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Department of Energy
Fundamentals Handbook

ELECTRICAL SCIENCE
Module 4
Batteries

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TERMINAL OBJECTIVE

1.0 **DESCRIBE** the operating characteristics of a lead-acid battery to include methods of voltage production, state of charge, and hazards associated with storage batteries.

ENABLING OBJECTIVES

1.1 **DEFINE** the following terms as they relate to batteries and voltaic cells:
- a. Voltaic cell
- b. Battery
- c. Electrode
- d. Electrolyte
- e. Specific gravity
- f. Ampere-Hour

1.2 **STATE** the purpose of a battery.

1.3 **DESCRIBE** the operation of a simple voltaic cell.

1.4 **STATE** the chemical equation for the reaction that occurs when a lead-acid battery is being charged or discharged.

1.5 **EXPLAIN** the relationship between specific gravity and state of charge of a lead-acid battery.

1.6 **DESCRIBE** the relationship between total battery voltage and cell voltage for a series-connected battery.

1.7 **STATE** the advantage of connecting a battery in parallel with respect to current-carrying capability.

1.8 **STATE** the difference between primary and secondary cells with respect to recharge capability.

ENABLING OBJECTIVES (Cont.)

1.9 **STATE** the advantage of each of the following types of batteries:
   a. Carbon-zinc cell
   b. Alkaline cell
   c. Nickel-cadmium cell
   d. Edison cell
   e. Mercury cell

1.10 **EXPLAIN** the adverse effects of a shorted cell.

1.11 **EXPLAIN** how gas generation is minimized for a lead-acid battery.

1.12 **EXPLAIN** how heat is generated in a lead-acid battery.

BATTERY TERMINOLOGY

Batteries are used for a wide variety of services throughout technology today. To begin to study battery operation and characteristics, a few terms that are used with batteries must be understood.

EO 1.1 DEFINE the following terms as they relate to batteries and voltaic cells:
a. Voltaic cell
b. Battery
c. Electrode
d. Electrolyte
e. Specific gravity
f. Ampere-Hour

Voltaic Cell

The term *voltaic cell* is defined as a combination of materials used to convert chemical energy into electrical energy. A voltaic or chemical cell consists of two electrodes made of different types of metals or metallic compounds placed in an electrolyte solution.

Battery

A *battery* is a group of two or more connected voltaic cells.

Electrode

An *electrode* is a metallic compound, or metal, which has an abundance of electrons (negative electrode) or an abundance of positive charges (positive electrode).

Electrolyte

An *electrolyte* is a solution which is capable of conducting an electric current. The electrolyte of a cell may be a liquid or a paste. If the electrolyte is a paste, the cell is referred to as a dry cell; if the electrolyte is a solution, it is called a wet cell.

Specific Gravity

Specific gravity is defined as the ratio comparing the weight of any liquid to the weight of an equal volume of water. The specific gravity of pure water is 1.000. Lead-acid batteries use an electrolyte which contains sulfuric acid. Pure sulfuric acid has a specific gravity of 1.835, since it weighs 1.835 times as much as pure water per unit volume.

Since the electrolyte of a lead-acid battery consists of a mixture of water and sulfuric acid, the specific gravity of the electrolyte will fall between 1.000 and 1.835. Normally, the electrolyte for a battery is mixed such that the specific gravity is less than 1.350.

Specific gravity is measured with a hydrometer. A simple hydrometer consists of a glass float inside a glass tube, as shown in Figure 1. The hydrometer float is weighted at one end and sealed at both ends. A scale calibrated in specific gravity is positioned lengthwise along the body of the float. The float is placed inside the glass tube, and the fluid to be tested is drawn into the tube. As the fluid is drawn into the tube, the hydrometer float will sink to a certain level in the fluid. The extent to which the hydrometer float protrudes above the level of the fluid depends on the specific gravity of the fluid. The reading on the float scale at the surface of the fluid is the specific gravity of the fluid.

