CHAPTER 2

Battery Technology

2.1. INTRODUCTION

The developments in the field of science, engineering and technology naturally tempt man in using and applying these developments to improve the comforts in life and enjoyment. The increase in complexity and standards in life style is characterized by a high demand for energy consumption. Even if energy is available, it should be available at a time, place, and under circumstances where desired or needed. It is, in this view point, cells and batteries are important in providing portable electrical energy. Transistorized and miniaturized equipments have such low power requirements that batteries have become competitive with other energy sources, in spite of their lower energy production. The variety of equipments used in diverse applications, by utilizing batteries as energy sources have spurred the development of many different types of batteries.

About six decades ago domestic uses of batteries were largely confined to flash lamps, radio sets and starter batteries for cars and motor cycles. Modern households typically have 40–50, hidden away in all sort of consumer products – from clocks and watches to personal CD players and mobile phones. Away from the home there are many other applications, particularly for large batteries. Examples include the standby batteries for emergency use in hospitals, hotels, departmental stores, telephone exchanges, etc; traction batteries for electric vehicles (tugs, tractors, wheel chairs, golf carts); batteries for solar panels or wind generators; defence batteries in armaments, missiles, submarines, torpedoes. Many of these applications demand a performance that is barely matched by traditional batteries and therefore, there is ever present demand for new and better varieties. One of the interesting features of batteries is the very wide range of sizes in which they are manufactured, from a stored energy content of 0.1 watt-hour (Wh) for a watch or calculator battery, to 100 MWh for a load-levelling battery in the electrical supply industry.

The conversion of chemical energy into electrical energy is the basis for the functioning of a galvanic cell, named after its inventor Luigi Galvani (1786). "Voltaic piles" of unlike metals in contact with an electrolyte, developed by Alessandro Volta (1800) was the first power source. A major advance in the evolution of the battery was the Daniell cell invented by J.F. Daniell (1836). Plante (1859) developed the essentials of the lead-sulfuric acid storage cell. In 1868 George Leclanche introduced a cell which was the forerunner of the present day dry cell. Because of the chemical similarities, the dry cell, is still referred to as a Leclanche-type cell. The first true dry cell was developed between 1886 and 1888 by Dr. Carl Gassner. T.A. Edison, Adams, Ruben, are the few others who have contributed to the development of battery technology.

The battery technology, historically considered electrochemical, combines the activities of the chemist, the chemical engineer, the metallurgist, the materials specialist, the electrical engineer, the electronic designer, the space specialist, the environmental engineer, the instrumental analyst, testing agencies as well as the application originator for expanded and new uses. The individual viewpoints of all these, cooperate to serve the diversified needs and desires of industries, as well as our daily lives in the electronic and space age.

2.2. BATTERIES AND THEIR IMPORTANCE

The conversion of chemical energy into electrical energy is a function of cells or batteries. A cell designates a single unit. A battery is an arrangement of two or more cells, usually connected in series or parallel to supply the necessary current or voltage or both.

The battery was the first practical source of electrical energy developed in man's search for portable power sources. Although many other techniques have been developed for supplying electrical power, the battery is still the most widely used source of electrical power when portability is the prime requisite. Batteries are used in watches, hearing aids, flash lights, radio sets, electric clocks, photoflash devices, emergency lighting, distress signalling, rescue devices, tape recorders, alarm systems, hand tools, toys, calculators, cordless appliances, telephone systems, electrotherapeutic purposes, electric bells, motor ignitions, space vehicles, military applications and a host of other applications. The development of semi conductor devices such as transistors, diodes, missiles, satellites and a great variety of mobile equipments, has imposed great demands for power sources which are compact, dimensionally adaptable, able to operate over a wide temperature range and highly dependable. The batteries meet these demands and therefore, are in continuous demand.

2.3. COMMERCIAL CELLS

The spontaneous redox reaction, which forms the basis of voltaic cell, is conveniently used in making many useful commercial cells. All voltaic cells do not find commercial applications. A useful commercial cell should meet the following basic requirements or specifications:

- Portability
- Should be compact and light weight
- Should provide economically priced, continuous electric supply
- High cell voltage and stable voltage plateau over most of the discharge
- High stored energy content per unit mass and per unit volume
- Low cell resistance
- High sustained power output
- Wide temperature range of operation
- Long inactive shelf life and long operational life.

