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[1.0] Battery (Storage Cell) Technologies

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* While traditional storage cell technologies remain common, many new technologies have been introduced, and some of them are coming into wide use. This chapter provides a survey of storage cell technologies.

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[1.1] STORAGE CELL FUNDAMENTALS

* In 1786, the Italian physiologist Luigi Galvani noticed by chance that when he stuck a copper hook into the spinal cord of a frog, which was in turn hanging from an iron hook, the frog's legs twitched. Galvani performed experiments that showed other pairs of dissimilar metals caused similar effects. He felt that he was seeing the discharge of some sort of "animal electricity" from the frog's muscles. Such experiments became fashionable, and led to a popular belief that electricity was an elemental "life force". This belief was illustrated by Mary Shelley's Gothic horror novel FRANKENSTEIN, with the monster brought to life by electricity, and by a range of electrical quack medical equipment that remained popular into the 20th century.

More practically, an Italian physicist named Count Alessandro Volta conducted further experiments with electrical currents produced by dissimilar metals. Volta concluded that the frog's muscle could be replaced by a salt solution or an acid solution, and the two dissimilar metals would still be able to produce an electric current. Volta made a stack of zinc and silver disks, with a zinc-silver pair separated by wet cloth containing a salt or weak acid solution, and was able to generate steady, fairly strong direct currents (DC) with this "Voltaic pile". This was an important advance in electrical research, since up to that time the only way to produce electricity was through building up static charges, say by rubbing fur with a rubber rod. This could produce substantial voltages but not sustained currents.

Volta's work was put onto a solid scientific basis in the 1830s, when the brilliant English scientist Michael Faraday established the fundamental principles of electrochemistry, which underlie the operation of storage cells

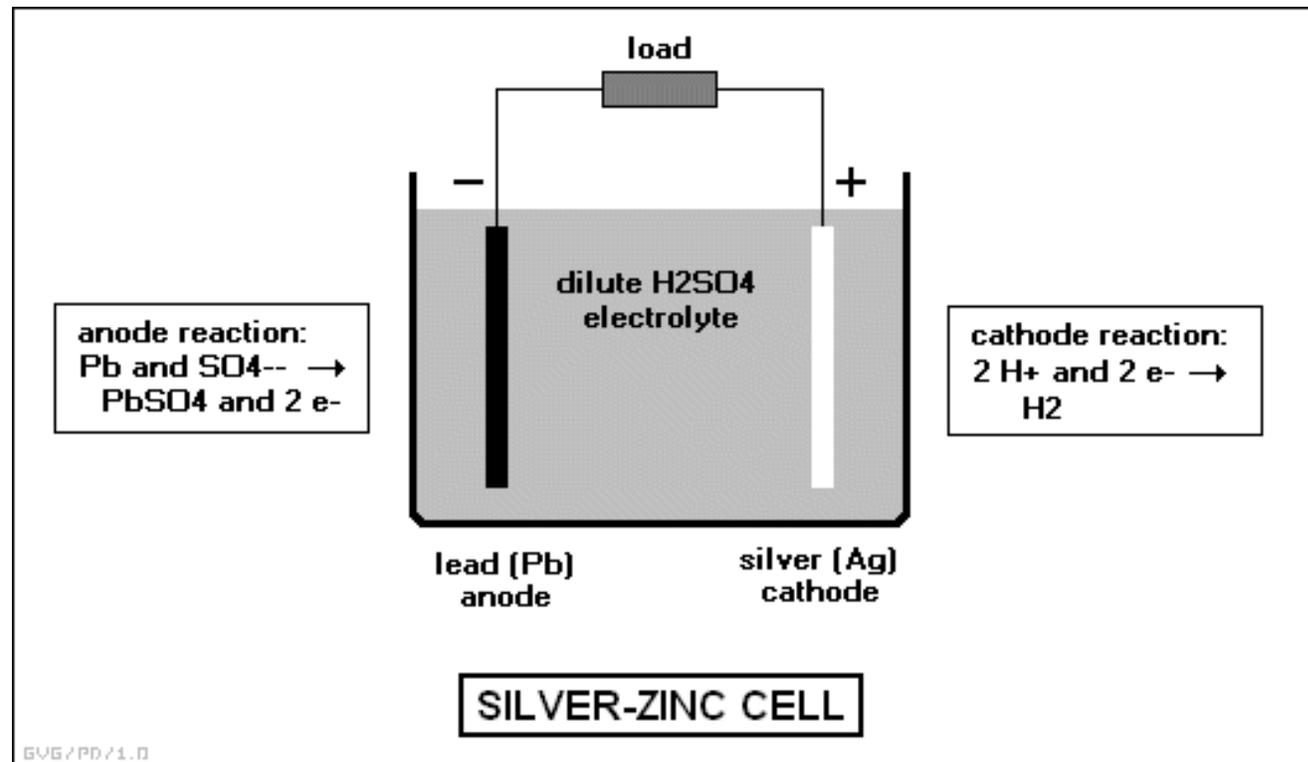
as well as other electrochemical processes such as electroplating. In 1836, the English chemist John Daniell developed the first modern storage cell using Faraday's principles.

