AEROCHAPTER®

THE PASSION STARTS HERE

AIRCRAFT CELLS & BATTERIES

PREM MAHENDRANATHAN

It is IMPORTANT to note that this book can be used for educational/training purposes only. When carrying out a procedure, you MUST always follow instructions stated in the relevant aircraft manual or manufacturer's handbook and also follow the requirements of your national regulatory authority.

Published by AeroChapter

Cells and Batteries

Batteries are an integral component of almost all aircraft electrical systems. They mainly serve as backup power for numerous items of avionics equipment, and are used in a wide range of other operations, including starting engines and auxiliary power units, thus assuring continuous power for navigation systems, and to provide ground power capability for maintenance and preflight checkouts. An aircraft battery must have the ability to withstand a wide range of operating temperatures, be easy to maintain, possess rapid recharge capability, and be sturdy enough to tolerate environmental ruggedness.

CELL

A *cell* is a device that stores electrical charges in a chemical form. A cell has two labelled ends, namely the positive (+) and negative (−) terminals. The positive terminal is called cathode and the negative terminal is called anode. The voltage of a typical cell is 1.5 volts (1.5V). The symbol for a cell is shown in Figure 1.

FIGURE 1 Symbol of a Cell

Cell Construction

A cell is composed of several negative and positive electrode plates, interwoven with single/multiple layers of separator material (Figure 2). This separator material varies with respect to the cell type. For example, a mixture of sulphuric acid and water is used as an electrolyte in a lead-acid cell, whereas porous rubber cellulose fibre is used in flooded cells.

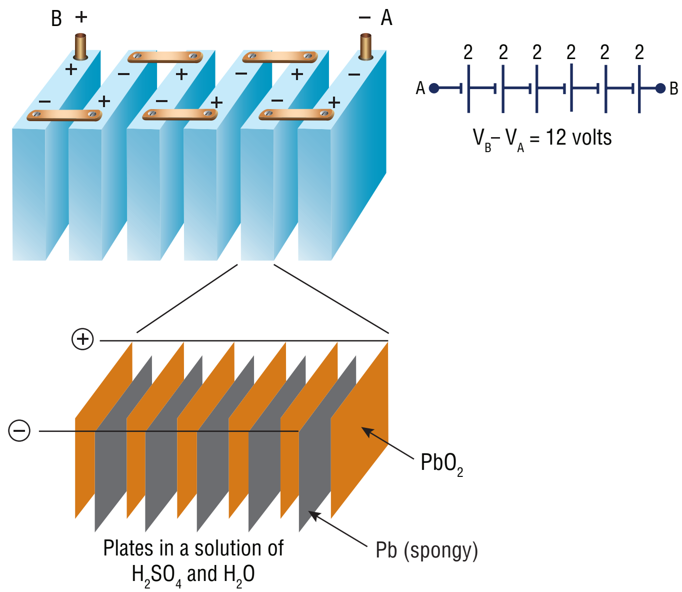


FIGURE 2 Construction of a Cell

BATTERY

A *battery* is formed when two or more cells are connected end-to-end. Several cells are connected to form batteries with different voltages such as 3V, 6V, 9V and so on, based on application requirements. As the voltage gets higher, the electrical force increases, thus delivering higher current. The symbol for a battery is shown in Figure 3.

FIGURE 3 Symbol of a Battery

Batteries convert stored chemical energy into electrical energy through electrochemical discharge reactions. Batteries supply electrical power to external devices when connected through a circuit, in which electrons discharges from the negative terminal and flow through the circuit to power the device.

Battery Rating

Batteries are rated based on their nominal voltage and ampere-hour capacity, as explained below.

- *Voltage rating:* The voltage rating is determined by the number of cells connected in series and the nominal voltage of each cell. Examples are 2V for a lead-acid battery and 1.2V for a nickel-cadmium battery. Usually, the voltage rating of aircraft batteries is 24V, which means that twelve 2V cells are present in a lead-acid battery, and twenty 1.2V cells in a nickel-cadmium battery.
- *Ampere-hour capacity:* The ampere-hour (Ah) capacity of a fully charged battery depends on its age, temperature and rate of discharge. Normally, aircraft batteries are rated at room temperature (25°C), the C-rate (1-hour rate), and at the beginning of the battery's life.

CHARACTERISTICS

Internal Resistance

The internal resistance is the resistance present inside the battery while the load is connected. The internal resistance has two components, one is the usual resistance from the component materials, and the other is due to electrochemical processes.

The internal resistance level varies with the state-of-charge of the battery. The low state of charge batteries will have high internal resistance.

The formula for internal resistance of a battery is given below.

$$R_i = \frac{(OCV - CCV)}{I}$$

R_i = internal resistance of a battery

OCV = open circuit voltage

CCV = closed circuit voltage

I = current (when the battery is loaded)

Specific Gravity

The specific gravity is defined as the ratio between the density of an object and a reference substance. The higher the specific gravity of the electrolyte solution in batteries, the less the internal resistance and greater their load current. The water formed dilutes the acid and eventually discharges the battery fully. A hydrometer is used to measure specific gravity.

