



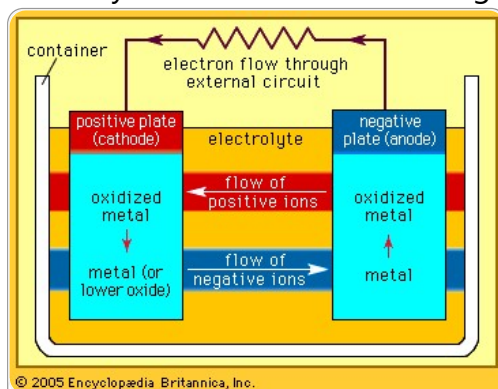
battery

battery, in electricity and electrochemistry, any of a class of devices that convert chemical energy directly into electrical energy. Although the term *battery*, in strict usage, designates an assembly of two or more galvanic cells capable of such energy conversion, it is commonly applied to a single cell of this kind.

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Cutaway view of an alkaline–manganese dioxide power cell. Every battery (or cell) has



electrochemical cell: basic components

Basic components of an electrochemical cell.

a cathode, or positive plate, and an anode, or negative plate. These electrodes must be separated by and are often immersed in an electrolyte that permits the passage of ions between the electrodes. The electrode materials and the electrolyte are chosen and arranged so that sufficient electromotive force (measured in volts) and electric current (measured in amperes) can be developed between the terminals of a battery to operate lights, machines, or

other devices. Since an electrode contains only a limited number of units of chemical energy convertible to electrical energy, it follows that a battery of a given size has only a certain capacity to operate devices and will eventually become exhausted. The active parts of a battery are usually encased in a box with a cover system (or jacket) that keeps air outside and the electrolyte solvent inside and that provides a structure for the assembly.

Commercially available batteries are designed and built with market factors in mind. The quality of materials and the complexity of electrode and container design are reflected in the market price sought for any specific product. As

new materials are discovered or the properties of traditional ones improved, however, the typical performance of even older battery systems sometimes increases by large percentages.

Batteries are divided into two general groups: (1) primary batteries and (2) secondary, or storage, batteries. Primary batteries are designed to be used until the voltage is too low to operate a given device and are then discarded. Secondary batteries have many special design features, as well as particular materials for the electrodes, that permit them to be reconstituted (recharged). After partial or complete discharge, they can be recharged by the application of direct current (DC) voltage. While the original state is usually not restored completely, the loss per recharging cycle in commercial batteries is only a small fraction of 1 percent even under varied conditions.

Principles of operation

The anode of an electrochemical cell is usually a metal that is oxidized (gives up electrons) at a potential between 0.5 volt and about 4 volts above that of the cathode. The cathode generally consists of a metal oxide or sulfide that is converted to a less-oxidized state by accepting electrons, along with ions, into its structure. A conductive link via an external circuit (e.g., a lamp or other device) must be provided to carry electrons from the anode to the negative battery contact. Sufficient electrolyte must be present as well. The electrolyte consists of a solvent (water, an organic liquid, or even a solid) and one or more chemicals that dissociate into ions in the solvent. These ions serve to deliver electrons and chemical matter through the cell interior to balance the flow of electric current outside the cell during cell operation.

Battery usefulness is limited not only by capacity but also by how fast current can be drawn from it. The salt ions chosen for the electrolyte solution must be able to move fast enough through the solvent to carry chemical matter between the electrodes equal to the rate of electrical demand. Battery performance is thus limited by the diffusion rates of internal chemicals as well as by capacity.

The voltage of an individual cell and the diffusion rates inside it are both reduced if the temperature is lowered from a reference point, such as 21 °C

(70 °F). If the temperature falls below the freezing point of the electrolyte, the cell will usually produce very little useful current and may actually change internal dimensions, resulting in internal damage and diminished performance even after it has warmed up again. If the temperature is raised deliberately, faster discharge can be sustained, but this is not generally advisable, because the battery chemicals may evaporate or react spontaneously with one another, leading to early failure.

