
Different types of batteries and developing lead acid batteries

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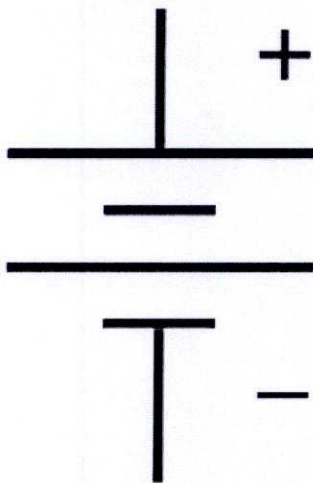
Battery (electricity)

An electrical **battery** is one or more electrochemical cells that convert stored chemical energy into electrical energy. Since the invention of the first battery (or "voltaic pile") in 1800 by Alessandro Volta and especially since the technically improved Daniell cell in 1836, batteries have become a common power source for many household and industrial applications. According to a 2005 estimate, the worldwide battery industry generates US\$48 billion in sales each year, with 6% annual growth.

There are two types of batteries: primary batteries (disposable batteries), which are designed to be used once and discarded, and secondary batteries (rechargeable batteries), which are designed to be recharged and used multiple times. Batteries come in many sizes, from miniature cells used to power hearing aids and wristwatches to battery banks the size of rooms that provide standby power for telephone exchanges and computer data centers

History

Main article: History of the battery



The symbol for a battery in a circuit diagram. It originated as a schematic drawing of the earliest type of battery, a voltaic pile.

In strict terms, a battery is a collection of multiple electrochemical cells, but in popular usage *battery* often refers to a single cell. For example, a 1.5-volt AAA

battery is a single 1.5-volt cell, and a 9-volt battery has six 1.5-volt cells in series. The first electrochemical cell was developed by the Italian physicist Alessandro Volta in 1792, and in 1800 he invented the first battery, a "pile" of many cells in series.

The usage of "battery" to describe electrical devices dates to Benjamin Franklin, who in 1748 described multiple Leyden jars (early electrical capacitors) by analogy to a battery of cannons. Thus Franklin's usage to describe multiple Leyden jars predated Volta's use of multiple galvanic cells. It is speculated, but not established, that several ancient artifacts consisting of copper sheets and iron bars, and known as Baghdad batteries may have been galvanic cells.

Volta's work was stimulated by the Italian anatomist and physiologist Luigi Galvani, who in 1780 noticed that dissected frog's legs would twitch when struck by a spark from a Leyden jar, an external source of electricity. In 1786 he noticed that twitching would occur during lightning storms. After many years Galvani learned how to produce twitching without using any external source of electricity. In 1791, he published a report on "animal electricity." He created an electric circuit consisting of the frog's leg (FL) and two different metals A and B, each metal touching the frog's leg and each other, thus producing the circuit A-FL-B-A-FL-B...etc. In modern terms, the frog's leg served as both the electrolyte and the sensor, and the metals served as electrodes. He noticed that even though the frog was dead, its legs would twitch when he touched them with the metals.

Within a year, Volta realized the frog's moist tissues could be replaced by cardboard soaked in salt water, and the frog's muscular response could be replaced by another form of electrical detection. He already had studied the electrostatic phenomenon of capacitance, which required measurements of electric charge and of electrical potential ("tension"). Building on this experience, Volta was able to detect electric current through his system, also called a Galvanic cell. The terminal voltage of a cell that is not discharging is called its electromotive force (emf), and has the same unit as electrical potential, named (voltage) and measured in volts, in honor of Volta. In 1800, Volta invented the battery by placing many voltaic cells in series, piling them one above the other. This voltaic pile gave a greatly enhanced net emf for the combination, with a voltage of about 50 volts for a 32-cell pile. In many parts of Europe batteries continue to be called piles.

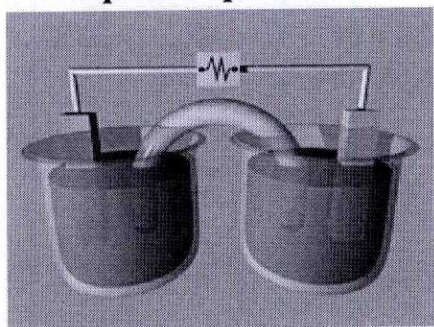
Volta did not appreciate that the voltage was due to chemical reactions. He thought that his cells were an inexhaustible source of energy, and that the associated corrosion effects at the electrodes were a mere nuisance, rather than an

unavoidable consequence of their operation, as Michael Faraday showed in 1834. According to Faraday, cations (positively charged ions) are attracted to the cathode, and anions (negatively charged ions) are attracted to the anode.

Although early batteries were of great value for experimental purposes, in practice their voltages fluctuated and they could not provide a large current for a sustained period. Later, starting with the Daniell cell in 1836, batteries provided more reliable currents and were adopted by industry for use in stationary devices, in particular in telegraph networks where they were the only practical source of electricity, since electrical distribution networks did not exist at the time. These wet cells used liquid electrolytes, which were prone to leakage and spillage if not handled correctly. Many used glass jars to hold their components, which made them fragile. These characteristics made wet cells unsuitable for portable appliances. Near the end of the nineteenth century, the invention of dry cell batteries, which replaced the liquid electrolyte with a paste, made portable electrical devices practical.

Since then, batteries have gained popularity as they became portable and useful for a variety of purposes.

Principle of operation



A voltaic cell for demonstration purposes. In this example the two half-cells are linked by a salt bridge separator that permits the transfer of ions, but not water molecules.

A battery is a device that converts chemical energy directly to electrical energy. It consists of a number of voltaic cells; each voltaic cell consists of two half-cells connected in series by a conductive electrolyte containing anions and cations. One half-cell includes electrolyte and the electrode to which anions (negatively charged

ions) migrate, i.e., the anode or negative electrode; the other half-cell includes electrolyte and the electrode to which cations (positively charged ions) migrate, i.e., the cathode or positive electrode. In the redox reaction that powers the battery, cations are reduced (electrons are added) at the cathode, while anions are oxidized (electrons are removed) at the anode. The electrodes do not touch each other but are electrically connected by the electrolyte. Some cells use two half-cells with different electrolytes. A separator between half-cells allows ions to flow, but prevents mixing of the electrolytes.

Each half-cell has an electromotive force (or emf), determined by its ability to drive electric current from the interior to the exterior of the cell. The net emf of the cell is the difference between the emfs of its half-cells, as first recognized by Volta. Therefore, if the electrodes have emfs $\mathcal{E}_1$ and $\mathcal{E}_2$, then the net emf is $\mathcal{E}_2 - \mathcal{E}_1$; in other words, the net emf is the difference between the reduction potentials of the half-reactions.

The electrical driving force or ΔV_{bat} across the terminals of a cell is known as the *terminal voltage (difference)* and is measured in volts. The terminal voltage of a cell that is neither charging nor discharging is called the open-circuit voltage and equals the emf of the cell. Because of internal resistance, the terminal voltage of a cell that is discharging is smaller in magnitude than the open-circuit voltage and the terminal voltage of a cell that is charging exceeds the open-circuit voltage. An ideal cell has negligible internal resistance, so it would maintain a constant terminal voltage of $\mathcal{E}$ until exhausted, then dropping to zero. If such a cell maintained 1.5 volts and stored a charge of one coulomb then on complete discharge it would perform 1.5 joule of work. In actual cells, the internal resistance increases under discharge, and the open circuit voltage also decreases under discharge. If the voltage and resistance are plotted against time, the resulting graphs typically are a curve; the shape of the curve varies according to the chemistry and internal arrangement employed.

As stated above, the voltage developed across a cell's terminals depends on the energy release of the chemical reactions of its electrodes and electrolyte. Alkaline and zinc-carbon cells have different chemistries but approximately the same emf of 1.5 volts; likewise NiCd and NiMH cells have different chemistries, but approximately the same emf of 1.2 volts. On the other hand the high electrochemical potential changes in the reactions of lithium compounds give lithium cells emfs of 3 volts or more.

Categories and types of batteries

Batteries are classified into two broad categories, each type with advantages and disadvantages.

- *Primary* batteries irreversibly (within limits of practicality) transform chemical energy to electrical energy. When the initial supply of reactants is exhausted, energy cannot be readily restored to the battery by electrical means.
- *Secondary* batteries can be recharged; that is, they can have their chemical reactions reversed by supplying electrical energy to the cell, restoring their original composition.

Some types of primary batteries used, for example, for telegraph circuits, were restored to operation by replacing the components of the battery consumed by the chemical reaction. Secondary batteries are not indefinitely rechargeable due to dissipation of the active materials, loss of electrolyte and internal corrosion.

Primary batteries

Primary batteries can produce current immediately on assembly. Disposable batteries are intended to be used once and discarded. These are most commonly used in portable devices that have low current drain, are used only intermittently, or are used well away from an alternative power source, such as in alarm and communication circuits where other electric power is only intermittently available. Disposable primary cells cannot be reliably recharged, since the chemical reactions are not easily reversible and active materials may not return to their original forms. Battery manufacturers recommend against attempting to recharge primary cells.

Common types of disposable batteries include zinc–carbon batteries and alkaline batteries. In general, these have higher energy densities than rechargeable batteries, but disposable batteries do not fare well under high-drain applications with loads under 75 ohms (75 Ω).

Secondary batteries

Secondary batteries must be charged before use; they are usually assembled with active materials in the discharged state. Rechargeable batteries or *secondary cells* can be recharged by applying electric current, which reverses the chemical

reactions that occur during its use. Devices to supply the appropriate current are called chargers or rechargers.

The oldest form of rechargeable battery is the lead–acid battery. This battery is notable in that it contains a liquid in an unsealed container, requiring that the battery be kept upright and the area be well ventilated to ensure safe dispersal of the hydrogen gas produced by these batteries during overcharging. The lead–acid battery is also very heavy for the amount of electrical energy it can supply. Despite this, its low manufacturing cost and its high surge current levels make its use common where a large capacity (over approximately 10 Ah) is required or where the weight and ease of handling are not concerns.

A common form of the lead–acid battery is the modern car battery, which can, in general, deliver a peak current of 450 amperes. An improved type of liquid electrolyte battery is the sealed valve regulated lead–acid battery (VRLA battery), popular in the automotive industry as a replacement for the lead–acid wet cell. The VRLA battery uses an immobilized sulfuric acid electrolyte, reducing the chance of leakage and extending shelf life. VRLA batteries have the electrolyte immobilized, usually by one of two means:

- *Gel batteries* (or "gel cell") contain a semi-solid electrolyte to prevent spillage.
- *Absorbed Glass Mat* (AGM) batteries absorb the electrolyte in a special fiberglass matting.

Other portable rechargeable batteries include several "dry cell" types, which are sealed units and are, therefore, useful in appliances such as mobile phones and laptop computers. Cells of this type (in order of increasing power density and cost) include nickel–cadmium (NiCd), nickel–zinc (NiZn), nickel metal hydride (NiMH), and lithium-ion (Li-ion) cells. By far, Li-ion has the highest share of the dry cell rechargeable market. Meanwhile, NiMH has replaced NiCd in most applications due to its higher capacity, but NiCd remains in use in power tools, two-way radios, and medical equipment. NiZn is a new technology that is not yet well established commercially.

Recent developments include batteries with embedded electronics such as USBCELL, which allows charging an AA cell through a USB connector, and smart battery packs with state-of-charge monitors and battery protection circuits to prevent damage on over-discharge. low self-discharge (LSD) allows secondary cells to be precharged prior to shipping.

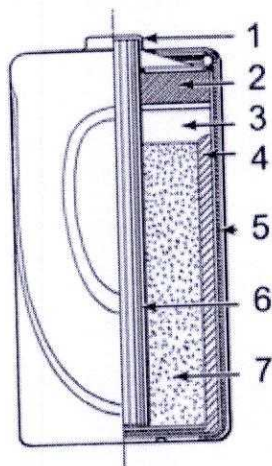
Battery cell types

There are many general types of electrochemical cells, according to chemical processes applied and design chosen. The variation includes galvanic cells, electrolytic cells, fuel cells, flow cells and voltaic piles.

Wet cell

A *wet cell* battery has a liquid electrolyte. Other names are *flooded cell*, since the liquid covers all internal parts, or *vented cell*, since gases produced during operation can escape to the air. Wet cells were a precursor to dry cells and are commonly used as a learning tool for electrochemistry. It is often built with common laboratory supplies, such as beakers, for demonstrations of how electrochemical cells work. A particular type of wet cell known as a concentration cell is important in understanding corrosion. Wet cells may be primary cells (non-rechargeable) or secondary cells (rechargeable). Originally, all practical primary batteries such as the Daniell cell were built as open-topped glass jar wet cells. Other primary wet cells are the Leclanche cell, Grove cell, Bunsen cell, Chromic acid cell, Clark cell, and Weston cell. The Leclanche cell chemistry was adapted to the first dry cells. Wet cells are still used in automobile batteries and in industry for standby power for switchgear, telecommunication or large uninterruptible power supplies, but in many places batteries with gel cells have been used instead. These applications commonly use lead-acid or nickel-cadmium cells.

Dry cell



Line art drawing of a dry cell:
1. brass cap, 2. plastic seal, 3. expansion space, 4. porous cardboard, 5. zinc can,
6. carbon rod, 7. chemical mixture.

A *dry cell* has the electrolyte immobilized as a paste, with only enough moisture in it to allow current to flow. Unlike a wet cell, a dry cell can operate in any orientation without spilling as it contains no free liquid, making it suitable for portable equipment. By comparison, the first wet cells were typically fragile glass containers with lead rods hanging from the open top, and needed careful handling to avoid spillage. Lead-acid batteries did not achieve the safety and portability of the dry cell until the development of the gel battery.

A common dry cell battery is the zinc-carbon battery, using a cell sometimes called the dry Leclanché cell, with a nominal voltage of 1.5 volts, the same as the alkaline battery (since both use the same zinc-manganese dioxide combination).

A standard dry cell comprises a zinc anode (negative pole), usually in the form of a cylindrical pot, with a carbon cathode (positive pole) in the form of a central rod. The electrolyte is ammonium chloride in the form of a paste next to the zinc anode. The remaining space between the electrolyte and carbon cathode is taken up by a second paste consisting of ammonium chloride and manganese dioxide, the latter acting as a depolariser. In some more modern types of so-called 'high-power' batteries (with much lower capacity than standard alkaline batteries), the ammonium chloride is replaced by zinc chloride.

Molten salt

Molten salt batteries are primary or secondary batteries that use a molten salt as electrolyte. Their energy density and power density give them potential for use in electric vehicles, but they operate at high temperatures and must be well insulated to retain heat.

Reserve

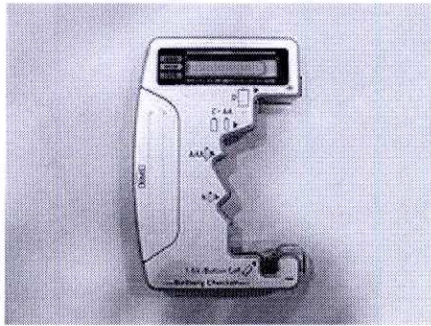
A reserve battery is stored in unassembled form and is activated, ready-charged, when its internal parts are assembled, e.g. by adding electrolyte; it can be stored unactivated for a long period of time. For example, a battery for an electronic fuze might be activated by the impact of firing a gun, breaking a capsule of electrolyte to activate the battery and power the fuze's circuits. Reserve batteries are usually designed for a short service life (seconds or minutes) after long storage (years). A

water-activated battery for oceanographic instruments or military applications becomes activated on immersion in water.

Battery cell performance

A battery's characteristics may vary over load cycle, over charge cycle, and over lifetime due to many factors including internal chemistry, current drain, and temperature.

Battery capacity and discharging



A device to check battery voltage.

A battery's **capacity** is the amount of electric charge it can store. The more electrolyte and electrode material there is in the cell the greater the capacity of the cell. A small cell has less capacity than a larger cell with the same chemistry, and they develop the same open-circuit voltage.

Because of the chemical reactions within the cells, the capacity of a battery depends on the discharge conditions such as the magnitude of the current (which may vary with time), the allowable terminal voltage of the battery, temperature, and other factors. The available capacity of a battery depends upon the rate at which it is discharged. If a battery is discharged at a relatively high rate, the available capacity will be lower than expected.

The capacity printed on a battery is usually the product of 20 hours multiplied by the constant current that a new battery can supply for 20 hours at 68 F° (20 C°), down to a specified terminal voltage per cell. A battery rated at 100 A·h will deliver 5 A over a 20-hour period at room temperature. However, if discharged at 50 A, it will have a lower capacity.

The relationship between current, discharge time, and capacity for a lead acid battery is approximated (over a certain range of current values) by Peukert's law:

$$t = \frac{Q_P}{I^k}$$

where

Q_P is the capacity when discharged at a rate of 1 amp.

I is the current drawn from battery (A).

t is the amount of time (in hours) that a battery can sustain.

k is a constant around 1.3.

For low values of I internal self-discharge must be included.

Internal energy losses and limited rate of diffusion of ions through the electrolyte cause the efficiency of a real battery to vary at different discharge rates. When discharging at low rate, the battery's energy is delivered more efficiently than at higher discharge rates, but if the rate is very low, it will partly self-discharge during the long time of operation, again lowering its efficiency.

Installing batteries with different A·h ratings will not affect the operation of a device (except for the time it will work for) rated for a specific voltage unless the load limits of the battery are exceeded. High-drain loads such as digital cameras can result in delivery of less total energy, as happens with alkaline batteries. For example, a battery rated at 2000 mA·h for a 10- or 20-hour discharge would not sustain a current of 1 A for a full two hours as its stated capacity implies.

Fastest charging, largest, and lightest batteries

As of 2012 Lithium iron phosphate (LiFePO_4) batteries were the fastest-charging and discharging batteries (supercapacitors, in some ways comparable to batteries, charge faster). The world's largest battery, composed of Ni–Cd cells, was in Fairbanks, Alaska. Sodium–sulfur batteries were being used to store wind power. Lithium–sulfur batteries have been used on the longest and highest solar-powered flight. The speed of recharging of lithium-ion batteries can be increased by manufacturing changes.

Battery lifetime

Primary batteries

Disposable (or "primary") batteries typically lose 8 to 20 percent of their original charge every year at room temperature (20°–30°C). This is known as the "self discharge" rate, and is due to non-current-producing "side" chemical reactions which occur within the cell even if no load is applied. The rate of the side reactions is reduced if the batteries are stored at lower temperature, although some batteries can be damaged by freezing. High or low working temperatures may reduce battery performance. This will affect the initial voltage of the battery. For an AA alkaline battery, this initial voltage is approximately normally distributed around 1.6 volts.

Discharging performance of all batteries drops at low temperature.

Secondary batteries

Storage life of secondary batteries is limited by chemical reactions that occur between the battery parts and the electrolyte; these are called "side reactions". Internal parts may corrode and fail, or the active materials may be slowly converted to inactive forms. Since the active material on the battery plates changes chemical composition on each charge and discharge cycle, active material may be lost due to physical changes of volume; this may limit the cycle life of the battery.



Rechargeable batteries.

Old chemistry rechargeable batteries self-discharge more rapidly than disposable alkaline batteries, especially nickel-based batteries; a freshly charged nickel cadmium (NiCd) battery loses 10% of its charge in the first 24 hours, and

thereafter discharges at a rate of about 10% a month. However, newer low self-discharge nickel metal hydride (NiMH) batteries and modern lithium designs have reduced the self-discharge rate to a relatively low level (but still poorer than for primary batteries). Most nickel-based batteries are partially discharged when purchased, and must be charged before first use. Newer NiMH batteries are ready to be used when purchased, and have only 15% discharge in a year.

Although rechargeable batteries have their energy content restored by charging, some deterioration occurs on each charge–discharge cycle. Low-capacity NiMH batteries (1700–2000 mA·h) can be charged for about 1000 cycles, whereas high-capacity NiMH batteries (above 2500 mA·h) can be charged for about 500 cycles. NiCd batteries tend to be rated for 1000 cycles before their internal resistance permanently increases beyond usable values. Under normal circumstances, a fast charge, rather than a slow overnight charge, will shorten battery lifespan. However, if the overnight charger is not "smart" and cannot detect when the battery is fully charged, then overcharging is likely, which also damages the battery. Degradation usually occurs because electrolyte migrates away from the electrodes or because active material falls off the electrodes. NiCd batteries suffer the drawback that they should be fully discharged before recharge. Without full discharge, crystals may build up on the electrodes, thus decreasing the active surface area and increasing internal resistance. This decreases battery capacity and causes the "memory effect". These electrode crystals can also penetrate the electrolyte separator, thereby causing shorts. NiMH, although similar in chemistry, does not suffer from memory effect to quite this extent. A battery does not suddenly stop working; its capacity gradually decreases over its lifetime, until it can no longer hold sufficient charge.



An analog camcorder battery [lithium ion].

Automotive lead–acid rechargeable batteries have a much harder life. Because of vibration, shock, heat, cold, and sulfation of their lead plates, few automotive batteries last beyond six years of regular use. Automotive starting batteries have many thin plates to provide as much current as possible in a reasonably small package. In general, the thicker the plates, the longer the life of the battery. They are typically drained only a small amount before recharge. Care should be taken to avoid deep discharging a starting battery, since each charge and discharge cycle causes active material to be shed from the plates.