* Storage cell operation is based on "reduction-oxidation (redox)" reactions. For example, Volta's scheme can be modeled by placing a bar of zinc at one side of a beaker containing a solution of weak sulfuric acid; placing a bar of silver at the other side of the beaker; and then wiring the two "electrodes" through a light bulb outside the beaker. The light bulb then starts glowing.

Sulfuric acid has the formula H_2SO_4 , and in solution it breaks down into two H^+ ions and a single SO_4^{--} ion. These ions allow electric current to flow through the solution, and so an ionic acid (or basic or salt) solution used to support an electrochemical reaction is known as an "electrolyte".

The SO_4^{--} ion easily reacts with, or "oxidizes", zinc to form zinc sulfate ($ZnSO_4$), which is released into the solution, eating away the zinc electrode. As each zinc sulfate molecule leaves the electrode, it leaves behind two electrons that flow through the external wire as a current to the silver electrode.

At the silver electrode, the electrons combine with or "reduce" the hydrogen ions in the solution to form diatomic hydrogen gas. The silver is inert and not consumed in the reaction. The negative zinc electrode is called the "anode", while the positive silver electrode is called the "cathode".



All modern storage cells use similar oxidation-reduction schemes, though the specific implementations vary widely. Some classes of storage cells can be "recharged" by running an electric current through them backwards, which reverses the chemical reactions and more or less restores things to their original condition.

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[1.2] STORAGE CELL DEFINITIONS & SPECIFICATIONS

* The popular terminology for storage cells is somewhat confusing. Storage cells are almost always referred to as "batteries" in common usage, but this is not technically correct.

The storage cell described in the previous section is just that, a "cell", not a "battery". It consists of one cathode and one anode in an electrolyte. A storage cell with specific electrode materials and electrolyte has a certain output voltage, and to get higher voltages with that specific technology, they must be electrically connected together in series as a "battery".

Flashlight cells are just that, cells, but the lead-acid battery used in an automobile consists of several cells packaged and chained together, so it is indeed a battery. A single cell of a lead-acid battery has a voltage of 2 volts, and so a 12-volt lead-acid battery has six cells in series.

This document will use the term "storage cell" or just "cell" by default, and reserve the term "battery" for when it is specifically appropriate. However, this is just to be precise, since at least in the US both cells and batteries are called "batteries" wherever they are sold and referring to them as "cells" or anything else will just cause confusion.

* There are two classes of storage cells: nonrechargeable or "primary" cells, for example typical cheap throwaway flashlight batteries, and rechargeable or "secondary" cells, for example an automotive lead-acid battery.

Storage cells can also be classified as "wet cells", which have liquid electrolytes; "dry cells", which have electrolytes in the form of a paste; and "solid electrolyte" cells, which as their name indicates use a completely solid electrolyte.

There are also standardized form factors for certain classes of storage cells, such as AAA and AA penlight cells; C and D flashlight cells; and the standard nine-volt brick-shaped "transistor radio" battery. Output voltages are also more or less standardized for these products. However, storage cells are otherwise not highly standardized items, as shopping for a watch button-style cell quickly proves.

Many storage cells can maintain their output voltage at a reasonably constant level over a fairly wide range of output currents. In electrical engineering terms, they are said to have a low "internal resistance". Those that have high internal resistance cannot operate at high current loads, since the voltage at their terminals drops below useful levels. Cells with high internal resistance will also burn up a high proportion of their stored electricity with their own resistance at high current loads, draining them prematurely.

This means that another parameter for storage cells is the maximum useful current output. Storage cell makers may also provide curves giving the fall-off in voltage with increasing current drain, from maximum voltage to the "cutoff voltage" specified for the cell.

By the way, the low internal resistance, or equivalently current capacity, of big automotive batteries makes them potentially dangerous. While their output voltages are so low that getting a shock off them is not a problem, if the output of a large automotive battery is shorted to the chassis ground the large currents flowing through the short

can cause an almost explosive flash and severe burns. It is not usually a good idea to wear a watch with a metal band while servicing a vehicle, since the vehicle's chassis is ground and a short from a "hot" wire could easily lead to a nasty accident.

The total energy capacity of a storage cell is measured in the number of hours it can supply a given level of current, or "ampere-hours". This is a straightforward figure of merit for storage cells based on the same technology, since they will all have the same voltage.

However, ampere-hours can be misleading for comparing different storage cell technologies, as the voltages may differ and the power output of a storage cell with a lower voltage is lower for the same level of output current. For this reason, the unit of "watt-hours" is used to compare energy storage capacity between different storage cell technologies.

A related rating is the "specific energy" of a storage cell, which gives the storage capacity of the cell relative to its mass. For example, a storage cell could be said to have a given number of watt-hours per kilogram. A related measure is the "energy density" of the cell, which gives its storage capacity relative to its volume, for example in watt-hours per liter.

