UNIT I - ENERGY SOURCES AND STORAGE DEVICES

Introduction - nuclear energy - light water nuclear power plant - breeder reactor, solar energy conversion - solar cells: principle, working and applications, types of batteries - primary battery (alkaline battery), secondary battery (lead acid battery, NICAD battery, lithium-ion battery), fuel cells (H_2-O_2 fuel cell). Super capacitors: storage principle, applications. Electric vehicles-working principles.

Nuclear energy:

The enormous amount of energy released during the nuclear chain reaction of heavy isotopes like U^{235} or PU^{239} is called Nuclear energy. In both processes like Nuclear fission and nuclear fission nuclear energy is released.

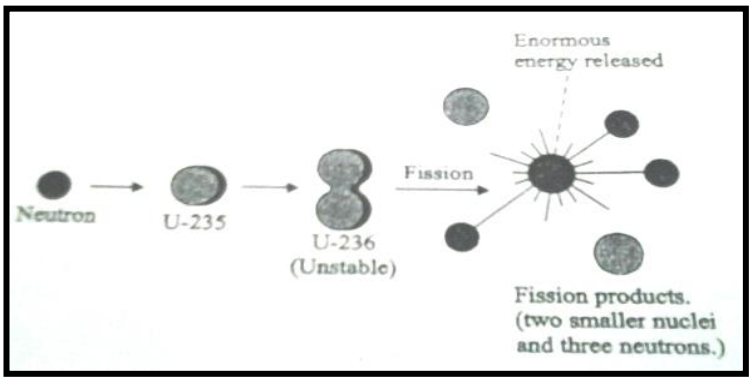
Nuclear fission:

Nuclear fission is defined as the process of splitting of heavier nucleus into two or more smaller nuclei with simultaneous liberation of large amount of energy.

E.g: $_{92}U^{235} + {}_0n^1 \rightarrow [_{92}U^{236}] \rightarrow {}_{56}Ba^{140} + {}_{36}Kr^{93} + 3\,{}_0n^1$

Characteristics of nuclear fission:

- A heavy nucleus U^{235} or Pu^{239} when bombarded by slow moving neutrons, split into two or more nuclei.
- Two or more neutrons are produced by fission of each nucleus.
- All the fission fragments are radioactive, giving off β and γ radiations.
- All the fission reactions are a self-propagating chain-reactions because fission products contain neutrons (secondary neutrons) which further cause fission in other nuclei.
- Large quantities of energy are produced as a result of conversion of small mass of nucleus into energy.
- The atomic weights of fission products range from about 70 to 160.
- The nuclear chain reactions can be controlled and maintained steadily by absorbing a desired number of neutrons. This process is used in nuclear reactor.
- Every secondary neutron released in the fission process does not strike a nucleus some escape into air and hence a chain reaction cannot be maintained.



- **Multiplication factor**: The number of neutrons resulting from a single fission is known as the multiplication factor. When the multiplication factor is less than 1 a chain reaction does not take place.

Fertile nucleide:

The non-fissionable nucleides such as U^{238} and Th^{232} are called fertile nucleides. These are converted into fissile nucleides.

Critical mass:

The minimum amount of fissionable material(U^{235}) required to continue the nuclear chain reaction is called critical mass. The critical mass of U^{235} lies between 1 Kg to 100 Kg.

Nuclear fusion:

It is the process of combination of lighter nuclei in to heaver nuclei

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S.No	Nuclear Fission	Nuclear Fusion
1.	It is the process of breaking a heavier nucleus.	It is the process of combination of lighter nuclei.
2.	It emits radioactive rays.	It does not emit any radioactive rays.
3.	It occurs at ordinary temperatures.	It occurs at high temperature.
4.	It gives rise to chain reaction.	It does not give rise to chain reaction.
5.	It emits neutrons.	It emits positrons.
6.	It can be controlled.	It cannot be controlled.
7.	The mass number and atomic number of new elements are lower than that of the starting elements.	The mass number and atomic number of the product is higher than that of the starting elements.
8.	E.g : $_{92}U^{235} + {}_0n^1 \rightarrow {}_{56}Ba^{140} + {}_{36}Kr^{93} + 3\,{}_0n^1$	E.g : $_1H^2 + {}_1H \rightarrow {}_2He^4$ + Energy
9.	Nuclear fission takes place in atom bomb	Nuclear fusion takes place in hydrogen bomb.

Nuclear reactor: The arrangement or equipment used to carry out fission reaction under controlled conditions is

called a nuclear reactor.

Example: The energy released (due to controlled fission of U^{235} in a nuclear reactor) can be used to produce steam which can run turbines and produce electricity.

Components of a nuclear reactor:

The main components of the nuclear reactor are

1) **Fuel rods**: The fissionable materials used in the nuclear reactor is enriched U^{235}. The enriched fuel is used in the reactor in the form of rods or strips.
   Example: U^{235}, PU ^{239}
   Function: It produces heat energy and neutrons that starts nuclear chain reaction.
2) **Control rods**: To control the fission reaction movable rods made of cadmium or boron are suspended between fuel rods. These rods can be lowered or raised and control the fission reaction by absorbing excess neutrons.
   If the rods are deeply inserted inside the reactor they will absorb more neutrons and the reaction becomes very slow. On the other hand, if the rods are pushed outwards they will absorb less neutrons and the reaction will be very fast.

