5.1 STORAGE BATTERIES: GENERAL

A storage battery is a device, which can be used repeatedly for storing energy at one time in the form of chemical energy during charging process for use at another time in the form of electrical energy during discharging process. A storage battery may consist of a single or a group of storage cells electrically interconnected. A storage cell consists of positive plate (or anode) and negative plate (or cathode) bearing the necessary electrochemically active materials immersed in an electrolyte solution. Figure 5.1 shows a storage cell of a Lead-acid battery.

Charging a battery consists of connecting the two plates to a dc supply of proper polarity for a sufficient length of time. Electrical energy is delivered by the dc supply to the battery, in which it produces certain chemical reactions so that the energy is converted into chemical energy. If a charged battery has its two terminals connected through a closed external electric circuit, the active materials of the plate will react chemically with the electrolyte, producing a
flow of current in the circuit. This conversion of chemical energy into electrical energy is called discharging the battery.

### 5.1.1 Chemical effects of electric current: Basic background

From his experiments, Faraday deduced two fundamental laws that govern the phenomenon of electrolysis. These are

#### 5.1.1.1 First law:

The mass of an ion liberated (m in kg) at an electrode is directly proportional to the quantity of electricity (i.e. charge Q in C) which passes through the electrolyte during time t (in s).

Mathematically: \[ m \propto Q \] or \[ m = Z \times Q = Z \times I \times t \] (5.1)

Where I: is the charging current in amperes.

Z: is the Electro Chemical Equivalent (E.C.E) of the substance.

#### 5.1.1.2 Second law:

The masses of different substances liberated by the same quantity of electricity are proportional to their chemical weights.

Mathematically: \[ \frac{m_1}{m_2} = \frac{E_1}{E_2} \] (5.2)

Where E: is the chemical equivalent weight & \[ E = \frac{a}{v} \] (a = atomic weight and v = valency).

Finally, combinations of the results of Faraday’s laws yields

\[ Z = \frac{1}{F} \times \frac{a}{v} \] (5.3)

Where F: is Faraday’s constant.

#### 5.1.1.3 Polarization (or back E.M.F):

Let us consider the case of two platinum electrodes dipped in dilute sulphuric acid. When a potential difference is applied through the electrodes a flow of current takes place. The \(\text{H}^+\) ions move towards the cathode and \(\text{O}^-\) ions move towards the anode and are absorbed there. These absorbed ions have a tendency
to go back to the electrolyte producing a back or an opposing E.M.F to the applied voltage. Consequently, for producing electrolysis, it is necessary that the applied voltage must be greater than the back E.M.F of electrolysis for that electrolyte.

**Example 5.1:**
In a copper refinery, copper is deposited on the cathodes with a current density 0.02 A/cm². Find the time needed to deposit a layer of 1 cm thickness of copper on the cathode. If 0.3 V is needed to send the current through the cell, find the electrical energy required for depositing 1 kg of copper. The density of copper may be taken as 8.9 gm/cm² and the E.C.E as 0.00033 g/C

**Solution 5.1:**
Let A cm² be cross-sectional area of the cathode, then for 1 cm thick of copper layer the mass of deposited copper  \( m = A \times 1 \times 8.9 \text{ gm} \). And as \( m = Z \times I \times t \), we get \( t = \frac{8.9A}{0.00033 \times 0.02A} = 1.357 \times 10^6 \text{ s} = 377 \text{ hr} \).

Now a current of 0.02A is required to deposit 8.9A×10⁻³ kg of copper. Therefore, current needed for depositing 1 kg of copper is given by

\[
\frac{0.02A}{8.9A \times 10^{-3}} = 2.247 \text{ A}
\]

\[\therefore \text{ Electrical energy used } = 0.3 \times 2.247 \times 377 \times 10^{-3} = 0.254 \text{ KWh} \]

**5.1.2 Available Battery Types**

**5.1.2.1 Acid vs. Alkaline**

The type of electrolyte used in their construction often classifies batteries. There are two common classifications; acid, and alkaline.

i) **Acid-based batteries** often use sulphuric acid as the major component of the electrolyte. Automobile batteries are acid-based. The electrolyte used in mildly acidic batteries is far less corrosive than typical acid-based batteries and usually includes a variety of salts that produce the desired acidity level. Inexpensive household batteries are mildly acidic batteries.
ii) **Alkaline batteries** typically use sodium hydroxide or potassium hydroxide as the main component of the electrolyte. Alkaline batteries are often used in applications where long-lasting, high-energy output is needed, such as cellular phones, portable CD players and radios, pagers, and flash cameras.

### 5.1.2.2 Wet vs. Dry

i) "**Wet**" cells refer to galvanic cells where the electrolyte is liquid in form and is allowed to flow freely within the cell casing. Wet batteries are often sensitive to the orientation of the battery. For example, if a wet cell is oriented such that a gas pocket accumulates around one of the electrodes, the cell will not produce current. Most automobile batteries are wet cells.

ii) "**Dry**" cells are cells that use a solid or powdery electrolyte. These kinds of electrolytes use the ambient moisture in the air to complete the chemical process. Cells with liquid electrolyte can be classified as "dry" if the electrolyte is immobilized by some mechanism, such as by gelling it or by holding it in place with an absorbent substance such as paper.

### 5.2 LEAD-ACID BATTERIES

#### 5.2.1 Lead-Acid Battery Components and Operation

A battery consists of a number of cells and each cell consists of the following components (see Fig.5.2):

i) Positive and negative plates: A plate consists of grid of cast antimonial lead alloy, which is covered with active material (*Lead Peroxide PbO₂* for +ve plate & *Sponge lead Pb* for –ve plate).

ii) Separators: Thin sheets of a porous material placed between the positive and negative plates for preventing contact between them.

iii) Electrolyte: Dilute Sulphuric Acid $\text{H}_2\text{SO}_4$. 
Fig. 5.2 Lead-Acid Battery Components
The grid structure in both pasted and tubular plate batteries is made from a lead alloy. A pure lead grid structure is not strong enough by itself to stand vertically while supporting the active material. Other metals in small quantities are alloyed with lead for added strength and improved electrical properties. The most commonly alloyed metals are antimony, calcium, tin, and selenium. The two most common alloys used today to harden the grid are antimony and calcium. Batteries with these types of grids are sometimes called "lead-antimony" and "lead calcium" batteries. Tin is added to lead-calcium grids to improve cyclability. The major differences between batteries with lead-antimony and lead-calcium grids are as follows:

i) Lead-antimony batteries can be deep cycled more times than lead calcium batteries.

ii) Flooded lead-antimony batteries require more frequent maintenance as they near end-of-life since they use an increasing amount of water and require periodic equalization charges.

iii) Lead-calcium batteries have lower self-discharge rates as shown in Fig. 5.3 and therefore, will draw less current while on float charge than lead-antimony batteries.

iv) Lead-calcium positive plates may grow in length and width because of grid oxidation at the grain boundaries. This oxidation is usually caused by long-term overcharging, which is common to Uninterruptible Power Supply (UPS) systems and other batteries on constant-float changing. Grids may grow in size sufficiently to cause buckling or rupture of their containers.

