

Primary Cells & Batteries

An Introductory Primer

Many portable electrical and electronic devices are designed to be powered from batteries – and in a lot of cases, from *primary* or non-rechargeable batteries. This is the familiar kind of battery which has a fixed amount of energy stored in it during manufacture, and once that energy has been used up the battery is simply thrown away and replaced.

There are many different types of primary battery now available, each with its own strengths and weaknesses. The aim of this data sheet is to give you a basic idea of these different types, how they work and the things to consider when you're selecting the most suitable type for a given job.

Before we look at each type in turn, though, let's clarify a few points about primary batteries in general.

Battery basics

Primary batteries have been around for about 200 years. Italian scientist Alessandro Volta is credited with developing in 1800 the first practical battery, which consisted of a stack of small electrochemical cells – each consisting of a silver plate and a zinc plate separated by a sheet of cardboard which had been soaked in salt water. Each cell generated a small amount of electrical energy, and by connecting all of the cells of his 'pile' in series, Volta could generate a useful voltage for his experiments.

It's in honour of Volta's achievement that we call the unit of electromotive force the volt, of course. We also tend to call this kind of cell a voltaic cell.

All primary cells effectively have energy stored in them when they're made, in the form of their component materials and chemicals. As we draw energy from them, the electrochemical energy is converted into electrical energy and some of the chemicals are used up.

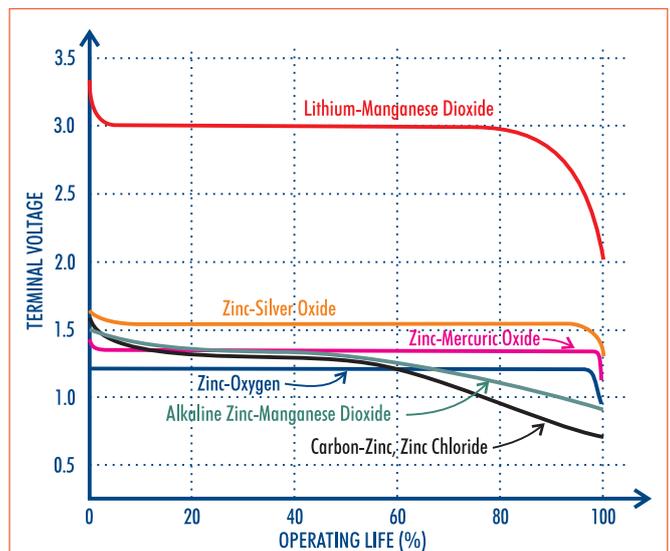
How do the cells actually produce electrical energy? In detail that's a fairly involved process, and a full explanation is beyond us here. However in simple terms it's by taking advantage of two main effects. One is that when any metal electrode is placed in an electrically conducting liquid (i.e., an electrolyte), the atoms at its surface tend to exchange electrons with the solution, becoming charged in the process.

Some of these charged atoms or ions tend to leave the metal and wander around in the solution. This tends to set up a small voltage difference between the metal electrode itself and the electrolyte, and this electrode potential varies from metal to metal according to their atomic structure. Some metals like lithium and zinc develop a negative voltage, while others like copper, mercury and silver develop a positive voltage.

Even the salts and other compounds of these metals tend to develop these electrode potentials, by the way, but not to the same extent.

The second main effect is that when two such electrodes are placed in the same electrolyte, a process of electrochemical oxidation and reduction is able to take place. Here oxidation is used to describe atoms losing electrons, and reduction to describe other atoms gaining electrons. The oxidation reaction occurs at one electrode, which gains electrons lost by ions from the electrolyte and becomes negatively charged – i.e., the cell's negative electrode. Conversely the reduction reaction occurs at the other electrode, which loses electrons to ions in the electrolyte and hence becomes positively charged – becoming the cell's positive electrode.