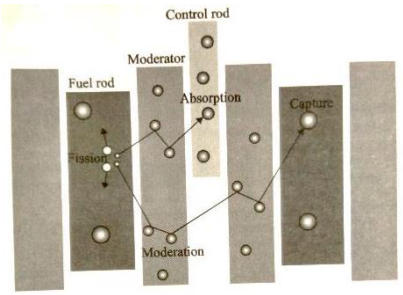
$$Cd_{43}^{113} + n_0^1 \rightarrow Cd_{43}^{114} + \gamma \text{ - ray}$$

$$B_5^{10} + n_0^1 \rightarrow B_5^{11} + \gamma - \text{ray}$$

Example: Cd ^{113}, B ^{10}

Function: It converts the nuclear chain reaction and avoids the damage of the reactors.

3) **Moderators**: The substances which are used to slow down the neutrons in a nuclear reactor are called moderators. When fast-moving neutrons collide with moderator they lose energy and gets slow down.



E.g : Ordinary water, Heavy water, Graphite, Beryllium.

Function: The kinetic energy of neutrons 1 MeV is reduced to 0.25 MeV

4) **Coolants**: In order to absorb the heat produced during fission a liquid called coolant is circulated in the reactor core. It enters the base of the reactor and leaves at the top. The heat carried by out-going liquid is used to produce steam.

Example: Water, Heavy water, liquid metal like Na or K, CO_2

Function: It cools the fuel core.

5) **Pressure vessel**: It encloses the core and also provides the entrance and exit passages for coolant.

Function: It withstand the pressure as high as 200 kg/cm^2

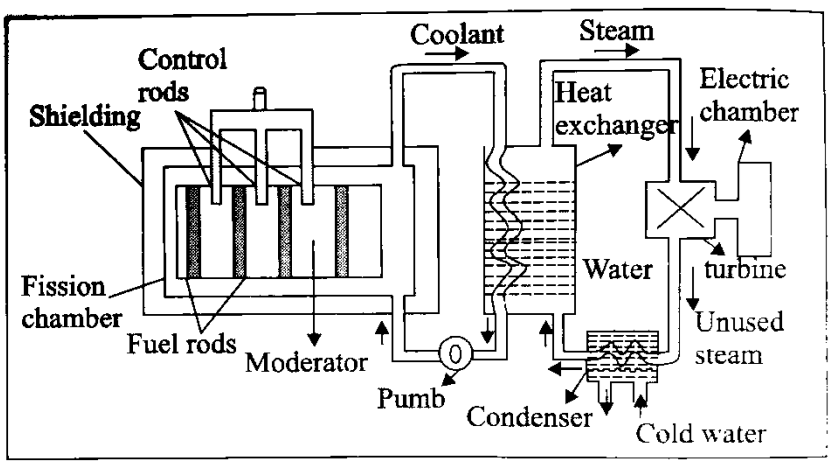
6) **Protective shield**: The nuclear reactor is enclosed in a thick massive concrete shield more than 10 meters thick.

Function: The environment and operating personnel's are protected from destruction in case of leakage of radiation.

7) **Turbine**: The steam generated in the heat exchanger is used to operate a steam turbine which drives a generator to produce electricity.

Light water nuclear power plant:

- Light water nuclear power plant is the one in which U235 fuel rods are submerged in water. Here the water acts as coolant and moderator.
- The fission reaction is controlled by inserting or removing the control rods of B 10 automatically from the spaces in between the fuel rods. The heat emitted by fission of U235 in the fuel core is absorbed by the coolant. The heated coolant water at about 300˚C then goes to the heat exchanger containing sea water. The coolant here transfers heat to sea water which is converted into stem. The steam then drives the turbines generating electricity.
- Though nuclear power plants are very important for production of electricity they will cause a serious danger to environment. So the waste is packed in concrete barrels which are buried deep in the sea.



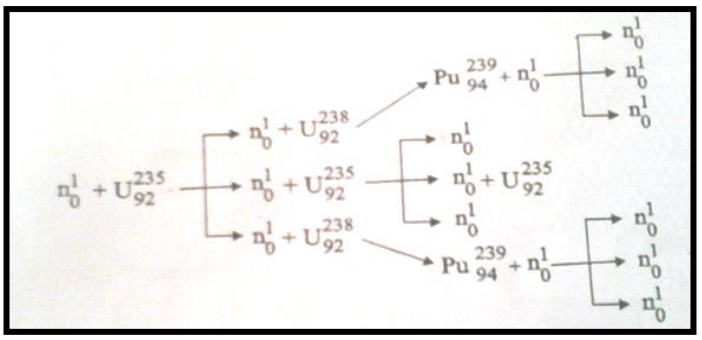
Light water Nuclear Power Plant

Breeder reactor:

Definition: Breeder reactor is the one which converts non-fissionable material like U^{238}, Th^{232} into fissionable material like U^{235}, Pu^{239}. Thus the reactor produces or breeds more fissionable material than it consumes.

