven alternators are more common. The power is generated in a somewhat similar fashion although on a larger scale than that of the portable generator. It is a more expensive method for generating electrical power but if other fuel supplies such as water and coal or furnace oil are not available at an economical rate to generate steam, there is no alternative. Figure 2.8 shows a modern diesel driven a.c. generator installed in a machine room as a standby power source.

Gas turbines

The gas turbine was developed directly as a result of development work in the 1940s to produce an aero engine that would give speeds higher than the speed of sound. The basic design has remained virtually unchanged. It comprises an air compressor, a means of injecting fuel under pressure, and an ignition chamber. The gas and fuel mixture when ignited produces a rapid expansion of gases which are forced out of an expansion chamber. This is fed to a series of turbine blades and produces sufficient power to drive a generator connected to the turbine shaft. The waste gases are then exhausted out of the system, although some units use the heat of the exhaust gases to heat the incoming air through a heat exchanger. The larger the unit the better its efficiency. In general a gas turbine generating plant is able to be started more quickly than a steam-driven turbine and because of this factor they are often used as emergency standby generators and as back-up supplies for peak loads. A starting motor is necessary to run the unit up to speed before injecting any fuel. Because of its size, weight and cost it is not suitable for small loads.

2.5.4   Other sources of dynamic electricity

Chemical sources

There are several variations of this method: the most common are those of the primary and secondary cell. These are discussed in detail in Chapter 3.
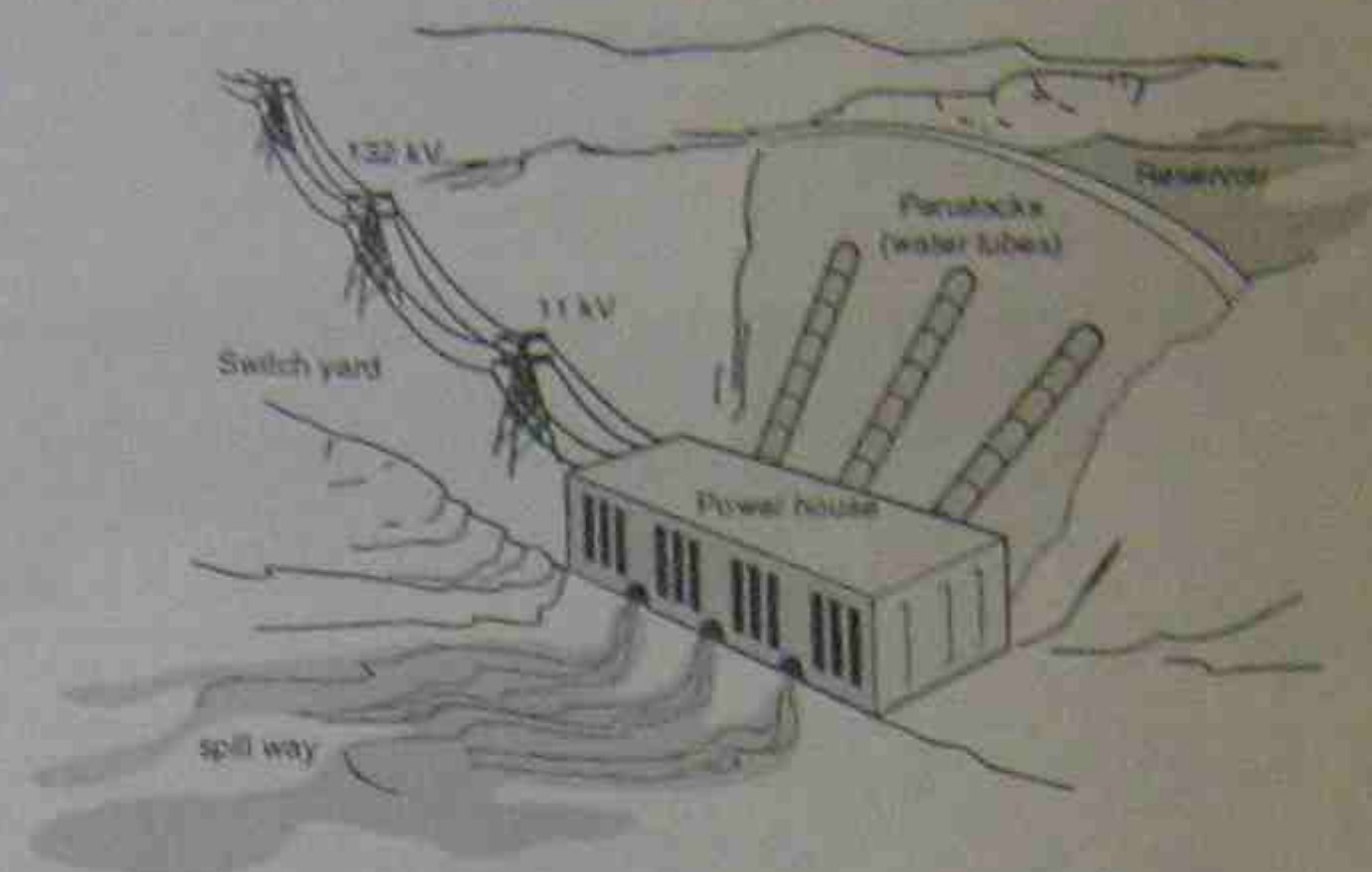
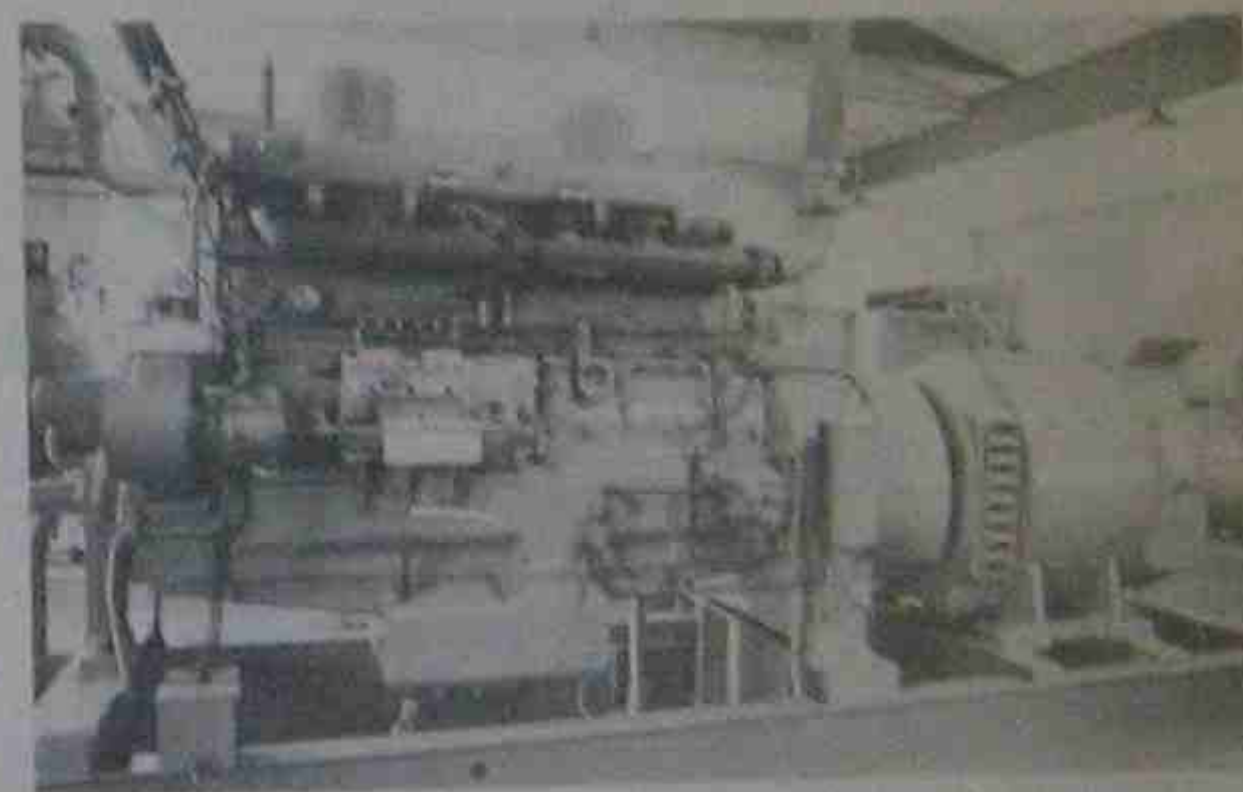**Figure 2.7** • Stylised hydroelectric station

Figure 2.8 • Diesel-driven a.c. generator used as an alternative power supply in the event of the mains power being interrupted
Civil Aviation Authority

A less common method is the combining of elements such as hydrogen, carbon and oxygen to form compounds such as methane, water or carbon dioxide. Chemical bonding involves ions and the transfer of electrons from one atom to another, energy being either generated or absorbed in the process. Adaptation of this method leads to a variation of a fuel cell. One type of fuel cell consists of two chambers with two porous electrodes separated by an electrolyte. Hydrogen and oxygen are supplied to the two chambers and, in the presence of a catalyst, react to provide ions and free electrons. A by-product is water. Fuel cells provide high efficiencies and under ideal conditions can last for many years.

A typical operating figure is 70 per cent. The fuel cell proper has no moving parts, produces no noxious fumes and some fuel cells produce potable water. This is an important reason for their use in space travel. Some fuel cell systems require extensive (and expensive) auxiliary equipment and their use is accordingly restricted.

Solar cells

The basis of the solar cell is a thin junction of two semiconductors. When light is shone on the junction, light energy is converted directly to electrical energy. Theoretically of unlimited life, they are subject to some deterioration of the materials and a consequent falling off in efficiency. Solar cell panels are available for battery charging and are finding a rapidly increasing use in remote areas. A similar type of cell is called a photovoltaic cell, the modern type being of similar material to the solar cell. The light falling on the cell generates a voltage that is read against a scale. Many modern automatic cameras use the cell to assist in setting the camera adjustments.

Typical operating efficiencies are in the region of 5 to 7 per cent. Figure 2.9 shows one use for solar cells—charging batteries in remote areas.
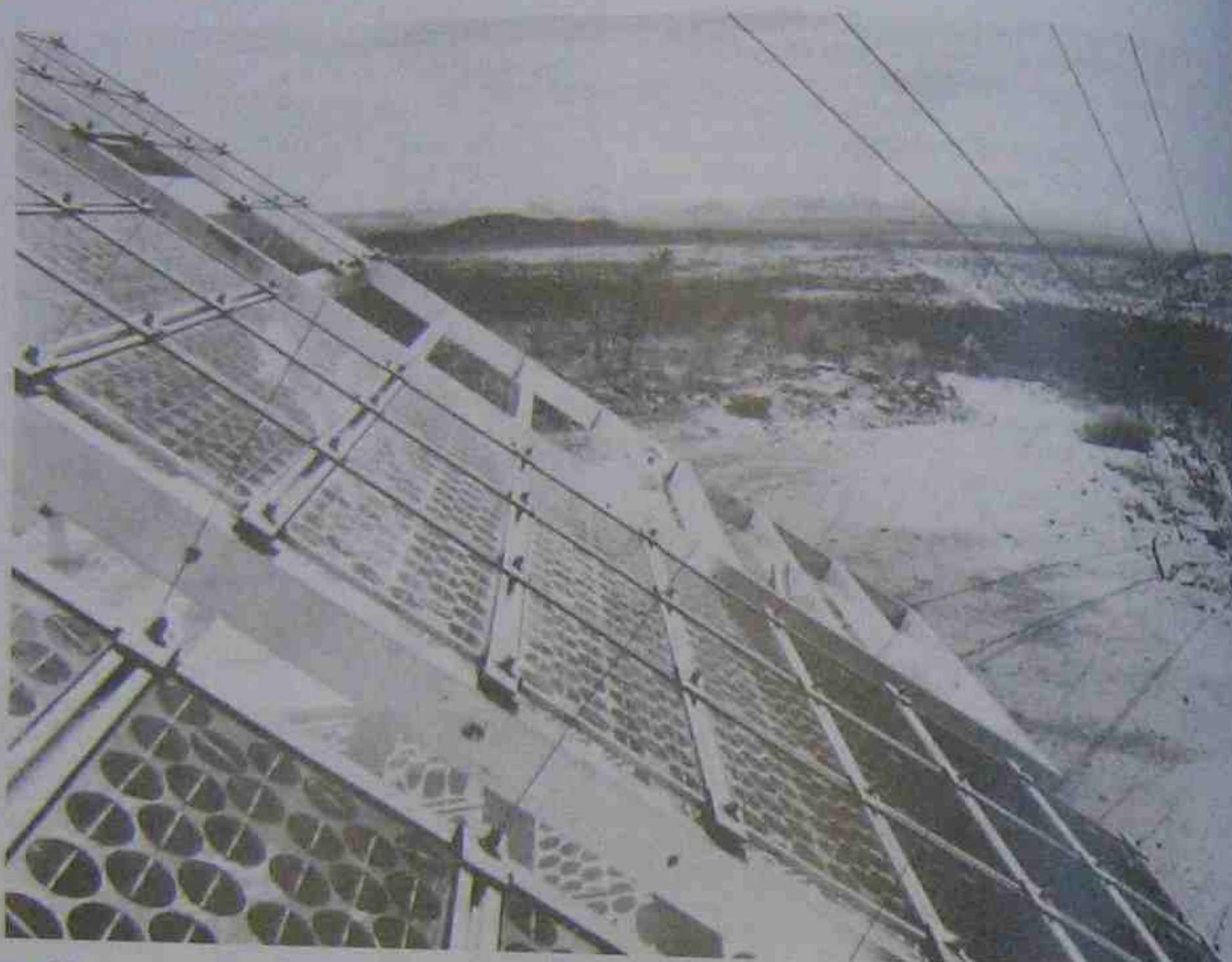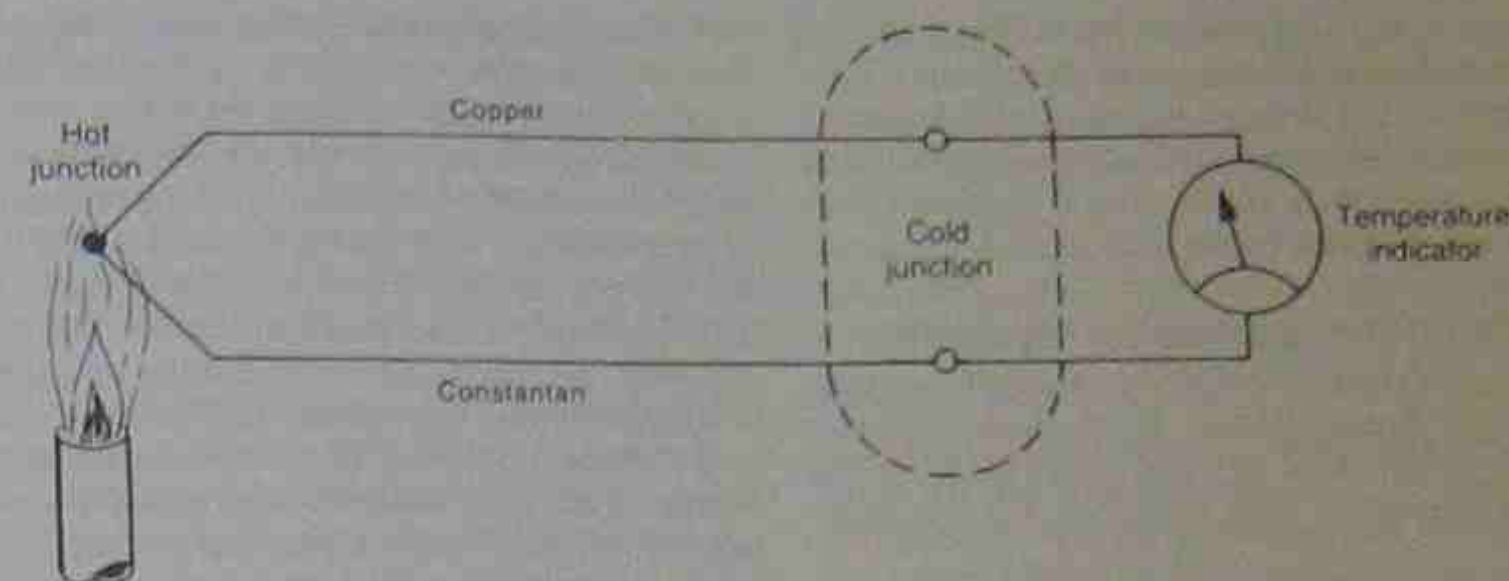
Figure 2.11 • Basic thermocouple

The potential differences produced are very small and the whole circuit, including the indicator, must have a very low opposition to the flow of electrons. Different conductor materials are used for various temperature ranges, a typical thermocouple being made of copper and constantan (an alloy). For a temperature rise of 200°C, the potential difference created would be of the order of 0.009 V. This would occur when the cold junction was at a temperature of 0°C. If the cold junction temperature was 32°C with the hot junction heated to 200°C, the output voltage would be approximately 0.004 V. For greater voltages, thermocouples are sometimes connected as a group, so their voltages add up to a higher value. The unit is then called a thermopile.

Piezoelectric sources

When certain materials are subjected to mechanical stress, a voltage is generated across the faces of the materials. This is called the piezoelectric effect. Materials most commonly used are naturally occurring crystals such as quartz and Rochelle salts. These are cut into chips (also called crystals), with their faces basically parallel to one or other of the three axes in the main crystal, and then mounted in holders before being connected into circuits.

When a voltage is applied to the opposite faces of the chip, it distorts and the movement can be measured. When the chip (crystal) is distorted, a voltage appears at the opposite faces. These two effects occur at a natural rate of resonance, depending mainly on the angle of cut and the physical dimensions of the crystals. As such, their most common use is in radio-transmitter circuits, although they can also be found as the initiating element in echo sounders, ultrasound diagnostic machines in hospitals, and for the generation of very-high-frequency sound waves in ultrasound cleaning machines.

In recent times it has been found that ceramic materials can be used to produce the same effect while having the advantages of being hard, chemically inert and not affected by humidity. Because of their ceramic nature they can be moulded into shape during manufacture, while slight variations in composition allow emphasis on specific properties required for a special application. For example, a high-voltage generator, as used in cigarette lighters, oxy-acetylene lighters and fuse ignition for explosives, would have different requirements to those of a transducer used for ultrasonic cleaning and degreasing. The first example requires a comparatively long length with a small cross-section while the second requires a large cross-sectional area and a very short length. Figure 2.12 shows an elementary striker ignition system.
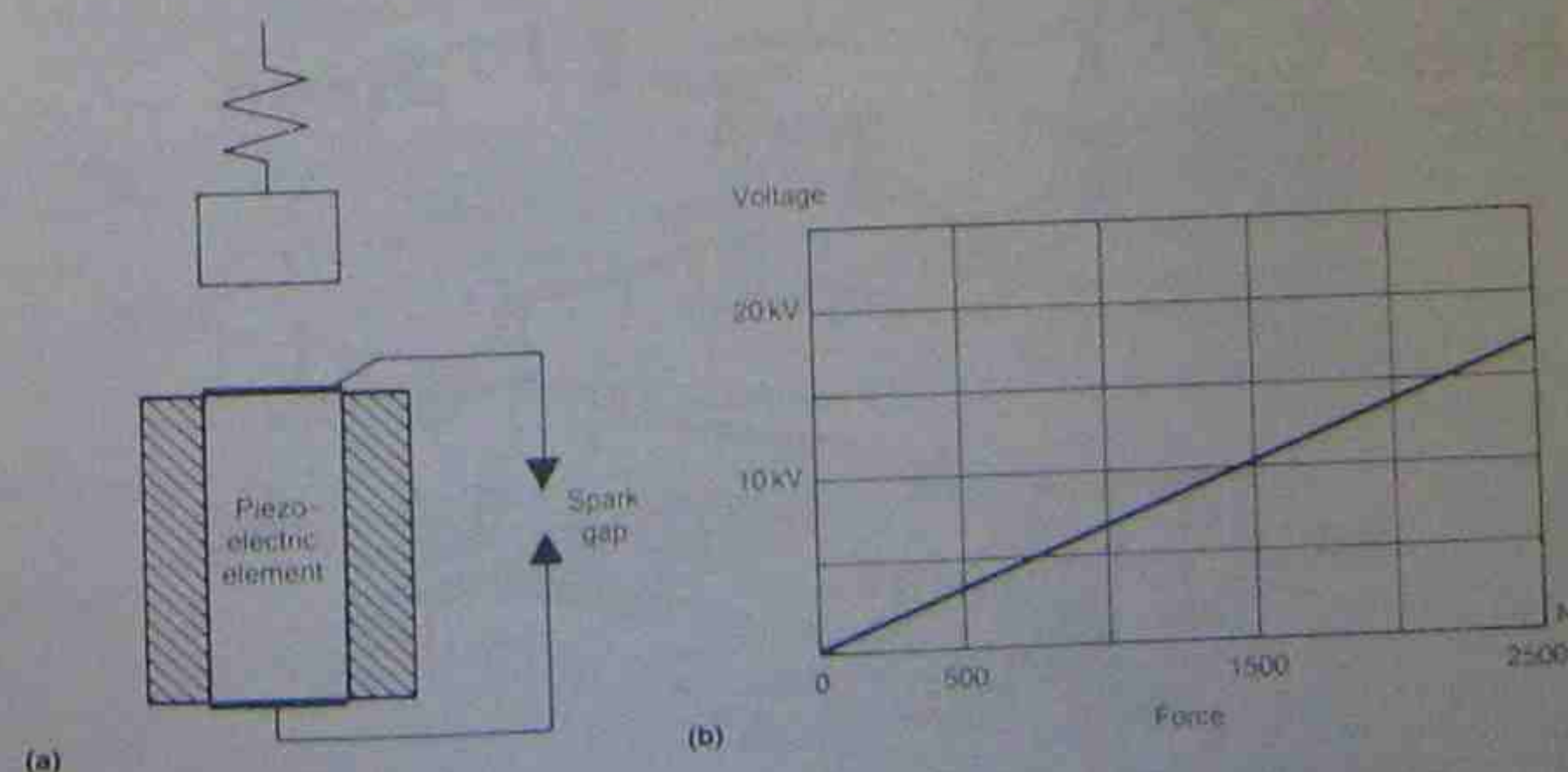

Figure 2.9 • Bank of solar cells mounted on a tower in the Northern Territory. A number of arrays similar to this have been installed to operate microwave repeater stations and obviate the need to provide more expensive alternative power supplies

Telec

Electrostatics

There are many effects of electrostatic charges. An electric shock from a car's door handle is one. The modern electrical meter case is usually of transparent plastic and rubbing it clean with a piece of cloth often causes the pointer to move across the scale without the meter being connected. Two common ways of producing substantial electrical charges are by the Wimshurst machine or the van de Graaff generator.

The Wimshurst machine consists of two parallel insulating plates rotating in opposite directions, the charge being conducted away by two sliding contacts (see Fig. 2.10).

The van de Graaff generator has a motor-driven rubber belt rubbing lightly against a comb. At the other end of the belt another comb conducts the charge to a hollow ball. This type of generator has its main use in the study of high voltage effects. Industrial uses of static electricity are discussed in section 2.4.4.

Thermoelectric sources

The thermoelectric method of voltage generation is mostly used as a means of temperature measurement. The thermocouple itself consists of two dissimilar metals joined at a point where the heat is applied (hot junction). A potential difference is created and appears at the other two ends (cold junction), where it is measured with a meter usually calibrated as a thermometer (see Fig. 2.11).

Figure 2.10 • Wimshurst machine

Figure 2.12 • Piezoelectric striker ignition system

and the accompanying graph shows the voltage that can be generated. A light weight hitting the element at a comparatively high speed is ample to produce the necessary voltage. The striker mechanism is usually operated by stressing a spring which is released by a pawl and this accelerates the weight towards the unit.

2.5.5 Early power distribution systems

At first, distribution systems consisted of supplying consumers with direct current power. This consisted of two conductors with the current flowing outwards from the generator in one direction and returning via the other conductor.

In an endeavour to minimise the size and length of conductors in street lighting, the circuits initially had banks of lamps connected in series. Carbon-arc lights were used and the overall voltage of a unit circuit was quite high.

As distribution systems grew in size and the number of customers increased, cable sizes became unwieldy. There were side effects such as return currents flowing through the earth. These caused such problems as early deterioration of metal pipes buried in the ground and unwanted voltages such as between iron fences and metal pipes entering the ground.

2.5.6 Modern power distribution systems

Almost without exception, electrical energy is distributed to consumers with a three-phase four-wire system. It is generated in power stations at voltages ranging from 7000 to more than 20 000 V. It is then transmitted to a switching yard where it is connected to various switches and transformers. These transform the voltages to suitable values for the next transmission stage.

Long-distance transmission of power usually means that the voltage is converted to very high voltages. In Australia, voltages of 132 kV, 330 kV and 500 kV are used.
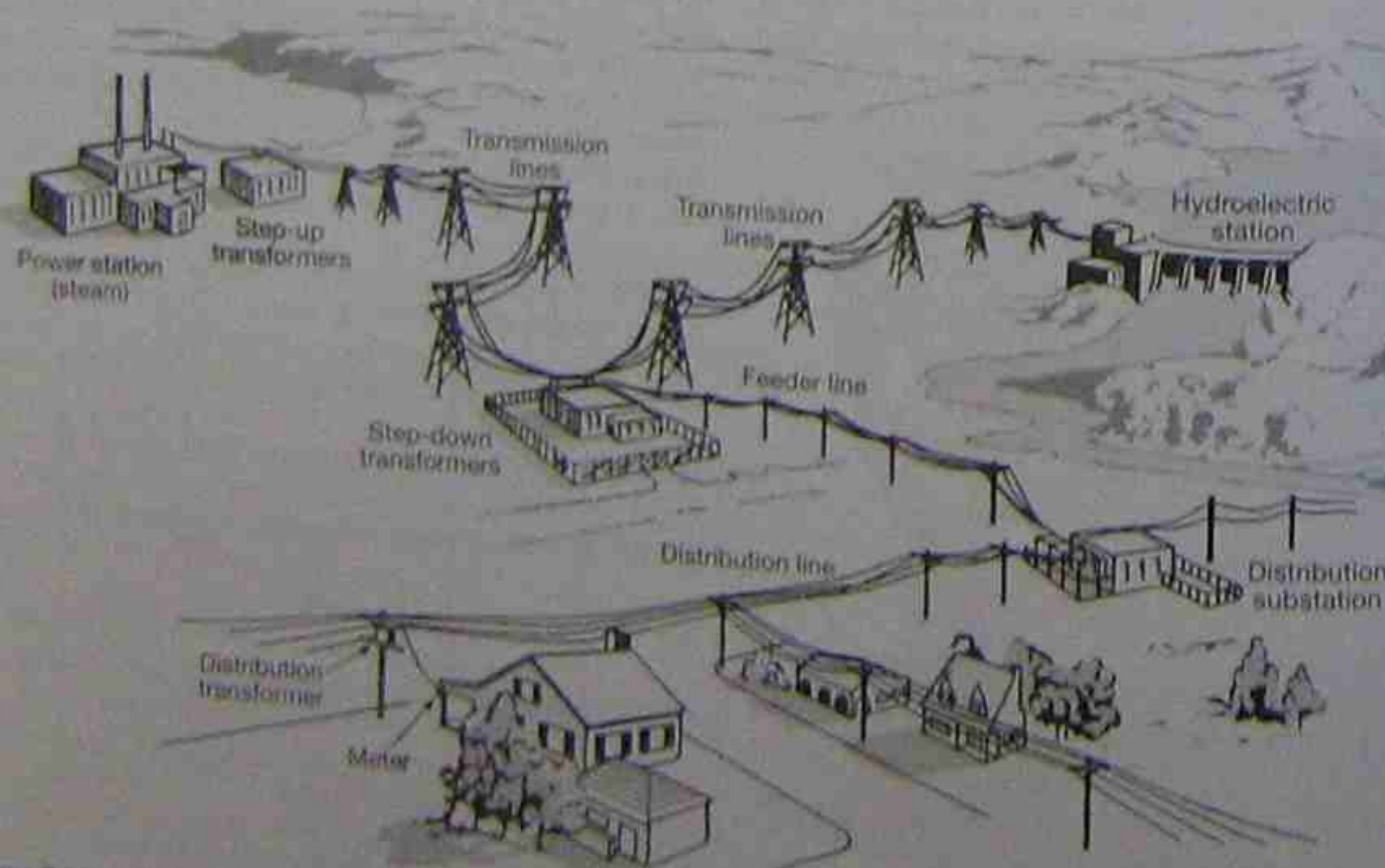
In Europe and some parts of the United States the voltages are even higher. Voltages in excess of 500 kV are encountered in large European systems.

The idea of using high voltages is to reduce power loss to a manageable level. Electrical power is a function of both the voltage and the current consumed in the load. If the current can be reduced to a lower value, the losses in the transmission lines can be reduced. The same amount of power can still be transmitted if the voltage is increased to a higher value but a lesser current flow.

At the consumer end of the transmission line the conductors lead into a substation where the voltages are reduced to lower levels. A result of this method is that power stations are needed, but there is, however, an increased need for substations to convert voltages to suitable levels. Substations are often cross-linked to other substations so that alternative routes for supplying the stations are available.

Figure 2.13 shows a generalised layout for a transmission system. The power station generates at 11 000 V and in its switching yard changes it to 132 000 V. It is then conducted to substations as a three-phase system.

2.6 CURRENT ELECTRICITY

2.6.1 Conductors and insulators

From an electrical point of view, all materials can be classified according to their behaviour in an electric circuit. Materials that conduct electricity quite easily are called conductors. Materials that offer a high opposition to the flow of electricity are called non-conductors or insulators. There is a third group of materials called semiconductors which conduct under some conditions and not under others.

Whether a material is a good or bad conductor cannot be decided in some arbitrary fashion because there is no

sharp dividing line. All materials have some opposition to the movement of electrons and the degree of opposition governs the use of the material. For example, an electric light receives electricity by means of a good conductor (copper) and, to ensure the electrons flow only where desired, the copper wires are encased in a plastic sheathing (a poor conductor, or a good insulator). The circumstances governing a material's use also have an effect on the selection.

Some salts are insulators when solid but are good conductors when molten. Neon is an insulator when not put under an electrical stress but becomes a conductor when the applied voltage is high enough to ionise the gas.

It is important to realise that there are degrees of conductivity. Under normal everyday use there is no perfect conductor, nor is there a perfect insulator. Semiconductors in the highly refined state are very poor conductors (i.e. good insulators). As their content of impurities is increased, their ability to conduct electrons also increases. Semiconductors are first purified and then 'doped' to the required degree of impurity to control the rate of flow of electrons through them.

Insulators that are porous and capable of absorbing moisture must be treated with caution because as they become damp their insulating qualities decrease markedly. These materials (e.g. wood) are often impregnated with varnish to prevent the absorption of moisture.

Conductors

The obvious characteristic of most good conductors of electricity is that they are metals. The common feature for any good conductor involves the outermost electrons in the valency ring or shell (see section 2.3.3). In the case of copper, the single electron in the valency ring is not held tightly to the nucleus because it is furthest away and shielded by the other orbits. It is easily removed by another atom and can be passed on from atom to atom. Because of this it is called a 'free' electron. Any good conductor has large numbers of free electrons. Not all metals conduct equally well. The best is silver, followed by copper, gold and then aluminium. The most practical conductor for general use is copper—arising from its good performance as a conductor and its relatively low cost.

Insulators (non-conductors)

The most outstanding characteristic of an insulator is that it contains very few or no free electrons under normal conditions. Without free electrons there can be no current flow and the electrons in the atom remain strongly bound to the nucleus. As a general guide only, the greater the number of electrons in the valency ring the better the material is as an insulator.

Semiconductors

The term semiconductors must not be misunderstood. They are not half-conductors. Pure semiconductors are insulators at low temperatures and reasonably good conductors at higher temperatures. The elements germanium and silicon are the most important of the semiconductors in the electrical and electronics industries, although there are some compounds used in special cases. Semiconductors belong to group 4 of the Periodic Table; that is, they have 4 electrons in their valency ring. Pure semiconductors are seldom used; they are usually doped with elements from groups 3 and 5 of the Periodic Table. Refer to Table 2.2 for a comparison of resistivity.

2.6.2 Electric circuits

There are three basic types of circuit. All are shown in Figure 2.14.

Open circuit

If the current path is not continuous between two points of potential difference, the circuit is referred to as an open circuit. Refer to Figure 2.14(a). The circuit has a break in it. No current can flow and the lamp is not alight. This condition occurs in a normal circuit when it is switched off.

Closed circuit

If the circuit is complete as in Figure 2.14(b) then current can flow and the lamp glows. This condition occurs in a normal circuit when it is switched on. A closed circuit is an essential condition for a current flow. To maintain a continuous current flow, a continuous source of electrical energy must be provided to maintain the potential difference at the beginning of the circuit. In Figure 2.14 a cur-

Figure 2.13 • Stylised distribution system

Table 2.2 • Conductors and insulators

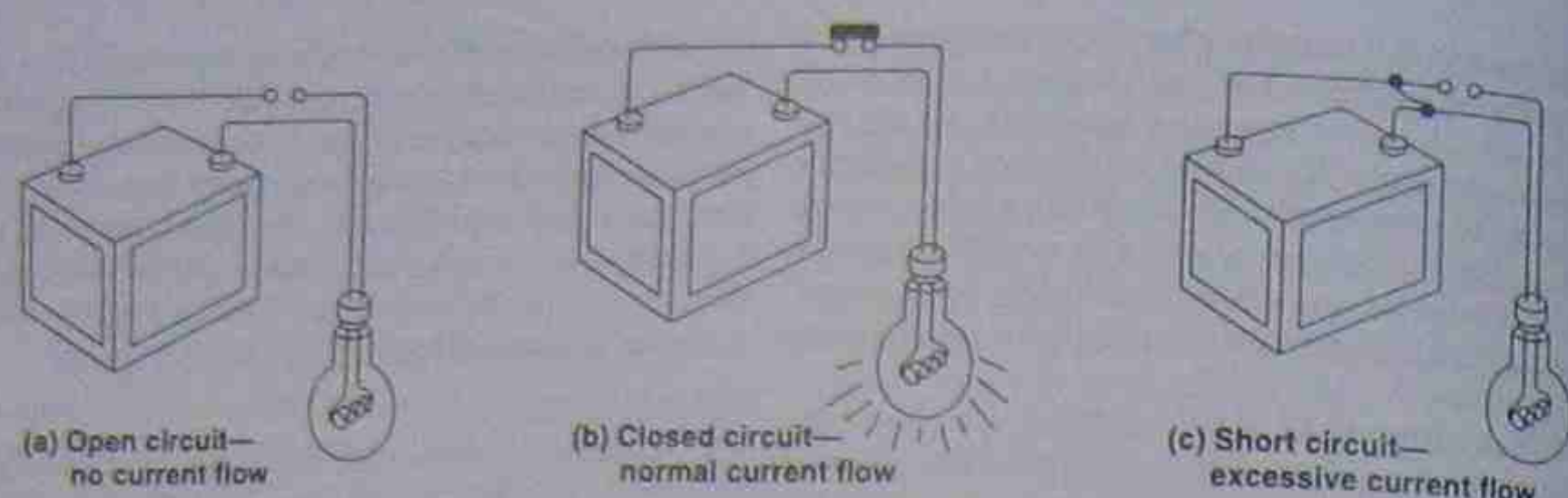| Category		Material	Approximate resistivity in ohm-metres (see section 2.10.3)
Insulator	high opposition to electron flow	glass	10 000 000 000 (10^{10})
		Bakelite	10 000 000 000 (10^{10})
		rubber	10 000 000 000 000 (10^{13})
		sulphur	10 000 000 000 000 (10^{13})
Semiconductor		silicon	0.8
		germanium	0.89
Conductor	low opposition to electron flow	silver	1.63×10^{-8}
		copper	1.72×10^{-8}
		aluminium	2.83×10^{-8}
		tungsten	5.50×10^{-8}

(a) Open circuit—
no current flow

(b) Closed circuit—
normal current flow

(c) Short circuit—
excessive current flow

Figure 2.14 • Types of circuits

battery is shown as the source of energy but other devices such as generators may be provided when greater quantities of energy are needed. Static electric charges generated by friction are not usually able to carry out this function.

