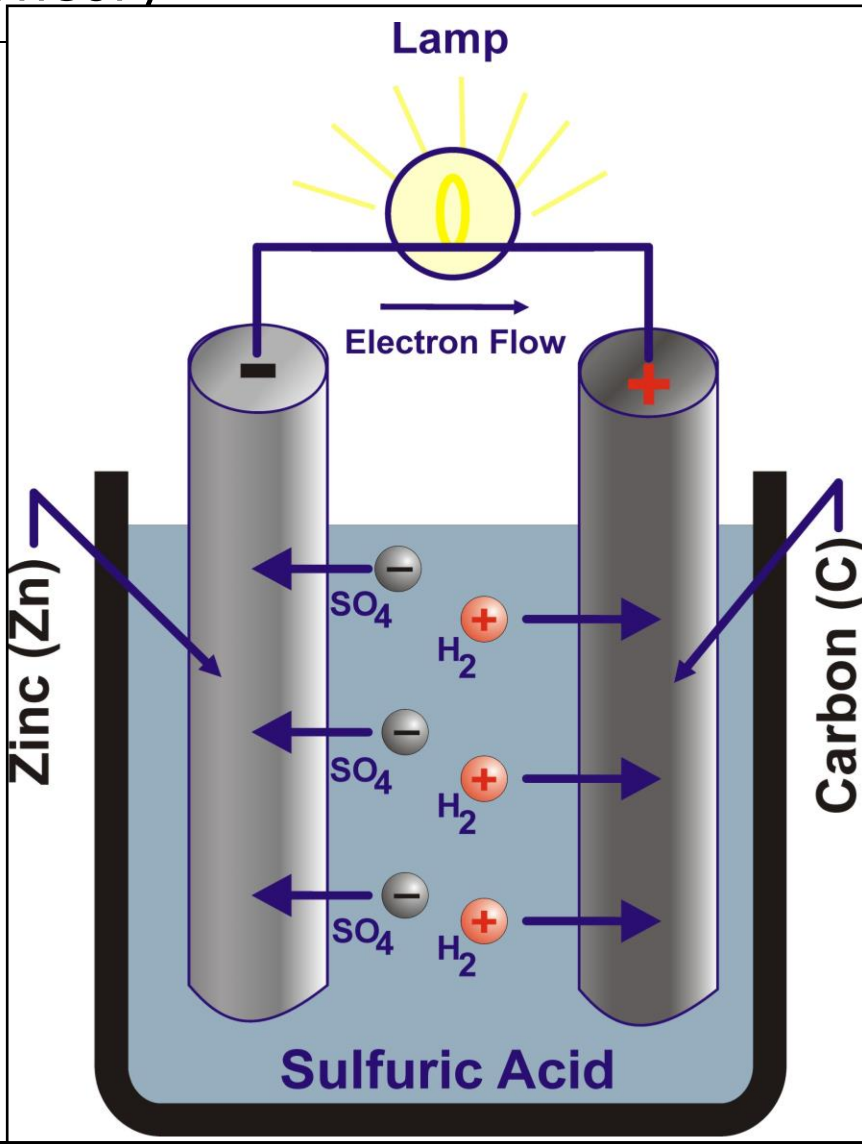
# Battery Theory

## A. The Cell

1. The cell is a device that transforms chemical energy into direct current (DC) electrical energy.
2. Types of Cells
   a. Cells are classified into two general types: primary and secondary. In a primary cell, chemical action eats away one of the electrodes, usually the negative, commonly made of zinc and is not reversible. When the cell is fully discharged, it is necessary to renew the active material or the cell must be discarded. In a secondary cell, active material, usually lead peroxide ($PbO_2$) is also chemically changed. However, it is restored to its original chemical structure by passing a current through the cell in a direction opposite that of the discharge.
   b. A battery is a group of two or more cells. The common electrical symbol for a battery is: 
3. Galvanic Cell
4. The simplest cell is known as a galvanic cell (Picture 1). It consists of a positive electrode (carbon) and negative electrode (zinc) suspended in an electrolyte (a solution of water and sulfuric acid). Positive and negative electrodes are the conductors by which current leaves or returns to the electrolyte. The electrolyte chemically acts upon the two electrodes to supply electrons and establish an electrical path between the conductors. The galvanic cell is a secondary cell.




Picture 1, Simple Galvanic Cell

## B. Types of Batteries

1. The primary cell's electrolyte is usually a moist paste and is commonly referred to as a dry cell. The secondary cell's electrolyte is in a liquid state and is called a wet cell.
2. In a primary cell, the chemical process of forming the solution is not reversible. For instance, zinc can be dissolved in ammonium chloride (a common paste electrolyte), but the process cannot be reversed. The flashlight battery, is an example of a primary cell.
3. In a secondary cell, the chemical action is reversible. The active element of the electrolyte plates out on the electrodes with current flowing in one direction, or it can be driven into solution by reversing current. Since a secondary cell can be recharged, it is referred to as a storage cell. The most common form of storage cell is the lead-sulfuric acid cell used in automobile batteries.
4. Primary Cell
   a. The most widely used primary cell is the zinc-carbon dry cell. The zinc serves a dual purpose; to contain the electrolyte, and to act as a negative terminal (electrode). The positive terminal is a carbon rod with a brass contact cap in the center of the cell. The electrolyte is a paste of concentrated ammonium chloride and cornstarch.
   b. When the zinc dry cell is assembled, the electrolyte chemical breaks down into positive ammonium ions and negative chloride ions. Zinc (negative electrode) comes in contact with the electrolyte. Positive zinc ions enter the electrolyte paste and drive (or repel) the positive ammonium ions toward the carbon (positive) electrode. This action produces the positive and negative charges on the electrodes necessary to create the emf. When an external circuit is connected between terminals, current flows

from the zinc electrode, through the external circuit, and back to the carbon electrode. This action takes place in every primary cell devised. One of the electrodes is always decomposed in this process. The electrode being decomposed in this common zinc dry cell (the negative electrode) also forms the case. Therefore, old cells can rupture, spill electrolyte, and damage equipment.

c. The potential of a dry cell depends upon two factors: the materials used for the electrodes and the chemical used as the electrolyte. A standard "D" cell produces an emf of approximately 1.5 volts. The physical size of the electrodes or quantity of electrolyte used does not affect the voltage rating of the cell but it does affect its current capability. Large size dry cells are capable of providing a greater current flow than smaller cells.