Illustration:

$$U_{92}^{238} + n_0^1 \rightarrow Pu_{94}^{239} + 2e^-$$



Non-fissionable → Fissionable

$$Pu_{94}^{239} + n_0^1 \rightarrow \text{Fission products} + 3n_0^1$$

In breeder reactor, of the three neutrons emitted in the fission of U^{235}, only one is used in propagating the fission chain with U^{235}. The other two are allowed to react with U^{238}. Thus two fissionable atoms of Pu^{239} are produced for each atom of U^{235} consumed. Therefore the breeder reactor produces more fissionable material than it uses.

The principle of breeder reactor is given below:

Significance:

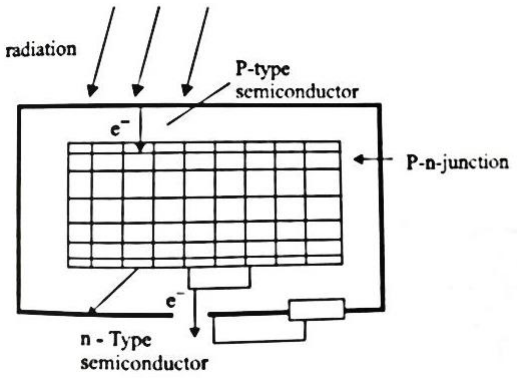
- The fissionable nucleides like U^{235} and Pu^{239} are called fissile nucleides.
- The non-fissionable nucleides like U^{238} and Th^{232} are called fertile nucleides. These are converted into fissile nucleides.
- Fissile nucleides are generated in breeder reactor. Hence its efficiency is more.

- Pu^{239} is manmade nuclear fuel. It is called secondary nuclear fuel.

Solar Cell: Definition: Photovoltaic cell is the one, which converts the solar energy directly into electrical energy.

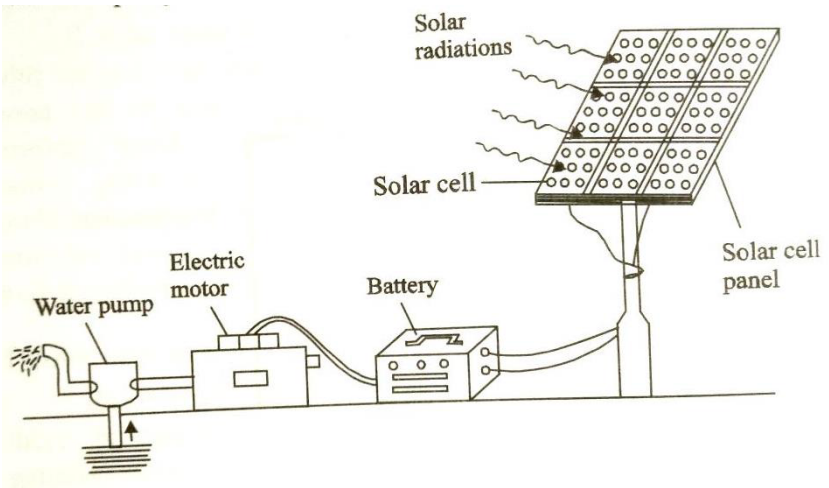
When a large number of photovoltaic cells are interconnected, solar cell is formed.

Principle: Solar cell consists of a p-type semiconductor (such as Si doped with B) and n-type semiconductor (such as Si doped with P). They are in close contact with each other. When the solar rays fall on the top layer of p-type semiconductor, the electrons from the valence band get promoted to the conduction band and cross the p-n junction into n-type semiconductor.



Working: When the solar rays fall on the outer layer of p-type semiconductor, the electrons in the valence band get promoted to the conduction band by absorbing light energy. Since the conduction electrons can easily cross the p-n junction into the n-type semiconductor, a potential difference between two layers is created.

This potential difference cause flow of electrons (ie: an electric current). The potential difference and hence current increases as more solar energy falls on the surface of the outer layer. When this p and n layers are connected to an external circuit, electrons flow from n-type to p-type, thereby the current is generated.



Uses:

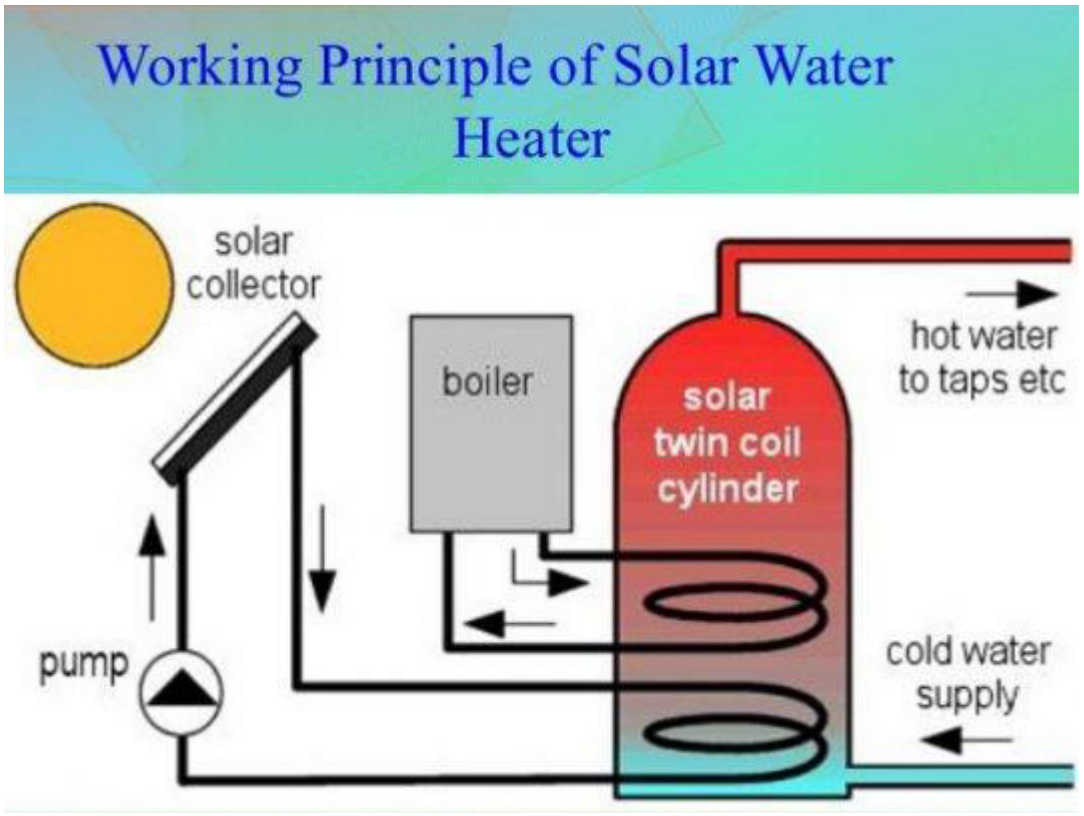
- Solar cells are used in boilers to produce hot water for domestic and industrial uses.
- Solar cells can be used for lighting purposes and for running pumps.
- They are used in remote areas where conventional electricity supply is not possible.
- Solar cells are used in calculators, TV, radio etc;
- Solar cells can be used to drive vehicles.
- The solar cells are used as source of power in space craft and satellites.

Disadvantages:

- The huge capital cost is the major limitations for the large scale of solar cells.
- During night and rainy days, other source of electricity is required.
- It produces only DC power.

Solar Water Heater:

First of all the Sun rays fall on the Solar Collector, which is consisted a black absorbing surface (absorber) that absorbs solar radiation, and transfers the heat energy to water flowing through it. After this, heated water is collected in a tank, insulated to prevent heat loss. Then the circulation of water from the tank through the collector and back to the tank continues automatically. An Insulated Storage Tank of a Solar Water Heater is useful to collect solar energy by collector panels to store hot water.



Batteries:

A battery is a device that stores energy and then discharges it by converting chemical energy into electricity

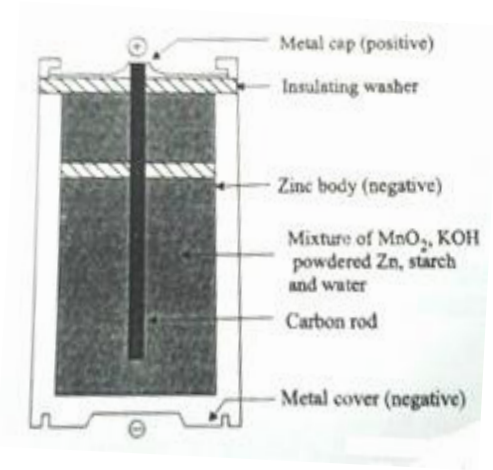
Types:

Primary battery: The cells in which electrode reactions cannot be reversed by passing an external electrical energy are called primary cells. When these cells are connected in series it forms a primary battery. E.g: Dry cell, Mercury cell, Lechlanche cell

Secondary cells: The cells in which electrode reactions can be reversed by passing an external electrical energy are called secondary cells. E.g : Lead acid storage cell, Lithium cell.

Alkaline battery:

Description: It is an improved form of dry cell in which the electrolyte NH_4Cl is replaced by KOH. In alkaline battery, the powdered zinc is mixed with KOH & MnO_2 to get a gel. A carbon rod (graphite),acts as cathode, is immersed in the electrolyte in the centre of the cell. The outside cylindrical Zinc body is made of zinc.



Cell reactions:

At anode: $Zn_{(s)} + 2OH^-_{(aq)} \rightarrow Zn(OH)_{2(s)} + 2e^-$

At cathode: $2MnO_2(s) + H_2O(l) + 2e^- \rightarrow Mn_2O_{3(s)} + 2OH^-_{(aq)}$

Overall cell reaction:

$Zn_{(s)} + 2MnO_2(s) + H_2O(l) \rightarrow Zn(OH)_{2(s)} + Mn_2O_{3(s)}$

The emf of the cell is 1.5 V.

The zinc anode used in the cell is made porous to provide a large electrode area. This leads to the delivery of more current.