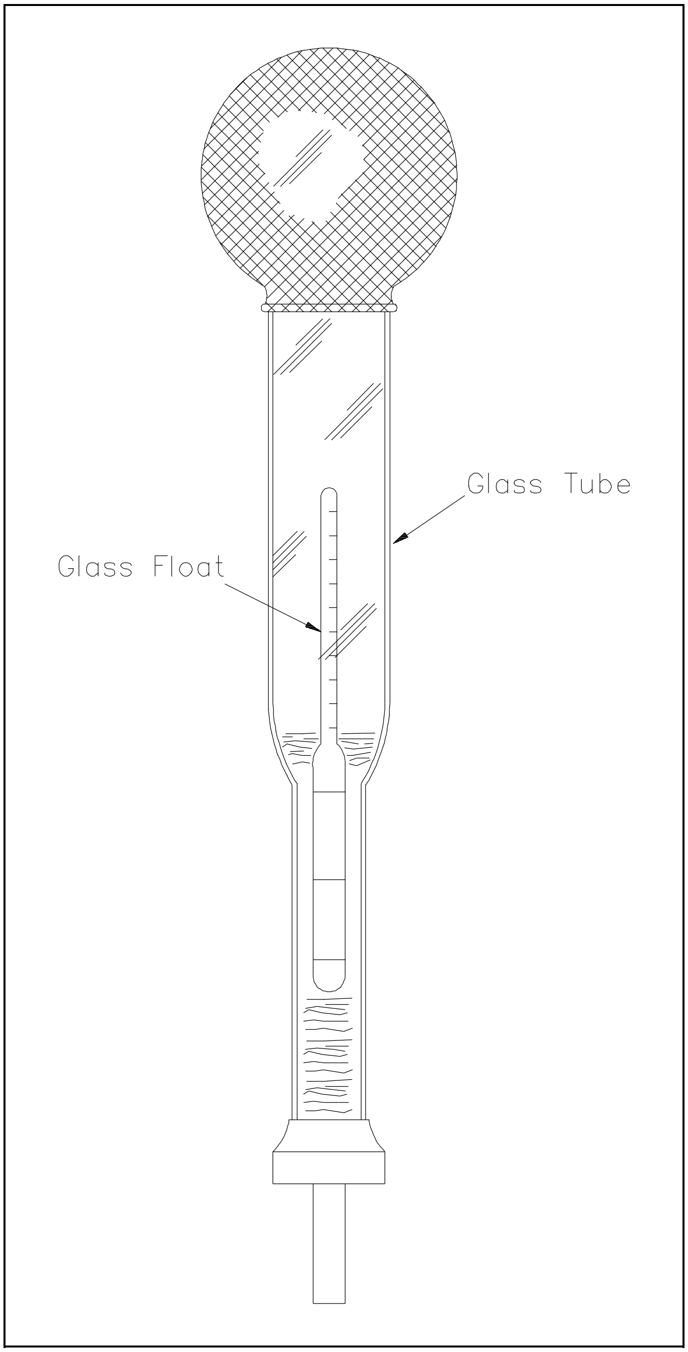

Figure 1 Simple Hydrometer

Ampere-Hour

An *ampere-hour* is defined as a current of one ampere flowing for one hour. If you multiply the current in amperes by the time of flow in hours, the result is the total number of ampere-hours. Ampere-hours are normally used to indicate the amount of energy a storage battery can deliver.

Summary

Battery terms are summarized below.

Battery Terminology Summary

- A voltaic cell is a combination of materials used to convert chemical energy into electrical energy.
- A battery is a group of two or more connected voltaic cells.
- An electrode is a metallic compound, or metal, which has an abundance of electrons (negative electrode) or an abundance of positive charges (positive electrode).
- An electrolyte is a solution which is capable of conducting an electric current.
- Specific gravity is defined as the ratio comparing the weight of any liquid to the weight of an equal volume of water.
- An ampere-hour is defined as a current of one ampere flowing for one hour.

BATTERY THEORY

A battery converts chemical energy to electrical energy. This conversion enables electrical power to be stored.

EO 1.2 STATE the purpose of a battery.

EO 1.3 DESCRIBE the operation of a simple voltaic cell.

EO 1.4 STATE the chemical equation for the reaction that occurs when a lead-acid battery is being charged or discharged.

EO 1.5 EXPLAIN the relationship between specific gravity and state of charge of a lead-acid battery.

Batteries

The purpose of a battery is to store chemical energy and to convert this chemical energy into electrical energy when the need arises.

As described in previous chapters, a chemical cell (or voltaic cell) consists of two electrodes of different types of metals or metallic compounds and an electrolyte solution which is capable of conducting an electric current.

A good example of a voltaic cell is one that contains zinc and copper electrodes. The zinc electrode contains an abundance of negatively charged atoms, and the copper electrode contains an abundance of positively charged atoms. When these electrodes are immersed in an electrolyte, chemical action begins. The zinc electrode will accumulate a much larger negative charge because it dissolves into the electrolyte. The atoms, which leave the zinc electrode, are positively charged and are attracted by the negatively charged ions of the electrolyte; the atoms repel the positively charged ions of the electrolyte toward the copper electrode (Figure 2).

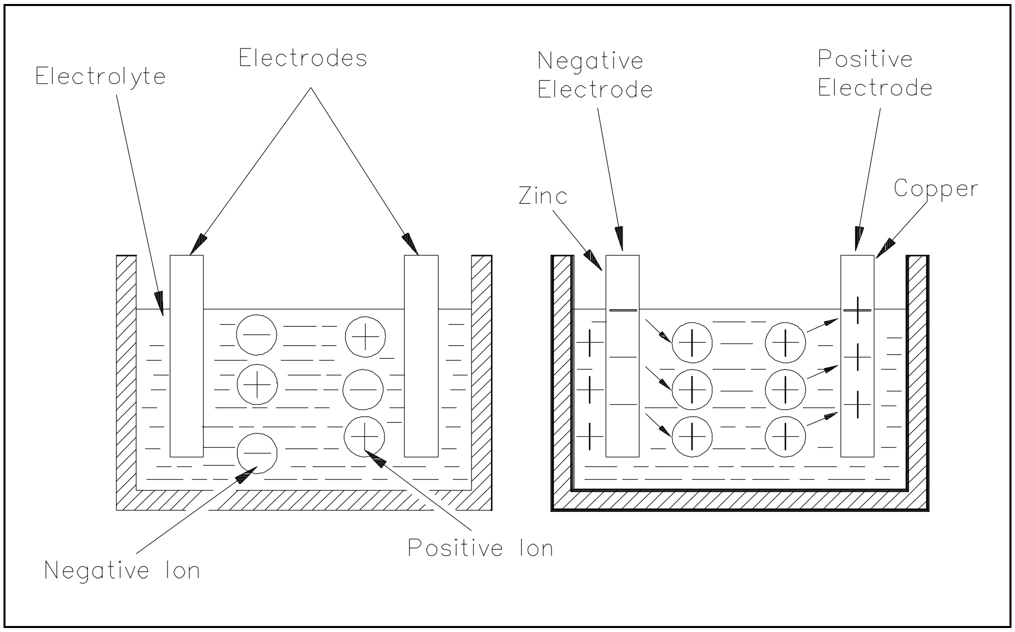

Figure 2 Basic Chemical Production of Electrical Power

This action causes electrons to be removed from the copper electrode, leaving it with an excess of positive charge. If a load is connected across the electrodes, the forces of attraction and repulsion will cause the free electrons in the negative zinc electrode to move through the connecting wire and load, and toward the positive copper electrode (Figure 3).

