

Batteries for Mobile Robots

1. Chemical Energy

Mobile robots move – therefore we need to consider the important question of where the energy required for locomotion is going to come from. In the case of large robots we would like to be able to drain energy at high peak rates. For smaller robots, we would like to have enough energy for several hours of continuous work. Internal combustion engines are out of the question, since the robots we are considering will be used indoors. Fuel cells, which combine hydrogen and oxygen, and do not produce toxic gases, will be an interesting source of energy in the future, but the technology has not yet matured for the kind of applications we consider here. Therefore we need to use some form of electrical energy stored in rechargeable batteries.

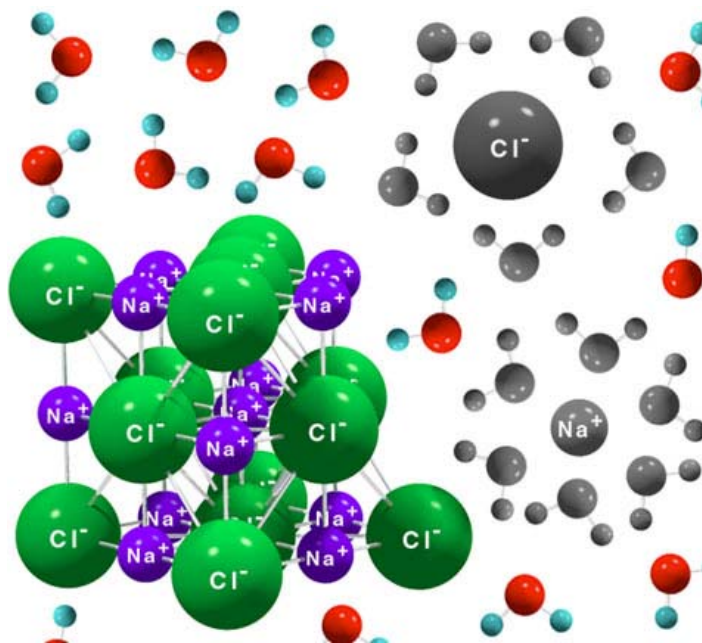
The electrical battery was invented several centuries ago. Rechargeable batteries have been around for many decades and are improved continually, from year to year. A battery consists of a negative and a positive electrode. Each electrode is made of a different material and there is a chemical reaction in the interior of the battery, a different one for each electrode but complementary. A modern battery can be understood, as a first approximation, as a kind of sandwich in which the top and bottom materials are the electrodes, and the material in the middle is the electrolyte. The electrolyte makes possible the chemical reactions inside the battery and transports ions from one electrode to the other. The electrolyte is also a reservoir of ions for the chemical reactions needed at the electrodes.

Summarizing: a battery transforms the chemical energy stored in the battery's material in electricity. Batteries which cannot be recharged are called primary batteries; rechargeable ones are called secondary batteries. We are interested here in rechargeable batteries, since primary batteries are too expensive in the long run.

2. Electrolytes

There are many spontaneous chemical phenomena triggered by the contact of one substance with another. Many salts, for example, readily dissolve in water and form ions. Table salt consists of sodium (Na) and chloride (Cl). When put into water, the sodium atoms separate from the chloride atoms. Water molecules are tightly bound whereas NaCl has weak ionic bonds – one electron is more tightly bound to the chloride than to the sodium. Also, water is a polar liquid, that means, water molecules have a positive and a negative side because the electrons charge is not distributed uniformly in the molecule. Water molecules “stick” to each other because of their polarity.

When NaCl dissolves in water, water molecules surround the sodium ion (Na^+) neutralizing its charge with their negative tails. The chloride ion (Cl^-) is neutralized by water atoms surrounding it with their positive sides oriented towards the chloride. NaCl is called an electrolyte because it dissociates in ions in water. Figure 1 shows an NaCl ionic crystal dissolving into water. Water molecules are negative on the oxygen side, positive to the side of the two hydrogen atoms.