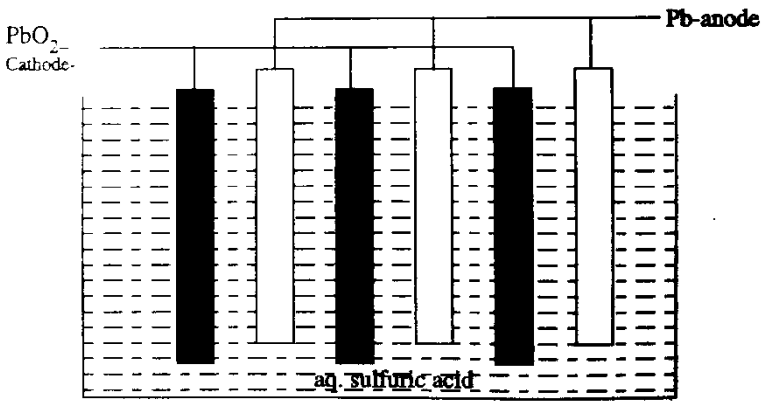
The dry battery is called a heavy duty battery because it sustains heavy use and has a longer shelf life. It performs better in cold weather than other type of batteries.

Uses:

It is used in calculators, watches etc;

Lead acid storage cell Or Lead accumulator:

Description: A lead acid storage battery consists of a number of (3 to 6) voltaic cells connected in series to get 6 to 12 V battery. In each cell, the anode is made of lead. The cathode is made of lead dioxide or a grid of lead, packed with PbO_2. A number of lead plates are connected in parallel and a number of PbO_2 plates are also connected in parallel. Various plates are separated from the adjacent ones by insulators like rubber or glass fibre. The entire combination is then immersed in dil.H_2SO_4 (38% by mass) having a density of 1.30 gm/ml. The entire set up is placed inside a polypropylene container.



The cell may be represented as: $Pb/PbSO_4//H_2SO_{4(aq)}/PbO_2/Pb$

Working: When the lead acid storage battery operates, at the anode lead is oxidized to Pb^{2+} ions and insoluble $PbSO_4$ is formed. At the cathode PbO_2 is reduced to Pb^{2+} ions and $PbSO_4$ is formed.

Cell reactions

At anode: Lead is oxidized to Pb^{2+} ions, which further combines with SO_4^{2-} forming insoluble $PbSO_4$.

$$Pb_{(s)} \rightarrow Pb^{2+}_{(aq)} + 2e^-$$
$$Pb^{2+}_{(aq)} + SO_4^{2-}{}_{(aq)} \rightarrow PbSO_{4(s)}$$

Overall anode reaction:

$$Pb_{(s)} + SO_4^{2-}{}_{(aq)} \rightarrow PbSO_{4(s)} + 2e^-$$

At cathode: PbO_2 gains electrons ie; Pb undergoes reduction at the cathode from +4 to +2. The Pb^{2+} an ion then combines with SO_4^{2-} ions forms insoluble $PbSO_4$.

$$PbO_{2(S)} + 4H^+ + 2e^- \rightarrow Pb^{2+}_{(aq)} + 2H_2O$$
$$Pb^{2+}_{(aq)} + SO_4^{2-}{}_{(aq)} \rightarrow PbSO_{4(s)}$$

Overall Cathodic Reaction:

$$PbO_{2(S)} + 4H^+ + 2e^- + SO_4^{2-}{}_{(aq)} \rightarrow PbSO_{4(s)} + 2H_2O$$

Overall cell reaction during discharging:

At anode:

$$Pb_{(s)} + SO_4^{2-}{}_{(aq)} \rightarrow PbSO_{4(s)} + 2e^-$$

At cathode:

$$PbO_{2(S)} + 4H^+ + 2e^- + SO_4^{2-}{}_{(aq)} \rightarrow PbSO_{4(s)} + 2H_2O$$

Overall cell reaction:

$$Pb_{(s)} + PbO_{2(S)} + 2H_2SO_4 \rightleftharpoons 2PbSO_{4(s)} + 2H_2O + \text{Energy (2V)}$$

From the above cell reactions it is clear that $PbSO_4$ is precipitated at both the electrodes and H_2SO_4 is used up. As a result, the concentration of H_2SO_4 decreases and hence the density of H_2SO_4 falls below 1.2 gm/ml. So the battery needs recharging.

Recharging the battery: The cell can be charged by passing current in the opposite direction. The electrode reaction gets reversed. As a result, Pb is deposited on anode and PbO_2 on the cathode. The density of H_2SO_4 also increases.

The net reaction during charging is

$$2PbSO_{4(s)} + 2H_2O + \text{Energy} \rightleftharpoons Pb_{(s)} + PbO_{2(S)} + 2H_2SO_4\ (>2V)$$

Uses:

- Lead storage cell is used to supply current mainly in automobiles such as cars, buses, trucks etc;
- It is also used in gas engine ignition, telephone exchanges, hospitals, power stations etc;

Lithium-ion Battery: A lithium-ion battery or Li-ion battery (abbreviated as LIB) is a type of rechargeable battery in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging.