"Deep-cycle" lead–acid batteries such as those used in electric golf carts have much thicker plates to aid their longevity. The main benefit of the lead–acid battery is its low cost; the main drawbacks are its large size and weight for a given capacity and voltage. Lead–acid batteries should never be discharged to below 20% of their full capacity, because internal resistance will cause heat and damage when they are recharged. Deep-cycle lead–acid systems often use a low-charge warning light or a low-charge power cut-off switch to prevent the type of damage that will shorten the battery's life.

Extending battery life

Battery life can be extended by storing the batteries at a low temperature, as in a refrigerator or freezer, which slows the chemical reactions in the battery. Such storage can extend the life of alkaline batteries by about 5%; rechargeable batteries can hold their charge much longer, depending upon type. To reach their maximum voltage, batteries must be returned to room temperature; discharging an alkaline battery at 250 mA at 0°C is only half as efficient as it is at 20°C. Alkaline battery manufacturers such as Duracell do not recommend refrigerating batteries.

Prolonging life in multiple cells through cell balancing

Analog front ends that balance cells and eliminate mismatches of cells in series or parallel combination significantly improve battery efficiency and increase the overall pack capacity. As the number of cells and load currents increase, the potential for mismatch also increases. There are two kinds of mismatch in the pack: state-of-charge (SOC) mismatch and capacity/energy (C/E) mismatch.

Though the SOC mismatch is more common, each problem limits the pack capacity (mAh) to the capacity of the weakest cell.

Cell balancing principle

Battery pack cells are balanced when all the cells in the battery pack meet two conditions:

1. If all cells have the same capacity, then they are balanced when they have the same State of Charge (SOC.) In this case, the Open Circuit Voltage (OCV) is a good measure of the SOC. If, in an out of balance pack, all cells can be differentially charged to full capacity (balanced), then they will subsequently cycle normally without any additional adjustments. This is mostly a one-shot fix.
2. If the cells have different capacities, they are also considered balanced when the SOC is the same. But, since SOC is a relative measure, the absolute amount of capacity for each cell is different. To keep the cells with different capacities at the same SOC, cell balancing must provide differential amounts of current to cells in the series string during both charge and discharge on every cycle.

Cell balancing electronics

Cell balancing is defined as the application of differential currents to individual cells (or combinations of cells) in a series string. Cells in a series string normally receive identical currents. A battery pack requires additional components and circuitry to achieve cell balancing. However, the use of a fully integrated analog front end for cell balancing reduces the required external components to just balancing resistors.

Cell mismatch results more from limitations in process control and inspection than from variations inherent in the lithium ion chemistry. The use of a fully integrated analog front end for cell balancing can improve the performance of series connected Li-ion Cells by addressing both SOC and C/E issues. SOC mismatch can be remedied by balancing the cell during an initial conditioning period and subsequently only during the charge phase. C/E mismatch remedies are more difficult to implement and harder to measure and require balancing during both charge and discharge periods.

This solution eliminates the quantity of external components, as for discrete capacitors, diodes, and most other resistors to achieve balance.

Battery sizes

Primary batteries readily available to consumers range from tiny button cells used for electric watches, to the No. 6 cell used for signal circuits or other long duration applications. Secondary cells are made in very large sizes; very large batteries can power a submarine. Large secondary batteries have been used to stabilize the electrical grid and help level out peak loads.

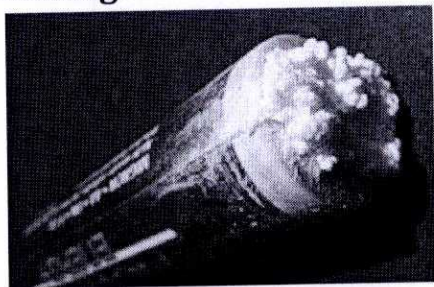
Hazards

Explosion

A battery explosion is caused by the misuse or malfunction of a battery, such as attempting to recharge a primary (non-rechargeable) battery, or short circuiting a battery. Car batteries are most likely to explode when a short-circuit generates very large currents. Car batteries liberate hydrogen, which is very explosive, when they are overcharged (because of electrolysis of the water in the electrolyte). The amount of overcharging is usually very small and generates little hydrogen, which dissipates quickly. However, when "jumping" a car battery, the high current can cause the rapid release of large volumes of hydrogen, which can be ignited explosively by a nearby spark, for example, when disconnecting a jumper cable.

When a battery is recharged at an excessive rate, an explosive gas mixture of hydrogen and oxygen may be produced faster than it can escape from within the walls of the battery, leading to pressure build-up and the possibility of bursting of the battery case. In extreme cases, the battery acid may spray violently from the casing of the battery and cause injury. Overcharging—that is, attempting to charge a battery beyond its electrical capacity—can also lead to a battery explosion, in addition to leakage or irreversible damage. It may also cause damage to the charger or device in which the overcharged battery is later used. In addition, disposing of a battery in fire may cause an explosion as steam builds up within the sealed case of the battery.

Leakage



Leaked alkaline battery.

Many battery chemicals are corrosive, poisonous, or both. If leakage occurs, either spontaneously or through accident, the chemicals released may be dangerous.

For example, disposable batteries often use a zinc "can" both as a reactant and as the container to hold the other reagents. If this kind of battery is run all the way down, or if it is recharged after running down too far, the reagents can emerge through the cardboard and plastic that form the remainder of the container. The active chemical leakage can then damage the equipment that the batteries were inserted into. For this reason, many electronic device manufacturers recommend removing the batteries from devices that will not be used for extended periods of time.

Environmental concerns

The widespread use of batteries has created many environmental concerns, such as toxic metal pollution. Battery manufacture consumes resources and often involves hazardous chemicals. Used batteries also contribute to electronic waste. Some areas now have battery recycling services available to recover some of the materials from used batteries. Batteries may be harmful or fatal if swallowed. Recycling or proper disposal prevents dangerous elements (such as lead, mercury, and cadmium) found in some types of batteries from entering the environment. In the United States, Americans purchase nearly three billion batteries annually, and about 179,000 tons of those end up in landfills across the country.

In the United States, the Mercury-Containing and Rechargeable Battery Management Act of 1996 banned the sale of mercury-containing batteries, enacted uniform labeling requirements for rechargeable batteries, and required that rechargeable batteries be easily removable. California, and New York City prohibit

the disposal of rechargeable batteries in solid waste, and along with Maine require recycling of cell phones. The rechargeable battery industry has nationwide recycling programs in the United States and Canada, with dropoff points at local retailers.

The Battery Directive of the European Union has similar requirements, in addition to requiring increased recycling of batteries, and promoting research on improved battery recycling methods. In accordance with this directive all batteries to be sold within the EU must be marked with the "collection symbol" (A crossed out wheeled bin). This must cover at least 3% of the surface of prismatic batteries and 1.5% of the surface of cylindrical batteries. All packaging must be marked likewise.

Ingestion

Small button cells can be swallowed, particularly by young children. While in the digestive tract the battery's electrical discharge may lead to tissue damage; such damage is occasionally serious and very rarely even leads to death. Ingested disk batteries do not usually cause problems unless they become lodged in the gastrointestinal (GI) tract. The most common place disk batteries become lodged, resulting in clinical sequelae, is the esophagus. Batteries that successfully traverse the esophagus are unlikely to lodge at any other location. The likelihood that a disk battery will lodge in the esophagus is a function of the patient's age and the size of the battery. Disk batteries of 16 mm have become lodged in the esophagi of 2 children younger than 1 year. Older children do not have problems with batteries smaller than 21–23 mm. Liquefaction necrosis may occur because sodium hydroxide is generated by the current produced by the battery (usually at the anode). Perforation has occurred as rapidly as 6 hours after ingestion.

Battery chemistry

Primary battery chemistries

Chemistry	Nominal	Specific	Elaboration
	Cell	Energy	
	Voltage	[MJ/kg]	

Chemistry	Nominal Cell Voltage	Specific Energy [MJ/kg]	Elaboration
Zinc-carbon	1.5	0.13	Inexpensive.
Zinc-chloride	1.5		Also known as "heavy duty", inexpensive.
Alkaline (zinc-manganese dioxide)	1.5	0.4-0.59	Moderate energy density. Good for high and low drain uses.
Nickel oxyhydroxide (zinc-manganese dioxide/nickel oxyhydroxide)	1.7		Moderate energy density. Good for high drain uses
Lithium (lithium-copper oxide) Li-CuO	1.7		No longer manufactured. Replaced by silver oxide (IEC-type "SR") batteries.
Lithium (lithium-iron disulfide) LiFeS ₂	1.5		Expensive. Used in 'plus' or 'extra' batteries.
Lithium (lithium-manganese dioxide) LiMnO ₂	3.0	0.83-1.01	Expensive. Only used in high-drain devices or for long shelf life due to very low rate of self discharge. 'Lithium' alone usually refers to this type of chemistry.
Mercury oxide	1.35		High drain and constant voltage. Banned in most countries because

Chemistry	Nominal Cell Voltage	Specific Energy [MJ/kg]	Elaboration
			of health concerns.
Zinc-air	1.35–1.65	1.59	Mostly used in hearing aids.
Silver-oxide (silver-zinc)	1.55	0.47	Very expensive. Only used commercially in 'button' cells.

Rechargeable battery chemistries

(includes data from energy density article)

Chemistry	Cell Voltage	Specific Energy [MJ/kg]	Comments
			Inexpensive. High/low drain, moderate energy density. Can withstand very high discharge rates with virtually no loss of capacity. Moderate rate of self discharge. Reputed to suffer from memory effect (which is alleged to cause early failure). Environmental hazard due to Cadmium – use now virtually prohibited in Europe.
NiCd	1.2	0.14	
			Moderately expensive. Moderate energy density. Moderate rate of self discharge. Higher discharge rates result in considerable loss of
Lead-acid	2.1	0.14	

Chemistry	Cell Voltage	Specific Energy [MJ/kg]	Comments
			capacity. Does not suffer from memory effect. Environmental hazard due to Lead. Common use – Automobile batteries
NiMH	1.2	0.36	Inexpensive. Performs better than alkaline batteries in higher drain devices. Traditional chemistry has high energy density, but also a high rate of self-discharge. Newer chemistry has low self-discharge rate, but also a ~25% lower energy density. Very heavy. Used in some cars.
NiZn	1.6	0.36	Moderately inexpensive. High drain device suitable. Low self-discharge rate. Voltage closer to alkaline primary cells than other secondary cells. No toxic components. Newly introduced to the market (2009). Has not yet established a track record. Limited size availability.
Lithium ion	3.6	0.46	Very expensive. Very high energy density. Not usually available in "common" battery sizes. Very common in laptop computers, moderate to high-end digital cameras and camcorders, and cellphones

Chemistry	Cell Voltage	Specific Energy [MJ/kg]	Comments
			Very low rate of self discharge. Volatile: Chance of explosion if short circuited, allowed to overheat, or not manufactured with rigorous quality standards.

Homemade cells

Almost any liquid or moist object that has enough ions to be electrically conductive can serve as the electrolyte for a cell. As a novelty or science demonstration, it is possible to insert two electrodes made of different metals into a lemon, potato, etc. and generate small amounts of electricity. "Two-potato clocks" are also widely available in hobby and toy stores; they consist of a pair of cells, each consisting of a potato (lemon, et cetera) with two electrodes inserted into it, wired in series to form a battery with enough voltage to power a digital clock. Homemade cells of this kind are of no real practical use, because they produce far less current and cost far more per unit of energy generated—than commercial cells

A voltaic pile can be made from two coins (such as a nickel and a penny) and a piece of paper towel dipped in salt water. Such a pile generates a very low voltage but, when many are stacked in series, they can replace normal batteries for a short time.

Sony has developed a biological battery that generates electricity from sugar in a way that is similar to the processes observed in living organisms. The battery generates electricity through the use of enzymes that break down carbohydrates, which are, in essence, sugar.

Lead acid cells can easily be manufactured at home, but a tedious charge/discharge cycle is needed to 'form' the plates. This is a process in which lead sulfate forms on the plates, and during charge is converted to lead dioxide (positive plate) and pure lead (negative plate). Repeating this process results in a microscopically rough surface, with far greater surface area being exposed. This increases the current the cell can deliver.

List of battery types

Types

Primary cells or non-rechargeable batteries	Secondary cells or rechargeable batteries	Batteries by application
- Alkaline battery - Aluminium battery - Atomic battery - Optoelectric nuclear battery - Nuclear micro-battery - Bunsen cell - Chromic acid cell - Clark cell - Daniell cell - Dry cell - Earth battery - Frog battery - Galvanic cell - Grove cell - Leclanché cell - Lemon battery - Lithium battery - Lithium air battery - Mercury battery - Molten salt battery - Nickel oxyhydroxide battery - Oxyride battery - Organic radical battery - Paper battery - Pulvermacher's chain - Reserve battery - Silver-oxide battery	- Flow battery - Vanadium redox battery - Zinc-bromine flow battery - Fuel cell - Lead-acid battery - Deep cycle battery - VRLA battery - AGM battery - Gel battery - Lithium air battery - Lithium-ion battery - Beltway battery - Lithium ion polymer battery - Lithium iron phosphate battery - Lithium-sulfur battery - Lithium-titanate battery - Molten salt battery - Nickel-cadmium battery - Nickel-cadmium battery	- Backup battery - Baghdad Battery - Battery (vacuum tube) - Battery pack - Battery room - Biobattery - Button cell - Car battery - CMOS battery - Common battery - Commodity cell - Electric vehicle battery - Flow battery - Inverter battery - Lantern battery - Nanobatteries - Nanowire battery - Local battery - Polapulse battery - Photoflash battery - Smart battery system - Thin film rechargeable lithium battery - Traction battery - Watch battery - Water-activated

• Solid-state battery • Voltaic pile ◦ Penny battery ◦ Trough battery • Water-activated battery • Weston cell • Zinc-air battery • Zinc-carbon battery • Zinc chloride battery	vented cell type • Nickel hydrogen battery • Nickel-iron battery • Nickel metal hydride battery ◦ Low self-discharge NiMH battery • Nickel-zinc battery • Organic radical battery • Polymer-based battery • Polysulfide bromide battery • Potassium-ion battery • Rechargeable alkaline battery • Silicon air battery • Sodium-ion battery • Sodium-sulfur battery • Super iron battery • Zinc-bromine flow battery • Zinc matrix battery	battery • Wet cell • Zamboni pile
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Primary cells:

Alkaline battery

Alkaline batteries are a type of primary batteries dependent upon the reaction between zinc and manganese dioxide (Zn/MnO_2). A rechargeable alkaline battery allows reuse of specially designed cells.

Compared with zinc-carbon batteries of the Leclanché or zinc chloride types, alkaline batteries have a higher energy density and longer shelf-life, with the same voltage. Button cell silver-oxide batteries have higher energy density and capacity but also higher cost than similar-size alkaline cells.

The alkaline battery gets its name because it has an alkaline electrolyte of potassium hydroxide, instead of the acidic ammonium chloride or zinc chloride electrolyte of the zinc-carbon batteries. Other battery systems also use alkaline electrolytes, but they use different active materials for the electrodes.

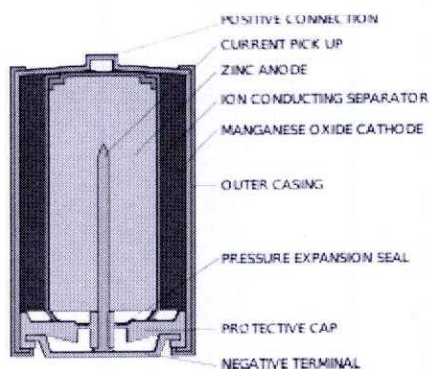
Alkaline batteries account for 80% of manufactured batteries in the US and over 10 billion individual units produced worldwide. In Japan alkaline batteries account for 46% of all primary battery sales. In Switzerland alkaline batteries account for 68%, in the UK 60% and in the EU 47% of all battery sales including secondary types.

History

Batteries with alkaline (rather than acid) electrolyte were first developed by Waldemar Jungner in 1899, and, working independently, Thomas Edison in 1901. The alkaline dry battery using the zinc/manganese dioxide chemistry was invented by Canadian engineer Lewis Urry in the 1950s while working for Union Carbide's Eveready Battery division in Cleveland, OH, building on earlier work by Edison. On October 9, 1957, Urry, Karl Kordesch, and P.A. Marsal filed US patent (2,960,558) for the alkaline battery. It was granted in 1960 and was assigned to the Union Carbide Corporation.

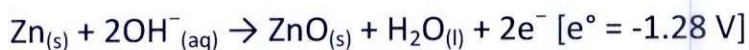
Chemistry

In an alkaline battery, the anode (negative terminal) is made of zinc powder, which gives more surface area for increased current, and the cathode (positive terminal) is composed of manganese dioxide. Unlike zinc-carbon (Leclanché) batteries, the electrolyte is potassium hydroxide rather than ammonium chloride or zinc chloride.

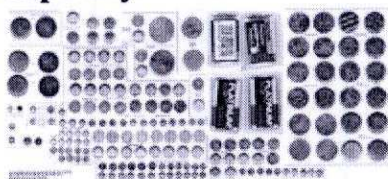


Section through an alkaline battery.

The half-reactions are:



Capacity



Several sizes of button and coin cells. Some are alkaline and others are silver oxide. Two 9v batteries were added as a size comparison. Enlarge to see the size code markings.

Capacity of an alkaline battery is greater than an equal size Leclanché cell or zinc-chloride cell because the manganese dioxide is purer and denser, and space taken up by internal components such as electrodes is less. An alkaline cell can provide between three and five times capacity.

The capacity of an alkaline battery is strongly dependent on the load. An AA-sized alkaline battery might have an effective capacity of 3000 mAh at low drain, but at a load of 1 ampere, which is common for digital cameras, the capacity could be as little as 700 mAh. The voltage of the battery declines steadily during use, so the

total usable capacity depends on the cut-off voltage of the application. Unlike Leclanche cells, the alkaline cell delivers about as much capacity on intermittent or continuous light loads. On a heavy load, capacity is reduced on continuous discharge compared with intermittent discharge, but the reduction is less than for Leclanche cells.

Voltage

The nominal voltage of a fresh alkaline cell is 1.5 V. Multiple voltages may be achieved with series of cells. The effective zero-load voltage of a non discharged alkaline battery varies from 1.50 to 1.65 V, depending on the purity of the manganese dioxide used and the contents of zinc oxide in the electrolyte. The average voltage under load depends on discharge and varies from 1.1 to 1.3 V. The fully discharged cell has a remaining voltage in the range of 0.8 to 1.0 V.

Current

The amount of current an alkaline battery can deliver is roughly proportional to its physical size. This is a result of decreasing internal resistance as the internal surface area of the cell increases. A general rule of thumb is that an AA alkaline battery can deliver 700 mA without any significant heating. Larger cells, such as C and D cells, can deliver more current. Applications requiring currents of several amperes, such as powerful flashlights and portable stereos, will require D-sized cells to handle the increased load.

Construction

Alkaline batteries are manufactured in standardized cylindrical forms interchangeable with zinc-carbon batteries, and in button forms. Several individual cells may be interconnected to form a true "battery", such as those sold for use with flashlights and the 9 volt transistor-radio battery.

A cylindrical cell is contained in a drawn steel can, which is the cathode connection. The cathode mixture is a compressed paste of manganese dioxide with carbon powder added for increased conductivity. The paste may be pressed into the can or deposited as pre-molded rings. The hollow center of the cathode is lined with a separator, which prevents mixing of the anode and cathode materials and short-circuiting of the cell. The separator is made of a non-woven layer of cellulose or a synthetic polymer. The separator must conduct ions and remain stable in the highly alkaline electrolyte solution.

The anode is composed of a dispersion of zinc powder in a gel containing the potassium hydroxide electrolyte. To prevent gassing of the cell at the end of its life, more manganese dioxide is used than required to react with all the zinc.

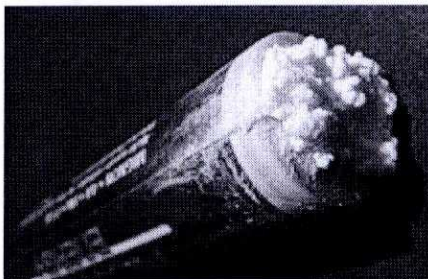
When describing standard AAA, AA, C, sub-C and D size cells, the anode is connected to the flat end while the cathode is connected to the end with the raised button.

Recharging of alkaline batteries

Main article: Recharging alkaline batteries

Some alkaline batteries are designed to be recharged (see rechargeable alkaline battery), but most are not. Attempts to recharge may cause rupture, or the leaking of hazardous liquids which will corrode the equipment.

Leaks



Leaked alkaline battery

Alkaline batteries are prone to leaking potassium hydroxide, a caustic agent that can cause respiratory, eye and skin irritation.^[note 1] This can be avoided by not attempting to recharge disposable alkaline cells, not mixing different battery types in the same device, replacing all of the batteries at the same time, storing in a dry place, and removing batteries for storage of devices.

All batteries gradually self-discharge (whether installed in a device or not) and dead batteries will eventually leak. Extremely high temperatures can also cause batteries to rupture and leak (such as in a car during summer).

The reason for leaks is that as batteries discharge — either through usage or gradual self-discharge — the chemistry of the cells changes and some hydrogen gas is generated. This out-gassing results in increasing pressure within the battery.

