NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

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SET-126

Basic Guide to Electrochemical Power Sources

(Guide élémentaire pour les sources d'énergie électrochimiques)

Published January 2012

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Preface

The purpose of this document is to give an overview of the most popular electrochemical power sources in the world, a battery. An electrochemical power source is defined as a system that transforms chemical energy to electrical energy that can be utilized by an external device. Although batteries are the most popular form of an electrochemical power source it also includes emerging technologies such as fuel cells and electrochemical capacitors.

It is written for the reader who has no, or limited, knowledge on the principles and operation of a battery. It explains the basic concepts of how a battery produces electricity and the construction of some of the more common battery technologies and configurations. It then takes a basic look at the various types of batteries and how they differ from one another, the advantages (and disadvantages) of each technology along with a short guide for selecting the correct technology for a given usage.

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Chapter 1 – INTRODUCTION

The purpose of this document is to give an overview of the most popular electrochemical power sources in the world, a battery. An electrochemical power source is defined as a system that transforms chemical energy to electrical energy that can be utilized by an external device. Although batteries are the most popular form of an electrochemical power source, it also includes emerging technologies such as fuel cells and electrochemical capacitors.

Batteries come in many form factors and chemistries. Regardless of the form or technology, the basic building block for any kind of battery is referred to as the cell. A battery can be comprised of a single cell, such as the power source used in the common flash light, to a package of multiple cells wired together. A multi-cell battery can be anything from the one in you laptop computer to the device in your automobile. Regardless of the size of the cells or the battery, the one thing they all have in common is the ability to produce electricity.

Batteries (either as a single cell or a collection of cells) are used in a wide variety of applications. These range from devices that provide power to the personal electronics of everyday life to large systems used in submarines and missiles. Regardless of the size or chemistry of the battery, they are designed and operate according to the same set of basic physical laws and principles.

Chapter 2 – HOW IS THE ELECTRICITY PRODUCED?

2.1 COMPONENTS OF AN ELECTROCHEMICAL CELL

Regardless of the cell basic design or material used, every cell has four major components: an anode, cathode, electrolyte and a separator.

Anode – The anode is the negative electrode and is the material that gives up electrons (also known as reduction) to the external circuit during the electrochemical reaction. The materials chosen for constructing the anode should:

a) Be an efficient reducing agent (that is easily gives up electrons);

b) Have good conductivity;

c) Be easy to process; and

d) Have a low cost.

For many years zinc was the material of choice, but more recently has been replaced by lithium due to its light weight.

Cathode – The cathode is the positive electrode and is the material that accepts electrons (also known as oxidation) from the external circuit during the electrochemical reaction. Materials for the cathode must be efficient oxidizers.

Electrolyte – The medium for transfer of ions between the anode and the cathode. The ideal electrolyte has good ionic conductivity, but is not electrically conductive. This means that the electrolyte can move ions without causing a short circuit within the cell (which is not a desirable occurrence). The electrolyte should also not be reactive with the other materials in the cell.

Separator – The material that provides mechanical isolation of the cathode and anode, but allows for the transfer of ions by being permeable to the electrolyte. Therefore the separator must be physically robust enough to assure the anode and cathode remains physically isolated, but permeable enough to allow for ionic transfer between the anode and cathode.

The following is an illustration of a basic cell.

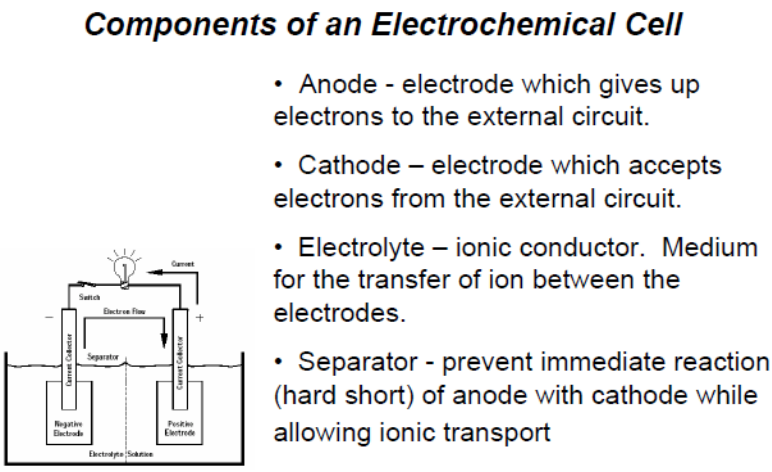


Figure 1: Components of a Cell.