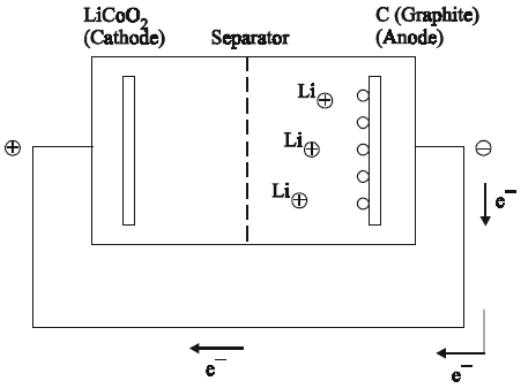


Fig. Lithium-Ion Battery

Electrodes:

Cathode : $LiCoO_2$

Anode : C (Graphite)

Electrolyte : Lithium salt with organic solvent

Separator : Permeable Membrane

Working: The reactants in the electrochemical reactions in a lithium-ion battery are the negative. Positive electrodes and the electrolyte providing a conductive medium for lithium ions to move between the electrodes. Electrical energy flows out from or in to the battery when electrons flow through an external circuit during discharge or charge, respectively. During discharge, the (positive) lithium ions move from the negative electrode (usually graphite) to the positive electrode (forming a lithium compound) through the electrolyte while the electrons flow through the external circuit in the same direction.

Discharging:

At Anode:

$$CLi_x \rightarrow C + xLi^+ + xe^-$$

At Cathode:

$Li_{1-x}\ CoO_2 + x\ Li^+ + xe^- \rightarrow Li^{3+}\ CoO_2$

Over all reaction:

$CLix + Li_{1-x}\ CoO_2 \rightarrow C + LiCoO_2 + Emf\ (3.7v)$

On Charging:

$C + LiCoO_2 + External\ energy \rightarrow CLi_x + Li_{1-x}\ CoO_2$

Advantages

1. They have high energy density than other rechargeable batteries
2. They are less weight
3. They produce high voltage out about 4 V as compared with other batteries.
4. They have improved safety, i.e. more resistance to overcharge.
5. No liquid electrolyte (immune from leaking).
6. Fast charge and discharge rate.

Disadvantage:

1. They are expensive.
2. They are not available in standard cell types.

Applications

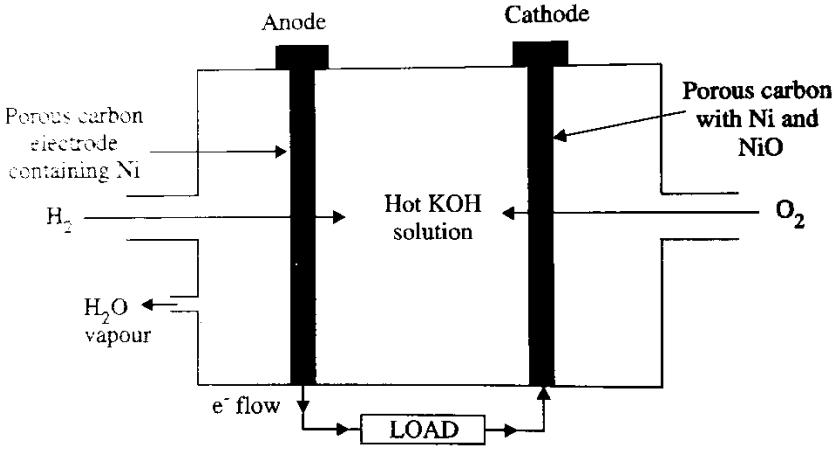
1. The Li-ion batteries are used in cameras, calculators.
2. They are used in cardiac pacemakers and other implantable device.
3. They are used in telecommunication equipment, instruments, portable radios and TVs, pagers.
4. They are used to operate laptop computers and mobile phones and aerospace applications.

Fuel cells: It is a voltaic cell which converts chemical energy of the fuel directly into electricity without combustion. The reactants, products and the electrolytes pass through the cell and hence it is called flow cell.

Fuel + O_2 → Oxidised products + Electricity

Description of H_2 - O_2 fuel cell: H_2-O_2 fuel cell consists of two porous electrodes namely anode and cathode. These electrodes are made up of compresses carbon with a little amount of Pt, Pd and Ag. In between these electrodes an electrolytic solution of 25% KOH is filled. The two electrodes are connected through a voltmeter. Fuel hydrogen gas is bubbled through the anode compartment under a pressure of 50 atm. The oxidizer oxygen gas is bubbled through the cathode compartment under a pressure of 50 atm. In this cell hydrogen is oxidized and oxygen is reduced. When the electrodes are connected a flow of electric current is observed.

The electrode reactions are



A hydrogen - oxygen fuel cell

At anode: Hydrogen molecules are oxidized at the anode with the liberation of electrons which then combine with hydroxide ions to form water.

$$2H_2 + 4OH^- \rightarrow 4\ H_2O + 4e^- \qquad E = +\ 0.83V$$

At **cathode**: he electrons produced at the anode pass through external wire to the cathode, where it is absorbed by oxygen and water to produce hydroxide ion.

$$O_2 + 2H_2O + 4\ e^- \rightarrow 4OH^- \qquad E = +0.40\ V$$

The overall cell reaction is

$$2H_2 + O_2 \rightarrow 2\ H_2O \qquad E = 1.23\ V$$

In actual practice, the emf of this fuel cell is 0.8 to 1.0 V The cell reaction is the same as combustion of hydrogen in air or oxygen. It may be noted that the only product discharged by the cell is water.

Advantages:

- The energy conversion is highly efficient,
- The cell produces drinking water.
- Noise and thermal pollution are low.
- It saves fossil fuels.