5. Secondary Cell

a. The secondary cell also produces electrical energy through the transformation of chemical energy. However, the chemical composition of the materials used is altered, rather than consumed, during transformation. When the chemical structure of the materials used is completely changed, emf ceases. The advantage of the secondary cell is that the original properties of the materials can be restored so that the cell can again furnish emf comparable to a new cell.

6. Storage Battery

a. A storage battery consists of two or more secondary cells connected in series. Each cell is contained in an acid proof compartment within the case. Cells are connected in series by lead- alloy connectors attached to the terminal posts of adjacent cells. A storage battery does not store electrical energy, but is a source of chemical energy which produces electrical energy. A variety of storage batteries are used for industry. Three of the most common are lead-acid, lead- antimony, and nickeliron-alkaline. Of these three types, the lead-acid is most widely used and is the one discussed in this chapter.

b. Storage batteries are indispensable equipment in the electrical power plant. Batteries in nuclear power stations ensure an adequate and uninterrupted supply of current for control functions, indication, protective relaying and regulating apparatus, emergency core cooling systems, and emergency lighting. A station battery has two outstanding characteristics:

1) The station battery instantaneously provides the most reliable source of emergency power when normal power fails.

2) The battery is capable of delivering very large quantities of power for short periods or discharging at low rates over extended time.

c. Thus, it can supply continuous light and power service when the need is greatest, while heavy surges of power are available when required. Recharging is performed at a low value because violent gassing occurs at high charge rates.

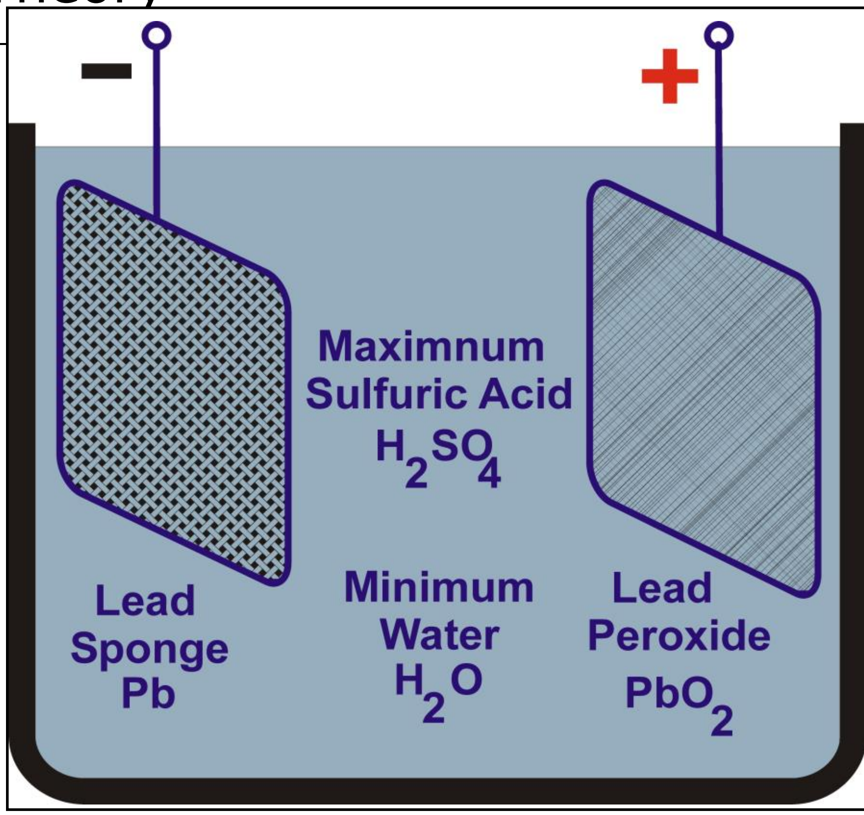
d. A station's lead-acid battery system can be designed to satisfy a variety of desired voltage ratings. Most DC powered equipment systems at a nuclear power station fall within one of the following DC voltage groups:

1) 24 volts, for radiation detection equipment, audible and visual alarm systems, communica-tions systems.

2) 125 volts, for switch gear systems, uninterruptible AC power supply systems, emergency lighting, supervisory control systems.

7. Lead-Acid Battery

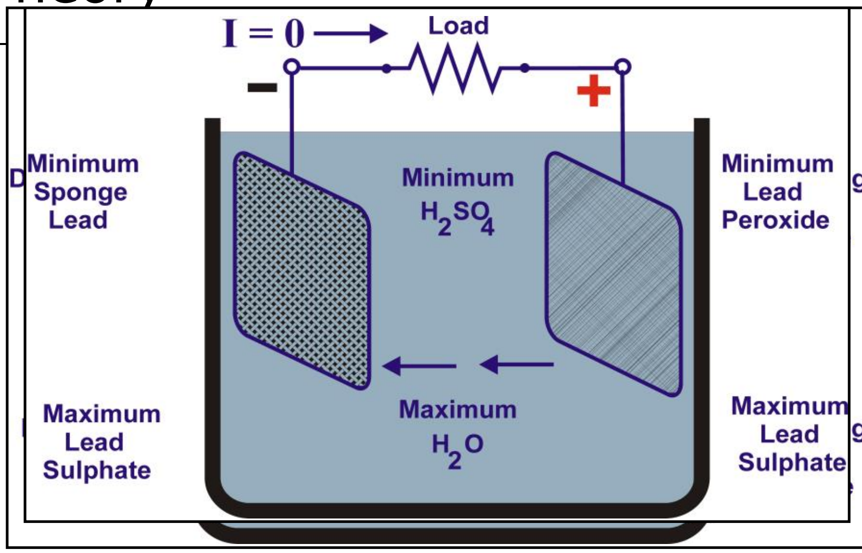
a. In a charged condition (Picture 2), The chemically active materials are lead peroxide (positive plates), sponge lead (negative plates), and a solution of sulfuric acid (H2SO) and water (H2O) called electrolyte. The




amount of sulfuric acid in the electrolyte is determined by a specific gravity measurement (discussed in more detail later). The lead peroxide and sponge lead are porous and absorb some of the electrolyte.