The fundamental relationship of electrochemical cell operation, put forth by the English physicist-chemist Michael Faraday in 1834, is that for every ampere that flows for a period of time, a matching chemical reaction or other change must take place. The extent of such changes is dependent on the molecular and electronic structure of the elements constituting the battery electrodes and electrolyte. Secondary changes may also occur, but a primary pair of theoretically reversible reactions must take place at the electrodes for electricity to be produced. The actual energy generated by a battery is measured by the number of amperes produced \times the unit of time \times the average voltage over that time. For a cell with electrodes of zinc and manganese dioxide (e.g., the common flashlight dry cell), one finds that a chemical equivalent of zinc weighs 32.5 grams (1.4 ounces) and that of manganese dioxide about 87 grams (3.1 ounces). The discharge of one equivalent weight of each of these electrodes will cause 32.5 grams of zinc to dissolve and 87 grams of manganese dioxide to change into a different oxide containing more hydrogen and zinc ions. Some of the electrolyte also will be consumed in the reaction. One chemical equivalent of each electrode produces one faraday, or 96,485 coulombs of current equal to 26.8 amperes per hour. If the cells operate at an average of 1.2 volts, this would yield 32.2 watt-hours of DC energy. Expressed another way, **Energy (joules) = nFV** , where n equals the number of chemical equivalents discharged, F is the Faraday constant (9.6485×10^4 coulombs per mole), V is the average (not necessarily constant) voltage of the cell for the period of the discharge, and $1 \text{ joule} \cong 2.78 \times 10^{-4} \text{ watt-hours}$.

There are a large number of elements and compounds from which to select potentially useful combinations for batteries. The commercial systems in common use represent the survivors of numerous tests where continued use

depends on adequate voltage, high current-carrying capacity, low-cost materials, and tolerance for user neglect. Better sealing technology and plastics are making further development of all cell systems possible, particularly those using very active lithium for the anode. This situation has yielded commercial cells with as much as 3.9 volts on load and very high current-carrying capability.

Battery manufacturers have designed many different sizes, voltages, and current loads for different specialized applications. In the case of common household batteries (*see table*), standard sizes and electrical properties have been established by the American National Standards Institute (ANSI) and the International Electrotechnical Commission (IEC). The most common sizes, given in the form ANSI (IEC), are AAA (R03), AA (R6), C (R14), D (R20), and 9V (6F22).

Common household batteries

Primary batteries

type	chemistry	sizes and common applications	features
zinc-carbon (Leclanché)	zinc alloy anode-manganese dioxide cathode with an electrolyte mix of 80 percent ammonium chloride and 20 percent zinc chloride surrounding a carbon rod electrode; 1.55 volts per cell, declining in use	widest range of sizes, shapes, and capacities (including all major cylindrical and rectangular jackets); used in remote controls, flashlights, portable radios	cheap and lightweight; low energy density; very poor for high-drain applications; poor performance at low temperatures; disposal hazard from toxic mercury and cadmium present in zinc alloy
zinc chloride	zinc anode-manganese dioxide cathode with zinc chloride electrolyte; 1.55 volts per cell, declining in use	wide range of cylindrical and rectangular jackets; used in motorized toys, cassette and CD players, flashlights, portable radios	usually labeled "heavy duty"; less voltage decline at higher drain rates and lower temperatures than zinc-carbon; typically 2–3 times the life of zinc-carbon batteries; environmentally safe
Alkaline			
zinc-	zinc anode-manganese	wide range of	long shelf life; leak-

Primary batteries

type	chemistry	sizes and common applications	features
manganese dioxide	dioxide cathode with potassium hydroxide electrolyte; 1.55 volts per cell	cylindrical and rectangular jackets; best for use in motorized toys, cassette and CD players	resistant; best performance under heavy loads; 4–10 times the life of zinc-carbon batteries
zinc-silver oxide	zinc anode-silver oxide cathode with a potassium hydroxide electrolyte; 1.55 volts per cell	button batteries; used in hearing aids, watches, calculators	high energy density; long shelf life; expensive
zinc-air	zinc anode-oxygen cathode with potassium hydroxide electrolyte	cylindrical, 9-volt, button, and coin jackets; used in hearing aids, pagers, watches	highest energy density of all disposable batteries; virtually unlimited shelf life; environmentally safe

Lithium

lithium-iron sulfide	lithium anode-iron sulfide cathode with organic electrolyte; 1.6 volts per cell	cylindrical and button batteries; used in digital cameras, small appliances	high energy density; supports high discharge rates; long shelf life; expensive
lithium-manganese dioxide	lithium anode-manganese dioxide cathode with organic electrolyte; 2.8–3.2 volts per cell	cylindrical and button batteries; used in digital cameras, small appliances	high energy density; supports high discharge rates; long shelf life; expensive

Secondary (rechargeable) batteries

type	chemistry	sizes and common applications	features
lead-acid	lead anode-lead dioxide cathode with sulfuric acid electrolyte	wide range of sizes; used in automobiles, wheelchairs, children's electric vehicles, emergency power supplies	cheapest and heaviest battery; long life; no memory effect; wide range of discharge rates