The potential difference that results allows the cell to function as a source of applied voltage.

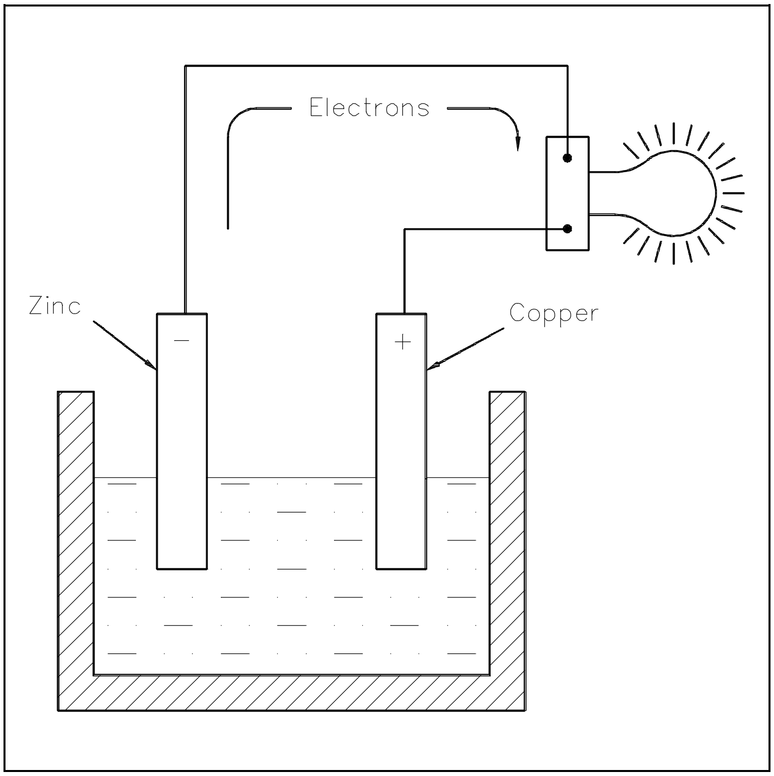

Figure 3 Electron Flow Through a Battery

Discharge and Charging of Lead-Acid Battery

In a lead-acid battery, two types of lead are acted upon electro-chemically by an electrolytic solution of diluted sulfuric acid (H_2SO_4). The positive plate consists of lead peroxide (PbO_2), and the negative plate is sponge lead (Pb), shown in Figure 4.

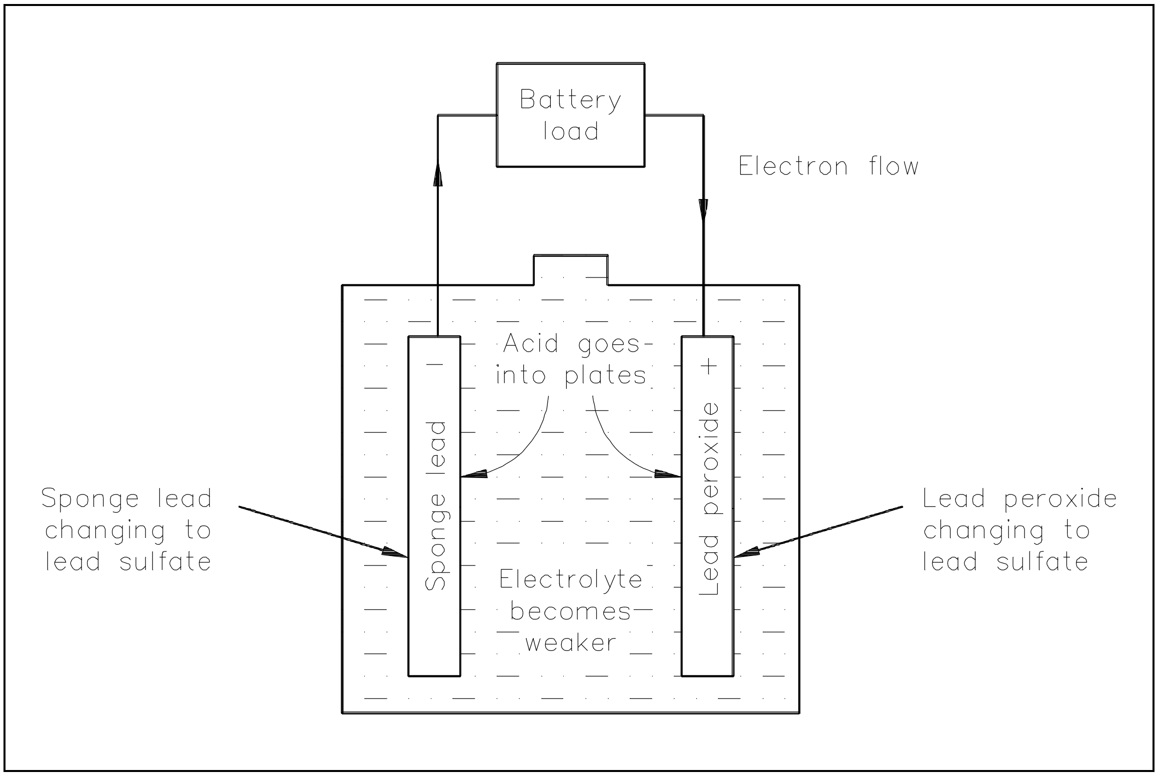

Figure 4 Chemical Action During Discharge

When a lead-acid battery is discharged, the electrolyte divides into H_2 and SO_4. The H_2 will combine with some of the oxygen that is formed on the positive plate to produce water (H_2O), and thereby reduces the amount of acid in the electrolyte. The sulfate (SO_4) combines with the lead (Pb) of both plates, forming lead sulphate ($PbSO_4$), as shown in Equation (4-1).