Picture 2, Fully Charged Lead-Acid Battery

b. As the battery discharges (Picture 3), sulfate ions (SO) in contact with the positive and negative plates, separate from the electrolyte. Lead sulfate (PbSO) is formed by chemical combination with the plate's active material. Thus, as the discharge continues, lead sulfate forms on both the positive and negative plates, and more acid is taken from the electrolyte. The electrolyte's water content becomes progressively higher (i.e., the ratio of water to acid increases) because lead peroxide (positive plate) releases its oxygen ion to accept the sulfate ion and the free oxygen ion combines with the acid's left over hydrogen ions to form water. Appropriate equations for a discharging battery are as follows:




$$\text{Postive plate}: PbO_2 + H_2SO_4 \rightarrow PbSO_4 + H_2 + O_2$$
$$\text{Negative plate}: Pb + H_2SO_4 \rightarrow PbSO_4 + H_2$$
$$\text{Water}: 2H_2 + O_2 \rightarrow 2H_2O$$

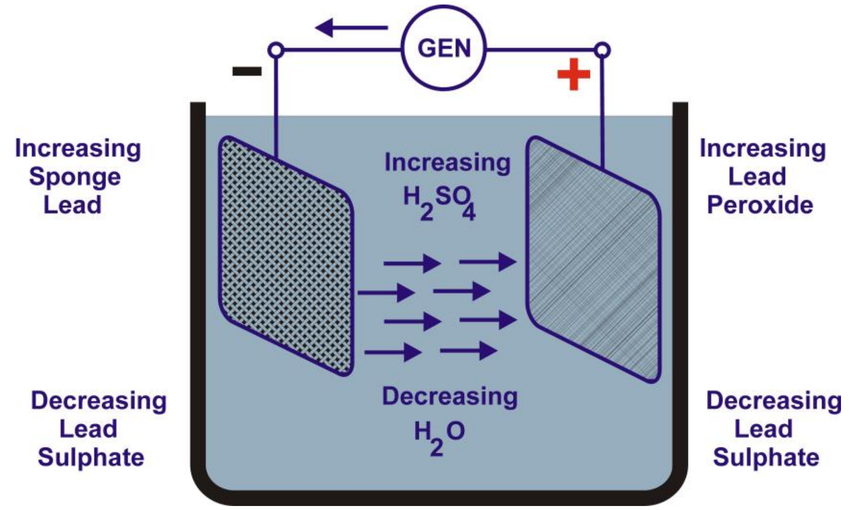
Picture 3, Discharging Lead-Acid Battery

c. This chemical action will continue until all of the acid is depleted or the plates are converted to lead sulfate. At this point, the battery no longer produces an emf and the electrolyte has been diluted with water (Picture 4).

Picture 4, Discharged Lead Acid Battery

d. The reverse action takes place when the battery is being charged (Picture 5). Sulfate ions held in the sulfated plate material are driven back into the electrolyte. The water ionizes into hydrogen and oxygen. Hydrogen combines with released sulfate ions, making sulfuric acid and oxygen migrates to the positive plate and combines with lead to form lead peroxide. When the battery is fully charged, the material of the positive plates is again pure lead peroxide and the negative plates pure lead. Further charging cannot raise specific gravity any higher. Appropriate equations for a charging battery are given below.

**Picture 5**




**Picture 5, Charging Lead-Acid Battery**

Water: $2H_2O \rightarrow 2H_2 + O_2$

Positive plate: $PbSO_4 \rightarrow Pb + SO_4; Pb + O_2 \rightarrow PbO_2$

Negative plate: $PbSO_4 \rightarrow Pb + SO_4$

Electrolyte: $2H_2 + 2SO_4 \rightarrow 2H_2SO_4$

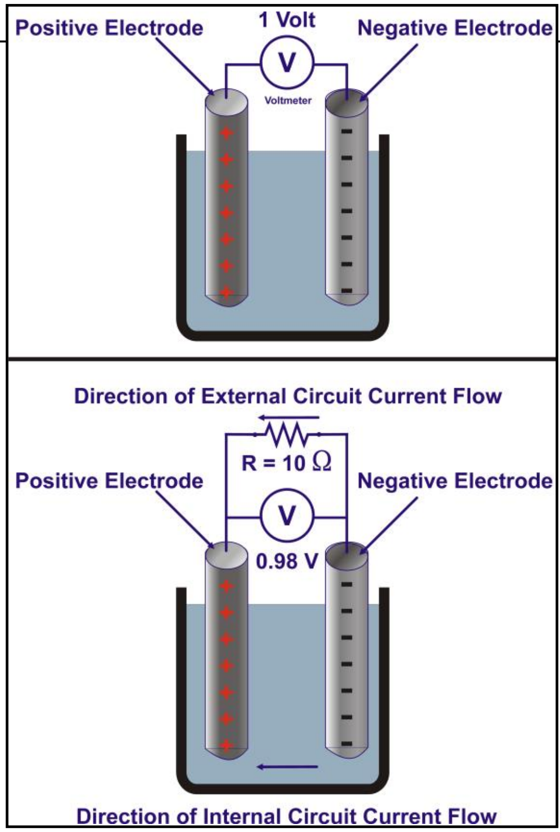
e. In conclusion, electrical energy is derived from a lead-acid cell as the plates react with the electrolyte. When sulfuric acid (H2SO), reacts with sponge lead to form lead sulfate (PbSO), positive hydrogen ions are formed and the plates become negatively charged. The positive ions migrate to the lead peroxide plate (PbO2) where a reaction between the sulfuric acid, lead peroxide, and positive hydrogen ion forms water (H2O) and lead sulfate. This results in the lead peroxide plate being positively charged. This chemical process can be shown by the chemical equation:

$$\xrightarrow{\text{discharge}}$$

$$Pb + PbO_2 + 2H_2SO_4 \text{discharge}$$

## C. Internal Resistance

1. The electrolyte (both liquid and paste) presents opposition to the motion of ions just as a conductor presents resistance to the flow of electrons. Part of