- Low initial cost
- Sealed and leak proof
- Rugged and resistant to abuse
- Safe in use and under accident conditions
- Should be capable of recharging with a capacity of many charge and discharge cycles, and to withstand overcharge and over discharge
- Sealed and maintenance free

In spite of their virtues, the high cost of cells and batteries makes the production of electricity in large quantities impracticable. However, they serve as convenient energy sources where small amount of energy is required for short duration of time.

Classification

The galvanic or voltaic cells used as source of electrical energy are of two types:

(i) primary cells and
(ii) secondary cells.

(i) Primary cells: A primary cell is the one in which electrical energy can be obtained at the expense of chemical energy only as long as the active materials are still present. Once these have been consumed, the cell can not be profitably or readily rejuvenated and must be discarded. Or in other words, they can not be recharged and re-used.

(ii) Secondary cells: A secondary cell, once used can be recharged by passing current through it. It can be used over and over again. The redox reaction gets reversed during recharging. Since the electrical energy brings about the chemical change, it is converted into chemical energy. Thus electrical energy is stored in the form of chemical energy and utilized for supplying the current when needed. Secondary cells are also known as storage cells.

Whereas, a primary cell acts only as a galvanic or voltaic cell, a secondary cell can act both as galvanic cell and electrolytic cell. During discharging it acts as a galvanic cell, converting chemical energy into electrical energy and during charging it acts as an electrolytic cell converting electrical energy into chemical energy.

Reserve Batteries

In this type of batteries, a key component is separated from the rest of the battery prior to activation. Usually the electrolyte is the component that is isolated. Batteries which use highly active component material are designed in this form to withstand deterioration in storage and to eliminate self discharge prior to use. The reserve design is also used for batteries required to meet extremely long or environmentally severe storage requirements.

When one of the key components of the cell is separated from the remainder of the cell, chemical reaction between the cell components (self discharge) is prevented and the battery is capable of long

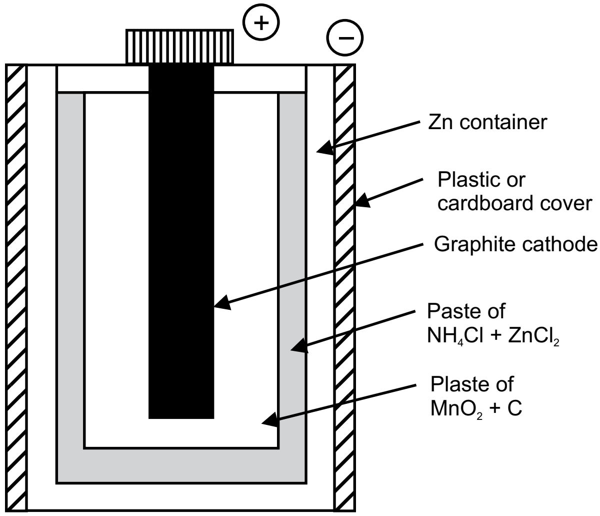

Fig. 2.1. Dry cell

Secondary reactions

The hydroxyl ions generated during the cell reaction liberate ammonia from ammonium chloride, which in turn combines with the Zn^{2+} ions to precipitate $[Zn[NH_3]_2Cl_2]$ complex.

$$2NH_4Cl + 2OH^- \rightarrow 2NH_3 + 2H_2O + 2Cl^-$$

$$Zn^{2+} + 2NH_3 + 2Cl^- \rightarrow [Zn\,[NH_3]_2\,Cl_2]$$

The secondary reactions are not involved directly in the electrode reaction and so they do not contribute to the emf of the cell. But these reactions are irreversible and therefore, the cell can not be recharged.

A fresh dry cell has a potential of l.5V. The voltage of the cell decreases gradually with usage and finally it has to be discarded.

Applications

Dry cells find extensive use in flash lights, portable radios, transistors, tape recorders, and similar electronic devices where small amount of current is required.