Eventually, the excess pressure either ruptures the insulating seals at the end of the battery, or the outer metal canister, or both. In addition, as the battery ages, its steel outer canister may gradually corrode or rust, which can further contribute to containment failure.

Once a leak has formed due to corrosion of the outer steel shell, potassium hydroxide absorbs carbon dioxide from the air to form a feathery crystalline structure of potassium carbonate that grows and spreads out from the battery over time, following along metal electrodes to circuit boards where it commences oxidation of copper tracks and other components, leading to permanent circuitry damage.

The leaking crystalline growths can also emerge from seams around battery covers to form a furry coating outside the device, that corrodes any objects in contact with the leaking device.

Disposal

When introduced in the 1960s, alkaline batteries contained a small amount of mercury amalgam to control side reactions at the zinc cathode. Improvements in the purity and consistency of materials have allowed manufacturers to reduce the mercury content in modern cells.^[14] Unlike other types of batteries, alkaline batteries are allowed to be disposed of as regular domestic waste in some locations. This, however, may not be environmentally friendly, as some alkaline batteries produced before 1996 contain mercury.^{[15][16]} For example the state of California has deemed all batteries as hazardous waste when discarded, and has banned the disposal of batteries with other domestic waste. In the US, one company shreds and separates the battery case metals, manganese and zinc. Another company mixes batteries in as a feedstock in steel making furnaces, to make low-grade steel such as rebar; the zinc fumes are recovered separately. In Europe battery disposal is controlled by the WEEE regulations, and as such alkaline batteries must not be thrown in with domestic waste. They should be disposed through local recycling stations/waste dumps. In the EU most stores that sell batteries are required by law to accept old batteries for recycling.

Applications

Alkaline batteries are used in many household items. This includes MP3 players, CD players, digital cameras, pagers, toys, lights, and radios, to name a few.

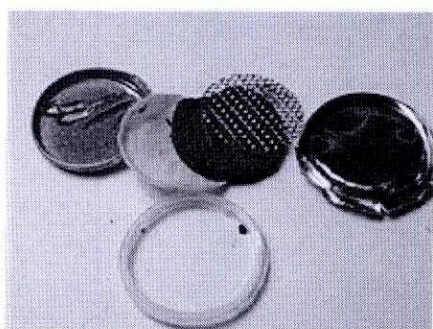
Lithium battery

Lithium batteries are disposable (primary) batteries that have lithium metal or lithium compounds as an anode. Depending on the design and chemical compounds used, lithium cells can produce voltages from 1.5 V to about 3.7 V, over twice the voltage of an ordinary zinc-carbon battery or alkaline battery. Lithium batteries are widely used in products such as portable consumer electronic devices.

Lithium primary batteries account for 28% of all primary battery sales in Japan but only 1% of all battery sales in Switzerland. In the UK and EU only 0.5% of all battery sales including secondar
Description

The term "lithium battery" refers to a family of different chemistries, comprising many types of cathodes and electrolytes.

The most common type of lithium cell used in consumer applications uses metallic lithium as anode and manganese dioxide as cathode, with a salt of lithium dissolved in an organic solvent.



Disassembled CR2032 battery From left — negative cup from inner side with layer of lithium (oxidized in air), separator(porous material), cathode (manganese dioxide), metal grid — current collector, metal casing (+)(damaged during opening the cell), on the bottom is plastic sealing ring

Another type of lithium cell having a large energy density is the **lithium-thionyl chloride cell**. Lithium-thionyl chloride batteries are generally not sold to the

consumer market, and find more use in commercial/industrial applications, or are installed into devices where no consumer replacement is performed. In this cell, a liquid mixture of thionyl chloride (SOCl_2) and lithium tetrachloroaluminate (LiAlCl_4) acts as the electrolyte and cathode respectively. A porous carbon material serves as a **cathode current collector** which receives electrons from the external circuit. Lithium-thionyl chloride batteries are well suited to extremely low-current applications where long life is necessary, such as wireless alarm systems.

y types are lithium primaries.

Chemistries

Chemistry	Cathode	Electrolyte	Nominal voltage	Open-circuit voltage	Wh/kg	Wh/dm ³
	Heat-treated manganese dioxide	Lithium perchlorate in propylene carbonate and dimethoxyethane	3 V	3.3 V	280	580
Li-MnO ₂ (Li-Mn, "CR")	The most common consumer grade battery, about 80% of the lithium battery market. Uses inexpensive materials. Suitable for low-drain, long-life, low-cost applications. High energy density per both mass and volume. Can deliver high pulse currents. Wide temperature range. With discharge the internal impedance rises and the terminal voltage decreases. Maximum temperature limited to about 60 °C. High self-discharge at high temperatures.					
Li-SOCl ₂	Thionyl chloride	Lithium tetrachloroaluminate in thionyl chloride	3.5 V	3.65 V	500	1200

Liquid cathode. For low temperature applications. Can operate down to -55 °C, where it retains over 50% of its rated capacity. Negligible

amount of gas generated in nominal use, limited amount under abuse. Has relatively high internal impedance and limited short-circuit current. High energy density, about 500 Wh/kg. Toxic. Electrolyte reacts with water. Low-current cells used for portable electronics and memory backup. High-current cells used in military applications. In long storage forms passivation layer on anode, which may lead to temporary voltage delay when put into service. High cost and safety concerns limit use in civilian applications. Can explode when shorted. Underwriters Laboratories require trained technician for replacement of these batteries. Hazardous waste, Class 9 Hazmat shipment.^[6]

Li-SOCl ₂ , BrCl, Li-BCX	Thionyl chloride	with Lithium tetrachloroaluminate in thionyl chloride	3.7-3.8 V	3.9 V	350	770
	bromine chloride					
Li-SO ₂ Cl ₂	Sulfuryl chloride		3.7	3.95	330	720

Liquid cathode. A variant of the thionyl chloride battery, with 300 mV higher voltage. The higher voltage drops back to 3.5 V soon as the bromine chloride gets consumed during the first 10-20% of discharge. The cells with added bromine chloride are thought to be safer when abused.

Liquid cathode. Similar to thionyl chloride. Discharge does not result in buildup of elemental sulfur, which is thought to be involved in some hazardous reactions, therefore sulfuryl chloride batteries may be safer. Commercial deployment hindered by tendency of the electrolyte to corrode the lithium anodes, reducing the shelf life. Chlorine is added to some cells to make them more resistant to abuse. Sulfuryl chloride cells give less maximum current than thionyl chloride ones, due to polarization of the carbon cathode. Sulfuryl chloride reacts violently

with water, releasing hydrogen chloride and sulfuric acid.

Sulfur dioxide on teflon- bonded carbon	Lithium bromide in sulfur dioxide with small amount of acetonitrile	2.85 V	3.0 V	250	400
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Li-SO₂ Liquid cathode. Can operate down to -55 °C and up to +70 °C. Contains liquid SO₂ at high pressure. Requires safety vent, can explode in some conditions. High energy density. High cost. At low temperatures and high currents performs better than Li-MnO₂. Toxic. Acetonitrile forms lithium cyanide, and can form hydrogen cyanide in high temperatures. Used in military applications.

Addition of bromine monochloride can boost the voltage to 3.9 V and increase energy density.

Carbon monofluoride	Lithium tetrafluoroborate in propylene carbonate, dimethoxyethane, and/or gamma- butyrolactone	2.8 V	3.1 V	360	680
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Li-(CF)_x
("BR") Cathode material formed by high-temperature intercalation of fluorine gas into graphite powder. High energy density (250 Wh/kg), 7 year shelf life. Used for low to moderate current applications in memory and clock backup batteries. Very good safety record. Used in aerospace applications, qualified for space since 1976. Used in military applications both terrestrial and marine, and in missiles. Also used in cardiac pacemakers. Maximum temperature 85 °C. Very low self-discharge (<0.5%/year at 60 °C, <1%/yr at 85 °C). Developed in 1970s by Matsushita.

	solid organic charge transfer complex (poly-2-vinylpyridine, P2VP)	2.8 V	3.1 V
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Li-I₂ Solid electrolyte. Very high reliability. Used in medical applications. Does not generate gas even under short circuit. Solid-state chemistry, limited short-circuit current, suitable only for low-current applications. Terminal voltage decreases with degree of discharge due to precipitation of lithium iodide. Low self-discharge.

Silver chromate	Lithium perchlorate solution	3.1/2.6 V	3.45 V
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Li-Ag₂CrO₄ Very high reliability. Has a 2.6 V plateau after reaching certain percentage of discharge, provides early warning of impending discharge. Developed specifically for medical applications, for example, implanted pacemakers.

Silver oxide+vanadium pentoxide (SVO)	lithium hexafluorophosphate or lithium hexafluoroarsenate in propylene carbonate with dimethoxyethane
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Li-Ag₂V₄O₁₁, Li-SVO, Li-CSVO Used in medical applications, like implantable defibrillators, neurostimulators, and drug infusion systems. Also projected for use in other electronics, such as emergency locator transmitters. High energy density. Long shelf life. Capable of continuous operation at nominal temperature of 37 °C. Two-stage discharge with a plateau. Output voltage decreasing proportionally to the degree of discharge. Resistant to abuse.

Addition of copper(II) oxide to the cathode material results in the Li-CSVO variant.

Copper(II) oxide	Lithium Perchlorate dissolved in 1.5 V	2.4 V
	Dioxolane	

Li-CuO Can operate up to 150 °C. Developed as a replacement of zinc-carbon and alkaline batteries. "Voltage up" problem, high difference between open-circuit and nominal voltage. Produced until mid-1990s, replaced by lithium-iron sulfide. Current use limited.

Li-
Cu₄O(PO₄)₂ Copper
oxyphosphate

2 See Li-CuO

Li-CuS Copper sulfide 1.5 V

Li-PbCuS Lead sulfide
and copper
sulfide 1.5 V 2.2 V

Li-FeS Iron sulfide Propylene
carbonate,
dioxolane,
dimethoxyethane 1.5-1.2
V

"Lithium-iron", "Li/Fe". used as a replacement for alkaline batteries.
See lithium — iron disulfide.

Li-FeS ₂	Iron disulfide	Propylene carbonate, dioxolane, dimethoxyethane	1.6-1.4 V	1.8 V	297
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"Lithium-iron", "Li/Fe". Used in Energizer lithium cells as a replacement for alkaline zinc-manganese chemistry. Called "voltage-compatible" lithiums. 2.5 times higher lifetime for high current discharge regime than alkaline batteries, better storage life due to lower self-discharge, 10 years storage time. FeS_2 is cheap. Cathode often designed as a paste of iron sulfide powder mixed with powdered graphite. Variant is Li-CuFeS_2 .

		3.3 V	90–110	
Li- FePO_4	Rechargeable. See Lithium iron phosphate battery.			
	Lead bismuthate	1.5 V	1.8 V	
Li- $\text{Bi}_2\text{Pb}_2\text{O}_5$	Replacement of silver-oxide batteries, with higher energy density, lower tendency to leak, and better performance at higher temperatures.			
Li- Bi_2O_3	Bismuth trioxide	1.5 V	2.04 V	
	Vanadium pentoxide	3.3/2.4 V	3.4 V	120/26 300/66 0 0
Li- V_2O_5	Two discharge plateaus. Low-pressure. Rechargeable. Used in reserve batteries.			
Li- CoO_2	Cobalt dioxide			
	Copper chloride			
Li- CuCl_2	Rechargeable.			
Li/Al-	Manganese			

MnO ₂	dioxide		
	Rechargeable.		
Li/Al-V ₂ O ₅	Vanadium pentoxide		
	Rechargeable.		
Li-ion	carbon	liquid	3.6-3.7 V
	Rechargeable. See lithium ion battery.		
Li-poly	polymer	solid	3.7 V
	Rechargeable. See lithium ion polymer battery.		
Li-air	porous carbon	organic, aqueous, glass-ceramic (polymer-ceramic composites)	
	Rechargeable. See Lithium-air battery.		

The liquid organic electrolyte is a solution of an ion-forming inorganic lithium compound in a mixture of a high-permittivity solvent (propylene carbonate) and a low-viscosity solvent (dimethoxyethane).

Applications

Lithium batteries find application in many long-life, critical devices, such as artificial pacemakers and other implantable electronic medical devices. These devices use specialized lithium-iodide batteries designed to last 15 or more years. But for other, less critical applications such as in toys, the lithium battery may actually outlast the device. In such cases, an expensive lithium battery may not be cost-effective.

Lithium batteries can be used in place of ordinary alkaline cells in many devices, such as clocks and cameras. Although they are more costly, lithium cells will provide much longer life, thereby minimizing battery replacement. However, attention must be given to the higher voltage developed by the lithium cells before using them as a drop-in replacement in devices that normally use ordinary zinc cells.



Sizes and formats

Small lithium batteries are very commonly used in small, portable electronic devices, such as PDAs, watches, camcorders, digital cameras, thermometers, calculators, laptop BIOS, communication equipment and remote car locks. They are available in many shapes and sizes, with a common variety being the 3 volt "coin" type manganese variety, typically 20 mm in diameter and 1.6–4 mm thick. The heavy electrical demands of many of these devices make lithium batteries a particularly attractive option. In particular, lithium batteries can easily support the brief, heavy current demands of devices such as digital cameras, and they maintain a higher voltage for a longer period than alkaline cells.

Lithium–air battery

The **lithium-air battery**, **Li-air** for short, is a metal-air battery chemistry that uses the oxidation of lithium at the anode and reduction of oxygen at the cathode to induce a current flow. Originally proposed in the 1970's as a possible power source for electric vehicles, Li-air batteries recaptured scientific interest in the late 2000's due to advances in materials technology and an increasing demand for environmentally safe and oil-independent energy sources. Currently, four types of Li-air batteries are being pursued; aprotic, aqueous, solid state, and mixed aqueous/aprotic.

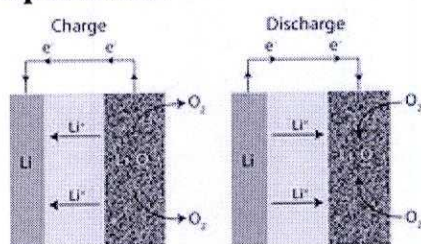
The major appeal of the Li-air battery is the extremely high energy density, a measure of the amount of energy a battery can store for a given volume, which rivals that of traditional gasoline powered engines. Li-air batteries gain this advantage in energy density since they use oxygen from the air instead of storing an oxidizer internally.

The technology is still in its infancy and will require significant research efforts in a variety of fields, however, scientists and industry alike see potential in its development.

History

In the mid-1990s, K.M. Abraham and co-workers demonstrated the first non-aqueous Li-air battery with the use of a Li negative electrode (anode), a porous carbon positive electrode (cathode), and a gel polymer electrolyte membrane that served as both the separator and ion-transporting medium. Oxygen from the atmosphere enters the pores of the carbon cathode to serve as the cathode active material. In the discharge of the Li-air battery, this oxygen is reduced and the products are stored in the pores of the carbon electrode. The Li ion conducting gel polymer electrolytes used to construct polymer Li-air cells included those based on polyacrylonitrile (PAN) and polyvinylidene fluoride (PVdF). The electrolyte can also be organic liquid, dry organic polymer or inorganic solid electrolytes.

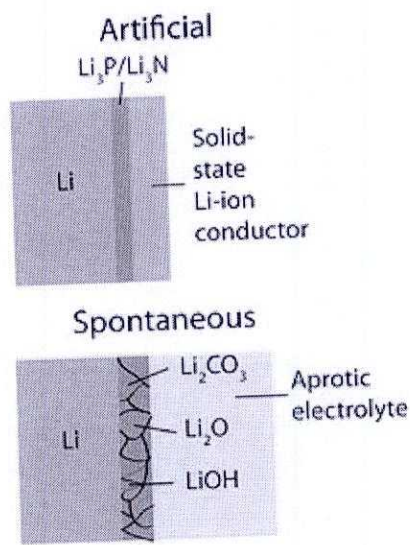
Operation



Schematic of lithium-air battery charge and discharge cycles

Although the electrochemical details vary by battery design (and consequently electrolyte type), in general, **lithium is oxidized at the anode forming lithium ions and electrons**. The electrons follow the external circuit to do electric work and the lithium ions migrate across the electrolyte to **reduce oxygen at the cathode**. When an externally applied potential is greater than the standard

potential for the discharge reaction, lithium metal is plated out on the anode, and O_2 is generated at the cathode.



Schematic of artificial vs. spontaneous electrolyte interface

Anode

Lithium metal is the current choice of anode material for Li-air batteries. At the anode, electrochemical potential forces the lithium metal to give off electrons as per the oxidation. The half reaction is given below:



Lithium has high specific capacity (3840 mAh/g) compared with other metal-air battery materials (2965 mAh/g for Zinc, 2965 mAh/g for aluminum) making it an excellent choice for an anode material. However, there are some issues associated with metallic lithium as the anode. Upon charging/discharging in aprotic cells, a multilayer deposition of lithium salts creates a mass diffusion barrier between the lithium and electrolyte which initially prevents further corrosion of the lithium metal but eventually inhibits the reaction kinetics between the anode and the electrolyte. This chemical heterogeneity of the solid-electrolyte interface (SEI) results in morphologically heterogeneous structure prone to non-uniform current distributions. Uneven current distributions further the dendrite growth and

typically leads to a short between the anode and cathode. Also, In aqueous cells problems at the SEI stem from the high reactivity of lithium metal with water.

Several approaches have been taken to overcome problems at the SEI associated with lithium metal anodes.

1. Formation of a Li-ion conductive artificial protective layer using novel di- and triblock copolymer electrolytes.

According to Seeo, Inc.¹ The electrolytes made from di- and triblock copolymer (e.g. polystyrene with the high Li-ion conductivity of a soft polymer segment, such as a poly(ethylene oxide PEO/ Li-salt mixture)) combine the mechanical stability of a hard polymer segment, which will inhibit dendrite shorts via mechanical blocking, with the high ionic conductivity of the soft polymer/lithium salt mixture.

2. Use of a Li-ion conducting glass or glass-ceramic material.

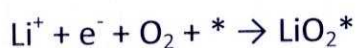
Li-ion conducting ceramic materials are (generally) readily reduced by lithium metal, and therefore a thin film of a lithium stable conducting material, such as Li_3P or Li_3N , could be inserted between the ceramic and metal. This ceramic based artificial SEI would not only inhibit the formation of dendrites, but would also protect the lithium metal from atmospheric contamination.

Cathode and electrolyte

At the cathode, reduction occurs by the recombination of lithium ions with oxygen. Currently, mesoporous carbon has been used as a cathode material with metal catalysts. Metal catalysts incorporated into the carbon electrode enhance the oxygen reduction kinetics and increase the specific capacity of the cathode. Manganese, cobalt, ruthenium, platinum, silver, or a mixture of cobalt and manganese are currently used as metal catalysts. A study by Abraham *et al.* found that manganese catalyzed cathodes performed best, with a specific capacity of 3137 mAh/g carbon, and cobalt catalyzed cathodes performed second best, with a specific capacity of 2414 mAh/g carbon.

The Li-air cell performance is limited by the efficiency of reaction at the cathode because most of the cell voltage drop occurs at the cathode. Thus, improvement of cathode in a Li-air battery is essential for overall Li-air cell performance enhancement. Currently, there exist multiple battery chemistry (for more see battery designs) delineated by electrolyte choice, so the exact electrochemical reaction at the cathode varies between Li-air batteries. The discussion below is focused on aprotic and aqueous electrolytes as the exact electrochemistry taking place in solid-state electrolytes is not well understood.

In a cell with an aprotic electrolyte lithium oxides are produced through reduction at the cathode:

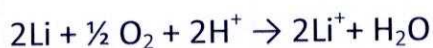


Where a "*" denotes a surface site on Li_2O_2 where the growth proceeds which is essentially a neutral Li vacancy in the Li_2O_2 surface.

It should be noted that lithium oxides are insoluble in aprotic electrolytes which leads to the cathode clogging.

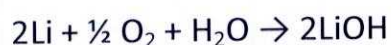
In a cell with an aqueous electrolyte the reduction at the cathode can also produce lithium hydroxide:

- Acidic electrolyte



A conjugate base is involved in the reaction. The theoretical maximal Li-air cell specific energy and Li-air cell energy density is 1400 Wh/kg and 1680 Wh/l respectively.

- Alkaline aqueous electrolyte



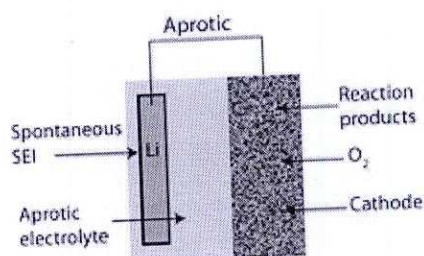
Water molecules are involved in the redox reactions at the air cathode. The theoretical maximal Li-air cell specific energy and Li-air cell energy density is 1300 Wh/kg and 1520 Wh/l respectively

The development of new cathode materials must account for the accommodation of substantial amounts of LiO_2 , Li_2O_2 , and/or LiOH without causing a blockage of the cathode pores and find suitable catalysts to make the electrochemical reactions energetically practical.

- As an example, dual pore system materials are the most promising in terms of energy capacity.
- The first pore system of the material serves as an oxidation product storage
- The second pore system of the material serves as transports oxygen.

Li-Air Battery Designs

Efforts in Li-air batteries have focused on four different chemical designs. All the designs have distinct advantages and significant associated technological challenges. It remains to be seen which design will become the standard for Li-air batteries of tomorrow.