Capacity

Capacity is the ability of a cell to deliver a given amount of current to the circuit in which it is used. The operating time period is based on the capacity of a storage battery. Once the battery is fully discharged, it is considered to be dead. For example, an 80-Ah battery must be recharged after 8 hours operation with an average discharge of 10-A.

The state of charge is defined as the capacity percentage available in relation to the capacity when it is fully charged. For example, the state of charge of a fully charged battery is 100%, while it is 70% for a 30% depleted battery.

The state of health is defined as the capacity of a battery to deliver current when it is fully charged. A battery's state of health reduces as the battery ages. For example, if a 30Ah rated battery can deliver 24Ah when fully charged, then its state of health is 24/30 = 80%.

Shelf Life

This is a time period during which the cell can be stored without losing more than 10% of its original capacity. The shelf life can be extended by storage in a cool, dry place, since heat stimulates the chemical reactions in the cell.

TYPES OF BATTERY

Primary Cells

Primary cells are ones that cannot be recharged after the discharge of voltage, because the electrolyte has been used up. The negative plate of a primary cell weakens as the material is absorbed irreversibly into the electrolyte solution, blocking the cell from restoration to its original condition. These cells have good charge retention capacity, and generally are cheaper. Most primary cells utilize electrolytes that are contained within a separator without liquid electrolyte, hence the name *dry cells*. They are used in flashlights, clocks and other portable applications. The types of primary cell batteries are explained below.

GALVANIC OR VOLTAIC CELLS

A combination of materials used to convert chemical energy into electric energy is known as a *voltaic cell*. This type of chemical cell consists of two electrodes made up of different types of metallic compounds, and an electrolyte solution capable of conducting an electric current.

Zinc (containing more negatively charged atoms) and copper (containing more positively charged atoms) are the most commonly used pair of electrodes. The corresponding metal plates are immersed in an electrolyte solution, where the chemical action takes place. The set-up is shown in Figure 4.

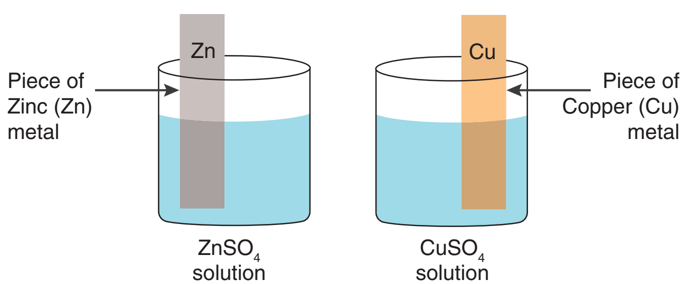


FIGURE 4 Electrodes and Electrolyte Solution

The positively charged atoms that leave the zinc electrode are attracted by the negative ions of the electrolyte, and vice-versa. These forces of attraction and repulsion will cause free electrons in the negative zinc electrode, connecting wires and bulb filament to move toward the positively charged copper electrode. The wet cell has a liquid electrolyte and the dry cell uses a paste electrolyte. Figure 5 is the schematic representation of a voltaic chemical cell.