Specific energy and energy density are used in comparisons between different classes of batteries, particularly for automotive propulsion applications. Electric-powered automobiles have always suffered from the limited energy capacity of electric storage cells compared to gasoline and other chemical fuels, and so obtaining storage cells with greater specific energy has been one of the most important goals of electric-automobile designers.

* As the previous section mentioned, rechargeable storage cells can be run backwards and more or less restored to their original, charged state. The "more or less" is important. The restored state is not a perfect replica of the original state, and so rechargeable storage cells degrade slightly every time until their storage capability fades out. For this reason, rechargeable storage cells are also described by the number of "charging cycles" they will tolerate. The number of cycles tends to be lower with greater average depth of discharge. Manufacturers may also provide curves showing how the storage cell's capacity slowly falls as the number of cycles increases.

Another parameter specific to rechargeable cells is "efficiency", or the ratio of power available when the cell is fully charged to the power required to recharge it. Other battery parameters include, of course, the physical dimensions and mechanical specifications of the battery; its shelf life; its expected service life, or how long it can be expected to survive in normal operation; and environmental limits on its operation, particularly temperature specs.

By the way, since the rate of chemical reactions increases at higher temperatures, it is customary to store flashlight cells in a refrigerator to prolong shelf life, though this is becoming less important as improved cell technologies have long shelf lives.

* For an example of storage cell specifications, the data sheet for the Duracell MX1500 AA-size alkaline cell provides a mechanical diagram with dimensions in millimeters, along with weight in grams and volume in cubic centimeters. The operating temperature range is specified as -20 to 54 degrees Celsius. Nominal output voltage is specified as 1.5 volts, with curves giving:

- Output voltage versus time for different levels of power drain.
- Hours of service versus power draw for different levels of output voltage.
- Total amount of energy delivered for given levels of power drain.

* Vendors have now gone beyond simply selling batteries and now sell complete battery-based power modules that can be designed into portable equipment. Such a power module consists of a pack containing cells, power output and recharging control, and control electronics.

The control electronics will include a small cheap digital microcontroller with electrically-programmable ROM to store battery parameters. The module communicates with the rest of the system through a two-wire serial-interface bus called the "SMBus", devised by Intel Corporation. Such schemes are now being standardized by an open specification called the "Smart Battery System (SBS)" that specifies the functionality, interfaces, and software protocols of the battery pack.

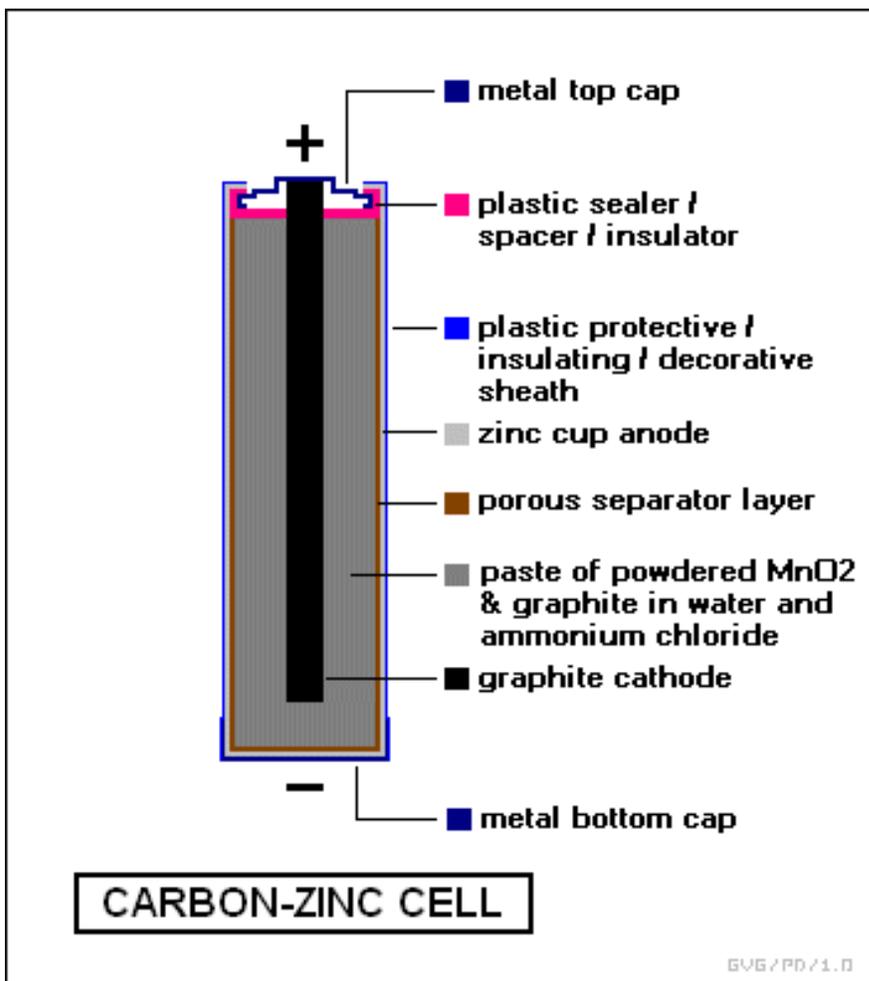
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[1.3] CARBON-ZINC & ALKALINE CELLS

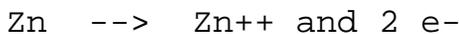
* The carbon-zinc cell was invented in the 1860s by a French chemist named Georges Leclanche, and is sometimes called the "Leclanche cell". It is also sometimes called the "dry cell", but this term is somewhat misleading as it can also be legitimately applied to similar storage cell technologies.