Now if there's no external connection between the two electrodes, the charges on them simply build up until the voltages between them and the electrolyte block any further oxidation and reduction, and the reactions stop. However if we connect the two electrodes via an external circuit, this allows electrons to flow between them and the electrochemical reactions keep going.



Discharge curves for one cell of each of the seven main types of primary battery, in each case normalised over their working discharge life.

Most batteries developed before about 1860 used cells in which two electrodes of metal or a metal compound were immersed in a liquid electrolyte, all housed in a jar or vat which had to be kept upright. However in most modern batteries the cells either have the electrolyte absorbed in a porous separator material (like Volta's salt-soaked cardboard) or they use a non-liquid electrolyte such as a paste or gel. This allows them to be packaged

PRIMARY BATTERY COMPARISON CHART

TYPE (CHEMISTRY)	COMMON NAME(S)	NOMINAL CELL VOLTS	INTERNAL RESISTANCE	MAXIMUM DISCHARGE RATE	COST	PROS & CONS	TYPICAL APPLICATIONS
Carbon-Zinc	'Standard duty'	1.5	MEDIUM	MEDIUM	LOW	Low cost, available in various sizes; but terminal voltage droops steadily during cell life	Torches, radios, toys & general purpose, electronic equipment.
Zinc Chloride	'Heavy Duty'	1.5	LOW	MEDIUM TO HIGH	LOW TO MEDIUM	Low cost, better at higher discharge rates & at lower temperatures; terminal voltage still droops	Cassette tape players/recorders & other motor-driven items, clocks, calculators, remote controls, multimeters etc.
Alkaline Zinc-Manganese Dioxide	'Alkaline'	1.5	VERY LOW	HIGH	MEDIUM TO HIGH	Better for high continuous or pulsed loads, & at low temperatures; but terminal voltage again droops	Heavy duty torches, photoflash units, battery shavers, digital cameras, handheld transceivers, portable CD players etc.
Lithium-Manganese Dioxide	'Lithium'	3.0	LOW	MEDIUM TO HIGH	HIGH	High energy density, very low self-discharge rate (excellent shelf life); good temperature tolerance	Watches, calculators, cameras (digital & film), DMMs & other test instruments.
Zinc-Mercuric Oxide	'Mercury cell'	1.35	LOW	LOW	HIGH	High energy density (compact); very flat discharge curve; good at higher temperatures	Calculators, pagers, hearing aids, watches, test instruments (voltage reference).
Zinc-Silver Oxide	'Silver Oxide cell'	1.5	LOW	LOW	HIGH	Very high energy density (very compact); very flat discharge curve; reasonable at lower temperatures	Calculators, pagers, hearing aids, watches, test instruments (voltage reference).
Zinc-Oxygen	'Zinc-Air cell'	1.45	MEDIUM	LOW	MEDIUM	High energy density, very light weight; flat discharge curve; but must have access to air	Hearing aids and pagers.

in essentially sealed containers, and known as dry cells and dry batteries.

By the way, strictly speaking a cell is a single electrochemical system with its own positive and negative electrodes and electrolyte, while a battery is a

number of these individual cells packaged together – and usually connected in series, to produce a higher voltage. Most common cylindrical 'batteries' are in fact single cells, but those in rectangular and other package shapes are often multiple-cell batteries. The terminal voltage is usually a good guide.

Cell performance

The performance of primary cells depends on a number of factors. For example the gross amount of electrochemical energy stored in the cell depends on the materials it's made from and the quantities of them used to make it. So different types of battery are potentially able to deliver different amounts of energy, even though in all cases larger batteries can deliver more energy than smaller ones. That's why many of the different types are made in a range of physical sizes: D cells, C cells, AA and AAA cells, button cells and so on.

But there's more to it than that. Even more than with secondary (rechargeable) batteries, the effective energy capacity of primary batteries depends heavily on other factors such as operating temperature and the rate at which the energy is drawn from the battery – i.e., its discharge rate.