Alkaline

nickel-	cadmium anode-nickel	common cylindrical	excellent performance
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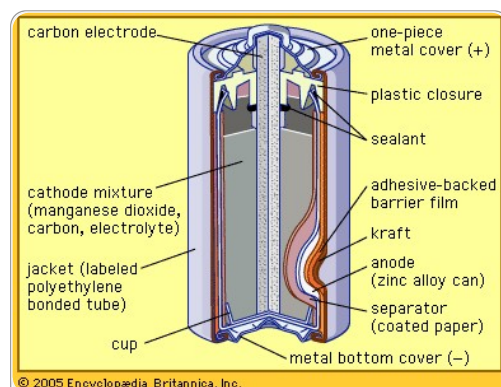
Primary batteries

type	chemistry	sizes and common applications	features
cadmium	dioxide cathode with potassium hydroxide electrolyte	jackets; used in power tools, cordless telephones, biomedical equipment	under heavy discharge; nearly constant voltage; best rechargeable cycle life; memory effect in some; cadmium highly toxic and carcinogenic if improperly recycled
nickel-metal hydride	lanthanide or nickel alloy anode-nickel dioxide cathode with potassium hydroxide electrolyte	some cylindrical jackets; used in smoke alarms, power tools, cellular telephones	high energy density; good performance under heavy discharge; nearly constant 1.2-volt discharge; no memory effect; environmentally safe
Lithium			
lithium-ion	carbon anode-lithium cobalt dioxide cathode with organic electrolyte	most cylindrical jackets; used in cellular telephones, portable computers	higher energy density and shorter life than nickel-cadmium; expensive; no memory effect

Primary batteries

Zinc–manganese dioxide systems

These batteries are the most commonly used worldwide in flashlights, toys, radios, compact disc players, and digital cameras. There are three variations: the zinc-carbon battery, the zinc chloride battery, and the alkaline battery. All provide an initial voltage of 1.55 to 1.7 volts, which declines with use to an end point of about 0.8 volt.



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The zinc-carbon battery, also called the Leclanché cell, is a traditional general-purpose dry cell. Invented by the French engineer Georges Leclanché in 1866, it immediately became a commercial success in large sizes because of its readily available low-cost constituent materials. It remains the least expensive dry cell and is available

Leclanché cell: modern version

Modern version of the Leclanché cell. This heavy-duty zinc-carbon primary battery is a dry cell with an immobilized electrolyte.

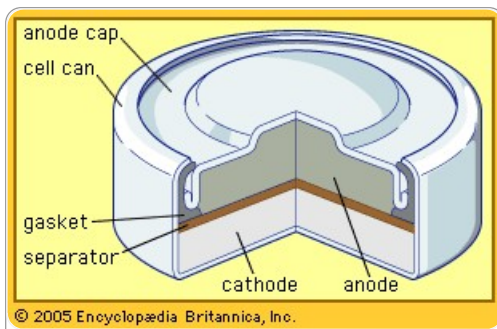
nearly everywhere. The anode of this battery is a zinc alloy sheet or "can," the alloy containing small amounts of lead, cadmium, and mercury. The electrolyte consists of a saturated aqueous solution of

ammonium chloride containing roughly 20 percent zinc chloride. The cathode is made of impure manganese dioxide (usually mined from selected deposits in Africa, Brazil, or Mexico). This compound is blended with carbon black and electrolyte to create a damp, active cathode mixture which is formed around a carbon collector rod, also called an electrode. All batteries of this type are provided with an overwrap structure with metal covers for electrical contact.

While first patented in 1899, the zinc chloride battery is really a modern adaptation of the zinc-carbon battery. Its commercial success is attributable in part to the development of plastic seals that have made it possible largely to dispense with the use of ammonium chloride. The manganese dioxide of the cathode is usually a blend of synthetic manganese dioxide of high purity with natural varieties. The zinc chloride battery is capable of greater continuous service than the zinc-carbon battery, particularly in motorized devices such as toys. Its use is also increasing because it can provide satisfactory performance without the use of highly toxic mercury and cadmium in the zinc alloy.

The highest power density (watts per cubic cm) of the zinc–manganese dioxide cells is found in batteries with an alkaline electrolyte, which permits a completely different type of construction. The alkaline battery became commercially available during the 1950s and is now the most popular household battery. A cathode of a very pure manganese dioxide–graphite mixture and an anode of a powdered zinc alloy are associated with a potassium hydroxide electrolyte and housed in a steel can. The zinc of early alkaline batteries contained 6 to 8 percent mercury, but present-day versions contain no added mercury so as to reduce the environmental impact of disposal. Alkaline batteries, moreover, provide much higher capacity to operate flashlights, toys, compact disc players, and radios than either of the other two zinc–manganese dioxide systems discussed above.

Zinc–mercuric oxide battery

**miniature power cell: cutaway view**

Cutaway view of a typical construction of a miniature power cell, as in, for example, a zinc–silver oxide or zinc–mercuric oxide system.