$$PbO_2 + Pb + 2H_2SO_4 \xrightarrow{\text{discharge}} 2PbSO_4 + 2H_2O \qquad (4\text{-}1)$$

As a lead-acid battery is charged in the reverse direction, the action described in the discharge is reversed. The lead sulphate ($PbSO_4$) is driven out and back into the electrolyte (H_2SO_4). The return of acid to the electrolyte will reduce the sulphate in the plates and increase the specific gravity. This will continue to happen until all of the acid is driven from the plates and back into the electrolyte, as shown in Equation (4-2) and Figure 5.

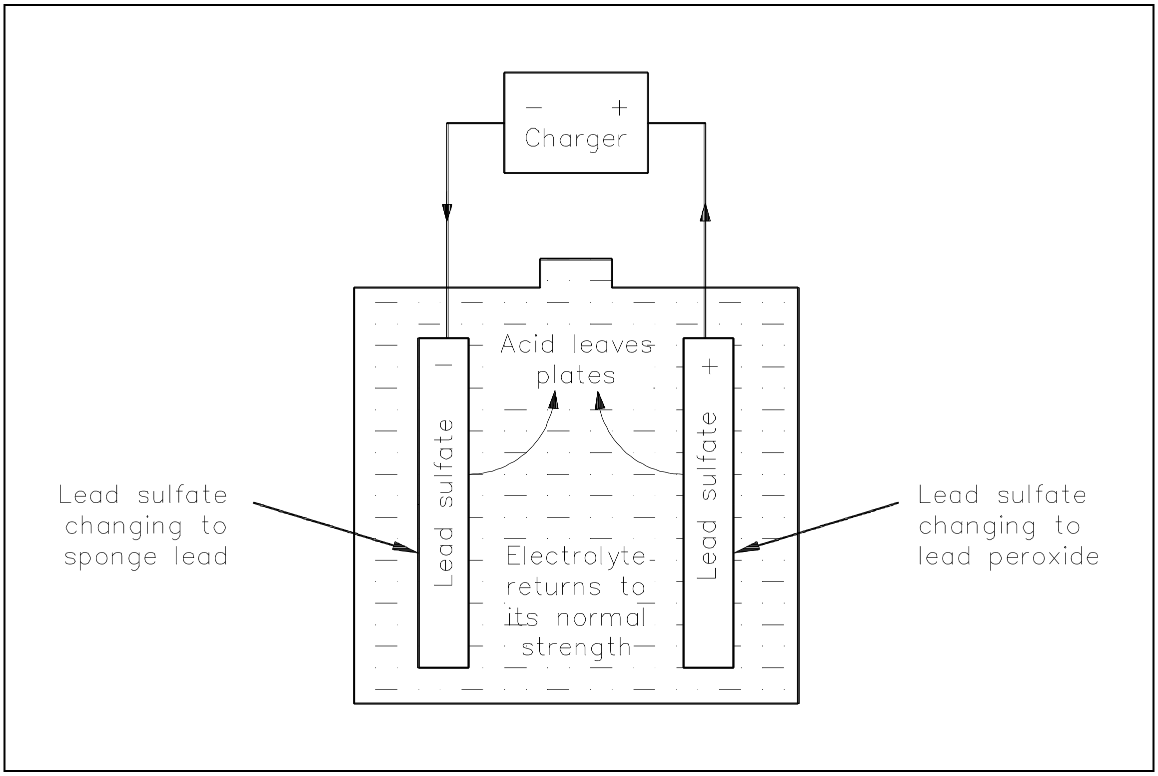

Figure 5 Chemical Action During Charging

$$PbO_2 + Pb + 2H_2SO_4 \overset{\text{charge}}{\leftarrow} 2PbSO_4 + 2H_2O \qquad (4\text{-}2)$$

As a lead-acid battery charge nears completion, hydrogen (H_2) gas is liberated at the negative plate, and oxygen (O_2) gas is liberated at the positive plate. This action occurs since the charging current is usually greater than the current necessary to reduce the remaining amount of lead sulfate on the plates. The excess current ionizes the water (H_2O) in the electrolyte. Since hydrogen is highly explosive, it is necessary to provide adequate ventilation to the battery whenever charging is in progress. Also, no smoking, electric sparks, or open flames are allowed near a charging battery.

The decrease in specific gravity on discharge is proportional to the ampere-hours discharged. While charging a lead-acid battery, the rise in specific gravity is not uniform, or proportional, to the amount of ampere-hours charged (Figure 6).