The chemical changes during charging and discharging cycles of the Lead-acid cell can be represented by the following single reversible equation:
5.2 Lead-Acid Batteries

At the negative electrode:

\[
Pb + HSO_4^- \xrightarrow{\text{Discharge}} PbSO_4 + H^+ + 2e^- \quad \xleftarrow{\text{Charge}} \quad Pb + HSO_4^- \]

For the overall cell:

\[
PbO_2 + Pb + 2H_2SO_4 \xrightarrow{\text{Discharge}} 2PbSO_4 + 2H_2O \quad \xleftarrow{\text{Charge}} \quad PbO_2 + Pb + 2H_2SO_4
\]

Fig. 5.3 Self-discharge rates of three grid materials

5.2.2 Battery Parameters

The discharging/charging behavior of a battery depends on a number of parameters, like current, voltage, and temperature. These parameters have to be specified when such data are compared.

5.2.2.1 Voltage

The cell equilibrium voltage of the reversible chemical changes during charging and discharging cycles of the lead-acid depends only on the acid concentration (see Fig. 5.4). It is independent of the present amount of lead, lead dioxide or lead sulfate, as long as all three substances are available in the electrode. In battery practice, mostly the approximation is used:
**Equilibrium cell voltage** = acid density (in g/cm$^3$) + 0.84  \hspace{1cm} (5.4)

In the case of reversible systems the cell equilibrium voltage cannot exactly measured (even at an open circuit), since the electrode process is not quite reversible. The voltage of each cell is approximately 2 V on an open circuit but is higher than 2 V when the battery is being charged and lowers than 2 V when being discharged. The nominal voltage of a battery is, therefore, the number of cells multiplied by 2.

The variations in the terminal potential difference of a cell on charge and discharge are shown in Fig.5.5. The voltage rate depends upon the rate of discharge (as illustrated in Fig.5.6). The rate of discharge is specified by the number of hours during which the cell reaches the specified final voltage. It is recommended that the final voltage should not allowed to fall to lower than 1.8 V, otherwise hard insoluble lead sulphate is formed on the plate which increases the internal resistance of the battery.

![Equilibrium cell voltage of the lead-acid battery referred to acid density and acid concentration in wt% H$_2$SO$_4$](image)

**Fig.5.4** Equilibrium cell voltage of the lead-acid battery referred to acid density and acid concentration in wt% H$_2$SO$_4$
5.2 Lead-Acid Batteries

The capacity of a battery is defined by international convention as the electrical charge in units of Ah that can be drawn from the battery until it reaches the specified final voltage (≈ 1.8 Volt). When the battery is discharged with a constant current, its capacity is given by the relation

\[ C_{Ah} = \frac{I \times \Delta t}{Ah} \]  \hspace{1cm} (5.5)

A more general definition would be:
The Ah-capacity of a cell depends upon:

i) **Rate of discharge.** The capacity of a cell is decreased with increase of rate of discharge. Rapid rate of discharge results in greater fall in potential difference of the cell due to its internal resistance. Moreover, with rapid discharge the weakening of the acid in the pores is also greater.

ii) **Temperature.** It is recommended not to work batteries above 40°C. As temperature is lowered, the speed of chemical reaction is decreased and the internal resistance increased resulting in a decrease of cell capacity.

iii) **Density of electrolyte.** As the density of electrolyte decreases, the speed of chemical reaction is decreased and the internal resistance increased resulting in a decrease of cell capacity.

iv) **Quantity of active material.** It is obvious that for obtaining a cell of a greater capacity, it is necessary to provide the plates with larger amounts of active material.

### 5.2.2.3 Effect of discharge rates on discharge capacity of lead-acid batteries

The useful ampere-hour capacity of a storage battery depends on the rate of discharge and is greater for a long low rate or an intermittent rate than for a short high rate. Figure 5.7 illustrates the effect of discharge rate upon the available ampere-hour capacity of lead-acid storage battery.

If a battery is discharged intermittently, it is evident that during periods of rest between discharges diffusion will continue, thus renewing the strength of acid in the pores of plates. It follows from this reasoning that the reduction in available capacity due to high rates of discharge largely disappears when the discharge is intermittent.
5.2 Lead-Acid Batteries

Fig. 5.7 The effect of discharge rate upon available ampere-hour capacity of lead-acid storage battery

5.2.2.4 Specific gravity of the electrolyte

One of the key parameters of battery operation is the specific gravity of the electrolyte. Specific gravity is the ratio of the weight of a solution to the weight of an equal volume of water at a specified temperature. Specific gravity is used as an indicator of the state of charge of a cell or battery. However, specific gravity measurements cannot determine a battery's capacity. During discharge, the specific gravity decreases linearly with the ampere-hours discharged as indicated in Figure 5.8.

Fig. 5.8 Changes in voltage and specific gravity during charge and discharge
Therefore, during fully charged steady-state operation and on discharge, measurement of the specific gravity of the electrolyte provides an approximate indication of the state of charge of the cell. The downward sloping line for the specific gravity during discharge is approximated by the equation 5.4.

The specific gravity for a given battery is determined by the application it will be used in, taking into account operating temperature and battery life. Typical specific gravities for certain applications are shown in Table 5.1.

<table>
<thead>
<tr>
<th>Specific gravities</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>Heavily cycled batteries such as for electric vehicles (traction)</td>
</tr>
<tr>
<td>1.26</td>
<td>Automotive (SLI)</td>
</tr>
<tr>
<td>1.25</td>
<td>UPS-Standby with high momentary current discharge requirements.</td>
</tr>
<tr>
<td>1.215</td>
<td>General application such as power utility and telephone application.</td>
</tr>
</tbody>
</table>

5.2.2.5 Efficiency

The efficiency of a cell can be considered in two ways:

i) The Ampere-hour efficiency (electrochemical efficiency), which is defined as the ratio of the ampere-hours output to the Ampere-hours of the recharge.

Mathematically, \[ \% \text{Ah - efficiency} = \frac{\text{Ah - discharge}}{\text{Ah - charge}} \times 100 \] (5.7)

ii) The Watt-hour efficiency, which is defined as the ratio of the Watt-hours output to the Watt-hours of the recharge.

\[ \% \text{Wh - eff} = \text{Ah - eff} \times \frac{\text{Average voltage during discharge}}{\text{Average voltage during recharge}} \times 100 \] (5.8)
5.2.2.6 Rating of lead-acid batteries

All batteries are given a normal (ampere-hour) capacity rating based on a certain time rate of discharge under specified conditions of temperatures and final voltage. For example a certain battery may have an 8-h rating of 1000 Ah discharging to 1.75 V per cell at a temperature of 77°F (24°C).

5.2.3 The Danger of Harm from Over Discharge

When the acid combines with the lead in the active material, the resulting lead sulfate occupies more space than the active material from which it is formed. The active material of all battery plates is porous, and this expansion of the sulfated material is accommodated by reduction in the size of pores in the active material. Further discharge, results in an excessive expansion, which so closes the pores in the active material that it becomes increasingly difficult to recharge the battery properly after an excessive discharge.