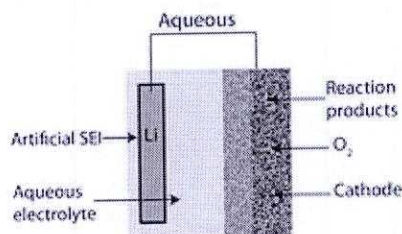
Schematic of aprotic type Li-Air battery design

Aprotic

Most worldwide effort on Li-air batteries has focused on the aprotic battery design. The aprotic design consists of a lithium metal anode, a liquid organic electrolyte, and a porous carbon cathode. Electrolytes can be made of any organic capable of solvating lithium salts (LiPF_6 , LiAsF_6 , $\text{LiN}(\text{SO}_2\text{CF}_3)_2$, and LiSO_3CF_3), but have typically consisted of carbonates, ethers, and esters. The carbon cathode is usually made of a high surface area carbon material with a nanosized metal oxide catalyst (commonly MnO_2 or Mn_3O_4). A major design advantage of the aprotic battery is the spontaneous formation of a barrier between the anode and electrolyte (much

like the barrier formed between electrolyte and carbon-lithium anodes in conventional Li-ion batteries) which protects the lithium metal from further reaction with the electrolyte. Practically, the aprotic battery design draws interest as it has been shown to be rechargeable. However, it has major drawbacks in that Li_2O_2 produced at the cathode is generally insoluble in the organic electrolyte leading to build up along the cathode/electrolyte interface. This makes cathodes in aprotic batteries prone to clogging and volume expansion which reduces conductivity and degrades battery performance over time.

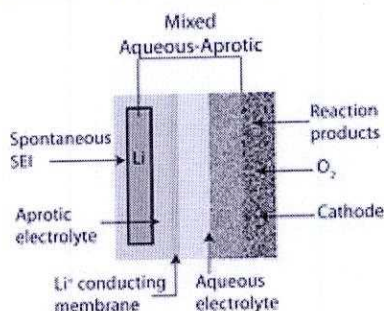
Aqueous



Schematic of aqueous type Li-Air battery design

The aqueous Li-air battery consists of a lithium metal anode, an aqueous electrolyte, and a porous carbon cathode. The aqueous electrolyte is simply a combination of lithium salts dissolved in water. The aqueous Li-air battery avoids the issue of cathode clogging experienced in aprotic batteries because the reaction products are water soluble, which allows aqueous Li-air batteries to maintain performance over time. The aqueous design also has a higher practical discharge potential than its aprotic counterpart. However, lithium metal reacts violently with water and thus the aqueous design requires a solid electrolyte interface between the lithium metal and aqueous electrolyte. Commonly, a lithium conducting ceramic or glass is used, but conductivities are generally low (on the order of 10^{-3} S/cm at ambient temperatures).

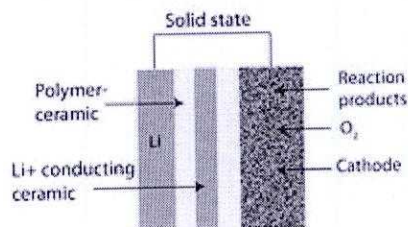
Mixed Aqueous/Aprotic



Schematic of a mixed aqueous-aprotic type Li-Air battery design

The aqueous/aprotic or mixed Li-air battery design is an attempt to unite advantages of both the aprotic and aqueous battery designs. Although there exist multiple hybrid designs, the common feature of these designs is a separated two-part (one part aqueous and one part aprotic) electrolyte connected by a lithium conducting membrane. A lithium metal anode is in contact with the aprotic side of the electrolyte while the porous cathode is in contact with the aqueous side. A lithium conducting ceramic is typically employed as the membrane joining the two electrolytes.

Solid State



Schematic of solid-state type Li-Air battery design

The solid-state battery design eliminates problems at the anode/cathode interfaces associated with using a liquid electrolyte. It is also attractive from a safety standpoint as organic solvents, currently used in lithium-ion batteries (and employed in the aprotic Li-air battery design), are flammable and at high temperatures the use of an organic electrolyte can lead to rupture and ignition of

the battery. Current solid-state Li-air batteries use a lithium anode, a ceramic, glass, or glass-ceramic electrolyte, and a porous carbon cathode. The anode and cathode are typically separated from the electrolyte by polymer-ceramic composites which enhance charge transfer at the anode and electrochemically couple the cathode to the electrolyte. The polymer-ceramic composites serve to reduce the overall impedance of the solid-state Li-air battery. The main drawback of the solid-state battery design is the low conductivity of most glass-ceramic electrolytes. Lithium aluminum germanium phosphate has been found to be an effective electrolyte, but the ionic conductivity of current lithium fast ion conductors are still lower than liquid electrolyte alternatives.

Challenges

There are many challenges facing the design of Li-air batteries, which currently limits their use to the laboratory. One of the largest challenges lies in keeping the battery protected from the environment. Atmospheric oxygen must be present at the cathode, but the cathode can be degraded by humidity.

Cathode

Most of the current limitations in Li-air battery development are seen at the cathode. One of the problems seen is incomplete discharge due to blockage of the porous carbon cathode with discharge product. The effect of pore size and pore size distribution is still poorly understood. Production of a cathode with high a pore size and ability to hold a large amount of Li_2O_2 is essential to Li-air battery development. Catalysts have shown promise in creating preferential nucleation of Li_2O_2 over Li_2O , which is irreversible with respect to lithium.

Anode

The current anode of choice in Li-air batteries is metallic Li, as Li offers the highest energy density. Due to the reactive nature of Li, the main challenge in anode development is preventing the anode from reacting. New interfacial materials or solid-state electrolytes will prevent anode degradation. Another area of concern when using metallic lithium cathodes is dendrite formation, which will lead to a short circuit within the battery.

Electrochemical

In current cell designs, the charge overpotential is much higher than the discharge overpotential. The presence of a significant charge overpotential indicates secondary reactions, besides recharging, are occurring. As a result, the electrical efficiency is only around 65%. There is some indication that catalysts, such as MnO_2 , Co, Pt, and Au can reduce the overpotentials, but the effect is still poorly understood. In addition, significant drops in cell capacity with increasing discharge rates have been observed by many researchers. The decrease in cell capacity is attributed to kinetic charge transfer limitations. Since the anodic reaction occurs very quickly, the charge transfer limitations are thought to occur at the cathode. Again, electrocatalysts could improve the charge transfer rate.

Environmental

Long term battery operation requires chemical stability of all the components of the cell. Current cell designs show poor resistance to oxidation by the reaction products and intermediates. Many aqueous electrolytes are also volatile, and can be lost over time. One of the largest barriers to fully operable commercial cells is the development of effective environmental interfaces. Atmospheric oxygen is intrinsically required for cell operation, but the cell must be shielded from the environment, as water vapor can rapidly degrade the system.

Applications

The primary application for Li-air battery development is automotive. The high specific energy densities and volumetric energy densities required for next-generation hybrid and electric vehicles are beyond current battery designs. Li-air batteries are attractive for any application where weight is a primary concern, such as in mobile devices. Flow batteries, such as the vanadium redox battery may offer better performance for applications such as off-grid power storage.

Zinc-carbon battery

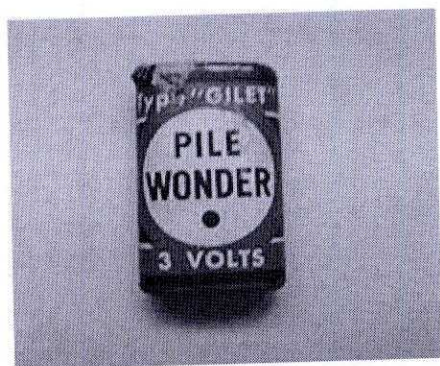
A **zinc-carbon dry cell or battery** is packaged in a zinc can that serves as both a container and negative terminal. It was developed from the wet Leclanché cell ($\text{le} \text{kle} \text{ch} \text{e}$). The positive terminal is a carbon rod surrounded by a mixture of manganese dioxide and carbon powder. The electrolyte used is a paste of zinc chloride and ammonium chloride dissolved in water. Zinc chloride cells are an improved version from the original ammonium chloride variety. Zinc-carbon

batteries are the least expensive primary batteries and thus a popular choice by manufacturers when devices are sold with batteries included. They are commonly labeled as *general purpose* batteries. They were the first commercial dry battery and made things such as flashlights and other portable devices possible, because the battery can function in any position. They can be used in low drain or intermittent devices such as remote controls, flashlights, clocks, or transistor radios. They are replaced, in many usages, by alkaline cells, and rechargeable NiMH batteries.

Zinc-carbon batteries account for only 6% of all primary battery sales in Japan and only 7% of all types of batteries sold in Switzerland. In the UK 20% of all portable batteries sold are zinc-carbon and in the EU 30%.

History

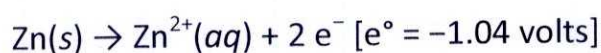
By 1876, the wet Leclanché cell was made with a compressed block of manganese dioxide. In 1886 Dr. Carl Gassner patented a "dry" version by using a zinc cup as the anode and making the electrolyte with a paste of plaster of Paris (and later, wheat flour) to gel and immobilize the electrolyte. In 1898 Conrad Hubert used consumer batteries manufactured by W. H. Lawrence to power what was the first flashlight, and subsequently the two formed the Ever Ready battery company. In 1900 Gassner demonstrated dry cells for portable lighting at the World's Fair in Paris. Continual improvements were made to the stability and capacity of zinc-carbon cells throughout the 20th Century; by the end of the century the capacity of a zinc-carbon cell had increased fourfold over the 1910 equivalent. Improvements include the use of purer grades of manganese dioxide, better sealing, and purer zinc for the negative electrode.



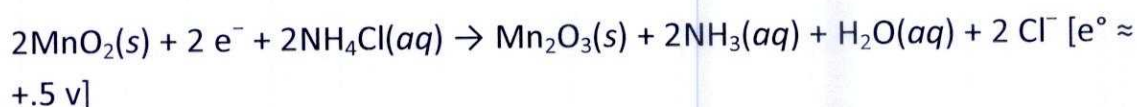
Old zinc-carbon 3V battery (around 1960), with cardboard casing

Chemical reactions

In a zinc–carbon dry cell, the outer zinc container is the negative terminal. The zinc is oxidised according to the following half-equation.



A graphite rod surrounded by a powder containing manganese(IV) oxide is the positive terminal. The manganese dioxide is mixed with carbon powder to increase the electrical conductivity. The reaction is as follows:



and the Cl^{-} combines with the Zn^{2+} .

In this half-reaction, the manganese is reduced from an oxidation state of (+4) to (+3).

There are other possible side-reactions, but the overall reaction in a zinc–carbon cell can be represented as:

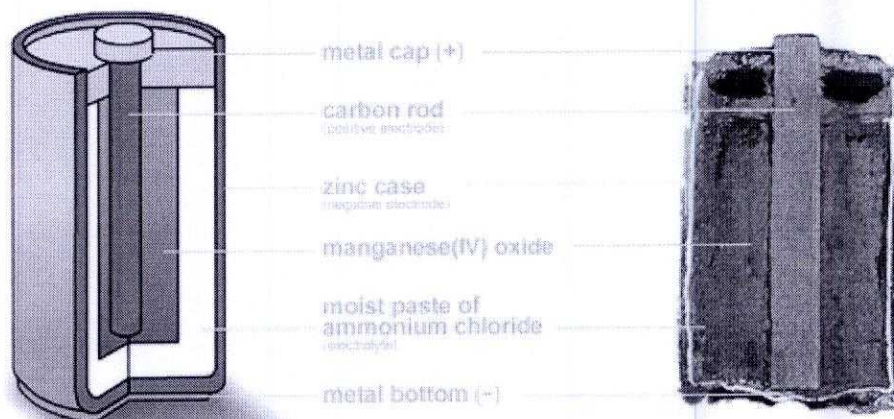


The battery has an e.m.f. of about 1.5 V. The approximate nature of the e.m.f is related to the complexity of the cathode reaction. The anode (zinc) reaction is comparatively simple with a known potential. Side reactions and depletion of the active chemicals increases the internal resistance of the battery, and this causes the e.m.f. to drop.

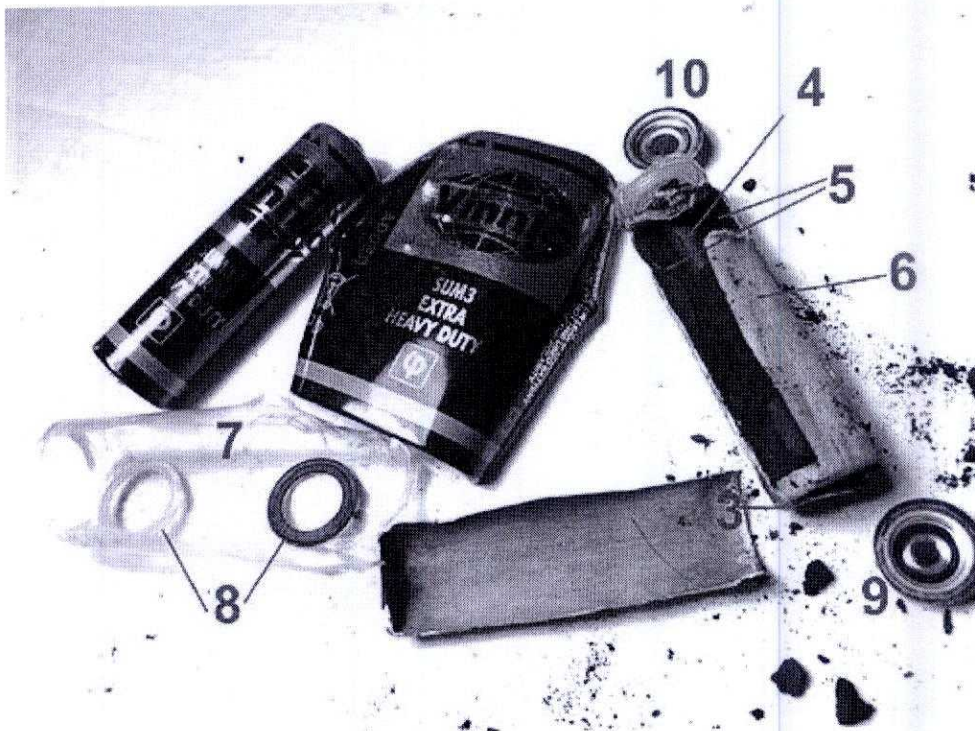
Although carbon is an important element of the battery's construction, it takes no part in the electrochemical reaction, instead only serving to collect current and reduce the resistance of the manganese dioxide mix. The cell could more properly be called a "zinc–manganese" cell.

Construction

The container of the zinc–carbon dry cell is a zinc can. The inside surface of the zinc can was originally treated with mercury. This decreased 'local action' where impurities in the zinc set up small areas of galvanic action which would cause the zinc to react with the electrolyte more quickly than it otherwise would. The mercury was subsequently banned by legislation in many jurisdictions on environmental grounds. The can contains a layer of NH_4Cl or ZnCl_2 aqueous paste impregnating a paper layer that separates the zinc can from a mixture of powdered carbon (usually graphite powder) & manganese (IV) oxide (MnO_2) which is packed around a carbon rod. Carbon is the only practical conductor material because every common metal will quickly corrode away in the positive electrode in salt based electrolyte.



Cross-section of a zinc–carbon battery.



Disassembled zinc chloride cell (similar to zinc carbon cell). 1:entire cell, 2:steel casing, 3:zinc negative electrode, 4:carbon rod, 5:positive electrode (Manganese dioxide mixed with carbon powder and electrolyte), 6:paper separator, 7:polyethylene leak proof isolation, 8:sealing rings, 9-negative terminal, 10-positive terminal (originally connected to carbon rod)

Early types, and low-cost cells, use a separator consisting of a layer of starch or flour. A layer of starch-coated paper is used in modern cells, which is thinner and allows more manganese dioxide to be used. Originally cells were sealed with a layer of asphalt to prevent drying out of the electrolyte; more recently a thermoplastic washer sealant is used. The carbon rod is slightly porous, which allows accumulated gas to escape while retaining the water for the electrolyte. The ratio of manganese dioxide and carbon powder in the cathode paste affects the characteristics of the cell; more carbon powder lowers the internal resistance, but more manganese dioxide improves capacity.

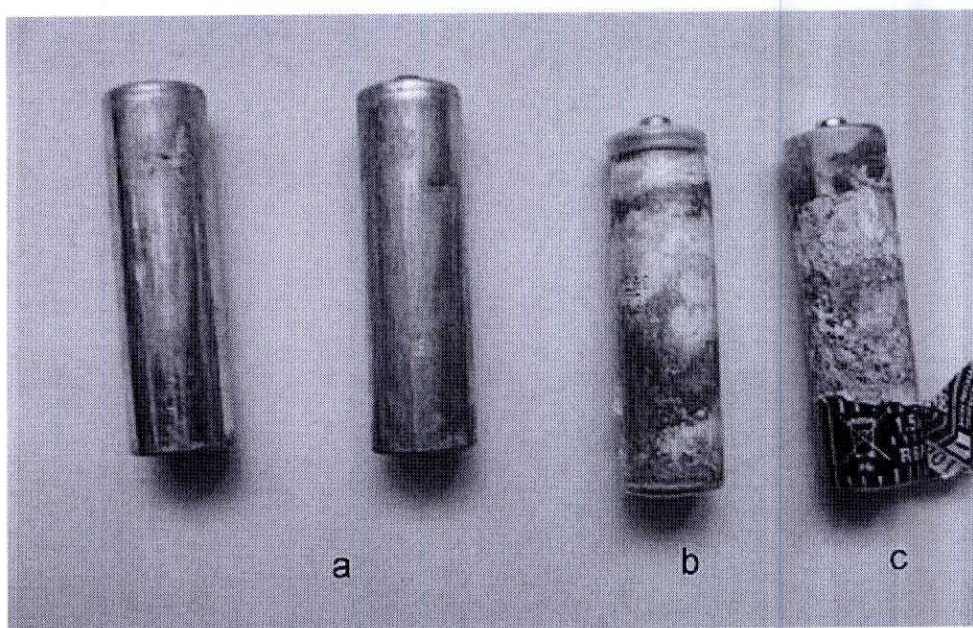
Flat cells are also made for assembly into batteries with higher voltages, up to about 450 volts. A number of flat cells are stacked up, and the whole assembly is coated in wax to prevent evaporation of water from the electrolyte.

Leakage

Generally, the materials of the cell are inexpensive and cheap to reproduce even though the cell is non-rechargeable. These cells have a low energy density; the voltage falls during use due to a drop in electrolyte concentration around the cathode and the time required for the Mn_2O_3 to diffuse away from the cathode.

These cells have a short shelf life as the zinc is attacked by ammonium chloride. The zinc container becomes thinner as the cell is used, because zinc metal is oxidized to zinc ions. When the zinc case thins enough, zinc chloride begins to leak out of the battery. The old dry cell is not leak proof and becomes very sticky as the paste leaks through the holes in the zinc case. The zinc casing in the dry cell gets thinner even when the cell is not being used, because the ammonium chloride inside the battery reacts with the zinc. An "inside-out" form with a carbon cup and zinc vanes on the interior, while more leak resistant, has not been made since the 1960s.

This picture shows the zinc container of fresh batteries at (a), and discharged batteries at (b) and (c). The battery shown at (c) had a polyethylene protection film (mostly removed in the photo) to keep the zinc oxide inside the casing.



Progressive corrosion of zinc-carbon batteries.

Environmental impact

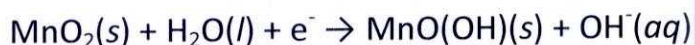
The environmental impact has been reduced since the addition of mercury was made illegal in most countries (in the US, it was under 1996 federal battery legislation).

Conveniently manufactured, and disposed, a single zinc–carbon dry cell has low environmental impact on disposal, compared with some other battery types. The manganese (III) is readily oxidized and so becomes immobilized; minute amounts of zinc, carbon and ammonium salts are also harmless.

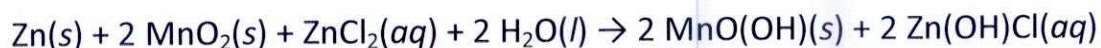
Thousands of tons of zinc–carbon batteries are discarded every year around the world, and are often not recycled.

The zinc chloride cell

The zinc chloride cell is an improvement on the original zinc–carbon cell, using purer chemicals and giving a longer life and steadier voltage output as it is used. These cells are often marketed as *heavy-duty* cells, to differentiate them from *general-purpose* zinc–carbon cells. This has been a source of consumer confusion after the introduction of alkaline cells, which last longer than the zinc-chloride heavy-duty cell. Instead of an electrolyte mixture containing much NH_4Cl , it is largely only ZnCl_2 paste. The cathode reaction is thus a little different:



as is the overall reaction:



Electrodes

Anode and cathode of an electrochemical device are defined by the direction of current flow, not the polarity of voltage. In electrolytic cells, the anode is referred as the *positive terminal* since all the anions (negative ions) will migrate to the anode to be selectively discharged while the cathode is the *negative terminal* because the cations (positive ions) will move to the cathode to be selectively discharged. Meanwhile, for voltaic cells, the anode is the negative terminal, while the cathode is the positive terminal. This is due to the convention which states that all anodes are terminals that undergo oxidation or release of electrons, and all

cathodes are terminals which undergo reduction. (Conventional) current departs at a cathode and enters a device at the anode, independent of the polarity of the voltage of the device.