In the simplest terms, a cell can be considered a roadway where the movement of electrons from the anode to the cathode takes place. This “roadway” is official called the REDOX (oxidation-reduction) reaction, and only generates energy when the anode is physically connected to the cathode to form an electric circuit (Figure 2). In a non-rechargeable cell, this is a one-way street, whereas in a rechargeable cell, it is a two-way street.

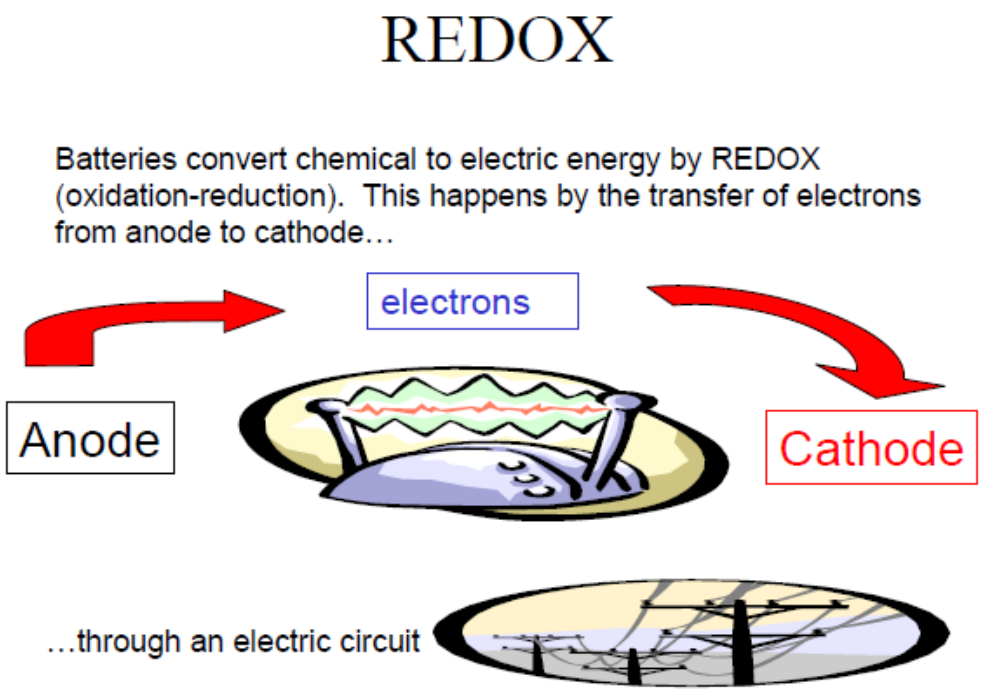


Figure 2: Movement of Electrons.

2.2 THE BASIC COMPONENT OF A BATTERY – THE CELL

As stated earlier, the cell is the basic building block of a battery. In the commercial world, as stated previously, there are instances where the term cell and battery are used interchangeably. The electrochemical device (i.e. the “D” or “AA” cell) that you put into your flashlight is called a battery, but in actuality is a single-cell battery.

Cells come in many different shapes and chemical combinations. As a rule they are designed to provide electricity in two different manners, either at low discharge rates for a long period of time (providing lots of energy), or at high discharge rates for a relatively short period of time (providing lots of power). In simple terms, this is determined by the chemical combinations chosen and the amount of surface area available for the reaction to take place. Unfortunately there are no cells today that can provide lots of power for long periods of time.

For commercial applications there are several basic designs, depending on the type of discharge rate for which it will be utilized. The alkaline cell, which we are all familiar with, is designed to provide energy (a low rate discharge rate over a long period of time) and designed using what is known as the “bobbin” construction, as illustrated in Figure 3 below.