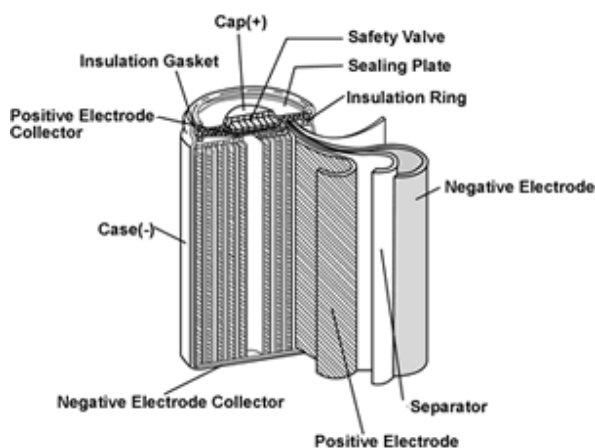
We are interested in electrolytes because they can make water conductive and also because many kinds of batteries depend on ionic reactions. The necessary ions are kept in water, wrapped in water molecules and ready to be used for a certain chemical reactions.

3. Redox reactions

A battery is capable of delivering current, i.e. a continuous electron flow, because the material used to build the negative electrode releases electrons during a chemical reaction whereas the material in the positive electrode absorbs them. The negative electrode is called the anode, the positive one is the cathode. This means that a chemical reaction is releasing electrons at the anode and another chemical reaction is consuming them at the cathode. Different types of batteries differ in the kind of reactions in their interiors and industry is always looking for new technologies that can deliver more stored energy for each gram of battery.

In a battery, the anode and cathode are separated by the electrolyte, whose only mission is to transport ions from one side to the other. The electrolyte can be purely liquid (as in car batteries) or can be put inside a porous material which also acts as electrode separator. The material in the negative electrode has to lose electrons - this is called oxidation. The material in the positive electrode has to absorb electrons - this is called reduction. For a battery we need two chemical reactions, an oxidation and reduction pair, also called a redox reaction pair. The specific example of NiCd batteries can make this clear.

The diagram shows a picture of a cylindrical NiCd battery. The negative and positive electrode are sheets of material set apart by a separator soaked with electrolyte. The three sheets are rolled as a cylinder, one of them is connected to the positive, one to the negative collector. There is safety valve to eliminate excess pressure from the chemical reactions.



In a charged NiCd battery, the cathode contains nickel oxyhydroxide (NiOOH) and the anode contains cadmium. The electrolyte consists of KOH, that is liquid potassium hydroxide. Cadmium atoms at the anode dissolve spontaneously in the electrolyte and transform in positive ions, releasing two electrons at the same time. This chemical reaction is expressed as:

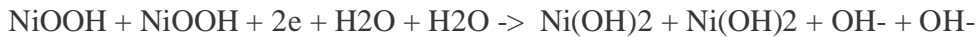


The cadmium ions combine immediately with the OH⁻ ions present in the electrolyte to form Cd(OH)₂:

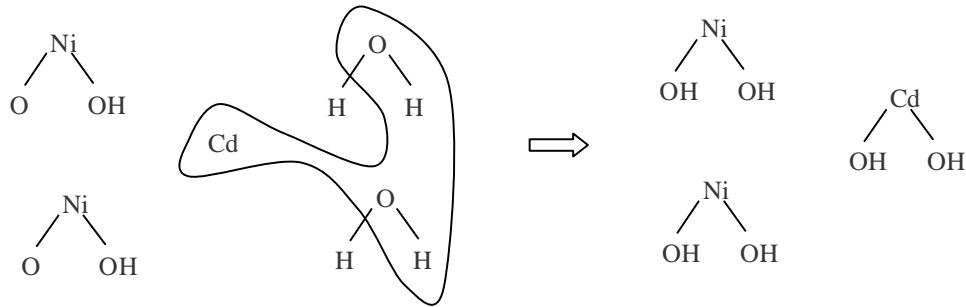


The chemical reaction at the anode can continue because the electrons move out of the anode the moment an electric device is connected to the negative and to the positive electrode. A current is established and electrons flow towards the cathode.

At the cathode there is another spontaneous reaction during battery discharge. Two electrons combine with nickel oxyhydroxide and water to form nickel hydroxide:



The two reactions can be better visualized with the following picture:

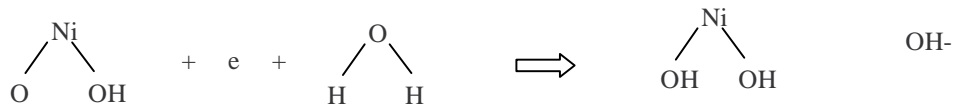


The curved line shows the reaction taking place in the anode. There is a flow of two electrons from the anode to the cathode.