Limitations

- They have low capacity
- Not intended for heavy duty

(i) Acid storage battery (Lead storage battery)

A simplified form of lead storage cell is as shown in Fig 2.3. The electrodes are lead grids. The anode grid is filled with spongy lead and the cathode grid is filled with lead dioxide (PbO_2). A number of electrode pairs with inert porous partitions in between, are dipped in approximately 20% sulfuric acid, which is the electrolyte. The battery is encased in a plastic container.

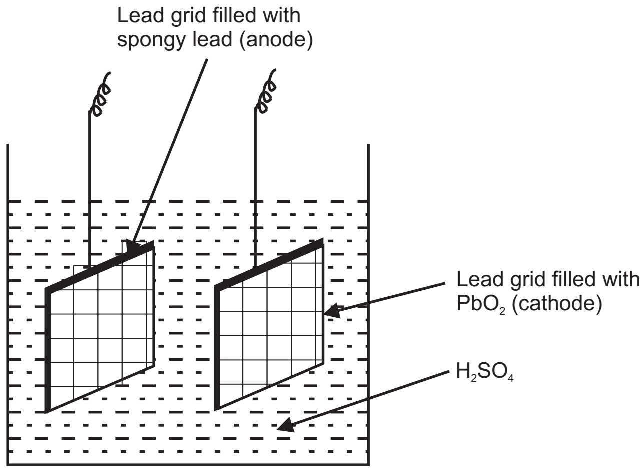

Fig. 2.3. Lead Storage Battery

Electrode reactions: The electrode reactions that occur during the discharge of the cell, i.e., on drawing current from the cell, are as follows:

At the anode,

$$Pb \rightarrow Pb^{2+} + 2e^-$$

$$Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4$$

$$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

At the Cathode,

$$PbO_2 + 4H^+ + 2e^- \rightarrow Pb^{2+} + 2H_2O$$

$$Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4$$

$$PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$

The net cell reaction is,

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$$

The product ($PbSO_4$) formed during discharge remains adhered on each electrode and is available at the site during recharging.

From the cell reaction, it is evident that the potential of the lead storage cell is dependent at any given temperature on the activity or concentration of sulfuric acid solution. Thus at 25°C and at a concentration of 7.4% sulfuric acid the potential developed by a pair of electrode is 1.90V; at 21.4%, 2.0V and at 39.2% 2.14V. Further, it is evident that sulfuric acid is consumed and water is produced during discharge. This results in the decrease in the specific gravity of the electrolyte.

Recharge reactions: When the density of sulfuric acid in the battery falls below 1.20gcm^{-3}, the battery needs charging. This is done by reversing the discharge reaction by applying externally a potential higher than that of the cell. The cell acts as an electrolytic cell, depositing lead and lead dioxide on the electrodes.

$$PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-}$$

$$PbSO_4 + 2H_2O \rightarrow PbO_2 + SO_4^{2-} + 4H^+ + 2e^-$$

$$2PbSO_4 + 2H_2O \rightarrow Pb + PbO_2 + 2H_2SO_4$$

During charging, sulfuric acid is regenerated in the cell.

The net reaction during charging and discharging can be represented as follows:

$$Pb(s) + PbO_2(s) + 2H_2SO_4(aq) \underset{\text{Charging}}{\overset{\text{Discharging}}{\rightleftharpoons}} PbSO_4(s) + 2H_2O\ (l)$$

Applications: Each electrode pair develops a potential of 2V. In order to obtain higher potential a number of electrode pairs are connected in series.

Lead storage batteries are extensively used in automobiles to start the engine. They are also used for electric supply in telephone exchangers, railway trains, hospitals, laboratories, etc., and for emergency power supplies.

Limitations:

- The potential decreases with decrease in concentration of sulfuric acid.
- Excessive discharge and quick charging shortens the life of the battery.
- Cell potential and the effectiveness is reduced at low temperature.
- Excessive charging may damage the electrodes and may also lead to explosion.

(ii) Alkaline storage battery: Nickel-cadmium cell

Nickel cadmium cell consists of a nickel wire gauze electrode grids. The anode grid consists of a mixture of spongy cadmium with 78% cadmium hydroxide, 18% iron, 1% nickel and 1% graphite. The cathode grid contains nickel hydroxide (80%), cobalt hydroxide (2%), graphite (18%) and traces of barium compound. Graphite increases the conductivity, the cobalt and barium compounds increases the efficiency of active material and also the cycle life. 6M KOH is the electrolyte.