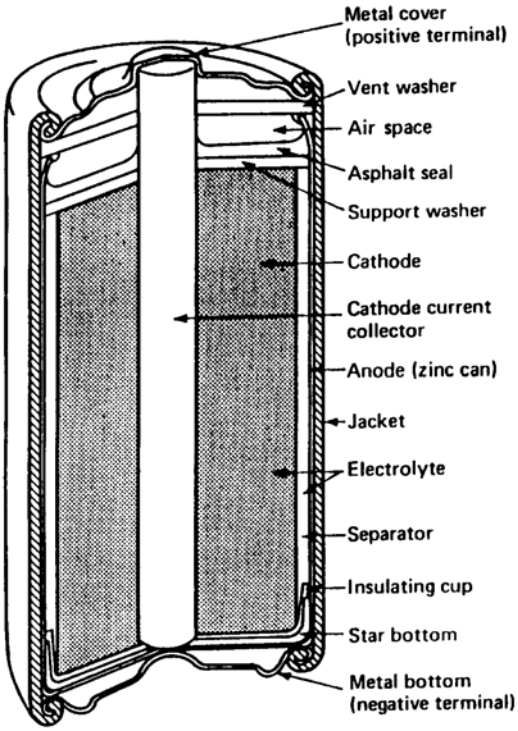


Figure 3: Bobbin Cell Construction.

The primary advantage of a bobbin design is that it is easy to manufacture. A variation of this design that is also easy to manufacture and is widely used in the commercial market for such items as hearing aids and cameras is the "button" cell, which is shown in Figure 4.

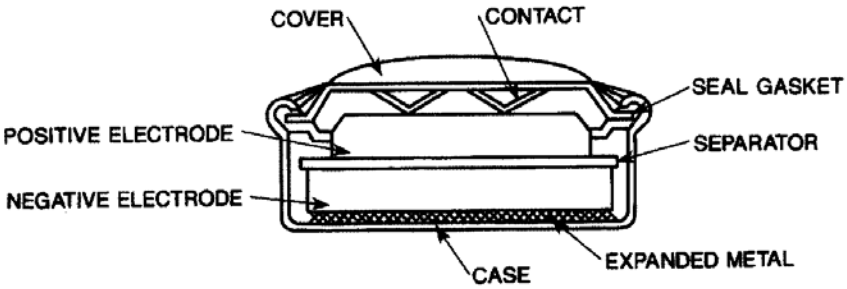


Figure 4: Button Cell Construction.

Another design that is very popular, especially for rechargeable batteries such as lithium ion, is the spirally wound or "jelly roll" design. This design is desirable where high rate discharges are required. Although more difficult to manufacture, its advantage compared to the bobbin and button designs is that it has more internal surface area for the anode and cathode, resulting in an increased ability to release electricity at a faster rate.

Many lithium-ion cells are now being packaged in prismatic containers, which enable efficient packaging of the cells into rectangular batteries. These cells are packed in a metalized plastic film not very different from a vacuum-packed coffee bag, or a steel container. The internal design can be either a stacking of individual electrodes or an elliptical jelly roll (see Figure 5).

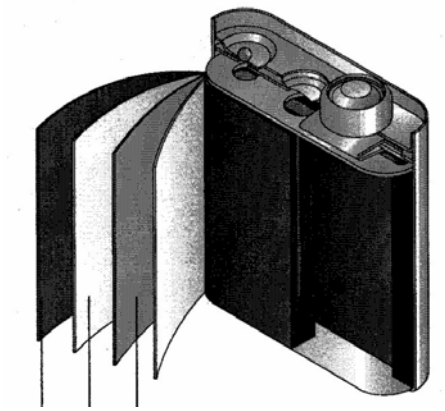


Figure 5: Prismatic Construction Cell – Elliptical Jelly Roll.

Regardless of the technology, all cells have internal safety devices to protect the cell from a catastrophic failure if abused. In the alkaline technologies, the electrochemistry is relatively benign, and the only safety device is a nylon seal that allows the internal material to leak out if the cell experiences overheating. On the other extreme are the lithium technologies. These cells have areas in the cans called vents which are specifically designed to rupture if the cell is abused (see Figure 6). They may also have special separators that melt if the internal temperature reaches a certain point, as well as 'positive temperature coefficient' devices that disconnects the circuit (and stops the flow of electricity) should the discharge rate be higher than the design can tolerate.

