

Battery (electricity)

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An electrical **battery** is a combination of one or more electrochemical cells, used to convert stored chemical energy into electrical energy. Since the invention of the first Voltaic pile in 1800 by Alessandro Volta, the battery has become a common power source for many household and industrial applications, and is now a multi-billion dollar industry.

Batteries may be used once and discarded, or recharged for years as in standby power applications. Miniature cells are used to power devices such as wristwatches and portable electronic devices; larger batteries provide standby power for telephone exchanges or computer data centers.

History

Main article: History of the battery

The name "battery" was coined by Benjamin Franklin for an arrangement of multiple Leyden jars (an early type of capacitor) after a battery of cannon.^[1] Strictly, a battery is a collection of two or more cells, but in popular usage *battery* often refers to a single electrical cell.^[2]

An early form of electrochemical battery called the Baghdad Battery may have been used in antiquity.^[3] However, the modern development of batteries started with the Voltaic pile, invented by the Italian physicist Alessandro Volta in 1800.^[4]

In 1780 the Italian anatomist and physiologist Luigi Galvani noticed that dissected frog's legs would twitch when struck by a spark from a Leyden jar, an external source of electricity.^[5] In 1786 he noticed that twitching would occur during lightning storms.^[6] After many years Galvani learned how to produce twitching without using any external source of electricity. In 1791 he published a report on "animal electricity."^[7] He created an electric circuit consisting of the frog's leg (FL) and two different metals A and B, each metal touching the frog's leg and each other, thus producing the circuit A-FL-B-A-FL-B...etc. In modern terms, the frog's leg served as both the electrolyte and the sensor, and the metals served as electrodes. He noticed that even though the frog was dead, its legs would twitch when he touched them with the metals.

Within a year, Volta realized the frog's moist tissues could be replaced by cardboard soaked in salt water, and the frog's muscular response could be replaced by another form of electrical detection. He already had studied the electrostatic phenomenon of capacitance, which required measurements of electric charge and of electrical potential ("tension"). Building on this experience, Volta was able to detect electric current through his system, also called a Galvanic cell. The terminal voltage of a cell that is not discharging is called its electromotive force (emf), and has the same unit as electrical potential, named (voltage) and measured in volts, in honor of Volta. In 1800, Volta invented the battery by placing many voltaic cells in series, literally piling them one above the other. This Voltaic pile gave a greatly enhanced net emf for the combination,^[8] with a voltage of about 50 volts for a 32-cell pile.^[9] In many parts of Europe batteries continue to be called piles.^{[10][11]}

Volta did not appreciate that the voltage was due to chemical reactions. He thought that his cells were an inexhaustible source of energy,^[12] and that the associated chemical effects (e.g. corrosion) were a mere nuisance, rather than an unavoidable consequence of their operation, as Michael Faraday showed in 1834.^[13] According to Faraday, cations (positively charged ions) are attracted to the cathode,^[14] and anions (negatively charged ions) are attracted to the anode.^[15]

Although early batteries were of great value for experimental purposes, in practice their voltages fluctuated and they could not provide a large current for a sustained period. Later, starting with the Daniell cell in 1836, batteries provided more reliable currents and were adopted by industry for use in stationary devices, particularly in telegraph networks where they were the only practical source of electricity, since electrical distribution networks did not then exist.^[16] These wet cells used liquid electrolytes, which were prone to leakage and spillage if not handled correctly. Many used glass jars to hold their components, which made them fragile. These characteristics made wet cells unsuitable for portable appliances. Near the end of the nineteenth century, the invention of dry



Various batteries (top-left to bottom-right): two AA, one D, one handheld ham radio battery, two 9-volt PP3, two AAA, one C, one camcorder battery, one cordless phone battery.

cell batteries, which replaced the liquid electrolyte with a paste, made portable electrical devices practical.^[17]

Since then, batteries have gained popularity as they became portable and useful for a variety of purposes.^[18]

Battery industry

According to a 2005 estimate, the worldwide battery industry generates US\$48 billion in sales each year,^[19] with 6% annual growth.^[20]