In normal electric circuits of this type there are further types of circuits called series and parallel circuits. These are discussed in Chapter 4.

Short-circuit

This type of circuit is to be avoided whenever possible. It is shown in Figure 2.14(c). The lamp is bypassed by a conductor connected direct from one terminal of the battery to the other. The expression used is that the lamp is 'shorted' out of the circuit, or the circuit has a 'dead short' on it. No current flows through the lamp but an excessive current flows direct from one terminal of the energy supply source to the other. The current flow is not limited by the load as in Figure 2.14(b). In this particular case, unless the battery is protected against excessive current flow in some way the battery and conductors can easily be damaged.

2.6.3 Direction of current flow

When electrons are in motion between two points in an electric circuit, the electron flow is referred to as current electricity. The path taken by the current is called an electric circuit. The terminals of the energy source are called its poles. One terminal of a battery is its positive pole and the other its negative pole.

The positive terminal is the pole that is charged positively. That is, it has a deficiency of negative charges or electrons. The negative terminal is the pole that has a ready supply of electrons freely able to move through an electric circuit.

Figure 2.15 shows two methods of indicating the direction of electric current flow. In an electric circuit the current flow is always from a point of higher potential to one of a lower potential.

In the early days of electrical experimentation it was wrongly assumed that current flow was always from a positive polarity to a negative one. This view lasted for so many years that it is still used today and is called 'conventional' current flow.

Only more modern experimentation showed that a current flow consisted of negative charges flowing towards the positive terminal. That is, an electric current flow was actually an 'electron flow'. The conventional current version had been in use for so long that it was considered unwise to adopt electron flow as the standard. However, in the United States, electron flow is often used, and to avoid the confusion caused by this practice, a wise student will always check which method is used when using circuits from the United States. This also applies to textbooks as well.

When no convention is stated, it is always assumed that the conventional current flow is being referred to. If electron flow is used, it must be clearly stated that it is being used, to avoid confusion. For the remainder of this book,

(a) Conventional current flow (+ to −)

(b) Electron flow (− to +)

Figure 2.15 • Direction of current flow

unless it is specifically stated otherwise, conventional current flow is to be assumed.

2.6.4 Current electricity units

Potential difference

The amount of current that flows in any particular circuit depends primarily on the amount of potential difference between the terminals of the circuit.

Potential means the charging of a body or the charging of one end of a conductor. This results in a difference of potential between two bodies or between two ends of a conductor. The term 'potential difference' is often shortened to the one word 'potential', having the same meaning.

Figure 2.16(a) shows that the rate of flow of water depends on the head or pressure. Increasing the pressure increases the flow of water.

In an electrical circuit the rate of flow of current also depends on the pressure (p.d.), if no other part of the circuit is altered (Fig. 2.16(b)).

If the resistance to flow remains the same, doubling the pressure on the water in a tank forces twice as much water through the pipe. Similarly, doubling the potential difference doubles the current. If a difference in potential of 2 units causes 1 A to flow, then a potential difference of 4 units causes a 2 A flow. That is, making the voltage twice as large will make the current flow twice as large, provided the opposition or resistance to flow is kept constant.

An electrical pressure is measured in units called volts. By definition (Chapter 1) a volt is the pressure causing 1 watt to be dissipated in a circuit when 1 ampere is flowing. By Ohm's law (see section 2.8) it is also the pressure causing 1 ampere to flow through a resistance of 1 ohm.

The following abbreviations and symbols are used to indicate electrical pressure:

pressure (p.d.)	V (general symbol)
volt	V
millivolt	mV
microvolt	μV
kilovolt	kV

Electrical resistance

If the movement of an electron in a conductor were traced, it could be shown that its movement, while irregular in direction, resulted in a general drift from negative to positive polarity along the conductor. The free electrons moving towards positive polarity collide with positive ions in the conductor and tend to recombine to form neutral atoms. At the time of the collision the electron is slowed down. It can accelerate again due to the applied e.m.f. but suffers further collisions with other ions. The slowing down is a measure of the opposition to current flow by the conductor. The outside source of energy must supply extra energy to accelerate the electron again, and the exchange of energy with further collisions results in the generation of heat and a rise in temperature of the conductor. For the same current flow, the lower the temperature rise, the lower is the conductor's electrical opposition to current flow.

This opposing force is called the electrical resistance of the circuit. Resistance is that property of a material which opposes the flow of electrons. The resistance of a conductor depends on its length, cross-sectional area, type of material and temperature. The following abbreviations and symbols are used to indicate resistance:

resistance	R (general symbol)
ohm	Ω
microhm	$\mu\Omega$
kilohm	kΩ
megohm	MΩ

Electric current

Current has been shown to be a flow of negative charges called electrons. For convenience these small charges are grouped into larger units called *coulombs*. The rate of flow is given as coulombs per second. In section 1.2 the ampere was given as the base electrical unit of flow and defined according to the magnetic force between parallel conductors. By definition, a current flow of 1 ampere transfers a charge of 1 coulomb (6.24×10^{18}) electrons each second. The following units and symbols are used to indicate electric current:

current	I (general symbol)
ampere	A
milliampere	mA
microampere	μA

14 kPa pressure   28 kPa pressure   42 kPa pressure

Pressure in kilopascals

Water flow = 5 litres per second   Water flow = 10 litres per second   Water flow = 15 litres per second

(a) Rate of flow of water

2 units p.d.   4 units p.d.   6 units p.d.

Lamp   Ammeter   2 A   3 A

(b) Rate of flow of current

Figure 2.16 • Relationships between pressure and rate of flow

2.7 MEASURING CURRENT ELECTRICITY UNITS

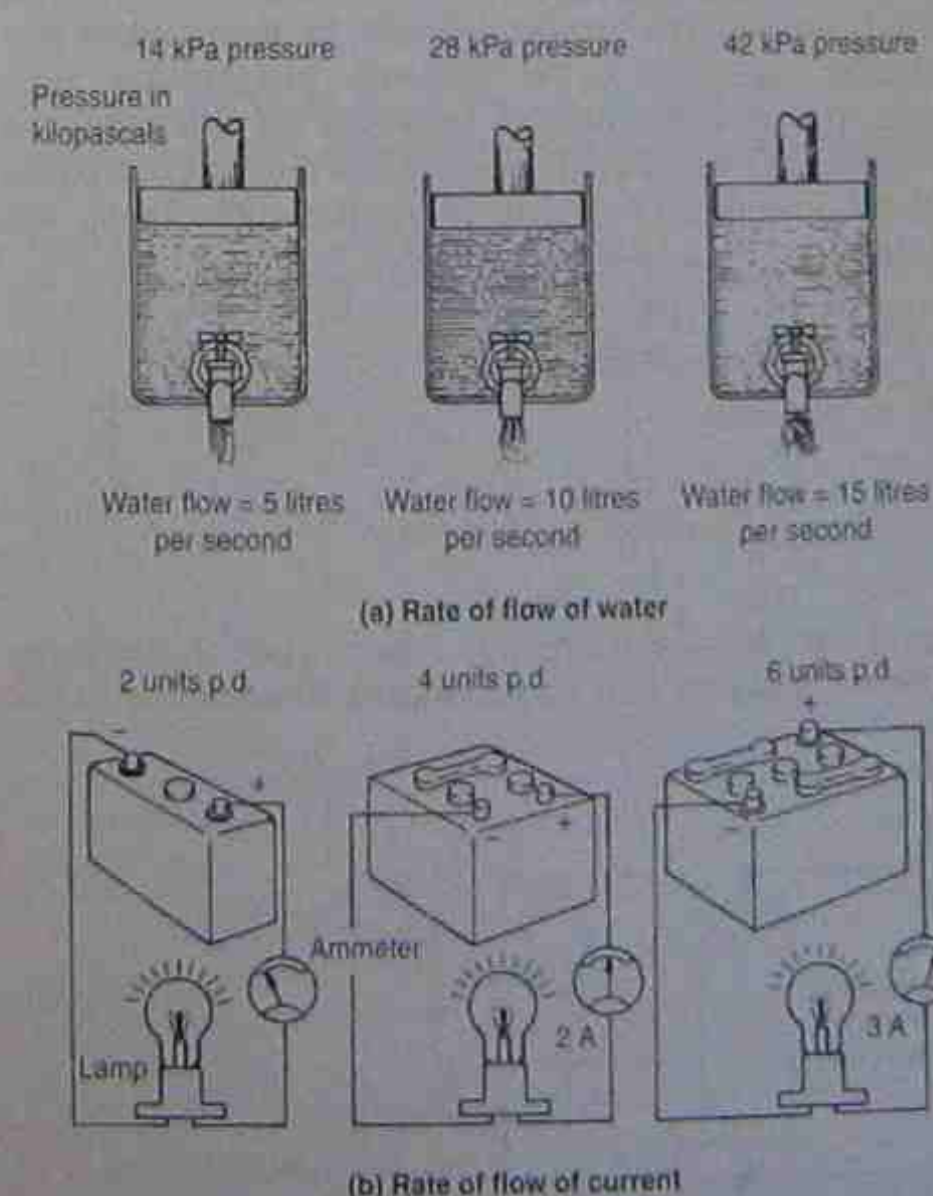The instruments most commonly used in circuit measurement are the voltmeter and the ammeter.

Ammeters must always be connected in series with a circuit. The meter terminal marked positive (+) must always be connected to the positive side of the circuit, otherwise the meter pointer will attempt to move backwards against the meter stops and may be damaged.

This rule applies to any type of meter having marked terminals, irrespective of whether it indicates current, voltage or any other quantity.

Voltmeters must always be connected in parallel with those two points in the circuit where the potential difference is to be measured.
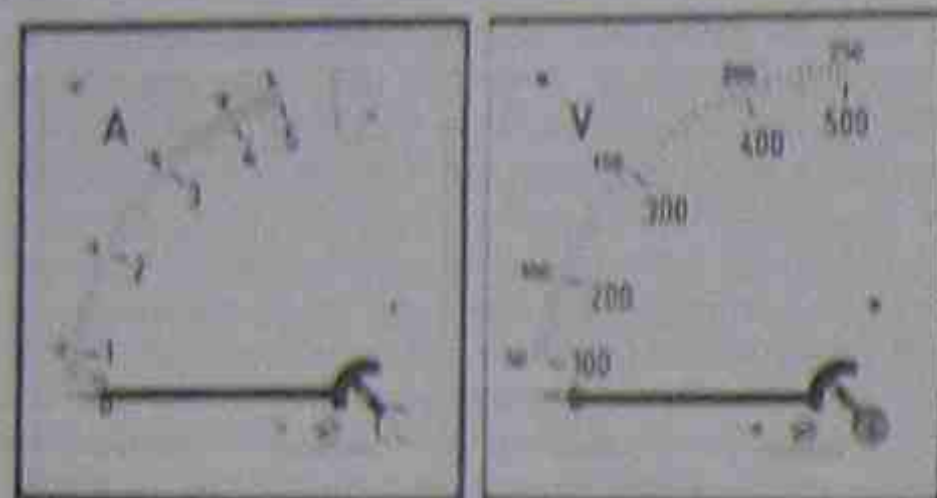
Figure 2.17 • Electrical measuring instruments: (a) ammeter; (b) voltmeter

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2.7.1 Ammeters

Ammeters have a very low resistance so that they will not appreciably restrict the flow of current in a circuit. Thus an ammeter should never be connected in parallel with any points in a circuit having a potential difference between them. If such an error should occur, the meter may be seriously damaged, due to excessive current passing through it.

A circuit showing how an ammeter (in series) and a voltmeter (in parallel) can be used to indicate the current and p.d. across a resistance of unknown value, in order that its value of resistance can be calculated, is given in Figure 2.18.

If the ammeter indicates 5 A and the voltmeter shows 6 V, then the value of the unknown resistance equals:

$$R = \frac{V}{I} = \frac{6}{5} = 1.2\ \Omega\ \text{(Refer to section 2.8.)}$$

2.7.2 Voltmeters

The value of resistance connected inside a voltmeter is very high (between 1000 and 20 000 Ω for each volt the
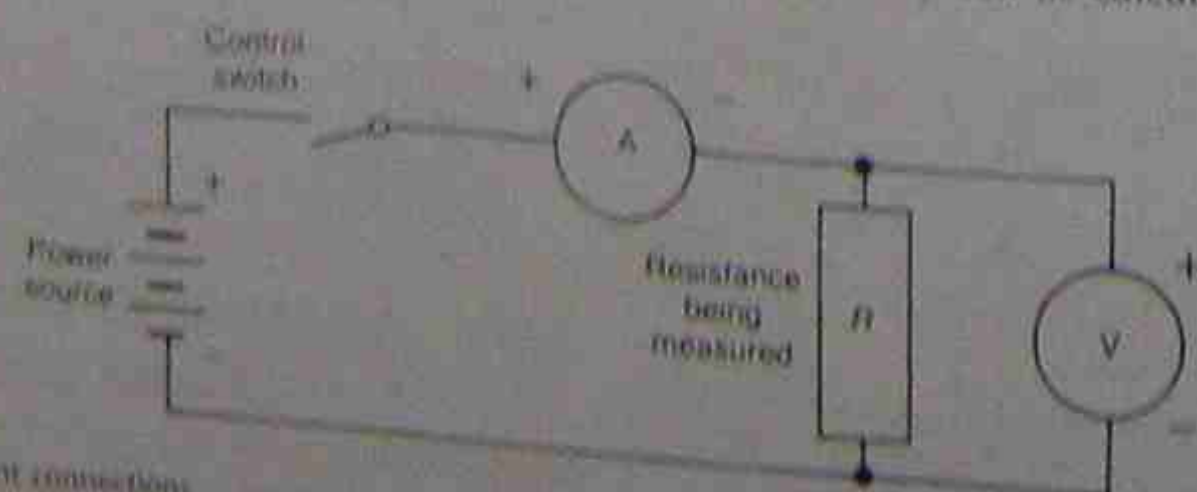
Figure 2.18 • Instrument connections

instrument can measure). The normal meter of good quality has at least 1000 Ω per volt. That is, a voltmeter that will read up to 50 V has an internal resistance of 50 × 1000 = 50 000 Ω.

The current flowing through the windings of such a meter, when connected across a p.d. of 50 V, will be very small (1 mA), so no damage will be caused by excessive current flow.

However, if the same meter were connected across a 250 V supply, the current would be five times as great (5 mA) and, although this is a small current, it is beyond the value for which the meter winding was designed so the meter could be damaged. Meters can only be used to measure voltages within their capacity. The maximum capacity of a meter is termed its full-scale deflection (f.s.d.) value.

If any meter pointer moves rapidly across the scale and beyond f.s.d. (the last, or highest, division mark), the power should be switched off immediately before further damage occurs to the meter.

2.8 OHM'S LAW

Ohm stated that in any electric circuit the current is directly proportional to the voltage, and inversely proportional to the circuit resistance:

> The current flowing between any two points in an electric circuit is directly proportional to the potential difference between these points, and also inversely proportional to the resistance of the circuit between these points.

The term 'directly proportional' means that as one quantity increases (in this case the p.d.), the quantity that depends upon it (the current) will also increase. When two quantities are said to be 'inversely proportional' this means that as one quantity increases (in this case, the resistance), the dependent quantity (the current) decreases.

Ohm's law can be expressed mathematically by the equation:

$$\text{current} = \frac{\text{p.d.}}{\text{resistance}}$$

Or, in symbols:

$$I = \frac{V}{R}\quad\text{(answer in amperes)}$$

Knowing this relationship, the value of any one unknown quantity can be calculated if the value of the

other two quantities is known, by transposing the equation to suit the known values:

$$R = \frac{V}{I}\quad\text{(answer in ohms)}$$

or

$$V = I \times R\quad\text{(answer in volts)}$$

The above three equations form the basis of many circuit calculations and their importance in any later studies of electrical theory cannot be overemphasised.

Table 2.3 • The three related factors in Ohm's law, showing quantities, units and their effects in an electrical circuit

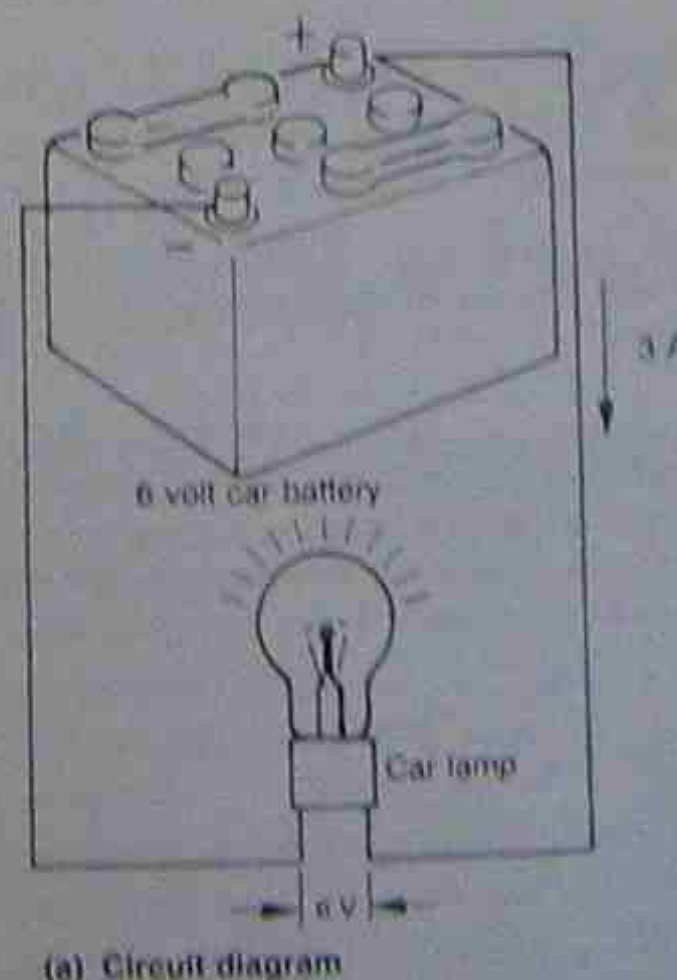| Quantity	Symbol	Unit	Symbol	Effect in circuit
Potential difference	V	volt	V	forces current through circuit
Resistance	R	ohm	Ω	opposition to flow of electrons
Current	I	ampere	A	electron flow

Example 2.1

Given that a lamp draws 3 A when connected to a 6 V battery, determine the resistance of the lamp.

Figure 2.19(a) shows such a circuit. Figure 2.19(b) shows the circuit in diagrammatic form, the lamp load being represented by a resistance symbol.

In this example the voltage and the current are known, so the equation used is:

$$R = \frac{V}{I} = \frac{6}{3} = 2\ \text{ohms}\ (2\ \Omega)$$

That is, the lamp resistance equals 2 Ω.

(a) Circuit diagram

(b) Schematic diagram

Figure 2.19 • Six-volt car battery connected to a lamp

2.9 ELECTRICAL POWER AND ENERGY

2.9.1 Electrical power

In section 1.3.2, electrical potential was defined in terms of power and current such that:

$$\text{voltage} = \frac{\text{power}}{\text{current}}$$

In general terms, then: $V = \frac{P}{I}$

By transposition: $P = VI$

In section 2.8 on Ohm's law it was shown that by transposition there were three variations of the one equation:

that is, $I = V/R,\quad V = IR,\quad R = V/I$

By substituting these variations in the basic power equation, above, then:

$$P = VI$$

From Ohm's law:

$$V = IR$$

then $P = I.IR$
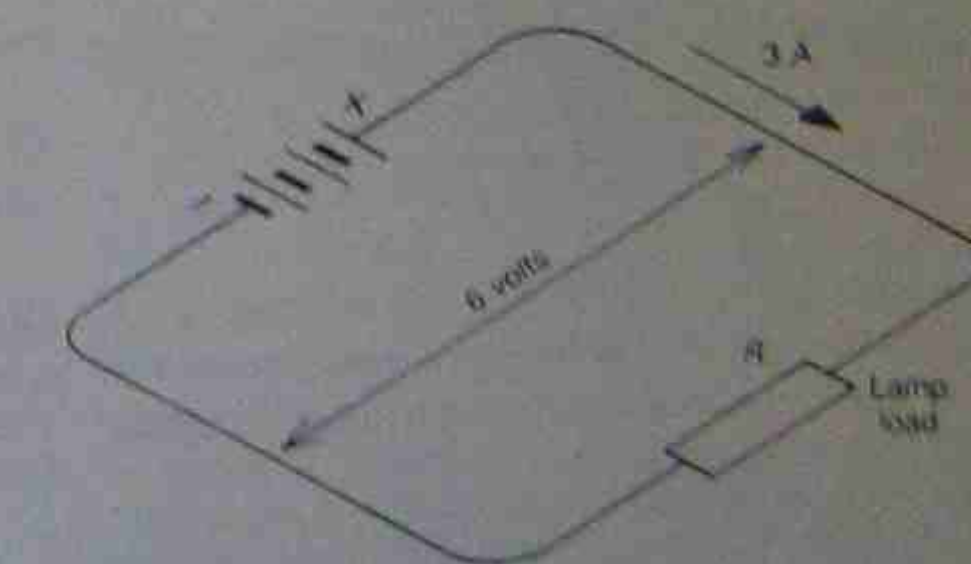
that is, $P = I^2R$

Similarly, with $I = V/R$:

$$P = V.V/R$$

that is, $P = \frac{V^2}{R}$

For electrical circuits: $\boxed{P = VI}$

also $\boxed{P = I^2R}$

and

$$P = \frac{V^2}{R}$$

That is, for a fixed or constant value of load resistance, power consumed is proportional to the square of the voltage. For example, doubling the applied voltage causes the power consumed to increase by two squared, or four times. Similarly, increasing the voltage three times causes an increase of nine times in power consumption. Mathematically this is expressed as:

$$P = V^2$$

In the opposite case, where the voltage remains constant and the load varies, the power is inversely proportional to the value of the load resistance. That is, doubling the value of load resistance reduces the power consumption to one-half the original value. (Remember, increasing the numerical value, in ohms, of the load resistance, decreases the current flowing.) For example, given the load resistance in a 12 V circuit is 4 Ω, the power consumed is 36 W. If the load on the supply is then reduced by doubling the load resistance value to 8 Ω, power consumption and current flowing also drops to half, or 18 W. Mathematically this is expressed as:

$$P = \frac{1}{R}$$

Example 2.2

A car with a 12 V system has two headlamps rated at 50 W each. When both lamps are alight, what current will they be drawing from the supply?

$$P = VI$$

By transposition:

$$I = \frac{P}{V} = \frac{2 \times 50}{12} = 8.33 \text{ A}$$

Example 2.3

A 240 V household radiator has a resistance of 23 Ω. Calculate the value of power drawn from the supply.

$$P = \frac{V^2}{R} = \frac{240^2}{23}$$
$$= 2504 \text{ W}$$

Power can also be measured directly with a wattmeter. The method for connecting a wattmeter is shown in Figure 2.20. It can be seen that the meter has two circuits: one to measure the current flowing, the other to measure the supply voltage. This type of meter, and its connections, is discussed more fully in section 7.6.1, 'Electrical measuring instruments'.

2.9.2 Electrical energy

Energy is the potential to do work. The amount of energy expended is given by:
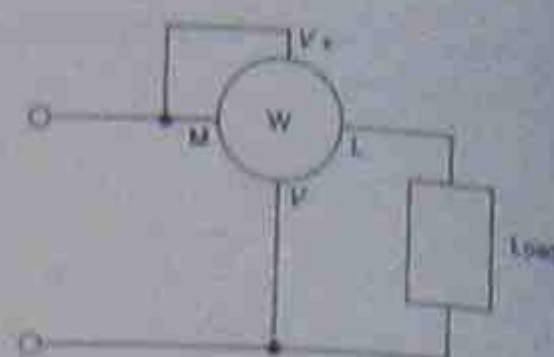
Figure 2.20 • Connections for measuring power with a wattmeter

energy = power × time applied

that is, $W = Pt$

where W = energy in joules
P = power in watts
t = time in seconds

Example 2.4

If the radiator in example 2.3 is left switched on for 2 hours, how much electrical energy would be used?

$$W = Pt$$
$$= 2504 \times 2 \times 3600$$
$$= 18\,028\,800 \text{ J}$$

As can be seen from this example, the number of joules of electrical energy used can be very large, so it is customary to use larger everyday units. Instead of the power of 1 watt, the kilowatt is used; and for time, the unit taken as 1 hour.

that is,   energy = power × time (answer in kilowatt-hours, kWh)

or $kWh = kW \times hours$

The two energy formulae above are identical except the units used, so the relationship between them is:

1 kWh = 3 600 000 J

The unit one kilowatt-hour (1 kWh) is sometimes referred to as a unit and occasionally as a kelvin. In each case 1 kWh = 1 unit = 1 kelvin.

Example 2.5

A 240 V radiator rated at 2504 W was switched on for 2 hours. Calculate the amount of electrical energy used (same radiator as in examples 2.3 and 2.4).

$$kWh = kW \times hours$$
$$= \frac{2504}{1000} \times 2 = 5 \text{ kWh}$$

Note that the answer in example 2.4 is the same as that in example 2.5.

that is, $\dfrac{18\,028\,800}{3\,600\,000} = 5$ kWh

Example 2.6

An electric motor rated at 5 kW output drives a machine for 4 hours. If the efficiency is 89 per cent, calculate the energy consumed.

$$P_{out} = 5 \text{ kW}$$
$$\therefore P_{in} = \left(5 \times \frac{100}{89}\right) \text{ kW}$$
$$energy = \frac{5 \times 100 \times 4}{89} = 22.47 \text{ kWh}$$

2.9.3 Cost of electrical energy

Electrical energy is sold like other commodities. The prices vary from state to state and sometimes within a state from one place to another. Supply authorities, like many other organisations, sell their commodity at varying rates even in the one area, depending on the use to which the energy is being put, as well as the quantity used and the time of use. Market forces, competition and the profit incentive can cause these tariffs to vary widely and often. A storage-type electric hot-water heater is generally on one of the lowest tariffs. These are controlled by a time switch so that it operates only during a period of low demand on the power stations. This method of operating during restricted times is usually referred to as 'off-peak loading' and is offered by the supply authorities as an incentive to economical operation of the power station. There is a growing tendency in most states of Australia to shift to a method of frequency control operated from a central point. In this manner individual suburbs can be switched on or off at will to suit prevailing load conditions. The method overcomes the lack of flexibility and control of the usual time switch. Due to the thousands of older installations still operating with a time switch it will be some considerable time before they are completely phased out of operation.

When a manual changeover switch is provided to allow the use of an appliance during periods when the load demands on the power station are greater, the water heater or other appliance is costed at a higher rate. Farmers with irrigation systems powered by electric motors operate under a similar system and are encouraged to irrigate at night.

2.9.4 Tariffs

Consumers are placed into various categories and the rates for energy vary accordingly. These categories vary from state to state but include:

- domestic
- community service
- commercial and general supplies
- rural
- industrial
- industrial (bulk, high voltage).

Domestic supplies, for example, have varying rates within the one category; a residence could have a consumption of 950 kWh in one period of three months. The

initial few units would be charged at one rate, while later units would be charged to the consumer at decreasing rates.

Example 2.7

A private residence consumes 1123 kWh of energy plus 803 kWh for a hot-water heater on an off-peak basis. Calculate the amount of the electricity bill, given the following tariff scale:

- off peak: all units 5.53¢/kWh
- general domestic: all units 14.66¢/kWh
- general service charge: $26.36

Cost:	water heater	803	×	5.53	=	44.41
	general	1123	×	14.66	=	164.63
	service charge					26.36
				Total		$235.40

2.10 FACTORS AFFECTING RESISTANCE

It was pointed out in section 2.6.4 that an electromotive force is needed to overcome the resistance of an electrical circuit and cause a current to flow. Resistance can be compared with the friction encountered by a ball rolling over a rough surface. In overcoming the resistance, the ball loses energy, which is converted to heat. Similarly, electrons lose energy in overcoming electrical resistance and the lost energy is also converted to heat.

Different types of materials and surfaces offer varying amounts of opposition to a moving object and in a similar fashion different types of conductor material offer varying amounts of resistance to the flow of an electrical current.

All parts of an electrical circuit offer resistance to current flow: the supply source, the conductors and the load. To compare different electrical conductors, a standard is necessary. Physical size is the easiest to control so length and cross-sectional area are used. While different materials have different resistances, it must also be recognised that temperature affects the value.

Thus the factors affecting resistance are:

- length
- cross-sectional area
- type of material
- temperature.

2.10.1 Length

Electrical resistance is associated with the collisions between moving electrons (the electric current) and the electrons and atoms of the conducting material. Because of the current flow, the number of collisions causing a transfer of energy to heat increases directly with the length of the conducting path. That is, the resistance of a conductor is proportional to its length:

$$R = l$$

2.10.2 Cross-sectional area

For any one value of current, increasing the cross-sectional area of a conductor allows the electrons to flow at a decreased density. Effectively the number of electron collisions is decreased, or causes a decreased energy loss. This in turn is shown as a decreased opposition or resistance to the flow of electrons, with less heat being generated. That is, the resistance of a conductor is inversely proportional to its cross-sectional area:

$$R \sim \frac{1}{A}$$

2.10.3 Type of material (resistivity)

Because each different type of conductor has a different atomic construction, each conductor has a different electrical resistance. In the two previous sections it was stated that $R \sim l$ and $R \sim 1/A$.

Combining both of these gives:

$$R \sim \frac{l}{A}$$

Length and cross-sectional area are the standard physical sizes for comparison purposes and each is applied to the various types of material in order to compare their resistances. The unit for length is the metre (m) and for area the square metre (m²). This means that theoretically each type of material is made up into a block 1 m long with a cross-sectional area of 1 m². The resistance is then measured along its length at a specified temperature and the value becomes the reference or standard. The formula $R \sim l/A$ is thus expressed in the form:

$$R = \frac{\rho l}{A}$$

where ρ (pronounced 'rho') = resistivity

> The resistivity for a material is defined as the resistance between the opposite faces of a 1 metre cube at a specified temperature.

In practice a block of material 1 m × 1 m × 1 m is cumbersome and expensive so a smaller sample of material is used and the resistance value obtained adjusted mathematically to the base size.

Knowing the resistivity of any material, the resistance of any conductor can be calculated, due allowances being made for temperature differences where necessary. In Table 2.4 some electrical materials are listed, together with their resistivity value.

The resistivity values given in the table are the resistance values between opposite faces of a 1 m × 1 m × 1 m cube at 20°C. The units are given in ohm-metres rather than as ohms/m³ because by transposition, the formula $R = (\rho l/A)$ can be written as $\rho = (RA)/l$

Using units ($R = \Omega$, $A = m \times m$, $l = m$) this becomes:

$$\rho = \frac{\Omega \times m \times m}{m}$$

$$\rho = \Omega\,m$$

Table 2.4 • Resistivity of selected materials

Conductor	Resistivity (ρ) at 20°C in ohm-metres	
aluminium	2.83×10^{-8}	
copper	1.72×10^{-8}	
gold	2.44×10^{-8}	Pure metals used
lead	2.04×10^{-8}	for conductors
platinum	10.09×10^{-8}	
silver	1.63×10^{-8}	
German silver	33×10^{-8}	
advance	49×10^{-8}	Alloys used as
manganin	48×10^{-8}	resistance wire
Nichrome	112×10^{-8}	

An inspection of the values in Table 2.4 shows that silver has the least resistance and is closely followed by copper. Because copper is less expensive than silver it is used extensively as an electrical conductor. The four materials listed at the end of the table as alloys are generally used for resistors; that is, they restrict the flow of electricity far more than those above them.

Example 2.8

Find the resistance of a copper cable 500 m in length that has a cross-sectional area of 2.5 mm². The resistivity of copper is $1.72 \times 10^{-8}\ \Omega\ m$.

$l = 500$ m (already given)

$A = 2.5\ mm^2 = \dfrac{2.5}{10^6}\ m^2$

Substituting these values in the equation:

$$R = \frac{\rho l}{A}$$

$$= \frac{1.72 \times 10^{-8} \times 500}{2.5 \times 10^{-6}}$$

$$= 3.44\ \Omega$$

Example 2.9

If 100 m of copper cable has a resistance of 1.35 Ω, what is the resistance of 1000 m of the same cable?

$R \sim l$

If l is increased $\dfrac{1000}{100}$ times, R is increased by the same ratio;

that is, $\dfrac{l\ (new)}{l\ (original)} = \dfrac{R\ (new)}{R\ (original)}$

$$\frac{1000}{100} = \frac{R\ (new)}{1.35}$$

that is, $10 = \dfrac{R\ (new)}{1.35}$

$R\ (new) = 10 \times 1.35 = 13.5\ \Omega$

Example 2.10

It is desired to manufacture a 15 Ω resistor from 0.2 mm² cross-sectional area manganin wire. What length is required?

$R = \dfrac{\rho l}{A}$, $A = \dfrac{0.2}{10^6}\ m^2$

Take ρ from Table 2.4 = $48 \times 10^{-8}\ \Omega\ m$:

$l = \dfrac{RA}{\rho}$

$$= \frac{15 \times 0.2 \times 10^{-6}}{48 \times 10^{-8}}$$

$$= 6.25\ m$$

The resistance value is strictly applicable only at 20°C, although at near temperatures the variation in resistance is small. For cases with greater temperature differences, allowances sometimes have to be made.