This is an alkaline-electrolyte battery system. In earlier times it was used in the form of button-sized cells for hearing aids and watches. Its energy density (watt-hours per cubic centimetre) is approximately four times greater than that of the alkaline zinc–manganese dioxide battery. However, because of its mercury content, the cell has been relegated to the role of a standard reference cell—providing an extremely reliable 1.35 volts to measure the

performance of other batteries.

Zinc–silver oxide battery

Another alkaline system, this battery features a silver oxide cathode and a powdered zinc anode. Because it will tolerate relatively heavy current load pulses and has a high, nearly constant 1.5-volt operating voltage, the zinc–silver oxide battery is commonly used in the form of a button cell in watches, cameras, and hearing aids. In spite of its high cost, the outstanding current-carrying capability of this cell has resulted in its use as a military torpedo battery. Miniature cells can be obtained with either divalent silver oxide or monovalent silver oxide, the former usually having somewhat higher capacity.

Lithium batteries

The area of battery technology that has attracted the most research since the early 1990s is a class of batteries with a lithium anode. Because of the high chemical activity of lithium, nonaqueous (organic or inorganic) electrolytes have to be used. Such electrolytes include selected solid crystalline salts (*see below*). This whole new science has encouraged the commercial production of some batteries having no separator layer between the anode and the liquid cathode, an unlikely condition for success in aqueous systems. A stable protective layer automatically forms on the lithium and serves as a separator. The protective layer becomes more porous on discharge to permit high-current operation at nearly constant voltages near 3.6 volts. This allows very high power density and energy density. Most commercial cells for the

consumer market do have separators placed during cell assembly in the factories yet still offer high energy and power density. Lithium batteries are especially attractive for use in certain aerospace applications, terrestrial portable military equipment, and such civilian applications as portable computers, cellular telephones, personal paging systems, heart pacemakers, and automated cameras.

Despite their obvious advantages, there are some limitations on the use of lithium batteries. Lithium is very sensitive to high temperatures, and the heat generated during discharging or recharging lithium batteries can cause the cell temperature to rise to the point at which battery ingredients combine spontaneously and the cell smokes or catches fire in a phenomenon known as "thermal runaway." Special separators and cell constructions have been developed to minimize this risk. Additionally, lithium cells must be manufactured under very dry conditions to prevent the absorption of moisture from the air; sealed inside a lithium cell, moisture combines with the lithium to produce lithium oxides and hydrogen gas, and the gas pressure can lead to cell failure. Lithium must be handled very carefully in the factory and many major manufacturers have had fires in their cell assembly rooms. The need to take measures to prevent fires, the required dry room conditions, and the inclusion of organic compounds in cell formulas combine to make lithium cells somewhat more expensive than other types of common batteries. In addition, there are government safety regulations that limit the weight of lithium in commercial shipments, making it prohibitively expensive to distribute lithium cells larger than the AA or AAA size.

Lithium–iron sulfide batteries in small sizes offer high capacity and low cost for both light and heavy loads, depending on the construction of the inside of the cell. In operations requiring 1.5 to 1.8 volts, these batteries are a potential substitute for some zinc–silver oxide batteries. In constructions where the electrodes consist of rolled-up ("jelly roll") strips like those of small nickel–cadmium batteries (discussed in the section Alkaline storage batteries), higher power density is obtained while still retaining high capacity for premium heavy-duty use, such as for digital cameras, motor-driven toys, and cellular telephones. A typical electrolyte might be lithium tetrafluoroborate salt in a solvent mixture of propylene carbonate, 2-methyl-2-oxazolidone, and

dimethoxyethane.

Lithium–manganese dioxide cell systems have slowly gained wider application in small appliances, especially automatic cameras. Batteries of this kind have an operating voltage of 2.8–3.2 volts and offer high energy density and relatively low cost for the capability of the cells.

The lithium–carbon monofluoride system has been among the more successful early commercial lithium miniature batteries. It has been used extensively in cameras and smaller devices, providing about 3.2 volts per cell, high power density, and long shelf life. Good low-temperature performance and constant voltage discharge over time are provided as well. The cost of carbon monofluoride is high, however.

Lithium–thionyl chloride batteries provide the highest energy density and power density commercially available. Thionyl chloride, a very corrosive and toxic chemical, serves not only as the electrolyte solvent but also as the cathode material. Formation of a film of lithium chloride salt on the lithium prevents a runaway reaction between the lithium anode and the adjacent liquid cathode material. The electrical contact and reaction centre of the cathode are composed of porous pressed and bonded carbon powder. The performance of this type of battery system at room temperature is very impressive. Moreover, the cell can operate at -54°C (-65°F), well below the point where aqueous systems function. Because of its high energy density and corrosive electrolyte, the lithium–thionyl chloride battery must be used with care and not be opened, burned, or disposed of casually. Such cells are useful for powering military equipment, providing backup power for aerospace systems, and operating personal pagers.