How batteries work

Main article: Electrochemical cell

A battery is a device that converts chemical energy directly to electrical energy.^[21] It consists of a number of voltaic cells; each voltaic cell consists of two half cells connected in series by a conductive electrolyte containing anions and cations. One half-cell includes electrolyte and the electrode to which anions (negatively-charged ions) migrate, i.e. the anode or negative electrode; the other half-cell includes electrolyte and the electrode to which cations (positively-charged ions) migrate, i.e. the cathode or positive electrode. In the redox reaction that powers the battery, reduction (addition of electrons) occurs to cations at the cathode, while oxidation (removal of electrons) occurs to anions at the anode.^[22] The electrodes do not touch each other but are electrically connected by the electrolyte, which can be either solid or liquid.^[23] Many cells use two half-cells with different electrolytes. In that case each half-cell is enclosed in a container, and a separator that is porous to ions but not the bulk of the electrolytes prevents mixing.

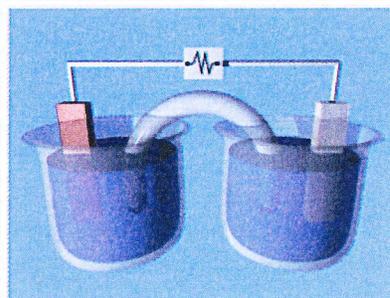
Each half cell has an electromotive force (or emf), determined by its ability to drive electric current from the interior to the exterior of the cell. The net emf of the cell is the difference between the emfs of its half-cells, as first recognized by Volta.^[9] Therefore, if the electrodes have emfs \mathcal{E}_1 and \mathcal{E}_2 , then the net emf is $\mathcal{E}_2 - \mathcal{E}_1$; in other words, the net emf is the difference between the reduction potentials of the half-reactions.^[24]

The electrical driving force or ΔV_{bat} across the terminals of a cell is known as the *terminal voltage (difference)* and is measured in volts.^[25] The terminal voltage of a cell that is neither charging nor discharging is called the open-circuit voltage and equals the emf of the cell. Because of internal resistance^[26], the terminal voltage of a cell that is discharging is smaller in magnitude than the open-circuit voltage and the terminal voltage of a cell that is charging exceeds the open-circuit voltage.^[27] An ideal cell has negligible internal resistance, so it would maintain a constant terminal voltage of \mathcal{E} until exhausted, then dropping to zero. If such a cell maintained 1.5 volts and stored a charge of one Coulomb then on complete discharge it would perform 1.5 Joule of work.^[25] In actual cells, the internal resistance increases under discharge,^[26] and the open circuit voltage also decreases under discharge. If the voltage and resistance are plotted against time, the resulting graphs typically are a curve; the shape of the curve varies according to the chemistry and internal arrangement employed.^[28]

As stated above, the voltage developed across a cell's terminals depends on the energy release of the chemical reactions of its electrodes and electrolyte. Alkaline and carbon-zinc cells have different chemistries but approximately the same emf of 1.5 volts; likewise NiCd and NiMH cells have different chemistries, but approximately the same emf of 1.2 volts.^[29] On the other hand the high electrochemical potential changes in the reactions of lithium compounds give lithium cells emfs of 3 volts or more.^[30]

Categories and types of batteries

Main article: List of battery types



A voltaic cell for demonstration purposes. In this example the two half-cells are linked by a salt bridge separator that permits the transfer of ions, but not water molecules.

Lead-acid battery

From Wikipedia, the free encyclopedia

Lead-acid batteries, invented in 1859 by French physicist Gaston Planté, are the oldest type of rechargeable battery. Despite having the second lowest energy-to-weight ratio (next to the nickel-iron battery) and a correspondingly low energy-to-volume ratio, their ability to supply high surge currents means that the cells maintain a relatively large power-to-weight ratio. These features, along with their low cost, make them attractive for use in motor vehicles to provide the high current required by automobile starter motors.

Electrochemistry

In the charged state, each cell contains electrodes of elemental lead (Pb) and lead (IV) dioxide (PbO₂) in an electrolyte of approximately 33.5% v/v (6 Molar) sulfuric acid (H₂SO₄).

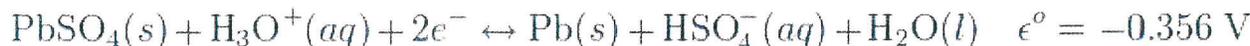
In the discharged state both electrodes turn into lead(II) sulfate (PbSO₄) and the electrolyte loses its dissolved sulfuric acid and becomes primarily water. Due to the freezing-point depression of water, as the battery discharges and the concentration of sulfuric acid decreases, the electrolyte is more likely to freeze during winter weather.

