10. CELLS AND SIMPLE CIRCUITS

THE PHYSICS OF ELECTRICITY

Cells and batteries are so common as they are used to power various devices including touches, watches, radios and even cars. The cells or batteries in these devices are sources of electricity, making it possible for the devices to work. Other than cells and batteries, there are so many other sources of electricity some of them are renewable while others are non-renewable. When you take a battery and connect it to a bulb with wires, the bulb lights. This connection, which comprises of the cell (source of electricity), and a bulb (load) joined with wires is a basic example of a circuit. There are two ways of connecting cells and loads in the circuit. A circuit can either be series or parallel. Sometimes the two connections may be combined in a single circuit.

WHY IT MATTERS

You may have wondered why the batteries used in calculators are disposed after use while the car battery is recharged and used again. How do you think bulbs in a house and other components are connected? And does the specific connection type affect the working of the loads? To design and create devices and processes that use electricity and circuits, engineers use the basic understanding of electricity and the physics behind circuits.

(a): Chemical sources of electricity

(b): Practical circuitry

Fig. 10.1: Physics of electricity

Shows a variety of chemical sources of electricity, including dry cells, lead-acid accumulators, and alkaline batteries. Their naming and choice for use depend on what they are composed of, how they work as well as their limitations and advantages over each other. On the other hand, while connecting circuits, the type of circuit affects the working of elements connected to the circuit. For example, shows a beautiful connection of outdoor bulbs. If the bulbs are connected in series, the entire set goes, other bulbs remain lit even when one or more bulbs are removed.

CHAPTER PREVIEW

- Electrical energy
- Direct Current (DC) circuits
- Simple electrical circuits
- Circuit symbols
- Potential difference and Electromotive force
- Electric Current
- Connecting circuits
- Cells in series
- Cells in parallel
- Bulbs in series
- Bulbs in parallel
- Sources of electricity
- Primary cells
- Defects of primary cells
- Secondary cells

Electrical energy

Electrical energy is a very crucial form of energy. It is used in many appliances including lighting, heating, and operating such devices as radios, computers and television sets among others. Cells are the simplest source of this electrical energy. For the electrical energy to be used, there must be a path called a circuit.

Direct Current (DC) circuits

Before the electron was discovered, scientists agreed to consider current as positive charge moving through a circuit from a positive terminal to the negative terminal of a battery. This is still used and the direction of current from positive to negative is thus referred to as convectional current. A DC current is the flow of current in one direction, that is, from the positive terminal to the negative terminal when a circuit is closed.

Simple electrical circuits

A circuit is a path that allows flow of charges. A switch is used to complete or break a circuit. A complete circuit has no gap and allows the flow of current and is called closed circuit. An open circuit has a gap and current cannot flow in such a circuit.

Activity 10.1: Setting up a simple circuit

The requirements are a dry cell, a bulb, connecting wires and a switch

- Set up as shown in the Fig. 10.2

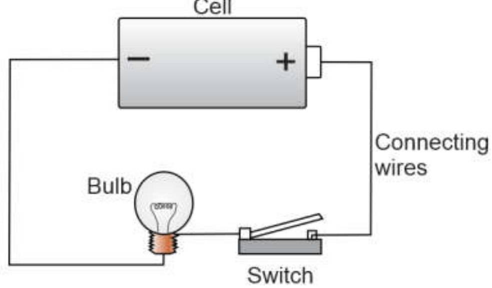

Fig. 10.2: A simple circuit

When the switch is closed, the bulb lights. This is because the circuit is complete and current flows. When switched off, the circuit becomes incomplete and the bulb goes off. The wires are good conductors of current. They allow current to pass through them.

The dry cell has stored electrical energy which can force charges to flow through the circuit. This energy is called electromotive force (e.m.f.) and is measured in volts with a voltmeter. When the circuit is closed, the cell creates a potential difference (p.d) between its terminals which allows charges to flow. P.d is thus only created when the current is flowing and is also measured in volts.

Circuit symbols

Consider the set-up circuit as shown in Fig. 10.2. Drawing every component as it appears could be so cumbersome. It would also be difficult to represent the diagram neatly and clear. The same diagram can be drawn as shown in Fig. 10.3.