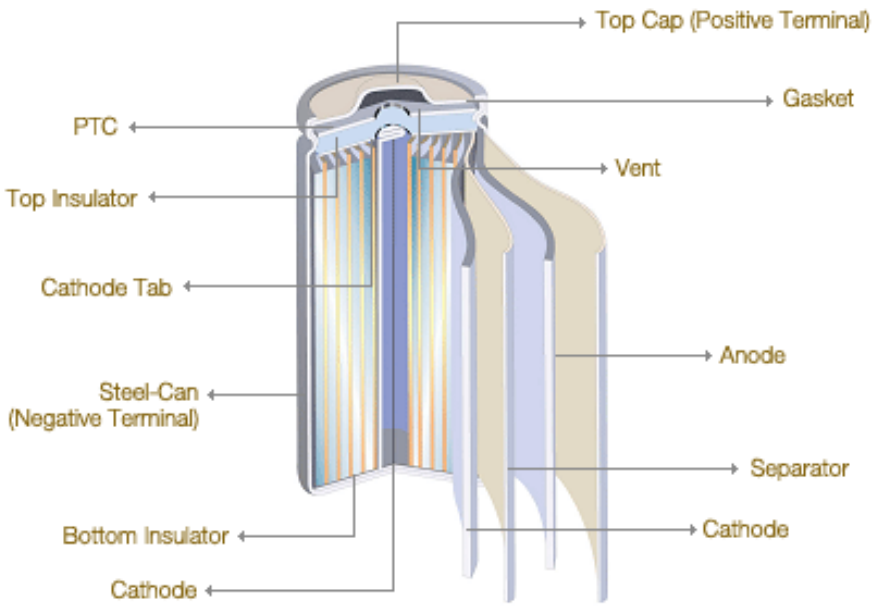


Figure 6: Spirally Wound Cell Construction.

2.3 BUILDING CELLS INTO BATTERIES

A battery is a collection of cells that are wired together inside a container and to terminals on the side of the container by which the electricity can be removed. Think of the battery for your cell phone or laptop computer. There are number of cells inside, and those flat contacts on the outside are used to remove and replace the internal energy.

In addition to those safety features within the cell, a battery normally contains additional features such as fuses, diodes (to prevent the charging of non-rechargeable batteries) and some type of circuit board or electronic component assemble that helps regulate the energy leaving the battery, or in the case of a rechargeable battery, the energy entering.

Figure 7 is a standard military battery and shows how cells can be wired together to produce electricity.

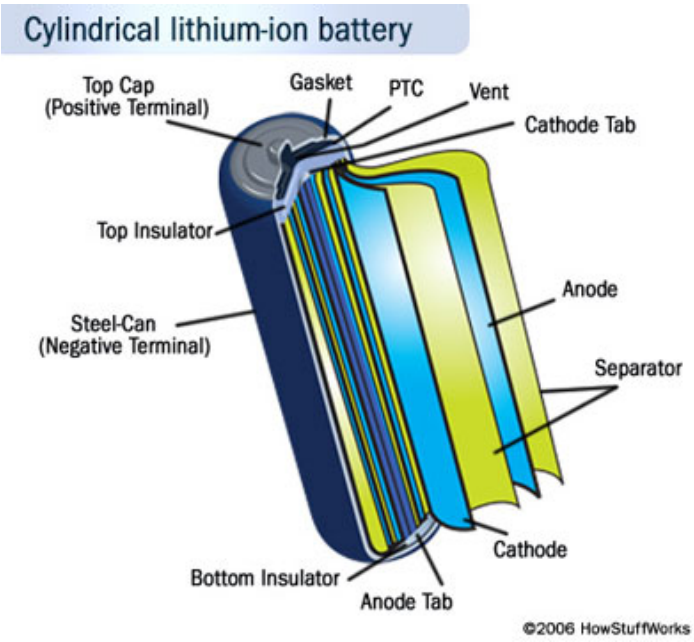


Figure 7: Lithium-Ion Cell Construction.