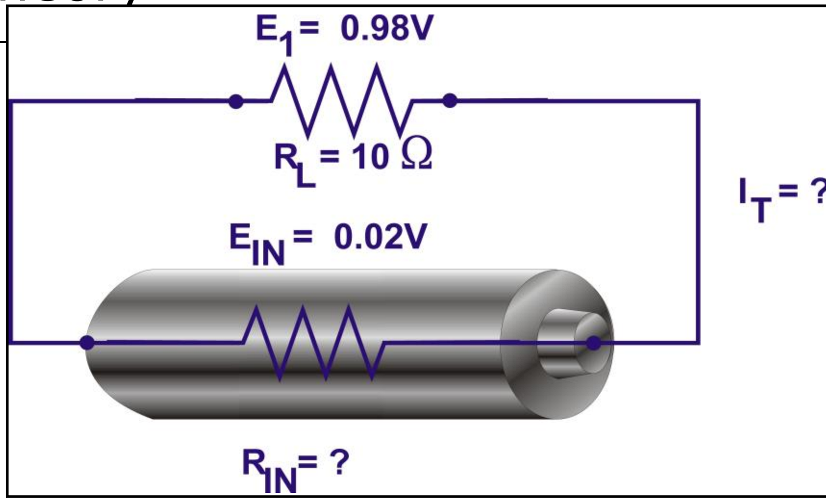



the total voltage developed by the cell must be used to move ions within the cell. This internal voltage requirement (or drop) must be subtracted from total emf produced by the cell. This, in turn, results in a lowered terminal voltage, but only if current is flowing in the external circuit. (Recall the rule for voltage in a series circuit). Therefore, the cell is said to have an internal resistance. All batteries have some internal resistance.

2. Computing Internal Resistance

   a. To determine internal resistance of a cell, two voltage measurements must be obtained: open circuit voltage and closed circuit voltage. The open circuit measurement is taken by placing a voltmeter across battery electrodes (Picture 6 (A)). Closed circuit voltage is taken with a low resistance load (required to allow high current flow) placed across battery electrodes (Picture 6 (B)).

Picture 6, Measurement of Cell Voltage




3. In Picture 7, there is a difference of 0.02 volts between the open and closed circuit voltage. This loss is attributed to increased circuit resistance caused by the cells internal resistance. Application of Ohm's law yields the actual value of battery internal resistance.

4. Picture 7 is a simplified version of Picture 6B.

Picture 7, Equivalent Schematic of Internal voltage in a Circuit

a. First, solve for external circuit current as in Chapter 2.

$$I_T = \frac{E_s}{R_L} = \frac{0.98\text{ v}}{10\,\Omega} = 0.098\text{ amps}$$

b. Since this is a series circuit, 0.098 amps will also be going through the internal resistance ($R_{IN}$). The difference between open and closed terminal voltages is 0.02 volts. Therefore, the voltage drop across the internal resistance ($E_{IN}$) must be 0.02 volts.

c. To solve for the internal resistance, just apply Ohm's law.

$$R_{IN} = \frac{E_{IN}}{I_T} = \frac{E_{open} - E_{closed}}{I_T} = \frac{0.02\text{ v}}{0.098\text{ a}}$$

d. Example: If terminal voltage is 20.5 volts in an open circuit and 20 volts in a closed circuit with a 20 ohm load, what is the battery's internal resistance?

e. Answer:

1) Determine circuit current using Ohm's law.

$$I_T = \frac{20\,v}{20\Omega} = 1amp$$

2) Determine the voltage drop across the internal resistance.

$E_{IN}=E_{open}-E_{closed}$=20.5v – 20v = 0.5 volts

3) Solve for the internal resistance by applying Ohm's law.

$$R_{in} = \frac{E_{in}}{I_T} = \frac{0.5\,v}{1a} = 0.5\,\Omega$$

4)

5)