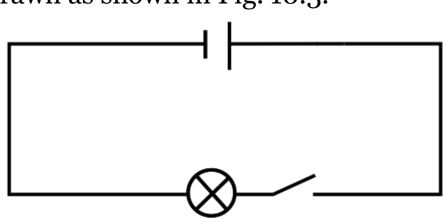

Fig. 10.3

In the above diagram, symbols have been used to represent connecting wires, a cell, a switch and the bulb. This way, circuits can then be represented neatly in diagrams and they can easily be understood by anyone familiar with the symbols.

Fig. 10.4 shows a few examples of symbols used in electrical circuits.

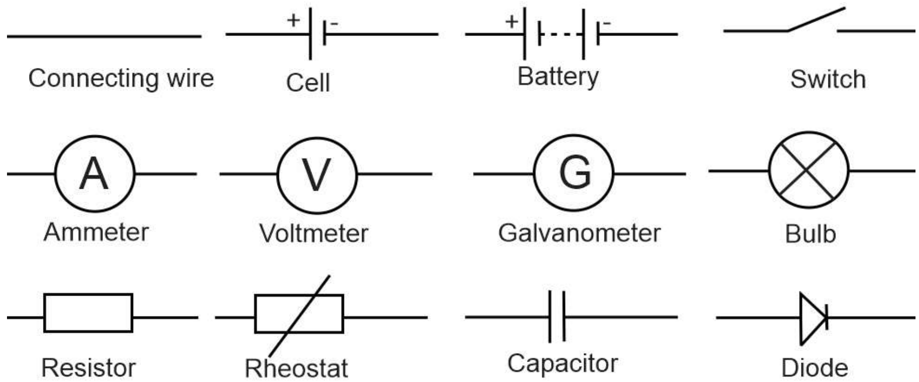

Fig. 10.4: Circuit diagram symbols

Potential difference and Electromotive force

A battery transforms chemical energy to electrical energy. Because of the chemical reactions in the battery, electrons are generated at its negative terminal while the positive terminal is said to be in shortage of electrons. When connected in a circuit, these electrons can then flow towards the positive terminal. The flow of electrons is what we will be referring to as the flow of charge. Therefore, when a circuit is connected and closed (is complete) charges can move through the circuit, from the negative terminal to the positive terminal of a cell (or battery). However, charges will not move unless there is a force to push them. Think of it as though the charges were at rest and they have to be pushed. The pushing of charge requires work to be done. This work required to push charges through charges is done by a force provided by the battery in the circuit. The amount of work done to move a charge from one point to another point is the potential difference (p.d.). Notice that a potential difference is created by a battery when a circuit is completed.

Activity 10.2: Investigating potential difference and electromotive force.

The requirements are a dry cell, a bulb, connecting wires, a switch and a voltmeter.

- Connect a simple circuit using the dry cell, bulb, and the switch
- Measure the terminal voltage of the cell (V_1) when the circuit is open
- Close the circuit and measure the terminal voltage of the cell (V_2)

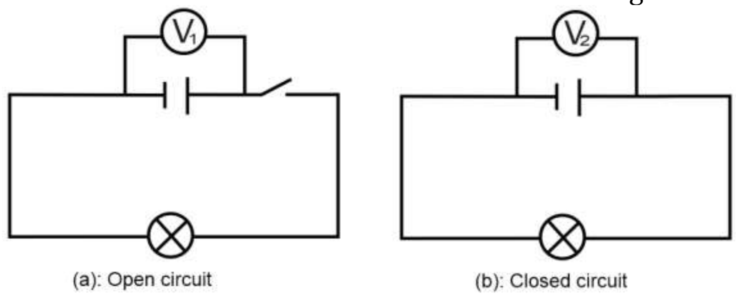

Fig. 10.5: Differentiating e.m.f and p.d

In the first set-up, the voltage across the terminals of the cell is measured in an open circuit (when current is not flowing). When the circuit is closed, the terminal voltage measured is the potential difference created by the cell for the charge to flow. It is noticeable that V_2 is slightly less than V_1. This effect is due to the internal resistance of the cell. Therefore, in an open circuit, when no current is flowing, the terminal voltage of a cell is maximum. This maximum voltage is the electromotive force (e.m.f.) of the cell (or battery).