2.3.1 Characteristics of a Battery

Electricity produced by the cells is released from the battery through the connector/terminal. Batteries have a specific ability to produce electricity. For non-rechargeable batteries, once this ability is fully utilized, the battery must be disposed. An example of this is the flashlight. When you turn on the flashlight you begin drawing electricity from the battery. If the flashlight remains on, the energy is slowly depleted which can be seen by the light slowly becoming dimmer.

For rechargeable batteries, this capability can be replenished once the battery is connected to an external energy source (i.e. the designated charger). This ability to replenish the battery is not 100% successful and each time a rechargeable battery is used and recharged (known as a cycle), it loses a minute amount of its original capacity (also known as capacity fade). The number of cycles that a rechargeable battery can accomplish and still retain a predetermined percentage of its original capacity is known as its cycle life, which for the majority of rechargeable batteries in use today is in the hundreds, if not thousands of cycles.

The ability of any battery technology to produce electricity is usually described in terms of ‘power’ and ‘energy’. This ability is based on the design of the cells, as discussed previously. The amount of electricity produced over a given period of time is referred to as the power, while the amount of electricity ‘contained’ in the battery is referred to as the energy. The basic difference between power and energy is how the electricity is removed from the battery. An example would be the gasoline in an automobile’s fuel tank. If you fill the fuel tank with gasoline, and run the auto at maximum acceleration, you will generate a lot of power over a relatively short period of time. However, if you let the auto idle, the fuel in the tank will generate energy over a significantly longer period of time.

There are several key characteristics of a battery:

- **Voltage** – The voltage of a battery is determined from the materials used for the anode and cathode and is given by the potential difference (the ability of electrons to move between the anode and cathode) between the two materials. This value (measured in volts) between the terminals provides the electricity that can be generated (or removed) by a battery. An analogy would be the water pressure in a hose. The greater the pressure in the hose, the faster the water moves. The same is true in a battery, the higher the voltage, the faster the electricity is removed from the battery.
- **Amperage** – The amperage of a battery defines the quantity of the current that is contained in the battery. Using the hose analogy – amperage would be the diameter of the hose.
- **Capacity** – The capacity of the battery is normally measured in units of amp-hours. Using the hose analogy again, the capacity would be the reservoir that supplies the water.

Multi-cell batteries are designed to have the cells in either 'series' or 'parallel' arrangements. The advantages of both are:

- **Series** – Batteries that have cells in a series configuration (Figure 8) have a higher voltage which means that the voltage at the terminal is higher than any individual cell. This is usually driven by the design of the end item. For example the 12-volt car battery is comprised of a total of six 2-volt cells.

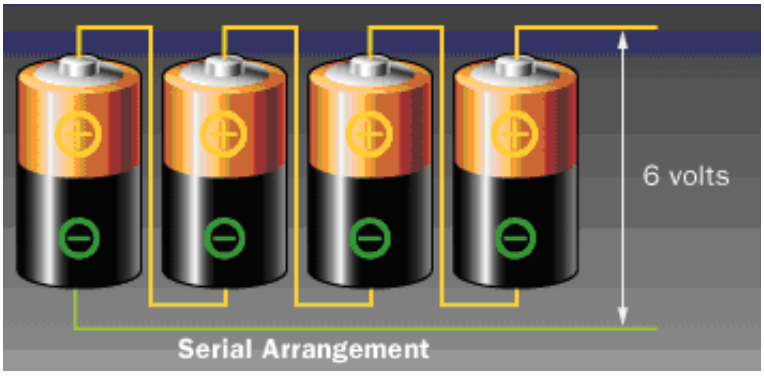


Figure 8: Cells in Series Arrangement – In this example the voltage is increased four fold but the multi-cell battery retains the capacity of a single cell.

- **Parallel** – By connecting cells in parallel (Figure 9) it allows for the use of the same cell voltage, but increases the overall capacity of a multi-cell battery.