The chemical reactions are (discharged to charged):

Cathode (reduction):



Anode (oxidation):



Lead-acid battery

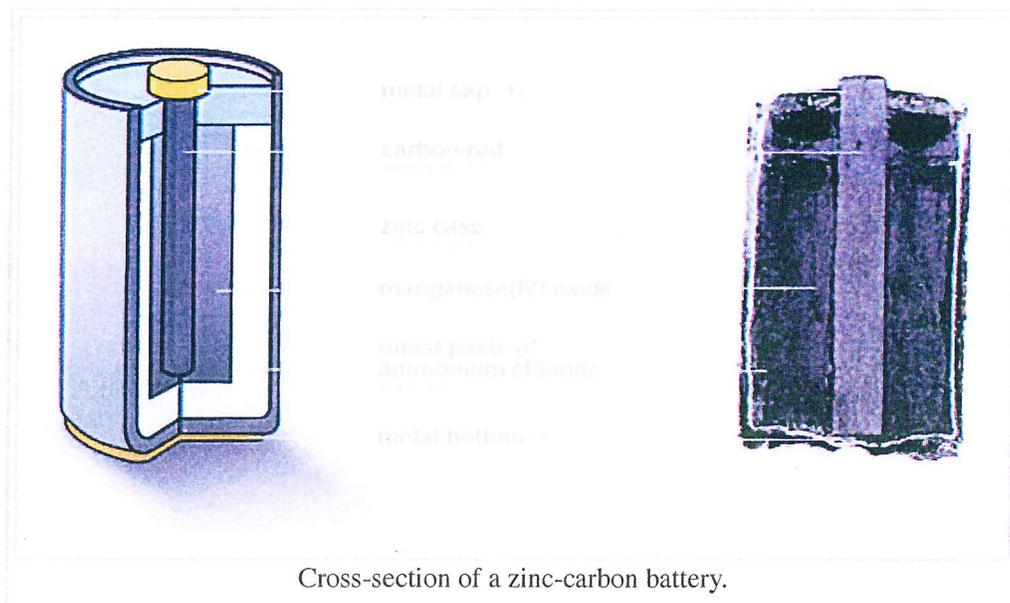


lead acid car battery

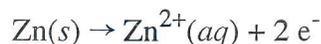
Energy/weight	30-40 Wh/kg
Energy/size	60-75 Wh/L
Power/weight	180 W/kg
Charge/discharge efficiency	50%-92% [1] (http://photovoltaics.sandia.gov/docs/PDF/batpapsteve.pdf)
Energy/consumer-price	7(sld)-18(fld) Wh/US\$ [2] (http://www.geocities.com/CapeCanaveral/Lab/8679/battery.html)
Self-discharge rate	3%-20%/month [3] (http://www.madkatz.com/ev/batteryTechnologyComparison.html)
Cycle durability	500-800 cycles
Nominal Cell Voltage	2.105 V

2.0V

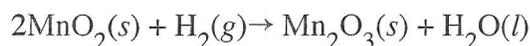
Dry Cell



In a dry cell, the outer zinc container is the negative terminal. The zinc is oxidised according to the following half-equation.



A graphite rod surrounded by a powder containing manganese(IV) oxide is the positive terminal. The manganese dioxide is mixed with carbon powder to increase the conductivity. The reaction is as follows:



The H_2 comes from the $\text{NH}_4^+(aq)$

Alkaline batteries and alkaline cells (a battery being a collection of multiple cells) are a type of disposable battery or rechargeable battery dependent upon the reaction between zinc and manganese (IV) oxide (Zn/MnO_2).

Compared with zinc-carbon batteries of the Leclanché or zinc chloride types, while all produce approximately 1.5 volts per cell, alkaline batteries have a higher energy density and longer shelf-life.



Batteries are classified into two broad categories, each type with advantages and disadvantages.^[31]

- *Primary* batteries irreversibly (within limits of practicality) transform chemical energy to electrical energy. When the initial supply of reactants is exhausted, energy cannot be readily restored to the battery by electrical means.^[32]
- *Secondary* batteries can be recharged; that is, they can have their chemical reactions reversed by supplying electrical energy to the cell, restoring their original composition.^[33]

Historically, some types of primary batteries used, for example, for telegraph circuits, were restored to operation by replacing the components of the battery consumed by the chemical reaction.^[34] Secondary batteries are not indefinitely rechargeable due to dissipation of the active materials, loss of electrolyte and internal corrosion.