Lemon battery

A **lemon battery** is a battery used in experiments proposed in many science textbooks around the world. It is made by inserting two different metallic objects, for example a galvanized nail and a copper coin, into an ion bridge (for example a lemon, a potato or paper soaked in salt water or acid). The copper coin serves as the positive electrode or cathode and the galvanized nail as the electron-producing negative electrode or anode. These two objects work as electrodes, causing an electrochemical reaction which generates a small potential difference. The origin of lemon and potato batteries is unknown.

The aim of this experiment is to show students how batteries work. After the battery is assembled, a multimeter can be used to check the generated voltage. For a more visible effect to be produced, a few lemon cells connected in series can be used to power a standard red LED. Flashlight bulbs are generally not used because the lemon battery cannot produce the amount of current required to light such bulbs. Digital clocks can work well, and some toymakers offer small kits with a clock that can be powered by two potatoes or lemons.



(A **lemon cell** battery is made with two metallic electrodes of different metals such as a copper penny or wire and a galvanized (zinc coated) nail joined with an ion bridge (for example a lemon, a potato or paper soaked in salt water). In practice, a single lemon cell is incapable of lighting a light bulb or even a flashlight bulb. One cell can provide neither the current nor the voltage of four lemons in series.)

Energy source

The energy for the battery comes from the chemical change in the zinc (or other metal) when exposed to an acid. The energy does not come from the lemon or potato. The zinc is oxidized inside the lemon, exchanging some of its electrons

with the acid in order to reach a lower energy state, and the energy released provides the power.

In current practice, zinc is produced by electrowinning of zinc sulfate or pyrometallurgic reduction of zinc with carbon, which requires an energy input. The energy produced in the lemon battery comes from reversing this reaction, recovering some of the energy input during the zinc production.

Calculations

Assuming that zinc and copper electrodes are used (such as a copper coin and a zinc plated nail) then a lemon could generate approximately 0.9 Volts.

The current depends on the size of the electrodes used and the strength of the ion bridge.

As an example, if we make some assumptions about the acidity of the lemon and the size of the electrodes, a current of 0.0003 amperes could be produced.

volts x amperes = watts

1 lemon: 0.9 volts x 0.0003 amperes = 0.00027 watts

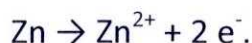
Flashlight bulb: 2.4 volts x 0.5 amperes = 1.2 watts, or about 5,000 lemons

Halogen bulb: 12 volts x 0.83 amperes = 10 watts, or about 37,000 lemons

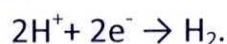
Red LED bulb: 1.7 volts x 0.0005 amperes = 0.00085 watts, or three lemons in series

Reactions

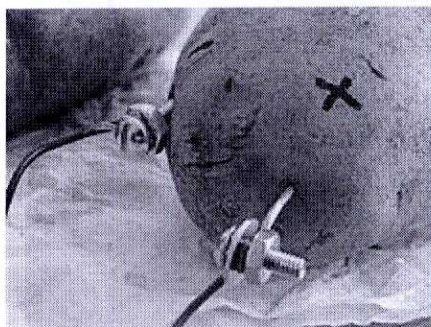
In a lemon battery, both oxidation and reduction occur. Consider the case of a zinc-copper battery; this battery is similar to the original "simple voltaic cells" invented by Alessandro Volta. At the anode, metallic zinc is oxidized, and enters the acidic solution as Zn^{2+} ions:



At the copper cathode, hydrogen ions (solvated protons from the acidic solution) are reduced to form molecular hydrogen:



Variations



Potato battery with copper and zinc electrodes

Potatoes, apples, sauerkraut, or any other fruit or vegetable containing acid or other electrolyte can be used, but lemons are preferred because of their higher acidity. In potatoes, for instance, the electrolyte is phosphoric acid, while in lemons it is citric acid. Other non-rusty metal combinations (such as magnesium-copper) are more effective; for example, using a magnesium strip instead of zinc increases the voltage from 0.9 volts to 1.3 volts with magnesium. However, zinc and copper are usually preferred because they are reasonably safe and easy to obtain.

Popular Culture

In the game Portal 2, GLaDOS's A.I. was embedded into a potato-battery-run computer.

In the NCIS Season 7 episode "Power Down", Forensic Tech Abby Schito uses lemons to power her stereo.

In the Bones Season 6 episode "The Blackout in the Blizzard," Angela and the other "squints" build a massive potato battery array in an attempt to power a cell phone. Illustrating the pathetically low output of such a system, it is successful for only a handful of seconds while using dozens of potatoes.

Secondary cell:

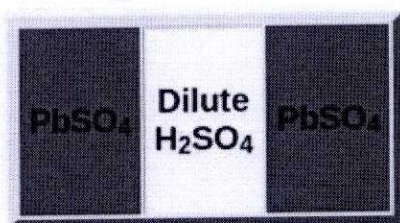
Lead-acid battery

Lead–acid batteries, invented in 1859 by French physicist Gaston Planté, are the oldest type of rechargeable battery. Despite having a very low energy-to-weight ratio and a low energy-to-volume ratio, their ability to supply high surge currents means that the cells maintain a relatively large power-to-weight ratio. These features, along with their low cost, make them attractive for use in motor vehicles to provide the high current required by automobile starter motors.

Lead–acid batteries (under 5 kg) account for 1.5% of all portable secondary battery sales in Japan by number of units sold (25% by price). Sealed lead–acid batteries accounted for 10% by weight of all portable battery sales in the EU in 2000.

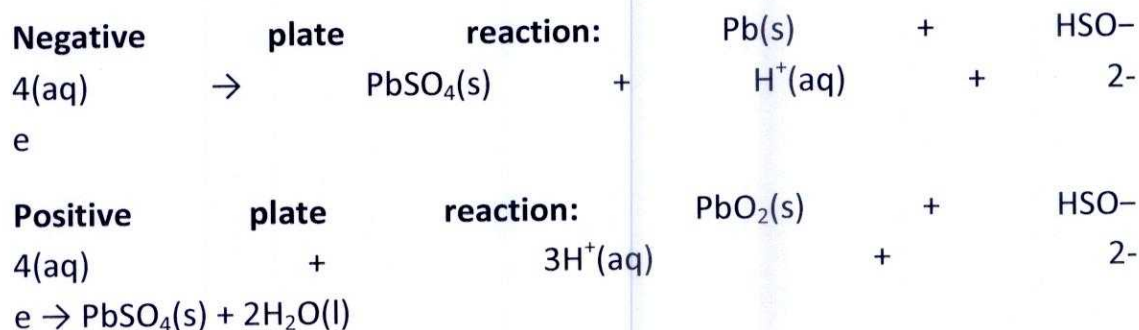
Electrochemistry

Discharge

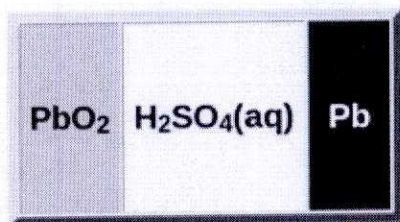


Fully Discharged: Two identical lead sulfate plates

In the discharged state both the positive and negative plates become lead(II) sulfate (PbSO_4) and the electrolyte loses much of its dissolved sulfuric acid and becomes primarily water. The discharge process is driven by the conduction of electrons from the positive plate back into the cell at the negative plate.

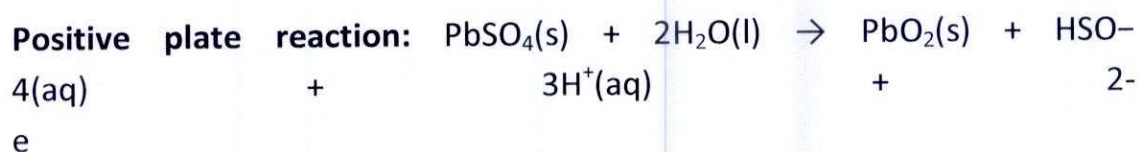
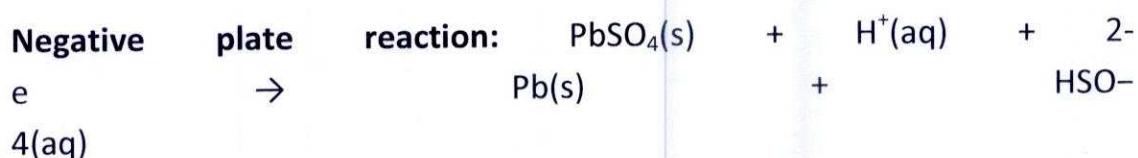


Charging



Fully Charged: Lead and Lead Oxide plates

In the charged state, each cell contains negative plates of elemental lead (Pb) and positive plates of lead(IV) oxide (PbO₂) in an electrolyte of approximately 33.5% v/v (4.2 Molar) sulfuric acid (H₂SO₄). The charging process is driven by the forcible removal of electrons from the negative plate and the forcible introduction of them to the positive plate.



Overcharging with high charging voltages generates oxygen and hydrogen gas by electrolysis of water, which is lost to the cell. Periodic maintenance of lead acid batteries requires inspection of the electrolyte level and replacement of any water that has been lost.

Due to the freezing-point depression of water, as the battery discharges and the concentration of sulfuric acid decreases, the electrolyte is more likely to freeze during winter weather.

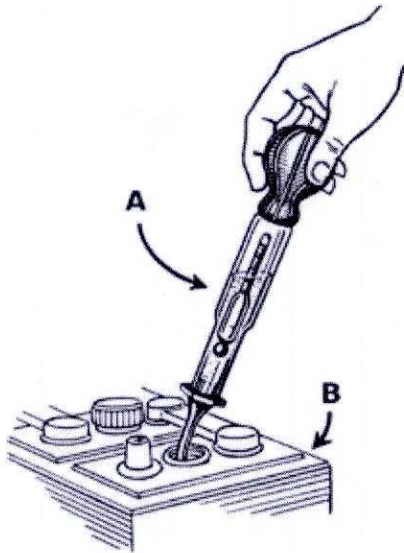
Voltages for common usages

These are general voltage ranges for *six-cell* lead-acid batteries:

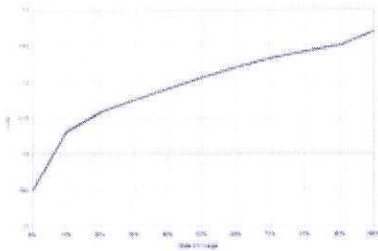
- Open-circuit (quiescent) at *full charge*: 12.6 V (2.1V per cell)
 - Open-circuit at *full discharge*: 11.7 V
 - Loaded at full discharge: 10.5 V.
 - Continuous-preservation (float) charging: 13.4 V for gelled electrolyte; 13.5 V for AGM (absorbed glass mat) and 13.9 V for flooded cells
1. All voltages are at 20 °C (68 °F), and must be adjusted $-0.0235\text{V}/^{\circ}\text{C}$ for temperature changes.
 2. Float voltage recommendations vary, according to the manufacturer's recommendation.
 3. Precise float voltage (± 0.05 V) is critical to longevity; insufficient voltage (causes sulfation) is almost as detrimental as excessive voltage (causing corrosion and electrolyte loss)
- Typical (daily) charging: 14.2 V to 14.4 V (depending on temperature and manufacturer's recommendation!)
 - Equalization charging (for flooded lead acids): 15 V for no more than 2.205 hours. Battery temperature must be absolutely monitored.
 - Gassing threshold: 14.4 V

Portable batteries, such as for miners' cap lamps headlamps typically have two or three cells.

Measuring the charge level



A hydrometer can be used to test the specific gravity of each cell as a measure of its state of charge.



A battery's open-circuit voltage can be used to estimate the state of charge, in this case for a 12-volt battery.

Because the electrolyte takes part in the charge-discharge reaction, this battery has one major advantage over other chemistries. It is relatively simple to determine the state of charge by merely measuring the specific gravity (S.G.) of the electrolyte, the S.G. falling as the battery discharges. Some battery designs include a simple hydrometer using colored floating balls of differing density. When used in diesel-electric submarines, the S.G. was regularly measured and written on a blackboard in the control room to indicate how much longer the boat could remain submerged.

The battery's open circuit voltage can also be used to gauge the state of charge. If the connections to the individual cells are accessible, then the state of charge of the each cell can be determined which can provide a guide as to the state of health of the battery as a whole.

Construction

Plates

The lead-acid cell can be demonstrated using sheet lead plates for the two electrodes. However such a construction produces only around one ampere for roughly postcard sized plates, and for only a few minutes.

Gaston Planté found a way to provide a much larger effective surface area. In Planté's design, the positive and negative plates were formed of two spirals of lead foil, separated with a sheet of cloth and coiled up. The cells initially had low

capacity, so a slow process of "forming" was required to corrode the lead foils, creating lead dioxide on the plates and roughening them to increase surface area. Initially this process used electricity from primary batteries; when generators became available after 1870, the cost of production of batteries greatly declined. Planté plates are still used in some stationary applications, where the plates are mechanically grooved to increase their surface area.

Faure pasted-plate construction is typical of automotive batteries. Each plate consists of a rectangular lead grid alloyed with antimony or calcium to improve the mechanical characteristics. The holes of the grid are filled with a paste of red lead and 33% dilute sulfuric acid. (Different manufacturers vary the mixture). The paste is pressed into the holes in the grid which are slightly tapered on both sides to better retain the paste. This porous paste allows the acid to react with the lead inside the plate, increasing the surface area many fold. Once dry, the plates are stacked with suitable separators and inserted in the battery container. An odd number of plates is usually used, with one more negative plate than positive. Each alternate plate is connected.

The positive plates are the chocolate brown color of lead dioxide, and the negative are the slate gray of "spongy" lead at the time of manufacture. In this charged state the plates are called 'formed'.

One of the problems with the plates is that the plates increase in size as the active material absorbs sulfate from the acid during discharge, and decrease as they give up the sulfate during charging. This causes the plates to gradually shed the paste. It is important that there is room underneath the plates to catch this shed material. If it reaches the plates, the cell short-circuits.

The paste contains carbon black, *blanc fixe* (barium sulfate) and lignosulfonate. The blanc fixe acts as a seed crystal for the lead-to-lead sulfate reaction. The blanc fixe must be fully dispersed in the paste in order for it to be effective. The lignosulfonate prevents the negative plate from forming a solid mass during the discharge cycle, instead enabling the formation of long needle-like crystals. The long crystals have more surface area and are easily converted back to the original state on charging. Carbon black counteracts the effect of inhibiting formation caused by the lignosulfonates. Sulfonated naphthalene condensate dispersant is a more effective expander than lignosulfonate and speeds up formation. This dispersant improves dispersion of barium sulfate in the paste, reduces hydroset time, produces a more breakage-resistant plate, reduces fine lead particles and thereby improves handling and pasting characteristics. It extends battery life by

increasing end-of-charge voltage. Sulfonated naphthalene requires about one-third to one-half the amount of lignosulfonate and is stable to higher temperatures.

Practical cells are usually not made with pure lead but have small amounts of antimony, tin, calcium or selenium alloyed in the plate material to add strength and simplify manufacture. The alloying element has a great effect on the life of the batteries, with calcium-alloyed plates preferred over antimony for longer life and less water consumption on each charge/discharge cycle.

About 60% of the weight of an automotive-type lead-acid battery rated around 60 Ah (8.7 kg of a 14.5 kg battery) is lead or internal parts made of lead; the balance is electrolyte, separators, and the case.

Separators

Separators between the positive and negative plates prevent short-circuit through physical contact, mostly through dendrites ('treeing'), but also through shedding of the active material. Separators obstruct the flow of ions between the plates and increase the internal resistance of the cell. Wood, rubber, glass fiber mat, cellulose, and PVC or polyethylene plastic have been used to make separators. Wood was the original choice, but deteriorated in the acid electrolyte. Rubber separators were stable in the battery acid.

An effective separator must possess a number of mechanical properties; such as permeability, porosity, pore size distribution, specific surface area, mechanical design and strength, electrical resistance, ionic conductivity, and chemical compatibility with the electrolyte. In service, the separator must have good resistance to acid and oxidation. The area of the separator must be a little larger than the area of the plates to prevent material shorting between the plates. The separators must remain stable over the battery's operating temperature range.

Applications

Most of the world's lead-acid batteries are automobile starting, lighting and ignition (SLI) batteries, with an estimated 320 million units shipped in 1999.^[6] In 1992 about 3 million tons of lead were used in the manufacture of batteries.

Wet cell stand-by (stationary) batteries designed for deep discharge are commonly used in large backup power supplies for telephone and computer centers, grid

energy storage, and off-grid household electric power systems. Lead–acid batteries are used in emergency lighting in case of power failure.

Traction (propulsion) batteries are used for in golf carts and other battery electric vehicles. Large lead–acid batteries are also used to power the electric motors in diesel-electric (conventional) submarines and are used on nuclear submarines as well. Valve-regulated lead acid batteries cannot spill their electrolyte. They are used in back-up power supplies for alarm and smaller computer systems (particularly in uninterruptible power supplies) and for electric scooters, electric wheelchairs, electrified bicycles, marine applications, battery electric vehicles or micro hybrid vehicles, and motorcycles.

Lead–acid batteries were used to supply the filament (heater) voltage, with 2 V common in early vacuum tube (valve) radio receivers.

Cycles

Starting batteries

Lead acid batteries designed for starting automotive engines are not designed for deep discharge. They have a large number of thin plates designed for maximum surface area, and therefore maximum current output, but which can easily be damaged by deep discharge. Repeated deep discharges will result in capacity loss and ultimately in premature failure, as the electrodes disintegrate due to mechanical stresses that arise from cycling. Starting batteries kept on continuous float charge will have corrosion in the electrodes and result in premature failure. Starting batteries should be kept open circuit but charged regularly (at least once every two weeks) to prevent sulfation.

Starting batteries are lighter weight than deep cycle batteries of the same battery dimensions, because the cell plates do not extend all the way to the bottom of the battery case. This allows loose disintegrated lead to fall off the plates and collect under the cells, to prolong the service life of the battery. If this loose debris rises high enough it can touch the plates and lead to failure of a cell, resulting in loss of battery voltage and capacity.

Deep cycle batteries

Main article: Deep cycle battery

Specially designed deep-cycle cells are much less susceptible to degradation due to cycling, and are required for applications where the batteries are regularly discharged, such as photovoltaic systems, electric vehicles (forklift, golf cart, electric cars and other) and uninterruptible power supplies. These batteries have thicker plates that can deliver less *peak current*, but can withstand frequent discharging.

Some batteries are designed as a compromise between starter (high-current) and deep cycle batteries. They are able to be discharged to a greater degree than automotive batteries, but less so than deep cycle batteries. They may be referred to as "Marine/Motorhome" batteries, or "leisure batteries".

Fast and slow charge and discharge



Charge current needs to match the ability of the battery to absorb the energy. Using too large a charge current on a small battery can lead to boiling and venting of the electrolyte. In this image a VRLA battery case has ballooned due to the high gas pressure developed during overcharge.

The capacity of a lead-acid battery is not a fixed quantity but varies according to how quickly it is discharged. An empirical relationship exists between discharge rate and capacity, known as Peukert's law.

When a battery is charged or discharged, this initially affects only the reacting chemicals, which are at the interface between the electrodes and the electrolyte. With time, the charge stored in the chemicals at the interface, often called "interface charge", spreads by diffusion of these chemicals throughout the volume of the active material.

If a battery has been completely discharged (such as by leaving the car lights on overnight) and then is given a fast charge for only a few minutes, the battery plates charge only near the interface between plate and electrolyte. The battery voltage may rise to be close to the charger voltage so that the charging current decreases significantly. After a few hours this interface charge will spread to the volume of the electrode and electrolyte, leading to an interface charge so low that it may be insufficient to start the car.

On the other hand, if the battery is given a slow charge, which takes longer, then the battery will become more fully charged. During a slow charge the interface charge has time to redistribute to the volume of the electrodes and electrolyte, while being replenished by the charger. The battery voltage remains below the charger voltage throughout this process allowing charge to flow into the battery.

Similarly, if a battery is subject to a fast discharge (such as starting a car, a current draw of more than 100 amps) for a few minutes, it will appear to go dead, exhibiting reduced voltage and power. However, it may have only lost its interface charge. If the discharge is halted for a few minutes the battery may resume normal operation at the appropriate voltage and power for its state of discharge. On the other hand, if a battery is subject to a slow, deep discharge (such as leaving the car lights on, a current draw of less than 7 amps) for hours, then any observed reduction in battery performance is likely permanent.

Valve regulated

In a valve regulated lead acid (VRLA) battery the hydrogen and oxygen produced in the cells largely recombine into water. Leakage is minimal, although some electrolyte still escapes if the recombination cannot keep up with gas evolution. Since VRLA batteries do not require (and make impossible) regular checking of the electrolyte level, they have been called *maintenance free batteries*. However, this is somewhat of a misnomer. VRLA cells do require maintenance. As electrolyte is lost, VRLA cells "dry-out" and lose capacity. This can be detected by taking regular internal resistance, conductance or impedance measurements. Regular testing reveals whether more involved testing and maintenance is required. Recent maintenance procedures have been developed allowing "rehydration", often restoring significant amounts of lost capacity.