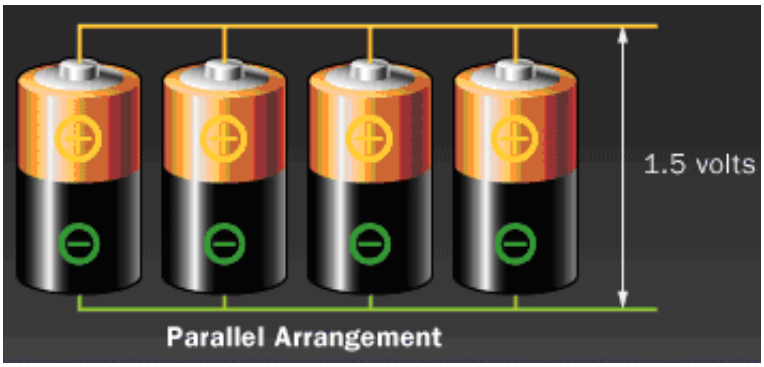


Figure 9: Cells in Parallel Arrangement – In this example the capacity is increased four fold but the multi-cell battery retains the voltage of a single cell.

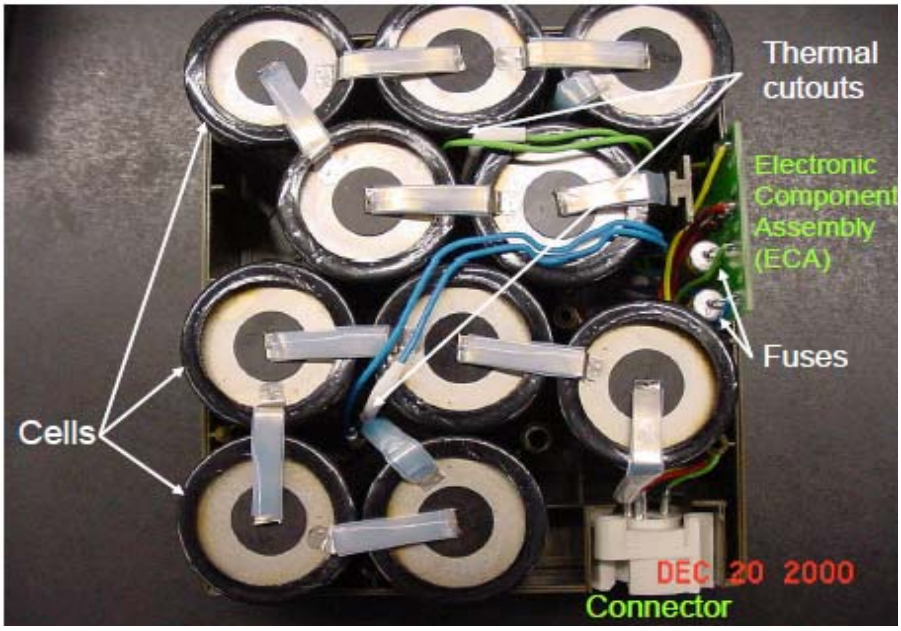


Figure 10: Cells Wired to Create a Battery.

2.3.2 Battery Life

All batteries have two types of life. One measurement is obviously the length of time that the battery will run a particular application. This "run time" is predicated on two factors, the amount of energy contained with the battery and the demand for energy from the application. The other measurement is what is referred to as the "shelf life", which is defined as the length of time (measured in some form of calendar time – normally months or years) that they battery can stay in an active state and still deliver a reasonable amount of energy.

Rechargeable batteries have a third measurement related to life and this is termed the "cycle life". Cycle life is defined as the number of discharge/charge cycles the battery can experience until it has lost so much energy due to capacity fade that the battery is no longer usable.

2.3.3 Battery Safety

Under normal use, a battery allows for the controlled release of electricity in the form of voltage and amperage. In very few instances, such as an accidental short circuit, the energy of the battery is released in an uncontrolled manner, with the potential for the violent release of the cell's internal materials (what is known as a "venting", but may seem as an explosion). To minimize the possibility of such an occurrence, virtually all batteries have some form of safety device built in. The extent and complexity of these devices depends on the size of the battery and the chemistry used in the individual cells. However, as the technology increases, more and more energy is being packaged into smaller and smaller volumes, resulting in a need for increasingly sophisticated safety features. The alkaline battery used in many consumer devices is a relatively benign electrochemical system and as such has minimal safety devices. On the opposite extreme are the lithium batteries used in today's personal electronics, which have redundant safety features at two levels – fuses, diodes, charge control circuitry at the battery level and pressure relief mechanism at the cell level.