5.2.4 Charging Methods for Lead-Acid Batteries

In practice, charging methods vary with the type of service. Generally, charging methods for lead-acid batteries are classified into three-categories as follows:

5.2.4.1 Constant voltage charging

Constant-voltage (often called constant-potential) chargers maintain nearly the same voltage input to the battery throughout the charging process, regardless of the battery's state of charge. Constant-voltage chargers provide a high initial current to the battery because of the greater potential difference between the battery and charger. A constant-voltage charger may return as much as 70% of the previous discharge in the first 30 minutes. This proves useful in many battery applications involving multiple discharge scenarios. As the battery charges its voltage increases quickly. This reduces the potential that has been driving the current, with a corresponding rapid decrease in charge current as depicted in Fig.5.9. As a result, even though the battery reaches partial charge quickly, obtaining a full charge requires prolonged charging. Given this
behavior, constant-voltage chargers are frequently found in applications that normally allow extended charging periods to attain full charge. Constant-voltage chargers should not be used where there is frequent cycling of the battery. *Repeated discharges without returning the cell to its full charge will eventually decrease the battery capacity and may damage individual cells.*

Constant-voltage chargers are most often used in two very different modes:

- As a fast charger to restore a high percentage of charge in a short time.
- Or as a charger to minimize the effects of overcharge on batteries having infrequent discharges as described below.

![Charge rate versus time for a typical constant-voltage charger](image)

**Fig.5.9 Charge rate versus time for a typical constant-voltage charger**

### 5.2.4.2 Float charging

Float charging is most commonly used for backup and emergency power applications where the discharge of the battery is infrequent. During float charging the charger, battery, and load are connected in parallel. The charger operates off the normal power supply, which provides current to the load during operation. In the event of normal power supply failure, the battery provides backup power until the normal power supply is restored. Since most equipment requires alternating current, a rectifier circuit is usually added between the battery and the load. Float chargers are typically constant-voltage chargers that operate at a low voltage. Operating the charger at a low voltage, usually less than about 2.4 V per cell, keeps the charging current low and thus minimizes the damaging effects of high-current overcharging.
5.2.4.3 Constant-current charging

Constant-current charging simply means that the charger supplies a relatively uniform current, regardless of the Battery State of charge or temperature. Constant-current charging helps eliminate imbalances of cells and batteries connected in series. Single-rate, constant-current chargers are most appropriate for cyclic operation where a battery is often required to obtain a full charge overnight. At these high rates of charge there will be some venting of gases. Positive grid oxidation will occur at elevated temperatures or extended overcharge times. Normally the user of a cyclic application is instructed to remove the battery from a single-rate constant-current charger within a period of time that permits full charge yet prevents excessive grid oxidation.

Another type of constant-current charger is the split-rate charger. A split-rate charger applies a high initial current to the cell and then switches to a low rate based on time of charge, voltage, or both.

5.2.4.4 Trickle charge

A trickle charge is a continuous constant-current charge at a low (about C/100) rate, which is used to maintain the battery in a fully charged condition. Trickle charging is used to recharge a battery for losses from self-discharge as well as to restore the energy discharged during intermittent use of the battery. This method is typically used for automotive (or SLI) and similar type batteries when the battery is removed from the vehicle or its regular source of charging. Trickle charging is also used widely for portable tools and equipment such as flashlights and battery powered screwdrivers.

5.2.4.5 Simple circuit charges lead-acid batteries

The circuit shown in Fig.5.10 charges lead-acid batteries in the conventional way: A current-limited power supply maintains a constant voltage across the battery (2.4V/cell or so, as specified by the battery manufacturer) until the charging current decreases below a current threshold defined by the capacity of the battery. At this point, the charger is placed in a trickle-charge mode. The
current threshold is typically 0.01C, where C refers to the battery capacity, which is specified in ampere-hours. When charging a battery, the term "C rate" refers to the current required, in theory, to charge a battery to its full battery capacity C in one hour. In actuality, power lost during the charge cycle ensures that all batteries charged at their C rate take more than an hour to reach full charge. Ideally, you could charge a 5A-hr battery in one hour if the charge current is 5A. Also, ideally, a C/10 charge rate (500mA) charges the same battery in 10 hours. However, the power loss mentioned previously increases these charge times beyond the two time spans stated above.

The charging voltage involves a trade-off between cell life and charging time. High voltage minimizes the time required, but at full charge it produces a large overcharging current that shortens the battery's life by oxidizing its grid. To save battery life at the expense of charging time, you can lower this current by decreasing the charging voltage. The ideal compromise is to charge at high voltage until the current drops to 0.01C or so and then lower the voltage to maintain a low trickle-charge current (<0.001C) after the battery is fully charged.

5.2.5 Indications of a fully-charged cell

The indications of a fully charged cell are (i) gassing, (ii) voltage, and (iii) specific gravity.

i) Gassing. When the cell is fully charged, it freely gives off hydrogen at cathode and oxygen at the anode. Gassing at both plates indicates that the current is no longer doing any useful work and hence should be stopped.

ii) Voltage. The voltage ceases to rise when the cell becomes fully charged.

iii) Specific gravity of the electrolyte. The specific gravity when the cell is fully charged is 1.21 as being measured by a float called hydrometer.
5.2 Lead-Acid Batteries

Fig. 5.10 This lead-acid-battery charger applies high voltage (15V) until the battery is charged and then applies 13.8V to maintain a small trickle charge

5.2.6 Maintenance of lead-acid batteries

Proper maintenance will prolong the life of a battery and will aid in assuring that it is capable of satisfying its design requirements. Flooded lead-acid batteries can function for 10 years or longer if properly maintained. The six general rules of proper maintenance are:

5.2.6.1 Matching the Charger to Battery Requirements

In general, lead-acid batteries may be recharged at any rate that does not produce excessive gassing, overcharge, or high temperatures. Discharged batteries may be recharged at a high current initially. However, once the battery approaches its full charge the current must be decreased to reduce gassing and excessive overcharging.
5.2.6.2 Avoiding Over discharge

In order to obtain maximum life from lead-acid batteries, they should be disconnected from the load once they have discharged their full capacity. The cutoff voltage of a lead-acid cell is usually around 1.75 V. However, the cutoff voltage is very sensitive to operating temperature and discharge rate. Like batteries discharged at a high rate will have a lower cutoff voltage than those discharged at a low rate. Greater capacities are obtained at higher temperatures and low discharge rates. The manufacturer should specify cutoff voltages for various operating temperatures and discharge rates.

Over discharge may cause difficulties in recharging the cell by increasing the battery's internal resistance. Also, over discharging may cause lead to be precipitated in the separator and cause a short in the cell or between cells.

5.2.6.3 Maintaining Electrolyte Levels

During normal operation, water is lost from a flooded lead-acid battery as a result of evaporation and electrolysis into hydrogen and oxygen, which escape into the atmosphere. One Faraday of overcharge will result in a loss of about 18g of water. Evaporation is a relatively small part of the loss except in very hot, dry climates. It is important that the electrolyte be maintained at the proper level in the battery. Only distilled water should be added to batteries. Overfilling must be avoided because the resultant overflow of acid electrolyte will cause tray corrosion, ground paths, and loss of cell capacity.