5. Battery Age vs. Internal Resistance

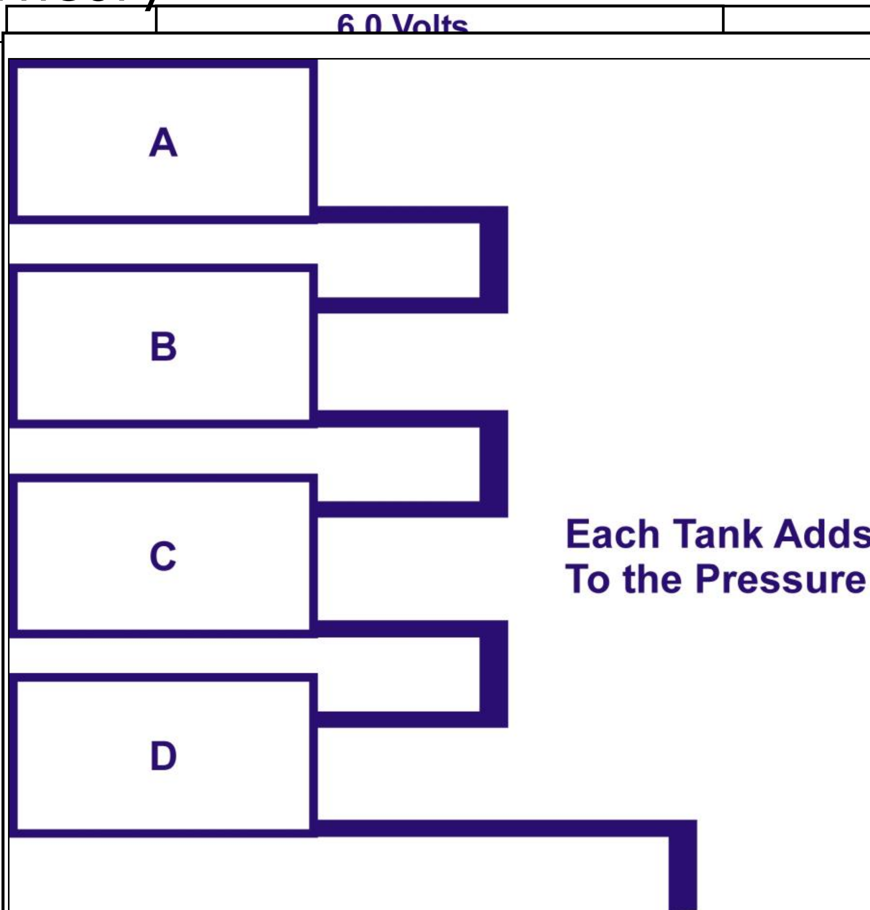
a. As a cell is used, chemical action becomes weak, internal resistance increases, and terminal voltage decreases until the battery can no longer furnish the current it was designed to supply.

## D. Combinations of Cells and Batteries

1. An electric circuit may require a voltage (or current) which a single cell cannot supply. To supply this need, groups of cells are combined in various series and parallel arrangements.

2. Series Batteries

a. In a series connection, the negative electrode of the first cell is connected to the positive of the second, the negative electrode of the second to the positive of the third, and so on. The positive electrode of the first cell and negative electrode of the last cell are used as terminals (Picture 8).



**Picture 9, Water Analogy for Series Grouping of Cells**

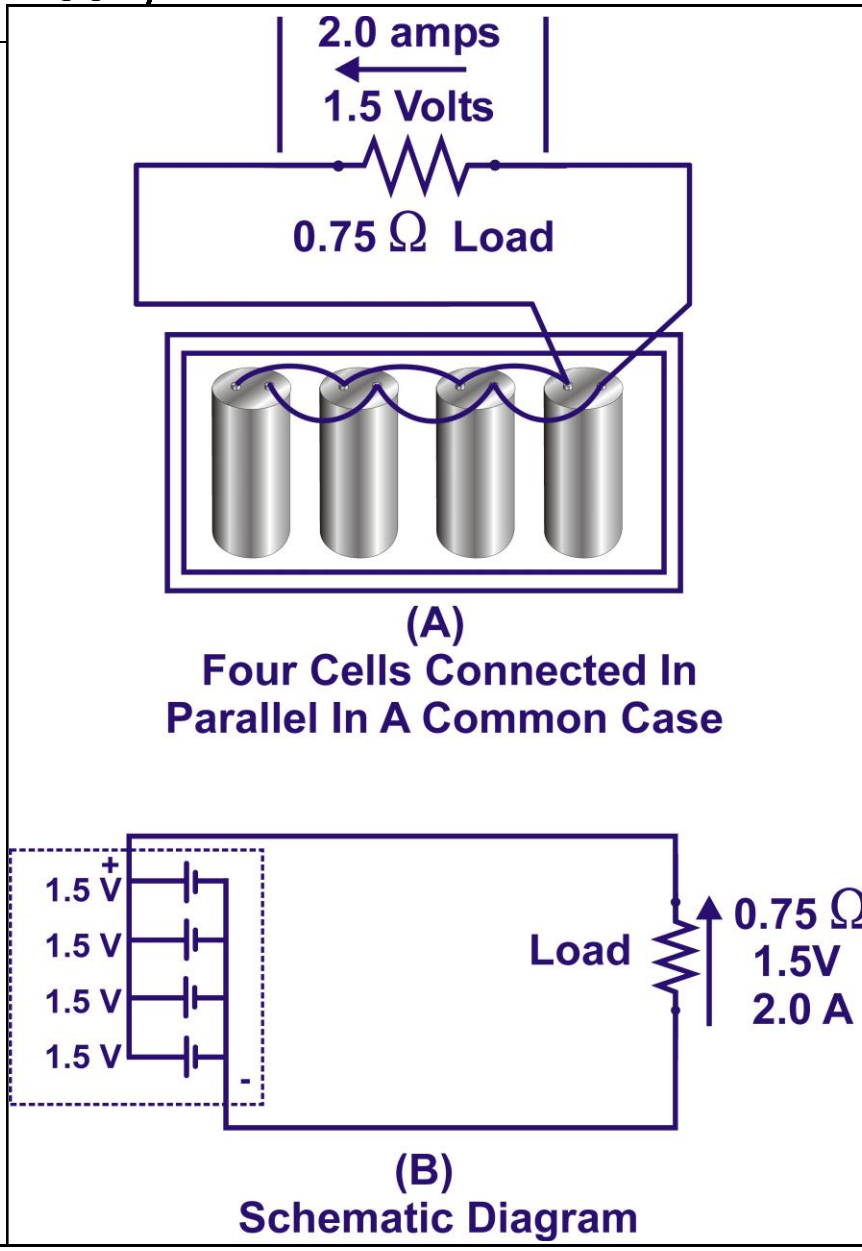
Picture 8, Method of Connecting Four 1.5 volt 0.5 Ampere Cells to Form a 6 Volt, 0.5 Ampere Battery

b. Using a mechanical analogy, the water head of a piping system is increased by placing more tanks above it (Pictrue 9). Each tank increases water pressure by increasing the depth. Four tanks increase pressure four times and water in the four tanks flows through each tank in turn. As a result, the water meets four times the resistance encountered in flowing through a single tank. Total internal resistance of the four cells grouped in series is four times that of a single cell. Resistance is additive in a series circuit. Thus, as cells are added in series, their internal resistance is additive.

c. Recall the laws of series circuits: the amount of current through a series circuit is the same throughout and the sum of individual voltage drops is equal to the source potential. This is also true in series connected cells or batteries. In Picture 8, four primary cells are connected so the resultant voltage applied to the load is equal to the sum of voltage of each cell. Current is equal to the current capability of one cell. Therefore, the 12 ohm load has a total of 6 volts across it and 0.5 amperes of current passing through it. If cells of unequal current capability are used, current available for the series circuit is determined by the lowest current producing cell. This is why a car battery is only as strong as its weakest cell and dies when only a single cell dries out.