For example in many types of primary cell the electrochemical reactions slow down at low temperatures, reducing the cell's ability to deliver electrical energy. Also the efficiency of many types of cell drops as higher currents are drawn from them, lowering their effective capacity.

For this reason, and unlike secondary batteries, primary cells and batteries are generally not given a capacity specification in ampere-hours or milliamp-hours. Instead most manufacturers simply quote a maximum discharge current, which is the maximum rate at which current may be drawn from the battery before its capacity and life are seriously reduced.

Some manufacturers also give 'Service Life' curves showing how the cell's terminal voltage drops over time, at this and lower discharge rates. Such curves may also specify the type of service involved: continuous drain, or two hours per day, or one hour per day, etc.

Temperature effects

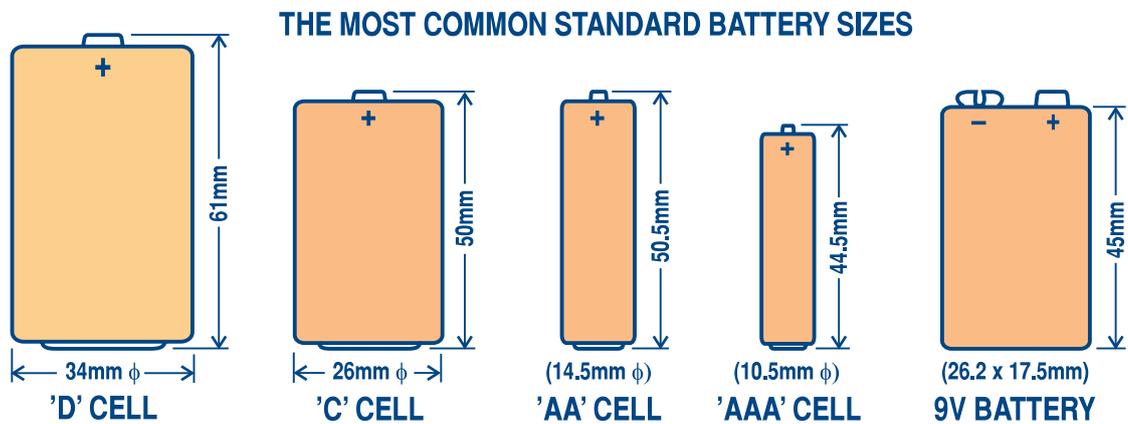
As already mentioned, many primary cells and batteries are less able to supply energy at lower temperatures because their chemical reactions slow down. So this type of battery is less suitable for use in very low temperature conditions.

Conversely, at temperatures above about 50°C the internal chemical activity can speed up sufficiently to cause the cell to discharge itself and rapidly lose its capacity. This means not only that these batteries should not be used at elevated temperatures, but that they shouldn't be stored at higher temperatures either.

In fact two good rules of thumb with most primary cells and batteries are (a) to store them at a low temperature when they're not being used (in an airtight container in a refrigerator, for example), and (b) to avoid either storing or using them at temperatures above 50°C.

Internal resistance

Like just about all other electrical components, primary cells have their own internal resistance – in this case present in both the electrode materials and the



electrolyte. As you might expect the internal resistance tends to be smaller in large cells than in small cells, and it also varies with the materials used. For example cells with metal electrodes tend to have a lower internal resistance than those with non-metallic or compound electrodes like carbon or manganese dioxide.

The main significance of internal resistance is that when current is drawn from the cell, some of the cell's electrical energy is wasted as heat – the power dissipated in the internal resistance. Similarly the voltage drop in the internal resistance lowers the cell's terminal voltage, which can cause problems for some kinds of load equipment (a radio set may stop working when the voltage drops below a certain value, for example).

Naturally both the energy wastage and the drop in terminal voltage will be greatest at relatively high discharge rates. So when a cell or battery is to be used to power equipment that draws fairly high current (even for brief periods), or is reasonably critical about the supply voltage regulation, it's generally desirable to choose a battery with low internal resistance.