Lithium–sulfur dioxide batteries have been used extensively in some emergency power units for aircraft and in military cold-weather applications (e.g., radio operation). The cathode consists of a gas under pressure with another chemical as electrolyte salt; this is analogous to the thionyl chloride electrolyte and its liquid cathode. The system functions well but has been found occasionally to vent noxious sulfur dioxide, especially after cold discharge and subsequent warm-up. The release of corrosive or toxic gases by any type of battery in a closed space, especially in an airplane, constitutes

a significant design disadvantage.

Air-depolarized batteries

A very practical way to obtain high energy density in a battery is to employ the oxygen in air for a "liquid" cathode material. If paired with an anode such as zinc, long cell life at low cost per watt-hour (for a dry cell) can be obtained because a given battery's volume may be devoted more completely to anode and electrolyte material. The battery, however, must be constructed in such a way that the oxygen is prevented from reaching the anode, especially during storage.

Zinc-air systems are commercially available in forms from very small cells, such as hearing-aid batteries, to relatively large boxlike batteries. Their principle and design are simple, but the actual batteries are, from a technical standpoint, difficult to manufacture. The "air electrode" is extremely thin and usually has a waterproof polymer-bonded porous carbon layer with a metal mesh reinforcement. A catalyst and a booster oxide may be included with the carbon to render oxygen more effectively active. The sealing of the edges of the composite electrode film and electrolyte proofing of the pores have been achieved with fluorocarbons and plastics. Fundamental improvements in electrode assembly, cell seal, and vent designs continue to be sought in scientific and engineering studies.

Aluminum-air batteries have not been a major commercial success to date, but their light weight and potentially high energy density have attracted much government support in the United States. Research efforts have been concentrated on developing better aluminum alloys and techniques to resist corrosion during shelf storage. Similarly, inhibitors for inclusion in the alkaline electrolyte are under study. Aluminum-air batteries also are being considered for applications in which the metal anode, the electrolyte, and the reaction products are mechanically removed and replaced to create a kind of fuel cell. If stability and design problems can be overcome, this system may very well prove attractive for many applications, including use in electric cars or trucks.

Other primary battery systems

Many other cell types are in use on a small scale. For example, cells that

produce a very predictable standard voltage are the Clark cell (zinc–mercurous sulfate–mercury; 1.434 volts) and the Weston cell (cadmium–mercurous sulfate–mercury; 1.019 volts). Magnesium–silver chloride and magnesium–lead chloride batteries are commonly employed in undersea operations where the salt water becomes the electrolyte when the battery is submerged or in situations where low risk to the environment is desired, as in balloon batteries.

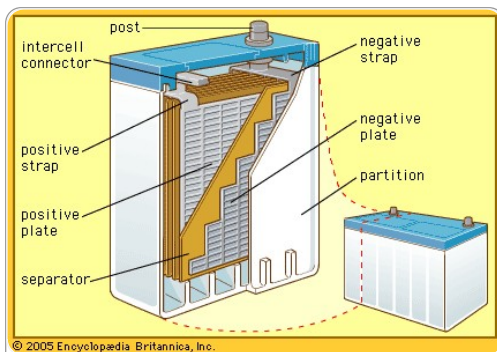
An important group of batteries consists of systems with a solid electrolyte in which the mixture of compounds is such that cell ions can slowly move from site to site in the electrolyte crystal structure. Examples include silver–silver rubidium iodide–iodine cells and lithium–lithium iodide–lead iodide mixtures. Batteries with ion-containing polymers are being studied extensively. In such devices, electrode conductivity is achieved by special polymer structure and doping with charged ions either chemically or electrically.

Storage batteries

In contrast to primary cells, which are discharged once and then discarded, storage batteries can be supplied with direct current (DC) of the correct polarity and recharged to or near their original energy content and power capability—i.e., they can repeatedly store electrical energy. In discharging, the difference in electrical potential (voltage) of a battery's electrodes causes electrons to flow through a powered device placed between the electrodes. In recharging, a DC voltage that is larger than a battery's original voltage is applied in the opposite direction to the battery's discharge direction. By this means, electrons are driven back through the charging circuit into the electrodes and chemical of the battery, largely restoring it to its original voltage, energy level, and power capability. In some batteries, such as nickel oxide–cadmium batteries, it is important to control the discharge depth of the battery to prevent it from acquiring a "memory," a circumstance in which the battery behaves as though its capacity is much less than when it was new. Proper choice of ingredients and construction features can greatly reduce the likelihood of this effect being encountered.