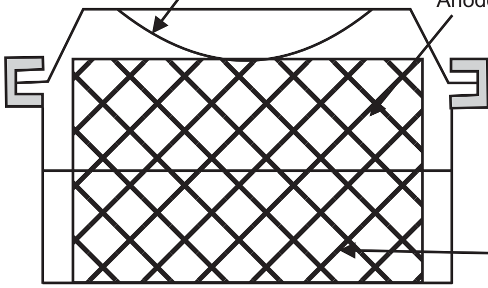

Fig. 2.4. Button type Ni-Cd cell

In a button type cell (Fig. 2.4), a cell cup acts as the cathode and a cell cover acts as anode. The electrodes consist of tablets wrapped in nickel wire gauze, separated by a fine porous separator soaked with the electrolyte. Sealing is accomplished by flanging the rim of the cell cup over the rim of the cell cover with a plastic washer in between, serving to insulate the cup from the cover.

Electrode reactions: During discharge,

At the anode, $Cd + 2OH^- \rightarrow Cd(OH)_2 + 2e^-$

At the cathode, $2Ni(OH)_3 + 2e^- \rightarrow 2Ni(OH)_2 + 2OH^-$

The net cell reaction is

$$Cd + 2Ni(OH)_3 \rightarrow 2Ni(OH)_2 + Cd(OH)_2$$

During charging, the above reaction is reversed.

The open circuit potential of the cell ranges from 1.4 to 1.28V. It is compact, light weight battery with good cycle characteristics, capacity and long shelf life.

Applications: Nickel cadmium cells are used in battery operated appliances such as pocket calculators, photo flash units, cordless garden tools, electric shavers, instruments, alarm systems, transmitters, receivers, emergency lighting, hearing aids, telemeters, etc.

2.6 MODERN BATTERIES

(i) Zinc-air cell

Zinc-air battery is a type of metal – air batteries, which use oxygen directly from the atmosphere to produce electrochemical energy. Oxygen diffuses into the cell and is used as the cathode reactant. The air cathode catalytically promotes the reaction of oxygen with an alkaline electrolyte and is not consumed or changed during discharge. As the cathode can be very compact, high energy densities are achieved.

The zinc-air cell consists of an anode, made up of loose, granulated powder of zinc mixed with an aqueous alkaline electrolyte (30% KOH) and a gelling agent to immobilize the composite and ensure adequate contact with zinc granules. Cathode is a carbon/catalyst mixture with a wet proofing agent coated on a nickel plated steel mesh support, and with an outer layer of gas permeable Teflon layer. The can halves housing the cathode and the anode active materials also act as the terminals. The two containers are provided by a plastic gasket as insulation between the two containers. The two electrodes are separated by an electrolyte absorbent separator. The catalyst layer contains carbon blended with oxides of manganese to form a conducting medium. A schematic representation of a typical zinc air button cell is given in Fig. 2.5. Air access holes on the cathode can provides a path for oxygen to enter the cell and diffuse to the cathode catalyst site.

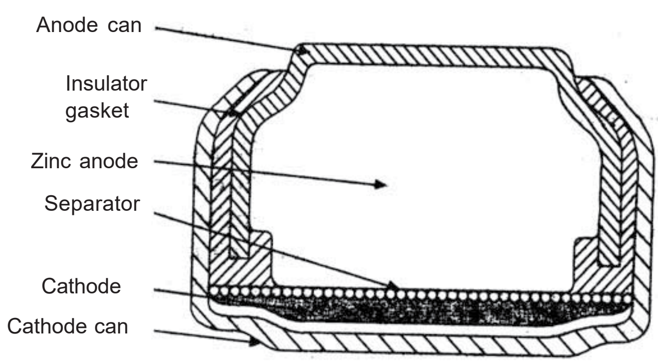

Fig. 2.5. Zinc-air cell

Electrode reactions:

At the anode,

$$Zn \rightarrow Zn^{2+} + 2e^-$$

$$Zn^{2+} + 2OH^- \rightarrow ZnO + H_2O$$

$$Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^-$$

At the cathode,

$$\tfrac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

Cell reaction:

$$Zn + \tfrac{1}{2} O_2 \rightarrow ZnO$$

The cell produces an open circuit potential of 1.4V.