2.10.4 Temperature (temperature coefficient of resistance)

For some materials, an increase in temperature causes an increase in resistance; the materials are said to have a positive temperature coefficient (PTC). Where a material has a lower resistance at higher temperatures, it is said to have a negative temperature coefficient (NTC). Some materials are specially made into resistors to take advantage of these characteristics.

> The temperature coefficient of resistance is defined as the change in resistance per ohm per degree Celsius.

Because resistance can change with temperature, values of resistivity are specified at a particular temperature. The resistance of most metallic conductors increases with temperature (PTC) and over a limited range the increase is a linear function of temperature or very close to it. This leads to a method of calculating the resistance of conductors at another temperature by what is called the inferred zero method. The inferred zero value varies

for different materials but the method is illustrated in Figure 2.21.

Copper has an inferred zero of −234.5°C and, as can be seen, the increase of resistance with temperature is basically linear. If a length of copper wire has a resistance of $R_0\ \Omega$ at 0°C, then theoretically, it will have zero resistance at −234.5°C. At a temperature t_1, the resistance would be R_1, while at t_2 it would have increased to R_2. Knowing the value of resistance at one temperature, the value of another temperature can be calculated from the following formula:

$$R_2 = \frac{R_1(234.5 + t_2)}{(234.5 + t_1)}$$

where R_1 = resistance at temperature t_1
R_2 = resistance at temperature t_2

Example 2.11

The resistance of a coil of copper wire is 34 Ω at 15°C. What would be its resistance at 70°C?

$R_2 = \dfrac{R_1(234.5 + t_2)}{(234.5 + t_1)}$

that is, $R_2 = \dfrac{34(234.5 + 70)}{(234.5 + 15)}$

$$= \frac{34 \times 304.5}{249.5}$$

$$= 41.5\ \Omega$$

A second method for calculating resistance values at different temperatures involves knowing the temperature coefficient of resistance (symbol α, pronounced 'alpha'). The temperature coefficient at a given temperature is defined as the change in resistance per ohm per degree change in temperature. Table 2.5 lists some conductors and their temperature coefficients of resistance.

For most metals the change in resistance per ohm per degree Celsius is constant, but the coefficient is not, since it is compared by a ratio with the previous value of resistance, which has changed with the difference in temperature. The temperature at which the value of the coefficient is effective is usually given by a subscript to the symbol
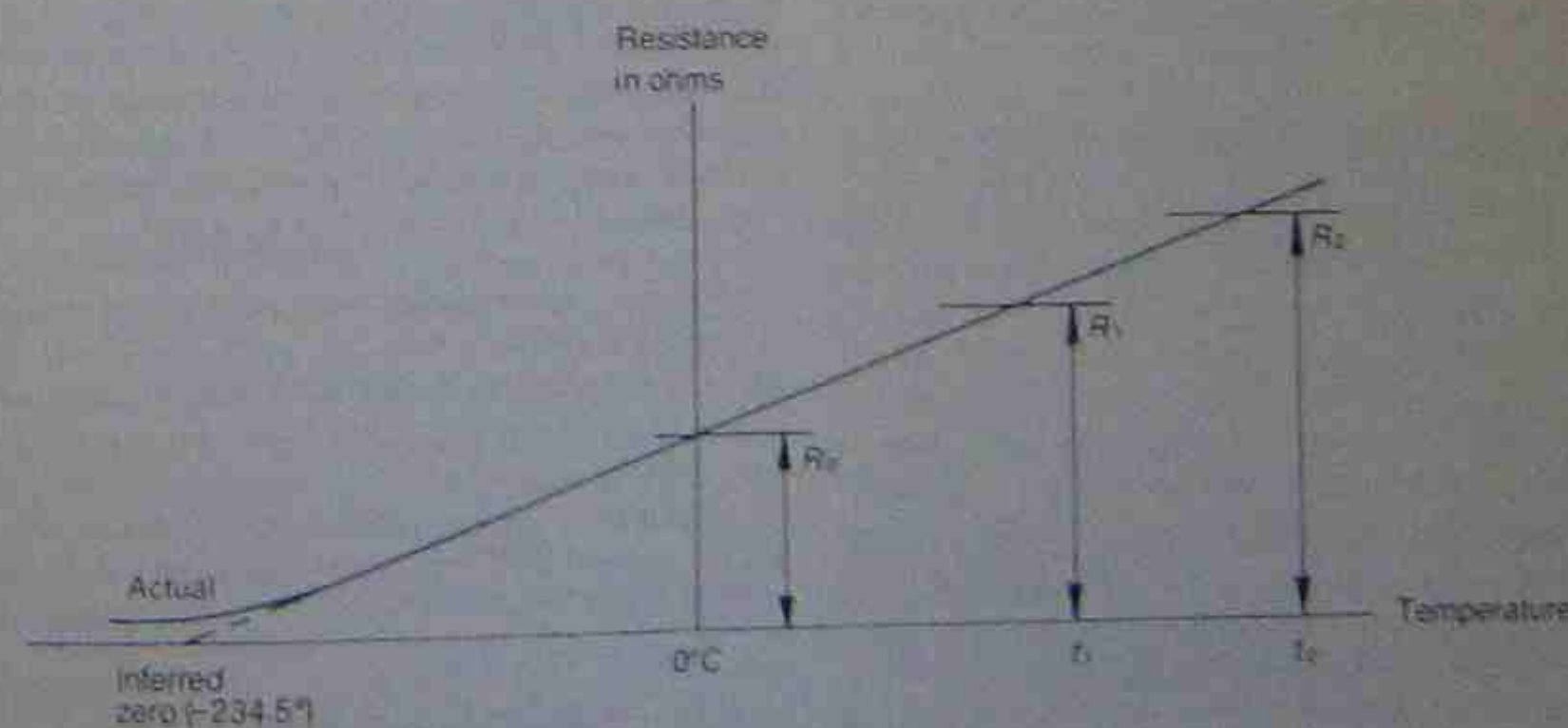

Figure 2.21 • Effect of temperature on resistance

Table 2.1 Temperature coefficient of resistance

Conductor	Temperature coefficient	
	R_0	R_{20}
aluminium	0.004 31	0.003 9
copper	0.004 27	0.003 93
gold	0.004 68	0.003 43
lead	0.004 11	0.003 9
platinum	0.003 87	0.003 9
zinc	0.004	0.004
tin	0.004 03	0.004
German silver	0.000 4	0.000 4
advance	0.000 02	0.000 03
manganin	0.000 01	0.000 01
constantan	0.000 2	0.000 2

R_0, R_{20} and R_{t}, indicating the temperature coefficients at 0°C and 20°C respectively.

$$R_t = \frac{\text{change in resistance per 1°C change in temp}}{\text{resistance at temperature } t}$$

A 2 Ω resistor at 0°C, if heated to 1°C, will increase its resistance by twice α_0, that is

new resistance = original resistance + $(2 \times \alpha_0)$

For a copper conductor where $\alpha_0 = 0.004$ 27,

the new resistance = 2 + (2 × 0.004 27)
= 2.008 54 Ω

Mathematically this can be developed into a general expression for finding the value of resistance at another temperature:

$$R_t = R_0(1 + \alpha_0 t)$$

where R_t = resistance at temperature t
R_0 = resistance at 0°C
t = temperature of R_t in °C
α_0 = temperature coefficient of resistance at 0°C

Example 2.12

A copper conductor has a resistance of 10 Ω at 0°C. Find the value of its resistance at 25°C.

$R_t = R_0(1 + \alpha_0 t)$
$R_1 = 10(1 + 0.004 27 \times 25)$
= 10 + 1.067
= 11.07 Ω

If the resistance of a conductor is known at some other temperature, the procedure has to be gone through twice (as shown in the following example).

Example 2.13

If the resistor in example 2.12 was known to be 11 Ω at 25°C, the problem could be one of finding its value at an operating temperature of 60°C.

Step 1: Find the resistance value at 0°C

$R_t = R_0(1 + \alpha_0 t)$
$11.07 = R_0(1 + (0.004 27 \times 25))$

from Table 2.1

that is, $R_0 = \dfrac{11.07}{1 + (0.004\ 27 \times 25)}$

$= \dfrac{11.07}{1.106}$

= 10 Ω (as in previous example)

Step 2: Having found the value at 0°C, use this to find the value at the second temperature. The formula is the same but the subscripts are used to indicate the second condition:

that is, $R_2 = R_0(1 + \alpha_0 t)$
= 10(1 + (0.004 27 × 60))
= 10 + 1.2562
= 11.56 Ω

An alternative method is that used in example 2.12, the use of a variation of the above formula

$$R_2 = R_1[1 + \alpha_1(t_2 - t_1)]$$

where R_2 = new resistance at temperature t_2
R_1 = original resistance at temperature t_1
α_1 = temperature coefficient of resistance at temperature t_1

This method enables the process to be done in one step but has the disadvantage of needing a value for α_1 of the original temperature t_1.

Example 2.14

The field windings of a generator have a resistance of 125 Ω at a temperature of 20°C. What will be the resistance of the windings when the machine temperature rise on full load to 60°C?

By the first method:

$R_t = R_0(1 + \alpha_0 t)$
$125 = R_0(1 + (0.004 27 \times 20))$
$R_0 = 1.085$
$R_0 = \dfrac{125}{1.085} = 115.16 \Omega$

Repeating the process:

$R_2 = R_0(1 + \alpha_0 t_2)$
= 115.16(1 + (0.004 27 × 60))

By the second method (one step only):

$R_2 = R_1[1 + \alpha_1(t_2 - t_1)]$
= 125[1 + 0.003 93(60 − 20)]
= 125 + 1.18 = 144.7 Ω

2.10.5 Superconductors

This is the name given to conductors that under carefully controlled conditions have no resistance and produce some unusual effects.

In certain chemically pure metals and a few special alloys, all opposition to current flow suddenly falls to zero when their temperature is reduced below a critical value. At or below this temperature the conductors are referred to as 'superconductors'. Lead, for example, becomes a superconductor at −256.8°C, that is, its resistance becomes zero.

Since a superconductor has no resistance, once a current flow is initiated the current will continue to flow at the same value without an applied potential. If a conductor has no resistance, then the current flow through it generates no heat. If no heat is generated in a conductor, the amount of current passed through it can be increased to quite high values.

The current flowing through a superconductor creates a magnetic field that becomes equal and opposite to any applied magnetic field.

Research has been going on for many years in an endeavour to produce a superconductor effect at higher temperatures. Current research has produced superconducting alloys with a critical temperature many degrees warmer than that of lead, but still well below 0°C.

2.10.6 Superconductor applications

Magnetic levitation

Japan is currently researching the use of ceramic magnets, mainly with the intent of using them for a train to run on or above tracks and supported there by magnetic levitation. Where most pure metals need to operate at a colder temperature than −269°K, the ceramic version can operate as a super conductor at around −143°K, that is, liquid nitrogen can be used to cool the conductor rather than using the much more expensive liquid helium. The speed of the train can be controlled by the simple expedient of altering the frequency of the power used to send the train along the tracks. Since it has effectively no friction from the tracks it is more silent and efficient. Indications are that a train of this type can be safely driven at much higher speeds than the more conventional train.

Magnetic resonance imaging

Another application for superconductors is in magnetic resonance imaging. Due to the cooling equipment needed, the unit tends to be somewhat larger than the conventional units in use today, but the system shows promise of producing better and cheaper images. Because of the larger currents used there is a correspondingly larger and more uniform magnetic field being passed through the body.

Particle accelerators

Particle accelerators also use superconductors for physics research. Ionised particles are accelerated by very intense

magnetic fields and the results of them smashing into other bodies is studied. It has been shown that there is an upper limit to the value of current that can be passed through a superconductor after which it tends to lose its superconductor status.

2.11   EFFECTS OF CONDUCTOR RESISTANCE

The size of conductors used to supply electrical equipment is governed by the current-carrying capacity of the conductor for that installation and the voltage drop of conductor.

2.11.1   Power loss in a conductor

In section 2.9.1 the formula $P = I^2R$ was derived. In a conductor supplying a load there is an inherent resistance and a current flowing through that resistance. Accordingly, power is consumed in the conductor. It is 'lost' as far as the load is concerned, and shows itself as heat by raising the temperature of the conductor and its surrounding insulation.

Example 2.15

A copper conductor of 2.5 mm² cross-sectional area are supplying a current of 15 A to an air-conditioner. If the conductor have a total resistance of 0.43 Ω, calculate the power lost in the conductor.

$P = I^2R$
= 15² × 0.43
= 96.75 W

This is almost equal to the heat produced by a 100 W incandescent lamp and for each minute the load is connected, 5800 J of heat is produced.

2.11.2   Current-carrying capacity

For each size of conductor there is a value of resistance ($R = \rho l/A$) so the power loss per unit length will depend on the current passing through the cable. The heat produced causes the conductor temperature to rise and if it exceeds certain values it can damage the insulation. Depending on the actual installation circumstances, heat can be dissipated at varying rates. Because the current flowing through the conductor resistance generates heat, standards have been determined that govern the maximum amount of current that can be allowed to flow in a conductor in any installation. A conductor in the open air can lose heat more readily than if it were one of several conductors in a conduit, all generating heat.

The Standards organisation recommends current-carrying values for conductors under different circumstances and these wiring rules are generally adopted throughout Australia and New Zealand. The Standards book is referred to as the Australian/New Zealand Wiring Rules AS/NZS 3000:2000.

2.11.3   Voltage drop in conductors

In example 2.15, mention was made of power lost due to the conductor resistance. Associated with this is a voltage

drop (Ohm's law, $V = IR$). AS/NZS 3000 also stipulates the maximum conductor voltage drop. The rule states that the voltage drop is not to exceed 5 per cent of the supply voltage; on a 240 V supply, this means 12 V is the maximum allowable.

For example 2.15, where the conductor resistance is 0.43 Ω and the current is 15 A:

$V = IR$ (Ohm's law)
$= 0.43 \times 15$
$= 6.45$ V (less than the allowable maximum)

Example 2.16

If the circuit run length in example 2.15 is 25 m, how much longer could it be before the allowable voltage drop would be exceeded on a 240 V supply?

total length of conductors is $2 \times 25 = 50$ m

(max. allowable resistance) $R = \dfrac{V}{I} = \dfrac{12}{15} = 0.8$ Ω

$R = l$ (section 2.10.1)

that is, $0.43 = 50$

$0.8 = \dfrac{50 \times 0.8}{0.43} = 93$ m

The extra conductor length could be $93 - 50 = 43$ m longer before exceeding the maximum permissible voltage drop; that is, since there are two supply conductors the run could be an extra 21.5 m.

2.11.4 Resistance tables

Conductor resistance can be established comparatively easily by reference to appropriate tables. The nominal resistance is often given in ohms per 1000 metres of cable and, by proportionate scaling either up or down, the resistance of any particular length of conductor can be obtained. For example, for 10 mm² cable the resistance of 100 m is 1.79 Ω. The resistance of 100 m would then be 0.179 Ω.

Care should be taken that any resistance values expressed in AS/NZS 3000 are not identified with the value given for the resistivity of copper in section 2.10.3, Table 2.4. The resistivity value given in this table is for 100 per cent pure copper, while the purity of commercial copper conductors is in the region of 95 per cent. Effectively the resistance of electrical cables is about 4 to 5 per cent higher than that of pure copper at the same temperature. Any resistivity table used should be examined to ensure that the quality of the conductor material is specified as either pure or commercial grade.

2.12 RESISTORS

A resistor is an electrical component that has the property of resistance. This resistance can be an advantage when connected into a circuit to produce a particular effect. It can be a disadvantage when its resistance produces an undesired effect.

Any conductor connecting a load to a supply at room temperature has resistance and it is considered a disadvantage, since voltage drop and heat are created. To counteract these unwanted effects, conductors have to be made larger to ensure the effects are reduced.

The following material applies to resistors and their construction. Their resistance has a finite value and is considered necessary to the working of an electrical circuit.

For most electrical work, resistors are constructed from either alloys of metals or from a carbon-based compound. A few are made from a compound similar to a semiconductor. These are called non-linear resistors and are discussed in section 2.13.

2.12.1 Wire-wound resistors

Three resistors are shown in Figure 2.22. The resistor at the top in Figure 2.22(a) is constructed with thinner wire and can carry a lesser current than that of the resistor shown in Figure 2.22(b). Owing to its greater physical size and current-carrying capacity, this resistor has a rating of 50 W. It needs a larger surface area to dissipate any heat created, or excessive temperatures will result. Wire-wound resistors are usually large enough to label them with their resistance value and power rating.

Both of these wire-wound resistors are fixed in value, but in Figure 2.23, showing some basic symbols, it can be seen that there are four resistors of this type that can be adjusted in value. The second and third units from the top can be preset, while the fourth unit can be adjusted while in service.

Resistors that can be varied while in service are often referred to as rheostats. They can be wire wound or the resistance element can consist of a carbon-based film. This type can carry only very small currents but their resistance can usually be varied over an extremely wide range. The physical make up of a rheostat often consists of the element manufactured in a circular pattern with a rotating contact able to be moved around the resistor element so varying the resistance. Usually both ends of the resistance element plus a connection to the rotating contact are brought out to suitable terminals.

2.12.2 Compound-based resistors

Carbon-based or conductive film based resistors are physically smaller and have lower power ratings. Common

(a) and (b) Wire-wound resistors

330 Ω, 5 W

27 Ω, 50 W

Spiral cut   End cap

Carbon-film coating
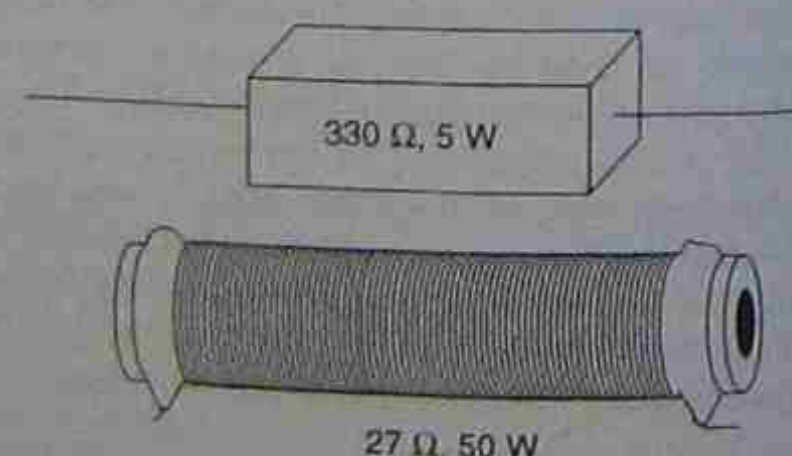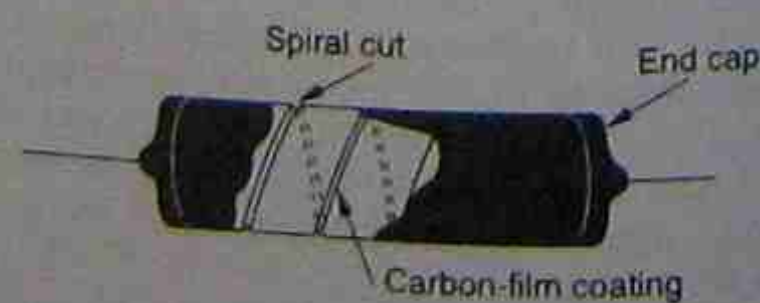
(c) Carbon-compound resistor

Figure 2.22 • Resistor types

Symbol	Object
Fixed resistor	
Adjustable resistor	
Tapped resistor	
Variable resistors	

Figure 2.23 • Basic resistor symbols

ratings are ¼ W, ½ W and 1 W. If these ratings are exceeded, rapid heat production will occur and destroy the resistor.

The construction of one of these resistors is shown in Figure 2.22(c). The resistive material is placed in the spiral of the body assembly. During manufacture, the actual composition of the compound can be varied so that the same length of spiral can be used to make resistors of different values.

Carbon-compound-based resistors are often so small that their resistor size and rating cannot easily be imprinted on them. This led to the development of a standard colour coding scheme for identification. The coloured bands on the fixed-value resistors are placed on one end during manufacture.

A later development of the carbon-based resistor was the metal-film resistor. The thin layer of compound placed in the spiral shown in Figure 2.22(c) is a metal-based resistive compound which replaces the carbon. After manufacture, the resistors are coated and branded with coloured bands to indicate their resistance and tolerance value.

Carbon-based film resistors are also manufactured as variable resistors and are then often called potentiometers. The volume control on a normal radio is one example of this type of variable resistor. It is shown in Figure 2.23 beneath the adjustable wire-wound resistor.

2.12.3 Power ratings

The power rating indicates the number of watts the resistor can dissipate without excessive heating. Dissipation means power is often wasted (I^2R_{loss}), because the heat is not used. For larger power ratings, resistance wire is used; for lower power ratings, a carbon-based composition is used.

The composition resistor gives good resistance stability with both temperature and age. The material is deposited on a ceramic body in which a helical groove is cut to give sufficient length. The physical size of the resistor body is often the only guide to its power rating. As an indication, the 0.5 W resistor has a body length in the order of 10 mm with a diameter of 4 mm.

2.12.4 Resistor colour codes

The composition resistor is generally suitable only for low power circuitry. Physically, the resistor is much smaller than a wire-wound resistor and there is a difficulty in labelling it with an appropriate value of resistance that can still be read. A system was developed using combinations of colours. The original system consisted of three colours (body one colour, one end another, with a coloured dot on the body) and the resistor was generally within a tolerance of ±20 per cent of its marked value. With improved manufacturing methods the physical size was reduced by using special compounds within a spiral on a ceramic body. This is shown in Figure 2.22(c). An improvement in accuracy led to closer tolerances. This in turn led to the use of three coloured bands with a fourth band being added to indicate the tolerance when desired. Ten per cent and 5 per cent tolerances then became relatively common. This stage is generally known as the four band code (see Fig. 2.24). The standard colour codes are shown in Table 2.6. It should be noted that in most cases the tolerance band is spaced slightly apart from the main indicating band and is always to the centre of the resistor body.

Example 2.17

Using Figure 2.24 and Table 2.6, determine the resistance values for the following resistors:

(a) green, black, yellow, with silver to indicate the tolerance
(b) brown, red, yellow
(c) yellow, violet, orange, gold.

(a) Green the first sig. figure = 5; black = 0; yellow (the multiplier) = 10^4; silver = ±10 per cent tolerance.
Resistor value = 5-0-0000 = 500 000 = 0.5 MΩ at ±10 per cent tolerance.

(b) Brown the first sig. figure = 1; red = 2; yellow = 10^4 with no tolerance band (= ±20%).
Resistor value = 1-2-0000 = 120 000 = 120 kΩ.

(c) Yellow the first sig. figure = 4; violet = 7; orange = 10^3
Resistor value = 4-7-000 = 47 000 = 47 kΩ with the gold band indicating ±5 per cent tolerance.
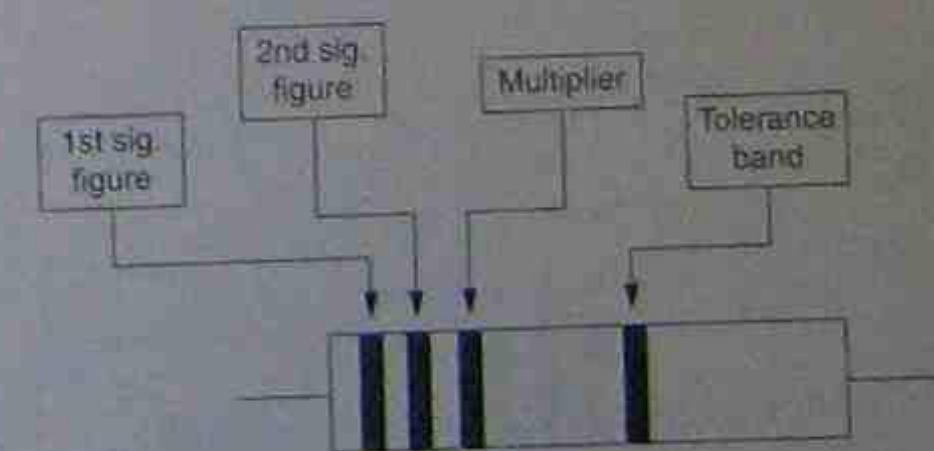

Figure 2.24 • Four band colour coding

Table 2.6 • Resistor colour code

Colour	Significant figures	Multiplier	Tolerance
Black	0	1 (10⁰)	
Brown	1	10 (10¹)	±1%
Red	2	100 (10²)	±2%
Orange	3	1 000 (10³)	
Yellow	4	10 000 (10⁴)	
Green	5	100 000 (10⁵)	
Blue	6	1 000 000 (10⁶)	
Violet	7	—	
Grey	8	—	
White	9	—	
Gold	—	0.1	±5%
Silver	—	0.01	±10%
None	—	—	±20%

The fourth band of either gold or silver is mainly used for indicating tolerances but if used in the third band position it indicates that the value of resistance must be divided by either 10 or 100 depending on which colour is used.

Five band colour codes

As the manufacturing process further improved it became necessary to indicate closer tolerances on resistors. The accuracy of the resistor being improved led to a wider range of standard or preferred values being produced, as shown in Table 2.7. This led to the introduction of a fifth band of colour. Currently resistors are reliably and accurately produced in large quantities with tolerances down to 1 per cent. As with the four band resistor, the tolerance band of the five band resistor is usually spaced slightly apart from the main indicating bands and towards the centre of the resistor body.

Example 2.18

Using Figure 2.25 and Table 2.6, determine the resistance value for the following resistors:

(a) green, black, black, orange, silver
(b) brown, red, black, yellow, gold
(c) yellow, violet, black, red, gold
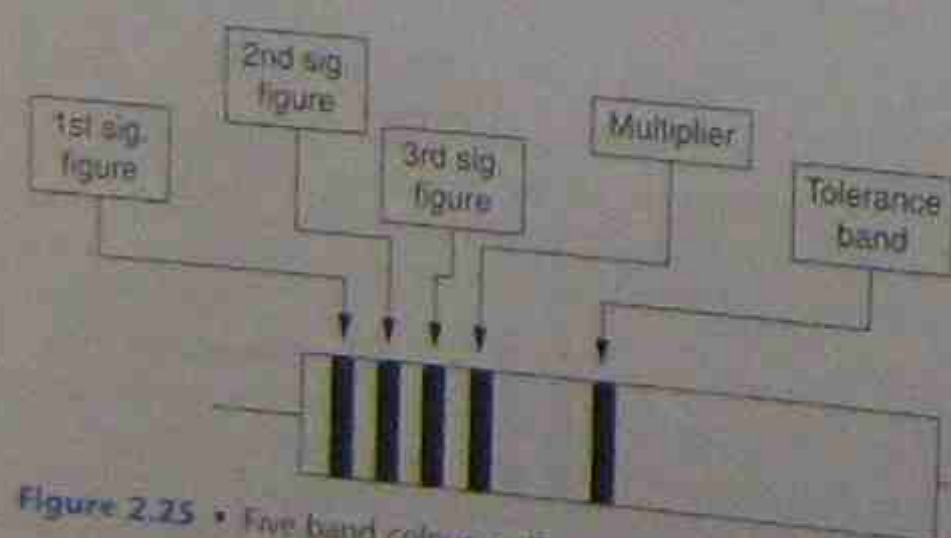
Figure 2.25 • Five band colour coding

(a) Green the first sig. figure = 5; black = 0; orange (the multiplier) = 10³, with a silver tolerance band.
    Resistor value = 5-0-0-000 = 500 000 = 0.5 MΩ with ±10 per cent tolerance as before in example 2.17(a).
(b) Brown the first sig. figure = 1; red = 2; black = 0; yellow = 10⁴, with a gold tolerance band.
    Resistor value = 1-2-0-0000 = 1 200 000 = 1.2 MΩ, ±5 per cent tolerance.
(c) Yellow the first sig. figure = 4; violet = 7; black = 0; red = 10², with a gold tolerance band.
    Resistor value = 4-7-000 = 470 000 = 47 kΩ, at ±5 per cent tolerance as before in example 2.17 (c).

Note the different colour bands from the four band colour code.

2.12.5 Preferred values of resistors

With the idea of rationalising the manufacturing process, the number of different values of resistors made was reduced to a standard called the preferred range.

The range was based on one movement of the logarithmic scale, divided into equal spaces—by choosing the appropriate tolerance value, individual intervening sizes could be selected.

Table 2.7 shows the preferred range for three series of tolerances.

Table 2.7 • Preferred range of resistor values

20% tolerance	10% tolerance	5% tolerance
10	10	10
		11
	12	12
		13
15	15	15
		16
	18	18
		20
22	22	22
		24
	27	27
33		30
	33	33
		36
	39	39
47		43
	47	47
		51
	56	56
68		62
	68	68
		75
	82	82
		91

2.13 NON-LINEAR OR TEMPERATURE-DEPENDENT RESISTORS

It was shown in section 2.10.4 that conductor resistance is affected by temperature. The rising or falling characteristic can be used to advantage in electrical circuits. Where the temperature of a circuit or device rises, the change in resistance is used to alter the circuit's behaviour to compensate for the temperature change. With electrical machinery, the resistors can be used in circuits that will switch the power off if temperatures shift outside a specified range.

2.13.1 Positive temperature coefficients (PTC)

Metals generally have a positive temperature coefficient of resistance, but a PTC semiconductor resistor is one in which the change in resistance is greatly increased over that change in a normal conductor. Two main materials are used. One is a metallic oxide such as barium oxide, which has a large PTC over a limited range; the other is silicon based with a smaller PTC over a larger range. The typically shaped characteristic is shown in Figure 2.26(a). The more usual method is to show the resistance values on a logarithmic scale, but in order to show the sharp knee of the curve as the PTC heats up, a representative curve has been drawn from test results on an actual resistor. It can be seen that the resistance is only 4 Ω at room temperature but rises rapidly once the temperature rises above about 50°C.

2.13.2 Negative temperature coefficients (NTC)

NTC resistors are made from oxides of chromium or nickel that have been modified by the addition of small amounts of semiconductor material. Similar tests were conducted on an NTC resistor and the results are shown in Figure 2.26(b). Again the more usual logarithmic scales have been avoided. The test resistor had a resistance of 2000 Ω

at room temperature of 10°C, and when raised to 80°C the resistance fell to 4 Ω. The characteristic is shown in Figure 2.26(b).

2.13.3 Low temperature coefficients

In some circumstances a resistor is required to retain its value over a range of temperatures. Special alloys have been developed for this purpose, one of which is manganin. In Table 2.5, manganin's temperature coefficient is given as 0.000 01. Its resistance change is so small compared with metallic elements generally that it is often listed as zero. Manganin is used where resistors of high temperature stability are required, as in measuring instruments.

2.13.4 Voltage-dependent resistors (VDRs)

A voltage-dependent resistor is manufactured from a mixture of materials and is usually presented in disc form with two leads for connection into a circuit. The VDR is connected in parallel with the voltage supply close to the circuit it has to protect. Normally non-conducting, it is given a voltage rating at which it breaks down and conducts. Its primary purpose is to protect equipment against voltage surges such as lightning strikes. Its response time is extremely quick, an obviously necessary characteristic. In some circuits VDRs are intended to blow a fuse or trip a circuit breaker to isolate the electrical circuit being protected. Depending on individual circuits the VDR might have to be replaced after it has operated, although in some circuits, once the excess energy has been dissipated, they can resume normal operation.

2.13.5 Light-dependent resistors (LDRs)

Most light-dependent resistors are usually made from cadmium sulphide mounted on a plate and covered with a vacuum-deposited metallic grid. To ensure there is no build-up of contamination and to protect the active material the resistor is mounted in an evacuated glass envelope or covered with a clear moulded plastic surface.

The resistance of the device varies considerably with the amount of light received on the surface. Typically the resistance in complete darkness can be as high as 10 MΩ
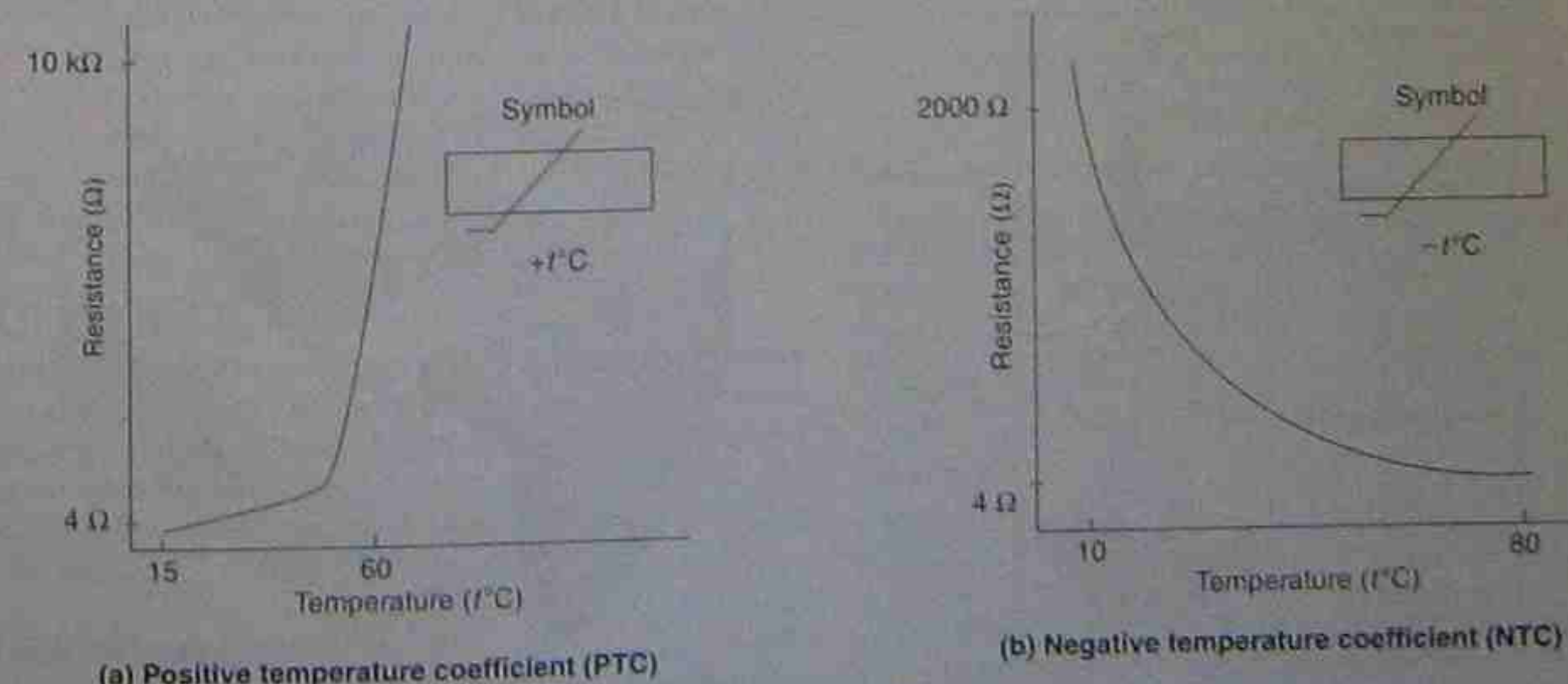

(a) Positive temperature coefficient (PTC)

(b) Negative temperature coefficient (NTC)

Figure 2.26 • Temperature-dependent resistors

2.14 OTHER ELECTRICAL COMPONENTS

2.14.1 Inductors

2.14.2 Capacitors

2.15 HEAT

2.15.1 Heat energy

2.15.2 Temperature

2.15.3 Specific heat capacity

$$energy = power \times time$$

$$E = Pt \ joules$$

where T = absolute temperature in K
    m = mass in kilograms
    c = specific heat capacity

Rather than using absolute values, the usual type of problem involves establishing the relationship between heat energy and temperature of a body. The above formula can be used but it is easier to use the Celsius scale than the Kelvin scale. (In section 1.3.1 it was stated that the temperature interval for both scales was identical.)

$$Q = mc(t_2 - t_1)$$

where Q = quantity of heat
    $(t_2 - t_1)$ = temperature difference in °C

Example 2.19

An aluminium pan of mass 0.5 kg containing 0.25 kg of water is heated from 20°C to 100°C. How much heat energy has been received by the pan and its contents?