Therefore;

- *Electromotive force*, (e.m.f) can be described as the total voltage in a circuit generated by a source like a cell. Electromotive force is not a physical force. It is basically the electrical energy required to move a unit charge from the negative terminal to the positive terminal of a cell when the circuit is open. The value of e.m.f. of a cell is the voltage of the cell in an open circuit. It is measured in units called volts by a voltmeter.
- *Potential difference* (p.d.) is the work done to move a unit charge between the negative and the positive terminal of the cell. When a circuit is complete, the battery creates a potential difference between the positive and negative terminal. Charges flows due to this potential difference. Potential difference is the measured voltage between the terminals of a cell in a

closed circuit. Measured in volts with a voltmeter.

In a circuit, the values of measured e.m.f and p.d. are usually different. Potential difference is usually less than the e.m.f. of a battery. This is because when the battery is in use, or the circuit is closed, a small amount of the e.m.f. is used in overcoming the internal resistance of the battery. The difference between e.m.f. and p.d. is called lost voltage. In the activity 10.2 for example, V_1 (e.m.f.) may be measured as 1.5 V while the V_2 (p.d.), when the circuit is closed may be 1.35 V. Therefore;

$$Lost\ voltage = e.m.f. - p.d.$$
$$= 1.5\,V - 1.35\,V = 0.15\,V$$

Electric Current

When an electric circuit is complete, charge flows through it. In such a circuit, it is said that there is a current; a flow of charge. Current is the rate at which charge flows past a point in a circuit. Its SI unit is Ampere (A). The symbol for current is I.

$$Current = \frac{charge}{time} \Rightarrow I = \frac{Q}{t}$$

NOTE: Time must be measured in seconds, while charge is measured in coulombs (C)

$$1\,A = 1\,Coul/sec$$
$$1\,milliampere\,(mA) = 10^{-3}\,A$$
$$1\,microampere\,(\mu A) = 10^{-6}\,A$$

Examples

1. Calculate the amount of current flowing if 240 coulombs of charge flows through a bulb for 2 minutes

   Solution

   $$I = \frac{Q}{t} = \frac{240}{2 \times 60} = 2A$$

2. The current in a single loop is 3.0 A. How long would it take for a charge of 3600 coulombs to flow?

   Solution

   $$I = \frac{Q}{t}$$
   $$3 = \frac{3600}{t} \Rightarrow t = 1200\,s = 20\,min$$

Test yourself

1. Draw a circuit sketch to distinguish between an open and a closed circuit
2. Why do we need to use circuit symbols while drawing circuits?
3. What is the function of a cell in a circuit?
4. Differentiate between electromotive force and potential difference of a cell.
5. What is electric current? What is the SI unit of electric current?
6. What is meant by the term conventional current?
7. The current passing through a point in a circuit is 8.5 A. How long would it take for a charge of 17000 C to flow?

Connecting circuits

Cells in series

This is the connection arrangement where the positive terminal of one cell is connected to the negative terminal of the next cell. This forms a battery which is a connection of two or more cells in series.

Activity 10.3: Connecting cells in series

Requirements are three dry cells, a bulb, connecting wires, a switch and a voltmeter and an ammeter.

- Connect a simple circuit as shown in Fig. 10.6 (a)
- Measure terminal voltage of the cell and the current
- Increase the cells to two, then three and measure total voltages and current. See Fig. 10.6 (b)
- Plug out one cell and note what happens to the bulb

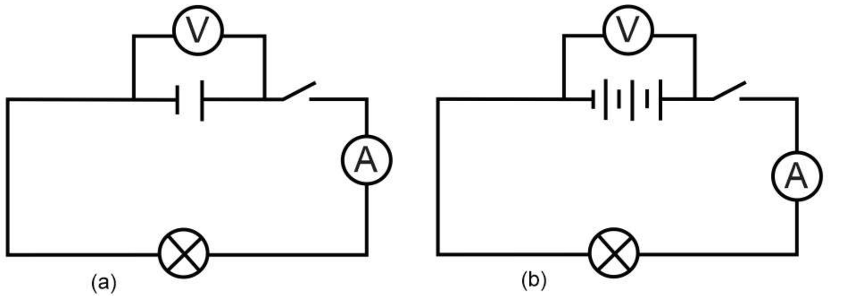

Fig. 10.6: Cells connected in series

In series, it can be observed that when the cells are increased;

- ✓ Voltage in the circuit increases
- ✓ Total voltage is the sum of the voltage in the cells: $V_T = V_1 + V_2 + V_3$
- ✓ Current through the circuit increases
- ✓ Brightness of a bulb increases with increase in cells
- ✓ When one cell is removed, the circuit breaks (bulb goes off).