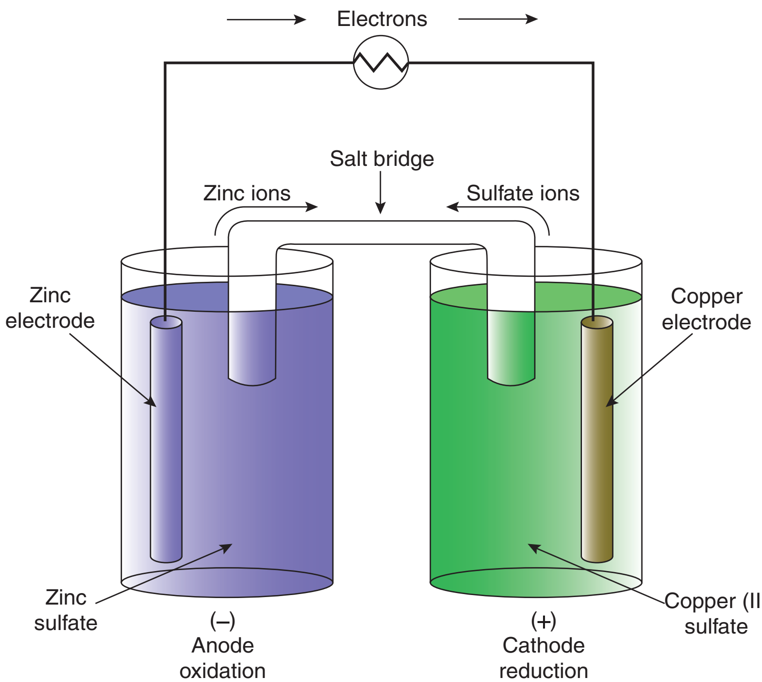


FIGURE 5 The Voltaic Cell

THE DANIELL CELL

This invention by an English chemist John Frederic Daniell can produce voltage with a high degree of accuracy, and is used as a standard reference voltage for testing instruments. In this cell, a copper container is filled with a saturated copper sulphate solution. A porous earthenware vessel with a zinc rod dipped in dilute sulphuric acid is kept within the copper container. When the positive cathode pole (copper) and negative anode pole (the zinc rod) are connected together, the electrons flow from the negative pole to the positive pole.

The earthen vessel prevents the copper ions from the copper sulphate solution from reaching the sulphuric acid solution. Deposition of copper takes place due to polarisation, which causes the copper sulphate solution to become more dilute. Figure 6 is the Daniel cell set-up.

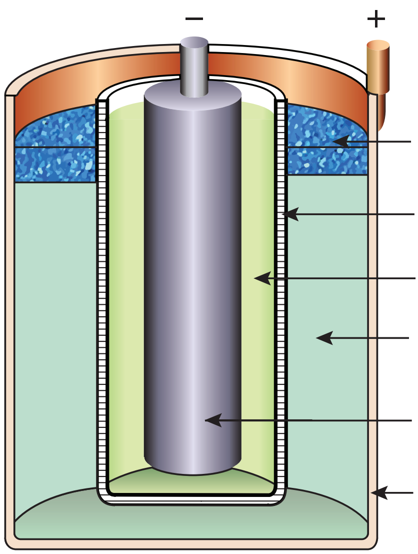


FIGURE 6 The Daniel Cell

THE LECLANCHÉ CELL

The Leclanché cell was invented by a French scientist George Leclanché, and consists of a carbon rod surrounded by manganese dioxide, and a carbon compound. A brass end cap acts as a cathode and a zinc case is a negative anode.

An electrolyte paste of aqueous ammonium chloride surrounds the manganese dioxide and carbon, and is separated from them by a linen casing.

During oxidisation, the zinc atoms on the zinc case give off electrons, and become positively charged ions. The electrons flow from the zinc case to the carbon rod, when an external circuit is connected. When the electrons enter the carbon, the manganese dioxide and water reacts to form manganese oxide and negative hydroxide ions. These ions then react with ammonium chloride and form ammonia and water. Figure 7 is the dry Leclanché cell.

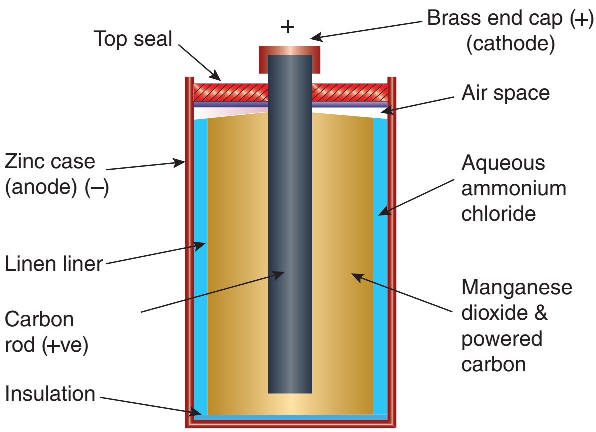


FIGURE 7 The Leclanché Cell

THE MERCURY CELL

This non-rechargeable primary cell uses a reaction between mercuric oxide and zinc electrolytes in an alkaline electrolyte. As shown in Figure 8, the outer case is the positive terminal and the top insertion cap is the negative terminal. The cell will hold its open circuit voltage of 1.35V for almost its entire life.

The cell consists of layers of zinc, potassium hydroxide and mercury oxide mixed with graphite which acts as a cathode. An insulating barrier is layered to separate the potassium hydroxide from the mercury oxide. When the circuit is completed, the electrons move from the anode to the cathode, the zinc oxidises to zinc oxide, and the mercury oxide undergoes reduction to form mercury.