Step 1 $Q_{pan} = mc(t_2 - t_1)$
    $= 0.5 \times 900 \times (100 - 20)$
    $= 36\,000$ J

Step 2 $Q_{water} = mc(t_2 - t_1)$
    $= 0.75 \times 4180 \times (100 - 20)$
    $= 250\,800$ J

Step 3   Heat energy added $= Q_{pan} + Q_{water}$
    $= 36\,000 + 250\,800$
    $= 286\,800$ J
    $= 286.8$ kJ

Example 2.20

A copper and an aluminium block (both of mass 1.5 kg) had 2 kJ of heat energy added to each. If the initial temperature was 25°C, calculate the final temperature for each block.

Step 1 $Q_{copper} = mc(t_2 - t_1)$
    $2000 = 1.5 \times 390 \times (t_2 - t_1)$
    that is, $(t_2 - t_1) = \dfrac{2000}{1.5 \times 390}$
    $= 3.4°C$

Step 2 $Q_{aluminium} = mc(t_2 - t_1)$
    $2000 = 1.5 \times 900 \times (t_2 - t_1)$
    that is, $(t_2 - t_1) = \dfrac{2000}{1.5 \times 900}$
    $= 1.5°C$

Step 3   Final temperatures: copper $25 + 3.4 = 28.4°C$
    aluminium $25 + 1.5 = 26.5°C$

2.15.4   Heat transfer

As stated in section 2.15, heat energy moves from high to low temperature levels, the rate of energy transfer depend-

ing partly on the temperature difference between the two levels. That is, a higher temperature difference gives a faster heat transfer rate than a lower temperature difference.

There are three recognised processes of heat transfer.

1. Conduction

As a material rises in temperature, the molecules and their associated electrons gain energy. This extra energy is transferred through the material by means of collisions between electrons and atoms.

2. Convection

Convection is the transfer of heat energy from one place to another by the actual motion of the material. For example, as a bowl of water is heated, the molecules near the heat source expand and rise through the water, while colder molecules move into their place. The currents generated in the water are called convection currents.

3. Radiation

Heat energy is transformed into radiant energy, which is similar to light or radio waves. In this form the energy can travel considerable distances and can also travel freely in a vacuum. When interference is met, the energy changes back into heat energy at the obstruction.

2.15.5   Thermal conductivity

The rate of heat conduction through a material is measured in watts and depends on:

1. temperature difference (gradient) across the material
2. cross-sectional area of transfer path
3. length of transfer path
4. type of material.

The best conductors of heat are metals; poor conductors such as wood or glass, offer higher opposition to heat energy flow.

Thermal conductivity is the ability of a material to transmit heat by conduction. For any one material this is a constant value and is often called the k-factor.

When heat is being generated in a material, as in the case of a conductor with an electric current flowing through it, the temperature of the conductor begins to rise. Heat energy then passes through the insulation at a rate determined by the material's thermal conductivity and is transferred away to the air. When the heat energy being generated is equal to the heat energy being lost, the temperature of the conductor stabilises—but at some temperature above that of the conductor's surroundings.

In this case heat energy losses can be an advantage but in the case of a hot-water storage heater they can be a disadvantage because they lead to lower efficiency and higher operating costs. To reduce the loss, and retain heat energy, manufacturers wrap the water container in a material that has poor thermal conductivity.

2.15.6   Electrical heating

Most electrical appliances rely on the principle that current flowing through a resistor consumes electrical energy and transforms it into heat energy. The actual quantity of heat energy produced depends on the length of time the appliance is connected to the power source.

Example 2.21

How many units of heat energy are created by a 26 Ω resistor connected to a 240 V supply if the supply is left switched on for 45 minutes?

$$P = \frac{V^2}{R}$$

$$= \frac{240^2}{26} = 2215 \text{ watts}$$

Heat energy: $W = Pt$
    $= 2215 \times 45 \times 60$
    $= 5\,980\,500$ joules
    $= 5981$ kJ

Example 2.22

The resistor in example 2.21 was used to heat a water urn containing 18 L of water. If the initial temperature was 15°C, what would be the final temperature? Assume the container absorbs 2000 J and the heat lost by radiation is 4000 J.

The 18 L of water weighs 18 kg, and 1 kg requires 4180 J to raise the temperature 1°C, therefore 18 kg requires $4180 \times 18 = 75\,240$ J to raise the temperature 1°C.

From example 2.21:

    total heat energy used $= 5\,980\,500$ J
    losses total $2000 + 4000 = 6000$ J
    ∴ useful heat $= 5\,980\,500 - 6000$
    $= 5\,974\,500$
    ∴ temperature rise $= \dfrac{5\,974\,500}{75\,240} = 79.5°C$

    final temperature of water $= 15 + 79.5 = 94.5°C$

Note that the cost of heating the water would be as described in section 2.9.4. The water heater above would have an electrical energy consumption of

$$W = Pt$$

$$= \frac{240^2}{26} \times \frac{1}{1000} \times \frac{45 \times 60}{3600}$$

$$= 1.66 \text{ kWh}$$

2.16   EFFECTS OF ELECTRICITY

Three effects of electricity have been mentioned so far. They are summarised briefly in sections 2.16.1 to 2.16.3. A fourth, or side effect (physiological) is described in section 2.16.4.

2.16.1   Chemical effects

Reference was made in section 2.5.4 to a voltage being produced between two dissimilar metals placed in a conducting solution called an electrolyte. Volta produced both the voltaic pile and the voltaic cell (see section 2.5). However, it was later discovered that this action could sometimes be reversed. It led to the modern electroplating methods and the secondary cell.

In a voltaic cell, corrosion is set up and is considered a

desirable effect because dynamic electricity is produced. In another situation the electrolytic action between two dissimilar metals in a damp situation produces a voltage but it is usually an undesirable effect. The same situation reproduced in an electroplating bath is a desirable result. For further information on these effects refer to Chapter 3.

2.16.2   Heating effects

When the opposition of a conductor (its resistance) is overcome by an applied voltage and a current flows, work is done and energy is expended. Heat is produced and this raises the temperature of the conductor and increases its resistance.

If a conductor of high resistance is concentrated in a small area with suitable safeguards and insulation, a source of heat is available as in the domestic radiator. Certainly if is a desirable result, but consider the end result if great quantities of heat are produced in the conductors supplying the electrical energy to the radiator. The conductors may be inside the hollow walls of a building and if the temperature around the enclosed conductors is raised sufficiently, the possibility of fire exists.

Steps must be taken to prevent such an undesirable event. The current flow must be reduced, or the conductor cross-sectional area increased. Both steps lead to reduced power loss and a reduced heating effect in the supply conductors.

2.16.3   Magnetic effects

Magnetism is created around any conductor when a current flows through it. If this magnetism is unwanted, consideration must be given to rerouting the conductors to diminish the effects. Magnetic compasses are subject to stray magnetic fields and care must be taken to ensure that they are not affected in any way. With large currents, considerable forces can be set up between conductors and precautions have to be taken in this case also.

When the magnetic effect is a desirable one, steps are taken to concentrate the magnetism in specific locations. The magnetic effect is increased by creating coils of conductors called solenoids. Many turns may be added to the coils to enhance the effects. For more details on magnetism see Chapter 5.

2.16.4   Physiological effects—electrocution

It can be argued that an electric shock is not an effect produced by electricity but is often an unwanted result brought about by unintended use and handling of electrical conductors. Seldom does it produce a desirable result. Electric fences to keep livestock in and the neighbour's children out might be considered desirable uses by some, but not by others. Indeed there are standards and safeguards that must be observed in this case.

The general effect of electric shock on the human body is unpleasant. Severe or prolonged cases of electric shock lead to the heart ceasing its rhythmic beating and entering a stage of fibrillation. The heart might stop beating altogether. Fibrillation is a state of very rapid unco-ordinated muscular spasms and causes a cessation of blood flow around the body.

Medical attendants use a 'defibrillator' in an attempt to start normal heart pumping action. A defibrillator is a

device in which a capacitor is charged. Electrodes connected to the machine are placed at appropriate places on the body and the capacitor is discharged in an attempt to shock the heart into resuming normal rhythm.

2.16.5 Supply voltages

Reduced power losses generally equate with higher voltages. To reduce power losses, the resistance of transmission conductors must be reduced as far as is practicable. The only steps that can be taken are to increase the cross-sectional area of a conductor, thus decreasing its resistance and at the same time decreasing the current flowing through it.

Increasing the cross-sectional area of a conductor is a task easily accomplished by replacing the conductors with larger ones. Decreasing the current flowing through a conductor and still maintaining the same power levels means that the voltage of the supply must be increased. For example, the family-room television receiver takes about 2.6 A on 240 V but would need more than 100 A if the supply voltage was 6 V.

A 415/240 V 50 Hz supply with neutral is standard for most installations in Australia. These voltages are a compromise between standardisation, safety, conductor size, practical convenience and economics. The possibilities of electric shock at these voltages are increased, but provided suitable precautions are taken, it is considered an acceptable risk. The Standards publication AS/NZS 3000 details suitable guidelines for installations under these conditions. There has been some agitation to adopt the European standard of a 230/400 V 50 Hz supply but with comparatively minor support at this stage. The general standard in the United States and Canada is 110-220/380 V 60 Hz supply.

It would be much safer if voltages were kept below a nominal voltage, say 6 V. The possibility of electric shocks would be minimised but it is not a practical or economic reality to operate such a system.

2.16.6 Effects of an electric shock

In spite of all precautions, accidents do happen, and electric currents can pass through the body. Electrical energy can be dangerous and the extent of the damage done to the body depends on the path it takes through the body and the amount of current flowing.

Path of current

There are two major types of current path through the human body. These are illustrated in Figure 2.31. In Figure 2.31(a) the path is from the hand through the arm, then back to the other conductor. No vital organs are in the path. In Figure 2.31(b) a faulty drill with no earth wire can cause the current to flow through the worker's body to earth. The current passes through the heart and lungs on its way to earth. It is a potentially more dangerous situation. A person can survive quite large electric shocks provided it does not pass through the body. The shock can be extremely painful and can cause burning of the skin and even create holes where the current enters and leaves.

Amount of electric current

The amount of current that can cause an electric shock varies widely from person to person. The principal factor
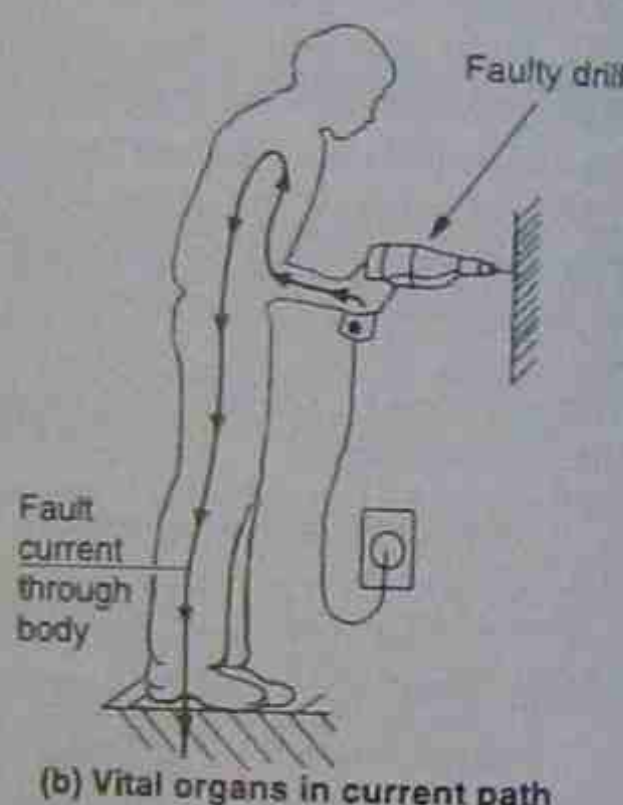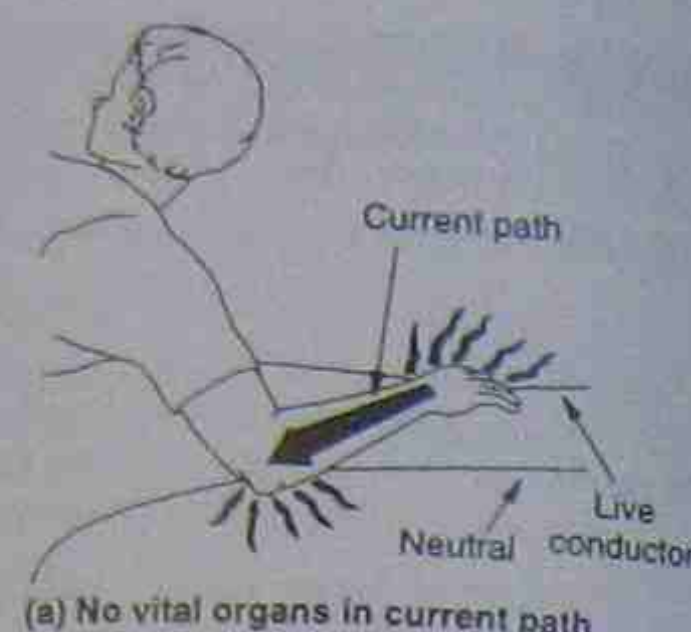
(a) No vital organs in current path

(b) Vital organs in current path

Figure 2.31 • Current paths through the human body

that governs whether the shock is mild or severe depends on the resistance of that body at any given voltage. A 1 mA current can cause extreme pain to an infant, while it is only an uncomfortable feeling to an adult. A 10 mA current can be fatal to infants and adults if it flows through the chest and/or the brain. Electrocution victims have survived much higher currents when the path of electricity is not through these areas.

On a 240 V domestic supply the adult human body in normal circumstances exhibits a resistance of about 1000 Ω to a current flow from hand to earth. This means that a current can reach a value of 200 mA or more.

Duration of an electric shock

It becomes difficult to predict what the effects of electrocution would be, because the path and the amount of current are involved, and also the time the electrical shock is applied is an important factor. Small amounts of electric current flowing for long periods can be just as lethal as large currents of short duration.

For electrical workers, one of the most common paths is from one hand to the other where the current flows through the heart and lungs. A form of paralysis sets in so that the muscles in the hands and arms contract and the person is usually unable to let go of the live conductors. The heart's rhythm is interrupted and can stop pumping blood around the body. Severe brain damage can occur in three to four minutes unless speedy action is taken.

2.16.7 Treatment for electrocution

Remove victim from the supply

Turn off the power supply if at all possible and remove the electrocuted victim. If the power supply cannot be turned off immediately, do not touch the victim without adequate precautions. Do so only by indirect means; for example, use a dry piece of wood or rope as insulation for yourself. Articles of clothing can be draped over the victim so that he or she can be pulled free of the live conductors.

Decision time—what type of resuscitation?

Once the victim is removed from the electrical supply a decision has to be made. There are two questions:

1. Is the victim breathing?
2. Is the victim's heart beating?

The answers to these questions determine the rescuer's next steps. If the victim is merely unconscious, action may not appear quite so urgent, but action is still required. If the victim's heart has stopped, chest massage is required. If the heart is beating but breathing has stopped, then mouth-to-mouth resuscitation may be required.

The application of chest massage and mouth-to-mouth resuscitation is beyond the scope of this book and references to proper training should be sought elsewhere.

Assistance

It is important to call for assistance. Sufficient information must be passed on to a third party to get additional help and/or resources. In the meantime, the rescuer should not stop resuscitation actions until directed to by someone in authority.

2.17 CIRCUIT PROTECTION

Electrical circuits are designed to work with specific maximum values of current. The circuit can be used for loads using lesser current values than the designed value but must be protected against higher values. For example, a 20 A circuit would be wired with conductors capable of carrying 20 A continuously. It is not designed to carry currents in excess of this figure.

2.17.1 Overload currents

An overload current is a current flow slightly greater than the designed value for any circuit. A current flow of 30 A or 35 A in a 25 A circuit would be considered an overload. Overload currents can be deliberate or accidental. Multi-outlet power boards are available with six or more general-purpose outlets mounted on them. To be of a legally approved type they must have some form of current-limiting device installed.

Two-way adapters plugged into general-purpose outlets enable two appliances to be used from the one outlet. They enable a circuit to be overloaded quite easily since there is no form of current limiting installed.

2.17.2 Fault currents

A fault current has a value greatly in excess of the circuit's rated value. An excessive current flow of say 1500 A in a 25 A circuit would be treated as a fault current. It is often created by a short-circuit on an appliance or machine, the only current-limiting factor in the circuit being the resist-

ance of the supply lines. For example, if a short occurred in a domestic socket-outlet 20 m distant from the switchboard, the current that would attempt to flow would be nearly 1700 A. A length of 20 m of 2.5 m² copper cable has a resistance of 0.143 Ω. Using Ohm's law:

$$I = 240/0.143 = 1680 \text{ A}$$

It should be noted that these figures enable a fault rating to be obtained. It is found by multiplying the voltage of the supply and the fault current, rather like obtaining a power rating as described earlier in section 2.9.1. It is, however, called a volt-ampere rating and the item of equipment has to be built to withstand these values; that is, 1680 A × 240 V = 403 200 VA or 403.2 kVA. The current flow would not necessarily reach 1680 A because the above calculations do not allow for the resistance of all the conductors reaching back to the supply source. This may be merely a transformer several hundred metres remote from the fault. Nevertheless, a short-circuit current would certainly approach 1000 A—a figure far too high for safety. It does, however, indicate the magnitude of fault currents.

2.17.3 Protection devices

While there are a great number of variations in the protection devices available, they can generally be classified into three groups as described below.

Fuses

The operating principle is one of fusing (melting with heat generated by the current flow) a metal at a specially designated position in the circuit (the fuse element). The intent is to protect the circuit and any connected equipment.

Circuit breakers

The operating principle is one of actually switching off the power to the faulty circuit. This can be done by either heat or the magnetic field generated by the flowing current. The intention is to protect the circuit and any connected equipment.

Residual current devices

The operating principle is to disconnect the power from the circuit when an unbalance in current occurs. It is discussed in more detail in section 2.17.6. Its purpose is to protect the operator of the circuit rather than the circuit and any connected equipment.

2.17.4 Fuses

A fuse holder and fuse is an electrical assembly placed in a circuit to protect that circuit against excessive current flow. A fuse element is a short metal link placed in the fuse holder and is intended to be destroyed by the higher than normal current. By being destroyed, it ensures that an open-circuit occurs, so preventing more current flowing in that circuit.

One popular model of a fuse is illustrated in Figure 2.32(a). Its usual size is 32 mm × 6 mm. It can be seen that the fuse element is very much smaller in cross-section than the conductors that would carry normal current flow. The replaceable fuse element has metal caps on the ends of a glass tube so that the fusible element can be readily seen.
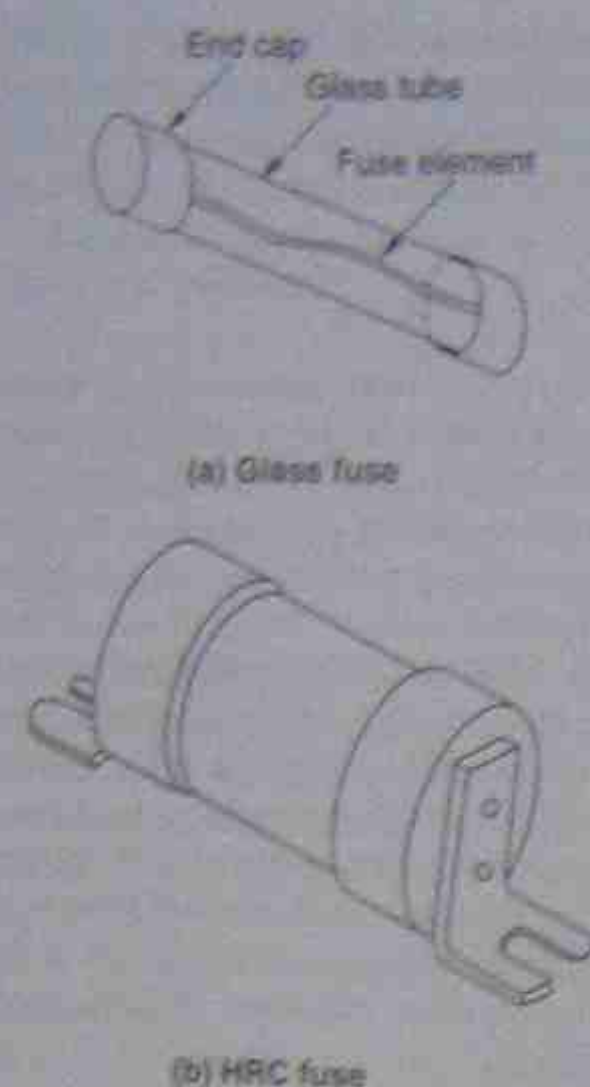
End cap
Glass tube
Fuse element

(a) Glass fuse

(b) HRC fuse

Figure 2.32 • Replaceable fuse elements

Once very popular as an auto fuse, they are seen less and less today owing to the influence of Asian cars on the Australian market. They are still used in great numbers in electronic equipment. They are designed to be replaced rather than repaired. The unit cost is relatively low and their use is mainly restricted to low-voltage circuits.

Porcelain 'house'-type fuses once common in both industrial and domestic installations are becoming fewer in number. The fusible element can be replaced with comparative ease but the process lends itself to the fusing element being replaced either with the wrong size or the wrong material. The element is exposed to the atmosphere and can deteriorate over a period of time. This affects its fuse rating—usually downward to a lesser current rating—and the element has a much broader tolerance and variable 'blowing' value.

In an endeavour to obtain reliable fuse ratings that are constant for lengthy periods, the high rupturing capacity (HRC) fuse was introduced. The fusible element is surrounded by an inert material in an insulated body to evacuate a stable temperature while in use.

This method of construction also enables it to safely interrupt the high fault currents so common in today's electrical systems. See Figure 2.32(b).

Since the HRC cartridge fuse retains much of the heat generated in previous loads, it tends to be subject to a memory effect that causes rupture of the cartridge for small overloads after a period of higher than normal currents, but not after normal full-load currents.

The HRC fuse element has a rating much less tolerant to a suitable blowing value than a porcelain fuse where the element is exposed to atmospheric conditions.

There is no replaceable section in an HRC fuse. A replacement cartridge must be used. The initial cost of the fuse assembly is higher than that of a porcelain fuse, as is the replacement cartridge.

In less common use are glass fuses containing a liquid

intended to quench the arc as the fuse element blows. The element cannot be repaired and must be replaced. Much higher costs are involved and their use is generally restricted to high-voltage distribution circuits.

2.17.5 Circuit breakers

Circuit breakers were once expensive, and as a consequence seldom used. They are now much cheaper and this, combined with the advantage of being easily reset, makes them a much more popular item to install. There is the added convenience of not having to replace a component and the dubious advantage of not needing trained personnel to restore power to a circuit. Untrained people can and do reset circuit breakers. If the fault is merely one of a slight overload or a temporary current surge, there are usually no problems associated with the event.

Resetting a circuit breaker after it has tripped can result in very high fault values as discussed earlier. If the breaker is tripped by a major fault, then resetting the breaker will simply cause it to trip again. If the circuit breaker continually trips and is just as often reset, considerable damage can be done to either the circuit or the circuit breaker.

Inspection of a porcelain fuse wedge can give some indication of the current values involved, but a circuit breaker cannot do this. A degree of commonsense and some basic electrical knowledge is needed when checking a tripped circuit breaker.

Thermally activated circuit breakers

Figure 2.33(a) illustrates the principle of operation of a thermally activated circuit breaker. The main operating element is a bimetal strip which holds the contacts closed in the 'on' position.

The load current flows either through the bimetal strip or through a heater coil wound around it. As the bimetal strip heats, it bends and eventually allows a spring to pull the two contacts apart, opening the electrical circuit.

Note that in the worst case the fault currents may be quite high, so the contacts themselves have to be substantial. To assist the contacts to cope with the burning effect of the fault current, there is often a built-in arc-quenching device.

The time taken to heat the bimetal strip leads to a time delay in the action. On a major fault, that means that fault currents may flow until the breaker is tripped.
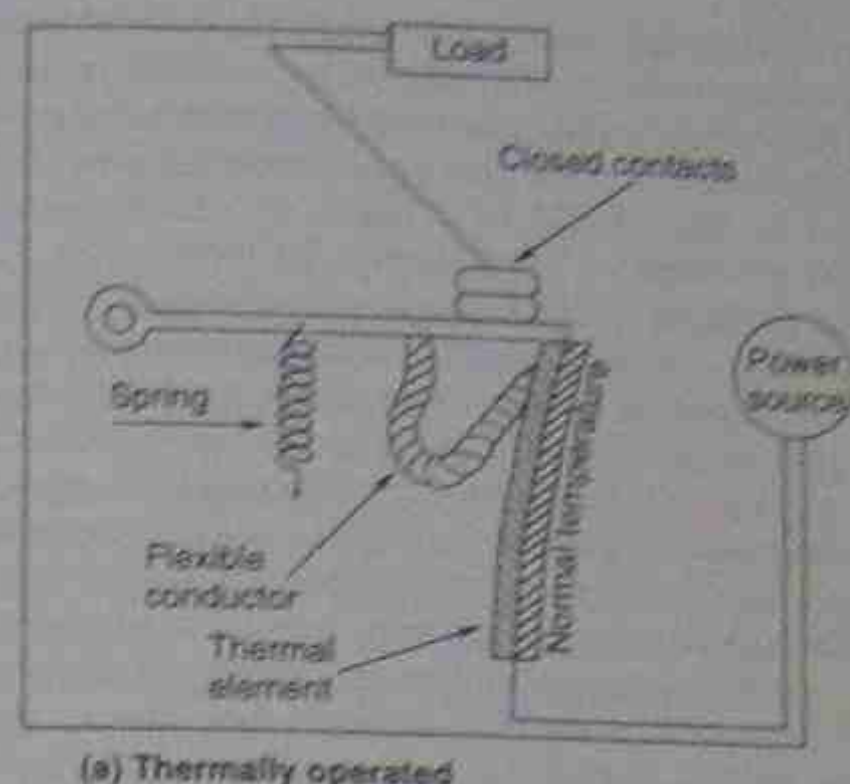
The amount of heat held by the bimetal strip enables the breaker to 'remember' previous loads and act more quickly, after a time, to smaller overloads.
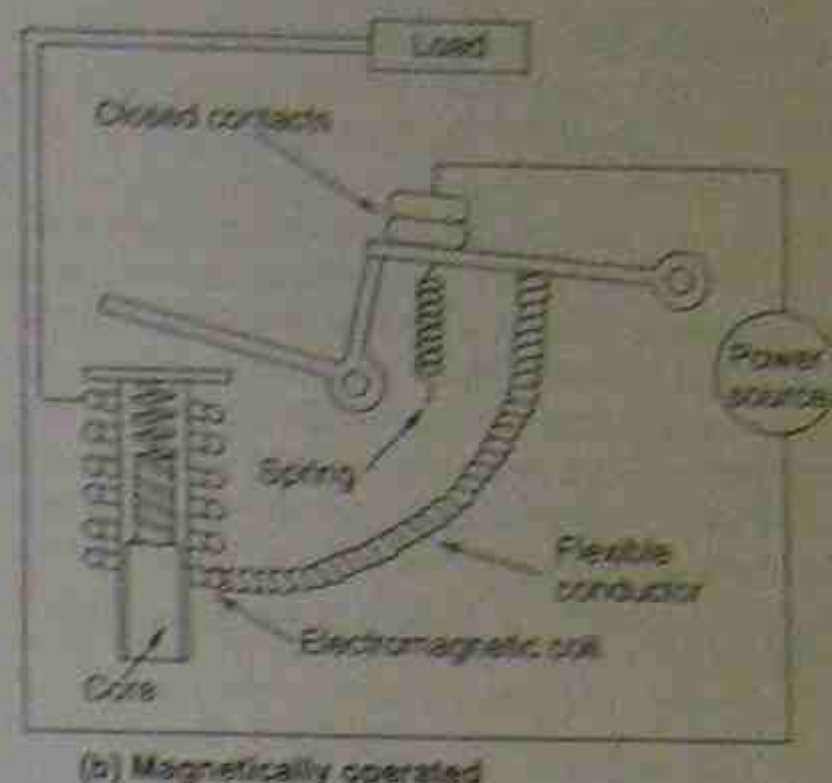
Magnetically operated circuit breakers

Figure 2.33(b) illustrates the principle of the magnetically operated circuit breaker. Any current flow through the circuit breaker is directed through a coil wound around a magnetic core. When the current is sufficiently large, it attracts an adjacent 'armature', so releasing the contacts and allowing a spring to pull them apart.

Combined thermal/magnetic activated circuit breakers

Generally there is no tolerance in tripping currents with a magnetically operated circuit breaker. If it trips at 20 A it will always trip at 20 A. The considerations for resetting a

---

(a) Thermally operated

Load
Closed contacts
Spring
Power source
Flexible conductor
Thermal element
Normal temperature

(b) Magnetically operated

Load
Closed contacts
Power source
Spring
Flexible conductor
Electromagnetic coil
Core

Figure 2.33 • Actions of a circuit breaker

magnetic circuit breaker are similar to those for the thermal type. The major difference between the two types is that the time delay of the magnetic type is almost non-existent—a few thousandths of a second.

It has been found that a more practical circuit breaker is one that combines the characteristics of both thermal and magnetic operation. The magnetic type has the quicker action and is more suited to high overload currents and is adjusted in manufacture to operate at higher currents, while the thermal section is better suited to handling slight overload currents and only tripping after a short time delay. It is also fitted with an arc-quenching mechanism.

2.17.6 Residual current devices

Core balance devices have been developed as a means of protecting users from the dangers of electric shock. Previously called earth-leakage circuit breakers, which caused them to be confused with another device, the name was changed to residual current device (RCD). By Australian standards it is mandatory for all new installations and/or circuits to have one installed.

An RCD is connected in series with both conductors so that the current flowing in one conductor returns via the second conductor. Special versions are available for three-phase work.

The operating principle is based on that of a balanced differential transformer. In Figure 2.34 it can be seen that a toroidal magnetic core has three coils wound on it. Two of these are identical and are connected in series with the connected load. Each has the same number of turns of the same size conductor, while the winding direction is such that each coil creates a magnetic flux opposing that created by the other coil. The net flux in the core is therefore zero.

The third coil is the sensing coil. While the two identical load coils have identical currents flowing through them, the sensing coil has no voltage induced in it.

Any current bypassing the return conductor and returning to the supply by an alternative path upsets the magnetic balance of the core. For example, an appliance with a resistive path to earth enables current to return without
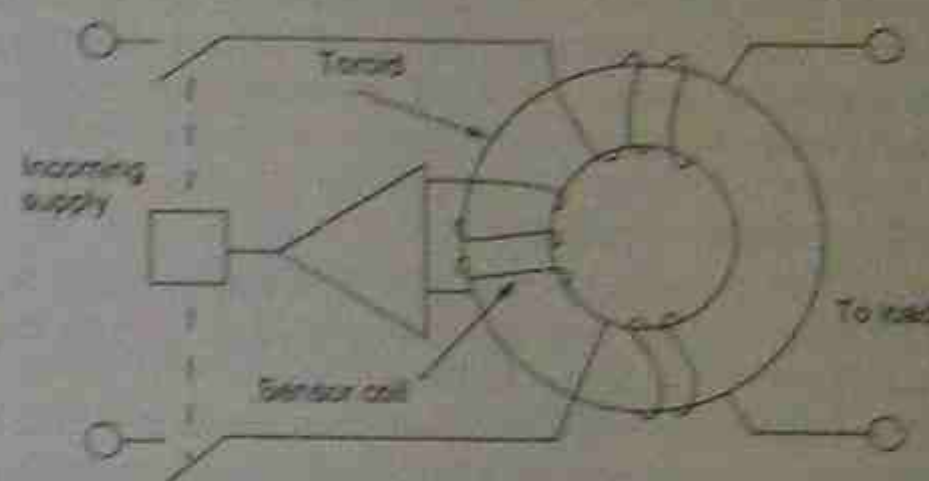

Figure 2.34 • Principle of a residual current device

passing through the conductors on the toroid. One winding produces a stronger magnetic field than the other and a net magnetic field exists in the core.

When this occurs, the sensing coil has a voltage induced in it. This voltage is connected to an electronic circuit where it is amplified to operate a tripping mechanism in the RCD. The RCD then disconnects the supply from the circuit.

Manufacturers can produce a variety of models with different tripping currents, but the usual household RCD is sufficient to sense an error and disconnect the supply. A common figure is 30 mA. The time for the RCD to act is so short that seldom is permanent harm caused to an individual.

At lower values, more protection is provided but the device is then subject to nuisance tripping. For example, a capacitor in the line for motor starting also has capacitance to earth. When the motor starts, it is possible for a leakage current to occur and isolate the circuit controlling the motor. Heaters are subject to leakage currents and can trip RCDs. Fluorescent lamps produce voltage surges that can trip RCDs.