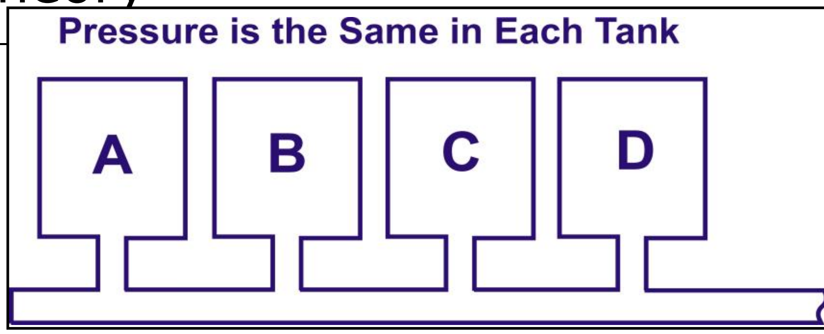
3. Parallel Batteries

a. In a parallel connection, two or more cells are connected with their positive electrodes on one line and negative electrodes on the other (Picture 10).




Picture 10, Method of Connecting Four 1.5v, 0.5 Ampere Cells to Form a 1.5v, 2.0 Ampere Battery

b. A mechanical analogy for parallel cell, or battery, grouping involves four level tanks of water connected to a single line (Picture 11). Connecting tanks to the same external pipe does not increase pressure. Since only one-fourth of the water flows from each tank in parallel, resistance offered is only one-fourth that of a single tank. Similarly, one-fourth of the current flows through each cell connected in parallel. Total internal resistance of four parallel cells is slightly less than one-fourth that of a

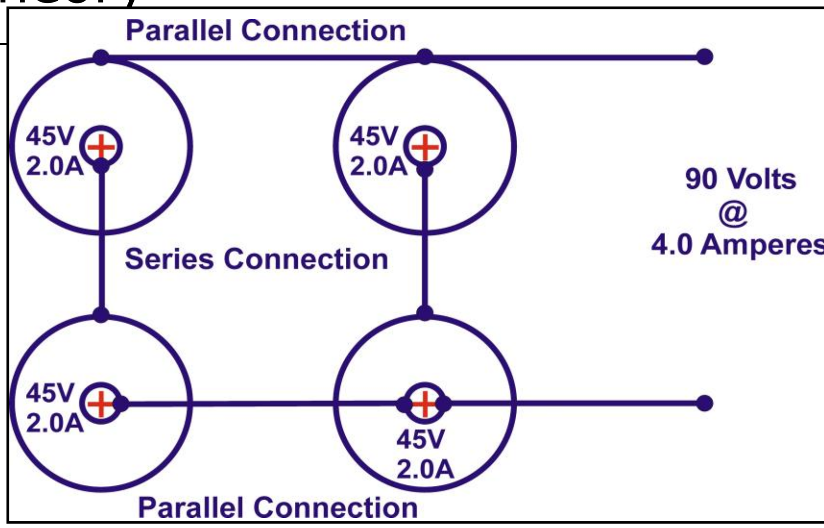



single cell. For parallel circuits, total resistance is equal to (or less than) the smallest resistance in the parallel circuit. This grouping allows more current flow than from one cell with four times the current capability because total internal circuit resistance is much less. Total current furnished by the group is equal to the sum of the currents of each cell or battery in the group.

Picture 11, Water Analogy for Parallel Grouping

c. Batteries connected in parallel conform to the laws of parallel circuits; the amount of total circuit current is equal to the sum of the individual branch currents and the total circuit voltage is equal to individual branch voltages. In Picture 10, a load connected to four 1.5 volt, 0.5 ampere batteries in parallel would draw 0.5 amps from each cell, resulting in a total of 2 amps of current. The combination of batteries in Picture 10 could provide approximately 4 times the current of one cell for the life expectancy of a single battery. Voltage across a parallel circuit is equal to voltage across any of its branches. Therefore, output voltage of this network is 1.5 volts.

d. Each branch of parallel battery arrangements must have batteries or cells producing the same voltage. Bad cells should not be connected in parallel with good cells as cells in good condition will need to supply more current to maintain total load current and also supply the lower voltage cell, which will also act as an additional resistance. This would rapidly




deplete good cells. When a bad cell is discovered in a bank of parallel cells, it is removed from the circuit.

e. If a large current at low voltage is necessary, parallel connected batteries are used. Two cells in parallel increase current capability and operating time.

4. Series-Parallel Batteries

a. To provide higher voltage output and more current capability at the same time, cells can be connected in series-parallel combinations. Picture 12 shows a series-parallel connection used to develop 90 volts with a 4 amp current capability (using four 45 volt, 2 amp cells). Station batteries are connected this way to provide a greater terminal voltage than the single cell battery, plus supply high values of current, such as in the station's 125 volt system.