Remember – the key to a cell's ability to produce electricity is the oxidation/reduction reaction. The more the materials used in this reaction are energetic, the more electricity will be produced. It is the job of the safety devices to make sure these reactions do not get out of control.

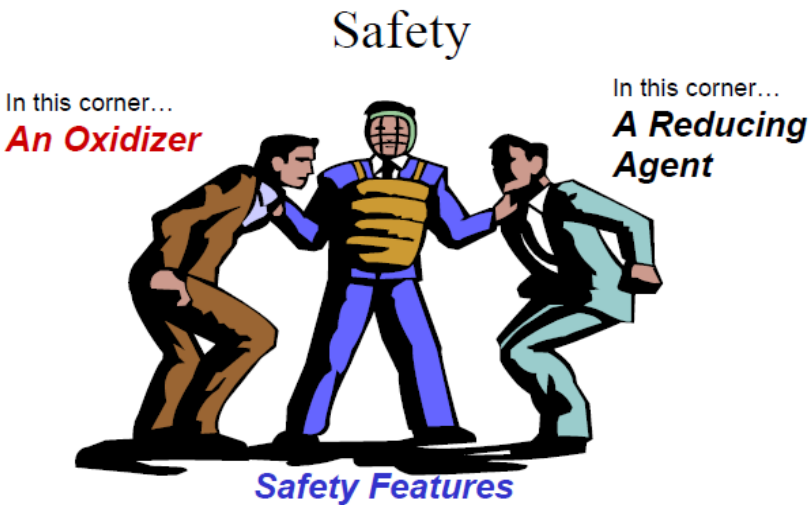


Figure 11: Safety is the Reaction Referee.

The reason that these safety features are designed into a cell/battery is to protect both the equipment it is used with and the person using the equipment. Batteries can be subjected to circumstances for which they were not intended, such a trying to charge a non-rechargeable battery, a short circuit due to physical abuse or even a manufacturing defect. When such a circumstance arises, it usually causes the cells to overheat, creating a significant increase in the internal pressure. With the more benign chemistries, this normally results in the battery leaking, such as with an alkaline battery in a flashlight (Figure 12).

Figure 12: Leaking Alkaline Battery.

With the newer, more energetic lithium chemistries, the result might be more like an explosion. Even with all the safety features in place, the battery can experience a catastrophic failure. Figure 13 shows a non-rechargeable lithium cell that has violent vented and caught fire. The mesh that is seen inside the cell is part of the internal jelly roll. Figure 14 illustrates the energy that can be released when a cell(s) violently vents, resulting in an explosion that blew away part of the battery container.

Figure 13: Vented Spirally Wound Cell.

Figure 14: Military Battery Following a Venting.

2.3.4 Classification of Batteries

Batteries come in many shapes, sizes and electrochemistries, but in general can be divided into three broad categories; primary, secondary and reserve. Each is described below.

2.3.4.1 Non-Rechargeable Batteries

The technical name for this class of battery is primary batteries and is characterized by the fact that after all of the electricity it can produce is consumed, they are discarded. The most common chemistry in the commercial market is the alkaline battery, with some non-rechargeable lithium technologies becoming popular. The biggest advantages of non-rechargeable batteries are:

- For given size, they are the lightest when measured as to the amount of electricity they can deliver.
- They have long shelf lives, meaning they can sit on a shelf in an inactive state for long periods of time and still delivery electricity (assuming they are stored at normal room temperatures).
- They are readily available in that they can delivery electricity almost immediately.
- They have a relatively low unit price (alkaline batteries being the cheapest and lithium batteries more expensive).

2.3.4.2 Rechargeable Batteries

Technically this class is known as secondary batteries. A rechargeable battery is characterized by the ability to have electricity regenerated by an outside source after being depleted, and to do this repeatedly (for many cycles). The commercial market is basically dominated by three electrochemistries – lead acid batteries for vehicles, nickel metal hydride and/or lithium ion for portable power tools and lithium ion for portable electronics. The advantages of rechargeable batteries are:

- Being reusable, they offer very low per usage costs.
- They can support very high drain rates.
- They are environmentally friendly (being reusable) and easily recycled.