During the cell reaction the electrolyte remains invariant and the air cathode acts only as a reaction site and is not consumed. A very thin cathode of the cell (about 0.5 mm) permits the use of very large zinc anode. This results in higher energy density.

Advantages

- High energy density
- Long shelf life (sealed)
- No ecological problems
- Low cost

Disadvantages

- Limited power out put
- Short activated life

Applications

- Used as a power source for hearing aids.
- Used in electronic pagers.
- Used in telemetry/voice transmitters.
- Used in various medical devices.
- Large zinc – air batteries used in railroad signaling, seismic telemetry, remote communications, etc.

(ii) Nickel-metal hydride batteries

The rechargeable nickel-metal hydride battery is similar in its characteristics to nickel-cadmium battery. The main difference is that nickel metal hydride battery uses hydrogen, adsorbed in a metal alloy for the active negative material in place of the cadmium in the nickel-cadmium battery.

The active material at the cathode of the nickel- metal hydride battery is nickel oxyhydroxide (NiOOH) and at the anode is hydrogen in the form of metal hydride. The metal alloy is capable of undergoing a reversible reaction as the battery is charged or discharged. Two types of metal alloys are used – AB_5 class of alloys consisting of lanthanum and nickel, and AB_2 class of alloy, consisting of titanium and zirconium. In both cases some of the base metals are replaced with other metals to achieve the desired characteristics. An aqueous solution of potassium hydroxide is used as the electrolyte.

The cathode in the nickel-metal hydride cell is a highly porous sintered or felt nickel substrate into which the nickel oxyhydroxide is impregnated or pasted. The anode is a highly porous structure with a nickel wire gauze grid into which the plastic bonded active hydrogen storage alloy is coated. The electrodes are separated with a synthetic non woven material, which serves as an insulator between the two electrodes and as a medium for absorbing the electrolyte. A button type cell is shown in Fig. 2.6.

Electrode reactions: During discharge,

At the anode, $$MH + OH^- \rightarrow M + H_2O + e^-$$

At the cathode, $$NiOOH + H_2O + e^- \rightarrow Ni(OH)_2 + OH^-$$

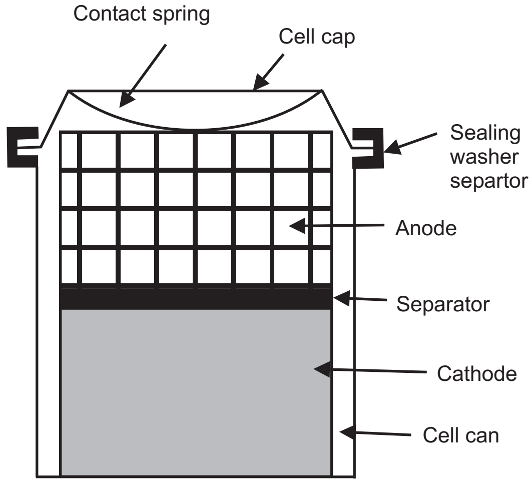

Fig. 2.6. Nickel-metal hydride button cell

The net cell reaction is, $MH + NiOOH \rightarrow M + Ni(OH)_2$

During charging, the above reaction is reversed.
The open circuit potential of the cell ranges from 1.25 – 1.35 V.

Advantages:

- High capacity.
- Sealed construction, no maintenance required.
- Cadmium free – minimal environmental problems.
- Rapid recharge capability.
- Long cycle life.
- Long shelf life.

Disadvantages: Performance is not as good as with nickel-cadmium batteries.

Applications:

- In consumer electronic devices such as cellular phones, computers, comcorders and other portable applications.
- In electric vehicles.

(iii) Lithium batteries

Lithium metal offers an attractive option be used as a battery anode material because of its light weight, low electrode potential, high electrochemical equivalence and good conductivity. For these reasons, use of lithium has predominated in the development of high performance, high energy density primary and secondary batteries.

The term lithium battery refers to a large family of batteries with a common feature of having lithium negative electrode (anode). The different lithium battery systems differ in the choice of electrolyte medium and of the positive electrode system.

Classification: Lithium batteries are classified into primary and secondary batteries. Primary battery is not chargeable and the secondary battery is chargeable.