Cells in parallel

This is a connection in which the positive terminals are joined together as well as the negative terminals.

Activity 10.4: Connecting cells in parallel

Requirements are three dry cells, a bulb, connecting wires, a switch and a voltmeter and an ammeter.

- Connect a simple circuit as shown in Fig. 10.7 (a).
- Measure terminal voltage of the cell and the current
- Increase the cells to two as shown in Fig. 10.7 (b), then three and measure total voltages and current.
- Plug out one cell and note what happens to the bulb

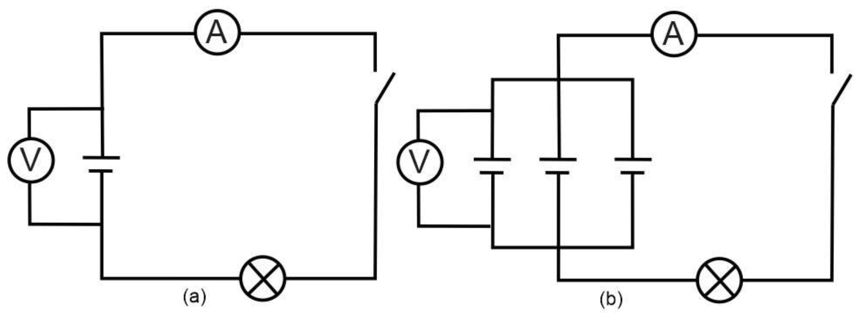

Fig. 10.7: Cells connected in parallel

In parallel connection of cells, the following can be concluded;

- ✓ Voltage remains the same as we increase the cells. That is $V_T = V_1 = V_2 = V_3$
- ✓ Current through the circuit remains the same as we increase the cells
- ✓ The brightness of the bulb remains the same
- ✓ The current is supplied for a longer time than in series connection. The cells thus can last longer than those connected in series
- ✓ When one cell is removed, the bulb still lights; the circuit is not broken.

Bulbs in series

Bulbs in series can be constructed by connecting light bulbs in such a way that there is only one loop through which charges flow. Bulbs are added to the same path with no branching points. As more and more bulbs are added to the circuit, the brightness of each bulb gradually decreases. This indicates that the current within the circuit is decreasing with the addition of more bulbs.

Bulbs connected in series are as in Fig. 10.8.

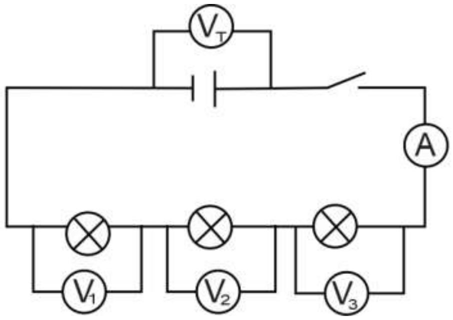

Fig. 10.8: Bulbs connected in series

For bulbs (or components) is series;

- ✓ The Same current flows through the bulbs; $I_T = I_1 = I_2 = I_3$
- ✓ Addition of more bulbs reduces their brightness
- ✓ The total voltage is the sum of voltages through each bulb; $V_T = V_1 + V_2 + V_3$
- ✓ When one bulb is disconnected the rest goes off. One bulb can disconnect the whole circuit. This makes it not suitable for electrical wiring of bulbs.

Bulbs in parallel

In parallel circuits, different circuit components are connected in different loops (branches) of the wire. Using three bulbs, a parallel circuit can be constructed as shown in Fig. 10.9.