VRLA types became popular on motorcycles around 1983, because the acid electrolyte is absorbed into the separator, so it cannot spill. The separator also helps them better withstand vibration. They are also popular in stationary applications such as telecommunications sites, due to their small footprint and installation flexibility.

The electrical characteristics of VRLA batteries differ somewhat from wet-cell lead–acid batteries, requiring caution in charging and discharging.

] Sulfation and desulfation

Lead–acid batteries lose the ability to accept a charge when discharged for too long due to *sulfation*, the crystallization of lead sulfate. They generate electricity through a double sulfate chemical reaction. Lead and lead dioxide, the active materials on the battery's plates, react with sulfuric acid in the electrolyte to form lead sulfate. The lead sulfate first forms in a finely divided, amorphous state, and easily reverts to lead, lead dioxide and sulfuric acid when the battery recharges. As batteries cycle through numerous discharges and charges, some lead sulfate is not recombined into electrolyte and slowly converts to a stable crystalline form that no longer dissolves on recharging. Thus, not all the lead is returned to the battery plates, and the amount of usable active material necessary for electricity generation declines over time.

Sulfation occurs in all lead–acid batteries during normal operation. It impedes recharging; sulfate deposits ultimately expand, cracking the plates and destroying the battery. Eventually so much of the battery plate area is unable to supply current that the battery capacity is greatly reduced. In addition, the sulfate portion (of the lead sulfate) is not returned to the electrolyte as sulfuric acid. The large crystals physically block the electrolyte from entering the pores of the plates. Sulfation can be avoided if the battery is fully recharged immediately after a discharge cycle. A white coating on the plates may be visible (in batteries with clear cases, or after dismantling the battery). Batteries that are sulfated show a high internal resistance and can deliver only a small fraction of normal discharge current.

Sulfation also affects the charging cycle, resulting in longer charging times, less efficient and incomplete charging, and higher battery temperatures.

The process can often be at least partially reversed by a desulfation technique called pulse conditioning, in which short but powerful current surges are

repeatedly sent through the damaged battery. Over time, this procedure tends to break down and dissolve the sulfate crystals, restoring some capacity.

Desulfation is the process of reversing the sulfation of a lead-acid battery. Desulfation is achieved by high current pulses produced between the terminals of the battery. This technique, also called *pulse conditioning*, breaks down the sulfate crystals that are formed on the battery plates. Short high current pulses tend to work best. Electronic circuits are used to regulate the pulses of different widths and frequency of high current pulses. These can also be used to automate the process since it takes a long period of time to desulfate a battery fully. Battery chargers designed for desulfating lead-acid batteries are commercially available. A battery will be unrecoverable if the active material has been lost from the plates, or if the plates are bent due to over temperature or over charging.

Batteries which have sat unused for long periods of time can be prime candidates for desulfation. A long period of self-discharge allows the sulfate crystals to form and become very large. Some typical cases where lead acid batteries are not used frequently enough are planes, boats (esp sail boats), old cars, and home power systems with battery banks that are under utilized.

Some charging techniques can aid in prevention such as equalization charging and cycles through discharging and charging regularly. It is recommended to follow battery manufacturer instructions for proper charging.

SLI batteries (starting, lighting, ignition; i.e. car batteries) have less deterioration because they are used more frequently vs deep cycle batteries. Deep cycle batteries tend to require more desulfation, can suffer from overcharging, and can be in a very large bank which leads to unequal charging and discharging.

Stratification

A typical lead-acid battery contains a mixture with varying concentrations of water and acid. There is a slight difference in density between water and acid, and if the battery is allowed to sit idle for long periods of time, the mixture can separate into distinct layers with the water rising to the top and the acid sinking to the bottom. This results in a difference of acid concentration across the surface of the plates, and can lead to greater corrosion of the bottom half of the plates.

Frequent charging and discharging tends to stir up the mixture, since the electrolysis of water during charging forms hydrogen and oxygen bubbles that rise

and displace the liquid as the bubbles move upward. Batteries in moving vehicles are also subject to sloshing and splashing in the cells, as the vehicle accelerates, brakes, and turns.

Risk of explosion



Car battery after explosion

Excessive charging electrolyzes some of the water, emitting hydrogen and oxygen. This process is known as "gassing". Wet cells have open vents to release any gas produced, and VRLA batteries rely on valves fitted to each cell. Wet cells come with catalytic caps to recombine any emitted hydrogen. A VRLA cell normally recombines any hydrogen and oxygen produced inside the cell, but malfunction or overheating may cause gas to build up. If this happens (for example, on overcharging) the valve vents the gas and normalizes the pressure, producing a characteristic acid smell. Valves can sometimes fail however, if dirt and debris accumulate, allowing pressure to build up.

If the accumulated hydrogen and oxygen within either a VRLA or wet cell is ignited, an explosion results. The force can burst the plastic casing or blow the top off the battery, spraying acid and casing shrapnel. An explosion in one cell may ignite the combustible gas mixture in remaining cells.

The cell walls of VRLA batteries typically swell when the internal pressure rises. The deformation varies from cell to cell, and is greater at the ends where the walls are unsupported by other cells. Such over-pressurized batteries should be carefully

isolated and discarded. Personnel working near batteries at risk for explosion should protect their eyes and exposed skin from burns due to spraying acid and fire by wearing a face shield, overalls, and gloves. Using goggles instead of a face shield sacrifices safety by leaving one's face exposed to acid and heat from a potential explosion.

Environment

Environmental concerns

According to a 2003 report entitled, "Getting the Lead Out," by Environmental Defense and the Ecology Center of Ann Arbor, Mich., the batteries of vehicles on the road contained an estimated 2,600,000 metric tons (2,600,000 long tons; 2,900,000 short tons) of lead. Some lead compounds are extremely toxic. Long-term exposure to even tiny amounts of these compounds can cause brain and kidney damage, hearing impairment, and learning problems in children. The auto industry uses over 1,000,000 metric tons (980,000 long tons; 1,100,000 short tons) every year, with 90% going to conventional lead-acid vehicle batteries. While lead recycling is a well-established industry, more than 40,000 metric tons (39,000 long tons; 44,000 short tons) ends up in landfills every year. According to the federal Toxic Release Inventory, another 70,000 metric tons (69,000 long tons; 77,000 short tons) are released in the lead mining and manufacturing process.

Attempts are being made to develop alternatives (particularly for automotive use) because of concerns about the environmental consequences of improper disposal and of lead smelting operations, among other reasons. Alternatives are unlikely to displace them for applications such as engine starting or backup power systems, since the batteries are low-cost although heavy.

Recycling

See also: Automotive battery recycling

Lead-acid battery recycling is one of the most successful recycling programs in the world. In the United States 97% of all battery lead was recycled between 1997 and 2001.^[18] An effective pollution control system is a necessity to prevent lead emission. Continuous improvement in battery recycling plants and furnace designs is required to keep pace with emission standards for lead smelters.

Additives

Since the 1950s chemical additives have been used to reduce lead sulfate build up on plates and improve battery condition when added to the electrolyte of a vented lead–acid battery. Such treatments are rarely, if ever, effective.

Two compounds used for such purposes are Epsom salts and EDTA. Epsom salts reduces the internal resistance in a weak or damaged battery and may allow a small amount of extended life. EDTA can be used to dissolve the sulfate deposits of heavily discharged plates. However, the dissolved material is then no longer available to participate in the normal charge/discharge cycle, so a battery temporarily revived with EDTA will have a reduced life expectancy. Residual EDTA in the lead–acid cell forms organic acids which will accelerate corrosion of the lead plates and internal connectors.

The active materials change physical form during charge/discharge, resulting in growth and distortion of the electrodes, and shedding of electrode into the electrolyte. Once the active material has fallen out of the plates, it cannot be restored into position by any chemical treatment. Similarly, internal physical problems such as cracked plates, corroded connectors, or damaged separators cannot be restored chemically.

Corrosion problems

Corrosion of the external metal parts of the lead–acid battery results from a chemical reaction of the battery terminals, lugs and connectors.

Corrosion on the positive terminal is caused by electrolysis, due a mismatch of metal alloys used in the manufacture of the battery terminal and cable connector. White corrosion is usually lead or zinc sulfate crystals. Aluminum connectors corrode to aluminum sulfate. Copper connectors produce blue and white corrosion crystals. Corrosion of a battery's terminals can be reduced by coating the terminals with petroleum jelly or a commercially available product made for the purpose.

If the battery is over-filled with water and electrolyte, thermal expansion can force some of the liquid out of the battery vents onto the top of the battery. This solution can then react with the lead and other metals in the battery connector and cause corrosion.

The electrolyte can weep from the plastic-to-lead seal where the battery terminals penetrate the plastic case.

Acid fumes that vaporize through the vent caps, often caused by overcharging, and insufficient battery box ventilation can allow the sulfuric acid fumes to build up and react with the exposed metals.

Maintenance precautions

Ammonia can neutralize spilled battery acid. Surplus ammonia and water evaporate, leaving an ammonium sulfate residue. Sodium bicarbonate (baking soda) is also commonly used for this purpose.

Lithium-ion battery

A **lithium-ion battery** (sometimes **Li-ion battery** or **LIB**) is a family of rechargeable battery types in which lithium ions move from the negative electrode to the positive electrode during discharge, and back when charging. Chemistry, performance, cost, and safety characteristics vary across LIB types. Unlike lithium primary batteries (which are disposable), lithium-ion electrochemical cells use an intercalated lithium compound as the electrode material instead of metallic lithium.

Lithium-ion batteries are common in consumer electronics. They are one of the most popular types of rechargeable battery for portable electronics, with one of the best energy densities, no memory effect, and only a slow loss of charge when not

in use. Beyond consumer electronics, LIBs are also growing in popularity for military, electric vehicle, and aerospace applications. Research is yielding a stream of improvements to traditional LIB technology, focusing on energy density, durability, cost, and intrinsic safety.

Charge and discharge

During discharge, lithium ions Li^+ carry the current from the negative to the positive electrode, through the non-aqueous electrolyte and separator diaphragm.

During charging, an external electrical power source (the charging circuit) applies an over-voltage (a higher voltage but of the same polarity) than that produced by the battery, forcing the current to pass in the reverse direction. The lithium ions then migrate from the positive to the negative electrode, where they become embedded in the porous electrode material in a process known as intercalation.

Construction



Cylindrical 18650 lithium iron phosphate cell before closing

The three primary functional components of a lithium-ion battery are the negative electrode, positive electrode, and the electrolyte. The negative electrode of a conventional lithium-ion cell is made from carbon. The positive electrode is a metal oxide, and the electrolyte is a lithium salt in an organic solvent. The electrochemical roles of the electrodes change between anode and cathode, depending on the direction of current flow through the cell.

The most commercially popular negative electrode material is graphite. The positive electrode is generally one of three materials: a layered oxide (such as

lithium cobalt oxide), a polyanion (such as lithium iron phosphate), or a spinel (such as lithium manganese oxide).

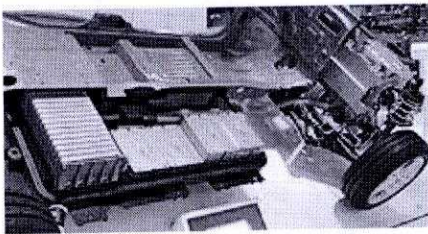
The electrolyte is typically a mixture of organic carbonates such as ethylene carbonate or diethyl carbonate containing complexes of lithium ions. These non-aqueous electrolytes generally use non-coordinating anion salts such as lithium hexafluorophosphate (LiPF_6), lithium hexafluoroarsenate monohydrate (LiAsF_6), lithium perchlorate (LiClO_4), lithium tetrafluoroborate (LiBF_4), and lithium triflate (LiCF_3SO_3).

Depending on materials choices, the voltage, capacity, life, and safety of a lithium-ion battery can change dramatically. Recently, novel architectures using nanotechnology have been employed to improve performance.

Pure lithium is very reactive. It reacts vigorously with water to form lithium hydroxide and hydrogen gas. Thus, a non-aqueous electrolyte is typically used, and a sealed container rigidly excludes water from the battery pack.

Lithium ion batteries are more expensive than NiCd batteries but operate over a wider temperature range with higher energy densities, while being smaller and lighter. They are fragile and so need a protective circuit to limit peak voltages.

Formats



Nissan Leaf's lithium-ion battery pack.

Li-ion cells are available in various formats, which can generally be divided into four groups:

- Small cylindrical (solid body without terminals, such as those used in laptop batteries)
- Large cylindrical (solid body with large threaded terminals)
- Pouch (soft, flat body, such as those used in cell phones)

- Prismatic (semi-hard plastic case with large threaded terminals, often used in vehicles' traction packs)

The lack of case gives pouch cells the highest energy density; however, pouch cells (and prismatic cells) require an external means of containment to prevent expansion when their state-of-charge (SOC) level is high.

History



Varta lithium-ion battery, Museum Autovision, Altlusheim, Germany

Lithium batteries were first proposed by M.S. Whittingham, now at Binghamton University, while working for Exxon in the 1970s. Whittingham used titanium(II) sulfide and lithium metal as the electrodes.

The reversible intercalation in graphite and intercalation into cathodic oxides was also already discovered in the 1970s by J.O. Besenhard at TU Munich. He also proposed the application as high energy density lithium cells. Electrolyte decomposition and solvent co-intercalation into graphite were severe drawbacks for long battery cycle life.

Primary lithium batteries in which the positive electrode is made from metallic lithium pose safety issues. As a result, lithium-ion batteries were developed in which both electrodes are made of a material containing lithium ions.

In 1979, John Goodenough demonstrated a rechargeable cell with high cell voltage in the 4V range using lithium cobalt oxide (LiCoO_2) as the positive electrode and lithium metal as the negative electrode. This innovation provided the positive electrode material which made LIBs possible. LiCoO_2 is a stable positive electrode material which acts as a donor of lithium ions, which means that it can be used with a negative electrode material other than lithium metal. By enabling the use of

stable and easy-to-handle negative electrode materials, LiCoO_2 opened a whole new range of possibilities for novel rechargeable battery systems.

In 1977, Samar Basu demonstrated electrochemical intercalation of lithium in graphite at the University of Pennsylvania. This led to the development of a workable lithium intercalated graphite electrode at Bell Labs (LiC_6) to provide an alternative to the lithium metal battery.

In 1980, Rachid Yazami also demonstrated the reversible electrochemical intercalation of lithium in graphite. The organic electrolytes available at the time would decompose during charging if used with a graphite negative electrode, preventing the early development of a rechargeable battery which employed the lithium/graphite system. Yazami used a solid electrolyte to demonstrate that lithium could be reversibly intercalated in graphite through an electrochemical mechanism. The graphite electrode discovered by Yazami is currently the most commonly used electrode in commercial lithium ion batteries.

In 1983, Dr. Michael Thackeray, Goodenough, and coworkers identified manganese spinel as a cathode material. Spinel showed great promise, given its low-cost, good electronic and lithium ion conductivity, and three-dimensional structure, which gives it good structural stability. Although pure manganese spinel fades with cycling, this can be overcome with chemical modification of the material. Manganese spinel is currently used in commercial cells.^[29]

In 1985, Akira Yoshino assembled a prototype cell using carbonaceous material into which lithium ions could be inserted as one electrode, and lithium cobalt oxide (LiCoO_2), which is stable in air, as the other. By using materials without metallic lithium, safety was dramatically improved over batteries which used lithium metal. The use of lithium cobalt oxide (LiCoO_2) enabled industrial-scale production to be achieved easily.

This was the birth of the current lithium-ion battery.

Modern batteries

In 1991, Sony and Asahi Kasei released the first commercial lithium-ion battery.

In 1989, Goodenough and Arumugam Manthiram of the University of Texas at Austin showed that cathodes containing polyanions, e.g., sulfates, produce higher voltages than oxides due to the inductive effect of the polyanion.

In 1996, Goodenough, Akshaya Padhi and coworkers identified lithium iron phosphate (LiFePO_4) and other phospho-olivines (lithium metal phosphates with the same structure as mineral olivine) as cathode materials.

In 2002, Yet-Ming Chiang and his group at MIT showed a substantial improvement in the performance of lithium batteries by boosting the material's conductivity by doping it with aluminium, niobium and zirconium. The exact mechanism causing the increase became the subject of widespread debate.

In 2004, Chiang again increased performance by utilizing iron phosphate particles of less than 100 nanometers in diameter. This decreased particle density almost one hundredfold, increased the cathode's surface area and improved capacity and performance. Commercialization led to a rapid growth in the market for higher capacity LIBs, as well as a patent infringement battle between Chiang and Goodenough.

As of 2011, lithium-ion batteries account for 66% of all portable secondary battery sales in Japan.

Electrochemistry

The three participants in the electrochemical reactions in a lithium-ion battery are the anode, cathode, and electrolyte.

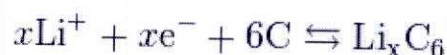
Both the anode and cathode are materials into which, and from which, lithium can migrate. During *insertion* (or *intercalation*) lithium moves into the electrode. During the reverse process, *extraction* (or *deintercalation*), lithium moves back out. When a lithium-based cell is discharging, the lithium is extracted from the anode and inserted into the cathode. When the cell is charging, the reverse occurs.

Useful work can only be extracted if electrons flow through a closed external circuit. The following equations are in units of moles, making it possible to use the coefficient x .

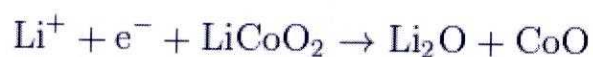
The positive electrode half-reaction (with charging being forwards) is:



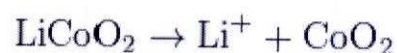
The negative electrode half-reaction is:



The overall reaction has its limits. Overdischarge supersaturates lithium cobalt oxide, leading to the production of lithium oxide, possibly by the following irreversible reaction:



Overcharge up to 5.2 Volts leads to the synthesis of cobalt(IV) oxide, as evidenced by x-ray diffraction



In a lithium-ion battery the lithium ions are transported to and from the cathode or anode, with the transition metal, cobalt (Co), in Li_xCoO_2 being oxidized from Co^{3+} to Co^{4+} during charging, and reduced from Co^{4+} to Co^{3+} during discharge.

Positive electrodes

Electrode material Average potential difference Specific capacity Specific energy

LiCoO_2	3.7 V	140 mA·h/g	0.518 kW·h/kg
LiMn_2O_4	4.0 V	100 mA·h/g	0.400 kW·h/kg
LiNiO_2	3.5 V	180 mA·h/g	0.630 kW·h/kg
LiFePO_4	3.3 V	150 mA·h/g	0.495 kW·h/kg
$\text{Li}_2\text{FePO}_4\text{F}$	3.6 V	115 mA·h/g	0.414 kW·h/kg
$\text{LiCo}_{1/3}\text{Ni}_{1/3}\text{Mn}_{1/3}\text{O}_2$	3.6 V	160 mA·h/g	0.576 kW·h/kg
$\text{Li}(\text{Li}_a\text{Ni}_x\text{Mn}_y\text{Co}_z)\text{O}_2$	4.2 V	220 mA·h/g	0.920 kW·h/kg

Negative electrodes

Electrode material Average difference potential Specific capacity Specific energy

Graphite (LiC ₆)	0.1-0.2 V	372 mA·h/g	0.0372-0.0744 kW·h/kg
Hard Carbon (LiC ₆)	? V	450 mA·h/g	? kW·h/kg
Titanate (Li ₄ Ti ₅ O ₁₂)	1-2 V	160 mA·h/g	0.16-0.32 kW·h/kg
Si (Li _{4.4} Si) ^[38]	0.5-1 V	4212 mA·h/g	2.106-4.212 kW·h/kg
Ge (Li _{4.4} Ge) ^[39]	0.7-1.2 V	1624 mA·h/g	1.137-1.949 kW·h/kg

Electrolytes

The cell voltages given in the Electrochemistry section are larger than the potential at which aqueous solutions can electrolyze, in addition lithium is highly reactive to water, therefore, nonaqueous or aprotic solutions are used.

Liquid electrolytes in lithium-ion batteries consist of lithium salts, such as LiPF₆, LiBF₄ or LiClO₄ in an organic solvent, such as ethylene carbonate, dimethyl carbonate, and diethyl carbonate. A liquid electrolyte conducts lithium ions, acting as a carrier between the cathode and the anode when a battery passes an electric current through an external circuit. Typical conductivities of liquid electrolyte at room temperature (20 °C (68 °F)) are in the range of 10 mS/cm (1 S/m), increasing by approximately 30–40% at 40 °C (104 °F) and decreasing by a slightly smaller amount at 0 °C (32 °F)

Unfortunately, organic solvents easily decompose on anodes during charging. However, when appropriate organic solvents are used as the electrolyte, the solvent decomposes on initial charging and forms a solid layer called the solid electrolyte interphase (SEI), which is electrically insulating yet provides sufficient ionic conductivity. The interphase prevents decomposition of the electrolyte after the second charge. For example, ethylene carbonate is decomposed at a relatively high voltage, 0.7 V vs. lithium, and forms a dense and stable interface.

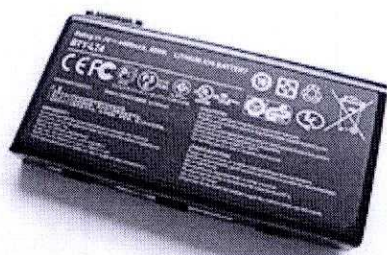
A good solution for the interface instability is the application of a new class of composite electrolytes based on POE (poly(oxyethylene)) developed by Syzdek et al.^{[42][43]} It can be either solid (high molecular weight) and be applied in dry Li-polymer cells, or liquid (low molecular weight) and be applied in regular Li-ion cells.