Points to note:

• RCDs are not suitable for all types of loads.
• RCDs do not limit earth leakage currents. They only limit the time the current flows. Painful electric shocks can still occur.
• RCDs should not be 'too' sensitive for better protection. They then become subject to nuisance tripping.

- In domestic situations, most faults occur with extension and appliance flexible cords. RCDs should protect these situations by being connected in general-purpose outlet circuits.

- RCDs cannot offer complete protection against electric shock. Many accidents occur when contact is made between a live conductor and neutral. An RCD will not operate in this situation.

- Because of their short time delay in acting, they do offer protection against electrocution for any length of time in situations that can lead to the heart rhythm being interrupted (ventricular fibrillation).

- Placing an RCD in a circuit is no excuse for complacency.

2.18   SAFETY

A working place is only as safe as a worker makes it. Safety depends on a set of rules and workers acknowledging and using them. In industry the rules are generally enforced both by management and unions, but when working alone, as in a domestic situation, self-discipline must be exercised.

2.18.1   Safe working

Safety rules are mostly a matter of commonsense. Safe work habits can be developed and used so that in time they will tend to become automatic.

Electrical energy is a useful source of power but can be dangerous when carelessly handled or misused. Some important points to be observed are:

- Make sure all connections are secure before turning on the power.

- Check the circuit carefully before connecting it to a power source. Test it thoroughly.

- Regard all equipment as being alive until testing has proved otherwise.

- When removing the power from equipment to work on it, take precautions to ensure that no-one will be able to turn the power on again until work is completed.

- Isolate switches or fuses, and place notices on the related equipment for others to read.

- When removing these notices, check to see that no-one else has placed another notice on or under your notice.

- If a local isolating switch is provided, make sure it is used. Place a notice on it also, before commencing work.

2.18.2   Earthing of equipment

As mentioned earlier, the resistance of the human body is in the region of 1000 Ω on a domestic supply of 240 V. This figure can vary according to working conditions.

In hot weather, body resistance falls, due to perspiration, and electric shocks can be of increased intensity. When working in damp conditions, similar considerations apply. Hand-to-hand resistance in bad conditions can fall to 500 Ω.

One way of reducing the possibility of an electric shock is by connecting all appliances to earth. This is usually

done by driving a metal stake into the ground in a suitable location. In larger installations it may be done by burying an earth mat which can extend several metres in all directions. In each case the earthing system must be placed in the ground to a depth at which the ground retains moisture.

In a multiple-earthed neutral system, each installation has at least one major earth point connected as solidly as possible to earth. Connected to this major earthing point is a conductor extending back to the main switchboard. This conductor is the main earthing conductor. It connects the earth stake to both the earth link and the installation's neutral link. In smaller installations the earth link is often omitted and all earthing conductors from submains and other circuits are required to be connected direct to the main earth conductor in an approved manner as required by the various supply authorities. All neutral conductors are connected to the installation's neutral link. The principle is illustrated in Figure 2.35.

When an appliance develops a fault, any current flows through its earth wire back to earth, so bypassing the operator. Referring back to Figure 2.31(b), it can now be seen that with an earthing conductor in place, the current path would have been through that conductor to earth rather than through the worker.

Depending on the fault and the circuit protection used, a fuse may blow, a circuit breaker may trip, or the residual current device might operate. In any event the expectation is that the operator is saved from electrocution.

Earthing conductors are important and should always be used. The only occasion where an earth wire is not used is on an appliance marked 'double insulated'. This is designated by a symbol of two concentric rectangles on the appliance body. In double-insulated equipment, extra precautions are taken with the insulation used and with the intention to protect the operator from electric shock.

With extension flexes and appliance plugs it is important to ensure that the earthing conductor is correctly
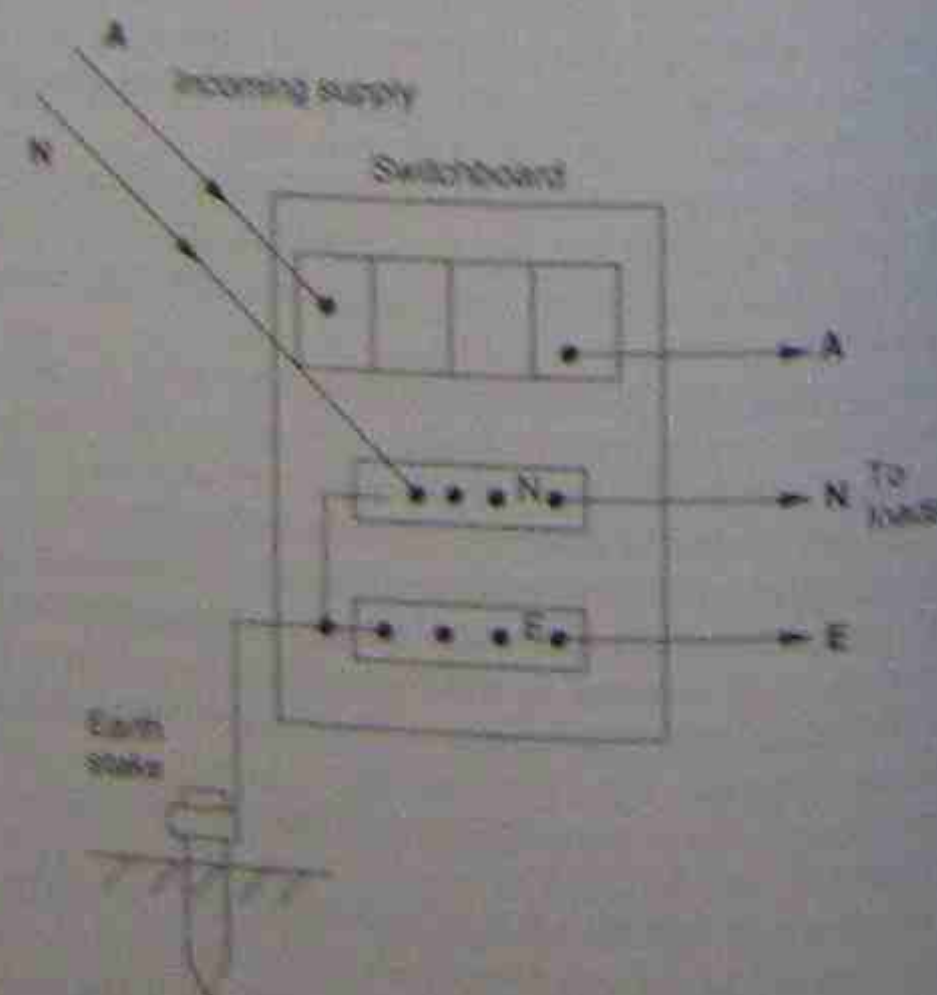

Figure 2.35 • Neutral and earth details at a main distribution...

connected to the earth pin. Modern plugs and sockets intended for 240 V use are branded in some way to indicate the appropriate conductors and connections and this procedure should always be observed.

2.18.3   Control of small fires

Under fault conditions, an electric current might generate sufficient heat to create a fire hazard. It is important to recognise that there are different types of fires and they sometimes need to be treated in specific ways with fire extinguishers adapted for that special purpose. For a fire to be self-sustaining it needs three common components—fuel, heat, and oxygen. If any one of these three can be removed the fire can be controlled. In 1999, fire extinguisher standards were modified so for some time one can expect to see two different types of markings for the same type of extinguisher. Previously some extinguisher bodies were painted different colours or had different coloured bands on them. Now all extinguisher bodies are painted red with narrower bands than previously painted and are now painted nearer the top of the body. It used to be a requirement that an inverted triangle be placed prominently above the extinguisher and painted to indicate the type of extinguisher. The new standard consists of a rectangular plate with a white outline of an extinguisher painted on a red background. It has to be placed above all extinguishers and mounted within specified vertical limits. It is applicable to all types of fire extinguishers. The type of extinguisher must be identified by the coloured band on the upper part of the body of the cylinder.

There are still six classes of extinguisher and these can broadly be separated into two general categories: electrically conductive and electrically non-conductive. There are three types of extinguisher in each category.

2.18.4   Types of fire extinguishers— colour coding

Electrically conductive extinguisher contents

1   **Water based**
The colour code for this type of extinguisher is unchanged. The body is plain red without a coloured band. The propellant is usually compressed air. It is intended to take the heat component from the fire. It is most effective with paper, wood and plastic fires.

2   **Foam**
Usually water based with compressed carbon dioxide as the propellant. The chemicals in the body cause foam to be generated on coming into contact with oxygen in the air. The foam causes a smothering effect and limits the amount of oxygen that the fire needs to continue burning. The body is painted red with a blue band near the top. Previously the complete body was blue. It is most effective with petrol and kerosene fires.

3   **Wet chemical**
Similar to the foam type, the chemicals produce foam on contact with air and cause a smothering effect. The body of the extinguisher is plain red with a buff coloured band. Previously the complete body was a buff colour. Propellant is often carbon dioxide. It is most effective against fires caused by cooking oils and fat.

Electrically non-conductive extinguisher contents

1   **Carbon dioxide**
This extinguisher can be recognised at a glance because of its distinctive horn on the hose used for directing its contents at the fire. The horn is intended to give a greater spread of the gas at the fire site. Carbon dioxide is an inert gas and is able to prevent oxygen from feeding the fire so enabling it to be put out. It is more effective in enclosed spaces because of the concentration of gas that can be achieved. Its identifying mark is a black band near the top of the cylinder. Previously it had a broad, black band half-way down the body. The gas being non-conductive is ideal for safely fighting fires on electrical equipment that is energised. The extinguisher is usually equipped with a pressure gauge to indicate its condition.

2   **Dry chemical**
One of the more versatile of the extinguishers, it can be used relatively effectively on most fires with the exception of class D fires involving combustible metals. See Table 2.9. It is most effective on fires involving paper, wood, plastic, petrol, kerosene, and liquid fuels such as butane and propane. Its action is to generate a foam that creates a smothering blanket on the fire so enabling the fire to be deprived of oxygen. It can be distinguished by the white band near the top of the red body. Previously it was a broad white band further down the body. It is also equipped with a pressure gauge to indicate its condition.

3   **Vaporising liquid**
The active agent is usually halogen-based hydrocarbon gas, which is stored under pressure in the extinguisher as a liquid. On being released from the cylinder it almost immediately reverts to an inert gas and smothers the fire. As with other gases it is more effective in enclosed spaces. The identifying colour is a yellow band near the top of the body of the extinguisher. Previously it was a broader yellow band half-way down the cylinder. The extinguisher is equipped with a pressure gauge to indicate its condition.

2.18.5   Electrical licensing

In view of the dangers of electricity and a need for electrical workers to have an understanding of electrical theory and safe practice, some form of regulation was deemed necessary. At first individual states attended to their own forms of licensing but as the idea gained momentum it gradually became an Australia-wide issue. Standards were laid down for the requirements of operation and installation of electrical equipment. Electrical workers had to ensure that these standards were met. The next logical step was the licensing of the electrical workers and to obtain these licences the workers had to achieve certain standards of competence in both theory and practice. These standards became progressively common to all Australian states and territories and eventually led to a common core modules system.

Currently, licensing of electrical workers is relatively uniform throughout all states in Australia and is governed by local licensing authorities. For most purposes

Table 2.9 • Extinguisher suitability for small fires

		Water	Foam	Wet chemical	Carbon dioxide	Dry chemical	Vap. liquid
A class	paper	yes*	yes	yes	yes NRS†	yes* A, B, E	yes
	wood						
	plastic						
B class	petrol	no	yes*	no	yes NRS	yes A, B, E	yes NRS
	kerosene						
C class	propane	no	no	no	yes NRS	yes* A, B, E	yes NRS
	butane						
E class	involving	no	no	no	yes* A, B, E	yes	yes*
	energised						
	electricity						
F class	cooking oils	no	yes NRS	yes*	yes NRS	yes B, E	no
	and fats						
D class	magnesium	special	purpose extinguisher		help required		
	sodium		(inflammatory metals)				

* Extinguisher best suited
† NRS = extinguishes not really suited, but will probably work with decreased effectiveness.

licensing requirements there are now two guiding bodies—The Electrical Regulatory Authority Council in which the local licensing authority has representation, and the National Uniform Electrical Licensing Advisory Council, which consists of members from training organisations and other interested parties. Flexibility became the issue because of the continual changing needs of industry and education generally.

This latter body considered that a national policy needed to be adopted and a relatively common assessment procedure developed. Statements of required competencies have been issued and all A class electrical workers

are expected to comply. It is then the duty of Registered Training Organisations to ensure that they guide their students towards reaching these standards. Industry has been requested to put in place approved training exit assessments for their trainee electrical workers. It is expected that electrical workers failing to achieve these standard exit assessments will remain as trainees unless and until they do achieve the required standard. Any further assessment will comprise both practical and theoretical skills and will be done at the student's own expense.

SUMMARY

- Matter is composed of molecules and atoms.
- Electrons are parts of atoms and are negatively charged.
- Matter can be charged by adding or subtracting electrons.
- Frictional electricity is static electricity.
- Electricity can be generated by passing conductors through a magnetic field by a method called *induction*.
- When electrical energy is generated on a continuing basis it is called *dynamic electricity*.
- There are several methods for generating electrical energy but the steam-turbine-driven generator is the most effective at present. The steam is condensed after use and most of the water regained is used again.
- The next most popular method is the water-driven turbine (hydroelectric). The water can be reused for other purposes downstream.
- Engine-driven generators are used where an adequate supply of fuel and water is not available for generating steam.
- Distribution is achieved by using alternating current. It is converted to high voltages for efficient transmission.
- Substations transform it back to consumer-usable voltages.

- Substations are usually interlinked to provide alternative supply routes in the event of breakdowns.
- Solar panels are used in remote areas to generate electrical energy. Batteries are charged as a 'reservoir' of electricity for use when there is no sun. This is not a suitable method for large quantities of power at present.
- To guide electrical energy to specific places and equipment, conductors and insulators are used in electrical circuits.
- Conductors have low resistance to electricity, while insulators have high resistance.
- Circuits are classified as either *open* or *closed*.
- In an open circuit, current cannot flow.
- In a closed circuit, current can flow to an electrical load.
- A short-circuit is a faulty circuit that cannot be used. High fault currents can flow.
- Fault currents are much larger than overload currents.
- Electrical circuits have to be protected against fault currents and overloads.
- Fuses or circuit breakers can be used to protect a circuit.
- Current flow can be designated as either conventional current flow or electron flow.

- If the type of current flow is not stated, then conventional current flow is assumed. It flows from the positive side of the supply, through the load, and then to the negative polarity.
- Electron flow is from negative to positive.
- Electrical pressure is measured by voltmeters and current flow by ammeters.
- Ohm's law describes the relationship between voltage, current and resistance to current flow in a circuit ($I = V/R$).
- Electrical power is measured in watts ($P = VI$).
- Electrical energy is measured in watt-hours ($W = Pt$).
- Electrical energy is charged by the supply company at a rate called a tariff (¢/kWh).
- The resistance of a metallic conductor is governed by its length, cross-sectional area, temperature, and the type of material used (resistivity).
- Conductor resistance causes temperature rise and power loss in a conductor. It shows as a voltage drop along the conductor.
- The temperature coefficient of resistance is an indication of a conductor's change in resistance as its temperature alters.
- A superconductor is a material of negligible resistance. This occurs only at very low temperatures.
- Resistors can be made from high-resistance conductors or they can be made from a carbon-based material.
- Resistors made of special alloys have a resistance that is constant over a range of temperatures.
- Heat produced by electrical energy causes a rise in temperature.
- Heat energy is related to temperature only by specific heat capacity.
- Heat is transferred from points of high temperature to points of low temperature.
- The rate of heat transfer to or from a body is governed by the material's thermal conductivity and the method by which it is transferred.

- Wire-wound resistors are more applicable to higher power ratings than carbon-based resistors.
- Resistors made from special compounds can be made to rise or fall in resistance as the temperature is increased. Some are called PTCs (positive temperature coefficient), others NTCs (negative temperature coefficient).
- Carbon-compound resistors are usually so small that there is only room on them for coloured bands to indicate their resistance value. They are made in a range of preferred values and tolerances.
- Other commonly used electrical components are inductors and capacitors.
- There are three effects of electricity—chemical, heating, and magnetic. A side-effect, often due to misuse, is electrical shock. It can be called a fourth effect.
- Electric shock effects are governed by the value of the voltage, the current that flows, the current path, and the length of time of application.
- Severe electric shocks can cause the heart and lungs to cease working. Resuscitation must be applied immediately. Self-protection from electric shock is essential.
- One limited form of protection from electric shock is the use of a core-balance transformer. It is usually called a residual current device (RCD) in this situation.
- An RCD is designed to provide limited protection to the user, rather than the circuit.
- Painful currents can still flow when an RCD is used, but the time of flow is generally very short. Care must still be taken.
- Protection against electrical fires can be provided by the supply of fire extinguishers of various types. Knowledge of the correct type to use is essential.
- Safe working in a safe environment is essential. Licensing is one means of regulating safety and the proper installation of electrical equipment.

EXERCISES

2.1   What is an atom? Use a drawing to illustrate your answer.

2.2   How do atoms of the various elements differ?

2.3   Explain the characteristics that all atoms have in common.

2.4   What is a free electron?

2.5   Explain the meaning of the terms *positive charge* and *negative charge*.

2.6   What electrical features distinguish an insulator from a conductor?

2.7   Place the following terms in the order in which they permit electron flow: *good conductor, good insulator, poor conductor.*

2.8   What is an electrical current flow?

2.9   What is the conventional direction of current flow?

2.10   Explain why the current drawn by a radiator heats

the element but does not appreciably heat the connecting leads.

2.11   What is meant by the term *resistivity* in relation to a conductor?

2.12   How is resistivity determined?

2.13   Explain the term *temperature coefficient of resistance.*

2.14   What four factors affect the resistance of a conductor?

2.15   Explain why a positive ion will attract electrons.

2.16   Explain why the length of a conductor affects its resistance.

2.17   What is Ohm's law?

2.18   List six conductors and six insulators.

2.19   List three different means for generating a potential difference and briefly explain each one.

2.20 Describe three ways in which heat may be transferred. Give an example of the use of each principle in electrical apparatus.

2.21 Why does an ammeter have to be connected in series in a circuit?

2.22 Why does a voltmeter have to be connected in parallel in a circuit?

SELF-TESTING PROBLEMS

2.23 A 32 V lamp draws a current of 2 A. Calculate its resistance and the wattage consumed.

2.24 An electric radiator is rated at 1000 W on 240 V. Find the current that flows and the resistance of the heating element.

2.25 A transistor radio operates on a 9 V battery and draws a current of 0.02 A. Calculate its internal resistance.

2.26 Find the resistance of the heating element in a 240 V 60 W electric soldering iron.

2.27 Calculate the weekly cost of running a 250 L electric hot water system rated at 2.75 kW on 240 V if the cost of energy is a flat rate of 4.46¢/kWh during the off-peak period.

2.28 If a household buys a deep-freeze unit with a power consumption of 300 W, how much will be added to the weekly household electricity bill? The average running time is 3 minutes in every 24 minutes and the cost of energy is 9.46¢/kWh.

2.29 Calculate the resistance of a 100 m reel of copper conductor if the cross-sectional area is 4.0 mm².

2.30 Calculate the resistance of 75 m of manganin resistance wire if the conductor diameter is 0.5 mm.

2.31 What length of Nichrome resistance wire with a cross-sectional area of 0.01 mm² is required to wind a resistance of 250 Ω?

2.32 What is the resistance value of each of the following resistors:
(a) Blue, red, red, gold?
(b) White, brown, orange, gold?
(c) Green, black, yellow?

2.33 What would be the rated maximum and minimum values of a resistor with a colour code of brown, black, black, gold?

2.34 Find the colour codes for the following resistors:
(a) 33 kΩ 5%
(b) 1 MΩ 20%
(c) 390 Ω 5%

2.35 The resistance of a motor winding is 1.8 Ω at 20°C. Find the resistance of the winding when the winding temperature stabilises at 65°C (α_{20} = 0.003 93).

2.36 The field winding of an electric motor has a resistance of 242 Ω at 15°C. What is its resistance at 40°C? (α_0 = 0.004 27)

2.37 A coil of wire has a resistance of 100.0 Ω at 0°C. If the resistance rises to 185.2 Ω at 200°C, find the temperature coefficient of resistance at 0°C and determine what metal is used to make the wire.

2.38 An electric urn raises the temperature of 12 L of water from 15°C to 60°C in 25 minutes. With a supply voltage of 240 V, calculate the current taken from the supply, assuming there are no heat losses.

2.39 An immersion heater requires 60 minutes to heat 40 L of water from 15°C to boiling point. Assuming no losses, calculate:
(a) the heat energy required in joules
(b) the kilowatt rating of the element
(c) the cost at 14.62¢/kWh.

2.40 A coil is to be wound with 200 metres of copper strip 2 cm wide by 0.5 cm thick. Calculate the resistance of the finished coil.

2.41 What will be the resistance of the above coil if it attains a working temperature of 60°C?

2.42 A coil of copper wire has a resistance of 4.0 Ω at a temperature of 16°C. Find its resistance at 5°C and 60°C.

2.43 The 12 V field winding of a generator was measured and found to have a resistance of 2.16 Ω at the ambient temperature of 15°C. Under operating conditions the temperature of the winding rose to 45°C. Calculate the new value of the field current.

2.44 In an oil-filled distribution transformer, the resistance of one of its windings was found by measurement to be 9.75 Ω at an ambient temperature of 17°C. On load, the average temperature of the windings rose to 60°C. Find the working resistance of the winding.

2.45 In a distribution transformer, the resistance of one of its windings rose from 4.52 Ω at an ambient temperature of 18°C to 5.71 Ω. Calculate the average rise in temperature of the windings. Assuming the insulation in the transformer was rated at a maximum working temperature of 60°C, state whether the operating temperature is excessive or not.

2.46 An electric jug heats 2 L of water from 15°C to boiling point in 4 minutes. Assuming losses of 10 per cent, calculate the wattage rating of the jug.

2.47 A length of 200 m of 0.25 mm diameter copper wire is used in winding a field coil. What is the resistance of the coil at both 20°C and 40°C?

2.48 If a 2 kW radiator is used for 4 hours per day and the tariff is 15¢/kWh, how much would the radiator cost to operate for a five-day week?

2.49 List the indicated values and tolerances for the following resistors:

(a) red	violet	yellow	silver
(b) brown	green	orange	gold
(c) red	red	black	none
(d) green	blue	black	gold
(e) green	black	yellow	gold
(f) orange	orange	brown	gold
(g) brown	red	orange	silver

2.50 List the indicated values and tolerances for the following resistors:

(a) yellow	orange	black	orange	gold
(b) green	blue	black	yellow	silver
(c) blue	red	black	orange	red
(d) grey	red	black	black	gold
(e) brown	green	black	gold	silver
(f) brown	red	black	yellow	silver
(g) red	red	black	silver	black

Chapter 3

Electrochemical effects

3.1   INTRODUCTION

In this chapter the following terms are used with respect to two electrodes immersed in an electrolyte. An *electrode* is an electrical conductor in contact with an electrolyte. The *electrolyte* is a conducting medium in which electrodes are placed; it provides a current path between the electrodes, and is often a liquid (see Fig. 3.1). *Electrochemistry* in general refers to two opposite processes—one using electrical energy to create a chemical effect, the other a chemical effect to create electrical energy.

The first process is often used in electro deposition: an external voltage source is applied across the electrodes and a current is made to flow through the electrolyte. The electrode connected to the positive polarity of the supply is called the *anode* and, following chemical changes, part of its material is transferred to the *cathode* or negative electrode. The anode is eventually destroyed. This process has been adapted for electroplating and the refining of metals.

The second process converts chemical to electrical energy. Electrical energy produced within a cell by the chemical change is able to flow out of the cell to any connected load. There are two major groups of cells: in one group the chemical action is such that it is not economically feasible to reverse this action, so the cells are simply replaced by new cells. In the second type it is feasible to reverse the chemical changes that have taken place so that the cell can be re-energised and reused.

3.2   PRIMARY CELLS

With the availability of modern supplies of electrical energy from mechanically driven generators, it is difficult to assess the importance of the primary cell.

After the development of the generator as a source of supply, the cell was relegated to a position of lesser importance and in many instances became a matter of only academic interest. Today the importance of the primary cell is again increasing, owing to the development of semiconductor technology.

During the development of the cell from the original voltaic form, many types were proposed, but the one that has successfully held the field is the Leclanché cell. The modern form of the cell still has a prominent position,

although many types of cell with different constructions have been developed comparatively recently.

3.2.1   Voltaic cells

Figure 3.1 shows a simple voltaic cell consisting of two metal plates, one of copper and the other of zinc, immersed in a solution of dilute hydrochloric acid.

The acid need not be hydrochloric acid. Other acids such as chromic, acetic or sulphuric can be substituted—indeed salt solutions such as common salt or copper sulphate can be used. In order to obtain a difference of potential between the two electrodes, only two conditions are necessary: electrodes must be of different metals and immersed in an electrolytic solution comprising an acid, alkali or salt. Because of early work in this area these cells came to be known as galvanic or, more popularly, voltaic cells after two men (Galvani and Volta).

The container is made from a non-metallic material (e.g. glass) that is not affected by the acid. It must not be made of a conducting material, and care should be taken that the electrodes do not touch each other.

Dissolving an electrolyte of hydrochloric acid (HCl) in pure water allows some of the acid to separate out into positive hydrogen ions (H^+) and negative chlorine ions (Cl^-). Some of the chlorine ions attack the zinc and create positive zinc ions (Zn^{++}). This leaves free electrons on the zinc electrode, giving it a negative charge. The positive zinc ions combine with other free chlorine ions, forming zinc chloride (ZnCl), a solid which sinks to the bottom of the container.

Simultaneously, positive hydrogen ions move across to the copper electrode. There they combine with surface electrons from the copper electrode and become neutralised hydrogen atoms. The hydrogen rises to the surface of the electrolyte and escapes as free hydrogen gas. The removal of electrons from the copper electrode causes it to have a positive charge, and the cell has a potential equal to the difference between the negative charge on the zinc electrode and the positive charge on the copper electrode. This potential difference is usually about 1 V.

This simple cell is not very practical because the copper electrode becomes covered with hydrogen gas, so preventing hydrogen ions taking further electrons from
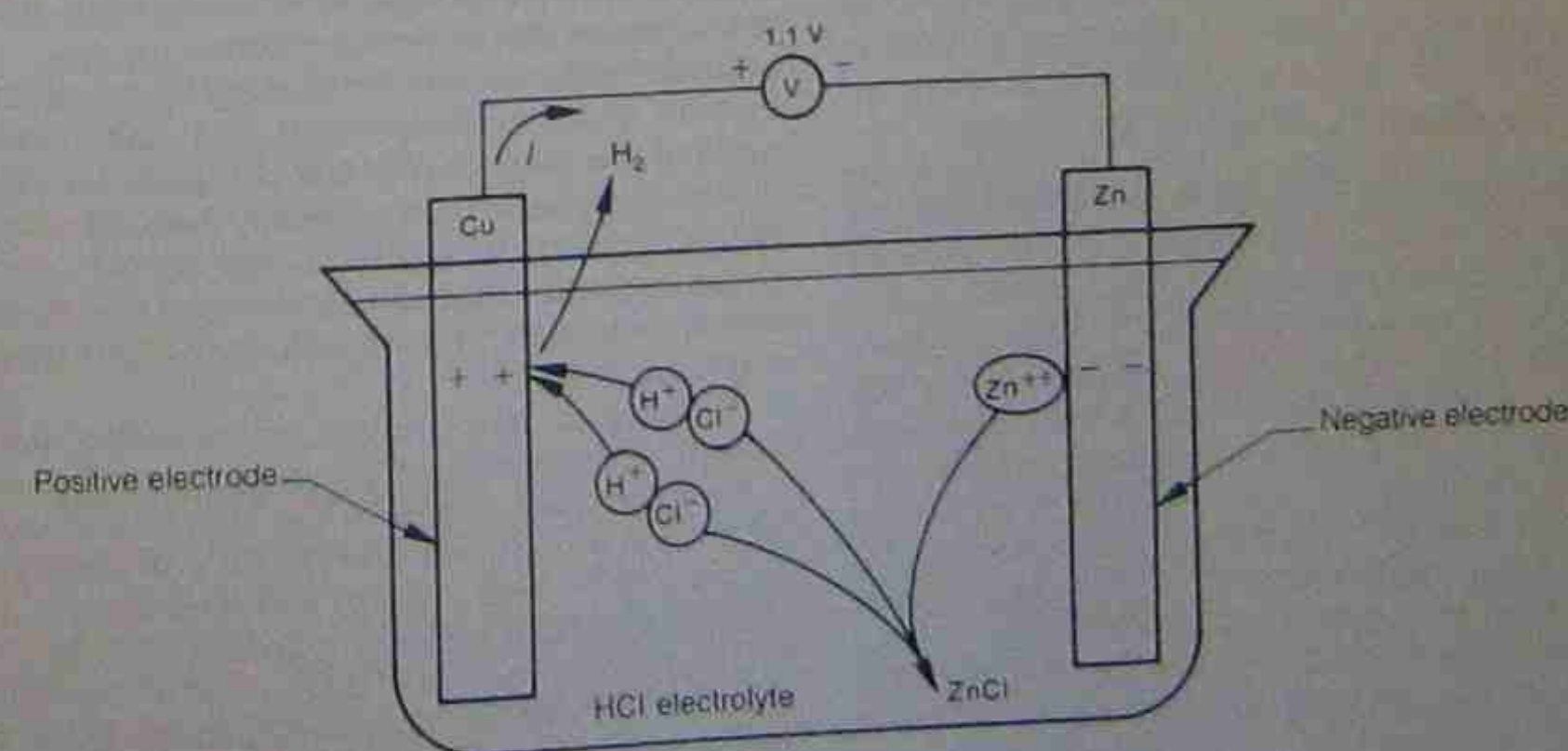
Figure 3.1 • Simple voltaic cell

the surface. This effect is known as *polarisation*: it reduces the output voltage and increases the internal resistance of the cell. Steps have to be taken to overcome the effect with depolarisers.

The zinc used to form the negative electrode may contain small quantities of impurities that tend to form individual cells by galvanic action within the main cell (see Fig. 3.2). Circulating currents are set up between the impurities and the electrode, causing the zinc to be eaten away even when the external load on the main cell is disconnected.

To reduce this local action it is necessary to use zinc electrodes that are as pure as possible. Local action is not confined to cells, but might occur in situations where different metals are in contact and moisture is present. The resulting action causes corrosion and destruction of the metals in contact. It is discussed further in section 3.14.3.
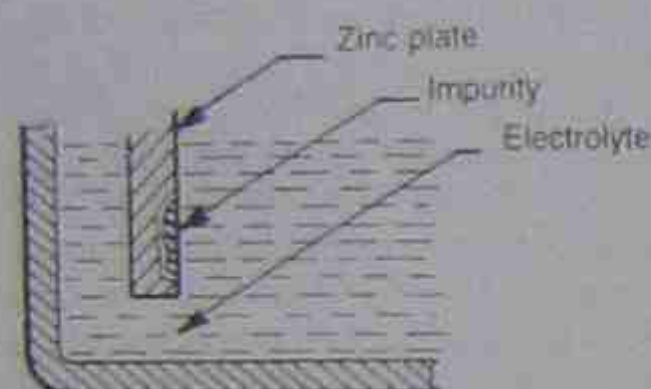
Figure 3.2 • Local action

3.2.2 Electrode potentials

It was mentioned above that two dissimilar metals in an electrolyte form a primary cell. Because of the number of metals and electrolytes available, standards have been developed by using prescribed electrolytes and electrodes. With this method, materials can be arranged in order to indicate relative potentials. The e.m.f. between the electrodes in a voltaic cell is due to the chemical activity between the electrodes and the electrolyte. Some metals react more readily in their ability to accept electrons. The electromotive force series (Table 3.1) lists electrode potentials.

For the cell shown in Figure 3.1 the voltage is the difference between the two electrode potentials given in Table 3.1, for example:

$$+0.34 - (-0.76) = 1.1 \text{ V}$$

Table 3.1 • Electromotive force series

Metal	Electrode potential in volts
aluminium	−1.67
zinc	−0.76
chromium	−0.71
iron	−0.44
cadmium	−0.40
lead	−0.13
hydrogen	0
copper	+0.34
silver	+0.8
gold	+1.42

Copper has a more positive value than zinc so becomes the positive electrode (anode). The other potential is subtracted from the anode value.

Example 3.1

What would be the e.m.f. of the cell shown in Figure 3.1 if the electrodes were iron and zinc?

From Table 3.1: zinc is −0.76, iron is −0.44. The iron potential is more positive (or less negative), so will become the positive electrode:

$$\text{e.m.f.} = -0.44 - (-0.76)$$
$$= -0.44 + 0.76$$
$$= 0.32 \text{ V}$$

3.2.3 Leclanché cell

This cell was a successful attempt to overcome the polarising effects of the voltaic cell. The original version was a 'wet' cell and later developments led to the 'dry' cell so popular today.

Wet cell

The construction in Figure 3.3(a) shows a central carbon rod surrounded by a cylinder of manganese dioxide, which is used as a depolarising agent. The hydrogen produced (as in the voltaic cell) combines with the oxygen in the depolariser to produce water.

Dry cell

The dry cell version of the Leclanché cell currently manufactured has carbon and zinc electrodes, a sal-ammoniac electrolyte, and manganese dioxide as the depolarising agent, just as in the original version of the cell. However, instead of a liquid electrolyte in an open container the dry cell has a stiff paste, which is virtually unspillable. In the usual version, the zinc electrode forms the container and the carbon electrode has a brass cap and protrudes through a sealing cap at the top of the cell. (See Fig. 3.3(b).)

The carbon rod is packed in the polarising element, which is a paste containing manganese dioxide, powdered sal-ammoniac, carbon, zinc chloride and water. The electrolyte usually consists of sal-ammoniac, zinc chloride and a porous matrix such as flour.

The dry cell version, with its output potential of approximately 1.5 V, overcame many of the inherent disadvantages of the original cell. It was lighter, robust, portable and virtually unspillable. The depolarising arrangements in both wet and dry types ensure a steadier output over a longer period of time, and coating of the zinc electrode with an amalgam of mercury largely overcomes the local action process.