Disadvantages:

- Pure hydrogen is costly.
- They cannot store electrical energy,
- Electrodes are expensive and short lived.
- Utmost care is required in storage of gaseous fuels under high pressure.

Uses:

- $H_2 – O_2$ fuel cell is used as auxiliary energy source in space vehicles, submarines and other military vehicles,
- $H_2 – O_2$ fuel cells are preferred in space crafts due to their lightness and product water is a valuable source of fresh water for the astronauts.

Super Capacitors

Super Capacitors can be defined as energy storage device that stores electrostatically by polarizing the electrolytic solution. They are specially designed capacitor which has huge capacitance value and energy density. They belongs to electrochemical capacitor family and its working on electric double layer (EDL)mechanism.

Construction

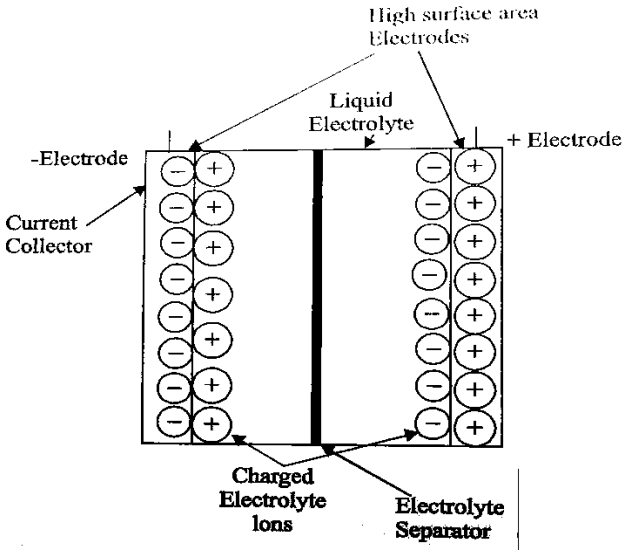
- A super capacitor consists of two porous electrodes
- A membrane, which separates positive and negative plated is called separator
- Electrodes are electrically connected with ionic liquid called electrolyte

Working

- When the voltage is applied to positive electrode, it attracts negative ions from electrolyte.
- When the voltage is applied to negative electrode, it attracts positive ions from electrolyte.
- These ions are stored near the surface of electrode and this ion decrease distance between electrodes.
- Due to decrease of distance of electrodes, the capacitance becomes very huge.

$C \alpha A / d$

Diagram:



Characteristics

1. Supercapacitors can be fully charged and discharged in seconds even in several degrees below zero.
2. SC's can be charged and discharged even up to a million times
3. SC's have very low energy densities vs batteries
4. SC's have very high self-discharge vs batteries

Advantage

Reduced size and weight vs batteries

Applications

1. Backup for uninterruptable power supply (UPS)
2. Light weight power supplies for small aircraft
3. Provide short duration power for various vehicle systems such as breaking or steering.
4. They are used in industrial lasers and medical equipment
5. Large super capacitors are used in wind turbines.

Ni-Cd Battery

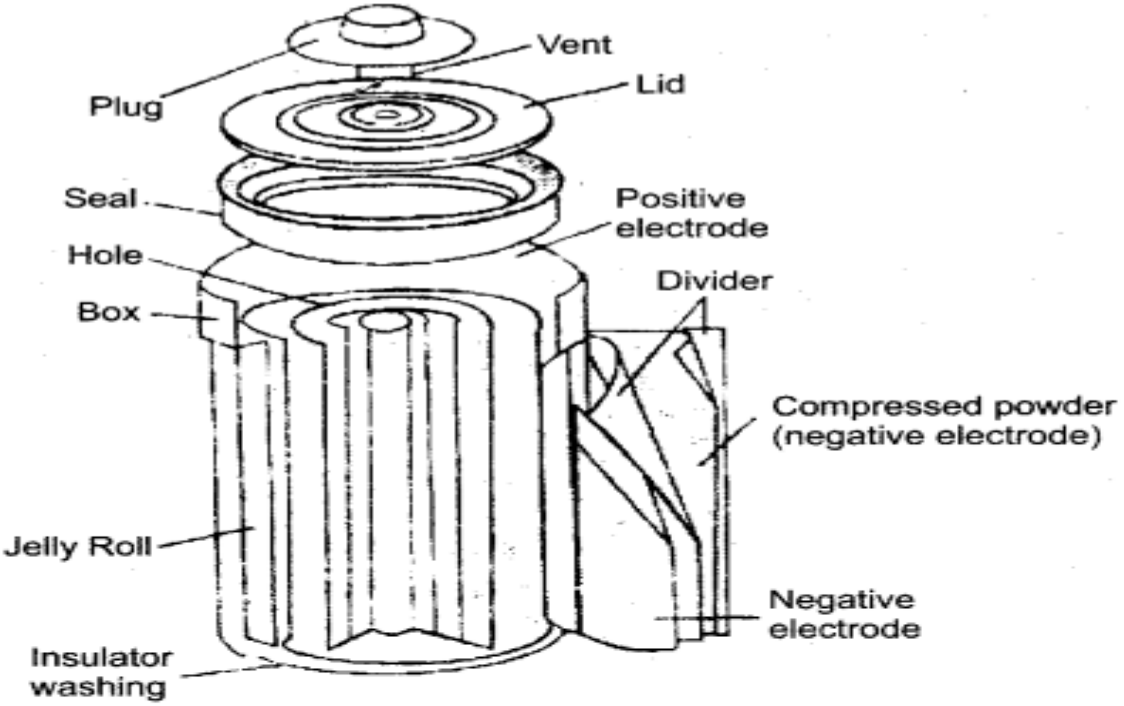


Fig. 3.22 Nickel Cadmium cell

$$\textbf{Anode}: Cd_{(s)} + 2OH^- \underset{\text{Charging}}{\overset{\text{Discharging}}{\rightleftharpoons}} CdO_{(s)} + H_2O_{(l)} + 2e^-$$