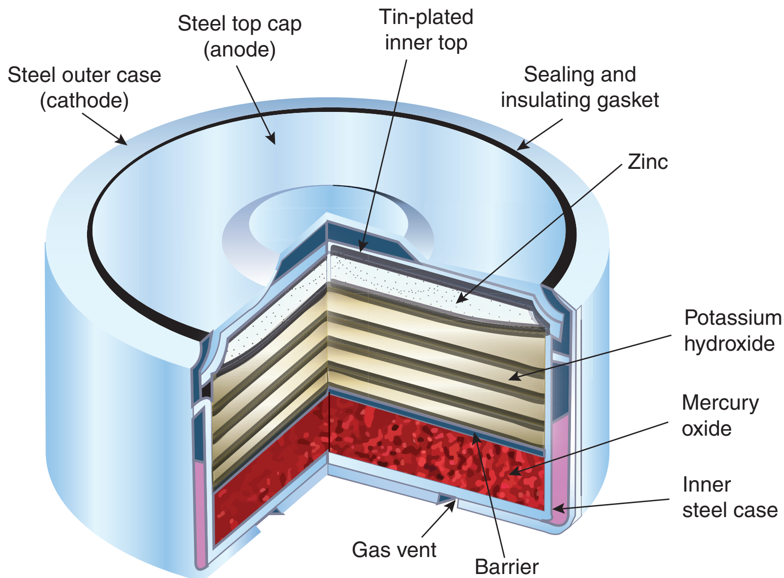


FIGURE 8 The Mercury Cell

Secondary Cells

Secondary cells are rechargeable types that are used in aircraft and many other devices. They can be electrically recharged by passing current through the cell after it has discharged. The interior chemicals are restored to their original condition during the recharging process. The cost of secondary cells is considerably higher than for primary cells, due to their high performance rate at heavy loads.

Based on their intending applications, secondary cells are divided into two sub-categories, namely:

1. Cells that are used as energy storage devices. Examples include emergency standby power sources and aircraft systems.
2. Cells that are used as primary cells, but are recharged after use. Examples include portable consumer electronics and electric vehicles.

The various types of secondary cells are explained below.

THE LEAD-ACID CELL

The lead acid cell consists of positive plates of lead peroxide (PbO2), negative plates filled with pure spongy lead (Pb), and a liquid electrolyte with 30% sulphuric acid and 70% water (Figure 9).

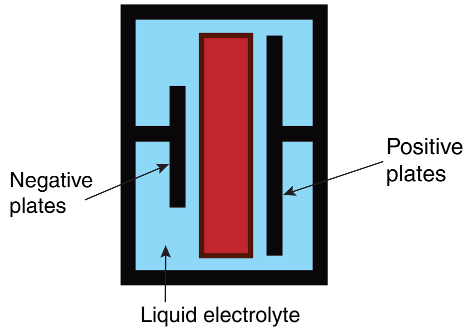


FIGURE 9 Positive and Negative Plates in a Lead-Acid Cell

Plates are made by pasting active material onto a grid structure that is made of lead or a lead alloy. The electrolyte is a mixture of sulphuric acid and water. Porous rubber, cellulose fibre or microporous plastic is used as a separator in flooded cells.

But in recombinant cells with starved electrolyte (absorption of electrolyte) technology, a glass fibre mat separator is used. Sometimes an additional layer of microporous polypropylene is used. Gel cells are made by absorbing the electrolyte with silica gel that is layered between the electrodes and separators.

The positive and negative plates are placed together with microporous plastic separators to prevent them from touching each other as shown in Figure 10. This whole bunch is placed in an acid proof container which is filled with the electrolyte solution. A vent at the top of the container is for the gases that are formed due to chemical reaction.

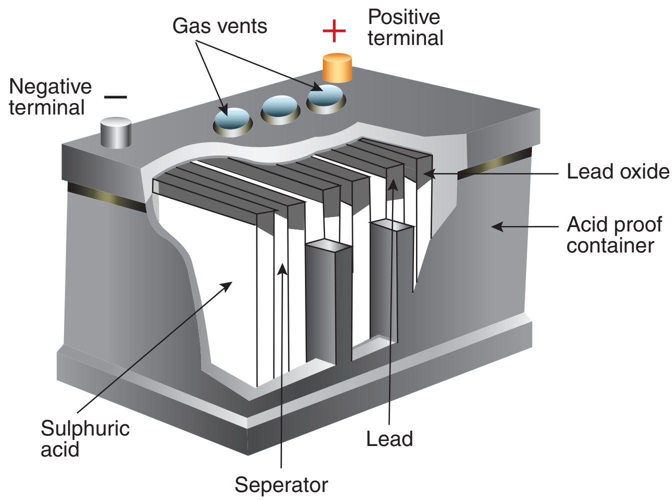


FIGURE 10 The Lead-Acid Cell

During discharge, hydrogen ions carry the positive charge and sulphate ions carry a negative charge. As a result, the plates become sulphated due to the deposition of lead sulphate. Hydrogen ions enter the positive plate and form water by combining with the oxygen of the lead peroxide. As a result, the positive plate lacks electrons and the negative plate has excess electrons.

Both the plates are coated with lead sulphate when the plates are externally connected by a conductor. This is when the battery is said to be discharged, since no further chemical action can take place. The battery gets recharged in a reverse process.

The normal voltage of a lead cell is 2V, a fully charged cell is 2.2V and a fully discharged cell is 1.8V.