The carbon-zinc cell consists of zinc cylindrical "cup" that makes up the anode -- which is separated from the external casing of the battery by an insulating spacer -- and a central carbon rod. The electrolyte is powdered ammonium chloride (NH_4Cl), an acid, in water, mixed with along with powdered manganese dioxide (MnO_2) and graphite to form a paste.

Zinc chloride (ZnCl_2) can also be used in place of ammonium chloride, providing longer service life at higher cost, and in fact carbon-zinc cells often use a small amount of zinc chloride along with the ammonium chloride. However, for simplicity this discussion assumes that only ammonium chloride is used.



The anode reaction of the carbon-zinc cell involves the double oxidation of a zinc atom, releasing two electrons into the external circuit:



The cathode reaction is supported by the manganese dioxide. The graphite powder is mixed to the manganese dioxide powder as manganese dioxide is not very conductive. While some sources call the central carbon rod the cathode, it is more properly the "cathode collector", as it is inert and simply provides a conductive path to the positive contact. In fact, this type of cell should more properly be known as a "manganese-zinc acidic" cell, but that's not the usage that was adopted.

The cathode reaction involves reduction of MnO_2 to Mn_2O_3 on the inert carbon cathode:

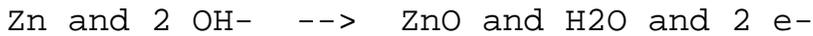


Carbon-zinc batteries will go dead prematurely if discharged too quickly, due to the buildup of reaction products around the carbon cathode, but they will "rejuvenate" if allowed to rest for a while, allowing the reaction products to disperse.

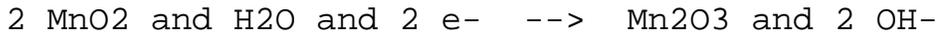
* The alkaline cell operates on similar principles, with a zinc anode and manganese dioxide mixed with graphite for the cathode. However, the electrolyte is potassium hydroxide (KOH), which is alkaline rather than acidic,

again mixed with manganese dioxide and graphite. It should be properly known as the "manganese zinc alkaline" cell, but once more that's not the usage that was adopted.

The anode reaction is:



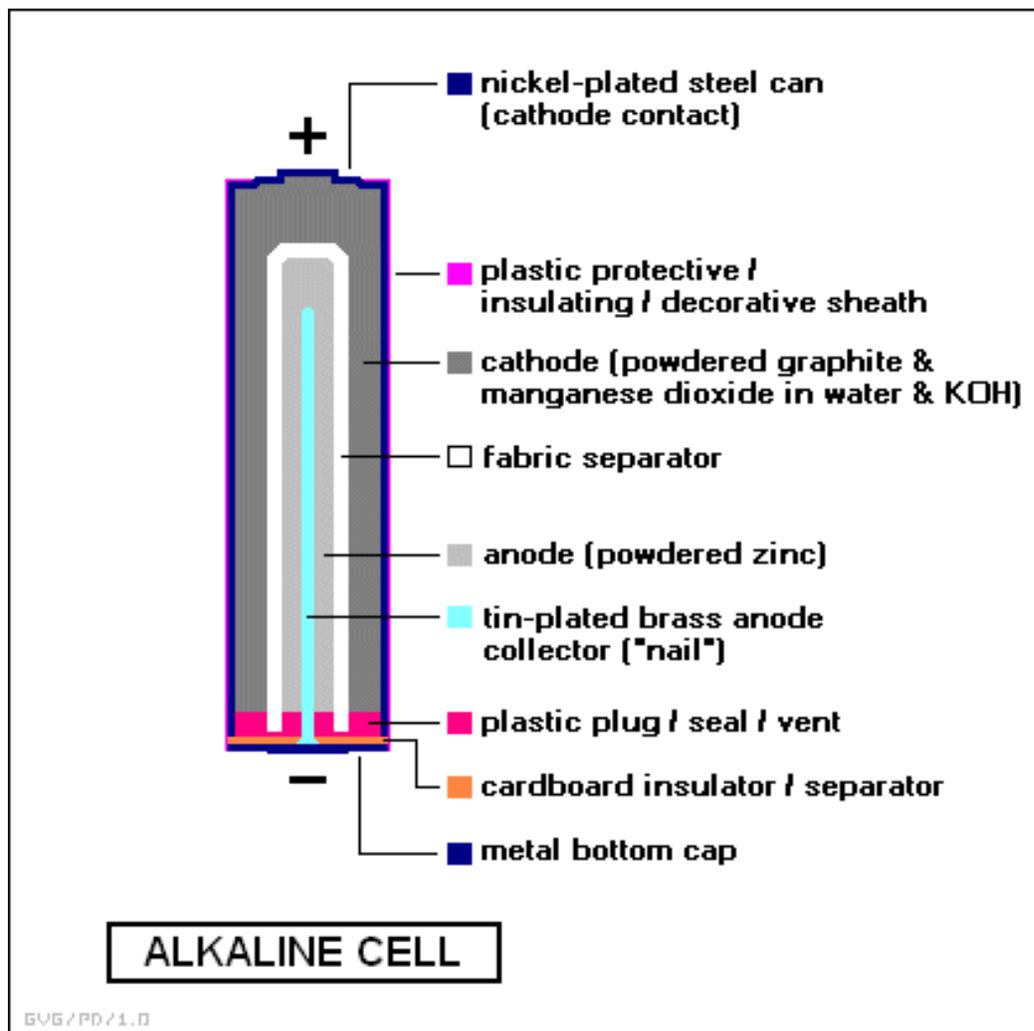
The cathode reaction is;