$$\textbf{Cathode}: 2Ni(OH)_{3(s)} + 2e^- \underset{\text{Discharging}}{\overset{\text{Charging}}{\rightleftharpoons}} 2Ni(OH)_{2(s)} + 2OH^-_{(aq)}$$

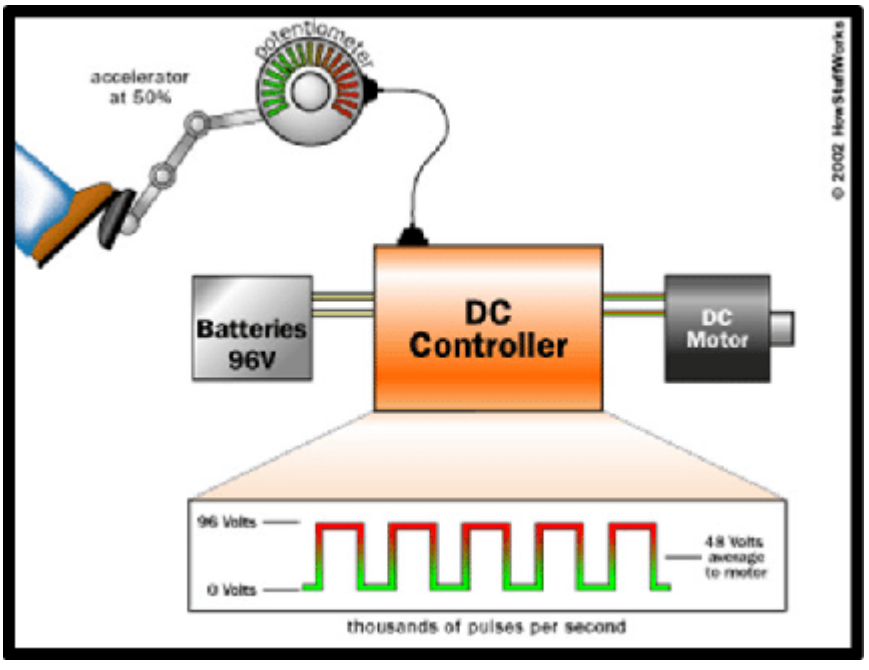
Net cell reaction takes place as following :

$$Cd_{(s)} + 2Ni(OH)_3(s) \underset{\text{Discharging}}{\overset{\text{Charging}}{\rightleftharpoons}} CdO_{(s)} + 2Ni(OH)_{2(s)} + H_2O_{(l)}$$

Electric vehicles-working principles.

To understand how an electric car works, consider the following points:

- When you charge the battery, it stores electrical energy. The stored energy is utilized to power the electric motor and other accessories/components.
- The flow of electrical energy to the motor is managed by the controller.
- The controller controls the flow of electricity based on the data received from the accelerator pedal.
- The controller takes power from the batteries and delivers it to the motor. The accelerator pedal hooks to a pair of potentiometers (variable resistors), and these potentiometers provide the signal that tells the controller how much power it is supposed to deliver. The controller can deliver zero power (when the car is stopped), full power (when the driver floors the accelerator pedal), or any power level in between.



- The electric motor draws energy from the battery and transforms it into mechanical energy.
- The transmission is in charge of delivering mechanical energy from the motor to the wheels.
- The energy produced by braking or slowing

the vehicle is returned to the battery pack.

- The battery pack can be charged using the charging port. The onboard charger converts Alternating Current (AC) to Direct Current (DC).
- You may charge the battery by attaching an external power source to the charging port on the car.
- An EV additionally includes an auxiliary battery that powers the vehicle's accessories and other equipment.
- A DC-to-DC converter converts high-voltage current from the battery pack to low-voltage current to replenish the auxiliary battery.

Advantages	Disadvantages
- Highly efficient	- Electricity storage is still expensive
- Reduced emissions	- Battery charging is time consuming
- High performance and low maintenance	- Primary resource depletion for some elements of the LIB
- Very responsive and have very good torque	- Range anxiety
- EV motors are quiet and smooth	- Battery degradation costs
- Are more digitally connected than conventional vehicles	- Sufficient public charging infrastructure is still lacking
- Simplified powertrain	- Causes indirect pollution
- Low electricity consumption	- Lacks the power to accelerate and climb quickly
- Good acceleration	- Are heavy due to overloaded batteries
- Can be charged overnight on low cost electricity produces by any type of power station, including renewables	

(Source: [11,18–28]).