The gradual drying out of the electrolyte paste and a limited amount of local action led to the recognition of a limited storage period—today called 'shelf life'. To get maximum usage out of a dry cell it is necessary to ensure that the cell is fresh and has had a minimal storage time or shelf life. High temperatures tend to reduce shelf life because local action and drying out of the electrolyte is speeded up. Humid conditions, usually associated with higher temperatures, tend to provide moisture for the cell to discharge itself. Conversely, lower temperatures reduce
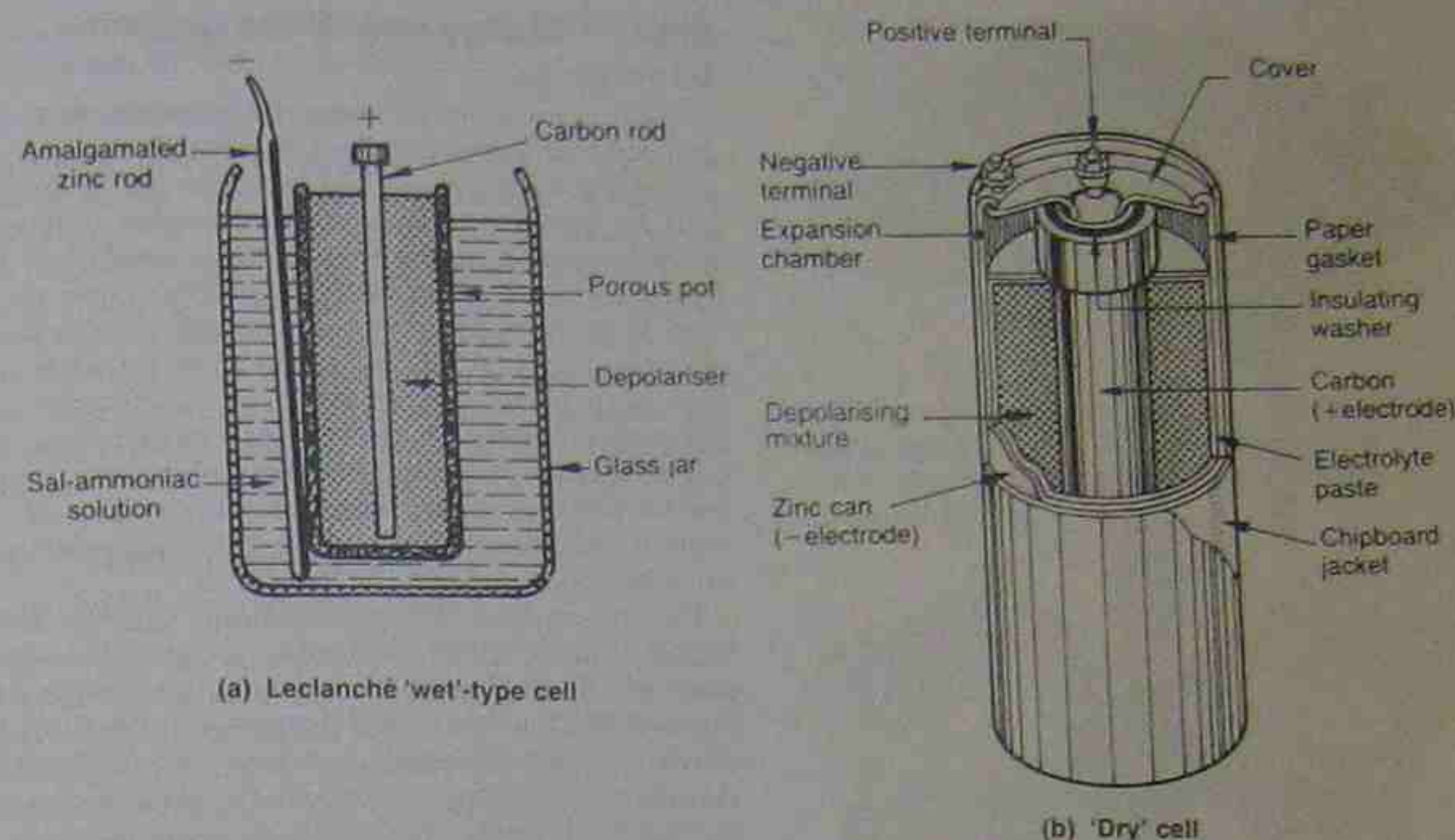

(a) Leclanché 'wet'-type cell

(b) 'Dry' cell

Figure 3.3 • Primary cells

the effects of local action and the drying out of the electrolyte. The cell should be stored in a cool dry atmosphere and kept clean. The miniature cells of the types discussed in section 3.9 have a longer life if these conditions are considered. In addition, care should be exercised in their handling. In many cases simply holding them between the fingers provides a very thin film through which the cell can discharge, so reducing the life cycle. A protective tissue should be used when handling them.

3.3 SECONDARY CELLS

Cells in general can be classified into two types: primary and secondary. With the primary cell discussed above it becomes necessary to renew the active materials periodically to reactivate the unit. That is, the materials once used have to be replaced. The process cannot be reversed as with the secondary cell. The secondary cell can be used until the chemical action within the cell ceases and no further electrical energy is available. The cell is then said to be discharged. The chemical process can then be reversed by charging the cell from a source of electrical energy and repeating the cycle. The procedure of creating a chemical change with electricity and then using this chemical change to create electricity when required gives rise to the alternative name of *storage cell* for the secondary cell.

3.3.1 Secondary cell types

The secondary cell has had many variations developed over the years but only two major types have persisted. They are the lead–acid cell and the nickel–alkaline cells. In the nickel–alkaline cells there are two further variations. Both use nickel with an alkaline electrolyte but one uses a cadmium-based electrode, while the other uses an iron-based electrode.

The lead–acid cell has remained virtually unchanged except for minor variations in internal construction.

3.4 LEAD–ACID CELLS

When compared with other types of cell of comparable size and weight, lead–acid cells can deliver higher current surges.

Variations in plate construction allow for individual specialised uses. For example, in automobiles, where the primary function is to start an engine, the plates are made thinner so that more of them can be fitted in the same-size battery case. This increases the plate surface area for further increased current surges, although at a cost of thinner and therefore weaker plates, which in turn leads to a reduced cell life.

3.4.1 Cell construction

In the fully charged condition the active material of the positive plate is lead peroxide, and the negative plate is spongy lead. The discharge action converts the plates to lead sulphate and water is produced, so diluting the electrolyte.

The active materials have no rigid mechanical form or strength, and it is necessary to mount them in a frame or grid. These are then known as pasted plates and are the most common form of construction (see Fig. 3.4). The method is adaptable to both positive and negative plates. The grid usually has antimony added to the lead for rigidity and extra mechanical strength.

To improve the plate area in contact with the electrolyte, numbers of plates of each polarity are connected in parallel and interleaved as shown in Figure 3.5.

The number of negative plates is one greater than that of positive plates, and an indication of the cell capacity is given by the number of negative plates, for example, 11-plate or 17-plate.

3.4.2 Charge and discharge cycles

Discharge cycle

Charge cycle

3.4.3 Testing lead-acid cells

State of charge – electrolyte density

The charge-discharge process

The basic electrolyte in a lead-acid cell is made from a mixture of water and sulphuric acid to a density of 1250 kg/m³ for new batteries. During charge and discharge cycles, water is either produced or removed from the solution, so altering the density of the electrolyte. As a general guide, the figure 1250 gives an indication of a fully charged cell in good condition and 1180 an indication of a discharged cell.

Cell condition—voltage on load

The terminal voltage is measured while the cell is on load. This test is more meaningful than the hydrometer test, which involves too many variable factors. It indicates the cell's condition or ability to supply an adequate current and tests the cell voltage while it is delivering that current. The value of the discharge current chosen is designed to show up weak or failing components or connections within the cell or battery.

The discharge current is usually about three times the figure of the ampere-hour rating (see section 3.11.1). That is, a 50 ampere-hour cell is discharged at 150 amperes for 15 to 20 seconds. Some manufacturers test their cells at a higher rate than this. With many modern batteries, connecting straps are inside the cell case and cannot be reached readily, so a 'whole battery' tester is used instead (Fig. 3.9). A different value of resistance is used and the whole battery is placed on load at the one time, instead of each cell being tested individually.

A reasonable cell condition is indicated if the voltage on load does not fall below 1.6 V. If the voltage falls rapidly, the condition of the cell is poor.

Figure 3.9 • High rate discharge tester. The adjustable load resistor is in the rear compartment

Sellleson Corporation

3.5 NICKEL–ALKALINE CELLS

There are two major types of nickel-alkaline cells, although they are known under various brand names. One has nickel-iron-based electrodes and the other has nickel-cadmium-based electrodes. For practical purposes each type has similar basic construction and an operating voltage of 1.2 V. There are major differences in construction to suit such specific purposes as engine starting, standby power supplies and emergency lighting.

3.5.1 Cell construction

Both electrodes are usually made of a powdered material held in pockets manufactured within a pressed steel frame. The active positive material is nickel hydroxide. The negative plate material is powdered iron for the iron-based cell and cadmium converting to cadmium hydroxide for the cadmium-based cell. The cell case is often a steel pressing, but for some purposes may be made of plastic. One form of construction for the steel case is shown in Figure 3.10. The electrolyte is mainly potassium hydroxide (caustic soda) dissolved in water, but may have some additives to lower the internal resistance of the cell.

The cell itself often contains several plates of each polarity, as in the lead-acid cell. The separation between plates is often by round pins instead of flat separators. Where a steel cell container is used it must be insulated from the plates as well as from other cells.

Figure 3.10 • Cut-away view showing the construction of a nickel-iron cell

Gardner Dianbodes

3.5.2 Charge and discharge cycles

The cycling process of the alkaline cell is complex and open to much discussion. The version presented below is a superficial one, simplified in the interests of student understanding. While referring to the nickel-cadmium cell in particular, the same reasoning is applicable to the nickel-iron cell.

Discharge cycle

The discharge cycle is shown in Figure 3.11(a). The electrolyte breaks down into potassium ions (K^+) and hydroxide ions (OH^-). The potassium ions attract hydroxide ions from the positive plate, effectively converting the nickel hydroxide to another form of hydroxide $Ni(OH)_2$ and leaving a net positive charge. Hydroxide ions from the electrolyte attach themselves to the negative plate material creating cadmium hydroxide $Cd(OH)_2$ and leaving a net negative charge. While the cell is discharging, the electrolyte appears to break down into ions and then recombine. The overall result is that the electrolyte condition remains virtually unchanged, unlike that occurring in the lead-acid cell.

Charge cycle

On the charge cycle (Fig. 3.11(b)) the electrolyte breaks down into potassium ions (K^+) and hydroxide ions (OH^-) as before, but the migration of hydroxide ions is in the reverse direction. Potassium ions attract hydroxide ions from the negative plate, converting it back to cadmium. These ions then combine to form electrolyte, and other hydroxide ions move across to the positive plate, there converting the nickel hydroxide plate material back to its original form $Ni(OH)_4$. Again the electrolyte takes no real part in the process, merely being the vehicle for the passage of ions from one electrode to the other.

A cell may be charged at any rate that does not produce excessive gassing or temperature rise. A cell voltage which does not exceed 1.7 V will generally meet these conditions, on the assumption that the charge is terminated when complete. Correct charging is an important factor in the maintenance of a nickel-iron cell and an effort should be made to ensure that the correct amount of charge, at the proper rate for the particular cell, is given.

3.5.3 Testing nickel-alkaline cells

The specific gravity of the electrolyte of a nickel-alkaline cell should be a value in the range 1.126–1.250. Over a period of time this can decrease (at a rate dependent on how the cell is treated). Under normal conditions the electrolyte plays no active part in the cell's cycle and cannot give an indication of the state of charge of the cell. Accordingly a hydrometer cannot be used successfully as a test instrument. If a cell is fully charged it is subject to gassing; if the charge rate is too high, then a cell is also subject to gassing whether fully charged or not, so this is no indication of the state of charge. The only practical method available is the high-discharge test. As a general guide the open-circuit voltage should be approximately 1.2 V. A cell that needs attention would give a voltage in the vicinity of 1.1 V.

Figure 3.12 shows typical voltages for charge and discharge cycles of nickel-alkaline cells. Note that the cell is subject to the same internal resistance effects as the lead-acid cell, although the internal resistance values are somewhat higher for the nickel-iron cell.

The charge curve also shows that the charging voltage tends to rise rather steeply as the cell approaches full charge. The charging voltage for a 6 V battery assembly will rise abruptly to 10 V and beyond when approaching the fully charged state at high rates of charge. Steps then have to be taken to prevent further charging taking place and before cell damage occurs.

(a) Discharge

$$NiOH_2 + KOH + Cd$$
Positive plate, Electrolyte, Negative plate

(b) Charge

$$NiOH_4 + KOH + Cd(OH)_2 + Elect. energy$$
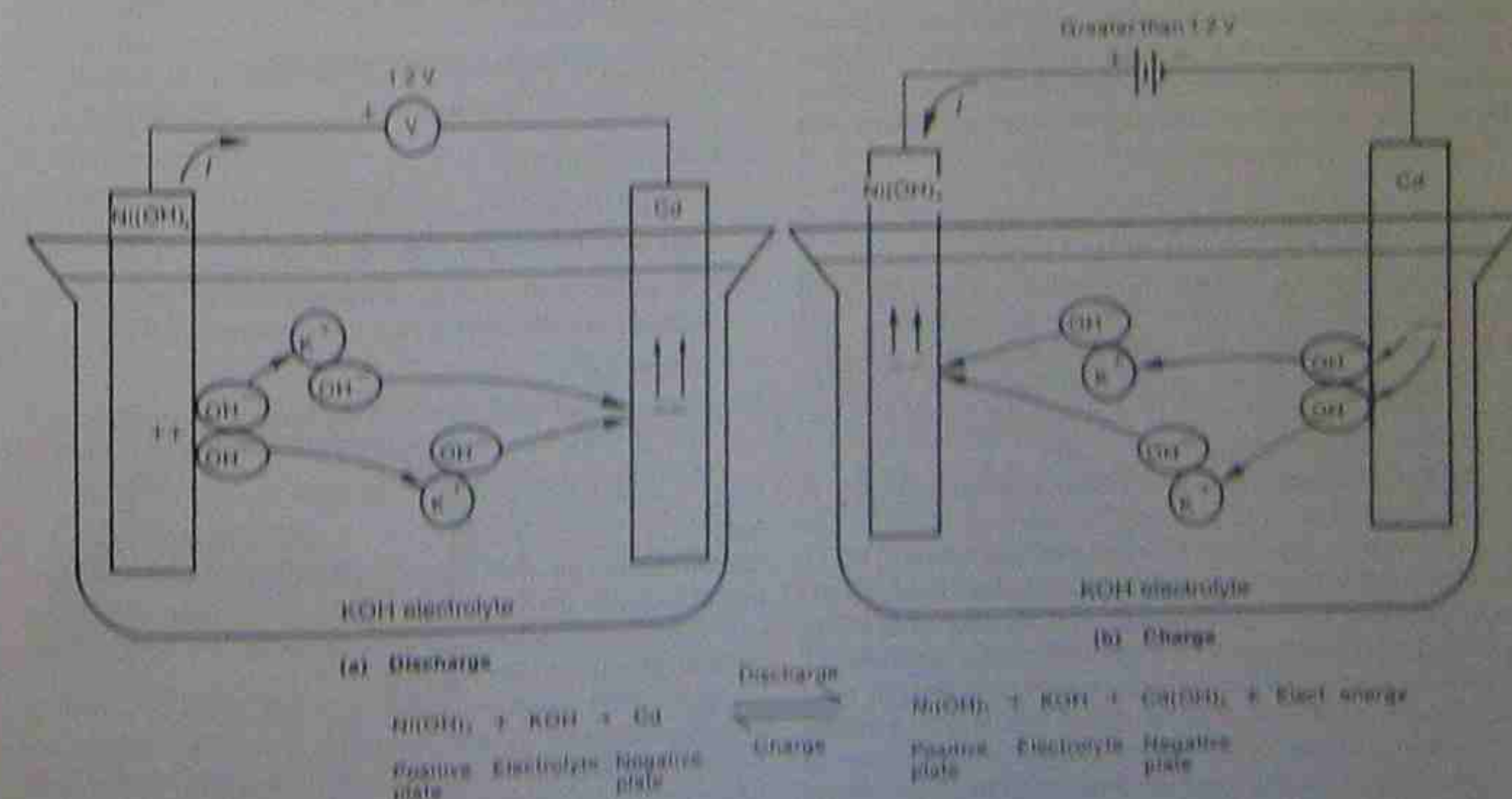Positive plate, Electrolyte, Negative plate

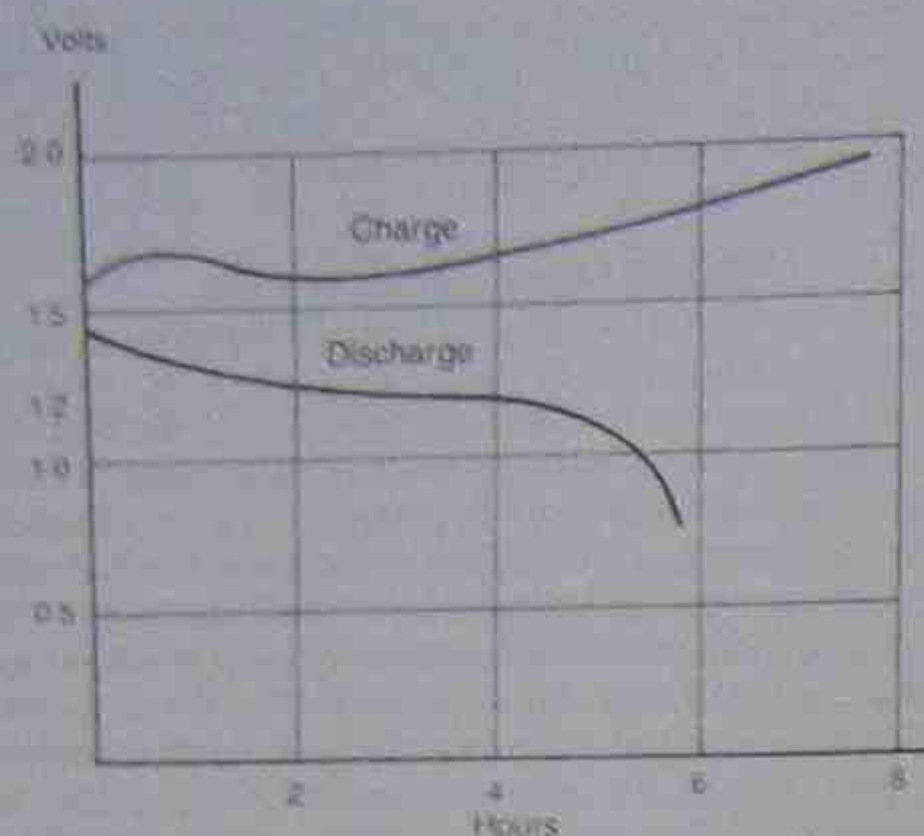Figure 3.11 • Approximate ionising and chemical action within a nickel-alkaline cell

Figure 3.12 • Nominal voltages of a nickel–iron cell

3.6 SEALED SECONDARY CELLS

A development of the secondary cell coming into prominence is the sealed secondary cell. Sometimes called low-maintenance or no-maintenance cells, they are a variation of the basic cell. Sealed to prevent loss of electrolyte, they have a pressure valve fitted to allow them to vent to the atmosphere if the gases generated build up to predetermined pressures.

To allow the cell to operate in any position, it is necessary to ensure that the electrolyte maintains the electrical circuit between the plates. For successful operation, the cells must never be charged at a rate that will cause any gas to build up excessive pressure within the cell.

Initially the charging rate can be adequate but as the cell approaches the fully charged condition, the charge rate must be reduced to a nominal one. This condition can usually be met by using constant voltage chargers, set at a maximum voltage in the vicinity of 2.26 V for lead–acid cells and about 1.4 V for alkaline cells. By preventing the loss of electrolyte, maintenance problems are reduced to keeping the cell terminals clean and ensuring that the voltage regulation is correct.

3.7 SAFETY PRECAUTIONS

Several precautions should be observed when working with secondary cells, on both charge and discharge. Cells or groups of cells have to be charged at specific rates for set times if a high degree of cell efficiency is to be maintained. Similarly cells should not be discharged below certain levels. Other requirements are:

1. *Adequate ventilation.* Any gases generated during charge or discharge must not be allowed to accumulate. There are three main dangers: risk of fire or explosion; inhalation by operators; and cross-contamination from one type of cell to another by the gases carrying minute quantities of electrolyte. The gas generated in lead–acid cells is hydrogen gas, a highly explosive mixture when mixed with oxygen in the atmosphere. Provided correct charging procedures are followed with sealed cells of any type, the cell has provision for absorbing any gases

generated, usually in the electrolyte. Sealed cells have provision for venting gases to the atmosphere in the event of excessive pressures being created within the cell.

2. *Protective clothing.* Eye protection must be included. Electrolytes are usually highly corrosive.

3. *Test equipment.* Separate equipment should be maintained for different types of cells.

4. *Isolation.* All charging and discharging should be carried out with some degree of isolation. Different types of cells should be kept separate from each other as the mixing of different types of electrolyte can cause explosive chemical reactions.

5. *Sealed cells.* Special care must be taken to ensure that designed current rates are not exceeded. Gases might otherwise be generated inside the cell at a faster rate than they can be reabsorbed, and the cell could then explode.

3.8 STORAGE CELL COMPARISONS

The advantages claimed for either lead–acid or nickel–alkaline cells tend to conflict and the real advantages actually depend on many factors. There has been strong competition between the two types of cells and for most choices the selection may depend on a particular application as well as on an individual's preference.

The following is a list of advantages for comparable-size cells of both types.

Lead–acid cells

1. Higher voltage per cell—2 V per cell against 1.2 V per cell.
2. Price—up to eight times cheaper than an alkaline cell.
3. Smaller for same capacity.
4. Availability—many non-related businesses stock the lead–acid cell.
5. Higher discharge currents available.
6. Lower internal resistance.

Nickel–alkaline cells

1. Can be left discharged without harm.
2. Can be overcharged without harm.
3. Life expectancy of approximately twenty years compared with three years for the lead–acid cell.
4. Less weight.
5. More rugged and substantial construction—better able to withstand mechanical and electrical abuse.
6. Electrolyte less subject to freezing in cold weather.

Note:
Notwithstanding the above comparisons, there is one version of the lead–acid cell that is made for stationary use. It has a life expectancy and cost structure comparable with that of the nickel–alkaline cell.

Larger than a normal lead–acid cell, each 2 V unit is usually mounted in a heavy glass case. The plates are made of lead sheet rather than a paste pressed into lead grids. Sufficient room is left at the bottom of the electrode for any discarded cell material to fall clear of the plates.

They were once used as a standby power supply in the event of a mains power failure or as backup to generating plant. The current trend is to use them as the main power supply and trickle charge them from the mains or a generating plant.

The battery bank usually comprises sufficient cells to produce the required voltage and supply connected equipment directly. Applications include control equipment in distribution substations and telephone exchanges.

Many isolated rural properties use stationary cells of this type as an electrical storage facility and have the battery bank charge maintained with either wind-driven generators or solar panels.

When alternating current is needed, the battery bank supplies an inverter, which converts the direct current to alternating current. This is then used to run connected equipment. Applications include 'no-break' supplies where safety is paramount and an interruption to a supply cannot be tolerated, for example, in aircraft navigational equipment.

3.9 OTHER CELLS IN USE— PRIMARY AND SECONDARY

3.9.1 Sealed zinc–mercury cells

In an effort to meet the above requirements, the zinc–mercury cell was developed. Some versions of this type of cell are rechargeable and strictly speaking can then be classified as a type of secondary cell. Figure 3.13 shows the general construction of one type of cell. The negative electrode is made from amalgamated zinc and the positive electrode from mercuric oxide. The electrolyte of potassium hydroxide is contained in an absorbent material placed between the two electrodes. A steel casing encloses the cell and the casing structure is usually such that, if excessive gas pressure is created in the cell, the gas can escape to the atmosphere and the cell then reseals automatically.

Typical uses of the sealed zinc–mercury cell are:

• pacemakers
• space and aviation
• blood-testing equipment
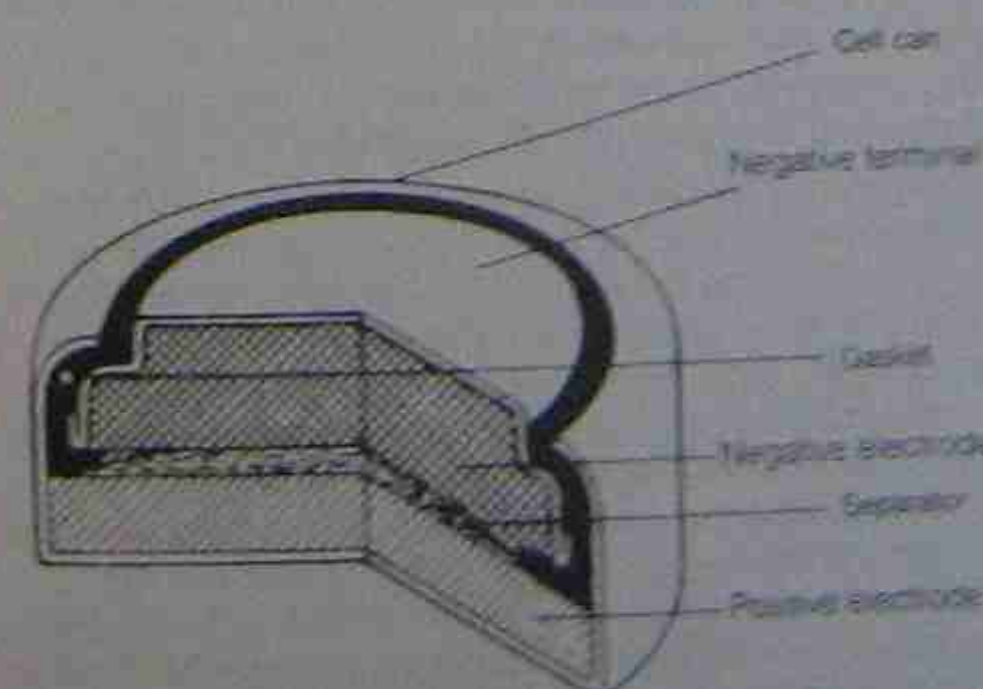• radiation detectors

• reference voltage sources
• wrist watches
• electronic thermometers
• sonobuoys
• tachometers
• laboratory meters
• radio beacons
• pH meters.

The open-circuit voltage of the cell is generally around 1.35 V. On load, this drops rapidly to approximately 1.33 V and maintains this virtually for the life of the cell.

3.9.2 Zinc–alkaline manganese dioxide cells

These have been the most recent cells to achieve extensive acceptance. The electrochemical system utilises a negative electrode of amalgamated zinc granules and a positive electrode of compacted manganese dioxide, made conductive with graphite. The electrolyte is potassium hydroxide held in cellulose-type separators. In construction, emphasis must be placed on the purity of the constituents to minimise contamination and local action.

The cells have a low internal resistance and a capacity for high current delivery. The system is stable and has a long shelf life. Its main application is in situations of relatively heavy current or continuous drain and the cells are suitable for photoflash work, motor drives in cameras, tape-recorders, toothbrushes, electric shavers and model toys. Depending on the materials used in the cell, the voltage will be in the range 1.47 V to 1.59 V.

3.9.3 Nickel–cadmium cells (vented)

Somewhat similar to the nickel–iron cell in some forms of construction, the electrodes consist of compounds of nickel and cadmium with an electrolyte of potassium hydroxide. The voltage per cell is 1.25 V. During discharge, trivalent nickel hydroxide is converted to the divalent state, the reverse occurring during charge. The negative plate in the charged state is metallic cadmium, which is converted to cadmium hydroxide during discharge.

3.9.4 Sealed nickel–cadmium cells

Along with other types of sealed cells, nickel–cadmium cells have the following special construction features to prevent a build-up of pressure caused by the generation of gases during the charge cycle:

1. negative electrodes of larger capacity than the positive electrodes
2. plate separators made particularly permeable to oxygen
3. a limited amount of electrolyte.

The construction method ensures that the positive plate reaches a state of full charge before the negative plate. The oxygen given off can pass through the plate separator and is absorbed by the negative plate. The limited amount of electrolyte available to the electrodes appears to assist in this transfer of oxygen. The electrolyte itself has a jelly-like consistency and is held in position between the electrodes by the cell construction.

Figure 3.13 • Sealed zinc–mercury cell

3.9.6 Gel cells or sealed lead-acid cells

3.9.7 Lithium cells

Construction

Figure 3.16 · A comparison of cell discharge characteristics (not to scale/accurate)

3.9.8 Nickel metal hydride cells (NiMH cells)

general portable electronic devices. They do need regular access to chargers to maintain their state of charge.

3.10 FUEL CELLS

In recent years the fuel cell has been the subject of much research and received a lot of publicity when it was used to provide electrical power for spacecraft. The principle of the fuel cell was first demonstrated in 1839 as the reversible gas cell (see Figure 3.15(a)). If the load is replaced by a d.c. supply, oxygen collects at the anode and hydrogen at the cathode. When the load is replaced, the cell generates a current flow until the gases have recombined to form water. The special electrodes of platinum black do not undergo a chemical change but merely act as catalysts.
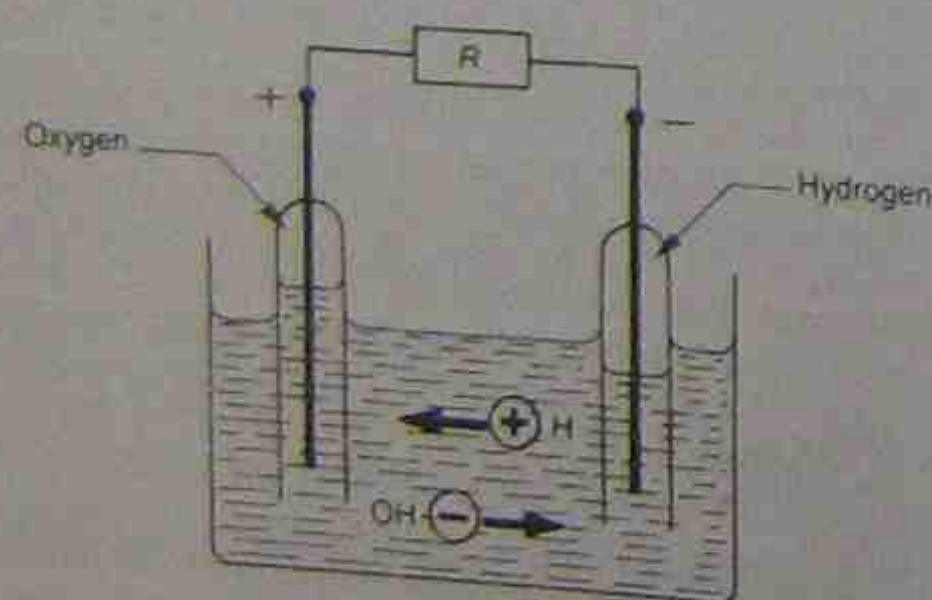
Another version of the fuel cell is shown in Figure 3.15(b). It consists of two chambers and two porous electrodes separated by an electrolyte. Hydrogen supplied to the upper chamber diffuses through electrode A and reacts with the electrolyte, forming positive ions and free electrons. The ions migrate through the electrolyte to electrode B where they combine with oxygen and electrons, which have passed through the external load, forming water.

This type of fuel cell gives more energy per unit mass than a storage battery and in addition water is produced as a useful by-product. Each kilowatt-hour of energy produces approximately half a litre of water.

Although much more research work needs to be done, it can easily be visualised that a solar cell could be used to produce electrical energy, which in turn could produce hydrogen and oxygen from water during daylight hours. The gases could be stored until required and then fed into a fuel cell to produce electrical energy again, not necessarily during daylight hours and without the use of storage batteries.

Research and development of the fuel cell is still proceeding. One of the lines being followed is the use of the gas given off by a plant during its growing processes. In the stationary situation these experimental cells are proving quite reliable and long-lived.

An advanced fuel cell of the type being developed today can deliver 50 A at approximately 0.6 V for many hours.

3.11 CELL CAPACITY AND OTHER FACTORS

3.11.1 Capacity

The capacity of a cell—its ability to deliver electrical energy—is usually expressed in ampere-hours. One ampere-hour is provided by a cell when 1 A flows for a period of 1 hour. The value is found from the product of the time in hours and the current flow in amperes. The figure obtained has to be qualified by factors such as discharge rates, cell temperatures, specific gravity of the electrolyte, and the final voltage reached as the cell is discharged.

3.11.2 Discharge rate

As discharge rates are increased, the ampere-hour capacity of a cell is decreased. For comparison purposes standard discharge times are employed, usually of either 8 or 10 hours, but this is variable depending on the intended use of the cell. If the maximum load for a cell is, for example, 20 A over a period of 5 hours, it is pointless testing it at other values because the figures obtained cannot be related to the cell's intended use. A cell's capacity can be considered from two viewpoints:

1. Its ability to deliver a continuous current over a specified period of time.
2. Its ability to deliver very high currents for short periods of time.

When a cell is required to provide very high discharge currents at low temperatures its 'cold cranking capacity' becomes an important factor. This is an indication of the cell's ability to perform its intended function by delivering the required high currents at reduced temperatures.

For engine starting, the cell might have to provide a high current for only a few seconds but there might also be a need for reserve capacity if start failures occur. Typical starting values of current for petrol engines are 400 A for 6 V systems or 200 A for 12 V systems, while for diesel engines the starting current for a 12 V system can be more than 1000 A. For larger industrial and marine engines the current can be tens of thousands of amperes.
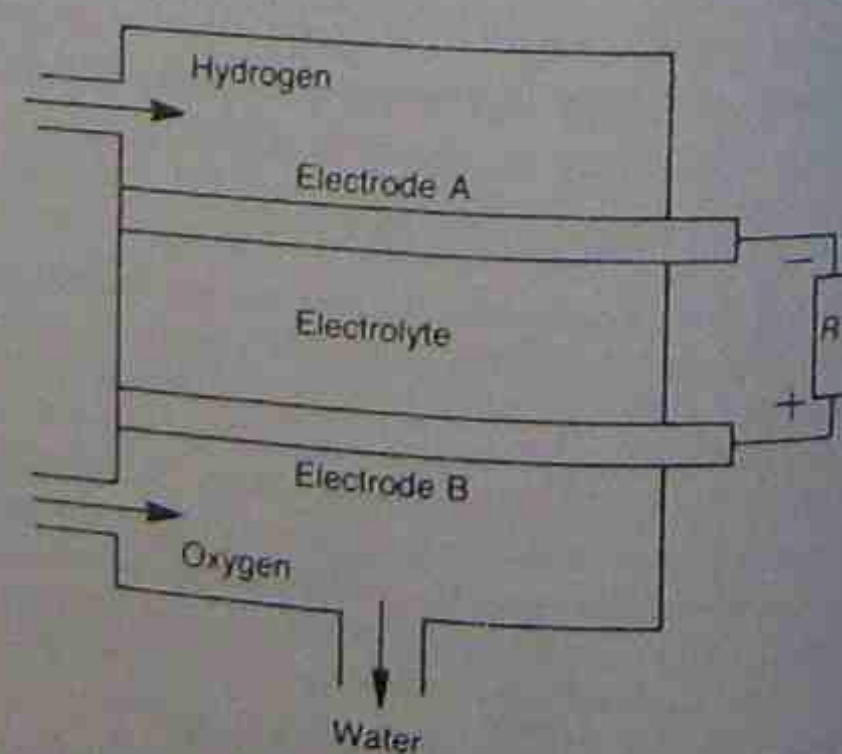
The maximum current capabilities of a cell are governed by design factors, most of which relate to the surface area of the plates actually in contact with the electrolyte, as well as the movement of fresh electrolyte into the active areas of the plates. As chemical changes take place in the electrolyte on cell discharge, the internal resistance of the cell increases and causes a greater internal voltage drop.