Sodium hydroxide (NaOH) can also be used as the electrolyte. This is the case for almost all cells that use potassium hydroxide as an electrolyte.

Despite the similarity in operation, the alkaline cell's structure is very different from that of the carbon-zinc cell. The alkaline cell is enclosed in a nickel-plated steel can that forms the positive cathode contact, which is separated from the bottom cap, which is the negative anode contact, by a cardboard spacer. The can contains the potassium hydroxide / manganese dioxide / graphite paste for the cathode reaction, separated from a core of powdered zinc by a fabric separator.

A tin-plated brass "nail" connected to the bottom cap is inserted up into the powdered zinc to conduct current to the cap. A plastic plug seals the bottom of the can and supports the fabric separator.



* Of course, all cells are covered with a plastic sheath to provide protection, insulation, and labeling. Alkaline cells have about twice the power density of carbon-zinc cells, but several times the cost. The carbon-zinc cell's virtue, probably its only virtue, is that it is dirt cheap.

Both carbon-zinc and alkaline cells have a cell voltage of about 1.5 volts, and are both regarded as environmentally benign, at least by the standards of storage cells. Carbon-zinc and alkaline storage cells are not in general rechargeable, but Raytheon did introduce a rechargeable alkaline battery series under the name Renewal in the late 1990s, though this product line was not commercially successful.

* An interesting variation on this technology has been promoted by a company in Israel named "Power Paper", after their product, which is literally printed onto cardboard boxes or similar substrates using silkscreen technology. The Power Paper cell is not actually made of paper, of course. In essence, it consists of a five-layer structure of silkscreened materials:

- A conductor layer.
- A zinc anode layer.
- An electrolyte / separator layer.
- A manganese dioxide cathode layer.
- A conductor layer.

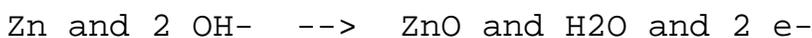
The whole assembly is sealed under a protective layer of plastic. The cell provides 1.5 volts, but multiple layers could be used to construct a battery with higher voltage if necessary. Storage capacity is 2.5 milliampere-hours per square centimeter. It has a shelf life of two years.

The Power Paper cell could be used for point-of-sale gimmicks to sell CDs or movies; for singing greeting cards; or for toys and novelties. The company has recently been promoting "smart notebooks", with a calculator, electronic memo taker, or even a simple computer game embedded on the cover. Another possible application is for a temperature-logging system to be built into packages for the transport of fresh fish, fowl, or produce. The system would include a microcircuit and a cheap temperature sensor, driven by a Power Paper cell, that would log temperatures while the package is in transport, allowing the buyer to determine who is responsible for a spoiled delivery.

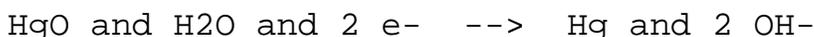
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[1.4] MERCURY, ZINC-AIR, & SILVER OXIDE BUTTON CELLS

* Calculators, hearing aids, and other small electronics devices use tiny nonrechargeable "button" cells. The original technology for button cells was the mercury cell, which had a mercuric oxide (HgO) cathode, an anode made of an amalgam of mercury and zinc, and an electrolyte consisting of potassium hydroxide mixed with zinc hydroxide (or Zn(OH)₂). The anode reaction is:

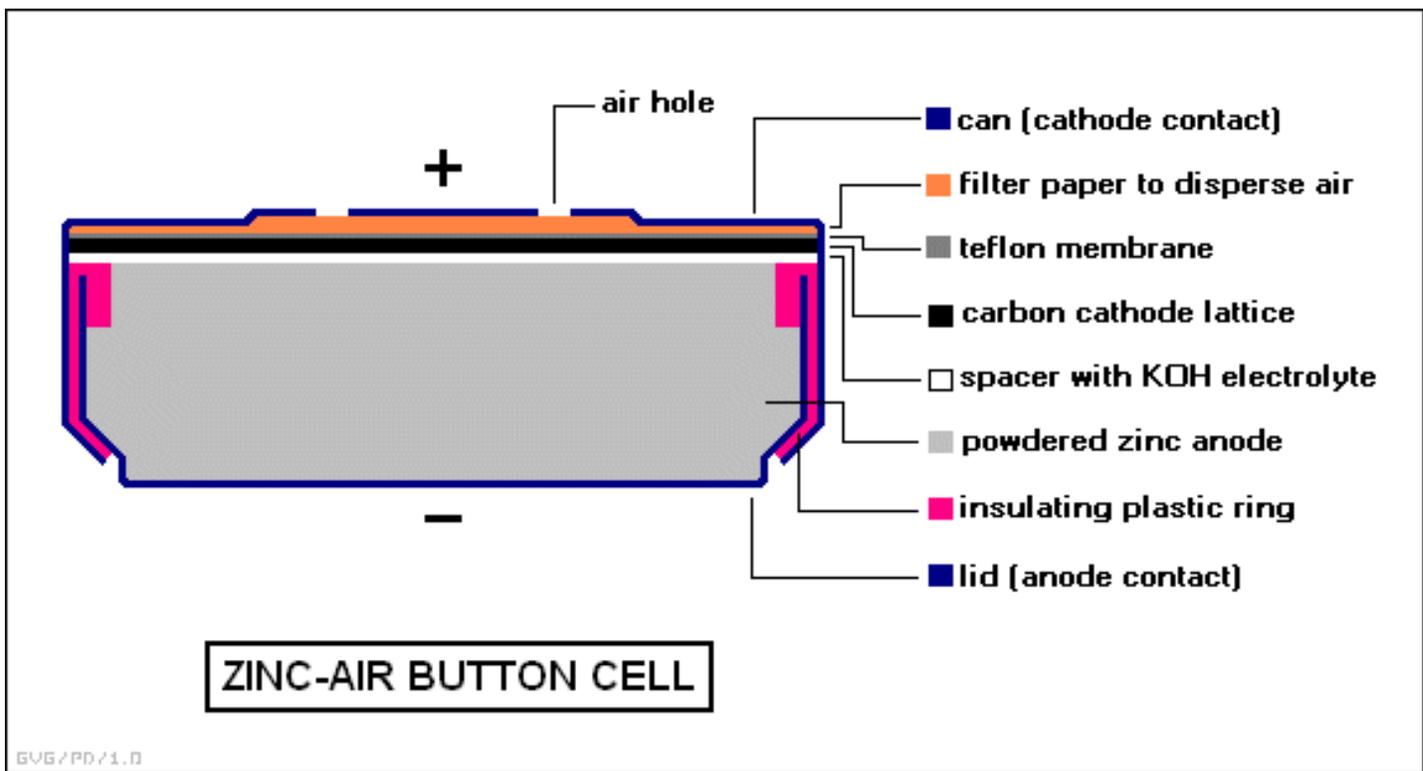


The cathode reaction is:



Mercury cells had a highly constant cell voltage of 1.35 volts. A similar cell could be made with cadmium instead of zinc, providing a cell voltage of 0.91 volts. As mercury is toxic, mercury cells are now banned in the US and some other countries and they are now only a curiosity.

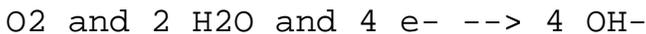
* Modern zinc-air button cells are similar to alkaline cells. The anode is powdered zinc mixed in a gel, the electrolyte is a layer of potassium hydroxide, and the cathode is a carbon disk, designed to support cathode reactions through the oxygen in the air. A porous Teflon membrane allows air into the cell while preventing electrolyte from leaking out.



The anode reaction is:



The cathode reaction is:



Zinc-air batteries have a cell voltage of about 1.65 volts. They have a very high energy density, but also have a high internal resistance and are not well suited to high-current applications. They have to be sealed in storage to keep the air out, but as long as they are kept sealed they have a long shelf life.

Large zinc-air cells have been used in consumer equipment, at least on a limited basis, and very large zinc-air batteries have experimentally used in vehicular applications.

* The silver oxide cell is similar in construction to the zinc-air type, with an anode of powdered zinc in gel with a potassium hydroxide electrolyte, except that instead of having a cathode made of carbon and exposed to the air, it is a silver screen pasted with silver oxide (Ag₂O).

They have a cell voltage of 1.55 volts, a flat discharge curve, and long shelf life. They can be recharged a limited number of times, but they are not generally recharged in practice.

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[1.5] LEAD-ACID, EDISON, NICAD, & NIMH CELLS

* The modern lead-acid battery is by far the most familiar rechargeable storage cell technology. The lead-acid cell was invented in 1859 by a French physicist, Gaston Plante. It uses dilute sulfuric acid for an electrolyte, lead for the anode, and lead oxide for the cathode.