The chemical reactions that occur in a lead-acid battery is shown below.

$$\text{Positive electrode: } PbO_2 + H_2SO_4 + 2H^+ + 2e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} PbsO_4 + 2H_2O \quad (1)$$

$$\text{Negative electrode: } Pb + H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} PbsO_4 + 2H^+ + 2e^- \quad (2)$$

$$\text{Overall cell reaction: } PbO_2 + pb + 2H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} 2PbsO_4 + 2H_2O \quad (3)$$

THE NICKEL-CADMIUM (NI-CAD) CELL

This is an alkaline cell in which the active materials are sintered onto the plates that are woven as a wire screen. The positive plate is infused with nickel oxyhydroxide and metallic cadmium is the negative plate. Nylon-cellophane-nylon separators are wrapped between the plates. The plates are aligned in a polymer container fitted with a vent plug at the top. A solution of distilled water and potassium hydroxide is used as an electrolyte. The cell construction is shown in Figure 11.

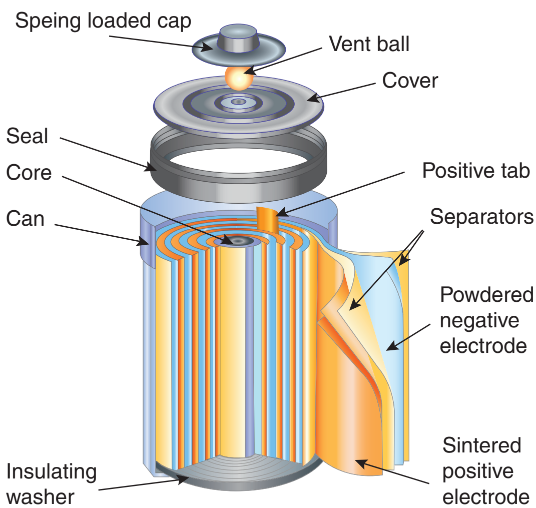
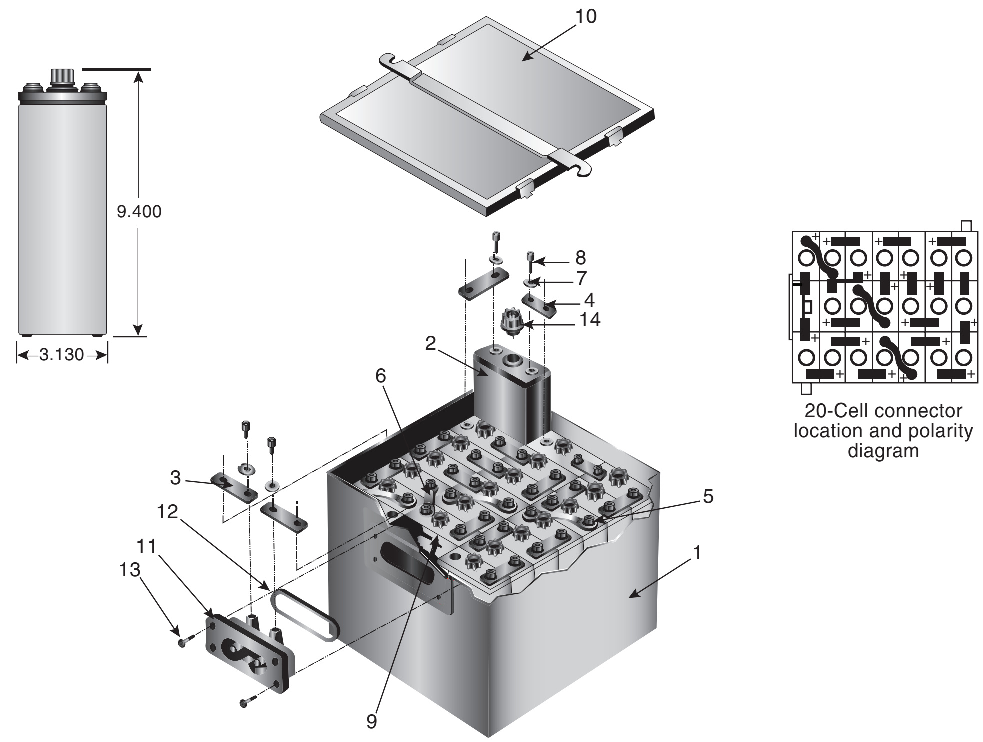


FIGURE 11 The Nickel-Cadmium Cell

As the battery discharges, hydrogen ions combine with the negative plates and electrons are released. Hydrogen ions from the positive nickel oxyhydroxide plate carry electrons and enter into the electrolyte. As a result, the electrons are driven from the positive plate and recovered by the negative plate. During charging, the hydroxide ions are forced from the negative plate and into the electrolyte, thus causing cadmium hydroxide to revert to metallic cadmium. When the cell is overcharged, it emits gas in the electrolyte and decomposes it by electrolysis. The voltage of a normal nickel cadmium cell is 1.2V and when fully charged is 1.5V.