Another issue that Li-ion technology is facing is safety. Large scale application of Li cells in Electric Vehicles needs a dramatic decrease in the failure rate. One of the solutions is the novel technology based on reversed-phase composite electrolytes, employing porous ceramic material filled with electrolyte.

Advantages and disadvantages

Note that both advantages and disadvantages depend on the materials and design that make up the battery. This summary reflects older designs that use carbon anode, metal oxide cathodes, and lithium salt in an organic solvent for the electrolyte.

Advantages



A lithium-ion battery from a laptop computer

- Wide variety of shapes and sizes efficiently fitting the devices they power.
- Much lighter than other energy-equivalent secondary batteries.^[45]
- High open circuit voltage in comparison to aqueous batteries (such as lead acid, nickel-metal hydride and nickel-cadmium).^[46] This is beneficial because it increases the amount of power that can be transferred at a lower current.
- No memory effect.
- Self-discharge rate of approximately 5-10% per month, compared to over 30% per month in common nickel metal hydride batteries, approximately

1.25% per month for Low Self-Discharge NiMH batteries and 10% per month in nickel-cadmium batteries. According to one manufacturer, lithium-ion cells (and, accordingly, "dumb" lithium-ion batteries) do not have any self-discharge in the usual meaning of this word. What looks like a self-discharge in these batteries is a permanent loss of capacity (see Disadvantages). On the other hand, "smart" lithium-ion batteries do self-discharge, due to the drain of the built-in voltage monitoring circuit.

- Components are environmentally safe as there is no free lithium metal.

Disadvantages

Cell life

- Charging forms deposits inside the electrolyte that inhibit ion transport. Over time, the cell's capacity diminishes. The increase in internal resistance reduces the cell's ability to deliver current. This problem is more pronounced in high-current applications. The decrease means that older batteries do not charge as much as new ones (charging time required decreases proportionally).
- High charge levels and elevated temperatures (whether from charging or ambient air) hasten capacity loss. Charging heat is caused by the carbon anode (typically replaced with lithium titanate which drastically reduces damage from charging, including expansion and other factors).

Internal resistance

- The internal resistance of standard (Cobalt) lithium-ion batteries is high compared to both other rechargeable chemistries such as nickel-metal hydride and nickel-cadmium, and LiFePO₄ and lithium-polymer cells. Internal resistance increases with both cycling and age. Rising internal resistance causes the voltage at the terminals to drop under load, which reduces the maximum current draw. Eventually increasing resistance means that the battery can no longer operate for an adequate period.
- To power larger devices, such as electric cars, connecting many small batteries in a parallel circuit is more effective and efficient than connecting a single large battery.

Safety requirements

If overheated or overcharged, Li-ion batteries may suffer thermal runaway and cell rupture. In extreme cases this can lead to combustion. Deep discharge may short-circuit the cell, in which case recharging would be unsafe. To reduce these risks, Lithium-ion battery packs contain fail-safe circuitry that shuts down the battery when its voltage is outside the safe range of 3–4.2 V per cell. When stored for long periods the small current draw of the protection circuitry itself may drain the battery below its shut down voltage; normal chargers are then ineffective. Many types of lithium-ion cell cannot be charged safely below 0°C.

Other safety features are required in each cell:

- Shut-down separator (for overtemperature)
- Tear-away tab (for internal pressure)
- Vent (pressure relief)
- Thermal interrupt (overcurrent/overcharging)

These devices occupy useful space inside the cells, add additional points of failure and irreversibly disable the cell when activated. They are required because the anode produces heat during use, while the cathode may produce oxygen. These devices and improved electrode designs reduce/eliminate the risk of fire or explosion.

These safety features increase costs compared to nickel metal hydride batteries, which require only a hydrogen/oxygen recombination device (preventing damage due to mild overcharging) and a back-up pressure valve.

Specifications and design

- Specific energy density: 150 to 250 W·h/kg (540 to 900 kJ/kg)
- Volumetric energy density: 250 to 620 W·h/l (900 to 1900 J/cm³)
- Specific power density: 300 to 1500 W/kg (@ 20 seconds and 285 W·h/l)

Because lithium-ion batteries can have a variety of cathode and anode materials, the energy density and voltage vary accordingly.

Lithium-ion batteries with a lithium iron phosphate cathode and graphite anode have a nominal open-circuit voltage of 3.2 V and a typical charging voltage of 3.6 V. Lithium nickel manganese cobalt (NMC) oxide cathode with graphite anodes

have a 3.7 V nominal voltage with a 4.2 V max charge. The charging procedure is performed at constant voltage with current-limiting circuitry (i.e., charging with constant current until a voltage of 4.2 V is reached in the cell and continuing with a constant voltage applied until the current drops close to zero). Typically, the charge is terminated at 3% of the initial charge current. In the past, lithium-ion batteries could not be fast-charged and needed at least two hours to fully charge. Current-generation cells can be fully charged in 45 minutes or less. Some lithium-ion varieties can reach 90% in as little as 10 minutes.

Battery charging procedure

The charging procedures for single Li-ion cells, and complete Li-ion batteries, are slightly different.

- A single Li-ion cell is charged in 2 stages:
 1. CC
 2. CV
- A Li-ion battery (a set of Li-ion cells in series) is charged in 3 stages:
 1. CC
 2. Balance (not required once a battery is balanced)
 3. CV

Stage 1: CC: Apply charging current to the battery, until the voltage limit per cell is reached.

Stage 2: Balance: Reduce the charging current (or cycle the charging on and off to reduce the average current) while the State Of Charge of individual cells is balanced by a balancing circuit, until the battery is balanced.

Stage 3: CV: Apply a voltage equal to the maximum cell voltage times the number of cells in series to the battery, as the current gradually declines asymptotically towards 0, until the current is below a set threshold of about 3% of initial constant charge current.

Variations in materials and construction

The increasing demand for batteries has led vendors and academics to focus on improving the power density, operating temperature, safety, durability, charging time, output power, and cost of LIB solutions.

LIB types

Area	Technology	Researchers	Target application	Date	Benefit
Cathode	Manganese spinel (LMO)	Lucky Chemical, Samsung, Nissan/AESC	Goldstar NEC, Hitachi, Hybrid electric vehicle, cell phone, laptop	1996	durability, cost
	Lithium iron phosphate	University of Texas/Hydro-Québec, /Phostech Lithium Inc., Valence Technology, A123Systems/MIT	Segway Personal Transporter, power tools, aviation products, automotive hybrid systems, PHEV conversions	1996	moderate density (2 A·h outputs 70 amperes) operating temperature >60 °C (140 °F)
	Lithium nickel manganese cobalt (NMC)	Imara Corporation, Nissan Motor		2008	density, output, safety
	LMO/NMC	Sony, Sanyo			power, safety (although limited durability)

Lithium iron fluorophosphate	University of Waterloo	2007	durability, cost (replace Li with Na or Na/Li)
Lithium air	University of Dayton Research Institute	2009	density, safety
5% Vanadium-doped Lithium iron phosphate olivine	Binghamton University	2008	output
Anode	Lithium-titanate battery (LT)	Altairnano	automotive (Phoenix Motorcars), electrical grid (PJM Interconnection Regional Transmission Organization control area, United States Department of Defense ^[76]), bus (Proterra)
Lithium vanadium oxide	Samsung/Subaru.	2007	density (745Wh/l)
Cobalt-oxide nanowires from	MIT	2006	density, thickness

genetically
modified virus

Three-

Dimensional

(3D) Porous

Particles

Composed of

Curved Two-

Dimensional

(2D) Nano-Sized

Layers

Georgia Institute
of Technology

high energy
batteries for
electronics and
electrical
vehicles

201
1

specific
capacity >
2000 mA·h/g,
high
efficiency,
rapid low-
cost synthesis

Iron-phosphate
nanowires from
genetically
modified virus

MIT

200 density,
9 thickness

Silicon/titanium
dioxide
composite
nanowires from
genetically
modified
tobacco virus

University
Maryland

explosive
detection
sensors,
biomimetic
of structures,
water-repellent
surfaces,
micro/nano
scale heat
pipes

201 density, low
0 charge time

Porous

silicon/carbon

nanocomposite

spheres

Georgia Institute
of Technology

portable
electronics,
electrical
vehicles,

201
0

high stability,
high capacity,
low charge
time

		electrical grid		
nano-sized wires stainless steel	Stanford University	wireless sensors networks,	2007	density (shift from anode-to cathode-limited), durability issue remains (wire cracking)
Metal hydrides	Laboratoire de Réactivité et de Chimie des Solides, General Motors		2008	density (1480 mA·h/g)
Silicon Nanotubes (or Silicon Nanospheres) Confined within Rigid Carbon Outer Shells	Georgia Institute of Technology, MSE, NanoTech Yushin's group	stable high energy batteries for cell phones, laptops, netbooks, radios, sensors and electrical vehicles	2010	specific capacity 2400 mA·h/g, ultra-high Coulombic Efficiency and outstanding SEI stability
Silicon nano-powder in a conductive polymer binder	Lawrence Berkeley National Laboratory, Environmental Energy Technologies	Automotive and Electronics	2011	high capacity anodes (1400 mA·h/g) with good cycling characteristics

		Division		
Electrode	LT/LMO	Ener1/Delphi, ^{[95][96]}	2006	durability, safety (limited density)
	Nanostructure	Université Paul Sabatier/Université Picardie Jules Verne	2006	density

Usage guidelines

Prolonging battery pack life

- Avoid deep discharge and instead charge more often between uses, the smaller the depth of discharge, the longer the battery will last.
- Avoid storing the battery in full discharged state. As the battery will self-discharge over time, its voltage will gradually lower, and when it is depleted below the low-voltage threshold (2.4 to 2.9 V/cell, depending on chemistry) it cannot be charged anymore because the protection circuit (a type of electronic fuse) disables it.
- Lithium-ion batteries should be kept cool; they may be stored in a refrigerator.
- The rate of degradation of Lithium-ion batteries is strongly temperature-dependent; they degrade much faster if stored or used at higher temperatures.

Multicell devices

Li-ion batteries require a battery management system to prevent operation outside each cell's safe operating area (over-charge, under-charge, safe temperature range) and to balance cells to eliminate SOC mismatches, significantly improving battery efficiency and increasing overall capacity. As the number of cells and load currents increase, the potential for mismatch also increases. There are two kinds of mismatch in the pack: state-of-charge (SOC) and capacity/energy ("C/E")

mismatch. Though SOC is more common, each problem limits pack capacity (mA·h) to the capacity of the weakest cell.

Safety

Lithium-ion batteries can rupture, ignite, or explode when exposed to high temperature. Short-circuiting a battery will cause the cell to overheat and possibly to catch fire. Adjacent cells may then overheat and fail, possibly causing the entire battery to ignite or rupture. In the event of a fire, the device may emit dense irritating smoke.

Replacing the lithium cobalt oxide cathode material in lithium-ion batteries with a lithium metal phosphate such as lithium iron phosphate, improves cycle counts, shelf life and safety, but lowers capacity. Currently, these 'safer' lithium-ion batteries are mainly used in electric cars and other large-capacity battery applications, where safety issues are critical.

Lithium-ion batteries normally contain safety devices to protect the cells from disturbance. However, contaminants inside the cells can defeat these safety devices

Recalls

In March 2007, Lenovo recalled approximately 205,000 batteries at risk of explosion. In August 2007, Nokia recalled over 46 million batteries at risk of overheating and exploding. One such incident occurred in the Philippines involving a Nokia N91, which uses the BL-5C battery.

In December 2006, Dell recalled approximately 22,000 laptop batteries from the US market. Approximately 10 million Sony batteries used in Dell, Sony, Apple, Lenovo/IBM, Panasonic, Toshiba, Hitachi, Fujitsu and Sharp laptops were recalled in 2006. The batteries were found to be susceptible to internal contamination by metal particles. Under some circumstances, these particles could pierce the separator, causing a short-circuit.

In October 2004, Kyocera Wireless recalled approximately 1 million mobile phone batteries to identify counterfeits.

Transport restrictions

In January 2008, the United States Department of Transportation ruled that passengers on commercial aircraft could carry lithium batteries in their checked

baggage if the batteries are installed in a device. Types of batteries affected by this rule are those containing lithium, including Li-ion, lithium polymer, and lithium cobalt oxide chemistries. Lithium-ion batteries containing more than 25 grams (0.88 oz) equivalent lithium content (ELC) are exempt from the rule and are forbidden in air travel. This restriction greatly reduces the chances of the batteries short-circuiting and causing a fire

Additionally, a limited number of replacement batteries may be transported in carry-on luggage. Such batteries must be sealed in their original protective packaging or in individual containers or plastic bags.

Some postal administrations restrict air shipping (including EMS) of lithium and lithium-ion batteries, and products containing these (for example: laptops, cell phones). Among these countries and regions are Hong Kong, Australia and Japan.

Research

Researchers are working to improve the power density, safety, recharge cycle, cost and other characteristics of these batteries.

Solid-state designs have the potential to deliver three times the energy density of typical 2011 lithium-ion batteries at less than half the cost per kilowatt-hour. This approach eliminates binders, separators, and liquid electrolytes. By eliminating these, "you can get around 95% of the theoretical energy density of the active materials."

Earlier trials of this technology encountered cost barriers, because the semiconductor industry's vacuum deposition technology cost 20–30 times too much. The new process deposits semiconductor-quality films from a solution. The nanostructured films grow directly on a substrate and then sequentially on top of each other. The process allows the firm to "spray-paint a cathode, then a separator/electrolyte, then the anode. It can be cut and stacked in various form factors.

Nickel–cadmium battery

The **nickel–cadmium battery (Ni–Cd battery)** (commonly abbreviated **NiCd** or **NiCad**) is a type of rechargeable battery using nickel oxide hydroxide and metallic cadmium as electrodes.

The abbreviation *NiCad* is a registered trademark of SAFT Corporation, although this brand name is commonly used to describe all Ni–Cd batteries. The abbreviation *NiCd* is derived from the chemical symbols of nickel (Ni) and cadmium (Cd).

There are two types of Ni–Cd batteries: sealed and vented. This article mainly deals with sealed cell Applications

Sealed Ni–Cd cells may be used individually, or assembled into battery packs containing two or more cells. Small cells are used for portable electronics and toys, often using cells manufactured in the same sizes as primary cells. When Ni–Cd batteries are substituted for primary cells, the lower terminal voltage and smaller ampere-hour capacity may reduce performance as compared to primary cells. Miniature button cells are sometimes used in photographic equipment, hand-held lamps (flashlight or torch), computer-memory standby, toys, and novelties.

Specialty Ni–Cd batteries are used in cordless and wireless telephones, emergency lighting, and other applications. With a relatively low internal resistance, they can supply high surge currents. This makes them a favourable choice for remote-controlled electric model airplanes, boats, and cars, as well as cordless power tools and camera flash units. Larger flooded cells are used for aircraft starting batteries, electric vehicles, and standby power.

Voltage

Ni–Cd cells have a nominal cell potential of 1.2 volts (V). This is lower than the 1.5 V of alkaline and zinc–carbon primary cells, and consequently they are not appropriate as a replacement in all applications. However, the 1.5 V of a primary alkaline cell refers to its initial, rather than average, voltage. Unlike alkaline and zinc–carbon primary cells, a Ni–Cd cell's terminal voltage only changes a little as it discharges. Because many electronic devices are designed to work with primary cells that may discharge to as low as 0.90 to 1.0 V per cell, the relatively steady 1.2 V of a Ni–Cd cell is enough to allow operation. Some would consider the near-constant voltage a drawback as it makes it difficult to detect when the battery charge is low.

Ni–Cd batteries used to replace 9 V batteries usually only have six cells, for a terminal voltage of 7.2 volts. While most pocket radios will operate satisfactorily at this voltage, some manufacturers such as Varta made 8.4 volt batteries with seven cells for more critical applications.

12 V Ni–Cd batteries are made up of 10 cells connected in series.

History

The first Ni–Cd battery was created by Waldemar Jungner of Sweden in 1899. At that time, the only direct competitor was the lead–acid battery, which was less physically and chemically robust. With minor improvements to the first prototypes, energy density rapidly increased to about half of that of primary batteries, and significantly greater than lead–acid batteries. Jungner experimented with substituting iron for the cadmium in varying quantities, but found the iron formulations to be wanting. Jungner's work was largely unknown in the United States. Thomas Edison adapted the battery design where he introduced the nickel–iron battery to the US two years after Jungner had built one. In 1906, Jungner established a factory close to Oskarshamn, Sweden to produce flooded design Ni–Cd batteries.

Production in the United States

The first production in the United States began in 1946. Up to this point, the batteries were "pocket type," constructed of nickel-plated steel pockets containing nickel and cadmium active materials. Around the middle of the twentieth century, sintered-plate Ni–Cd batteries became increasingly popular. Fusing nickel powder at a temperature well below its melting point using high pressures creates sintered plates. The plates thus formed are highly porous, about 80 percent by volume. Positive and negative plates are produced by soaking the nickel plates in nickel- and cadmium-active materials, respectively. Sintered plates are usually much thinner than the pocket type, resulting in greater surface area per volume and higher currents. In general, the greater amount of reactive material surface area in a battery, the lower its internal resistance.

Recent developments

In the past few decades, Ni–Cd batteries have had internal resistance as low as alkaline batteries. Today, all consumer Ni–Cd batteries use the "swiss roll" or "jelly-roll" configuration. This design incorporates several layers of positive and negative material rolled into a cylindrical shape. This design reduces internal resistance as there is a greater amount of electrode in contact with the active material in each cell.

Popularity

Advances in battery-manufacturing technologies throughout the second half of the twentieth century have made batteries increasingly cheaper to produce. Battery-powered devices in general have increased in popularity. As of 2000, about 1.5 billion Ni–Cd batteries were produced annually. Up until the mid 1990s, Ni–Cd batteries had an overwhelming majority of the market share for rechargeable batteries in consumer electronics.

At one point, Ni–Cd batteries accounted for 8% of all portable secondary (rechargeable) battery sales in the EU, and in the UK for 9.2% (disposal) and in Switzerland for 1.3% of all portable battery sales.

Now, in the EU and under the Battery Directive, sales of Ni–Cd batteries to consumers for portable use been greatly restricted.

Battery characteristics

Comparison with other batteries

Recently, nickel–metal hydride and lithium-ion batteries have become commercially available and cheaper, the former type now rivaling Ni–Cd batteries in cost. Where energy density is important, Ni–Cd batteries are now at a disadvantage compared with nickel–metal hydride and lithium-ion batteries. However, the Ni–Cd battery is still very useful in applications requiring very high discharge rates because it can endure such discharge with no damage or loss of capacity.

Advantages

When compared to other forms of rechargeable battery, the Ni–Cd battery has a number of distinct advantages:

- The batteries are more difficult to damage than other batteries, tolerating deep discharge for long periods. In fact, Ni–Cd batteries in long-term storage are typically stored fully discharged. This is in contrast, for example, to lithium ion batteries, which are less stable and will be permanently damaged if discharged below a minimum voltage.

- Ni–Cd batteries typically last longer, in terms of number of charge/discharge cycles, than other rechargeable batteries such as lead/acid batteries.
- Compared to lead–acid batteries, Ni–Cd batteries have a much higher energy density. A Ni–Cd battery is smaller and lighter than a comparable lead–acid battery. In cases where size and weight are important considerations (for example, aircraft), Ni–Cd batteries are preferred over the cheaper lead–acid batteries.
- In consumer applications, Ni–Cd batteries compete directly with alkaline batteries. A Ni–Cd cell has a lower capacity than that of an equivalent alkaline cell, and costs more. However, since the alkaline battery's chemical reaction is not reversible, a reusable Ni–Cd battery has a significantly longer total lifetime. There have been attempts to create rechargeable alkaline batteries, or specialized battery chargers for charging single-use alkaline batteries, but none that has seen wide usage.
- The terminal voltage of a Ni–Cd battery declines more slowly as it is discharged, compared with carbon–zinc batteries. Since an alkaline battery's voltage drops significantly as the charge drops, most consumer applications are well equipped to deal with the slightly lower Ni–Cd cell voltage with no noticeable loss of performance.
- The capacity of a Ni–Cd battery is not significantly affected by very high discharge currents. Even with discharge rates as high as 50C, a Ni–Cd battery will provide very nearly its rated capacity. By contrast, a lead acid battery will only provide approximately half its rated capacity when discharged at a relatively modest 1.5C.
- Nickel–metal hydride (NiMH) batteries are the newest, and most similar, competitor to Ni–Cd batteries. Compared to Ni–Cd batteries, NiMH batteries have a higher capacity and are less toxic, and are now more cost effective. However, a Ni–Cd battery has a lower self-discharge rate (for example, 20% per month for a Ni–Cd battery, versus 30% per month for a traditional NiMH under identical conditions), although low self-discharge NiMH batteries are now available, which have substantially lower self-discharge than either Ni–Cd or traditional NiMH batteries. This results in a preference for Ni–Cd over NiMH batteries in applications where the current draw on the battery is lower than the battery's own self-discharge rate (for example, television remote controls). In both types of cell, the self-discharge rate is highest for a full charge state and drops off somewhat for

lower charge states. Finally, a similarly sized Ni–Cd battery has a slightly lower internal resistance, and thus can achieve a higher maximum discharge rate (which can be important for applications such as power tools).