Lead-acid batteries

The so-called lead-acid battery has long been the most widely used



automobile battery: cutaway view

Construction of the automotive-type lead-acid battery (cutaway view). A storage battery not only holds its charge for a long time, but it also can be recharged.

rechargeable portable power source. Most such batteries are constructed of lead plates, or grids, where one of the grids, the positive electrode, is coated with lead dioxide in a particular crystalline form, along with additives such as calcium lignosulfate. The electrolyte, composed of sulfuric acid, participates in the electrode reactions where lead sulfate is formed and carries current in moving ions. Recent estimates show that in terms of capacity in use (watt-hours), the lead-acid battery has

20 times as much capacity as either the nickel-cadmium or nickel-iron alkaline rechargeable battery (described below).

The lead-acid battery system has been successful because of the following features: wide capability range for high or low current demand over usual ambient temperatures; good cycle life with high reliability for hundreds of cycles, especially with good recharge control (a gram of positive active material may deliver as many as 100 ampere-hours during the service life of such a battery); relatively low cost (lead is less expensive per kilogram or per ampere-hour than nickel, cadmium, lithium, or silver); comparatively good shelf life for a rechargeable system when stored; high cell voltage at 2.1 volts per cell; ease of fabricating lead components by casting, welding, or rolling; and a high degree of salvageability at low melting temperatures.

An area of continued interest for investigators working on lead-acid batteries is reduction of battery weight. Lead dioxide and lead have the lowest energy density of the major electrode materials in wide use, and they are rarely discharged in a highly efficient manner. At low rates of discharge, only about 60 percent of the active materials are cycled; at high rates of discharge, utilization can fall to 10 percent.

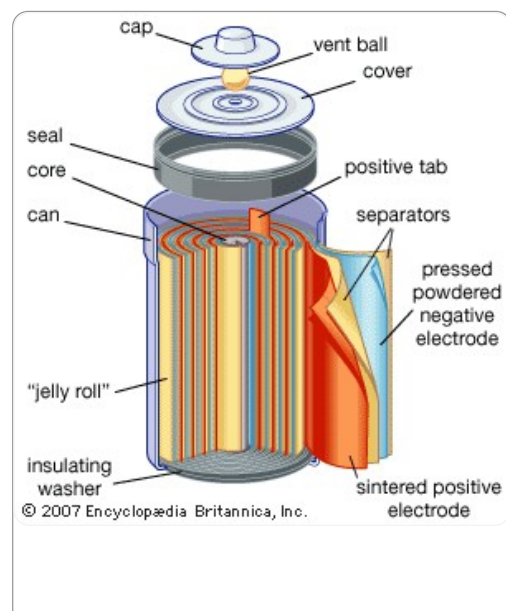
Lead-acid batteries are generally classified into three groups: (1) starting-lighting-ignition (SLI) batteries, (2) traction batteries, and (3) stationary batteries. The automotive SLI battery is the best-known portable rechargeable

power source. High current can be obtained for hundreds of shallow-depth discharges over a period of several years. Traction batteries are employed in industrial lift trucks, delivery trucks, and other vehicles. While some are readily portable, others may weigh several tons. The great weight often serves to stabilize the vehicle during operation. Stationary batteries are now much more common than was once the case. These batteries have heavier grid structures and other features to give them long shelf life. They are used to power emergency lights, in uninterruptible power systems for hospitals, factories, and telephone exchanges, and for storage of energy generated by terrestrial solar cells.

In a lead-acid battery the active material of the positive electrode, lead dioxide, combines with the electrolyte, sulfuric acid, to produce lead sulfate and water during discharge. At the negative electrode the constituent lead combines with the sulfuric acid ions to produce lead sulfate and hydrogen ions, thereby replacing the hydrogen ions consumed at the positive electrode. The water formed and the loss of sulfate dilute the electrolyte, lowering its density. Because of this, the state of charge of a lead-acid battery can be determined from the specific gravity of the electrolyte.

Alkaline storage batteries

In secondary batteries of this type, electric energy is derived from the chemical action in an alkaline solution. Such batteries feature a variety of electrode materials; some of the more notable ones are briefly discussed in this section.