The sulfuric acid dissociates into two hydrogen ions (protons) and a sulfate group. The sulfate group reacts with the lead anode to form lead sulfate and releases two electrons through the external circuit. This is the oxidation reaction, which can be summarized as:



At the cathode, the two electrons cause a reaction to create lead sulfate and water. This is the reduction reaction, which can be summarized as:



At full discharge, both anode and cathode are covered with lead sulfate, and the electrolyte is mostly water. As the sulfuric acid solution is denser than water, a "densitometer", consisting of no more than a dropper with pellets of varying densities and different colors, can be used to examine the cell's charge level. Reversing the current flow reverses the reactions, recharging the cell.

A standard automotive battery consists of a box-shaped casing with internal divider walls to separate its series-connected cells. The electrodes in each cell are built as sets of interleaved plates to provide the maximum surface area for the electrochemical reaction.

Each cell in a lead-acid battery provides about two volts. Lead-acid batteries usually have large capacities, though they tend to run down quickly. They can be recharged hundreds of times until their electrodes are too eroded to allow the battery to hold a charge. They have indefinite shelf lives if stored without electrolyte.

Lead-acid batteries are cheap and effective, and at present are the sole practical choice where high power capacities are required at sensible cost. Ruggedized and sealed lead-acid storage batteries are in common use in portable equipment with large power requirements. However, lead-acid batteries are bulky, and their active materials are environmentally hazardous and so require recycling as a reasonable environmental safety measure.

* A new type of lead-acid battery was introduced in the late 1990s that operates on the same chemical principles, but has a radically different construction. The electrodes are formed as thin plates, with the electrolyte stored in a separator sheet between the plates, and stored in a sealed can in a "wound" or "jelly-roll" configuration. The improved battery configuration provides a higher energy density, though the environmental issues remain much the same.

This is about the only significant innovation in lead-acid battery design in over a century of the technology's existence. To be sure, there have been improvements in packaging materials for lighter weight and greater reliability, but Gaston Plante would see little in a modern lead-acid battery that he didn't find familiar.

Trying to come up with a high-capacity rechargeable cell with a higher energy density at a reasonable cost has

proven extremely difficult. This was frustrating even a century ago, and the well-known American inventor Thomas Alva Edison spent a fortune trying to build a rechargeable cell that could improve on Plante's invention.

The result was the "nickel-iron" cell, or "Edison cell", and though it still lives on in industrial uses, it never came close to displacing the lead-acid battery. The Edison cell uses an iron anode, a nickel oxide cathode, and a potassium hydroxide electrolyte.

The Edison cell provides a voltage of about 1.15 volts per cell. Its main virtue is that it is extremely rugged, tolerating discharge treatment that would ruin other types of storage cells, and has a very long service life.

* The "nickel-cadmium" or "nicad" cell is similar to the Edison cell, but uses a cadmium rather than an iron anode. A nicad cell is generally a cylinder with layers of cadmium and nickel oxide separated by absorbent layers containing KOH electrolyte. The anode reaction is:



The cathode reaction is:



These are reversible reactions. The nicad produces about 1.2 volts per cell. It has a low internal resistance and its cell voltage remains remarkably constant until the cell is almost discharged.

While Edison batteries are generally built as large industrial units that physically resemble lead-acid batteries, nicads are built mostly for rechargeable consumer equipment and so have smaller form factors. Nicads were once predominant as rechargeable batteries in consumer gear, but they tended to be ruined by complete discharge, and the heavy-metal cadmium anode made them an environmental nuisance. Nicads are still in widespread use, particularly for portable power tools where their ability to provide large amounts of current on demand makes them particularly useful, but are now increasingly being replaced by improved rechargeable battery types.

* One such improved rechargeable technology is the "nickel-metal hydride (NiMH)" cell. Most designs are similar to nicads, but replace the cadmium anode with a "metal hydride", based on complex metallic alloys that can store large quantities of hydrogen. The cathode is nickel oxide, the electrolyte is a solution of potassium hydroxide, stored in a polymer separator sheet. The anode reaction, with "(M)" representing the metal hydride, is:



The cathode reaction is:



They have a typical cell voltage of 1.2 volts, which tends to remain flat through the cell discharge cycle. They tend to have a high self-discharge rate, but are relatively environmentally benign.

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[1.6] LITHIUM TECHNOLOGY

* Lithium is an excellent material for making storage cell anodes, as it gives up electrons very easily and is very light. Lithium cells can provide an order of magnitude better energy density than lead-acid cells.

One of the big problems with lithium is that reacts violently with moisture, and manufacturing lithium cells requires a moisture-free environment. Lithium cells also require venting and other safety systems to keep them from exploding if moisture does infiltrate the case, or if such cells are heated. This delayed their use for a very long time. There are a bewildering range of lithium cell technologies. They can be basically divided into non-rechargeable lithium cells, and rechargeable "lithium-ion" cells.

* The conceptually simplest and most common nonrechargeable lithium cell is the "lithium-manganese" cell. This has a lithium anode, a manganese dioxide cathode, and a carbonate electrolyte. The anode reaction is:



The cathode reaction is:



The cell voltage is about 3 volts. Such cells are constructed in a jelly roll configuration, with a sheet of lithium foil, a separator sheet containing electrolytic salts, and a sheet of manganese dioxide rolled up together. They have an indefinite shelf life.