Based on the type of cathode material used, lithium primary cells are classified as follows:

(a) Soluble-cathode cells: In this type of cells liquid or gaseous cathode materials, such as sulphur dioxide or thionyl chloride, are used. These substances dissolve in the electrolyte or are the electrolyte solvent.

(b) Solid-cathode cells: These types of cells use solid material for the cathode substances, such as V_2O_5, MnO_2, CuS, Fe_2S_3, CuO, etc.

(c) Solid electrolyte cell: This type of cells use electrolytes in the solid form it self as the cathode. PbI_2, PbS, etc., are used as solid electrolyte cathodes.

The electrolytes used in lithium batteries can not be aqueous solutions, because of the high reactivity of lithium with water. Therefore non aqueous electrolytes are to be used in lithium batteries. The different types of electrolytes used are of the following types:

- Lithium salt solutions in organic solvents such as propylene carbonate, dioxolane, THF, ethers, acetonitrile, etc.
- Solvents like thionyl chloride, sulfuryl chloride, which are also the electro active species at the cathode, mixed with lithium salts to provide ionic conductivity.
- A lithium ion conducting solid electrolyte such as LiI or LiI + Al_2O_3
- An organic polymer, which can conduct lithium ions. e.g., Polyethylene oxide.
- A molten salt. e.g., Molten LiCl + KCl

Lithium batteries based on the combinations of the above types of solvent-electrolyte system and positive electrodes have been produced and tested.

Advantages of Lithium batteries

- High cell voltage, up to above 4 V, depending on the cathode material. This is because of the very negative electrode potential of Li/Li^+.
- High energy density due to the low atomic mass of lithium. 1F is released by the dissolution of 7 g of the metal.
- Operation over a wide temperature range, from about 70 to – 40° C.
- Flat discharge characteristics-constant voltage and resistance through most of the discharges of many lithium cells.
- Superior shelf-life.

Lithium-Manganese dioxide cell: Lithium-Manganese dioxide (Li / MnO_2) cell is a solid cathode lithium cell. It consists of a lithium anode and manganese dioxide cathode. A solution of lithium halide in organic solvent serves as the electrolyte. A coin cell is shown in Fig. 2.7.

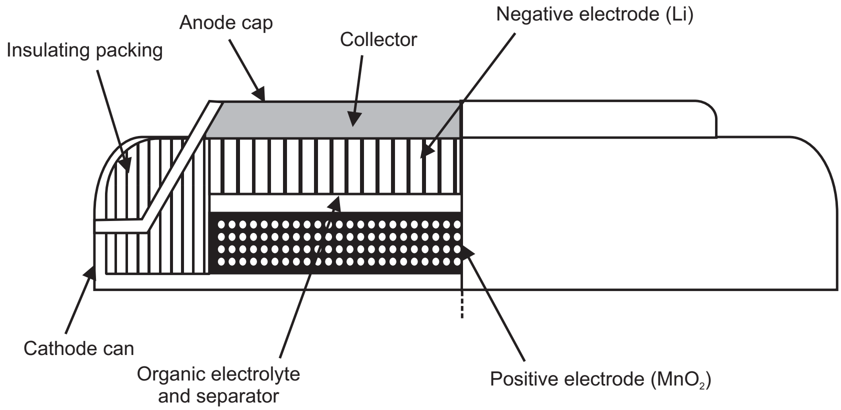

Fig. 2.7. Lithium-MnO_2 button cell

The manganese dioxide pellet and lithium anode disc are separated by a non woven polypropylene separator impregnated with the electrolyte. The cell is sealed with the can serving as the cathode terminal and the cap as the anode terminal.

Electrode reactions:

At the anode, $Li \rightarrow Li^+ + e^-$

At the cathode, $MnO_2 + Li^+ + e^- \rightarrow LiMnO_2$

The net cell reaction is, $Li + MnO_2 \rightarrow LiMnO_2$

Mn^{4+} is reduced to Mn^{3+}, with the Li^+ entering the MnO_2 crystal lattice.

Applications

- As a long time memory backup
- In watches, calculators, cameras, lighting equipments, toys and other consumer electronics.