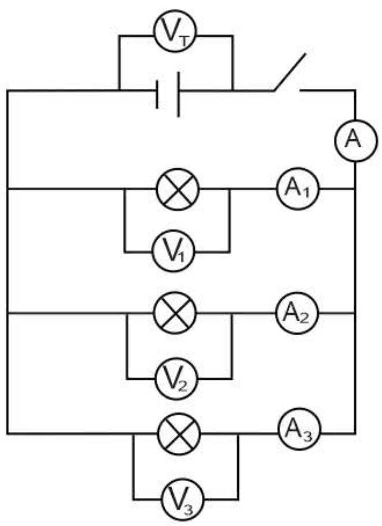

Fig. 10.9: Bulbs connected in parallel

In parallel connection;

- ✓ The bulbs give light of same brightness but brighter than those in series
- ✓ All bulbs have the same voltage; $V_T = V_1 = V_2 = V_3$
- ✓ Current is split at the junction and thus different currents flow through the bulbs
- ✓ Total current is the sum of individual currents; $I_T = I_1 + I_2 + I_3$
- ✓ When one bulb is disconnected, the rest continues to light.
- ✓ Every bulb can be controlled by its own switch.

If one bulb is removed from its socket, current still flows in the other branches. Removing the third bulb transforms the circuit from a three-bulb parallel circuit to a two-bulb parallel circuit. If the appliances in a household were connected in parallel, one appliance can work without the other appliances having to be on. Since each appliance is in its own separate branch, it can then have its own switch. This is why appliances and bulbs in a home are wired with parallel connections.

Sources of electricity

For a circuit to be complete, there must be a source of electric current. A cell is the source of continuous current. The end of a cell with a higher potential (fewer electrons) is called the positive terminal while the end with lower potential (higher number of electrons) is called the negative terminal. Other than a cell, there are many other sources of electric current including batteries, generators, solar panels and thermocouples among others. In this topic, we concentrate on chemical sources.

Chemical sources of electricity
These are sources that produce electromotive force due to chemical reactions. A good example is an electrochemical cell where simultaneous oxidation-reduction process occurs between the electrolyte and the electrodes. Examples of electrochemical cells are the primary cells and the secondary cells (storage cells)

Primary cells
These are cells formed by dipping two different metals into an electrolyte. They produce an electric current through irreversible chemical reactions. Primary cells cannot, therefore, be recharged.
The two metals used are called electrodes. The metal which is higher in electrochemical series becomes the negative terminal while the other becomes positive terminal. Atoms of the negative terminal release electrons to form negative ions. The electrons move to the positive terminal through the wire. At the positive terminal, the electrons will be released to the positive ions in the electrolyte forming a gas.
Primary cells include;
- A simple cell
- Dry cell
- Leclanche' cell

A simple cell
A simple cell, also called voltaic cell, can be thought of as an experimental version of the primary cells. This cell can be set up in the laboratory and be used to explain the working principle of primary cells. Its components are;
i. Two electrodes; copper and zinc. Zinc being higher in electrochemical series is the negative terminal called cathode. Copper is the positive terminal called anode. If any two rods are used, the negative terminal is the source of electrons; the metal that reacts with the acid faster.
ii. Electrolyte; dilute sulphuric acid (H_2SO_4). The liquid responsible for the chemical reactions.

Activity 10.5: Making a simple cell
The requirements are a copper rod, zinc rod, a beaker with dilute sulphuric acid connecting wires, a small light bulb, and a milliammeter.
- Clean the copper and zinc rods thoroughly
- Put the two rods in a beaker containing dilute sulphuric acid.
- Observe what happens to the strips.
- Connect the strips externally to a millimetre, and a light bulb.

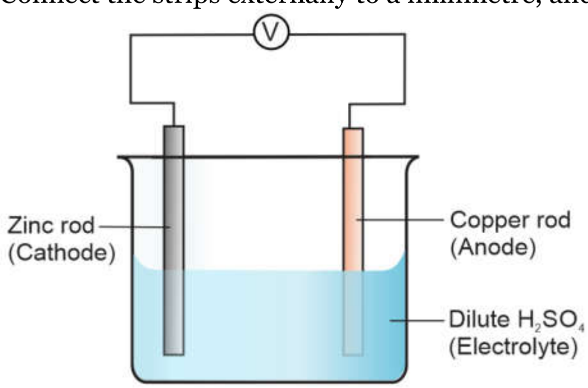

Fig. 10.10: Simple cell

When the two rods are dipped in dilute sulphuric acid, a reaction is observed. Tiny bubbles of gas are seen around the zinc rod. This shows that zinc is reacting with the acid faster than copper. When connected to an external circuit, the ammeter deflects. This indicates a flow of current. Large bubbles of a gas are then seen around the copper rod. This gas is hydrogen. The zinc plate later is seen to be corroded ('eaten away') by the acid.