The components of a nickel-cadmium battery are shown in Figure 12.



Item	Description	Quantity
1	Can Assembly	1
2	Cell Assembly	20
3	Connector	12
4	Connector	5
5	Connector	3
6	Connector	1
7	Belleville Spring	42

Item	Description	Quantity
8	Socket Head Cap Screw	42
9	Spacer	1
10	Cover Assembly	1
11	Receptacle Assembly	1
12	Rectangular Ring	1
13	Phillips head Screw	4
14	Filler Cap and Vent Assembly	20

FIGURE 12 Components of a Nickel-Cadmium Cell

The chemical reactions that occur in a nickel-cadmium battery are shown below.

$$\text{Positive electrode: } 2NiOOH + 2H_2O + 2e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} 2Ni(OH)_2 + 2(OH)^-$$

$$\text{Negative electrode: } Cd + 2(OH)^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} Cd(OH)_2 + 2e^-$$

$$\text{Overall cell reaction: } 2NiOOH + Cd + 2H_2O \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} 2Ni(OH)_2 + Cd(OH)_2$$

Earlier commercial airplane models, such as the 777, 747 and MD-11, used nickel cadmium (Ni-Cad) batteries, which are heavier, larger and less powerful.

Maintenance requirements of Ni-Cad batteries

All aircraft Ni-Cad batteries require routine maintenance check-ups in order to maximize service life, in addition to ensuring the safety and continued airworthiness of aircraft. Maintenance procedures include capacity checks, cell equalization, cleaning to remove corrosion and carbonate build-up, and electrolyte adjustment.

For sealed-cell batteries, very little maintenance is required, since there is no requirement for electrolyte adjustment or corrosion cleaning. However, capacity checks are carried out periodically. Normally, maintenance intervals for commercial aircraft batteries can be from 100 to 1000 flying hours.

Storage of Ni-Cad batteries

Ni-Cad batteries can be stored in any state of charge and over temperature ranging between -65°C and 60°C. However, it is best to store batteries between 0 and 30°C for maximum shelf life. Vented-cell batteries are stored with the terminals shorted together. Shorting of sealed-cell batteries during storage is not recommended, as it may cause cell venting and/or cell reversal.

When left on open circuit during periods of non-operation, self-discharging occurs at a rapid rate. As a rule of thumb, the self-discharge rate of sealed cells is approximately 1% per day at 20°C (when averaged over 30 days), and the rate increases by 1% per day for every 10°C rise in temperature. The self-discharge rate is slightly less for vented cells. Usually, the capacity lost through self-discharge is recoverable when charged in the usual manner.

THE LITHIUM ION (LI-ION) CELL

The lithium battery is a primary cell whereas a lithium ion cell is a secondary cell type, which is widely used in portable electronic equipment and in military aircraft. The positive electrode is made of lithium cobalt oxide (LiCoO2) or lithium iron phosphate (LiFePO4) and the negative electrode is made of carbon (graphite). The electrolyte is made up of lithium salts in an organic solvent. Figure 13 shows the lithium-ion cell.

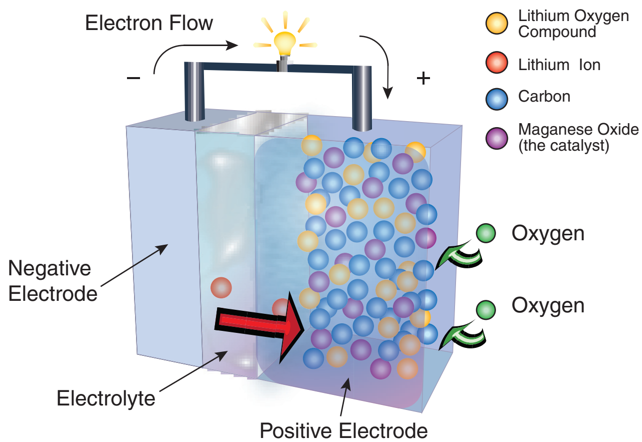


FIGURE 13 The Lithium Ion Cell

Charging of Li-Ion batteries

The charging and discharging processes of all lithium ion batteries more or less work in same manner. During charging, lithium ions from the positive electrode reach the negative electrode through the electrolyte, and remain there. The cells store energy during this charging process, that can used later when discharging.

Discharging of Li-Ion batteries

During discharge, the lithium ions are transferred from the negative electrode to the positive electrode (Figure 14). And this process is reversed during charging. These cells can hold charge well, but can explode if overheated.