Primary batteries

Primary batteries can produce current immediately on assembly. Disposable batteries are intended to be used once and discarded. These are most commonly used in portable devices that have low current drain, are only used intermittently, or are used well away from an alternative power source, such as in alarm and communication circuits where other electric power is only intermittently available. Disposable primary cells cannot be reliably recharged, since the chemical reactions are not easily reversible and active materials may not return to their original forms. Battery manufacturers recommend against attempting to recharge primary cells.^[35]

Common types of disposable batteries include zinc-carbon batteries and alkaline batteries. Generally, these have higher energy densities than rechargeable batteries,^[36] but disposable batteries do not fare well under high-drain applications with loads under 75 ohms (75 Ω).^[31]

Secondary batteries

Main article: Rechargeable battery

Secondary batteries must be charged before use; they are usually assembled with active materials in the discharged state. Rechargeable batteries or *secondary cells* can be recharged by applying electrical current, which reverses the chemical reactions that occur during its use. Devices to supply the appropriate current are called chargers or rechargers.

The oldest form of rechargeable battery is the lead-acid battery.^[37] This battery is notable in that it contains a liquid in an unsealed container, requiring that the battery be kept upright and the area be well ventilated to ensure safe dispersal of the hydrogen gas produced by these batteries during overcharging. The lead-acid battery is also very heavy for the amount of electrical energy it can supply. Despite this, its low manufacturing cost and its high surge current levels make its use common where a large capacity (over approximately 10Ah) is required or where the weight and ease of handling are not concerns.

A common form of the lead-acid battery is the modern car battery, which can generally deliver a peak current of 450 amperes.^[38] An improved type of liquid electrolyte battery is the sealed valve regulated lead acid (VRLA) battery, popular in the automotive industry as a replacement for the lead-acid wet cell. The VRLA battery uses an immobilized sulfuric acid electrolyte, reducing the chance of leakage and extending shelf life.^[39] VRLA batteries have the electrolyte immobilized, usually by one of two means:

- *Gel batteries* (or "gel cell") contain a semi-solid electrolyte to prevent spillage.
- *Absorbed Glass Mat* (AGM) batteries absorb the electrolyte in a special fiberglass matting

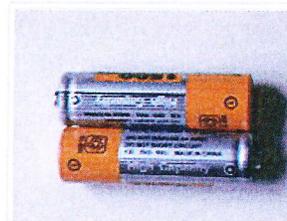
Other portable rechargeable batteries include several "dry cell" types, which are sealed units and are therefore useful in appliances such as mobile phones and laptop computers. Cells of this type (in order of increasing power density and cost) include nickel-cadmium (NiCd), nickel metal hydride (NiMH) and lithium-ion (Li-ion) cells.^[40] By far, Li-ion has the highest share of the dry cell rechargeable market.^[20] Meanwhile, NiMH has replaced NiCd in most applications due to its higher capacity, but NiCd remains in use in power tools, two-way radios, and medical equipment.^[20]

Recent developments include batteries with embedded functionality such as USBCELL, with a built-in charger and USB connector



From top to bottom: SR41/AG3, SR44/AG13 (button cells), a 9-volt PP3 battery, an AAA cell, an AA cell, a C cell, a D Cell, and a large 3R12. (Ruler in centimeters.)

Rechargeable batteries traditionally self-discharge more rapidly than disposable alkaline batteries, especially nickel-based batteries; a freshly charged NiCd loses 10% of its charge in the first 24 hours, and thereafter discharges at a rate of about 10% a month.^[57] However, modern lithium designs have reduced the self-discharge rate to a relatively low level (but still poorer than for primary batteries).^[57] Most nickel-based batteries are partially discharged when purchased, and must be charged before first use.^[58]