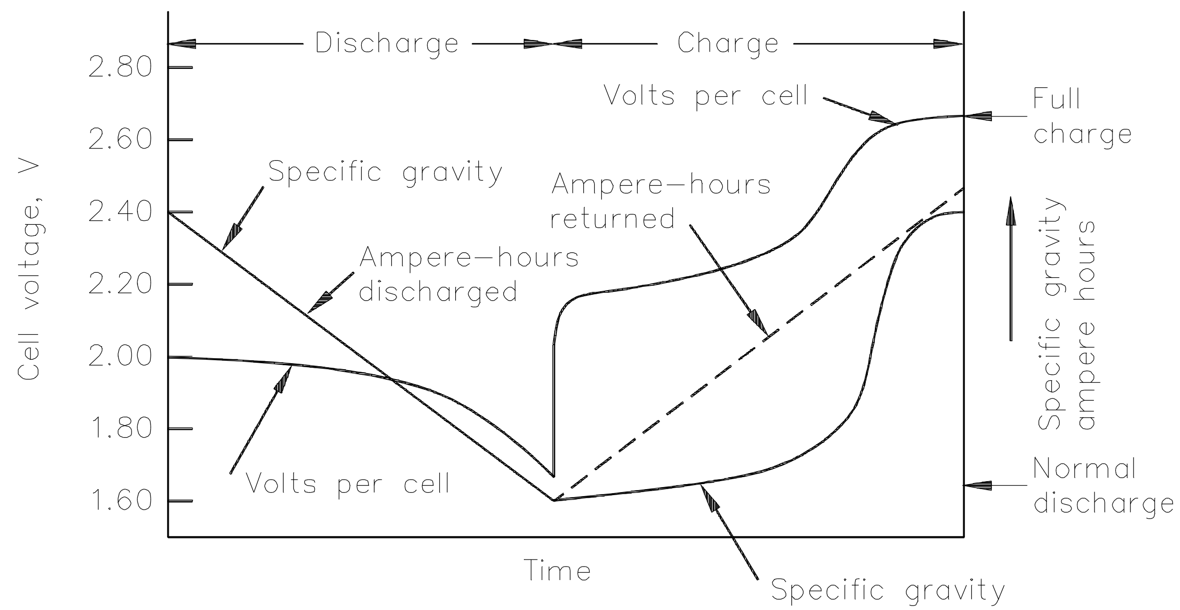

Figure 6 Voltage and Specific Gravity During Charge and Discharge

The electrolyte in a lead-acid battery plays a direct role in the chemical reaction. The specific gravity decreases as the battery discharges and increases to its normal, original value as it is charged. Since specific gravity of a lead-acid battery decreases proportionally during discharge, the value of specific gravity at any given time is an approximate indication of the battery's state of charge. To determine the state of charge, compare the specific gravity, as read using a hydrometer, with the full charge value and the manufacturer's published specific gravity drop, which is the decrease from full to nominal charge value.

Example: A lead-acid battery reads 1.175 specific gravity. Its average full charge specific gravity is 1.260 and has a normal gravity drop of 120 points (or.120) at an 8 hour discharge rate.

Solution:

Fully charged - 1.260
Present charge - 1.175

The battery is 85 points below its fully charged state. It is therefore about 85/120, or 71%, discharged.

Summary

Battery theory is summarized below.

Battery Theory Summary

- The purpose of a battery is to store chemical energy and to convert this chemical energy into electrical energy when the need arises.
- A voltaic cell develops a potential difference when electrodes of two different metals are immersed in an electrolyte. One electrode accumulates a positive charge. The potential difference is due to the difference in charge between the two electrodes.
- The chemical equation for a lead-acid battery during discharge is:

$$PbO_2 + Pb + 2H_2SO_4 \xrightarrow{\text{discharge}} 2PbSO_4 + 2H_2O.$$

- The chemical equation for a lead-acid battery during charge is:

$$PbO_2 + Pb + 2H_2SO_4 \xleftarrow{\text{charge}} 2PbSO_4 + 2H_2O.$$

- When a lead-acid battery is discharged, electrolyte and the active material on the plates of the battery are consumed to produce water and lead sulphate.
- When a lead-acid battery is charged, electrical energy is added to the battery, causing the water and lead sulphate to be consumed and produce electrolyte and active material.
- Since specific gravity of a lead-acid battery decreases proportionally during discharge, the value of specific gravity at any given time is an approximate indication of the battery's state of charge.

BATTERY OPERATIONS

Once the basic theory behind the operation of batteries is understood, we can apply these concepts to better understand the way batteries are utilized.

EO 1.6 DESCRIBE the relationship between total battery voltage and cell voltage for a series-connected battery.

EO 1.7 STATE the advantage of connecting a battery in parallel with respect to current-carrying capability.

EO 1.8 STATE the difference between primary and secondary cells with respect to recharge capability.

Series Cells

When several cells are connected in series (Figure 7), the total voltage output of the battery is equal to the sum of the individual cell voltages. In the example of the battery in Figure 7, the four 1.5V cells provide a total of 6 volts. When we connect cells in series, the positive terminal of one cell is connected to the negative terminal of the next cell. The current flow through a battery connected in series is the same as for one cell.