There are many other nonrechargeable lithium cell configurations, such as "lithium sulfur dioxide", "lithium thionyl chloride", and "lithium polycarbonate monofluoride", with complicated constructions and chemistries that are substantially more capable than lithium-manganese but not as cheap, and so not in as widespread use.

The latest generation of nonrechargeable lithium cells uses a polymeric electrolyte. Such "lithium polymer" cells of course have electrical characteristics similar to those of the predecessors, but they can be more easily built in flat or rectangular configurations that are very useful for lightweight portable equipment.

* The high cell voltage of the lithium ion cell means that it is not interchangeable with standard zinc-carbon or alkaline cells. A nonrechargeable "lithium disulfide" cell or "voltage compatible lithium cell" has been introduced that does provide a cell voltage of 1.5 volts. Lithium disulfide cells are also built in a jelly roll configuration, with a lithium anode, an electrolytic separator sheet, an iron disulfide (FeS₂) cathode, and an aluminum cathode collector. It is lighter than an alkaline cell, has high capacity, and has a very long shelf life.

* Lithium is easier to handle in its ionized form, and so rechargeable lithium cells, which have to deal with the hazards of being recharged, have been traditionally based on lithium compounds. Again, there are many variations, but a typical "lithium ion" cell has a carbon anode, a lithium cobalt dioxide or manganese dioxide cathode, and an electrolyte consisting of a lithium salt in solution.

Lithium-ion cells have a cell voltage of about 3.6 volts. They have high internal resistance and are not suited to high current applications. They have very long cycle lives, up to a thousand cycles for single cells, and their storage capacity does not degrade significantly with cycling. They are increasingly becoming the rechargeable battery of choice for portable consumer electronics equipment, though they are expensive.

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[1.7] STORAGE CELL SUMMARY

* As the number of storage cell technologies makes them confusing, a summary table comes in handy to help keep them straight.

CARBON-ZINC (LECLANCHE) CELL:

anode: zinc cup
cathode: manganese dioxide in graphite powder
electrolyte: ammonium chloride & zinc chloride in water
cell voltage: 1.5 volts

Non-rechargeable, poor storage density, but very cheap.

ALKALINE CELL:

anode: nickel-plated steel cup
cathode: manganese dioxide in graphite powder
electrolyte: potassium hydroxide in water
cell voltage: 1.5 volts

(Generally) non-rechargeable, storage density about twice that of the carbon-zinc cell, but several times more expensive.

MERCURY BUTTON CELL:

anode: zinc
cathode: mercuric oxide
electrolyte: potassium hydroxide in paste
cell voltage: 1.35 volts

Non-rechargeable. A variation on this technology used cadmium instead of zinc and provided a cell voltage of 0.91 volts. The first button cell technology, now obsolete due to environmental concerns.

ZINC-AIR BUTTON CELL:

anode: powdered zinc in gel
cathode: carbon disk exposed to air
electrolyte: potassium hydroxide layer
cell voltage: 1.65 volts

Non-rechargeable. Most popular current button cell technology, also some applications in larger cell formats.

SILVER OXIDE BUTTON CELL:

anode: powdered zinc in gel
cathode: silver grid pasted with silver oxide
electrolyte: potassium hydroxide layer
cell voltage: 1.55 volts

Nonrechargeable.

LEAD-ACID CELL:

anode: lead
cathode: lead oxide
electrolyte: sulfuric acid
cell voltage: 2 volts

The standard large capacity battery technology. Can be recharged hundreds of times and very cheap, but bulky and environmentally noxious.

NICKEL-IRON (EDISON) CELL:

anode: iron
cathode: nickel oxide
electrolyte: potassium hydroxide
cell voltage: 1.15 volts

Heavy-duty rechargeable unit, used in some industrial applications.

NICKEL-CADMIUM (NICAD) CELL:

anode: cadmium
cathode: nickel oxide
electrolyte: potassium hydroxide
cell voltage: 1.2 volts

The original rechargeable cell for portable gear, now used mostly in gear that needs high power levels on demand.

NICKEL-METAL HYDRIDE (NIMH) CELL:

anode: metal hydride
cathode: nickel oxide
electrolyte: potassium hydroxide solution in separator sheet
cell voltage: 1.2 volts

Greater capacity than nicads but more expensive.

LITHIUM-MANGANESE DIOXIDE CELL:

anode: lithium foil
cathode: manganese dioxide
electrolyte: separator sheet impregnated with electrolytic salts
cell voltage: 3 volts

The most common non-rechargeable lithium cell.

LITHIUM DISULFIDE CELL:

anode: lithium foil
cathode: iron disulfide with aluminum cathode contact
electrolyte: separator sheet impregnated with electrolytic salts
cell voltage: 1.5 volts

"Voltage compatible" lithium cell as direct replacement for carbon-zinc or alkaline cells.

LITHIUM-ION CELL:

anode: inert carbon sheet
cathode: manganese dioxide
electrolyte: electrolyte separator sheet with lithium ions
cell voltage: 3.6 volts

Rechargeable lithium cell.

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