5.2.6.4 Cleaning

Keeping the battery clean will minimize corrosion of cell post connectors and steel trays and avoid expensive repairs. Batteries commonly pick up dry dirt, which can be readily blown off or brushed away. This dirt should be removed before moisture makes it a conductor of stray currents. The top of the battery can become wet with electrolyte any time a cell is overfilled. The acid in this electrolyte does not evaporate and should be neutralized by washing the battery with a solution of baking soda and hot water, approximately 1 kg of
baking soda to 4 L of water. After application of such a solution, the area should be rinsed thoroughly with water.

**Example 5.2:**
A discharged lead-acid battery is charged at 8 A for 2 hours after which it is charged through a resistor of R ohms. If discharge period is 6 hours and the terminal voltage remains fixed at 12 V, find the value of R assuming the Ah efficiency of the battery as 80%.

**Solution 5.2:**
Ah input = 8 × 2 = 16
Ah output = 16 × 0.8 = 12.8

Discharge current = \( \frac{12.8}{6} = 2.133 \) A

\[
R = \frac{12}{2.133} = 5.63 \Omega
\]

**Example 5.3:**
Six cells, 12-V lead-acid battery, with negligible internal resistance, is to be charged at a constant rate of 10 A from a 24-V DC supply. If the e.m.f of each cell at the beginning and end of the charge is 1.9 V and 2.4 V, what should be the value of maximum and minimum resistance to be connected in series with the battery.

**Solution 5.3:**
*Beginning of Charge:* Total back e.m.f. of battery = 6 × 1.9 = 11.4 volt

\[
\therefore \text{Net driving voltage} = 24 - 11.4 = 12.6 \text{ V}
\]

\[
R_{\text{max}} = \frac{12.6}{10} = 1.26 \Omega
\]

*End of Charging:* Back e.m.f. of battery = 6 × 2.4 = 14.4 volt

Net driving voltage = 24 - 14.4 = 9.6 V

\[
R_{\text{min}} = \frac{9.6}{10} = 0.96 \Omega
\]
**Example 5.4:**
A lead-acid battery of 60 cells is charged from a supply of 250 V. Each cell has an e.m.f. of 2 volts at the start of charge and 2.5 V at the end. If internal resistance of each cell is 0.1 Ω and if there is an external resistance of 19 Ω in the circuit, calculate (a) the initial charging current (b) the final charging current and (c) the additional resistance which must be added to give a finishing charge rate of 2 A.

**Solution 5.4:**
Supply voltage \( V = 250 \text{ V} \)

Back e.m.f of the battery \( E_b \) at start = \( 60 \times 2 = 120 \text{ V} \)

And at the end = \( 60 \times 2.5 = 150 \text{ V} \)

Internal resistance of the battery = \( 60 \times 0.1 = 6 \text{ Ω} \)

Total circuit resistance = \( 19 + 6 = 25 \text{ Ω} \)

Net charging voltage at start = \( 250 - 120 = 130 \text{ V} \)

Initial charging current = \( \frac{130}{25} = 5.2 \text{ A} \)

Final charging current = \( \frac{100}{25} = 4 \text{ A} \)

Let \( R \) be the external resistance, then \( 2 = \frac{100}{R+6} \) which yields \( R = \frac{88}{2} = 44 \text{ Ω} \)

Additional resistance required = \( 44 - 19 = 25 \text{ Ω} \)

**Example 5.5:**
A car battery has a storage capacity of 80-Ah at 12-V. Neglecting losses, how many of these batteries would be needed to supply a residential load of 5 kW for 24 hours?

**Solution 5.5:**
The energy demanded is \( 5 \text{ kW} \times 24 \text{ h} = 120 \text{ kWh} \).

The energy stored in one battery = \( 80 \text{ Ah} \times 12 \text{ V} = 960 \text{ Wh} \).

The number of batteries required = \( \frac{120 \times 10^3}{960} = 125 \)
5.3 NICKEL-CADMIUM BATTERIES

A number of secondary, i.e. rechargeable, alkaline batteries or cells incorporate cadmium as an active electrode material. The most important and best known of these is the nickel-cadmium cell which is based on the reversible electrochemical reactions of cadmium and nickel in a potassium hydroxide (alkaline) electrolyte.

5.3.1 Historical Background

The era of battery invention had started in 1798, when the Italian physicists Count Alessandro Volta build his first "Voltaic Pile". The crude battery consists of a stack of paired copper zinc discs separated from one another by cardboard discs moistened with salt or acid solution. However, the German scientist Dr. Carl Gassner introduced the first dry cell, a cell much like today's carbon-zinc batteries, in 1888. The Energizer Company developed the first commercially viable alkaline batteries, revolutionizing portable alkaline cell, in 1959. The first miniature nickel cadmium rechargeable battery system was then introduced in 1960 for use in hearing aids and watches. The wheels of history continue its running until 1992, when Energizer introduces the world's first AA lithium battery—the world's most powerful AA battery.

5.3.1.1 Nickel-Cadmium rechargeable batteries are vital in daily life: Why?

These batteries are essential in many portable and industrial applications. These include consumer applications as power tools, personal computers, cellular phones, household appliances, etc., for which demand is constantly increasing, and industrial uses as in aircraft and railroad.

They are safe and recyclable and, alongside the development of other battery couples, Ni-Cd batteries continue to provide unique benefits for specific applications.
It is thanks to Ni-Cd batteries that the electric car has developed significantly in Europe and that many other types of electric vehicles will continue to be developed in the future.

This is simply because nickel-cadmium battery technology offers the best combination of power, energy, cycle life and cost of all existing electric vehicle batteries.

5.3.2 Ni-Cd Battery Components and Operation

With prismatic-type Nickel-Cadmium batteries, the detailed construction include (see Fig. 5.11):

i) Cell containers (or case) are made of nickel-plated steel.

ii) Active material, nickel hydroxide (positive or anode) and cadmium oxide (negative or cathode), are encased in finely perforated steel pockets.

iii) Plate separators are inserted to keep the cathode from touching the anode.

iv) Positive and negative plates are welded or bolted to heavy steel bus bars. Plate groups are interleaved and are separated by thin plastic rods.

v) The alkaline electrolyte is a solution of potassium hydroxide.

The active materials are converted on charging and discharging in accordance with the chemical reaction which may be written as follows:

\[
2\text{Ni(OH)}_3 + \text{Cd} \leftrightarrow \text{Charge/Discharge} \rightarrow 2\text{Ni(OH)}_2 + \text{Cd(OH)}_2
\]  

(5.9)

The system stores chemical energy when the battery is charged, and this chemical energy is converted back to electrical energy on discharge. *Reversibility* of the reaction under extreme environmental conditions is one of the outstanding properties of the Ni-Cd electrochemical system.

5.3.3 Advantages of Nickel-Cadmium Batteries

i) *Constant-voltage source.* Close voltage regulation during discharge.

ii) *Rapid-charge acceptance.* Can be completely recharged at high rates without damage.
iii) *Long life.* Designed to give exceptionally long life under cycle and float service.

iv) *Extreme-temperature operation.* Normal and high-rate discharge and charge possible at temperatures from –40 to + 165°F (–40 to + 74°C).

v) *Excellent charge retention.* Charged cells filled with electrolyte retain approximately 70 percent of their charge after 1 year of idle storage at normal temperature.

vi) *Storage ability.* Can be laid up in any state of charge for long periods without attention or fear of deterioration.

vii) *Discharge in any position.* Can be discharged in any position.

viii) *Easy maintenance.* Negligible loss of water during service. Records of specific gravity are not necessary.

ix) *Small size and light weight.* Nicad sintered plate batteries are smaller and lighter than conventional batteries under high current drain conditions.