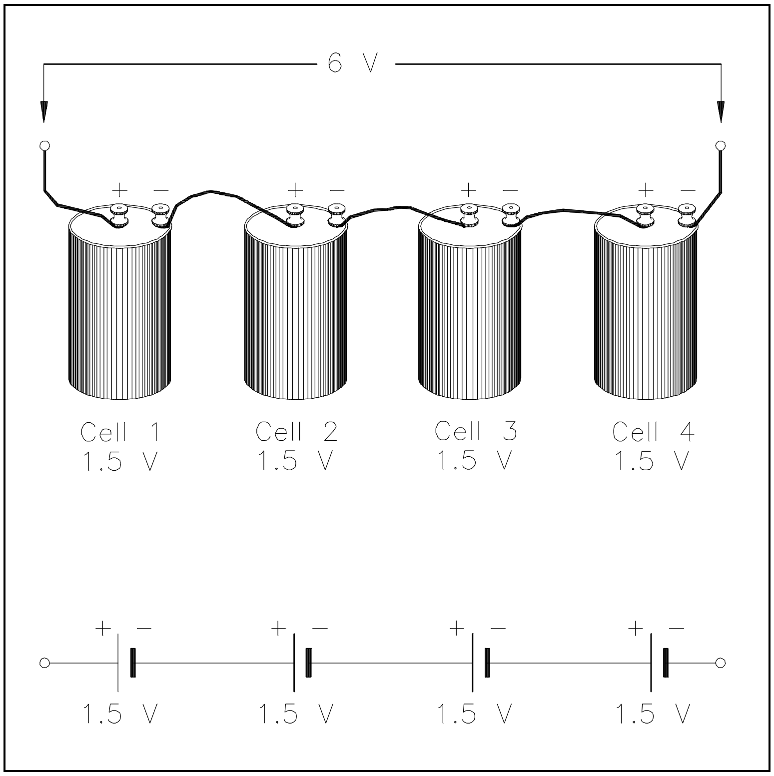

Figure 7 Cells Connected in Series

Parallel Cells

Cells connected in parallel (Figure 8), give the battery a greater current capacity. When cells are connected in parallel, all the positive terminals are connected together, and all the negative terminals are connected together. The total voltage output of a battery connected in parallel is the same as that of a single cell. Cells connected in parallel have the same effect as increasing the size of the electrodes and electrolyte in a single cell. The advantage of connecting cells in parallel is that it will increase the current-carrying capability of the battery.

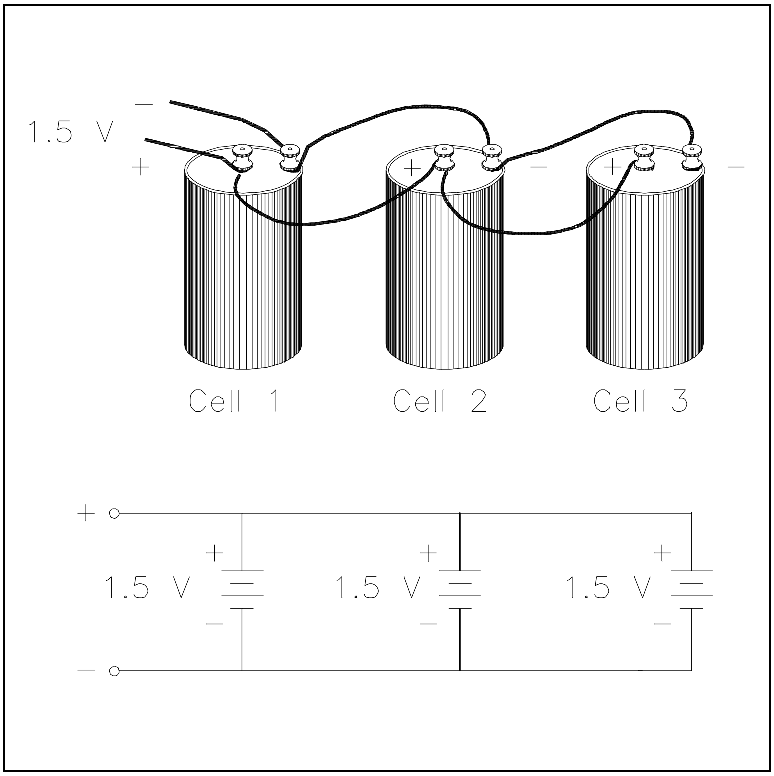

Figure 8 Cells Connected in Parallel

Primary Cell

Cells that cannot be returned to good condition, or recharged after their voltage output has dropped to a value that is not usable, are called *primary cells*. Dry cells that are used in flashlights and transistor radios (e.g., AA cells, C cells) are examples of primary cells.

Secondary Cells

Cells that can be recharged to nearly their original condition are called *secondary cells*. The most common example of a secondary, or rechargeable cell, is the lead-acid automobile battery.

Capacity

The capacity of a storage battery determines how long the storage battery will operate at a certain discharge rate and is rated in ampere-hours. For example, a 120 ampere-hour battery must be recharged after 12 hours if the discharge rate is 10 amps.

Internal Resistance

Internal resistance in a chemical cell is due mainly to the resistance of the electrolyte between electrodes (Figure 9).

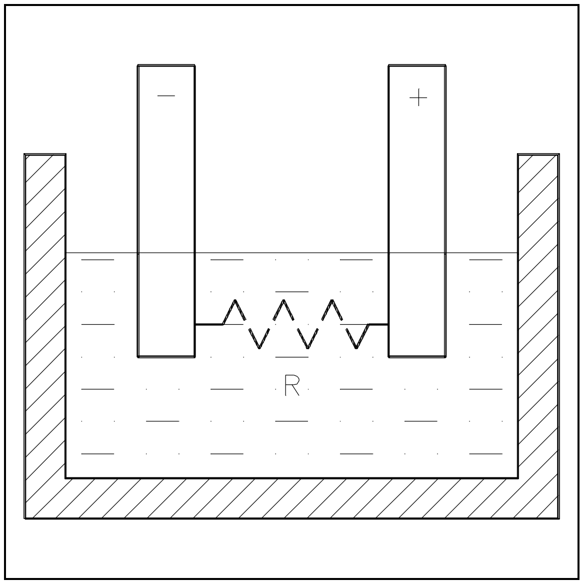

Figure 9 Internal Resistance in a Chemical Cell

Any current in the battery must flow through the internal resistance. The internal resistance is in series with the voltage of the battery, causing an internal voltage drop (Figure 10).