Picture 12, Method of Connecting Four 45 Volt, 2 Ampere Cells to Form a 90 volt, 4 Ampere Source

## E. Battery Capacity

1. Battery Ratings

a. Fully charged lead-acid batteries are rated by the amount of discharge current continuously supplied for a specified period. Output voltage must be maintained above a minimum level (1.5 to 1.8 volts per cell). Battery Capacity is the amount of energy obtainable from a storage battery. It is usually expressed in ampere-hours (Ah) and based on a given duration of continuous discharge. Common discharge times used for rating storage batteries are 8 hours and 20 hours.

b. Example:

c. A 120 Ah battery is based on the 8 hour discharge rate. What is the value of constant current continuously delivered over that 8 hour period?

d. Answer:

Continuous Current = $\frac{\text{Rating}}{\text{Time Base}} = \frac{120\text{ An}}{8\text{hrs}} = 15\text{amps}$

e. Ratings of a lead-acid battery are also for a given temperature (such as 80°F). Higher temperatures, due to high current flow or ambient temperature, increase chemical reaction and current capability. However, operation above 110°F shortens battery life. Lower temperatures reduce voltage and current output due to decreased chemical action. Ampere-hour capacity is reduced approximately 0.75 percent for every 1°F decrease in temperature.

2. Factors Effecting Battery Capacity

a. Capacity of a battery depends on the number, design, and dimensions of plates and the quantity of electrolyte. The amount of energy fully charged battery delivers depends on the discharge rate, temperature, and age of the cell. Because of these variables, there are various methods of rating battery capacity. The method is also determined by the service the battery will deliver. For example, automobile batteries are given two ratings. The twenty hour rate is an ampere-hour rating based on a starting temperature of 80°F, constant current output for 20 hours, and a final voltage of 1.75v per cell. The second rating given automobile batteries is called the cold-rating. This indicates the number of minutes a battery can deliver 300 amps (normal starting current) at 0°F.

b. For low rate discharge service batteries (such as station batteries), the 8 hour rate has been used as the standard. This is an ampere-hour rate for 8 hours at a pre-specified temperature resulting in pre-determined minimum final voltage. Therefore, if a station battery rated at 60 Ah is based on the 8-hour discharge rate, it will provide a constant rated current of 7.5 amps for 8 hours.

3. Specific Gravity

a. It is possible to determine a battery's state of charge, between fully charged and discharged, by measuring the specific gravity of the electrolyte. Specific gravity is a ratio comparing the density of a substance (sulfuric acid in this case) with the density of water. Concentrated sulfuric acid is 1.835 times as heavy as an equal volume of water, therefore, its specific gravity is 1.835. The specific gravity of water is 1, by definition.

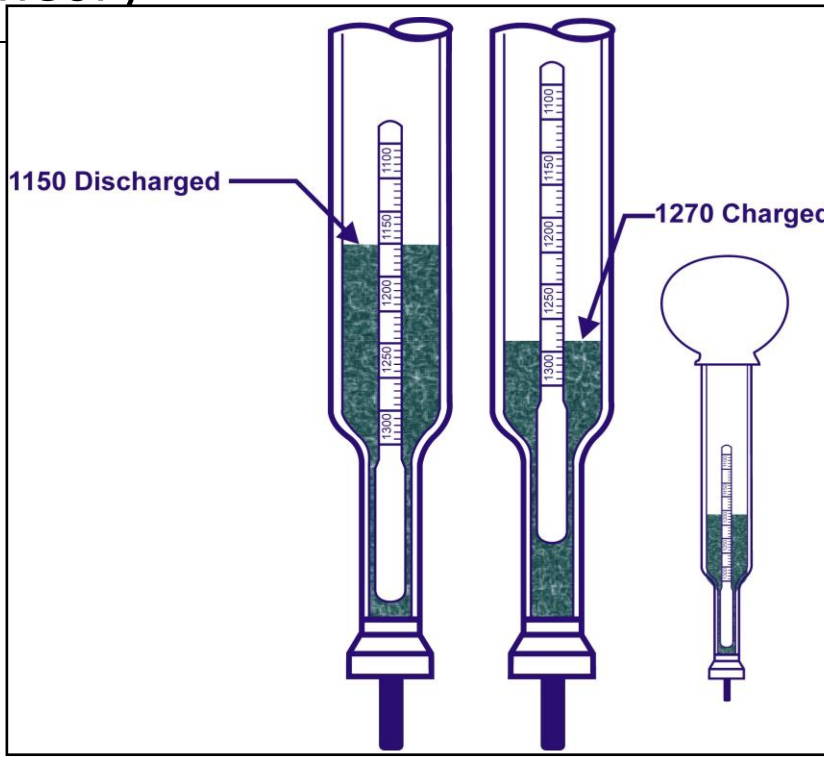
4. In a fully charged automobile battery cell, the mixture of water and sulfuric acid has a specific gravity of 1.280 at room temperatures of 70° to 80°F (Table 3-1). As the cell discharges, water formed dilutes the acid and lowers specific gravity. When specific gravity is down to approximately 1.160, the cell is essentially discharged.

**TYPICAL SPECIFIC GRAVITIES**

| | |
|---|---|
| 1.280 specific gravity | 100% charged |
| 1.250 specific gravity | 75% charged |
| 1.220 specific gravity | 50% charged |
| 1.190 specific gravity | 25% charged |
| 1.160 specific gravity | Very little useful capacity left |
| 1.130 specific gravity | Discharged |