---

**Fig.5.11 Cutaway view of a nickel-cadmium battery**
Chapter 5: Storage Batteries & Fuel Cells

5.3.4 Applications of Ni-Cd-type Batteries

These applications are principally of two types industrial and portable batteries.

5.3.4.1 Industrial nickel-cadmium batteries

Nickel-cadmium batteries for industrial uses are of the vented (or open) or semi-sealed type. Applications for industrial batteries include railway uses such as locomotive starting, emergency braking, coach lighting and air conditioning, track-side power for signaling and warning lights and others. Other uses include standby power for alarm systems, emergency lighting, military communications, solar energy storage, navigation equipment, military equipment, hospital operating theatres and many others. Semi-sealed industrial batteries are used in aeronautical applications where they are used to start engines and also to provide stand-by power for aircraft systems when the principal power source fails. After long periods of operation most vented or semi-sealed cells may require electrolyte maintenance by topping up with distilled water.

5.3.4.2 Portable nickel-cadmium batteries

Nickel-cadmium batteries for portable use are of the sealed type. They may be of cylindrical, button or prismatic design. Sealed nickel-cadmium batteries are in strong demand for use in consumer electronic equipment such as cellular telephones, portable tools, toys, camcorders and other domestic cordless appliances. They are also used for memory back up in computing equipment, military and civil communications, emergency lighting and many other similar applications. Sealed cells require no maintenance and may be recharged up to 2000 times.
5.3.5 Nickel-Metal Hydride (Ni-MH)

Battery designers have investigated several other types of metals that could be used instead of cadmium to create high-energy secondary batteries that are compact and inexpensive. The nickel-metal-hydride cell is a widely used alternative.

The anode of a Ni-MH cell is made of a hydrogen storage metal alloy, the cathode is made of nickel oxide, and the electrolyte is a potassium hydroxide solution.

According to one manufacturer, Ni-MH cells can last 40% longer than the same size Ni-Cd cells and will have a life span of up to 600 cycles. This makes them useful for high-energy devices such as laptop computers, cellular phones, and camcorders. Ni-MH batteries have a high self-discharge rate and are relatively expensive to purchase.

5.4 ZINC-CARBON (Z-C) DRY-TYPE BATTERIES

Zinc-carbon cells are widely used "Household" batteries because of their relatively low cost. Household batteries are those batteries that are primarily used to power small, portable devices such as flashlights, radios, laptop computers, toys, and cellular phones.

5.4.1 Z-C Components

Zinc-carbon cell (Fig.5.12) is composed of

i) Container. The outer protective casing of the battery is made of zinc.

ii) Cathode. Manganese dioxide and carbon mixture is molded to the inside walls of the container.

iii) Anode. Powered zinc metal anodes are the electrodes that are oxidized.

iv) Separator. Separator paper insulation is inserted to keep the cathode from touching the anode.

v) Electrolyte. A saturated solution of ammonium chloride in addition to zinc chloride is used as the electrolyte.
Fig. 5.12 Cross-section of a zinc chloride cell (D-size)

5.4.2 Disadvantages of Z-C Battery

Notable drawbacks to these kinds of batteries are that

i) Zinc-carbon cells are not rechargeable and they have a sloping discharge curve (i.e., the voltage level decreases relative to the amount of discharge).

ii) The outer, protective casing of the battery is made of zinc. The casing serves as the anode for the cell and, in some cases, if the anode does not oxidize evenly, the casing can develop holes that allow leakage of the mildly acidic electrolyte, which can damage the device being powered.

iii) When nickel-zinc cells are recharged, the zinc does not redeposit in the same "holes" on the anode that was created during discharge. Instead, the zinc re-deposits in a somewhat random fashion, causing the electrode to become misshapen. Over time, this leads to the physical weakening and eventual failure of the electrode.
5.5 LITHIUM BATTERIES

Lithium is a promising reactant in battery technology, due to its high electronegativity. The specific energy of some lithium-based cells can be five times greater than an equivalent-sized lead-acid cell and three times greater than alkaline batteries. Lithium cells will often have a starting voltage of 3.0 V. These characteristics translate into batteries that are lighter in weight, have lower per-use costs, and have higher and more stable voltage profiles.

The chemical reaction in one kind of lithium cell is

\[
\text{Li} + \text{MnO}_2 \xrightarrow{\text{Charge}} \text{LiMnO}_2 \quad \text{(5.10)}
\]

One company now produces secondary lithium-ion batteries with a voltage of 3.7 V, "four times the energy density of Ni-Cd batteries," "one-fifth the weight of Ni-Cd batteries," and can be recharged 500 times.

Figure 5.13 shows a detailed construction of Lithium-manganese dioxide cell.

![Fig.5.13 Construction of a Lithium-manganese dioxide cell](image-url)
5.6 STATIC UPS SYSTEMS

5.6.1 Power Your Lifeline

In the Digital Age, the need for reliable, clean, and high-quality power supply has never been greater. For example, consider that your company depends on electronic commerce as a bond to your customers for sales orders, customer inquiries and technical questions. Imagine the power goes out. Suddenly you are cutoff from your lifeline (the power), drowning without a lifeboat. This is just one of many scenarios that disastrous power outages produce without proper electrical protection.

A static UPS system is a circuit which ensures a continuous power supply to the load irrespective of outages, spikes, brownouts, or other disturbances from the normal incoming mains supply. It is achieved by using solid-state circuitry which employs a battery or possibly kinetic energy as the alternative energy source. On the market today on-line and stand-by UPS’s are considered as premium power conditioners that provide:

i) Continuity of power-supply.

ii) High quality of power supply that retains tight voltage regulation and great common mode noise attenuation.

iii) Low maintenance requirements.

5.6.2 Background

The development of static UPS clearly was dependent on the availability of solid-state switching devices. The earliest conversion systems available in 1960 for dc to ac were no more than mechanical vibrators with ratings no higher than 500 VA used for radio/communications applications. The advent of power transistors enabled the first true static inverters to be built, applications in the early years being communication and instrumentation. Thyristors then became available and, gradually, ratings of modules increased. It should be remembered in these early days that switching devices suffered from wandering
characteristics due to operating temperature and aging. In time these problems were solved. By approximately 1960 computers began to require UPS systems.

From inception to today’s designs we have seen dramatic improvements, efficiency originally at 80 to 81 percent compares with claimed efficiencies of up to 98 percent for present designs. The size of systems also has reduced considerably; modern designs are now some 60 percent less in proportion. Maintenance costs are much reduced and reliability figures now quoted are some 10 years mean time between failures for a single module. Note this figure does not allow for battery reliability. Figures for a multimodule parallel redundant system are subject to variations and circuit complexity, but as a guide 20 years is achievable.