Nickel (hydroxide)–cadmium systems are the most common small rechargeable battery type for portable appliances. The sealed cells are equipped with “jelly roll” electrodes, which allow high current to be delivered in an efficient way. These batteries are capable of delivering exceptionally high currents, can be rapidly recharged hundreds of times, and are tolerant of abuse such as overdischarging

rechargeable battery: cutaway view

Nickel (hydroxide)-cadmium cell of “jelly roll” construction. This rechargeable battery is commonly used in portable devices.

or overcharging. Nonetheless, compared with many primary batteries and even lead-acid batteries, nickel-cadmium batteries are heavy and have comparatively limited energy density. They last longer and

perform better if fully discharged each cycle before recharge. Otherwise, the cells may exhibit a so-called memory effect, in which they behave as if they had lower capacity than was built into the battery pack. Larger nickel-cadmium batteries are used for starting aircraft engines and in emergency power systems. They also have found application in other backup power systems where very high currents, low temperature conditions, and high reliability are special factors. In addition, they are used in tandem with a solar-powered current source to provide electric power at night.

Nickel (hydroxide)–zinc batteries are attractive from a development viewpoint. If their cycle life can be significantly improved, systems of this sort may become a viable substitute for nickel-cadmium batteries or lead-acid traction batteries.

Nickel (hydroxide)–iron batteries can provide thousands of cycles but do not recharge with high efficiency, generating heat and consuming more electricity than is generally desirable. They have been used extensively in the European mining industry, however.

Nickel (hydroxide)–hydrogen cells were developed primarily for the U.S. space program. Research has shown that such alloys as lanthanum-nickel in certain proportions will reversibly dissolve or release hydrogen in proportion to changes in pressure and temperature. The hydrogen in these cells can serve as an active anode material. Nickel–metal hydride batteries are replacing nickel-cadmium batteries in many applications because of their higher capacity per unit volume, the absence of toxic cadmium, and, compared with rechargeable lithium batteries, their greater tolerance of abuse. Nickel–metal hydride batteries are used in most electric and hybrid-electric vehicles.

Alkaline zinc–manganese dioxide rechargeable cells are sold commercially as a substitute for some other systems where moderate amounts of electricity are needed. Their high energy density and low cost encourage further

engineering work and commercial introduction.

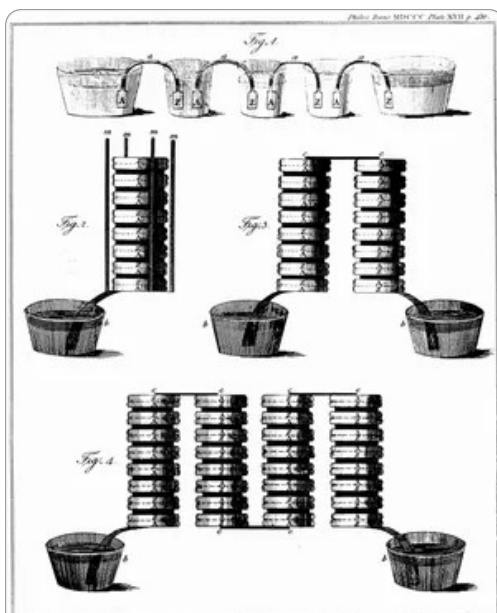
Silver (oxide)–zinc batteries are expensive but are employed where high power density, good energy-cycling efficiency, low weight, and low volume are critical. After years of use in torpedoes and mines, they have become important in special vehicles for underwater tests and submarine exploration. They also are employed in portable radar units and communications equipment, as well as in aircraft and space vehicles.

Lithium storage batteries

Rechargeable lithium–metal anode batteries show commercial promise, with theoretical energy densities that range from 600 to 2,000 watt-hours per kilogram. Even after allowance is made for the inactive parts of such cells, the net energy density is still competitive with aqueous systems. Commercially available systems of this type include lithium–cobalt oxide, lithium–nickel oxide, lithium–manganese dioxide, and lithium–molybdenum disulfide. Much current research is devoted to developing better oxide and sulfide structures and better solvent combinations, as well as to preventing the unsafe formation of finely divided lithium during the recharging of the cells.

Major commercial success for rechargeable lithium-based batteries came with the development of lithium-ion cells. The difficult problem of preventing lithium dendrite formation on charging was solved in these cells by using specially selected carbon powders as a base in which to insert lithium ions to form a weak compound that functions as a high-voltage, high-energy-density anode. While the energy density is lower than for lithium–metal anode batteries, their added safety is well worth the sacrifice. These batteries are now available for portable computers, cellular telephones, and other devices. The usual cathode is an expensive special cobalt oxide. Alternatives are being studied in which much or all of the cobalt is replaced by either nickel or manganese or by these elements along with stabilizing ions such as aluminum and chromium. Even with all of the added safety of the lithium-ion form, it is still a critical requirement to have precise electronic controls for charging and discharging.