2.3.4.3 Reserve Batteries

A reserve battery is very similar to a primary battery in that it is intended as single use application. The difference from a typical primary battery is that the electrolyte is isolated from the anode and cathode

until the battery is activated. This gives the battery a virtually unlimited shelf life, which makes them ideal for use in military applications such as missiles and smart munitions, but virtually no use in the commercial market.

2.4 CHOOSING THE BEST TECHNOLOGY

When choosing the right battery or electrochemistry, there are several important aspects to consider. First let's assume that you are the normal consumer and you are looking for the right technology to buy for use in your application. The first decision you have to make is – do I use a non-rechargeable or rechargeable technology? When making this decision you might want to consider:

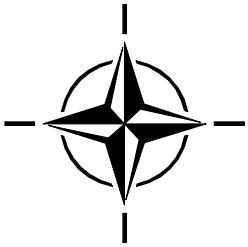
- Will I use the battery once – or will I use it repeatedly? If used repeatedly, then use a rechargeable battery.
- Will the battery sit on the shelf for long periods of time, or will it be used on a regular basis? If the battery will sit on a shelf for a long period (such as a flashlight for emergencies), then use a non-rechargeable battery.
- Am I willing to pay a premium for better performance or reliability? If for example performance is important, than I might want to buy one of the new non-rechargeable lithium batteries as opposed to an alkaline battery.

If you were to design a battery for that same application, you must make the same decisions as above, but also consider several other critical parameters, such as:

- What is the voltage requirement of the system? This will dictate the possible chemistries that can be used and the number of cells required in the battery.
- Do I have weight and/or volume limitations? The smaller or lighter the package required, the more energetic the chemistry has to be, with an increased attention paid to the safety devices incorporated into the overall design.
- What is the temperature range in which the battery must operate? Some technologies work better in cold temperatures, while others perform better in hot temperatures. There are some technologies that perform well at both temperature extremes.
- What type of electrical demands will be placed on the battery? Will the battery be required to deliver low rates of electricity for long periods of time (such as in a home smoke detector), or will it be required to produce a lot of electricity in a very short period of time (such as starting your automobile)?

Table 1 gives a brief comparison of the more widely used battery technologies in the commercial market.

Table 1: Battery Comparison.

Non-Rechargeable Battery Chemistries	**Description**
Alkaline	The battery used in the majority of non-electronics consumer applications. Good for high- and low-drain uses compared to many other technologies.
Lithium-iron disulfide	Considered a 'premium' replacement for alkaline batteries due to the having higher capacity, better performance at low and high temperatures and longer shelf life.
Lithium-manganese dioxide	The most common consumer grade non-rechargeable lithium battery. Suitable for low-drain, long-life, low-cost applications.
Mercuric oxide	Banned in most countries because of health concerns related to the mercury content.
Silver-zinc	Very expensive. Only used commercially in "button" cells.
Zinc-air	Mostly used in hearing aids.
Zinc-carbon	Inexpensive. Has been replaced by alkaline batteries in most instances.
Rechargeable Battery Chemistries	**Description**
Nickel cadmium	Environmental hazard due to cadmium – use now virtually prohibited in Europe in commercial application, but large cells are still in use for industrial applications. Being replaced by newer nickel-based and lithium technologies.
Lead acid	Moderate rate of self discharge. Environmental hazard due to lead, but the battery is almost 100% recyclable. Most common use is in automobiles and trucks.
Nickel metal hydride	Introduced as an alternative to nickel cadmium batteries, but has a high rate of self-discharge. Used in commercial applications (power tools) and seen as a battery for electric vehicles.
Nickel zinc	Have a low self-discharge rate and no toxic components. Newly introduced to the market (2009). Has not yet established a track record.
Lithium ion	Most expensive of the rechargeable technologies but also has the highest energy content. Widely used in consumer personal electronics, such as laptop computers, digital cameras and cell phones. Due to the safety issues related to use of lithium, individual cells are not available to the consumer.

For those interested in a more in-depth knowledge related to batteries, books such as "Handbook of Batteries" by David Linden are recommended.