Rechargeable lithium batteries: Rechargeable lithium batteries offer advantages like high energy density, higher cell voltage and longer charge retention or shelf life, when compared to conventional aqueous secondary cells. However, they have disadvantages such as low cycle life, relatively poor low temperature performance and capacity fading. A variety of cathodic materials and electrolytes are being used in these secondary cells as in the case of primary lithium batteries. A classification with components, characteristics and examples is given in Table 2.1.

$$xLi^+ + xe^- + xC_6 \rightleftarrows xLiC_6$$

The net reaction during charging and discharging is represented as follows:

$$LiCoO_2 + C_6 \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} Li_{1-x}\,CoO_2 + C_6L_x$$

Advantages

- They have high energy density than other rechargeable batteries.
- They are light weight.
- They produce high voltage out of 4 V.
- They have improved safety, i.e., more resistance to overcharge.
- No liquid electrolyte means they are immune from leaking.
- Fast charge and discharge rate.

Disadvantages

- They are expensive.
- They are not available in standard cell types.

Applications

- The Li-ion batteries are used in portable devices: these include mobile phones, laptops and tablets, digital cameras and camcorders, electronic cigarettes, handheld game consoles and torches (flashlights).
- Li-ion batteries are used in tools such as cordless drills, sanders, saws and a variety of garden equipment including whipper-snippers and hedge trimmers.
- Because of their light weight, Li-ion batteries are used for energy storage for many electric vehicles from electric cars to pedelec (**pedelec** is a bicycle where the rider's pedalling is assisted by a small electric motor), from hybrid vehicles to advanced electric wheelchairs, from radio-controlled models and model aircraft to the Mars Curiosity rover.
- They are used in cardiac pacemakers and other implantable devices.
- They are used in telecommunication equipment, instruments, portable radios and TVs, pagers.

2.7. FUEL CELLS

The conventional method of utilizing the chemical energy of a fuel involves several steps and can be depicted as follows:

Chemical energy → Thermal energy → Mechanical energy → Electrical energy.

Thermal energy liberated during the combustion of a fuel is used to convert water into steam. The steam is used to drive a turbine that drives the generator to produce electrical energy. There is a loss of energy in every step and only a maximum of 40% energy of the fuel is converted into electricity.

In a galvanic cell chemical energy is directly converted into electrical energy and the efficiency of conversion is very high. As in the case of combustion of fuels, the reaction taking place in a galvanic cell is also a redox reaction. But the only difference is that oxidation and reduction reactions in a cell take place at two different electrode surfaces separated from each other. The electrons liberated at the anode flow to the cathode, thereby generating electricity. Therefore, it was thought that if the oxidation of the fuel and reduction of the oxidant, oxygen, can be carried out separately at a distance between the two, then there can be an identical situation as in the case of a galvanic cell. Electrons liberated during the oxidation of the fuel can flow to the reduction zone of oxygen. The attempt in this direction by several scientists over quite a long period of time lead to the invention of fuel cells, in which chemical energy of a fuel is directly converted into electrical energy.

The principle of the fuel cell was discovered in 1839 by Sir William Grove, who has been acknowledged as the "Father of the Fuel Cell". Grove was interested in reversing the process of electrolysis, which is what a fuel cell precisely achieves. The term "fuel cell" was coined in 1889 by Ludwig Mond and Charles Langer, who attempted to use air and coal gas to generate electricity. In 1932, Francis Bacon improved on the platinum catalysts of Mond and Langer, and soon Harry Karl Ihrig, of Allis Chalmers Manufacturing Company demonstrated a 20 horsepower fuel cell powered tractor. NASA began using fuel cells in the late 1950s and continue to do so today. With the advent of new technologies, the applications of fuels cells have now been extended extensively in various fields.

Definition: A fuel cell is a galvanic cell in which the chemical energy contained in a readily available fuel oxidant system is converted directly into electrical energy by means of electrochemical processes in which the fuel is oxidized at the anode.

Like any other electrochemical cell, the fuel cell has two electrodes and an electrolyte. However, the fuel and the oxidizing agents are continuously and separately supplied to the two electrodes of the cell, at which they undergo reactions. These cells are capable of supplying current as long as they are supplied with the reactants.

A fuel cell essentially consists of the following arrangement:

Fuel / electrode / electrolyte / electrode / oxidant.