To improve a cell's ability to deliver high discharge currents for a short period of time, plates are made as thin as is practically possible to ensure that the electrolyte percolates into as much of the plate material as it can and so enable more of it to take part in the chemical process. The thinner plates are physically weaker, and extra care is needed in handling the cell.

For stationary cells, where heavy-duty discharge cycles are not usually a requirement, long life and reliability become more dominant factors. For lead–acid cells in particular, plate construction may be of pure lead, and the cases consist of glass for easy maintenance.

3.11.3 Temperature

Cells in general operate with increased efficiency at higher temperatures. Internal losses are less, the electrolyte diffuses into the plate material more readily and, as in operation the internal losses are transformed into heat, a cell can maintain a temperature slightly above its surroundings. Increased operating temperatures also increase the rate of internal corrosion and lead to shorter operational life.

3.11.4 Electrolyte density (specific gravity)

The electrolyte of lead–acid cells is dilute sulphuric acid. To promote long life, this should be as dilute as can be arranged, because internal plate corrosion and local action are thereby reduced. Deterioration of the plate separators is also reduced.

Against this is the fact that higher densities give increased cell capacity, improved voltage discharge characteristics and a reduction in the volume of electrolyte required. For stationary cells a maximum electrolyte density of 1210 kg/m^3 (1.210 specific gravity) is a nominal value. For automobile work a nominal value is 1280 kg/m^3 (1.280 SG). For tropical service this value may be reduced to 1250 kg/m^3 (1.250 SG) while in cold climates it may be increased to reduce the possibility of electrolyte freezing.

Alkaline cells do not vary much in electrolyte density of approximately 1200 kg/m^3 (1.200 SG) between types of use although the density does gradually decrease in service to approximately 1150 kg/m^3 (1.15 SG). At this stage it is often replaced. Unlike a lead–acid cell, a healthy alkaline cell is not affected by electrolyte freezing.

3.11.5 Final voltage

The term final voltage is used to designate the minimum useful and accepted voltage at various rates of discharge.

3.11.6 Ampere-hour efficiency

Ampere-hour efficiency is the ratio of the number of ampere-hours obtainable during discharge to that required to restore the cell to its original condition. However, the value varies widely depending on the use of the cell. Typical figures are:

lead–acid cell	90%
nickel–cadmium cell	75–80%
fuel cell	up to 90%

3.11.7 Capacity/mass

The ratio of watt-hours per unit mass varies widely with the type of use to which the cell is subjected and is mainly applicable to lightweight portable cells.

Typical figures are:

	watt-hours/kg
Leclanché-type zinc–carbon cell	20–40
sealed zinc–mercury cell	90–110
silver oxide–cadmium cell	40–60
silver–zinc cell	90–150
zinc–alkaline manganese dioxide cell	60–70

Table 3.2 gives a representative listing of commercially available cells and summarises their main characteristics.

Table 3.2 • Summary of commercially available cells

Cell	Positive electrode	Negative electrode	Electrolyte	Volts/cell	Type
Daniell	copper	zinc	sulphuric acid	1.1	wet primary
lead–acid	lead peroxide	lead	sulphuric acid	2.0	wet secondary
nickel–iron	nickel–oxide	iron	potassium hydroxide	1.2	wet secondary
carbon–zinc	carbon	zinc	ammonium and zinc chloride	1.5	dry primary
zinc–alkaline manganese dioxide	manganese dioxide	zinc	potassium hydroxide	1.5	dry primary or secondary
mercury	mercuric oxide	zinc	potassium hydroxide	1.3	dry primary
nickel–cadmium	nickel	cadmium hydroxide	potassium hydroxide	1.25	dry secondary

(a) Reversible gas cell

(b) Hydrox fuel cell

Figure 3.15 • Fuel cells

3.12   BATTERIES

A battery consists of a group of cells connected together. To provide a battery having a higher voltage than a single cell, several cells are connected in series. Connecting a group of cells in parallel provides a battery that has a greater current-carrying capacity.

3.12.1   Cells in series

A group of cells connected in series to a load has the same value of current flowing through them as flows through the load. The total voltage is the sum of the cell voltages. For the voltages of individual cells, see Table 3.2.

Example 3.2

How many nickel-cadmium cells would be required to construct a 5 V battery?

From Table 3.2, a nickel-cadmium cell has a voltage of 1.25 V.

$$\therefore \text{ number of cells} = \frac{5}{1.25} = 4$$

3.12.2   Cells in parallel

Cells connected in parallel can contribute to a current flow far greater than that obtainable from a single cell.

Example 3.3

A 10 Ω resistor is to be placed across a 1.5 V source. If the source is to be constructed of cells each capable of supplying 25 mA, how many cells must be connected in parallel?

$$I = \frac{V}{R} = \frac{1.5}{10} = 150 \text{ mA}$$

$$\therefore \text{ number of cells} = \frac{150}{25} = 6 \text{ (in parallel)}$$

Before connecting cells in series or parallel, precautions should be taken to ensure that the cells are of the same type and in good condition. A cell with a voltage of 1.5 V cannot be placed in parallel with one of a different voltage. If this is done, circulating currents are set up with the possibility of destroying both cells. Placing a discharged cell in series with one in good condition prevents the good cell from working satisfactorily.

3.12.3   Cell resistance

Cells and batteries have resistance like other electrical conductors. When a battery is being charged, a higher voltage has to be used, the extra voltage being needed to overcome the internal resistance. On discharge the cell voltage is lower for the same reason.

A car battery with six 2 V cells in series to give a nominal value of 12 V typically requires 14 V to charge it.

Example 3.4

A 12 V battery requires 14.7 V to charge it at 20 A. Find the internal resistance of each cell. After charging has been completed and the battery voltage has stabilised,

what is the terminal voltage if the battery supplies a 20 A load? (See Fig. 3.16.)

Charging

Extra voltage = 14.7 − 12 = 2.7 V

$$R_i = \frac{V}{I} = \frac{2.7}{20} = 0.135 \ \Omega$$

$$\therefore \text{ resistance/cell} = \frac{0.135}{6} = 0.0225 \ \Omega$$

Discharging

$$V = IR = 0.135 \times 20 = 2.7 \text{ V}$$

$$\therefore \text{ terminal voltage} = 12 - 2.7$$
$$= 9.3 \text{ V}$$
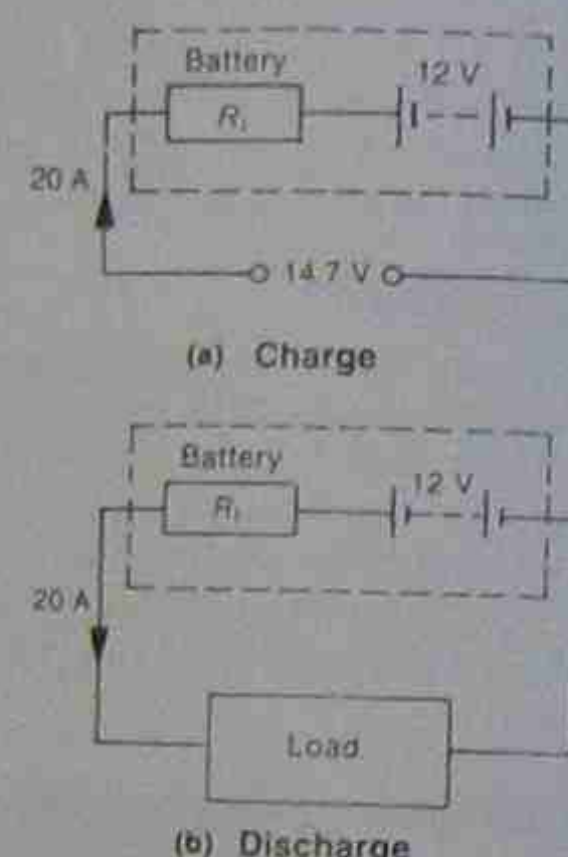

(a) Charge

(b) Discharge

Figure 3.16 • Circuits for example 3.4

Normally battery internal resistance varies considerably between charging and discharging, and also at different current rates. The effect of internal resistance is to increase the amount of energy required to charge a battery and to reduce that available for useful purposes. It causes a loss of energy on both charge and discharge cycles, and gives a decreased operating efficiency.

Example 3.5

The open-circuit voltage of a battery is 6 V. Find the internal resistance if the voltage drops to 5 V when a 10 Ω resistor is connected across the battery (see Fig. 3.17).
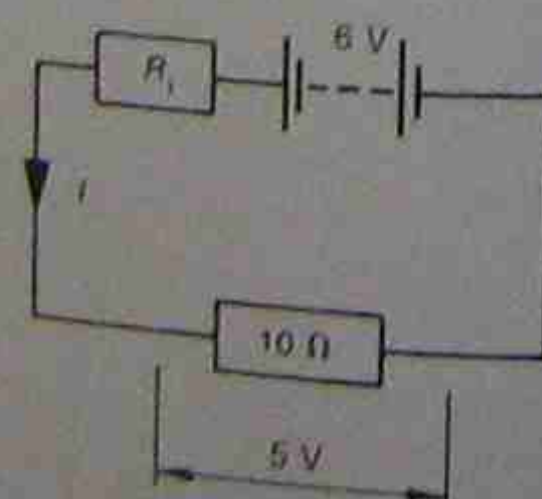

Figure 3.17 • Circuit for example 3.5

$$\text{current flowing } I = \frac{V}{R} = \frac{5}{10} = 0.5 \text{ A}$$

The voltage drop is due to the internal resistance when the current is 0.5 A.

$$\therefore R_i = \frac{V}{I} = \frac{1}{0.5} = 2 \ \Omega$$

3.12.4   Battery maintenance

For maximum service life from batteries a maintenance routine is necessary. Points to observe are as follows:

1. Ensure that terminals are clean and tight to give good electrical contact.

2. Ensure that connecting terminals are of a suitable material. The electrode potential of the two materials should be as close as possible.

3. Check the electrolyte level regularly and keep it within the range of required levels. The plates must be kept covered and not allowed to dry out. With lead–acid cells in particular, this leads to reduction in ampere-hour capacity. Unless specified otherwise, approximately 3 to 4 mm of electrolyte above the plates is usually sufficient. Some types of battery construction have been designed to reduce the electrolyte loss problem. Special filler caps have been fitted to allow the cell to release the hydrogen and oxygen gases generated. Because the gases come from the electrolyte, this gas escape leads to a reduction in electrolyte level.

4. The battery case must be kept clean of electrolyte.

5. The battery must be suitably protected from extreme temperatures and positioned where it is less likely to be physically damaged—but in a ventilated position.

6. The battery must not be charged or discharged at excessively high current rates.

7. The rates of current charge or discharge must be within specified design levels.

3.13   STANDBY POWER SUPPLIES

Standby power supplies are used to provide a backup service in the event of mains power failures. Even where large engine-driven alternators are intended for that purpose, there is still a need for a battery supply to sense power failures and for engine starting.

The main requirements of such a system are:

1. to provide a bridging supply until generating sets can be started;

2. to provide power for starting emergency generating plant;

3. to provide emergency lighting for evacuation of buildings;

4. to provide reliable on-site power for computer or other electronic systems such as cash registers, communications equipment, fire and security systems, load-sensing systems for starting additional generating plant, and navigation equipment;

5. continuity of supply for electronic memories.

By its nature, the use of a standby power supply is nearly always in an emergency. Ideally a standby plant

should never need to be used, yet it must always be available for instant use. This means that reliability is of exceptional importance and must exist with a minimum of maintenance. The batteries must have a long life with a low self-discharge rate and lose a minimum of electrolyte over long periods. The type of batteries chosen for any particular duty will depend on any special requirements of that duty. For example, the battery chosen for train lighting would have to meet such requirements as deep charge and discharge cycles as well as be able to withstand physical shocks and vibration. A battery chosen to supply power to a telephone exchange would be stationary and subject to a continual charge from the supply at a virtual constant rate, sufficient to keep the battery fully charged and to supply the load demand on the exchange. A battery under these latter conditions would have a life of three to four times the life of the former.

3.13.1   Charging methods

There are two systems for recharging secondary cells although there are variations of these two methods. The aim of both is to keep a bank of cells—a battery—in a fully charged condition without excessive gassing.

Constant voltage charging

This is the most common method used—and the cheapest. The charger is set at a suitable voltage (typically 2.25 V/cell) and the charging current becomes a function of the difference between this voltage and the cell voltage. Initially the charging rate is at a maximum for a discharged cell and, as the cell voltage rises, the charging current decreases, until it reaches a minimum value determined by the charger voltage. This action gives rise to the term 'taper charging'. The voltage of the charger has to be chosen to suit on-site conditions. A high voltage gives a faster recharge but leads to excessive gassing and reduced cell life. The electrolyte might also need more frequent topping up.

In standby situations the charger should be able to handle continuously connected loads and also have sufficient capacity to recharge the bank after emergency duties. Under these conditions the cell bank is said to be 'floating' or on a 'float charge'.

Constant current charging

The charging current should be limited to a final or finishing rate governed by the cell size, yet adequate enough to recharge the cell after use, so bringing it back to a fully charged condition. The voltage of the battery rises steadily as the charging continues and any load system connected must not be affected by this change in voltage. Where discharging is heavy, step charging may be used, where a high rate of charge is used initially, dropping abruptly to the finishing rate at a predetermined voltage. With constant current charging, some form of electronic control is required to monitor the changing conditions of charge. That is, the cell voltage is sensed at the charger and used to keep the current rate steady.

3.14   ELECTROLYSIS

Pure water is a very poor conductor of electricity but if a small amount of an acid, alkali or salt is added, the water

can become quite a good conductor. As in a cell, if an electric current flows through the electrolyte, it dissociates the molecules of the substances in solution into ions and these may appear at the anode and cathode. The act of dissociation is called electrolysis. If copper sulphate is dissolved in water and a current passed through it, the ions produced are a positive copper ion (Cu^{++}), and a negative sulphate (SO_4^{--}).

From the electron theory discussed in Chapter 2, the negative ion has an excess of electrons and the positive ion a deficiency of electrons. When the ions are produced in the electrolyte they are attracted to the electrode with the opposite polarity. That is, the positive ions are attracted to the negative electrode (cathode) and the negative ions are attracted to the positive electrode (anode). The positive ions accept electrons at the cathode and the negative ions give up electrons at the anode, so neutralising both ions. This transfer of charges constitutes the current flowing through the electrolyte. The conduction of charges can be described as a convection effect, the charges being carried to the electrode by the ions. The dissociation of ions can be written as:

$$CuSO_4 \rightleftharpoons Cu^{++} + SO_4^{--}$$

The arrow pointing to the right indicates dissociation and the arrow pointing to the left indicates that recombination can take place to form neutral molecules of copper sulphate.

The electrical conduction is different to that occurring in a metal conductor. In a metal conductor the electrical energy is transferred by electrical charges passed on from atom to atom. Electrolytic conduction involves transfer of matter and is accompanied by a chemical change. This electrolytic effect is illustrated in Figure 3.18.

If two copper plates are immersed in a solution of water and copper sulphate, and a voltage is applied to the two electrodes, a current will flow. When the current flows, several things occur virtually simultaneously.

1. The copper sulphate breaks down into positive copper ions (Cu^{++}) and negative sulphate ions (SO_4^{--}).
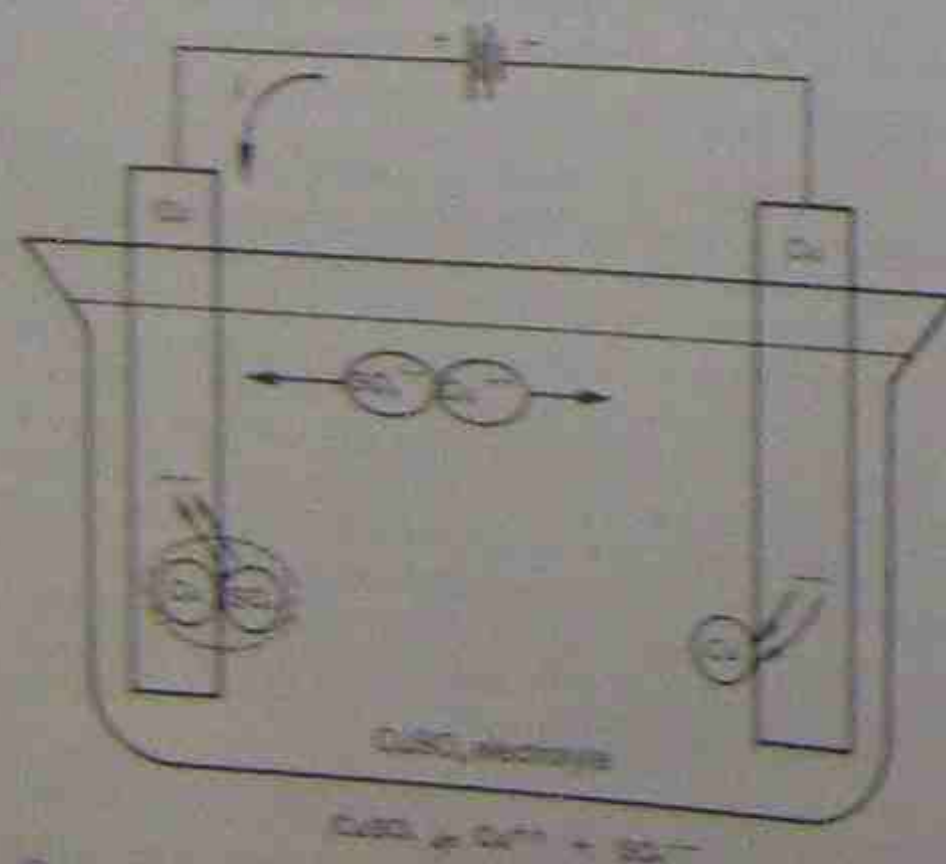

Figure 3.18 • Electrolysis with copper electrodes in water sulphate solution

2. Positive copper ions are attracted to the cathode. On reaching this electrode, each ion absorbs two electrons to form neutral atoms of copper which are deposited on the cathode.
3. Negative sulphate ions are attracted towards the anode, and each ion on reaching this electrode gives up two electrons. This compensates for the two electrons absorbed at the cathode and the transfer of charges from one electrode to the other constitutes current flow through the electrolyte.
4. Ions cannot exist without a charge, so the sulphate ion combines with an atom of copper at the anode to form a molecule of copper sulphate, which goes into solution in the electrolyte. Accordingly, the density of the electrolyte remains constant and the net effect is the transfer of copper atoms from the anode to the cathode.

This reaction occurs in the electrolytic refining of copper. A copper ingot to be refined is used as an anode and a thin copper plate as a cathode. Copper goes into solution in the electrolyte and is deposited as pure copper on the cathode. Impurities in the ingot fall to the bottom of the bath as a sludge. Depending on the source of the copper, this sludge might contain other metals that are sufficiently concentrated to warrant further extraction processing. The above description applies to only the main reactions. There are other lesser reactions that may or may not be desirable. In the above reaction, for example, gases such as hydrogen and oxygen may be generated, as well as sulphuric acid. The electrolyte may require additives to control these reactions.

In some cases the electrolyte may be molten salts or ores through which a current is passed. Depending on the actual process, it may then be called electro-reduction, rather than electrolytic refining, which is a more expensive process.

3.14.1 Electroplating

The electrolysis method for transferring copper from one electrode to another—electro-deposition—can be used with other metals to create coatings of one type of metal on another. This process is called electroplating and has many aims. The major ones are for decoration and protection but it can also be used for repairs such as building up worn shafts. In this case a hard metal such as chromium is used. Where rusting is a problem, soft metals such as zinc or cadmium can be used. For decorative purposes articles may be made of a serviceable material and then plated with more precious metals such as silver or gold. The object that is to receive a coating of metal is used as a cathode in an electrolyte consisting of a salt of the metal to be plated. There are two main methods:

1. The anode may be soluble and consist of the same metal as that to be used in the plating process. It is plated on to the cathode.
2. The anode may be inert and it is then necessary to replenish the electrolyte by adding new material in some form to make up for the metal lost in the plating process.

In addition to the composition of the bath itself there are several other factors that affect the plating process. Some of these are:

1. **Current density.** For best-quality plating it is necessary to electroplate at a certain current. For example, an average general figure is 200 A per square metre surface area of cathode. The current value is proportioned down to suit, but is also varied according to the finish required.
2. **Conductivity.** The electrolyte should have good conductivity to minimise power losses and rough uneven deposits.
3. **Temperature.** Some plating baths work better at specific temperatures.
4. **Metal distribution.** Irregularly shaped objects tend to have some of their parts nearer the anode than others, giving uneven deposits of electroplated metal.
5. **Base metal structure.** Some base metals cause the electroplate to be extensions of their own crystalline structure. Cast iron, for example, can cause a copper plate to be crystalline in both structure and appearance.

Figure 3.19 shows the basic requirements of an electroplating bath. There are two anodes, one either side of the object to be plated, and suspended in the electrolyte between them is the object to be plated. For example, the anodes could be copper bars, the electrolyte a solution of sodium cyanide and caustic soda in water (a mixture that will work with more metals than copper sulphate) and the cathode the article to be copper plated. The solution is highly poisonous and also gives off highly toxic fumes, so care must be exercised. The current through the electrolyte must be adjusted to suit the plating requirements.
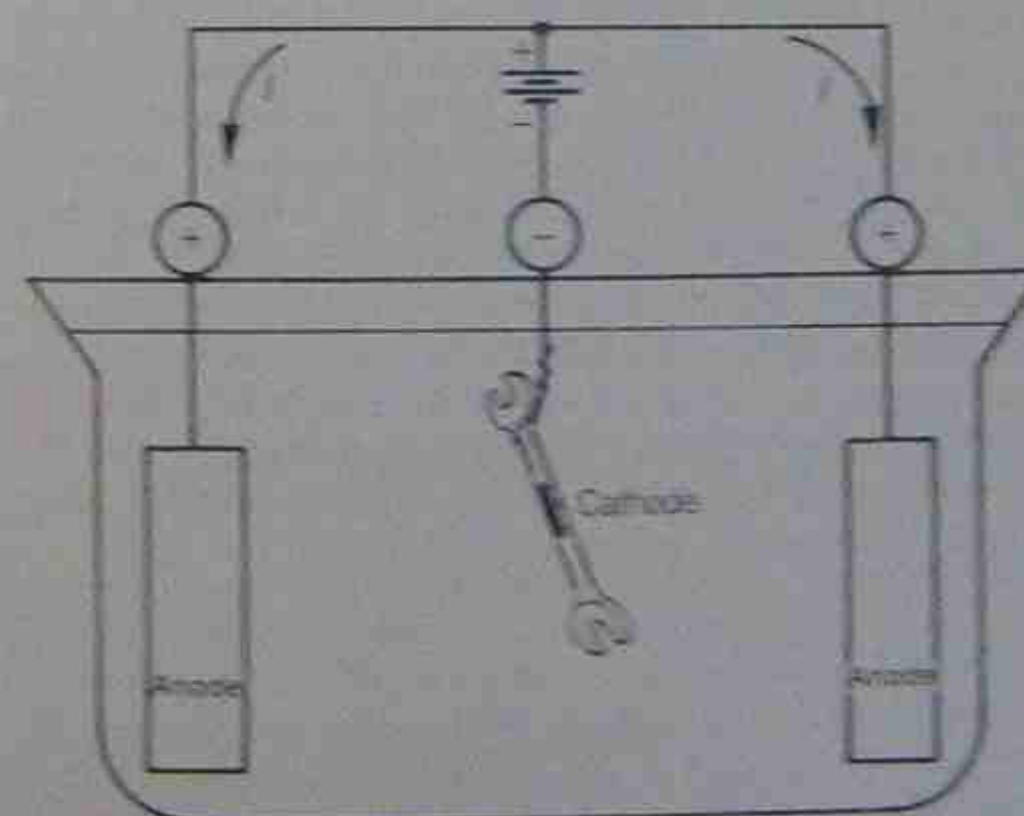

Figure 3.19 • Basics of an electroplating bath

3.14.2 Faraday's laws

1. *The mass of metal deposited is proportional to the current flowing and the duration of its flow.*
2. *The mass of metal deposited by a quantity of electric charge is proportional to the electrochemical equivalent of the metal.*

Faraday's first law merely states that equal amounts of any one type of element will be deposited by the same quantity of electricity in coulombs (C); that is, 1 A flowing for 30 seconds, 2 A for 15 seconds or 3 A for 10 seconds. In each case the quantity of electricity is 30 C and each will deposit the same mass of metal.

that is, $m = It$

Faraday's second law states that the different amounts deposited by different elements for the same quantity of electricity will be proportional to their electrochemical equivalents. The electrochemical equivalent of any element is proportional to its relative atomic mass and its valency:

$$z \propto \frac{\text{relative atomic mass}}{\text{valency}}$$

If this ratio is divided by Faraday's constant (96 500), an absolute equivalent value can be given:

that is, $z = \dfrac{\text{relative atomic mass}}{\text{valency} \times 96\ 500}$

Inserting the electrochemical equivalent value into the first relationship gives the formula:

$$\boxed{m = Itz}$$

where m = mass of metal deposited
I = current flowing in amperes
t = time of current flow in seconds
z = electrochemical equivalent

Atomic masses and valencies can be found from tables and the equivalent values then calculated, but tables can also provide equivalent values directly. Table 3.3 lists equivalents for selected materials in their most stable states.

The higher the equivalent value, the greater is the amount of metal deposited for any one quantity of electric charge.

Example 3.6

Find the amount of zinc deposited by an electrolytic refining bath in 24 hours if the current flowing is 5000 A.

$$m = Itz$$
$$= 5000 \times (24 \times 3600) \times 3.39 \times 10^{-7}$$
$$= 146.5 \text{ kg}$$

Table 3.3 • Electrochemical equivalents

Material	Electrochemical equivalent (kilogram per coulomb or kg/C)
aluminium	9.30×10^{-8}
cadmium	5.82×10^{-7}
copper	3.29×10^{-7}
zinc	3.39×10^{-7}
silver	1.12×10^{-6}
nickel	3.04×10^{-7}
chromium	1.80×10^{-7}

Note that this figure would apply at 100 per cent efficiency and would be modified according to the efficiency of the bath.

That is, if the bath efficiency were 50 per cent, the amount of purified metal recovered from the bath would be half the above figure, or 73.25 kg.

The actual efficiency figure would depend on the type of metal being deposited, the chemical make-up of the electrolyte, the voltage applied and the current flowing through the bath. Not all the current flowing in the system does useful work (e.g. some current will produce heat and hydrogen gas). Some electroplating baths operate at efficiencies of 90 per cent or more, while others (such as chromium being deposited in a chromic acid solution) operate at efficiencies in the 12 per cent range.

The electrolytic method of deposition produces metals with a high purity, but is expensive and requires large amounts of electrical energy. It can be used to advantage in conjunction with hydroelectric schemes, where large amounts of electrical energy can be made available at a comparatively cheap operating cost.

A demonstration electroplating bath is shown in Figure 3.20.

Figure 3.20 • Electrolytic deposition. One of the demonstration electroplating baths at Regency Park College
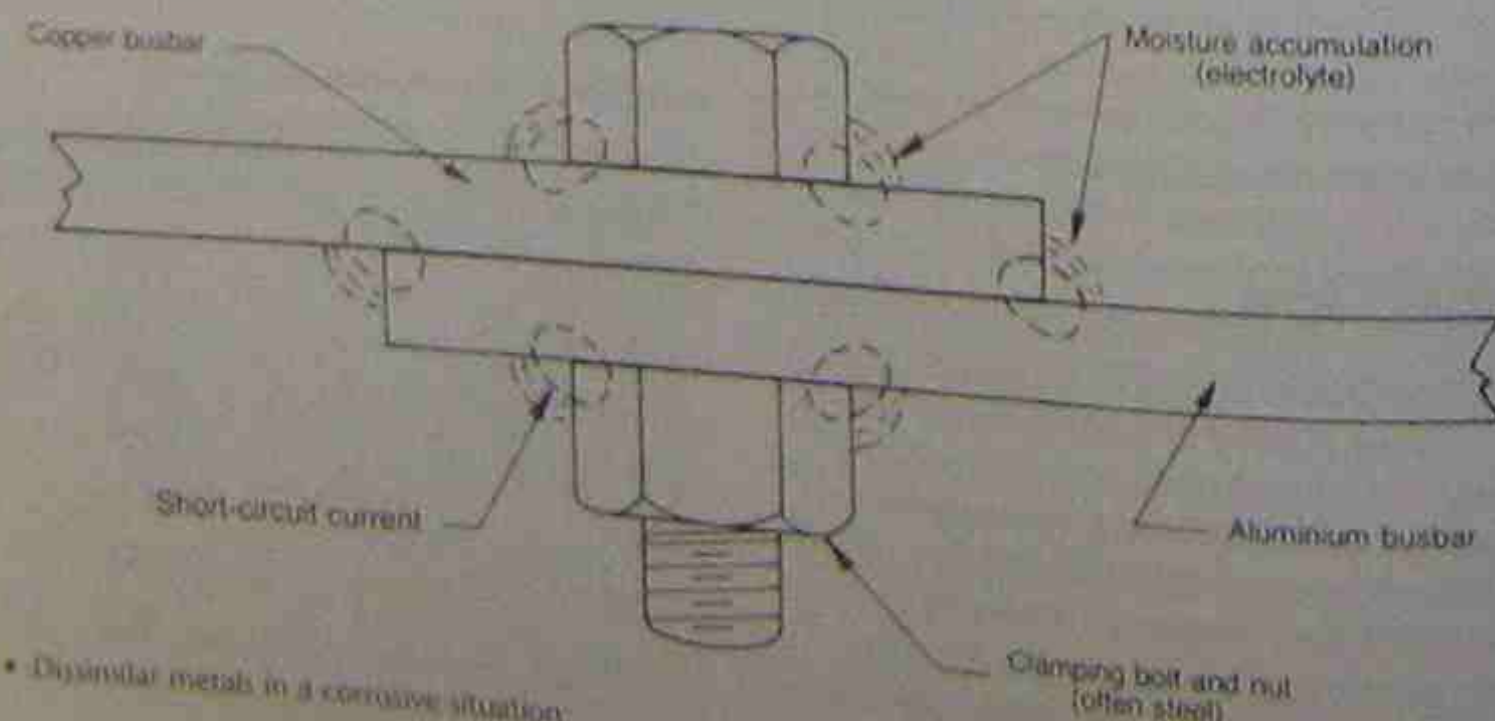
Regency Park College

Figure 3.21 • Dissimilar metals in a corrosive situation

Example 3.7

Find the energy consumed in example 3.6 if the supply voltage was 25 V.

$$W = Pt$$
$$= \frac{25 \times 5000}{1000} \times 24$$
$$= 3000 \text{ kWh}$$

It should be realised that the production of metals by electrolysis is usually on a far larger scale than in single baths or cells. Where a firm has 100 cells in operation, the above figure becomes 300 000 kWh per 24-hour day and at a nominal cost of 2¢/kWh, gives an operating cost of $6000 per day just for electrical energy.

3.14.3 Disadvantages of electrolysis— electrolytic corrosion

Dissimilar metals

The best-known effect of destructive corrosion occurs when two different metals are in contact in the presence of an electrolyte. An increasing problem in Australia is the extension of copper conductors with aluminium conductors. The copper and aluminium act as electrodes and electrolyte is present from condensation or rain that contains dissolved sulphur products. A simple cell is created (see section 3.2.1) and is effectively short-circuited on itself, as illustrated in Figure 3.21.

The metal with the higher potential becomes the anode and will tend to go into solution in the electrolyte (i.e. will corrode). The result is a progressively deteriorating electrical connection, generation of heat, and eventual failure of the connection. In some circumstances the heat produced can set fire to an installation and the problem is then more than just the failure of an electrical circuit.

The way to retard this type of corrosion is to minimise the number of connections where dissimilar metals are joined, and prevent the entry of moisture to the joint by applying paint or other covering. Alternatively, all the materials being joined can be electroplated with the same metal, for example, cadmium.

Stray electric currents

Stray electric currents in the earth have many causes— inadequate earthing of electrical systems is only one. Underground pipes and cables become corroded by the electrolytic action of these currents. Dissimilar metals in damp ground and adjacent to each other produce the same result as described above and, in turn, generate more stray electrical currents. The electrical bonding of tracks in electric traction systems helps to reduce underground stray currents, and the covering of underground pipes and conductors with plastic sheaths minimises the corrosive effects. The corrosion tends to be more concentrated at sharp bends in underground pipe work and appropriate measures to avoid this should be taken where practicable.

3.14.4 Electrolytic protection

Electrolytic corrosion can be minimised by two general methods.

Sacrificial anodes

Anodes made of zinc blocks are bolted inside boilers and to the metal hulls of ships adjacent to bronze propellers. The intention is to sacrifice a metal block, which can be replaced comparatively easily, rather than risk the corrosion of the boiler or ship's hull.

Cathodic protection

An external d.c. voltage is applied between the equipment to be protected and earth, such that the equipment is at a lower potential than the surrounding soil. In practice it has been found that most forms of corrosion can be prevented when the pipes or other metallic structures are approximately 0.5 V negative with respect to the surrounding soil.