During recharge of the battery the direction of the arrow is inverted: the reactions are reversible and the original structure of the electrodes is restored. The battery charger forces a current in the inverse direction as during discharge and reverses the chemical reactions. Of course this can be done only a fixed number of times, before the battery has deteriorated so badly that it becomes unusable.

The main alternative to NiCd batteries for small mobile robots are NiMH batteries. The positive electrode contains nickel again, while the negative electrode contains some kind of metallic alloy that can absorb hydrogen. Some alloys are very good at that, absorbing many hydrogen atoms in its structure.

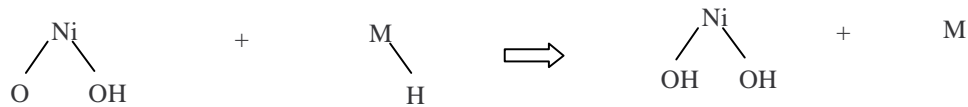
In NiMH batteries the reaction at the positive electrode is exactly the same as in the case of NiCd batteries, as shown in the figure. A water molecule is ionized, a proton and the electron attach to NiOOH to form Ni(OH)₂.



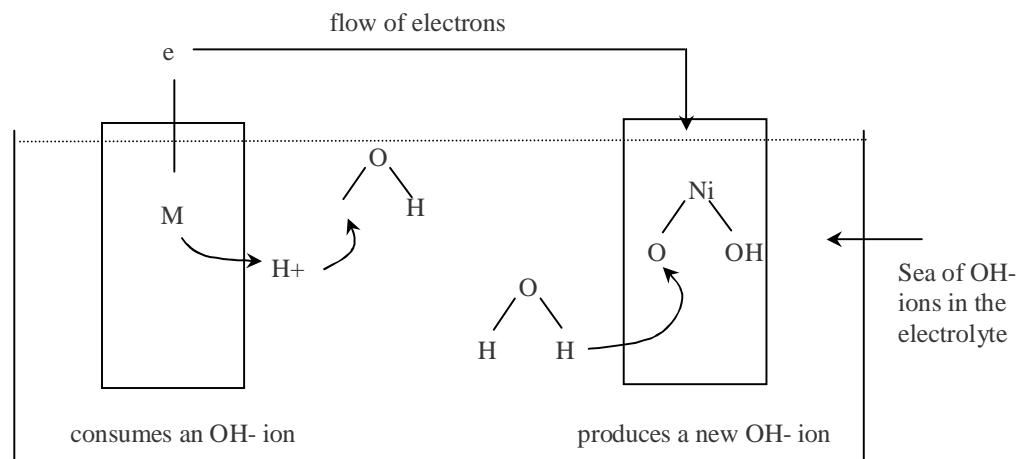
The reaction in the negative electrode takes place when the metal releases the stored hydrogen and combines it with an OH⁻ ion to form water, setting free an electron:



The complete redox pair is similar to NiCd batteries:



The formula of the redox pair obscures the fact that electron transport takes place between the anode and cathode and that the ion OH⁻ is being also produced and absorbed at the electrodes. Since the transport of electrons is very fast and since the transport of ions very slow, a reserve of OH⁻ ions is needed in the electrolyte. This is provided by the dissolved potassium hydroxide, KOH.



4. Issues of battery selection

The batteries used for mobile robots must have a set of desired characteristics that limit the choices available. The main issues are:

- Geometry of the batteries. The shape of the batteries can be an important characteristic according to the form of the robots.
- Durability. We would like to be able to recharge the batteries many times in order to save costs.
- Capacity. The capacity of the battery pack in milliamperes-hour is important. It determines how long the robot will run until a new charge is needed.
- Initial cost. This is an important parameter, but a higher initial cost can be offset by a longer expected life.
- Environmental factors. Used batteries have to be disposed of and some of them contain toxic materials.