Now we should be ready to look at the various types of primary cell and battery in current use.

Carbon-zinc batteries

These are basically the earliest type of commercially practical battery, a direct descendant of the battery developed by French scientist Georges Leclanché in 1868. As the cheapest and most widely available dry cell and battery they're still very popular.

The positive electrode of this type of battery is actually manganese dioxide, but with carbon mixed with it and a carbon rod down the centre to reduce internal resistance. The negative electrode is zinc, which generally also forms the can, and the electrolyte is a mixture of ammonium chloride and zinc chloride in water.

Carbon-zinc batteries have a nominal terminal voltage of 1.5V, but this gradually droops during service and is generally described as 'sloping' even by the manufacturers. Initially they have a fairly low internal resistance, but this gradually increases as

their chemicals are consumed – and also at lower temperatures and in low humidity. The shelf life also tends to be poor, especially at higher temperatures.

In fact this type of battery is not a particularly good performer at either low or high temperatures, but can otherwise give reasonable performance. Its main advantages are low cost and ready availability in a wide range of sizes.

Zinc-chloride batteries

This type is essentially a development from and an enhanced 'heavy duty' version of the carbon-zinc battery, designed to deliver more current and provide about 50% more capacity for a given size.

The physical construction is very similar to the carbon-zinc type, with a manganese dioxide/carbon positive electrode and a zinc negative electrode and can. However the electrolyte is now only zinc chloride in water, which improves the efficiency of the reactions at the electrodes.

The terminal voltage is again 1.5V, and this type also has a sloping terminal voltage as the chemicals are consumed (including the water). Its internal resistance gradually increases also. However its performance is better at low temperatures than the carbon-zinc type, and slightly better at higher temperatures. The shelf life is also longer.

The higher energy density and capacity of this type combined with relatively low cost makes it reasonably popular for powering equipment with motors and other high-drain items.

'Alkaline' batteries

The alkaline zinc-manganese dioxide or 'alkaline' battery offers much higher energy density and hence capacity than either the carbon-zinc or zinc chloride type – up to 800% that of the carbon-zinc, in some applications. It is also capable of higher discharge current levels. However it tends to be significantly more expensive, and somewhat heavier.

The construction is quite different from the earlier types, even though some of the same basic materials are used. This time the manganese dioxide and carbon

form the positive electrode (connected to the steel can), while the zinc is in powdered form as the negative electrode, which is actually mixed to form a gel with potassium hydroxide as the electrolyte.

The nominal terminal voltage of an alkaline cell is again 1.5V, and although it again slopes during the cell's life, the fall is rather more gradual than with the carbon-zinc or zinc chloride types. The internal resistance is also considerably lower, and remains so until almost the end of the battery's life.

Alkaline batteries have a very long shelf life, and also give better performance at both lower and higher temperatures.

Despite their higher cost and weight, alkaline batteries are so much better performers than the carbon-zinc or zinc chloride types in almost all respects that they're essentially the 'premium' primary battery. They're

especially suitable for any application involving fairly high discharge current levels.

Lithium batteries

The lithium-manganese dioxide primary battery is a relatively recent development, taking advantage of the high electrode potential and energy density of lithium metal. They offer considerably greater energy density and capacity than even alkaline cells, for a relatively small increase in cost.

The lithium is in the form of very thin foil and is pressed inside a stainless steel can, to form the negative electrode. The positive electrode is manganese dioxide, mixed with carbon to improve its conductivity, and the electrolyte is lithium perchlorate dissolved in propylene carbonate. (Lithium reacts strongly with water, so an aqueous solution can't be used. The batteries must also be manufactured and sealed in an inert gas atmosphere.)

The nominal terminal voltage of the lithium cell is 3.0V, twice that of most other primary cells, and it remains almost flat during the discharge life. It also has a very low self-discharge rate, giving it a very long shelf life. The internal resistance is also quite low, and remains so during the working life.