5.6.3 UPS System Configuration

Generally, static UPS systems are classified into three modes of operations:

i) **Standby (or Off-line) UPS.**

ii) **On-line UPS.**

5.6.3.1 Stand-by (or Off-line) static UPS

Figure 5.14 shows a typical configuration of a standby UPS using single conversion topology.

i) **Normal mode of operation.** In this design, the normal line power from utility grid is used to supply equipment.

ii) **Emergency mode of operation.** If the incoming AC-power fails, a transfer switch, after a brief delay up to 4 milliseconds, transforms the load to the battery-backed inverter. During the 4 milliseconds transfer time, however, data can be lost or corrupted and files may be damaged. Most modern computer equipment can sustain a power switch time of up to 300ms, but some older equipment may shut down during the transfer time.

iii) **Efficiency.** A standby UPS system does not provide any transient protection, power harmonic cancellation or voltage regulation.
5.6.3.2  On-line UPS system

Figure 5.15 shows a typical configuration of an on-line UPS using double conversion topology.

i)  Normal mode of operation. In this design, the critical-type loads (e.g. sensitive electronic measurement equipment, medical applications, and true mission-critical computing or networking hardware) are always fed through the UPS. The incoming AC-power from utility grid is rectified into DC-power, which charges a bank of batteries. This DC-power is
then inverted back into AC-power to feed the load (i.e. double conversion topology).

ii) *Emergency mode of operation.* If the incoming AC-power fails, the inverter is fed from the batteries and continues to supply the load.

iii) *Efficiency.* An on-line UPS system provides very high isolation of the critical load from all power line disturbances, improves user-end power factor, and cancels out power system harmonics.

### 5.6.3.3 On-line UPS vs. Standby UPS

- An on-line UPS has no transfer time because the inverter continuously supplies battery power to the load whether the main power is active or not.
- An off-line UPS is inherently more cost effective than an on-line because the inverter is off most of the time.
- When switching from main power to battery power, known as transfer time, an off-line UPS stops providing power to equipment for a few milliseconds (typically up to 4ms).

### 5.6.4 Elements of UPS system

Each U.P.S. system, as a minimum, shall consist of the following major components:

#### 5.6.4.1 AC Rectifier / Charger

Incoming AC power shall be converted to regulated DC output by the rectifier/charger. The rectifier/charger shall be a constant potential, phase controlled, (6-pulse) solid-state type with voltage and current control circuitry. The components within the rectifier shall be capable of operating independently from the remaining system.

#### 5.6.4.2 Static Inverter

The static inverter shall be a Ferro-resonant type, which generates single-phase AC power. The inverter shall be capable of providing continuous and
uninterruptible output power while operating from any DC source within the operating input range. The inverter bridge shall use power transistors, and Insulated Gate Bipolar Transistors, (IGBTs) to generate the square wave input for the Ferro-resonant transformer.

### 5.6.4.3 Static Transfer Switch (Zero Breaks).

The static switch shall be a naturally commutated, high-speed transfer device provided as an integral part of the U.P.S. The control of the unit shall provide an automatic or manual uninterrupted transfer of the load to the bypass.

The Static switch shall automatically transfer the critical load after the control logic senses inverter system disturbances (e.g. inverter failure, inverter over-current, and inverter over-voltage/under-voltage) or low DC disconnects. The control circuit shall be capable of re-transferring the critical load to the inverter output when the system disturbance is removed and the inverter output is within specification.

The transfer logic shall not allow a transfer to the bypass source if one of the following conditions exist: bypass source out of sync with inverter output or bypass source not available.

### 5.6.4.4 Manual Bypass Switch.

A manually operated 2-position electro-mechanical bypass switch shall be provided to facilitate system maintenance. In the bypass position, this switch and the static switch input breaker shall isolate the static switch from the bypass source and connect the output directly to the bypass power source.

### 5.6.4.5 Battery Bank

Modular steel tray design can be used to assemble rechargeable-type battery bank (see Fig.5.16b).
5.6.5 UPS System Applications

They are incorporated into supply system for data-processing equipment, process control, power-network supervisory systems, medical equipment, and operational centers of police forces and fire departments, radio relay stations and particularly important manufacturing plant.

(a) A continuous duty, solid-state, on-line, 3-50 KVA-single phase UPS

(b) Modular Steel Tray
- Meets Zone 4 seismic requirements
- Stacked eight rechargeable lead-acid batteries.

(c) Portable-type power station (UPS system for emergency)
- 180 W, 12 V DC input, and 220 V AC-output.

Fig. 5.16 UPS system modular design assembly and components
5.7 FUEL CELLS

5.7.1 What is a Fuel Cell?

A fuel cell is an electrochemical device that combines hydrogen fuel and oxygen from the air to produce electricity, heat and water. Fuel cells operate without combustion, so they are virtually pollution free. Since the fuel is converted directly to electricity, a fuel cell can operate at much higher efficiencies than internal combustion engines, extracting more electricity from the same amount of fuel. The fuel cell itself has no moving parts - making it a quiet and reliable source of power.

5.7.2 Hydrogen Fuel Cells – Basic Principles

The basic operation of the hydrogen fuel cell is extremely simple. The first demonstration of a fuel cell was by Grove in 1839, using an experiment along the lines of that shown in Figures 5.17a and 5.17b. In Figure 5.17a, water is being electrolyzed into hydrogen and oxygen by passing an electric current through it. In Figure 5.17b, the power supply has been replaced with an ammeter, and a small current is flowing. The electrolysis is being reversed – the hydrogen and oxygen are recombining, and an electric current is being produced.

Another way of looking at the fuel cell is to say that the hydrogen fuel is being “burnt” or combusted in the simple reaction: \( \text{2H}_2 + \text{O}_2 \rightarrow \text{2H}_2\text{O} \)

However, instead of heat energy being liberated, electrical energy is produced. The experiment shown in Figures 5.17a and 5.17b makes a reasonable demonstration of the basic principle of the fuel cell, but the currents produced are very small. The main reasons for the small current are

i) The low ‘contact area’ between the gas, the electrode, and the electrolyte basically just a small ring where the electrode emerges from the electrolyte.

ii) The large distance between the electrodes – the electrolyte resists the flow of electric current.
5.7 Fuel Cells

Figure 5.17 (a) The electrolysis of water. The water is separated into hydrogen and oxygen by the passage of an electric current. (b) A small current flows. The oxygen and hydrogen are recombining.

To overcome these problems, the electrodes are usually made flat, with a thin layer of electrolyte as in Figure 5.18. The structure of the electrode is porous so that both the electrolyte from one side and the gas from the other can penetrate it. This is to give the maximum possible contact between the electrode, the electrolyte, and the gas. However, to understand how the reaction between hydrogen and oxygen produces an electric current, and where the electrons come from, we need to consider the separate reactions taking place at each electrode. These important details vary for different types of fuel cells, but if we start with a cell based around an acid electrolyte, as used by Grove, we shall start with the simplest and still the most common type.
5.7.2.1 Acid electrolyte fuel cell

At the anode of an acid electrolyte fuel cell, the hydrogen gas ionizes, releasing electrons and creating $\text{H}^+$ (or protons).

$$2\text{H}_2 \rightarrow 4\text{H}^+ + 4\text{e}^- \quad (5.11)$$

This reaction releases energy. At the cathode, oxygen reacts with electrons taken from the electrode, and $\text{H}^+$ ions from the electrolyte, to form water.

$$\text{O}_2 + 4\text{e}^- + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O} \quad (5.12)$$

Clearly, for both these reactions to proceed continuously, electrons produced at the anode must pass through an electrical circuit to the cathode. Also, $\text{H}^+$ ions must pass through the electrolyte. An acid is a fluid with free $\text{H}^+$ ions, and so serves this purpose very well. Certain polymers can also be made to contain mobile $\text{H}^+$ ions. These materials are called proton exchange membranes, as an $\text{H}^+$ ion is also a proton. Comparing equations 5.11 and 5.12 we can see that two hydrogen molecules will be needed for each oxygen molecule if the system is to be kept in balance. This is shown in Figure 5.19. It should be noted that the electrolyte must only allow $\text{H}^+$ ions to pass through it, and not electrons. Otherwise, the electrons would go through the electrolyte, not a round the external circuit, and all would be lost.