How this happens
Sulphuric acid is composed of hydrogen and sulphate ions; chemically written as,

$$H_2SO_{4(aq)} \rightleftharpoons 2H^+_{(aq)} + SO_4^{2-}{}_{(aq)}$$

When the two electrodes are dipped in the acid, zinc being higher in electrochemical series reacts with the acid faster liberating electrons, zinc ions and hydrogen ions. This process eats up the zinc rod in another process termed as local action.

$$Zn_{(s)} \rightleftharpoons Zn^{2+}{}_{(aq)} + 2^{e-}$$

The liberated electrons move to the positive terminal, copper rod through the external wire. A current thus flows through the circuit.

The hydrogen ions move to the copper rod, within the electrolyte. At the copper rod, the hydrogen ions combine with the incoming electrons to form hydrogen gas. The hydrogen gas is seen as bubbles around the positive terminal.

$$2H^{+}{}_{(aq)} + 2e \rightleftharpoons H_{2(g)}$$

The accumulation of bubbles around the copper strip is called *polarization*.

Defects of primary cells

Local action

This is the reaction process between the negative terminal and the electrolyte in which the negative terminal is eaten away by the electrolyte. In a simple cell, for example, local action is the process in which the zinc plate is eaten away by the dilute sulphuric acid.

Local action can be minimized by coating zinc with mercury. This process is called amalgamation. Using pure zinc can also help reduce local action.

Polarization

This when the produced hydrogen gas accumulates on the positive terminal. This insulates the positive terminal cutting off production of current eventually. This is what causes internal resistance of the cell. In a simple cell, for example, polarization is the accumulation of hydrogen gas bubbles around the copper plate, insulating it from charge flow.

Polarization can be minimized by adding depolarizer in the solution, and especially around the positive terminal. A depolarizer is an oxidizing agent which converts the hydrogen gas into water. Examples of depolarizers include potassium dichromate and Manganese (IV) oxide.

The Leclanche' cell

In this cell, carbon rod is used as the positive terminal and zinc as the negative electrode. The electrolyte is ammonium chloride solution (NH_4Cl).

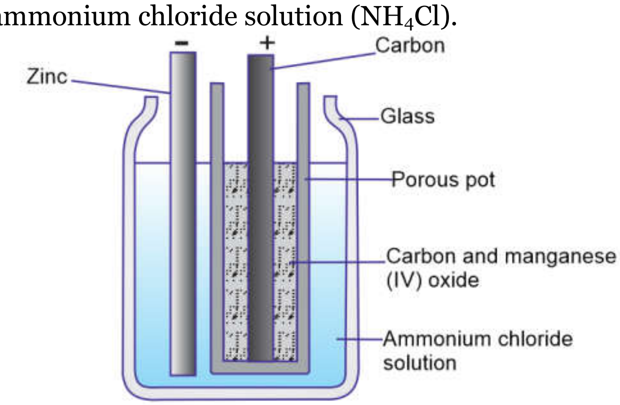

Fig. 10.11: Lecanche' cell

Polarization is reduced by use of manganese (IV) oxide (MnO_2) which oxidizes hydrogen into water. Local action still occurs. They are used in operating bells and telephone boxes.

The dry cell

It is referred to as dry because it contains no liquid. As shown in Fig. 10.12, carbon rod is the positive terminal while zinc plate is the negative terminal. The electrolyte ammonium chloride jelly or paste, the manganese (IV) oxide is used as the depolarizer while *carbon powder increases the surface area of conduction*.