With no current flow, the voltage drop is zero; thus, the full battery voltage is developed across the output terminals (V_B). If a load is placed on the battery, load resistance (R_L) is in series with internal resistance (R_i).

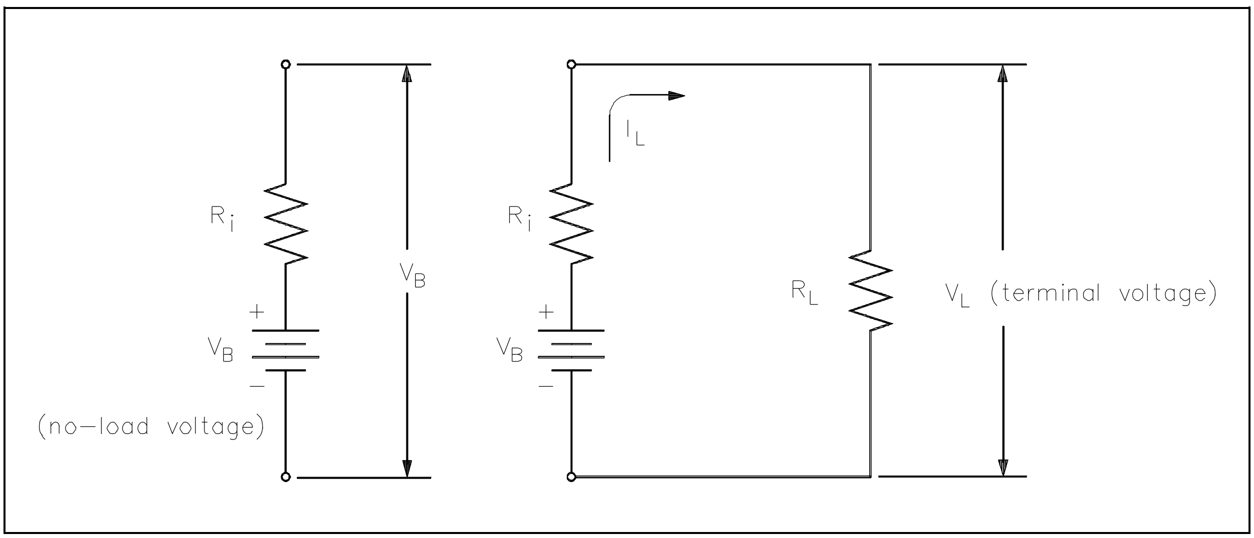

Figure 10 Internal Voltage Drop

When current flows in the circuit (I_L), the internal voltage drop (I_LR_i) drops the terminal voltage of the battery as shown in Equation (4-3). Thus, internal resistance reduces both the current and voltage available to the load.

$$V_L = V_B - I_LR_i \tag{4-3}$$

Shelf Life

The *shelf life* of a battery is the time which a battery may be stored and not lose more than 10 percent of its original capacity.

Charge and Discharge

The *charge* of a battery may refer to as one of two things: (1) the relative state of capacity of the battery, or (2) the actual act of applying current flow in the reverse direction to return the battery to a fully-charged state.

Discharge, simply stated, is the act of drawing current from a battery.

Summary

Battery operations are summarized below.

Battery Operations Summary

- The output voltage of a battery connected in series is equal to the sum of the cell voltages.
- A battery that is connected in parallel has the advantage of a greater current-carrying capability.
- Secondary cells can be recharged; primary cells cannot be recharged.
- The unit for battery capacity is the ampere-hour.
- Internal resistance in a battery will decrease the battery voltage when a load is placed on the battery.
- Shelf life is a term that is used to measure the time that a battery may sit idle and not lose more than 10 percent of its charge.
- The charge of a battery may refer to one of two things: (1) the relative state of capacity of the battery, or (2) the actual act of applying current flow in the reverse direction to restore the battery to a fully-charged condition.
- Discharge refers to the act of drawing current from a battery.

TYPES OF BATTERIES

The lead-acid battery is the most common type of battery in use today. There are other types of storage batteries, each having certain advantages.

EO 1.9 STATE the advantage of each of the following types of batteries:

a. Carbon-zinc cell
b. Alkaline cell
c. Nickel-cadmium cell
d. Edison cell
e. Mercury cell

Wet and Dry Cells

Wet and dry cells are classified by the type of electrolyte the battery uses. The electrolyte of a cell may be a liquid or a paste. If the electrolyte is a paste, the cell is referred to as a dry cell. If the electrolyte is a solution, the cell is called a wet cell.

Carbon-Zinc Cell

The carbon-zinc cell is one of the oldest and most widely used types of dry cells. The carbon in the battery is in the form of a rod in the center of the cell which acts as the positive terminal. The case is made from zinc and acts as the negative electrode. The electrolyte for this type of cell is a chemical paste-like mixture which is housed between the carbon electrode and the zinc case. The cell is then sealed to prevent any of the liquid in the paste from evaporating.

The advantage of a carbon-zinc battery is that it is durable and very inexpensive to produce. The cell voltage for this type of cell is about 1.5 volts.

Alkaline Cell

The alkaline cell is so called because it has an alkaline electrolyte of potassium hydroxide. The negative electrode is made from zinc, and the positive electrode is made of manganese dioxide. The typical alkaline cell generates 1.5 volts. The alkaline cell has the advantage of an extended life over that of a carbon-zinc cell of the same size; however, it is usually more expensive.