At the anode, fuel under goes oxidation:

$$\text{Fuel} \rightarrow \text{Oxidation product} + ne^-$$

At the cathode, the oxidant gets reduced:

$$\text{Oxidant} + ne^- \rightarrow \text{Reduction products}$$

The electrons liberated from the oxidation process at the anode can perform useful work when they pass through the external circuit to the cathode.

Advantages

Theoretically the efficiency can be 100%. But actually it is about 50–80%, owing to over potential and resistance of the cell.

- High efficiency of the energy conversion process.
- No moving parts and so elimination of wear and tear.
- Silent operation.
- Absence of harmful waste products.
- No need of charging.

Limitations

- Cost of power is high as a result of the cost of the electrodes.
- Fuels in the form of gases and oxygen need to be stored in tanks under high pressure.
- Power output is moderate.
- To have an appreciable voltage, a battery of fuel cells must be available.

Classification of Fuel cells

Fuel cells can be classified into three categories :

(i) Direct fuel cells
(ii) Indirect fuel cells
(iii) Regenerative fuel cells.

In a **direct fuel cell**, the products of the cell reaction are discarded. In a **regenerative fuel cell**, the spent reactants are regenerated from the products by using thermal, electrical or photochemical methods. In an **indirect fuel cell**, the fuel of the cell is obtained from organic fuel. For example, in the reformer fuel cells organic fuels are converted into hydrogen. A biochemical fuel cell is another type of indirect cell in which a biochemical substance is decomposed by means of an enzyme in solution to produce hydrogen.

Hydrogen-Oxygen fuel cell

Hydrogen-oxygen fuel cell is a simplest type of fuel cell in which hydrogen gas is used as a fuel and oxygen gas as oxidant. A schematic diagram of $H_2 - O_2$ fuel cell is shown in Fig. 2.9.

The cell consists of a porous carbon electrode impregnated with catalysts such as finely divided platinum or palladium as anode. The cathode is also a porous carbon electrode impregnated with platinum or silver as catalyst. The electrolyte is an aqueous solution of KOH. The hydrogen gas fuel is continuously supplied at the anode and oxygen gas is supplied at the cathode. As the hydrogen gas diffuses through the anode, it is adsorbed on the electrode surface and reacts with hydroxyl ions to form water. At the cathode oxygen diffusing through the electrode is adsorbed and reduced to hydroxyl ions. These electrode reactions are summarized below:

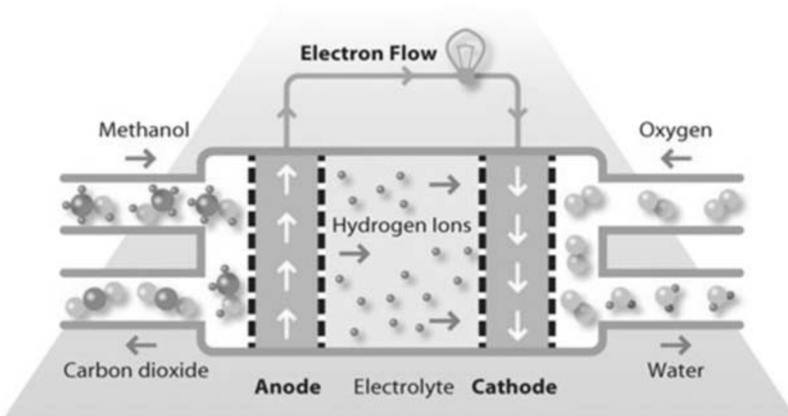

Fig. 2.10. Methanol fuel cell

Electrolyte

Sulphuric acid is used.

Electrode reactions

At the anode: $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$

At the cathode: $3/2\ O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$

Fuel cell reaction: $CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2H_2O$

Fuel (methanol) and air or oxygen are fed to the electrodes. The cell potential is 1.21 V at 25 °C. The acid electrolyte offers the advantage of easy removal of CO_2, a product of the cell reaction.

Uses

In all kinds of portable, automotive and mobile applications like,

- Powering laptop, computers, cellular phones, digital cameras.
- Fuel cell vehicles (FCVs).
- Spacecraft applications.
- Any consumables which require long lasting power compared to Li-ion batteries.