Evolution of batteries: From experiments to everyday usage

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Abstract. *Batteries serve as a universal storage of potential energy, which can be later transformed by electrical devices into another type of energy, such as sound, light, heat or kinetic energy.*

The first battery was invented by Alessandro Volta and was called Voltaic pile. It was used for research on electricity and electromagnetism. Since that, construction and technologies changed, as well the batteries parameters. For example, Voltaic pile and its early successors were huge and non-rechargeable, which limited the battery usage in mobile devices. Hence, the invention of rechargeable battery led to the commercial success of batteries. And rechargeability was not the only parameter that was the aim of research. During the evolution, many types of batteries were invented. But as different devices have different needs, the existence of several battery technologies is an advantage. Today we have advanced batteries suitable for various devices and their needs, so, for example, both electromobile and toothbrush can be powered.

Keywords

electricity, battery, energy, history, lithium-ion, NiMH, lead-acid, Galvani, Volta, rechargeability

1. Introduction

Based on the law of conservation of energy, the energy cannot be created, just transformed. For example, the electricity can be transformed into sound, light, heat and motion energy. Before the electricity was understood, there were almost no methods for storing energy, so the invention of the battery was important. The era of studying electricity dates to the beginning of the 17th century, when William Gilbert coined the term electricity. In 1660 a German scientist Otto von Guericke invented the machine for producing static electricity. Charles Franois de Cisternay du Fay found out that there are two types of electricity and Benjamin Franklin named them as a positive and negative charge. Franklin also discovered the electricity from lighting. The 19th century was crucial for discoveries in electromagnetics. Michael Faraday first discovered the electromagnetic induction. James Maxwell interpreted Faraday's theories in a mathematical way into Maxwell's equations. Nikola Tesla created and patented the first AC induction motor. Tesla came with alternating current in the distributing system, instead of direct current propagated by Edison. He also experimented with a wireless power transmission.

The battery was discovered during experiments with a behaviour of electricity and magnetism. The first battery, named as the Voltaic pile, built Alessandro Volta thanks to his deep knowledge of chemistry and physicist. The invention of the telegraph increased the importance of the batteries. There arose requirements for the batteries, such as stability of the current and voltage and the mobility of the battery. The development of the rechargeable battery allowed usage in mobile devices and commercial use. With innovations, such as electromotor and flashlight, were coming new and more strict requirements. The price of the battery was important for commercial success and the capacity for long operation of the device without charging. Besides, batteries are used for balancing the fluctuations of the electrical distributing system.

Increasing need for mobile electric devices and their specific properties lead to differentiation of batteries into various types. This types are characterized by various properties and the main properties of batteries are following:

The type of the battery: it means if is it a primary (non-rechargeable) or secondary (rechargeable) cell.

The voltage which can the battery produce and associated internal impedance are determining its current-carrying capability.

The capacity of the battery is measured in amperes per hour and is equal to the amount of electric charge which can be delivered at the rated voltage.

The lifetime energy throughput is in watts per hour and determines how much energy can be taken out and into a cell before the capacity of the battery reduces to 80 % of the initial capacity. Similar, while easier characteristic is an amount of charge-discharge cycles before the capacity is lowered.

The discharging curve determines the relation between voltage and percentage of capacity discharged. The effort is to have a flat discharge curve, so the voltage remains constant during using the battery.

The temperature characteristic of the battery is important as well, as the voltage and time for discharging can change with temperature changes.

The physical requirements determine the geometry and size of the cell, weight and the location of the terminals.

Deep discharge: Important is also the ability of a deep discharge.

Application requirements: The battery must fulfil the application requirements, so it must have a right capacity and produce the right voltage and current.

The cost of the battery affects the final price of the product.

Nowadays we have different types and technologies of batteries suitable for various devices and their needs. We use them in everyday mobile devices, such as mobile phones, laptops, watches, cars, medical devices, space probes, big storage of energy, etc.

2. Historical artifact

Possibly the first occurrence of technology that can be used as an electric battery was dated to the Parthian Empire period, which was between 247 BC and 224 AC in today's Iran and Iraq. The unusual artefact unearthed in 1938 near Baghdad a German archaeologist Wilhelm Knig. Baghdad battery, also named as Parthian Battery, is a 14 cm [5] long yellow clay jar containing a cylindrical copper pipe held by asphalt to the jar (see fig. 1). The copper pipe encased an iron rod that was found completely oxidised.