**Fig.5.18**
Basic cathode–electrolyte–anode construction of a fuel cell.
Fig. 5.19 Electrode reactions and charge flow for an acid electrolyte fuel cell. Note that although the negative electrons flow from anode to cathode, the “conventional current” flows from cathode to anode.

5.7.2.2 Alkaline electrolyte fuel cell

In an **alkaline electrolyte fuel cell** the overall reaction is the same, but the reactions at each electrode are different. In an alkali, hydroxyl (OH\(^-\)) ions are available and mobile. At the anode, these react with hydrogen, releasing energy and electrons, and producing water.

\[
2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \tag{5.13}
\]

At the cathode, oxygen reacts with electrons taken from the electrode, and water in the electrolyte, forming new OH\(^-\) ions.

\[
O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \tag{5.14}
\]

For these reactions to proceed continuously, the OH\(^-\) ions must be able to pass through the electrolyte, and there must be an electrical circuit for the electrons to go from the anode to the cathode. Also, comparing equations 1.4 and 1.5 we see that, as with the acid electrolyte, twice as much hydrogen is needed as oxygen. This is shown in Figure 5.20. Note that although water is consumed at the cathode, it is created twice as fast at the anode.
Fig.5.20 Electrode reactions and charge flow for an alkaline electrolyte fuel cell. Electrons flow from anode to cathode, but conventional positive current flows from cathode to anode.

5.7.2.3 What Limits the Current?

At the anode, hydrogen reacts, releasing energy. However, just because energy is released, it does not mean that the reaction proceeds at an unlimited rate. The reaction has the “classical” energy form shown in Figure 5.21. Although energy is released, the ‘activation energy’ must be supplied to get over the “energy hill”. If the probability of a molecule having enough energy is low, then the reaction will only proceed slowly. Except at very high temperatures, this is indeed the case for fuel cell reactions.

Fig.5.21 Classical energy diagram for a simple exothermic chemical reaction
The three main ways of dealing with the slow reaction rates are
i) The use of catalysts.
ii) Raising the temperature.
iii) Increasing the electrode area.

The first two can be applied to any chemical reaction. However, the third is special to fuel cells and is very important. Clearly, the rate at which the reaction happens will be proportional to the area of the electrode. This is very important. Indeed, electrode area is such a vital issue that the performance of a fuel cell design is often quoted in terms of the current per cm$^2$.

The micro-structural design and manufacture of a fuel cell electrode is thus a very important issue for practical fuel cells. In addition to these surface area considerations, the electrodes may have to incorporate a catalyst and endure high temperatures in a corrosive environment.

5.7.3 Fuel Cell Types

5.7.3.1 Phosphoric Acid type fuel cells

This type of fuel cell is commercially available today. More than 200 fuel cell systems have been installed all over the world - in hospitals, nursing homes, hotels, office buildings, schools, utility power plants, an airport terminal, even a municipal waste dump. Phosphoric acid fuel cells generate electricity at more than 40% efficiency -- and nearly 85% of steam this fuel cell produces is used for cogeneration -- this compares to about 35% for the utility power grid in the United States. Operating temperatures are in the range of 400°F.

5.7.3.2 Proton Exchange Membrane type fuel cells

These cells operate at relatively low temperatures (about 200°F), have high power density, can vary their output quickly to meet shifts in power demand, and are suited for applications, - such as in automobiles - where quick startup is required. According to the U.S. Department of Energy, "they are the primary candidates for light-duty vehicles, for buildings, and potentially for much smaller applications such as replacements for rechargeable batteries."
proton exchange membrane is a thin plastic sheet that allows hydrogen ions to pass through it. The membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that are active catalysts. Hydrogen is fed to the anode side of the fuel cell where the catalyst encourages the hydrogen atoms to release electrons and become hydrogen ions (protons). The electrons travel in the form of an electric current that can be utilized before it returns to the cathode side of the fuel cell where oxygen has been fed. At the same time, the protons diffuse through the membrane to the cathode, where the hydrogen atom is recombined and reacted with oxygen to produce water, thus completing the overall process.

5.7.3.3 Molten Carbonate type fuel cells

Molten carbonate fuel cells promise high fuel-to-electricity efficiencies and operate at about 1,200°F. To date, molten carbonate fuel cells have been operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products. 10 kW to 2 MW molten carbonate fuel cells have been tested on a variety of fuels. Carbonate fuel cells for stationary applications have been successfully demonstrated in Japan and Italy.

5.7.3.4 Solid Oxide type fuel cells

Another highly promising fuel cell, the solid oxide fuel cell (SOFC) could be used in big, high-power applications including industrial and large-scale central electricity generating stations. Some developers also see solid oxide use in motor vehicles and are developing fuel cell auxiliary power units (APUs) with SOFCs. A solid oxide system usually uses a hard ceramic material instead of a liquid electrolyte, allowing operating temperatures to reach 1,800°F. Power generating efficiencies could reach 60%. One type of SOFC uses an array of meter-long tubes, and other variations include a compressed disc that resembles the top of a soup can. Tubular SOFC designs are closer to commercialization
5.7 Fuel Cells

and are being produced by several companies around the world. Demonstrations of tubular SOFC technology have produced as much as 220 kW.

5.7.3.5 Alkaline type fuel cells

Long used by NASA on space missions, these cells can achieve power-generating efficiencies of up to 70 percent. They use alkaline potassium hydroxide as the electrolyte. Until recently they were too costly for commercial applications, but several companies are examining ways to reduce costs and improve operating flexibility.

5.7.3.6 Direct Methanol fuel cells

These cells are similar to the PEM cells in that they both use a polymer membrane as the electrolyte. However, in the DMFC, the anode catalyst itself draws the hydrogen from the liquid methanol, eliminating the need for a fuel reformer. Efficiencies of about 40% are expected with this type of fuel cell, which would typically operate at a temperature between 120-190°F. Higher efficiencies are achieved at higher temperatures.

5.7.3.7 Regenerative Fuel Cells

Still a very young member of the fuel cell family, regenerative fuel cells would be attractive as a closed-loop form of power generation. Water is separated into hydrogen and oxygen by a solar-powered electrolyser. The hydrogen and oxygen are fed into the fuel cell, which generates electricity, heat and water. The water is then recirculated back to the solar-powered electrolyser and the process begins again. NASA and others are currently researching these types of fuel cells worldwide.