5. Battery size vs. Specific Gravity

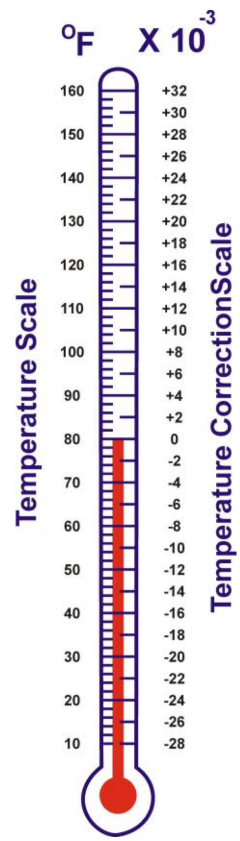
   a. In a station battery a large volume of electrolyte is used. Specific gravity in the fully charged state is about 1.210 to 1.225. For a portable automobile battery, a much smaller volume of electrolyte is used and the specific gravity is 1.275 to 1.300 when fully charged. Temperature is a factor when determining specific gravity for a particular application. Batteries exposed to extremely cold climates require electrolytes of higher specific gravity (more acid) to prevent freezing. Batteries used in hot climates require a lower specific gravity to prevent overheating. Sulfuric acid has a lower freezing point but also a lower boiling point than water. The decrease is specific gravity from fully charged to fully discharged varies with the volume of electrolyte. For large volumes of electrolyte, the drop is as small as 0.030. For small volumes, (as in automobile batteries), it can be as large as 0.180.




b. To measure specific gravity, a hydrometer is used. In the syringe type hydrometer (Picture 13), a small quantity of the electrolyte is drawn from the cell into the syringe. A weighted bulb floats in the electrolyte. The depth at which it floats is a measure of the specific gravity of the electrolyte being tested. The bulb stem is marked with values of specific gravity. The decimal point is usually omitted for convenience. On the surface of the syringe is the specific gravity reading of the electrolyte.

Picture 13, Typical Hydrometer

c. Specific gravity of an electrolyte varies inversely with electrolyte temperature. An increase of 3°F in electrolyte temperature results in a drop of about 0.001 in specific gravity (or vice versa for an decrease in temperature). At ordinary room temperatures, the difference between indicated specific gravity and actual specific gravity is only minor (Specific gravity is based on 80°F), but at extremes of temperature, the correction can become very important. The effect temperature has on specific gravity is shown in Picture 14. 80°F is normal and temperature




**Picture 14, Temperature Correction of Specific Gravity**

correction is zero. To find actual specific gravity, every 10°F difference from 80°F will require a correction factor of ± 0.004 included with the hydrometer reading. If the temperature of the electrolyte is 60°F, subtract 0.008 from the indicated specific gravity reading. If the temperature is 100°F, add 0.008 to the indicated specific gravity.

6. Battery Chargers

   a. The most common source of DC power at a power is station batteries. They are normally placed in parallel with one or more battery chargers. Battery chargers convert alternating current (AC) to direct current (DC) and charge the battery at a low rate, enough to counteract the small internal losses present in every storage battery. Battery chargers can supply normal DC system loads while maintaining the floating charge on the battery. This ensures the battery is constantly ready, fully or almost fully charged, in the event the plant's normal AC power becomes limited. Emergency systems are often tied to a battery bus due to the high degree of dependability.

## F. SUMMARY

1. This discussion has shown effects, advantages, and disadvantages of cells or batteries in various combinations. With this knowledge, one can predetermine effects a bad cell will have on a station's battery and interpret the rating of a station battery and amount of power available in the battery.

2. A cell is the basic unit used to derive DC electrical energy from chemical energy. There are two types of cells. Chemical action in a primary cell cannot be reversed. This means that a primary cell cannot be recharged, but must be discarded as the electrolyte is unreplaceable. The primary cell normally uses a paste as its active material and is referred to as a dry cell. In a secondary cell, or wet cell, the electrolyte simply exchanges ions with the plates in a chemical process which can be reversed. This is done by passing a current through the cell in a direction opposite that of the discharge. When all previously exchanged ions have been forced back to their original material, the cell is fully charged and ready to be used in full capacity again. A battery consists of two or more cells connected to supply the required voltage and current capabilities.

3. Three chemically active parts of the battery are the positive plate, negative plate, and electrolyte, which is a solution of acid and water. As the battery is discharged, lead peroxide ($PbO_2$) of the positive electrode unites with hydrogen ions (H) and with sulfate ions (SO) to form water and lead sulfate (PbSO). The lead sulfate is also produced by combining lead (Pb) on the negative plate with sulfate ions. The net result is the development of an emf and the dilution of the electrolyte with water.

4. All batteries have some value of internal resistance. This is because the electrolyte resists migration of ions. Therefore, part of the chemically produced emf must be used to overcome this resistance. Internal resistance in cells follow the same rules as external resistance in the circuit. If two cells

are placed in series, internal resistances are additive to the circuit. If two cells are placed in parallel, total internal resistance will be equal to or less than the smaller internal resistance. This will cause terminal voltage to decrease until the cell can no longer furnish the amount of current it was designed to supply.

5. When combining cells in various arrangements, it is best to follow voltage and current laws for that type of circuit arrangement. When two or more cells are added in series, voltages are additive but combined current capability is equal to that of the lowest current cell. If the cells are connected in parallel, total terminal voltage is equal to the single cell's voltage and current capabilities are additive. To increase both voltage and current rating of the cell group, they must be in a series-parallel combination.

6. Available DC energy or capacity in a battery is expressed in ampere-hours (Ah). The ampere-hour rating is the amount of current a battery can supply in a given time. When determining its capacity, the battery must be fully charged at the start of the discharge. When rating station batteries, 8 hours is usually used as a standard time. Therefore, if a battery is rated at 96 Ah, it will deliver 12 amps for 8 hours (96 ÷ 8 = 12) before voltage drops to a predetermined discharge level. A battery can deliver a current higher than its rating for a time shorter than its rating. For example, if the battery is rated at 96 Ah, it can deliver 24 amps for 4 hours. The reverse is also true. It can deliver 6 amps for 16 hours.

7. The state of charge of a cell is determined by measuring specific gravity of the electrolyte. Specific gravity is the ratio of the density of a substance (such as the electrolyte) to water. Specific gravity of a cell will decrease during discharge due to chemical conversion of acid to water. During recharging, water is converted to acid. Specific gravity increases to its

maximum value, which is determined by initial acid concentration of the electrolyte for a fully charged condition.

**PRACTICE:**

1 What is an electric cell?

2. What is the simplest cell known?