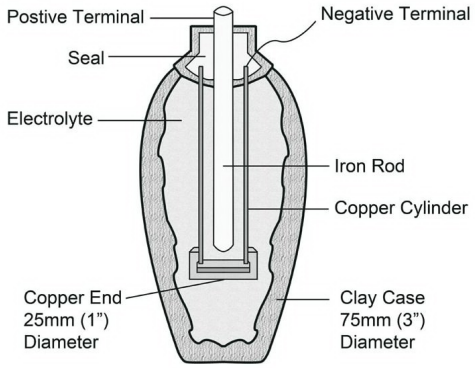

Fig. 1. The construction of the Baghdad battery. Source: [3].

Dr Marjorie Senechal and his students made a replica and proved, that this battery could conduct an electric current and produce voltage, but there is no documentation about the experiment. This old battery could be used for electro planting, or for medical purposes like combine acupuncture with electric current and give a shock to the person to make him acknowledge a divine experience. On the other hand, there were not found any written records, connecting wires, or electroplated metals and it's uncertain if it was a battery.

3. First experiments

The first official device for storing electric charge, named as Leyden jar, was developed independently by two electricians in 1745. One was cleric Ewald Georg Von Kleist from Germany, and the other was Pieter Van Musschenbroek from Leyden in Holland. They invented a glass jar with water and two electrodes, the first inside the jar and the second outside. When someone touched the jar, the positive charge in the water moved to the hand. Afterwards, by touching the wire with the other hand, the positive and negative charge were connected, which produced a slight spark or even shock (to the person).

This discovery was important for later experiments and studies of electricity. A Polish physicist Daniel Gralath experimented with connecting more Leyden jars in parallel. He found out that the total possible stored charge will increase. American Benjamin Franklin did experiments with connected Leyden jars charged with an electrostatic generator. He discovered that these linked capacitors could be charged and discharged simultaneously and in 1748 the term "electrical battery" was used for the first time.

Essential were also experiments with the electricity of Italian physicists Luigi Galvani. His experiments were close to the invention of the battery. While he was cutting frogs leg affixed on the brass hook with a steel scalpel, he touched the leg, and it twitched (see fig. 2). He believed that its an electrical fluid in muscles and animals can generate electricity, which named "animal electricity". Galvani published an essay Commentary on the Effect of Electricity on Muscular Motion in 1791.

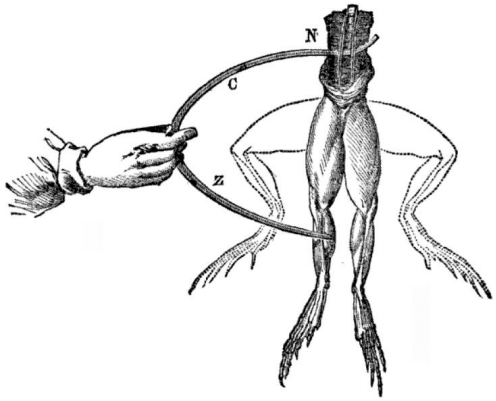

Fig. 2. Galvani's experiment with frogs leg. Source: [7].

4. From experiments to today's batteries

Galvani's rival, an Italian physicist and chemist Alessandro Volta, disagreed with his theory about animal electricity and repeated his experiments. He tried to use many different metals and found that the reason for twitching legs was the contact of two different metals. He studied the difference between the electrical effect of various metals and sorted them by electromotive force. This information about electrode potentials was later necessary for choosing battery electrodes. He found out, that for generating the continuous flow of electric power can be used not only frogs leg but also some fluids, like salt water or dilute acids. This invention, using two different metals and as the electrolyte the salt water, is now called the galvanic cell. This experiment disproved the Galvani's theory about animal electricity. After this experiment, Volta constructed in 1799 the first battery, today called by him "Voltaic pile". Electrolyte made from paper soaked in salt water separated zinc and copper discs. He added many layers of these disc pairs to the pile to reach the desired voltage (see fig. 3).

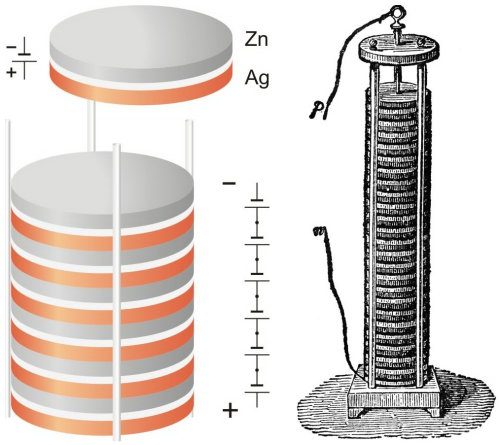

Fig. 3. Volta's pile. Source: [16], [17].