As an example: the batteries used in the FU-Fighters 2002 robotic soccer team were packs of 8 NiMH units with a nominal capacity of 2000 mAh. With this batteries the robots could be used for several hours. The size of the batteries allows them to be placed at the bootom of the robot.



5. Comparison of battery types

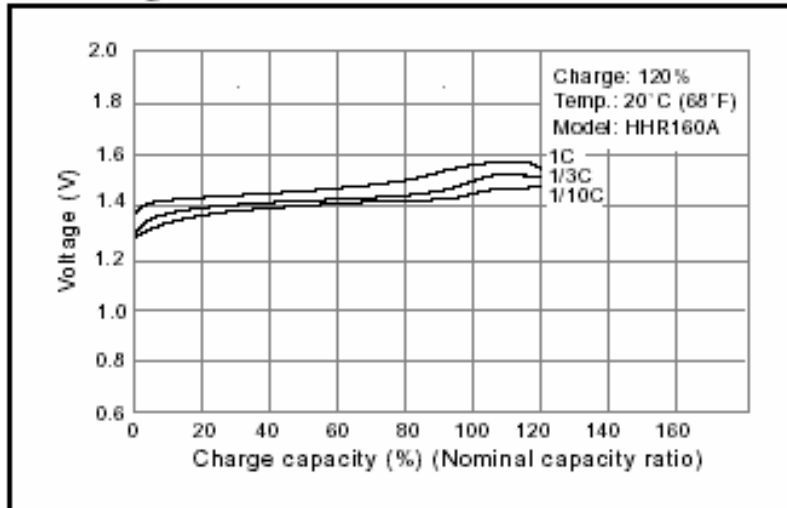
Rechargeable batteries differ in several important respects according to the technology used. In robotics, we are interested in a batteries with high energy density, that is, they should provide much power and be of low weight. NiCD and NiMH are the most popular rechargeable batteries for robots, while Li-ion batteries are used in laptops. The new Li-ion polymer and reusable alkaline batteries have characteristics that could make them interesting in the future.

Charge

We will compare in what follows the NiCd against the NiMH batteries. The first important parameter is how do both batteries charge. Figure x and y show the charging curves for NiMH and NiCd batteries, respectively.

There are three curves in figure x. If the nominal capacity of a battery is 160 mAh, for example, then 160 mA is called a “C”. A C is the current that can be delivered by this specific battery during an hour. Batteries can be charged by circulating through the battery a current of one C, more than one C or a fraction of a C. Usually a fraction of a C is used and this means that several hours are needed until the battery is fully charged. The curve for NiMH batteries (Panasonic HHR 160A) shows that the voltage increases slightly when the cell is gradually charged. These batteries can be overcharged with 20% more energy than its nominal capacity. A charge with one C leads to a slightly higher voltage in the cell as a charge with 1/3 C.

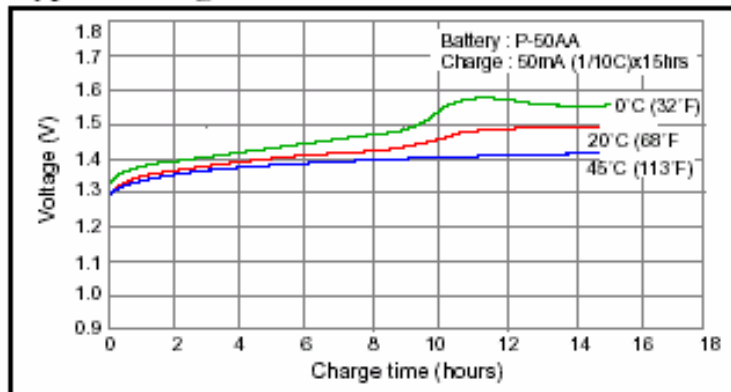
- Charge characteristics



NiMH charging curve with three different currents

The next curve, for NiCd batteries, shows that the voltage reached by the batteries is also affected by the temperature. At 45 degrees Celsius the final voltage is 1.4 volts for each cell, at 0 degrees it is more than 1.5 V.