Rechargeable batteries

Although rechargeable batteries may be refreshed by charging, they still suffer degradation through usage. Low-capacity nickel metal hydride (NiMH) batteries (1700-2000 mA·h) can be charged for about 1000 cycles, whereas high capacity NiMH batteries (above 2500 mA·h) can be charged for about 500 cycles.^[59] Nickel cadmium (NiCd) batteries tend to be rated for 1,000 cycles before their internal resistance increases beyond usable values. Normally a fast charge, rather than a slow overnight charge, will result in a shorter battery lifespan.^[59] However, if the overnight charger is not "smart" and cannot detect when the battery is fully charged, then overcharging is likely, which will damage the battery.^[60] Degradation usually occurs because electrolyte migrates away from the electrodes or because active material falls off the electrodes. NiCd batteries suffer the drawback that they should be fully discharged before recharge. Without full discharge, crystals may build up on the electrodes, thus decreasing the active surface area and increasing internal resistance. This decreases battery capacity and causes the "memory effect". These electrode crystals can also penetrate the electrolyte separator, thereby causing shorts. NiMH, although similar in chemistry, does not suffer from memory effect to quite this extent.^[61] When a battery reaches the end of its lifetime, it will not suddenly lose all of its capacity; rather, its capacity will gradually decrease.^[62]

Automotive lead-acid rechargeable batteries have a much harder life.^[63] Because of vibration, shock, heat, cold, and sulfation of their lead plates, few automotive batteries last beyond six years of regular use.^[64] Automotive starting batteries have many thin plates to provide as much current as possible in a reasonably small package. In general, the thicker the plates, the longer the life of the battery.^[63] Typically they are only drained a small amount before recharge. Care should be taken to avoid deep discharging a starting battery, since each charge and discharge cycle causes active material to be shed from the plates.

"Deep-cycle" lead-acid batteries such as those used in electric golf carts have much thicker plates to aid their longevity.^[65] The main benefit of the lead-acid battery is its low cost; the main drawbacks are its large size and weight for a given capacity and voltage.^[63] Lead-acid batteries should never be discharged to below 20% of their full capacity,^[66] because internal resistance will cause heat and damage when they are recharged. Deep-cycle lead-acid systems often use a low-charge warning light or a low-charge power cut-off switch to prevent the type of damage that will shorten the battery's life.^[67]

Extending battery life

Battery life can be extended by storing the batteries at a low temperature, as in a refrigerator or freezer, because the chemical reactions in the batteries are slower. Such storage can extend the life of alkaline batteries by ~5%; while the charge of rechargeable batteries can be extended from a few days up to several months.^[68] In order to reach their maximum voltage, batteries must be returned to room temperature; discharging an alkaline battery at 250 mAh at 0°C is only half as efficient as it is at 20°C.^[36] As a result, alkaline battery manufacturers like Duracell do not recommend refrigerating or freezing batteries.^[35]

Prolonging life in multiple cells through cell balancing

Analog front ends that balance cells and eliminate mismatches of cells in series or parallel combination significantly improve battery efficiency and increase the overall pack capacity. As the number of cells and load currents increase, the potential for mismatch also increases. There are two kinds of mismatch in the pack: State-of-Charge (SOC) and capacity/energy (C/E) mismatch. Though the SOC mismatch is more common, each problem limits the pack capacity (mAh) to the capacity of the weakest cell.

Cell balancing principle

Battery pack cells are balanced when all the cells in the battery pack meet two conditions:

1. If all cells have the same capacity, then they are balanced when they have the same State of Charge (SOC.) In this case, the Open Circuit Voltage (OCV) is a good measure of the SOC. If, in an out of balance pack, all cells can be differentially charged to full capacity (balanced), then they will subsequently cycle normally without any additional adjustments. This is mostly a one shot fix.

A battery's characteristics may vary over load cycle, charge cycle and over life time due to many factors including internal chemistry, current drain and temperature.

Battery capacity and discharging



A device to check battery voltage.

The more electrolyte and electrode material there is in the cell, the greater the capacity of the cell. Thus a small cell has less capacity than a larger cell, given the same chemistry (e.g. alkaline cells), though they develop the same open-circuit voltage.^[46]

Because of the chemical reactions within the cells, the capacity of a battery depends on the discharge conditions such as the magnitude of the current (which may vary with time), the allowable terminal voltage of the battery, temperature and other factors.^[46] The available capacity of a battery depends upon the rate at which it is discharged.^[47] If a battery is discharged at a relatively high rate, the available capacity will be lower than expected.