Volta's pile construction was not ideal, the significant weight of discs compressed the paper, which caused shortcuts. So in 1800 a Scottish chemist William Cruickshank improved the pile by adding disc next to each other instead of putting them up on each other vertically in a column. This horizontal battery was named "trough battery". In 1802, he made the first battery for mass production, which consisted of zinc and copper plates with dilute acid or brine electrolyte. Everything was placed into sealed wooden box. After that, batteries were used either as an experiment in research and as a part of electrical devices.

5. Batteries for daily use

During the first part of 19th century, there was important ongoing research on electricity, which influenced battery research. For instance, the most important were following. In 1820 André-Marie Ampère discovered electricity through magnetism and in 1831 Michael Faraday described Faraday's Law.

But also during this era, the batteries were already in use. The research of the batteries was aiming at batteries production with higher capacity, stable current and voltage, cheaper construction, mobility, etc.

Batteries based on Volta's pile were having a problem with hydrogen molecules bubbling away as hydrogen gas. In 1836 an English chemist and physicist John Frederic Daniell developed "Daniell cell". His solution eliminated hydrogen production from the first electrolyte using the second electrolyte for absorbing the hydrogen. This cell with copper sulphate and zinc sulphate as electrolytes was able to provide current for steadier and longer time and was less corrosive. Daniell's battery produced around 1.1 volts and was used for many years in telegraphs, telephones, etc.

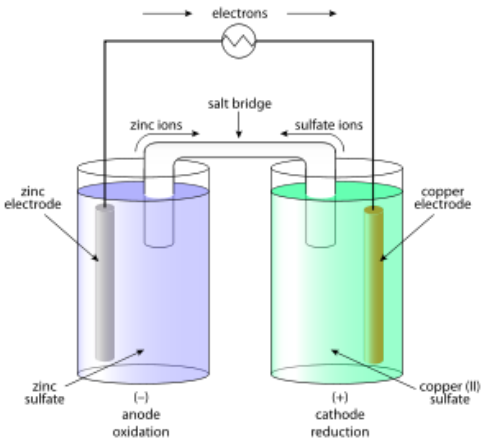

Fig. 4. The principle of Daniell cell. Source: [26].

The first fuel cell, named as "gas voltaic battery" was discovered by Welsch scientist Sir William Robert Grove in 1839. This cell produced electricity from the chemical reaction of oxygen and hydrogen.

All previously invented batteries were primary cells. However, in 1859 a French physicist Gaston Planté invented a lead-acid battery, the first rechargeable battery. The cell could be recharged applying reverse current. The construction was following: two lead sheets (lead anode and a lead dioxide cathode) separated by rubber strips were rolled into a spiral and immersed in the sulfuric acid solution.

Batteries with a liquid electrolyte were impractical for mobile usage, as the electrolyte could leak out. Therefore, a French electrical engineer Georges Leclanché came with an invention of "dry cell". The mobility was achieved by changing the electrolyte from liquid to paste consistency. This early dry cell was used for telephones. However, it was suitable only for short calls as the internal resistance of the battery increased during long discharging, which caused a voltage drop. Leclanché's dry cell later upgraded a German scientist Carl Gassner. He changed the electrolyte to ammonium chloride paste combined with a small amount of

zinc chloride. It fixed the Leclanché's cell's voltage drop issue. His invention commercially succeeded, and the later versions of this cell are used until today.

The next big step to modern batteries made in 1899 a Swedish engineer Ernst Waldemar Jungner with his invention of an alkaline battery. The cell consisted of nickel cathode and cadmium anode. American inventor Thomas Alva Edison took his idea, changed cadmium for iron and patented his NiFe cell. He wanted to sell it to manufacturers of early electromobiles. Because of the high cost, short life and current leak, Edison's battery could not compete with lead-acid cells and the time proved the gasoline engine to be more practical. But even without application in automotive industry, the battery became commercially successful as Edison was a great businessman.

The alkaline battery surpassed lead-acid batteries in 1932 when German scientists Shlecht and Ackermann increased electrode area by sintering. Such NiCd battery lasted longer and allowed higher load currents. The first small and really usable alkaline battery developed in 1949 Canadian chemical engineer Lewis Frederick Urry. He worked for Eveready Battery company and wanted to extend the life of zinc-carbon batteries, and he found that it is better to use alkaline as an electrolyte. The cathode was made from manganese dioxide and powdered zinc anode. These alkaline batteries could provide higher current, least much longer than zinc-carbon batteries and were much cheaper than previous versions of alkaline batteries. In 1989 was in Research Center Battelle-Geneva developed NiMH battery. The NiMH battery was improving known nickelhydrogen battery technology developed in 1970. The NIMH battery is similar to NiCd battery but differ in anode material. NiMH batteries have at least two times higher capacity at the same size as NiCd batteries. The energy density of NiMH batteries can compete with Lithium-ion batteries. As they are environmentally friendly, can be charged fast and allow many life cycles, they are used in many applications until today. They powered early mobile phones, toothbrushes, cameras and many other devices. However, NiMH batteries suffered from memory effect; therefore, NiMH batteries are often replaced with lithium-ion cells nowadays.