Disadvantages

- The primary trade-off with Ni–Cd batteries is their higher cost and the use of cadmium. This heavy metal is an environmental hazard, and is highly toxic to all higher forms of life. They are also more costly than lead–acid batteries because nickel and cadmium cost more.
- One of the biggest disadvantages is that the battery exhibits a very marked negative temperature coefficient. This means that as the cell temperature rises, the internal resistance falls. This can pose considerable charging problems, particularly with the relatively simple charging systems employed for lead–acid type batteries. Whilst lead–acid batteries can be charged by simply connecting a dynamo to them, with a simple electromagnetic cut-out system for when the dynamo is stationary or an over-current occurs, the Ni–Cd battery under a similar charging scheme would exhibit thermal runaway, where the charging current would continue to rise until the over-current cut-out operated or the battery destroyed itself. This is the principal factor that prevents its use as engine-starting batteries. Today with alternator-based charging systems with solid-state regulators, the construction of a suitable charging system would be relatively simple, but the car manufacturers are reluctant to abandon tried-and-tested technology.

Availability

Ni–Cd cells are available in the same sizes as alkaline batteries, from AAA through D, as well as several multi-cell sizes, including the equivalent of a 9 volt battery. A fully charged single Ni–Cd cell, under no load, carries a potential difference of between 1.25 and 1.35 volts, which stays relatively constant as the battery is discharged. Since an alkaline battery near fully discharged may see its voltage drop to as low as 0.9 volts, Ni–Cd cells and alkaline cells are typically interchangeable for most applications.

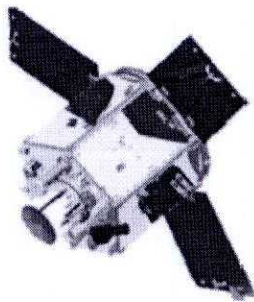
In addition to single cells, batteries exist that contain up to 300 cells (nominally 360 volts, actual voltage under no load between 380 and 420 volts). This many

cells are mostly used in automotive and heavy-duty industrial applications. For portable applications, the number of cells is normally below 18 cells (24V). Industrial-sized flooded batteries are available with capacities ranging from 12.5Ah up to several hundred Ah.

Characteristics

The maximum discharge rate for a Ni–Cd battery varies by size. For a common AA-size cell, the maximum discharge rate is approximately 18 amps; for a D size battery the discharge rate can be as high as 35 amps.

Model-aircraft or -boat builders often take much larger currents of up to a hundred amps or so from specially constructed Ni–Cd batteries, which are used to drive main motors. 5–6 minutes of model operation is easily achievable from quite small batteries, so a reasonably high power-to-weight figure is achieved, comparable to internal combustion motors, though of lesser duration. In this, however, they have been largely superseded by lithium polymer (Lipo) and lithium iron phosphate (LiFe) batteries, which can provide even higher energy densities.



The RazakSAT used Ni–Cd batteries.

Charging

Ni–Cd batteries can be charged at several different rates, depending on how the cell was manufactured. The charge rate is measured based on the percentage of the amp-hour capacity the battery is fed as a steady current over the duration of the charge. Regardless of the charge speed, more energy must be supplied to the battery than its actual capacity, to account for energy loss during charging, with faster charges being more efficient. For example, an "overnight" charge, might

consist of supplying a current equals to one tenth the amperehour rating (C/10) for 14–16 hours; that is, a 100 mAh battery takes 10mA for 14 hours, for a total of 140 mAh to charge at this rate. At the rapid-charge rate, done at 100% of the rated capacity of the battery in 1 hour (1C), the battery holds roughly 80% of the charge, so a 100 mAh battery takes 120 mAh to charge (that is, approximately 1 hour and fifteen minutes). Some specialized batteries can be charged in as little as 10–15 minutes at a 4C or 6C charge rate, but this is very uncommon. It also exponentially increases the risk of the cells overheating and venting due to an internal overpressure condition: the cell's rate of temperature rise is governed by its internal resistance and the square of the charging rate. At a 4C rate, the amount of heat generated in the cell is sixteen times higher than the heat at the 1C rate. The downside to faster charging is the higher risk of overcharging, which can damage the battery, and the increased temperatures the cell has to endure (which potentially shortens its life).

The safe temperature range when in use is between -20°C and 45°C . During charging, the battery temperature typically stays low, around 0°C (the charging reaction absorbs heat), but as the battery nears full charge the temperature will rise to $45\text{--}50^{\circ}\text{C}$. Some battery chargers detect this temperature increase to cut off charging and prevent over-charging.

When not under load or charge, a Ni–Cd battery will self-discharge approximately 10% per month at 20°C , ranging up to 20% per month at higher temperatures. It is possible to perform a trickle charge at current levels just high enough to offset this discharge rate; to keep a battery fully charged. However, if the battery is going to be stored unused for a long period of time, it should be discharged down to at most 40% of capacity (some manufacturers recommend fully discharging and even short-circuiting once fully discharged), and stored in a cool, dry environment.

Charging method

A Ni–Cd battery requires a charger with a slightly different voltage than for a lead–acid battery, especially if the battery has 11 or 12 cells. Also a charge termination method is needed if a fast charger is used. Often battery packs have a thermal cut-off inside that feeds back to the charger telling it to stop the charging once the battery has heated up and/or a voltage peaking sensing circuit. At room temperature during normal charge conditions the cell voltage increases from an initial 1.2 V to an end-point of about 1.45 V. The rate of rise increases markedly as the cell approaches full charge. The end-point voltage decreases slightly with increasing temperature.

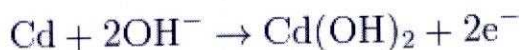
Electrochemistry

A fully charged Ni–Cd cell contains:

- a nickel(III) oxide-hydroxide positive electrode plate
- a cadmium negative electrode plate
- a separator, and
- an alkaline electrolyte (potassium hydroxide).

Ni–Cd batteries usually have a metal case with a sealing plate equipped with a self-sealing safety valve. The positive and negative electrode plates, isolated from each other by the separator, are rolled in a spiral shape inside the case. This is known as the jelly-roll design and allows a Ni–Cd cell to deliver a much higher maximum current than an equivalent size alkaline cell. Alkaline cells have a bobbin construction where the cell casing is filled with electrolyte and contains a graphite rod which acts as the positive electrode. As a relatively small area of the electrode is in contact with the electrolyte (as opposed to the jelly-roll design), the internal resistance for an equivalent sized alkaline cell is higher which limits the maximum current that can be delivered.

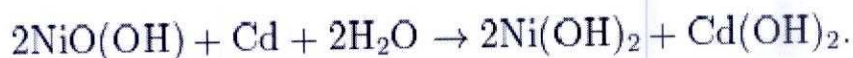
The chemical reactions during discharge are:



at the cadmium electrode, and



at the nickel electrode. The net reaction during discharge is



During recharge, the reactions go from right to left. The alkaline electrolyte (commonly KOH) is not consumed in this reaction and therefore its specific gravity, unlike in lead–acid batteries, is not a guide to its state of charge.

When Jungner built the first Ni–Cd batteries, he used nickel oxide in the positive electrode, and iron and cadmium materials in the negative. It was not until later that pure cadmium metal and nickel hydroxide were used. Until about 1960, the chemical reaction was not completely understood. There were several speculations

as to the reaction products. The debate was finally resolved by spectrometry, which revealed cadmium hydroxide and nickel hydroxide.

Another historically important variation on the basic Ni-Cd cell is the addition of lithium hydroxide to the potassium hydroxide electrolyte. This was believed to prolong the service life by making the cell more resistant to electrical abuse. The Ni-Cd battery in its modern form is extremely resistant to electrical abuse anyway, so this practice has been discontinued.

Problems

Overcharging

Overcharging must be considered in the design of most rechargeable batteries. In the case of Ni-Cd batteries, there are two possible results of overcharging:

- If the negative electrode is overcharged, hydrogen gas is produced.
- If the positive electrode is overcharged, oxygen gas is produced.

For this reason, the negative electrode is always designed for a higher capacity than the positive, to avoid releasing hydrogen gas. Hydrogen gas can be released, creating the real danger of explosion. There is still the problem of eliminating oxygen gas, to avoid rupture of the cell casing. Ni-Cd cells are vented, with seals that fail at high internal gas pressures. The sealing mechanism must allow gas to escape from inside the cell, and seal again properly when the gas is expelled. This complex mechanism, unnecessary in alkaline batteries, contributes to their higher cost.

Ni-Cd cells dealt with in this article are of the sealed type (see also vented type). Cells of this type consist of a pressure vessel that is supposed to contain any generation of oxygen and hydrogen gasses until they can recombine back to water. Such generation typically occurs during rapid charge and discharge and exceedingly at overcharge condition. If the pressure exceeds the limit of the safety valve, water in the form of gas is lost. Since the vessel is designed to contain an exact amount of electrolyte this loss will rapidly affect the capacity of the cell and its ability to receive and deliver current. To detect all conditions of overcharge demands great sophistication from the charging circuit and a cheap charger will eventually damage even the best quality cells.

Cell reversal

Another potential problem is reverse charging. This can occur due to an error by the user, or more commonly, when a battery of several cells is fully discharged. Because there is a slight variation in the capacity of cells in a battery, one of the cells will usually be fully discharged before the others, at which point reverse charging begins seriously damaging that cell, reducing battery life. The by-product of reverse charging is hydrogen gas, which can be dangerous. Some commentators^[who?] advise that one should never discharge multi-cell Ni-Cd batteries to zero voltage; for example, incandescent lights should be turned off when they are yellow; before they go out completely.

A common form of this deprecation occurs when cells connected in series develop unequal voltages and discharge near zero voltage. The first cell that reaches zero is pushed beyond to negative voltage and gases generated open the seal and dry the cell.

In modern cells, an excess of *anti-polar material* (basically active material ballast at positive electrode) is inserted to allow for moderate negative charge without damage to the cell. This excess material slows down the start of oxygen generation at the negative plate. This means a cell can survive a negative voltage of about -0.2 to -0.4 volts. However if discharge is continued even further, this excess ballast is used up and both electrodes change polarity, causing destructive gassing (gas generation).

Battery packs with multiple cells in series should be operated well above 1 volt per cell to avoid placing the lowest capacity cell in danger of going negative. Battery packs that can be disassembled into cells should be periodically zeroed and charged individually to equalize the voltages. However, this does not help if old and new cells are mixed, since their different capacities will result in different discharge times and voltages.

Memory and lazy battery effects

Ni-Cd batteries may suffer from a "memory effect" if they are discharged and recharged to the same state of charge hundreds of times. The apparent symptom is that the battery "remembers" the point in its charge cycle where recharging began and during subsequent use suffers a sudden drop in voltage at that point, as if the battery had been discharged. The capacity of the battery is not actually reduced substantially. Some electronics designed to be powered by Ni-Cd batteries are able

to withstand this reduced voltage long enough for the voltage to return to normal. However, if the device is unable to operate through this period of decreased voltage, it will be unable to get enough energy out of the battery, and for all practical purposes, the battery appears "dead" earlier than normal.

There is evidence that the memory effect story originated from orbiting satellites, where they were typically charging for twelve hours out of 24 for several years.^[8] After this time, it was found that the capacities of the batteries had declined significantly, but were still fit for use. It is unlikely that this precise repetitive charging (for example, 1,000 charges/discharges with less than 2% variability) could ever be reproduced by consumers using electrical goods.

An effect with similar symptoms to the memory effect is the so-called *voltage depression* or *lazy battery effect*. This results from repeated overcharging; the symptom is that the battery appears to be fully charged but discharges quickly after only a brief period of operation. In rare cases, much of the lost capacity can be recovered by a few deep-discharge cycles, a function often provided by automatic battery chargers. However, this process may reduce the shelf life of the battery.^[9] If treated well, a Ni–Cd battery can last for 1,000 cycles or more before its capacity drops below half its original capacity.

Dendritic shorting

When not used regularly, dendrites tend to develop. Dendrites are thin, conductive crystals that may penetrate the separator membrane between electrodes. This leads to internal short circuits and premature failure, long before the 800–1,000 charge/discharge cycle life claimed by most vendors. Sometimes, applying a brief, high-current charging pulse to individual cells can clear these dendrites, but they will typically reform within a few days or even hours. Cells in this state have reached the end of their useful life and should be replaced. Many battery guides, circulating on the Internet and online auctions, promise to restore dead cells using the above principle, but achieve very short-term results at best.

Environmental consequences of cadmium

Ni–Cd batteries contain between 6% (for industrial batteries) and 18% (for consumer batteries) cadmium, which is a toxic heavy metal and therefore requires special care during battery disposal. In the United States, part of the battery price is a fee for its proper disposal at the end of its service lifetime. Under the so-called "batteries directive" (2006/66/EC), the sale of consumer Ni–Cd batteries has now

been banned within the European Union except for medical use; alarm systems; emergency lighting; and portable power tools. This last category is to be reviewed after 4 years. Under the same EU directive, used industrial Ni–Cd batteries must be collected by their producers in order to be recycled in dedicated facilities.

Cadmium, being a heavy metal, can cause substantial pollution when landfilled or incinerated. Because of this, many countries now operate recycling programs to capture and reprocess old batteries.

Safety

Manufacturers typically supply instructions for safe handling, use, and disposal. These warn against physical damage, short-circuiting when fully charged, and overcharging.

Batteries by application:

Backup battery

A **backup battery** provides power to a system when the primary source of power is unavailable. Backup batteries range from small single cells to retain clock time and date in computers, up to large battery room facilities that power uninterruptible power supply systems for large data centers. Small backup batteries may be primary cells; rechargeable backup batteries are kept charged by the prime power supply.

Aircraft emergency batteries

Backup batteries in aircraft keep essential instruments and devices running in the event of an engine power failure. Each aircraft has enough power in the backup batteries to facilitate a safe landing. The batteries keeping navigation, ELUs (emergency lighting units), emergency pressure or oxygen systems running at altitude, and radio equipment operational. Larger aircraft have control surfaces that

run on these backups as well. Aircraft batteries are either nickel-cadmium or valve-regulated lead acid type. The battery keeps all necessary items running for between 30 minutes and 3 hours. Large aircraft may have a ram air turbine to provide additional power during engine failures.

Burglar alarms

Backup batteries are almost always used in burglar alarms. The backup battery prevents the burglar from disabling the alarm by turning off power to the building. Additionally these batteries power the remote cellular phone systems that thwart phone line snipping as well.

Computers

Modern personal computer motherboards have a backup battery to run the clock circuit and retain configuration memory while the system is turned off. This is often called the CMOS battery. The original IBM AT, for example, used a small primary lithium battery to retain the clock and configuration memory. Modern systems use either primary or rechargeable batteries. Primary batteries required periodic replacement; rechargeable types often lasted as long as the system they supported.

Backup batteries are used in uninterruptible power supplies, and provide power to the computers they supply for a variable period after a power failure, usually long enough to at least allow the computer to be shut down gracefully. These batteries are often large sealed lead-acid batteries.

Server-grade disk array controllers often contain onboard disk buffer, and provide an option for a "backup battery unit" (BBU) to maintain the contents of this cache after power loss. If this battery is present, disk writes can be considered completed when they reach the cache, thus speeding up I/O throughput by not waiting for the hard drive. This operation mode is called "write-back caching".

Telephony

A local backup battery unit is necessary in some telephony and combined telephony/data applications built with use of digital passive optical networks. In such networks there are active units on telephone exchange side and on the user side, but nodes between them are all passive in the meaning of electrical power usage. So, if a building (such as an apartment house) loses power, the network

continues to function. The user side must have standby power since operating power isn't transferred over data optical line.

Telecommunications networks and data centers

A valve-regulated lead-acid battery (VRLA) is a battery type that is popular in telecommunications network environments as a reliable backup power source. VRLA batteries are used in the outside plant at locations such as Controlled Environmental Vaults (CEVs), Electronic Equipment Enclosures (EEEs), and huts, and in uncontrolled structures such as cabinets.

GR-4228, *VRLA Battery String Certification Levels Based on Requirements for Safety and Performance*, is a new industry-approved set of VRLA requirements that provides a three-level compliance system. The compliance system provides a common framework for evaluating and qualifying various valve-regulated lead-acid battery technologies. The framework intends to alleviate the complexities associated with product introduction and qualification.

For a VRLA, the quality system employed by the manufacturer is an important key to the overall reliability of it. The manufacturing processes, test and inspection procedures, and quality program used by a manufacturer should be adequate to ensure that the final product meets the needs of the end user, the application, and industry-accepted standards and processes (i.e., ANSI/IEC, TL9000, and GR-78, *Generic Requirements for the Physical Design and Manufacture of Telecommunications Products and Equipment*).

Hospitals

Power failure in a hospital would result in life threatening conditions for patients. Patients undergoing surgery or on life support are reliant on a consistent power supply. Backup generators or batteries supply power to critical equipment until main power can be restored.

Nonvolatile BIOS memory

Nonvolatile BIOS memory refers to a small memory on PC motherboards that is used to store BIOS settings. It was traditionally called **CMOS RAM** because it used a low-power Complementary metal-oxide-semiconductor (CMOS) SRAM (such as the Motorola MC146818 or similar) powered by a small battery when system power was off. The term remains in wide use but it has grown into a misnomer:

nonvolatile storage in contemporary computers is often in EEPROM or flash memory (like the BIOS code itself); the remaining usage for the battery is then to keep the real-time clock going. The typical NVRAM capacity is 512 bytes, which is generally sufficient for all BIOS settings. The CMOS RAM and the real-time clock have been integrated as a part of the southbridge chipset and it may not be a standalone chip on modern motherboards.

CMOS mismatch

CMOS mismatch errors typically occur if the computer's power-on self-test program:

1. Finds a device that is not recorded in the CMOS.
2. Does not find a device that is recorded in the CMOS.
3. Finds a device that has different settings than those recorded for it in CMOS.
4. Detects a CMOS checksum error.

CMOS battery



Type CR2032 button cell, most common CMOS battery.

The memory and real-time clock are generally powered by a CR2032 lithium coin cell. These cells last two to ten years, depending on the type of motherboard, ambient temperature and the length of time that the system is powered off, while other common cell types can last significantly longer or shorter periods, such as the CR2016 which will generally last about 40% as long. Higher temperatures and longer power-off time will shorten cell life. When replacing the cell, the system time and CMOS BIOS settings may revert to default values. This may be avoided by replacing the cell with the power supply master switch on. On ATX

motherboards, this will supply 3V standby power to the motherboard even if it is apparently "switched off", and keep the CMOS memory energized.

Some computer designs have used non-button cell batteries, such as the cylindrical "1/2 AA" used in the Power Mac G4 as well as some older IBM PC compatibles, or a 3-cell NiCd CMOS battery that looks like a "barrel" (common in Amigas and older IBM PC compatibles), which serves the same purpose.

To access the BIOS setup when the machine fails to operate, occasionally a drastic move is required. In older computers with battery-backed RAM, removal of the battery and short circuiting the battery input terminals for a while did the job; in some more modern machines this move only resets the RTC. Some motherboards offer a CMOS-reset jumper or a reset button. In yet other cases, the EEPROM chip has to be desoldered and the data in it manually edited using a programmer. Sometimes it is enough to ground the CLK or DTA line of the I²C bus of the EEPROM at the right moment during boot, this requires some precise soldering on SMD parts. If the machine lets you boot but does not want to let you into the BIOS setup, one possible recovery is to deliberately "damage" the CMOS checksum by doing direct port writes using DOS *debug.exe*, corrupting some bytes of the checksum-protected area of the CMOS RAM; at the next boot, the computer typically resets its setting to factory defaults. for example:

```
c:\debug
-o 70 10
-o 71 aa
-q
```

Biobattery

Biobattery (also known as Biological battery) is an electricity generation device that utilizes energy sources such as carbohydrates, protein, amino acids, fat by digesting enzymes

Passive

A system in which reactive substances such as glucose and oxygen are absorbed into electrodes through a process of natural diffusion. In contrast, systems in which reactive substances are supplied by force. In general, passive-type systems have a more simple structure suitable for miniaturization

Active

With "active type" biobatteries reactive substance introduced using techniques as stirring, convection. Active type systems have a more complicated structure and are more suited to higher power devices.

Pros and cons of different types of batteries:

	Lead acid battery	NiCd Battery	NiMh Battery	Li-po Battery	Standard Li-ion Battery
Maintenance	Free	Not free	Not free	Free	Free
Energy density	Medium	Medium	Medium	High	High
Cost	The cheapest	Cheap	Cheap	Expensive	Cheap
Weight	Heavy	Medium	Medium	Light	Light
Charging capability	No fast charge	Fast charge	Fast charge	Fast charge	Fast charge
Storage option	No	No	No	Yes(care has to be taken)	Yes

Choosing appropriate battery type

Choosing appropriate battery type

Lead acid battery

- **Easy to Make:** These batteries are the easiest for manufacturers to make.
- **Reliable:** Lead acid batteries are very reliable.
- **Tolerant to Overcharging:** Lead acid batteries can take up slow charges as well as fast charge.
- **Can Be Stored for Long Periods of Time:** Lead acid batteries discharge and lose their power when they are stored with the electrolyte solution inside them.
- **Several Brands and Price Ranges:** Lead acid batteries are available in a huge range of brands, costs and sizes
- **Self-Discharge:** The self-discharge is among the lowest of rechargeable battery systems.

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