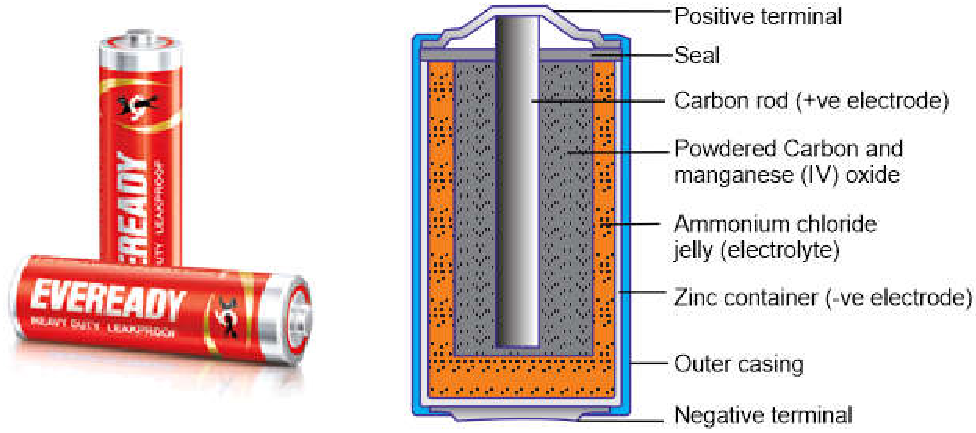

Fig. 10.12: Dry cell

The hydrogen gas produced is oxidized by manganese (IV) oxide- the depolarizer- to water, which eventually makes the cell wet after use. The zinc casing is also eaten away after some time. They are used in torches, radios calculators etc.

Secondary cells

They are also called storage cells since they store electrical charge as chemical energy. They can be recharged. The chemical reaction between the electrodes and the electrolyte is reversible. Examples of secondary cells include a lead-acid accumulator and the alkali accumulator.

Lead-acid accumulator

In a lead-acid accumulator, there is an arrangement of cells. Each cell has one group of positive plates made of lead (IV) oxide and one group of negative plates made of spongy lead. The plates are dipped in dilute sulphuric acid, the electrolyte. The sulphuric acid has a concentration of about 38% with a relative density of about 1.84. Fig. 10.13 shows the appearance and the layout of a lead-acid accumulator respectively.

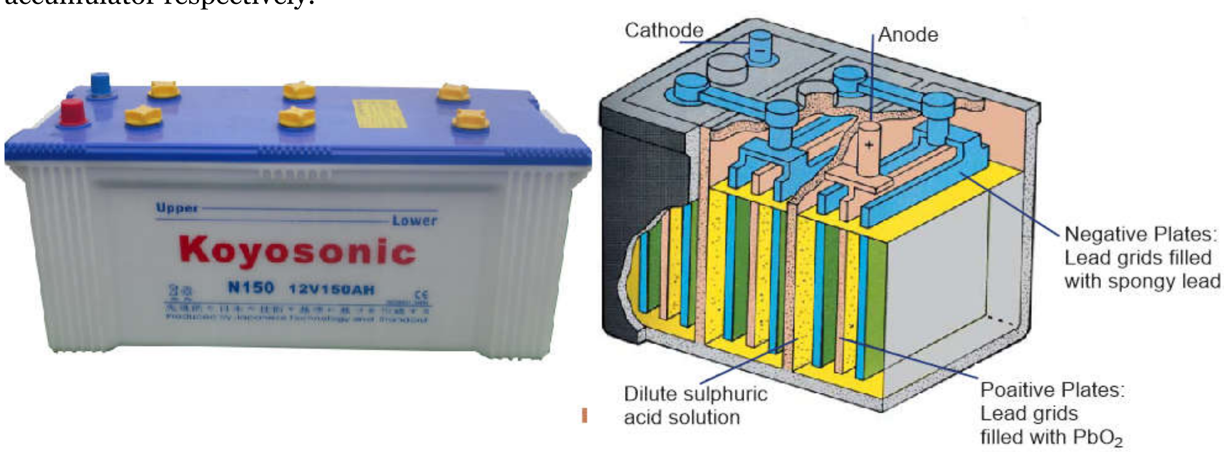

Fig. 10.13: Lead-acid accumulator

When charging them, oxygen is produced at the anode and hydrogen at the cathode. The oxygen reacts with lead to form lead (IV) oxide which is deposited at the anode. The hydrogen formed has no effect. When in use, they are discharging. During discharge, current flows in opposite direction with oxygen being formed at the cathode and hydrogen at the anode. The colour of the positive electrode changes from brown to grey.

Lead-acid accumulators have caps which can be opened to fill up the electrolyte in the cell. The caps are also opened while charging to facilitate gassing (the release of gases produced during charging)

They are rated in ampere-hours i.e. 30 Ah means that it can supply 1 ampere for 30 hours or 2 amperes for 15 hours etc.