The lithium battery performs well at low temperatures, and advanced types are used in communications satellites, space vehicles and military applications.

Mercury cells

Zinc-mercuric oxide or 'mercury' cells take advantage of the high electrode potential of mercury to offer a very high energy density combined with a very flat discharge curve.

Mercuric oxide forms the positive electrode, sometimes mixed with manganese dioxide. The negative electrode is metallic zinc powder, and the electrolyte is usually potassium hydroxide, absorbed in a multi-layer

separator.

The nominal terminal voltage of a mercury cell is 1.35V, and this remains almost constant over the life of the cell. They have a low internal resistance, which is again fairly constant.

Although made only in small 'button' sizes, mercury cells are capable of reasonably high pulsed discharge current levels and are thus suitable for applications such as quartz analog watches and hearing aids as well as voltage references in instruments, etc.

Silver oxide cells

The zinc-silver oxide cell takes advantage of the high electrode potential of silver to again provide a high energy density combined with a very flat discharge curve.

The silver oxide forms the positive electrode, again sometimes mixed with a small amount of manganese dioxide. The negative electrode is powdered metallic zinc, mixed into a gel with the electrolyte – which is usually either potassium hydroxide or sodium hydroxide. A separator membrane stops the negative electrode gel from mixing with the positive electrode.

The nominal terminal voltage of a silver oxide cell is slightly over 1.5V, and remains almost flat over the life of the cell – which is not as long as that of a mercury cell of the same size and weight. The internal resistance is also low and relatively constant. Low temperature performance is quite good.

The silver oxide cell is again made only in small 'button' sizes of modest capacity, but has a relatively good pulsed discharge capability. It's again mainly used in watches, hearing aids, pagers and test instruments.

Zinc-air cells

The zinc-oxygen cell is a recently developed type, emerging from research into fuel cells. It offers very high energy density and a flat discharge curve – but combined with a relatively short working life.

The negative electrode is formed of powdered zinc, mixed with the potassium hydroxide electrolyte to form a paste or 'slurry'. This is retained inside a small metal can by a separator membrane which is porous to ions, and on the other side of the membrane is simply air – to provide the oxygen which forms the positive 'electrode'. The air/oxygen is inside an outer can of nickel-plated steel which also forms the cell's positive connection, lined with another membrane to distribute the oxygen over the largest area.

Actually there's no oxygen or air in the zinc-oxygen cell when it's made. Instead the outer can has a small entry hole with a covering seal, which is removed to admit air and 'activate' the cell. The zinc is consumed as the cell supplies energy, which is typically for around 60 days.

The nominal terminal voltage of a zinc-oxygen cell

is 1.45, and the discharge curve is relatively flat. The internal resistance is only moderately low and they are not suitable for heavy or pulsed discharging.

The zinc-oxygen cell is again made mainly in 'button' and 'pill' sizes, and is mainly used in hearing aids, pagers etc.

Precautions

As you can see from the above, many types of primary battery contain highly corrosive electrolytes like potassium hydroxide ('caustic potash'). Others contain toxic materials such as mercuric oxide or highly reactive materials like lithium – which can explode on contact with water.

This means that great care should be taken when disposing of used batteries. Opening them can also be quite dangerous, and could easily result in serious burns, poisoning or other injuries.

Note also that most types of primary cell and battery are not designed to be re-charged, and in some cases attempting to do so can result in the cell exploding. This is particularly true with normal alkaline zinc-manganese dioxide, lithium-manganese dioxide, zinc-mercuric oxide and zinc-silver oxide cells. So in general it's very unwise to attempt recharging any of these cells and batteries.

There is a type of alkaline zinc-manganese dioxide battery made specifically to be recharged – see the companion datasheet on recharging for more information on this. It is also possible to 'rejuvenate' a carbon-zinc or zinc chloride cell or battery that is only partially discharged, with a suitably designed circuit. This can extend their life, but with reduced capacity.