SUMMARY

- Two dissimilar metals in a conducting medium (an electrolyte) form a voltaic cell.
- When a load is connected to a voltaic cell, chemical energy is converted into electrical energy. As the process continues, at least one of the metals is eaten away by being transformed chemically into a different compound.
- Different metals produce different voltages. The electromotive force series table indicates the voltages that can be expected from metals in various electrolytes.
- Primary cells are cells that, once depleted, cannot be renewed without replacing the entire contents of the two constituent parts. They cannot be recharged by reversing the chemical changes that have taken place.
- There are several versions of primary cells available. Most are designed for specific purposes. Voltage varies from type to type.
- Primary cells are of two types—wet and dry. For portable use and general convenience the cells are mostly the so-called dry type.
- Secondary cells can be recharged. The chemical change that takes place on discharge can be reversed by applying a voltage to the cell and recharging it. The plates are restored to their original chemical state, and the process can be repeated.
- Owing to the internal resistance of a cell, energy is lost on both charge and discharge cycles.
- Lead–acid secondary cells can be tested for state of charge by testing the density of the sulphuric acid electrolyte.
- Lead–acid cells can also be checked with a high-rate discharge tester.
- It is difficult to assess the state of charge of a nickel–alkaline cell by testing the electrolyte density.
- Use of a high-rate discharge tester is one method for assessing the state of charge of a nickel–alkaline cell.
- The equipment for testing lead–acid and nickel–alkaline cells must not be mixed because the electrolytes react with each other.
- Several types of secondary cells are available.
- Sealed secondary cells have to be charged at carefully controlled rates, owing to generated gases creating excessive pressures within the cell casing.
- When working with batteries, precautions have to be taken to ensure the safety of the operators.
- Fuel cells are another form of secondary cell. Many depend on the supply of a gas for their operation.
- Development is continuing on producing a fuel cell that is continuous in operation either with a gas, plant life, or microbes.
- Cell capacity is measured in ampere-hours at specific discharge rates.
- Cells can be compared by:
  —ampere-hour efficiency
  —capacity versus mass
  —final discharge voltage
  —initial output voltage.
- Cells can be connected in either series or parallel to form a bank or battery of cells. In series, the voltage available is increased. In parallel, the current available is increased but at the voltage of the individual cells.
- Cells must be of identical types to be used in parallel.
- Batteries must be regularly maintained.
- Batteries can be charged by using either a constant voltage or a constant current procedure. Both methods have advantages.
- Electroplating is a technique whereby chemical changes that take place in the electrolytic process can be put to good use. Material can be given a decorative finish, be built up or reduced in size, and made resistant to corrosion and/or staining.
- Electrolytic corrosion is created by joining two different metals in a damp atmosphere with dust or pollution of a type that will dissolve in the water. Precautions might have to be taken to ensure that the join between two different metals is kept dry.
- Electrolytic corrosion can be reduced in some cases by providing sacrificial anodes. It can also be reduced by applying a reverse voltage to neutralise stray ground currents that might be flowing.

EXERCISES

3.1 What is the essential difference between a primary and a secondary cell?

3.2 Name three types of primary cell.

3.3 What is meant by the term *polarisation*?

3.4 What is meant by the term *local action*?

3.5 Discuss how the condition of a lead–acid cell can be tested.

3.6 What is generally understood by the term *ampere-hour capacity*? Give examples.

3.7 What safety precautions must be taken with secondary cells on charge? Explain why these safety precautions are necessary.

3.8 What is the difference between a cell and a battery?

3.9 Why would the use of plain iron nails in a galvanised roof have undesirable effects? If the nails were also galvanised, explain why there would be no effect.

3.10 If a copper-cable high-tension distribution system was extended with aluminium conductors to a new subdivision, what effects could be expected to take place at the junction of the two types of conductors?

3.11 Sketch a zinc–carbon dry cell, showing its major components.

3.12 A hydrometer reading of a lead–acid cell shows 1.100. Is the battery usable, or should it be recharged?

SELF-TESTING PROBLEMS

3.13 A 470 Ω resistor is connected to a mercury cell. What current flows through the resistor? (Use Table 3.2.)

3.14 How many zinc–carbon cells must be connected in series to construct a battery of 13.5 V?

3.15 An alkaline cell rated at 0.3 ampere-hour is connected to a load of 1.5 kΩ. What is the approximate service life of the cell?

3.16 A nickel–cadmium cell is rated at 0.4 ampere-hour. How many such cells must be connected in parallel to supply current to a 10 Ω load for a period of 200 hours?

3.17 If a 12 V lead–acid battery drops to a terminal voltage of 11.8 V when delivering a current of 20 A, calculate the battery's internal resistance.

3.18 If the terminal voltage of a lead–acid cell varies between 2.1 and 1.8 V during discharge, calculate the number of cells required to give 230 V at:
   (a) the beginning of discharge
   (b) the end of discharge.

3.19 A battery of 20 cells connected in series is charged from a 100 V supply. If a current limiting resistor of 4 Ω is used and the terminal voltage per cell is 2 V and 2.7 V respectively at the beginning and end of charge, calculate the charging current at:
   (a) the beginning of charge
   (b) the end of charge.

3.20 Calculate the mass of copper deposited by an electrolytic deposition process using a bank of cells when a current of 5000 A flows for a total of 20 hours' running time. Assume cell efficiency to be 90 per cent.

3.21 An alkaline cell was charged for 13 hours at a constant potential with a current of 600 mA. It was then discharged at 600 mA for 10 hours at an average voltage of 1.15 V.

   Calculate the ampere-hour efficiency.

Chapter 4

Resistors and resistive networks

4.1 INTRODUCTION

In previous chapters the fundamentals of electricity were introduced, together with various means of producing electrical energy. This chapter concentrates on an analysis of series, parallel and combined circuits as found in practice, and builds on the material in previous chapters. The student is encouraged to assess the circuits critically and reduce them to one simple resistor with a value equivalent to the complete circuit. The text is confined to direct current circuits and adopts the usual practice of conventional current flow, that is, current flow from the positive terminal of a supply to the negative terminal.

4.2 TYPES OF ELECTRICAL CIRCUITS

Although Figure 4.1 shows only one piece of electrical equipment connected to a source of electrical energy, it is quite often necessary to connect many pieces of equipment to the one power source. For example, in a domestic residence there might be many lights and heaters as well as an electric cooking range connected to the supply lines.

There are many different ways in which an appliance can be connected to the supply source but all of these circuits consist of a combination of two basic types of circuits. These are called series and parallel circuits.

4.2.1 Series-connected circuits

In a series-connected circuit there is only one path for the current flow when moving from the higher potential terminal to the lower potential terminal. Any one piece of apparatus will never have more than one conductor connected to each connecting terminal. Figure 4.2(a) shows a series connected circuit. It is not always convenient to
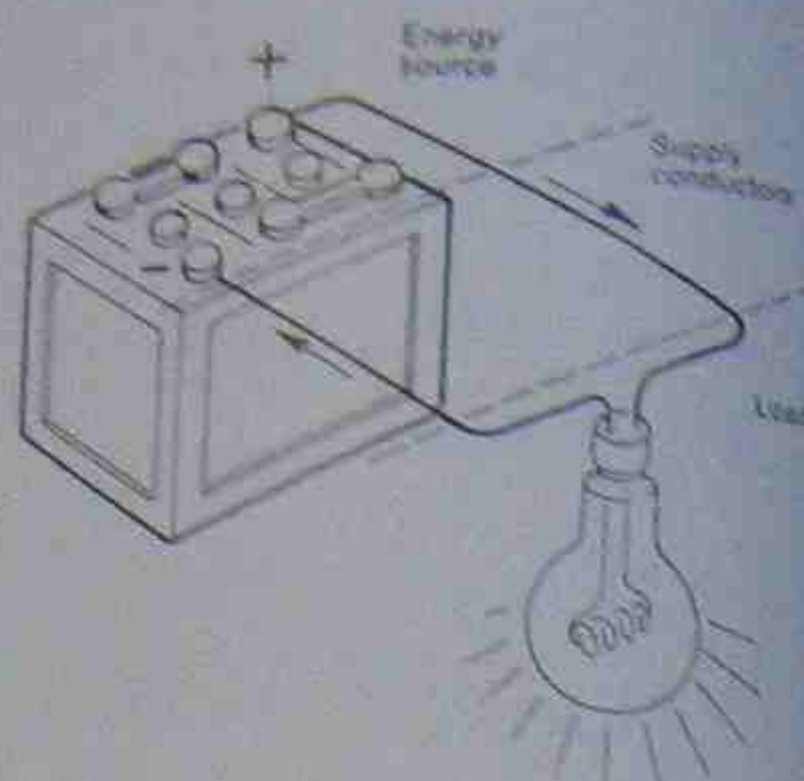

**Figure 4.1** • Basic electrical circuit

draw each piece of apparatus in pictorial form, so standard symbols are often used instead. Figure 4.2(b) shows the circuit drawn in symbolic form.

4.2.2 Parallel-connected circuits

In a parallel-connected circuit there is more than one path for the current to flow between the higher and lower potential terminals. The circuit of a lamp, clothes iron and radiator connected in parallel across a 240 V supply is shown pictorially in Figure 4.3(a). The same circuit is also shown in Figure 4.3(b) using resistance symbols to replace the apparatus. The three separate current paths between the two supply terminals are shown. Each appliance is connected to the supply by looping out of the terminals of the previous appliance. Note that some of the terminals now have more than one conductor connected to them.
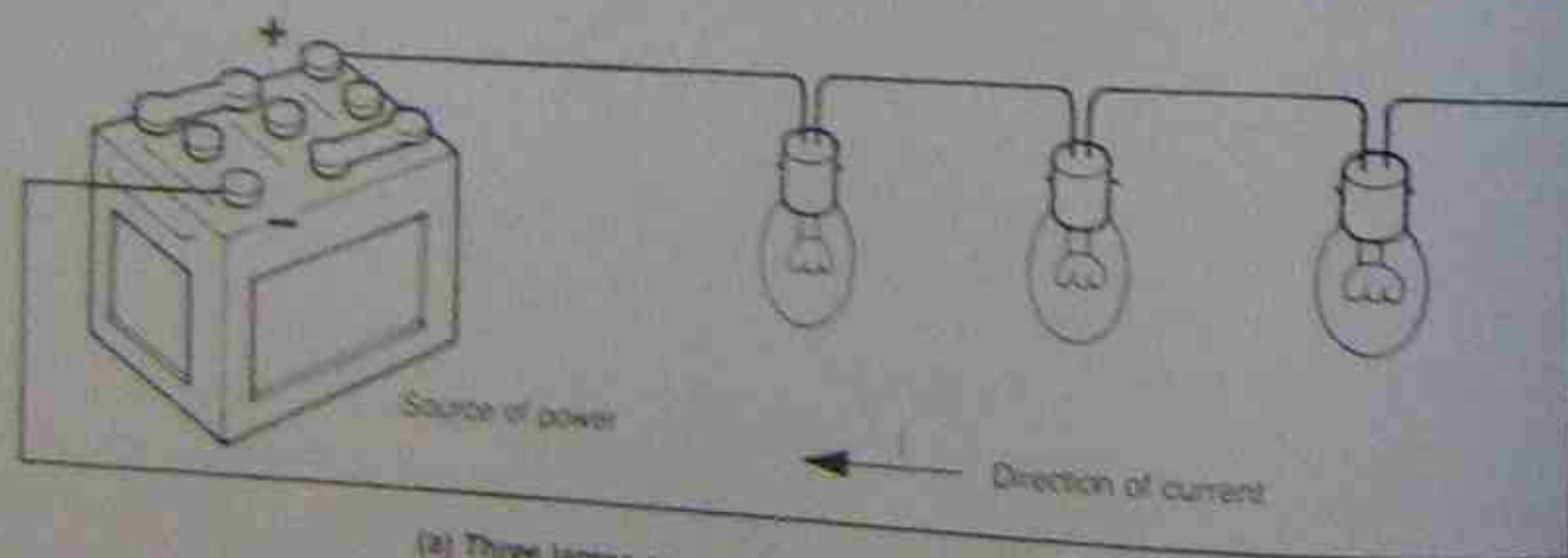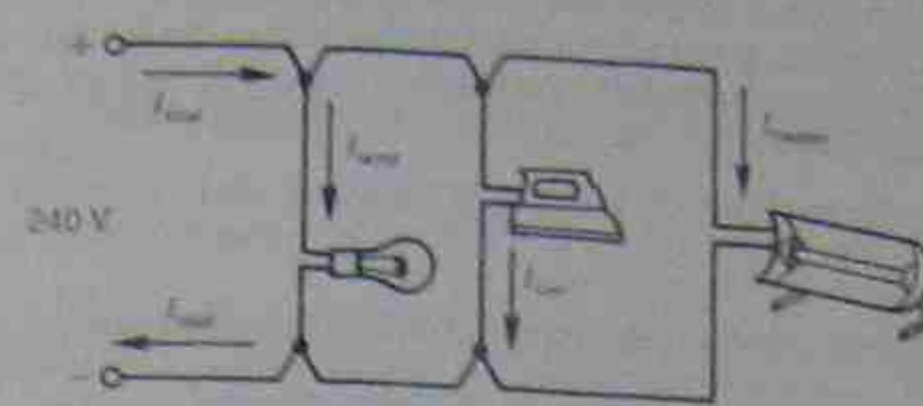

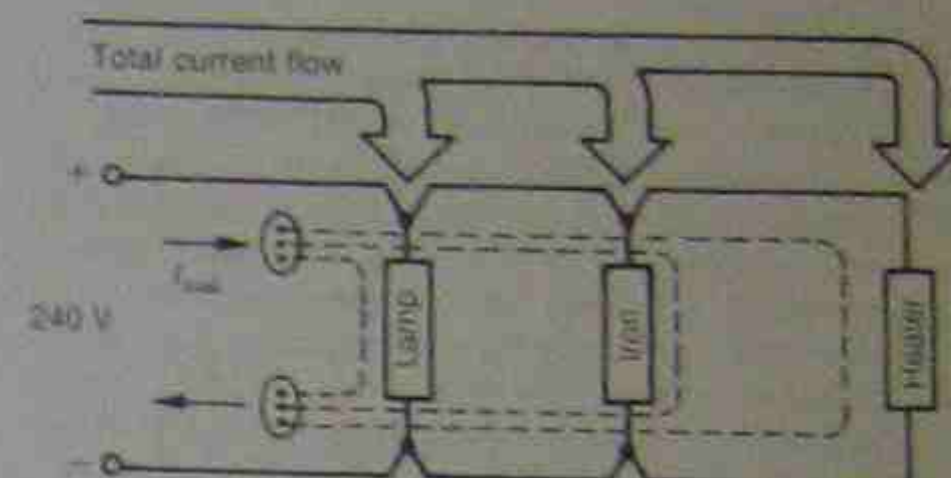**(a) Three lamps connected in series to a battery**
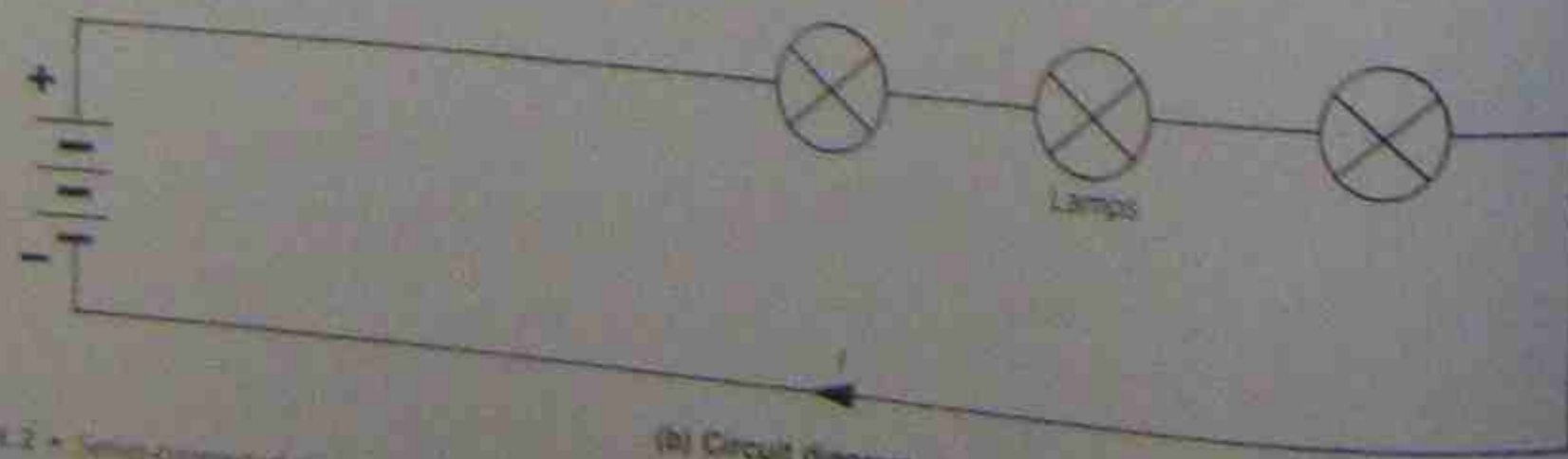
(b) Circuit diagram

Figure 4.2 • Series-connected circuit

(a) Three appliances connected in parallel to a supply source

Figure 4.3 • Parallel-connected circuit

4.3 SERIES CIRCUIT ANALYSIS

4.3.1 Total opposition to current flow

As mentioned above, the criterion for a series circuit is that there is only one current path connected across the supply. One result of this is that the opposition to current flow has a cumulative effect on the whole circuit. To find the total opposition to current flow in any series-connected circuit, the values in ohms (Ω) of the individual resistors are added (see Fig. 4.4).

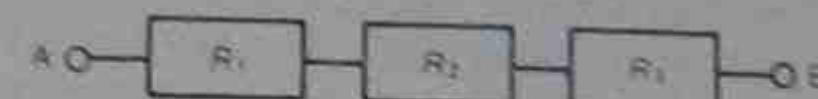**Figure 4.4** • Resistors in series

$$R_{total} = R_1 + R_2 + R_3 + \ldots$$

Example 4.1

Calculate the total resistance between the terminals A and B in Figure 4.5, given: $R_1 = 5\ \Omega$, $R_2 = 10\ \Omega$, $R_3 = 20\ \Omega$, $R_4 = 5\ \Omega$.

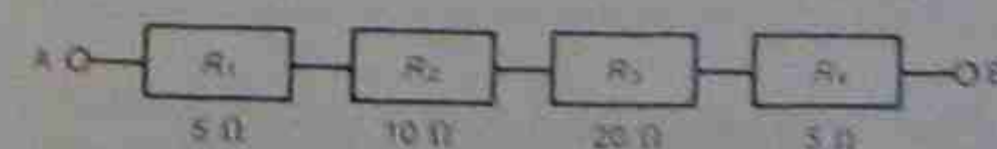First draw the circuit and then write down the formula.

Figure 4.5 • Circuit diagram for example 4.1

$$R_{total} = R_1 + R_2 + R_3 + R_4$$
$$= 5 + 10 + 20 + 5$$
$$= 40\ \Omega$$

Example 4.2

Find the value of R_2 in the circuit of Figure 4.6 if $R_{total} = 30\ \Omega$.

Figure 4.6 • Circuit diagram for example 4.2

(b) Circuit diagram for (a) showing the three current paths

$$R_{total} = R_1 + R_2 + R_3 + R_4$$
that is, $50 = 10 + R_2 + 10 + 5$
$$\therefore R_2 = 50 - 10 - 10 - 5$$
$$= 25\ \Omega$$

4.3.2 Current in series circuits

If there is only one path for current flow there can be only one value of current. It is said that the current flow in a series circuit is constant; that is, the current is the same value at any point in the series circuit.

If 5 A is flowing at point A in Figure 4.4, then measuring the current at any other point in the series circuit will show the same value.

4.3.3 Voltages in series circuits

In the circuit illustrated in Figure 4.7, it can be seen that all the supply voltage is applied to the load. This voltage overcomes the 200 Ω resistance of the load and forces 1 A through the circuit. It is said that 200 V is expended or 'dropped' across the load.

Figure 4.8 indicates a circuit where half the supply voltage is dropped across each of two load resistances connected in series.

The effect is as though the load of 200 Ω in Figure 4.8 were divided into two equal parts and the applied voltage also divided into two equal parts.

Consider the voltage drops in a series circuit by examining Figure 4.9. This illustration shows three equal resistances, R_1, R_2 and R_3 (each 2 Ω), connected in series with a 6 V battery and an ammeter.

The voltmeters V_1, V_2 and V_3 are each connected in parallel with the resistances R_1, R_2 and R_3 respectively. The total voltage drop across R_1 and R_2 is measured by V_4 and

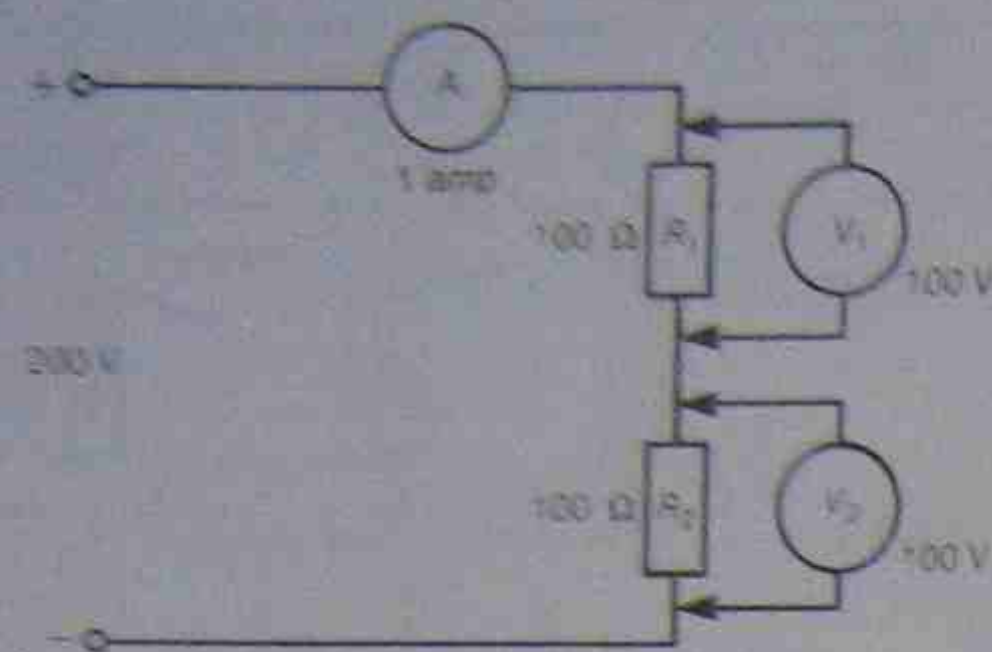**Figure 4.7** • Single load connected to a supply source

Figure 4.8 • Two loads connected in series to a supply source

the total drop across R_1, R_2 and R_3 is measured by V_S and is equal to the applied battery voltage (V).

The ammeter measures the current flowing from the battery under a pressure of 6 V. With three equal-value resistors in series, the potential differences in each case will be equal ($V = IR = 2$ V in Fig. 4.9). If the resistors in series are not equal in value, the potential differences across each resistor will not be equal. Note, however, that the sum of their potential differences will always be equal to the supply voltage irrespective of whether the resistors are equal or not.

In this example the readings on each meter, V_1, V_2 and V_3 are the same and equal to one-third of the total applied voltage, or 2 V.

In section 4.3.1 it was shown that the resistance of a series circuit was equal to the sum of the individual resistances connected between these points:

$$R_{total} = R_1 + R_2 + \ldots$$

Between the terminals of V_4, R_1 and R_2 are connected in series, so the resistance between these two points is double the resistance between the terminals of either V_1, V_2 or V_3. Therefore V_4 should indicate $2 + 2 = 4$ V. Similarly, V_5 is equal to the sum of the voltage drops between its terminals; that is:

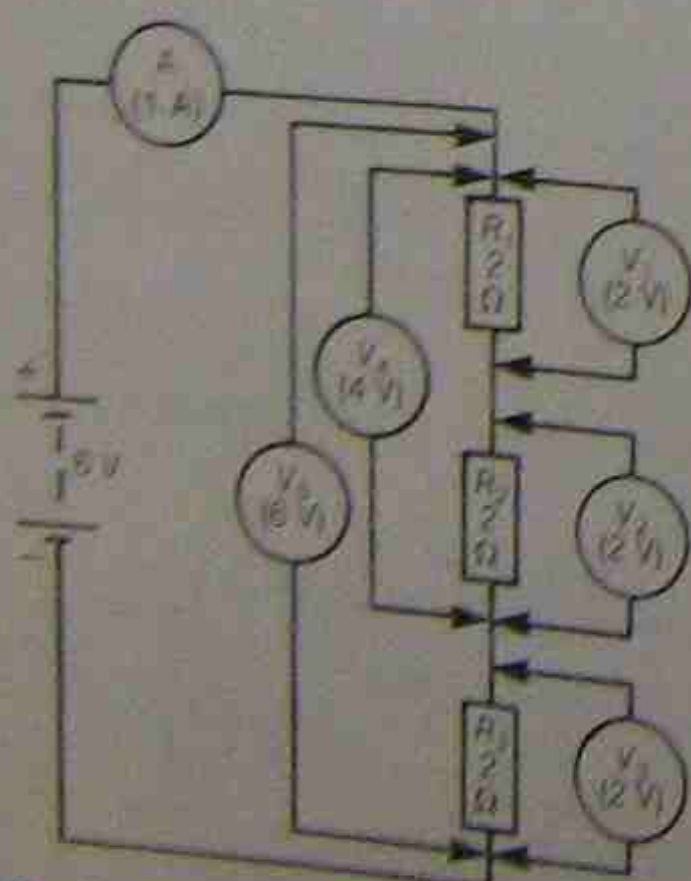$$V_1 + V_2 + V_3 = 2 + 2 + 2 = 6 \text{ V}$$

Figure 4.9 • Potential differences in a series circuit

These facts can be summarised by saying that when current is forced through a circuit against the resistance of that circuit, a fall of potential occurs across the resistance.

The voltage applied to a series circuit is equal to the sum of the individual voltage drops in the circuit. That is:

$$V_{total} = V_1 + V_2 + V_3 + \ldots$$

This is often expressed as Kirchhoff's voltage law:

The algebraic sum of the voltage drops around a circuit equals the applied voltage.

Example 4.3

What is the total voltage necessary to force a current of 5 A through the circuit of Figure 4.10?
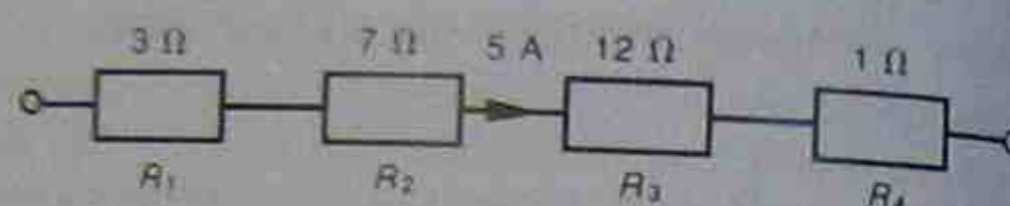

Figure 4.10 • Circuit diagram for example 4.3

The quickest method of calculating the value of V is to find the equivalent resistance of the circuit and multiply it by the total current:

$$R_{total} = R_1 + R_2 + R_3 + R_4$$
$$= 3 + 7 + 12 + 1$$
$$= 23 \ \Omega$$
$$V = IR = 5 \times 23 = 115 \text{ V}$$

This value can be checked by finding the sum of all the voltage drops:

$$V_1 = IR_1 = 5 \times 3 = 15 \text{ V}$$
$$V_2 = IR_2 = 5 \times 7 = 35 \text{ V}$$
$$V_3 = IR_3 = 5 \times 12 = 60 \text{ V}$$
$$V_4 = IR_4 = 5 \times 1 = \underline{5 \text{ V}}$$
$$V_{total} = V = 115 \text{ V}$$

4.3.4 Conditions for series circuits— summary

1. **Resistance**

$$R_{total} = R_1 + R_2 + R_3 + \ldots$$

2. **Current**

There is one path for current, so there is one constant value of current throughout the series circuit.

3. **Voltage**

The applied voltage equals the sum of the individual voltage drops around the series circuit:

$$V_{total} = V_1 + V_2 + V_3 + \ldots$$

4.3.5 Power in series circuits

In Chapter 2, reference was made to power consumption being:

$$P = I^2 R = VI = \frac{V^2}{R}$$

The same formulae are still applicable in this type of work.

However, it is necessary to be careful that the correct values are chosen.

Example 4.4

In Figure 4.11, three resistors are connected in series across a 240 V supply. Find the power consumption of each resistor and the total power consumed by the circuit.
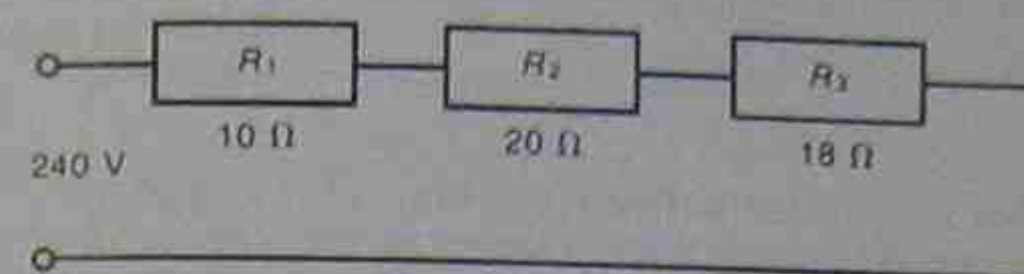

Figure 4.11 • Circuit diagram for example 4.4

There are two methods for finding the power consumption of a circuit:

1. Obtain the power consumption for each resistor and add those values to find the total.

2. Obtain the total resistance, total voltage and current, and then use these values to find the total power consumption.

Method 1

Each resistor is taken individually and the values used in the calculations apply only to that resistor. To use Ohm's law or the power formulae, two quantities must be known. The resistor value is known, so either the voltage across it or the current through it must be known.

$$R_{total} = R_1 + R_2 + R_3$$
$$= 10 + 20 + 18$$
$$= 48 \ \Omega$$
$$I = \frac{V_{total}}{R_{total}} = \frac{240}{48} = 5 \text{ A}$$

That is, all resistors have 5 A flowing through them (a series circuit).

Power consumed in 10 Ω resistor:

$$P = I^2 R = 5^2 \times 10 = 250 \text{ W}$$

Power consumed in 20 Ω resistor:

$$P = I^2 R = 5^2 \times 20 = 500 \text{ W}$$

Power consumed in 18 Ω resistor:

$$P = I^2 R = 5^2 \times 18 = 450 \text{ W}$$

Total power = 250 + 500 + 450 = 1200 W

Method 2

$$R_{total} = R_1 + R_2 + R_3$$
$$= 10 + 20 + 18$$
$$= 48 \ \Omega$$
$$P_{total} = I^2 R_{total} = 5^2 \times 48 = 1200 \text{ W}$$

This second method gives the total power, but not individual power ratings as in the first method.

In a circuit with only one current path, any break in the circuit will cause all current to stop flowing. Circuit power consumption is reduced to zero and the full supply voltage appears across the ends of the open circuit. Where more than one series resistor is involved, the voltage across a break may exceed the original voltage drop across individual resistors. The circuit will remain inoperative until the cause of the open circuit is found and rectified.

A partial short-circuiting of one of the series resistors is equivalent to presenting a lower resistance to the supply source, and current flow will increase. If the short-circuit occurs nearer the supply source, the current flow can then increase to a value that might cause damage to the circuit or its conductors. If the circuit is fitted with circuit protection, then under normal conditions the protection will operate and the complete circuit will be isolated from the supply source.

4.4 PARALLEL CIRCUIT ANALYSIS

Parallel circuits are multiple circuits, in that they have more than one current path between the two terminals of the power source.

The major difference between series and parallel circuits is illustrated in Figure 4.12. In Figure 4.12(a) only one current path is shown, while in Figure 4.12(b) it can be seen that the current from the source divides into several components when the parallel section is reached and recombines again to flow to the source. For each path $I = V/R$, where R is the resistance of that path.
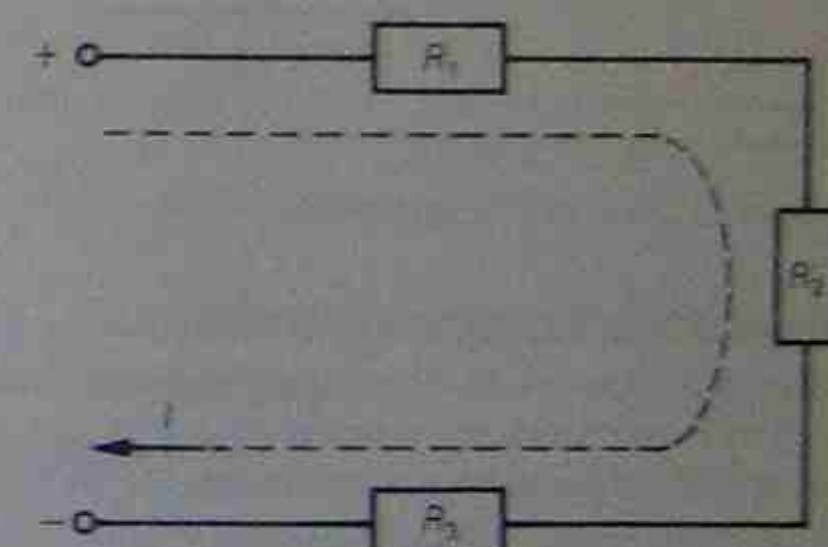
(a) Series circuit
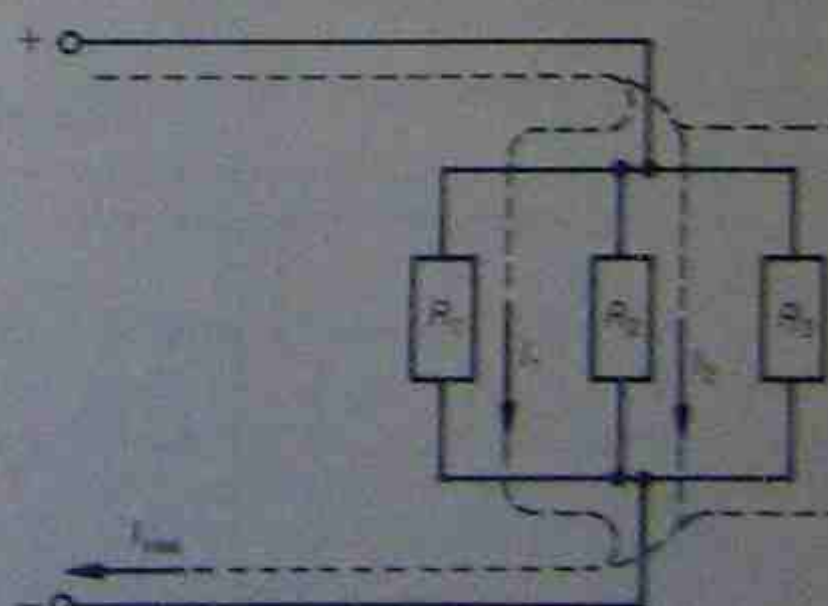
(b) Parallel circuit

Figure 4.12 • Basic types of circuits