5.7.4 Fuel Cells Applications

There are many uses for fuel cells — right now, all of the major automakers are working to commercialize a fuel cell car. Fuel cells are powering buses, boats, trains, planes, scooters, and even bicycles (see Figures 5.22). There are fuel cell-powered vending machines, vacuum cleaners and highway road signs. Miniature fuel cells for cellular phones, laptop computers and portable
electronics are on their way to market. Hospitals, credit card centers, police stations, and banks are all using fuel cells to provide power to their facilities. Wastewater treatment plants and landfills are using fuel cells to convert the methane gas they produce into electricity. The possibilities are endless.

5.7.4.1 Stationary

More than 200 fuel cell systems have been installed all over the world — in hospitals, nursing homes, hotels, office buildings, schools, utility power plants, and an airport terminal, providing primary power or backup. In large-scale building systems, fuel cells can reduce facility energy service costs by 20% to 40% over conventional energy service.

5.7.4.2 Residential

Fuel cells are ideal for power generation, either connected to the electric grid to provide supplemental power and backup assurance for critical areas, or installed as a grid-independent generator for on-site service in areas that are inaccessible by power lines. Since fuel cells operate silently, they reduce noise pollution as well as air pollution and the waste heat from a fuel cell can be used to provide hot water or space heating for a home. Many of the prototypes being tested and demonstrated for residential use extract hydrogen from propane or natural gas.

5.7.4.3 Transportation

All the major automotive manufacturers have a fuel cell vehicle either in development or in testing right now — Honda, Toyota, Daimler Chrysler, GM, Ford, Hyundai, and Volkswagen — you name it. They speculate that the fuel cell vehicle will not be commercialized until at least 2004.

5.7.4.4 Portable Power

Miniature fuel cells, once available to the commercial market, will help consumers talk for up to a month on a cellular phone without recharging. Fuel cells will change the telecommuting world, powering laptops and palm pilots hours longer than batteries. Other applications for micro fuel cells include
5.7 Fuel Cells

Pagers, video recorders, portable power tools, and low power remote devices such as hearing aids, smoke detectors, burglar alarms, hotel locks and meter readers. These miniature fuel cells generally run on methanol, an inexpensive wood alcohol also used in windshield wiper fluid.

5.7.4.5 Landfill/Wastewater Treatment

Fuel cells currently operate at landfills and wastewater treatment plants across the country, proving themselves as a valid technology for reducing emissions and generating power from the methane gas they produce.

5.7.4.6 Space shuttle

Electrical power for NASA's Space Shuttle Orbiter is provided by fuel cell power plants designed, developed, and built by UTC Fuel Cells. In the Orbiter, a complement of three 12kW fuel cells produces all onboard electrical power; there are no backup batteries, and a single fuel cell is sufficient to insure safe vehicle return (see Fig.5.23). In addition, the water produced by the electrochemical reaction is used for crew drinking and spacecraft cooling.
(a) 5kW fuel cell power plant uses PEM (Proton Exchange Membrane) technology
  ➔ For homes and operating capabilities for light commercial applications.

(b) Portable-type Hydrogen fuel cell

(c) UTC Fuel Cells’ Proton Exchange Membrane (PEM) cell
  ➔ For use in transportation applications.

(d) Hydrogen source fuel cell developed by UTC & Shell Oil

Fig. 5.23 Fuel cells applications
5.7.5 Fuel Cells Benefits

i) Quiet enough to be installed indoors.

ii) Normal conversation possible right next to fuel cell.

iii) Does not require soundproofing or hearing protection unlike combustion engines (see Fig. 5.24).

iv) Converts 40 percent of available fuel to electricity (80 percent with heat recovery) compared with 20 percent conversion for traditional combustion power plants (see Fig. 5.25).

v) Reduces fuel costs and conserves natural resources

vi) Clean Emissions. Compared with traditional combustion power plants fuel cells (see Fig. 5.26):

➔ Eliminates 40,000 pounds of acid rain and smog-causing pollutants from the environment per year

➔ Reduces carbon dioxide emissions by more than 3.5 million pounds per year

Fig. 5.24 Noise reduction using fuel cells compared with combustion engines
Chapter 5: Storage Batteries & Fuel Cells

Fig. 5.25 Efficiency using fuel cells compared with combustion engines

Fig. 5.26 Fuel cell air emissions
PC25 emissions from one year of operation
5.8 PROBLEMS: CHAPTER 5

P 5.1. In a copper refinery, copper is deposited on the cathodes with a current density 0.025 A/cm². Find the time needed to deposit a layer of 1.5-cm thickness of copper on the cathode. If 0.3 V is needed to send the current through the cell, find the electrical energy required for depositing 1 kg of copper. The density of copper may be taken as 8.9 gm/cm² and the E.C.E as 0.00033 g/C

P 5.2. What are the different factors, which affect the value of the open-circuited voltage of a fully charged lead acid cell?

P 5.3. Define the following terms in storage batteries technology: (a) Ah-capacity of a cell, (b) Ah-efficiency of a cell, and (c) Wh-efficiency of a cell.

P 5.4. What are the major differences between batteries with lead-antimony and lead-calcium grids?

P 5.5. Explain briefly the different factors that affect the Ah-capacity of a lead-acid battery cell.

P 5.6. Define the specific gravity of the electrolyte in a lead-acid storage battery. What are the factors that must be taken into account in determining the specific gravity for a given lead-acid battery?

P 5.7. What are the dangers of harm that result from over discharge of a lead-acid battery?

P 5.8. Define the following concepts in the technology of charging a lead-acid storage batteries: (a) Float charge, and (b) Trickle charge.
P 5.9. Twenty-five lead-acid cells each of 200 Ah at 10-hour rate are to be fully charged at constant current for 12 hours. The Ah efficiency is 80% and the DC supply is 110 V. The e.m.f of each cell at the beginning and at the end of charge is 1.8 V and 2.6 V; respectively. Calculate the maximum and the minimum values of the external resistance necessary. Internal resistance of the cells should be neglected.

P 5.10. A discharged lead-acid battery is put on charge at 5 A for 3.5 hours at a mean charging voltage of 13.5 V. It is then discharged in 6 hours at a constant terminal voltage of 12 V through a resistance R ohms. Determine:

i) Value of R for a Ah efficiency of 85%.

ii) Wh-efficiency of the battery.

P 5.11. Explain why Nickel-Cadmium rechargeable batteries are vital in daily life? State the advantages of nickel-cadmium type batteries.

P 5.12. Show how the modern technology of Ni-MH type batteries has improved the performance of Nickel-Cadmium rechargeable batteries.

P 5.13. What are the main drawbacks of the common "Household" Zinc-carbon batteries?

P 5.14. "Lithium is a promising reactant in battery technology". Give an engineering explanation to this expression.

P 5.15. What are the necessities of using UPS systems?

P 5.16. Explain briefly with neat sketches the available on-line and standby UPS system configurations. Compare
between the two UPS systems. Enumerate practical applications for each UPS type.

P 5.17. What is a fuel cell? Explain using schematic diagram the functioning operation of a fuel cell?

P 5.18. Enumerate practical applications of fuel cell technology.