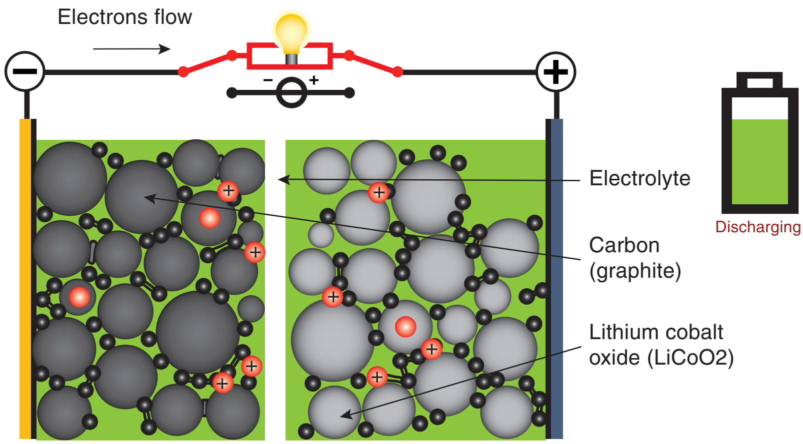


FIGURE 14 Discharging in Lithium Ion Cell

The movement of ions through the electrolyte and the electrons through the external circuit are interconnected processes. If one process stops, the other one ceases too. When the battery is fully discharged, the movement of ions and electrons stops, and the battery loses its power. A similar thing happens when you switch off the appliance that a battery is powering. However, the battery will continue discharging at a very slow rate even when the appliance is switched off. In order to prevent overheating and rare incidences of explosion, the newer lithium ion batteries have built-in electronic controllers that can regulate charging and discharging rates.

Advantages of Li-Ion batteries

- No regular maintenance required to ensure their performance.
- Highly reliable when compared to nickel-cadmium batteries.
- High energy density, which gives extra and extended power between charges.
- Lower self-discharge rate than other rechargeable cells such as Ni-Cad and NiMH (Nickel-metal-hydride) batteries.
- The battery can be recharged at any stage of charge, unlike NiCad batteries which need to be fully discharged before recharging.

Disadvantages of Li-Ion batteries

- Ageing is the major disadvantage. This depends on time, and the number of charge and discharge cycles.
- Thermal runaway causes lithium ion batteries to heat up and catch fire. This occurs when the batteries are overcharged or short circuited due to internal malfunction.

PRIMARY VS SECONDARY CELLS

Features	Primary	Secondary
Initial cost	Cheap	Expensive
Weight	Lighter	Comparatively heavier
Size	Smaller	Comparatively larger
Self-discharge rate	Lower	Higher
User-friendliness	Easy	Complex
Recharging need	Disposable	Requires periodic recharging
Maintenance	Disposable	Requires regular maintenance
Charge retention	Good	Comparatively poor
Replacement	Readily available	May require pre-ordering
Life-cycle cost	High	Low
Suitability	Not suitable for heavy load performance	Best suitable for heavy load performance
Applications	Limited to specific applications such as in toys, watches and so on	Broader spectrum of uses including high-cost military applications

CELLS CONNECTED IN SERIES AND PARALLEL

Cells in Series

We can connect the same type of cells in series when a higher voltage is needed. The resistance and the minimal current must be the same for all the cells. In this type, the positive terminal of one cell is connected to the negative terminal of the other.

The voltage output is the sum of voltages of the individual cells, but the total capacity remains the same. The secondary cells are connected in series within the battery case in aircraft storage batteries. Figure 15 shows the cells connected in series.

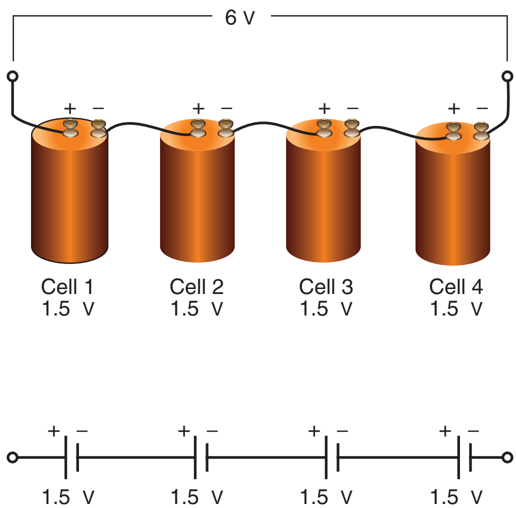


FIGURE 15 Cells Connected in Series

Cells in Parallel

Cells connected in parallel provide greater current carrying capacity. This type of battery system is commonly used in aircraft engine starting systems. In this case, all the positive terminals are connected together and all the negative terminals are connected together. The current output of all the cells are added but the total voltage output of the whole battery remains the same. For example, a battery with many 1.5V cells connected in parallel will still provide 1.5V total output. Figure 16 shows the cells connected in parallel.