6. Lithium based batteries

More demanding application of batteries in electronics resulted in usage of lithium as the battery anode. Such cells accomplished high energy density, small memory effect and low self-discharge. Lithium batteries also have some disadvantages as ageing, chemical reactiveness, a need for protection circuits and higher production cost. Lithium as the battery anode was first time used in 1970 by English chemist M. Stanley Whittingham but the origin of this invention dates to 1912 by American physical chemist Gilbert Newton Lewis. Their spread came in 1977 after application and research in Bell Labs where were studied for mobile devices because of their large energy density. It took almost ten years of research until the first safe and industrial applicable battery was made. Previous experiments were trying to use various types of electrodes, but there was a problem with an instability of lithium, runaway of gases causing flames and changes on lithium electrode after charging cycles. The battery from Akira Yoshino was stable, as it used lithium cobalt and lithium ion as electrodes. The lithium cobalt is stable in the air. The lithium-ion battery was commercialised in Japanese company Sony in 1991. Since that model the evolution of lithium-ion batteries continued but all the changes are minor.

The area of batteries is important and can have a big impact on the Czech Republic, as it was estimated to contain about 330 000 tonnes [42] of lithium in the Ore Mountains underground. The Tesla company which is using lithium in their batteries want to make between Prague and Ore Mountains a factory. The benefits would also be cheap land and use of Czech Crown. The Czech Republic is interested in Tesla, but maybe can even be independent and produce own batteries. Tesla batteries are not used just in Tesla electromobiles and other electrical devices, but also as a storage of renewable energy. The solar power is stored in the Tesla batteries to power an island of Ta'u in American Samoa, and it allows to supply almost 100 % [44] of islands power needs from renewable energy.

7. Innovations and battery future

There exist hundred of prototypes and proposals, but they haven't been commercialised yet. Such ideas are often emerging, but only a few of them are successfully used. I chose some of them which are revolutionary.

Previous types of batteries were based on chemical reactions, but a nuclear energy can be used as well. There exist prototypes of nuclear batteries with long lifetime (hundreds of years). However, they have very small current. Such batteries can be used for space probes, autonomous drones, cardiostimulators and other lengthy operation devices.

Other interesting prototypes of the gas cell are based on proton exchange membrane. They use the reaction of hydrogen and oxygen, and the waste is water vapour. They can be used in cars but also in space probes, but the vapour may cause oxidation of the electronic. Therefore it is not usable for laptops, mobiles, etc.

8. Conclusion

In the beginning, the batteries were used by scientists to study and understand electricity. Soon after the discovery of the battery, they became a power for telegraphs, first telephones and other early electrical devices. It led to a need

for more compact batteries with better capacity and stable voltage and current.

Therefore, scientists were working on improving batteries with using various methods of chemical and physical processes. First batteries were not rechargeable. However, Gaston Planté invented the lead-acid battery which allowed repetitive usage of the battery. The mobility of batteries ensured Georges Leclanché with his invention of the "dry cell". The electrolyte had a paste consistency and was suitable for mobile devices. In the 19th century came alkaline batteries composed of nickel and cadmium or iron electrodes. Nickel showed to be a useful element and was used in batteries of the 20th century, such as NiCd and NiMH cells. The NiMH batteries were used in first mobile phones and almost every mobile device and are still used until today. At the end of the 20th century came a boom with lithium-ion batteries, that surpassed other cells in various parameters.

Today are mainly used lithium-ion batteries due to their power-to-weight ratio. It took many years until these batteries were safe for commercial use. The instability of lithium caused explosions, so modern construction and protection circuits are needed.

Future research should aim in an area, where was not possible to use batteries due to specific conditions, such as long liveness, extra low weight and small size. New technology for storing and regaining the energy can open innovative possibilities for batteries, for example in space probes, cardiostimulators or drones.

Acknowledgements

I acknowledge the aid of educational licence of Grammarly. I also acknowledge Karel Kubíček for helpful comments and English corrections.

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