Development of batteries

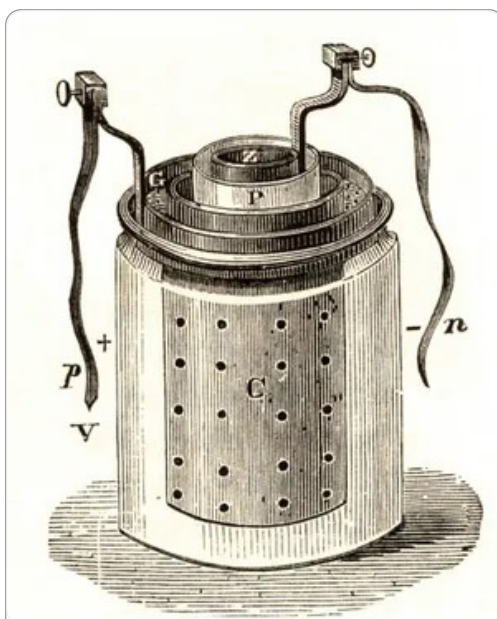


Alessandro Volta: wet pile

Illustration from "On the Electricity Excited by the Mere Contact of Conducting Substances of Different Kinds," Alessandro Volta's paper announcing his invention of the wet pile in the *Philosophical Transactions of the Royal Society*, 1800.

The Italian physicist Alessandro Volta is generally credited with having developed the first operable battery. Following up on the earlier work of his compatriot Luigi Galvani, Volta performed a series of experiments on electrochemical phenomena during the 1790s. By about 1800 he had built his simple battery, which later came to be known as the "voltaic pile." This device consisted of alternating zinc and silver disks separated by layers of paper or cloth soaked in a solution of either sodium hydroxide or brine. Experiments performed with the voltaic pile eventually led Michael Faraday to derive the quantitative laws of electrochemistry (about 1834). These laws, which established the exact relationship between the quantity of

electrode material and the amount of electric power desired, formed the basis of modern battery technology. *See also* Faraday's laws of electrolysis and Faraday's law of induction.



Daniell cell

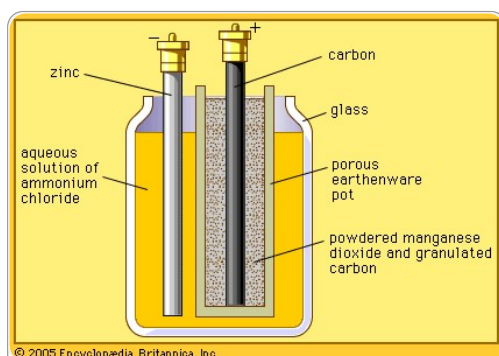
The Daniell cell, a wet storage battery.

Various commercially significant primary cells were produced on the heels of Faraday's theoretical contribution. In 1836 John Frederic Daniell, a British chemist, introduced an improved form of electric cell consisting of copper and zinc in sulfuric acid. The Daniell cell was able to deliver sustained currents during continuous operation far more efficiently than Volta's device.

Further advances were effected in 1839 by the British physicist William Robert Grove with his two-fluid primary cell consisting of

amalgamated zinc immersed in dilute sulfuric acid, with a porous pot separating the sulfuric acid from a strong nitric acid solution containing a platinum cathode. The nitric acid served as an oxidizing agent, which prevented voltage loss resulting from an accumulation of hydrogen at the cathode. The German chemist Robert Wilhelm Bunsen substituted inexpensive carbon for platinum in Grove's cell and thereby helped promote its wide acceptance.

In 1859 Gaston Planté of France invented a lead-acid cell, the first practical storage battery and the forerunner of the modern automobile battery. Planté's device was able to produce a remarkably large current, but it remained a laboratory curiosity for nearly two decades.



Georges Leclanché's cell

Georges Leclanché's cell. Invented in 1866, this dry cell and its later variations, the zinc chloride and alkaline cells, are batteries commonly used throughout the world.

French engineer Georges Leclanché's prototype of the zinc–manganese dioxide system paved the way for the development of the modern primary battery. The original version of the Leclanché cell was "wet," as it had an electrolyte consisting of a solution of ammonium chloride. The idea of employing an immobilized electrolyte was finally introduced in the late 1880s and launched the dry-cell industry that continues to flourish today.

The invention of alkaline electrolyte batteries (specifically, storage batteries of the nickel-cadmium and nickel-iron type) between 1895 and 1905 provided systems that could furnish much-improved cycle life for commercial application. The 1930s and '40s saw the development of the zinc–silver oxide and zinc–mercuric oxide alkaline batteries, systems that provided the highest energy yet known per unit weight and volume. Since the mid-20th century, advances in construction technology and the availability of new materials have given rise to smaller yet more powerful batteries suitable for use in a wide array of portable equipment. Perhaps most notable have been the entrance of lithium batteries into the commercial market and the development of nickel-hydrogen and

nickel–metal hydride cells for use in spacecraft, computers, cellular telephones, and other applications.

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