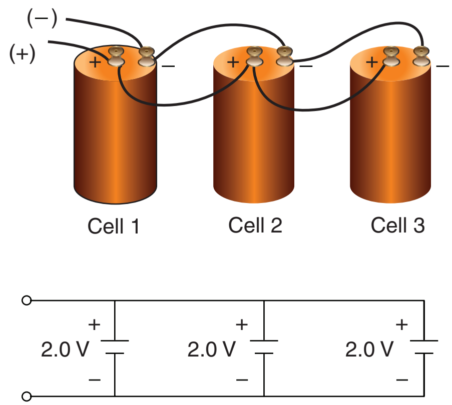


FIGURE 16 Cells Connected in Parallel

FUEL CELLS

Fuel cells are capable of producing electrical energy as long as active materials are fed to the electrodes. Here, the active materials are not an integral part of the device. These types of cells are commonly used in space vehicles, in addition to the recent advancement in electric vehicles and aircraft design systems. The various types of fuel cells are described below.

The PEM (Proton Exchange Membrane) Cell

The PEM cell consists of two electrodes (cathode and anode) that are separated by an electrolyte. A solid organic polymer is used as an electrolyte. Oxygen passes through the cathode and hydrogen fuel is fed into the anode side. As a result, generation of electricity, heat and water all take place. This electron movement creates a current that can be utilised. They then returned to the cathode to reunite with hydrogen and oxygen in a water molecule. A fuel cell can produce between 50-250kW of power.

The PAFC (Phosphoric Acid Fuel Cell)

These fuel cell types use liquid phosphoric acid as an electrolyte. They are widely used in various stationary applications such as in airport terminals due to their stability and performance.

The MCFC (Molten Carbonate Fuel Cell)

These fuel cells use a solution of lithium and potassium carbonate, soaked in a matrix as an electrolyte. They can operate at very high temperatures of up to 650°C, and the output ranges from 10kW to 2MW.

The SOFC (Solid Oxide Fuel Cell)

These types use a ceramic material of solid zirconium oxide as an electrolyte. They were developed by Boeing as a fuel cell for APU (Auxiliary Power Applications) and are used in high-power industrial purposes. They can operate at very high temperatures of up to 1000oC and the power output is up to 200kW.

Alkaline Fuel Cell

An aqueous solution of alkaline potassium hydroxide soaked in a matrix is used as an electrolyte. These fuel cells are used in spacecraft to provide electricity and drinking water. They can operate at temperatures of up to 200°C and the power output ranges from 300W to 5kW.

Regenerative Fuel Cell

In this type, water is separated into hydrogen and oxygen by a solar-powered electrolyser. These elements are then fed into the fuel cell system, which generates heat, water and electricity. Since this is a closed-loop type of cell, the water is then re-circulated back to the electrolyser to begin the process again.

RESERVE CELLS

In this type of cell, the electrolyte is separated from the remaining components, until just before activation. The electrolyte remains inactive in a solid state until it reaches its melting point, paving the way for ionic conduction, and thus activating the cell. They are commonly found in thermal batteries and are used in sensitive (time/temperature/pressure) detonation devices in missiles, projectiles and other weapon systems. Water activated, electrolyte activated, gas activated and heat activated batteries are the four types of reserve cells.

BOEING 787 BATTERY SYSTEM

Reference: Boeing website

"The 787 Dreamliner has two primary rechargeable batteries – the main and auxiliary power unit (APU).

The main battery "powers up" aircraft systems bring the airplane to life before the engines have been started. Once the engines are started, the electrical energy to run the systems comes from generators.

It also is used to support ground operations such as refueling and powering the braking system when the airplane is towed. The main battery also provides backup power for critical systems during flight in the extremely unlikely event of a power failure. It is located in the forward electronics equipment (EE) bay, which is under the main cabin floor at the front of the airplane.

The APU battery supplies power to start the APU, which in turn can start the airplane engines. The APU, and its battery, also serves as part of the multiple layers of redundancy that would ensure power in the rare possibility of a loss of primary sources of power.

After extensive testing, Boeing ultimately selected the lithium-ion type battery because it has the right functionality and chemistry to deliver a large amount of power in a short period of time to do a high-energy task like start a jet engine. It then has the ability to recharge in a relatively short period of time so that it is available for the critical backup role that it plays during flight.

Earlier commercial airplane models, such as the 777, 747 and MD-11, used nickel cadmium (NiCd) batteries, which are heavier, larger and less powerful.

Batteries, like other technologies, have advanced significantly, and lithium-ion type batteries match up with the unique requirements of advanced aircraft.

Lithium-ion batteries have other key advantages that suit it for modern jet application:

- The required high voltage and high current production
- Improved power quality
- An ability to recharge quickly
- Similar functionality to that of Ni-Cad batteries while weighing 30 percent less
- Compact – about the size of the average car battery

Since entering service, Boeing 787 lithium-ion batteries, each with eight cells, have logged more than 2.2 million cell-hours on the ground and in the air during more than 50,000 flight-hours."

AEROCHAPTER®

THE PASSION STARTS HERE