Example:

1. A battery is rated at 30 Ah. For how long will it work if it steadily supplies a current of 3 A?

   Solution

   Q = It, hence t = Q / I => 30 / 3 = 10 hours.

Test yourself

1. A battery is rated 120 AH. How long will it work if it steadily supplies a current of 4 A?
2. The current capacity of an accumulator is 40 Ah. Find the amount of current flowing if the accumulator is used for 600 minutes.

Maintenance of lead-acid accumulators

i. The level of the electrolyte should be checked regularly. If it falls below the plates, topping should be done. Topping is the addition of distilled water in a lead-acid battery when the electrolyte level falls below the plates. Water is used so as to maintain a lower concentration of the dilute sulphuric acid.
ii. The accumulator must be charged when the e.m.f falls below 1.8V
iii. Large currents should not be drawn from the battery for a long time.
iv. Avoid shorting circuiting the terminals. Short circuiting causes large currents to flow. This destroys the cells in the accumulator.
v. Do not overcharge.
vi. The terminals should always be kept clean and greased. Dirty terminals can cause discharge on top of the battery casing along the grime.
vii. Leaving the battery in a discharge mode for long causes inactivation of the cells. The lead sulphate will end being not reversible while charging.
viii. Do not smoke near a charging battery. The gases produced during charging are highly flammable.
ix. The accumulator should not be placed directly on the ground during storage. It should be rested on an insulator like a wooden block. Temperature differences between the top and the bottom causes a difference in voltage between the top of the battery and the bottom. This causes a discharge of the battery, even though to a small extent.

Alkaline accumulators

They are very light batteries and can be recharged. They are used in ships, hospitals and buildings where large currents are required for emergencies. In these accumulators, potassium hydroxide (KOH) or Nickel hydroxide (Ni (OH) forms the positive electrode while iron forms the negative electrode. They are two types nickel cadmium (NiCd) and nickel iron (NiFe).

Fig. 10.14: Alkaline batteries

Advantages of alkaline accumulators over lead-acid accumulators

i. Large currents can be drawn from them
ii. They require little maintenance
iii. They can be short-circuited without being destroyed
iv. They can withstand rough treatment
v. They do not deteriorate when not in use
vi. They are portable
vii. They can remain discharged for a long time without getting ruined.

Disadvantages of alkaline accumulators over lead-acid accumulators

i. They are very expensive
ii. They have lower e.m.f per cell. Alkaline batteries have cells of 1.5 V each while lead-acid accumulators' cells are of 2 V each.

Cells and Simple Circuits Topical Question

1. Explain bulbs in a household are all connected in parallel.
2. Distinguish between a primary cell and a secondary cell.
3. State two advantages of an alkaline battery over a lead-acid battery
4. In large current circuits, large resistors in parallel are preferred to low resistors in series explain
5. A car battery requires topping up with distilled water occasionally. Explain why this is necessary and why distilled water is used.
6. Explain how polarization reduces current in simple cell.
7. State one advantage of a lead-acid accumulator over a nickel-iron (NiFe) accumulator.
8. State the purpose of Manganese dioxide in a dry cell
9. State a reason why the caps of the cells of a lead- acid battery are opened when charging the battery.
10. A student learned that a battery of eight dry cells each 1.5V has a total e.m.f of 12V the same as a car battery. He connected in series eight new dry batteries to his car but found that they could not start the engine. Give a reason for this observation
11. A current of 0.08A passes in a circuit for 2.5 minutes. How much charge passes through a point in the circuit?
12. The compressor on an air conditioner draws 40.0 A when it starts up. If the start-up time is 0.50 s, how much charge passes a cross-sectional area of the circuit in this time?
13. Calculate the current when a charge of 240 C passes a point in a circuit in a time of 2 minutes.
14. In a certain experiment, a charge of 96500 C passed through a point. Calculate the time taken when a current of 0.20 A was drawn.
15. The charge that passes through the filament of a certain light bulb in 5.00 s is 3.0 C. What is the current in the light bulb?
16. Draw a well-labelled diagram of a dry cell
17. Explain why the e.m.f of a dry cell drops if a large current is drawn for a short time and then recovers if allowed to rest
18. Name two measurements you would need to determine whether a lead accumulator is fully charged.