The battery capacity that battery manufacturers print on a battery is usually the product of 20 hours multiplied by the maximum constant current that a new battery can supply for 20 hours at 68 F° (20 C°), down to a predetermined terminal voltage per cell. A battery rated at 100 A·h will deliver 5 A over a 20 hour period at room temperature. However, if it is instead discharged at 50 A, it will have a lower apparent capacity.^[48]

The relationship between current, discharge time, and capacity for a lead acid battery is approximated (over a certain range of current values) by Peukert's law:

$$t = \frac{Q_P}{I^k}$$

where

Q_P is the capacity when discharged at a rate of 1 amp.

I is the current drawn from battery (A).

t is the amount of time (in hours) that a battery can sustain.

k is a constant around 1.3.

For low values of I internal self-discharge must be included.

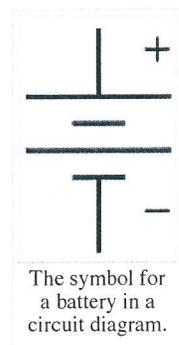
In practical batteries, internal energy losses, and limited rate of diffusion of ions through the electrolyte, cause the efficiency of a battery to vary at different discharge rates. When discharging at low rate, the battery's energy is delivered more efficiently than at higher discharge rates,^[48] but if the rate is too low, it will self-discharge during the long time of operation, again lowering its efficiency.

Installing batteries with different A·h ratings will not affect the operation of a device rated for a specific voltage unless the load limits of the battery are exceeded. High-drain loads like digital cameras can result in lower actual energy, most notably for alkaline batteries.^[31] For example, a battery rated at 2000 mA·h would not sustain a current of 1 A for the full two hours, if it had been rated at a 10-hour or 20-hour discharge.

Fastest charging, largest, and lightest batteries

Lithium iron phosphate (LiFePO₄) batteries are the fastest charging and discharging, next to supercapacitors.^[49] The world's largest battery is in Fairbanks, Alaska, composed of Ni-Cd cells.^[50] Sodium-sulfur batteries are being used to store wind power.^[51] Lithium-sulfur batteries have been used on the longest and highest solar powered flight.^[52] The speed of recharging for lithium-ion batteries may be increased by manipulation.^[53]

Battery lifetime



Life of primary batteries

Even if never taken out of the original package, disposable (or "primary") batteries can lose 8 to 20 percent of their original charge every year at a temperature of about 20°–30°C.^[54] This is known as the "self discharge" rate and is due to non-current-producing "side" chemical reactions, which occur within the cell even if no load is applied to it. The rate of the side reactions is reduced if the batteries are stored at low temperature, although some batteries can be damaged by freezing. High or low temperatures may reduce battery performance. This will affect the initial voltage of the battery. For an AA alkaline battery this initial voltage is approximately normally distributed around 1.6 volts.

Typical alkaline battery sizes and capacities^[55] (at lowest discharge rates, to 0.8V/cell)

Diagram 	Size 	ANSI/NEDA 	IEC 	Capacity (mA·h) 	Voltage 	Energy, theoretical (J) 	Mass (g) 	Height (mm) 	Diameter (mm) 	Length (mm) 	Width (mm) 
	AAAA	25A	LR8D425	625	1.5	3375	6.5	42.5	8.3	cylinder	---
	J	1412A	4LR61	625	6	13500	30	48.5	prismatic	35.6	9.18
	9V	1604A	6LR61	625	9	20250	45.6	48.5	prismatic	26.5	17.5
	N	910A	LR1	1000	1.5	5400	9	30.2	12	cylinder	---
	AAA	24A	LR03	1250	1.5	6750	11.5	44.5	10.5	cylinder	---
	AA	15A	LR6	2890	1.5	15390	23	50.5	14.5	cylinder	---
	C	14A	LR14	8350	1.5	45090	66.2	50	26.2	cylinder	---
	D	13A	LR20	20500	1.5	110700	148	61.5	34.2	cylinder	---
	Lantern	915A	4R25Y	26000	6	561600	885	112	prismatic	68.2	68.2
	Lantern	908A	4LR25X	26000	6	561600	885	115	prismatic	68.2	68.2
	Lantern	918A	4LR25-2	52000	6	1123200	1900	127	prismatic	136.5	73

Discharging performance of all batteries drops at low temperature.^[56]

Life of rechargeable batteries