Nickel-Cadmium Cell

The nickel-cadmium cell is a secondary cell, and the electrolyte is potassium hydroxide. The negative electrode is made of nickel hydroxide, and the positive electrode is made of cadmium hydroxide. The nominal voltage of a nickel-cadmium cell is 1.25 volts. The nickel-cadmium battery has the advantage of being a dry cell that is a true storage battery with a reversible chemical reaction (i.e., it can be recharged). The nickel-cadmium battery is a rugged, dependable battery. It gives dependable service under extreme conditions of temperature, shock, and vibration. Due to its dependability, it is ideally suited for use in portable communications equipment.

Edison Cell

In an edison cell the positive plate consists of nickel and nickel hydrate, and the negative plate is made of iron. The electrolyte is an alkaline. Typical voltage output is 1.4 volts, and it should be recharged when it reaches 1.0 volts. The edison cell has the advantage of being a lighter and more rugged secondary cell than a lead-acid storage battery.

Mercury Cell

Mercury cells come in two types; one is a flat cell that is shaped like a button, while the other is a cylindrical cell that looks like a regular flashlight battery. Each cell produces about 1.35 volts. These cells are very rugged and have a relatively long shelf life. The mercury cell has the advantage of maintaining a fairly constant output under varying load conditions. For this reason, they are used in products such as electric watches, hearing aids, cameras, and test instruments.

Summary

Battery types are summarized below.

Battery Types Summary

- If the electrolyte is a paste, the cell is referred to as a dry cell. If the electrolyte is a solution, the cell is called a wet cell.
- The advantage of a carbon-zinc battery is that it is durable and very inexpensive to produce.
- The alkaline cell has the advantage of an extended life over that of a carbon-zinc cell of the same size.
- The nickel-cadmium battery has the advantage of being a dry cell that is a true storage battery with a reversible chemical reaction.
- The edison cell has the advantage of being a lighter and more rugged secondary cell than a lead-acid storage battery.
- The mercury cell has the advantage of maintaining a fairly constant output under varying load conditions.

BATTERY HAZARDS

Because batteries store large amounts of energy, there are certain hazards that are associated with battery operation. These hazards must be fully understood to ensure safe operation of batteries.

EO 1.10 EXPLAIN the adverse effects of a shorted cell.

EO 1.11 EXPLAIN how gas generation is minimized for a lead-acid battery.

EO 1.12 EXPLAIN how heat is generated in a lead-acid battery.

Shorted Cell

Cell short circuits can be caused by several conditions, which include the following: faulty separators; lead particles or other metals forming a circuit between the positive and negative plates; buckling of the plates; or excessive sediments in the bottom of the jar. The primary cause of some of these occurrences is overcharging and overdischarging of the battery, which causes sediment to build up due to flaking of active material and buckling of cell plates.

Overcharging and overdischarging should be avoided at all costs. Short circuits cause a great reduction in battery capacity. With each shorted cell, battery capacity is reduced by a percentage equal to one over the total number of cells.

Gas Generation

A lead-acid battery cannot absorb all the energy from the charging source when the battery is nearing the completion of the charge. This excess energy dissociates water by way of electrolysis into hydrogen and oxygen. Oxygen is produced by the positive plate, and hydrogen is produced by the negative plate. This process is known as gassing.

Gassing is first noticed when cell voltage reaches 2.30-2.35 volts per cell and increases as the charge progresses. At full charge, the amount of hydrogen produced is about one cubic foot per cell for each 63 ampere-hours input. If gassing occurs and the gases are allowed to collect, an explosive mixture of hydrogen and oxygen can be readily produced. It is necessary, therefore, to ensure that the area is well ventilated and that it remains free of any open flames or spark-producing equipment.

As long as battery voltage is greater than 2.30 volts per cell, gassing will occur and cannot be prevented entirely. To reduce the amount of gassing, charging voltages above 2.30 volts per cell should be minimized (e.g., 13.8 volts for a 12 volt battery).

Battery Temperature

The operating temperature of a battery should preferably be maintained in the nominal band of 60-80°F. Whenever the battery is charged, the current flowing through the battery will cause heat to be generated by the electrolysis of water. The current flowing through the battery (I) will also cause heat to be generated (P) during charge and discharge as it passes through the internal resistance (R_i), as illustrated using the formula for power in Equation (4-4).

$$P = I^2 R_i \tag{4-4}$$

Higher temperatures will give some additional capacity, but they will eventually reduce the life of the battery. Very high temperatures, 125°F and higher, can actually do damage to the battery and cause early failure.

Low temperatures will lower battery capacity but also prolong battery life under floating (i.e., slightly charging) operation or storage. Extremely low temperatures can freeze the electrolyte, but only if the battery is low in specific gravity.

Summary

Battery hazards are summarized below.

Battery Hazards Summary

- Short circuits cause a great reduction in battery capacity.
- To prevent short circuits in a battery, overcharging and overdischarging should be avoided at all costs.
- The adverse effect of gassing is that if gassing occurs and the gases are allowed to collect, an explosive mixture of hydrogen and oxygen can be readily produced.
- To reduce the amount of gassing, charging voltages above 2.30 volts per cell should be minimized.
- Whenever the battery is charged, the current flowing through the battery will cause heat to be generated by the electrolysis of water and by I^2R_i power generation.
- Higher temperatures will give some additional capacity, but they will eventually reduce the life of the battery. Very high temperatures, 125°F and higher, can actually do damage to the battery and cause early failure.