Typical charge characteristics

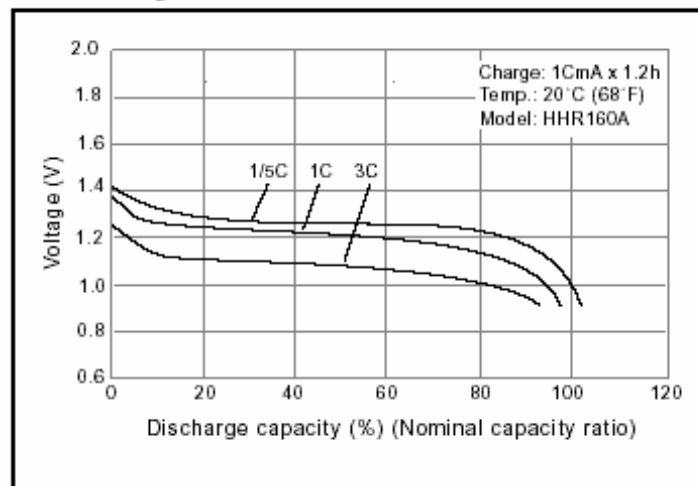


Discharge

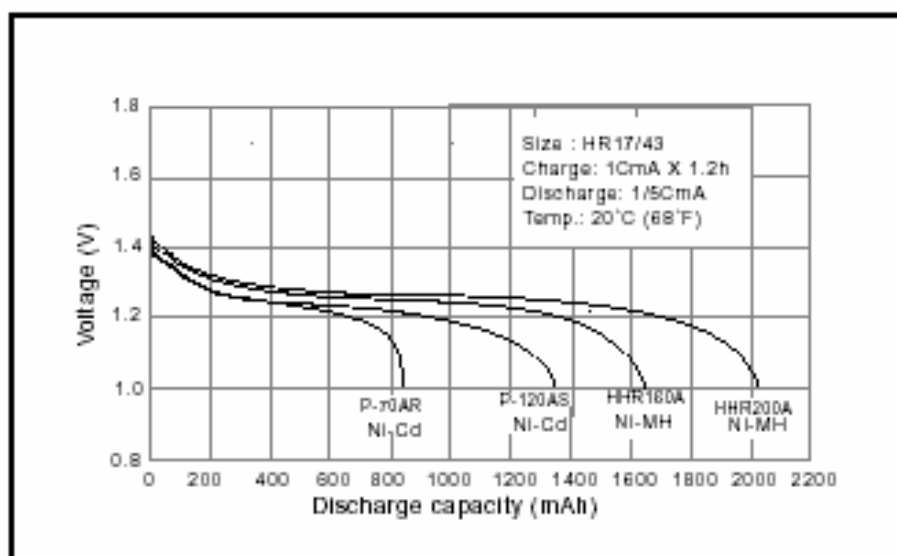
Both NiCd and NiMH batteries have a flat discharge curve. That means that the energy is extracted from the batteries and the voltage only drops significantly when the capacity limit has been reached. This is important for applications, since we would not like voltage to degrade continuously as the battery's energy is consumed. The curve shows that if

energy is extracted at a rate of 3C, then the voltage drops slightly compared to the voltage obtained when the battery is delivering one C. The curve shows that there is no precise way of determining from voltage alone the state of the battery. The battery could be 20% discharged or 80% discharged and it would still deliver almost the same voltage and the same current.

- Discharge characteristics



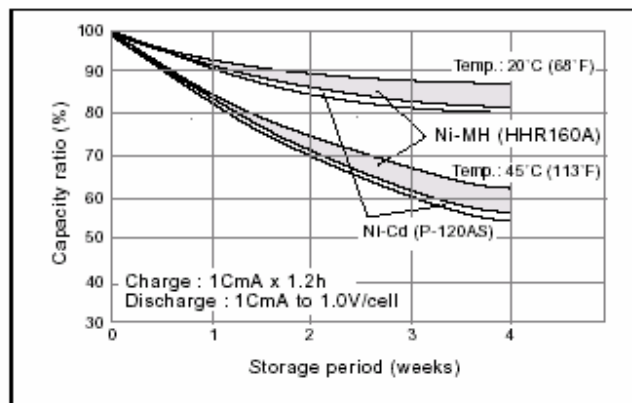
The next figure compares NiCd with NiMH batteries. The NiCd batteries are rated at 700 and 1200 mAh. The NiMH batteries at 1600 and 2000 mAh. NiMH can store more energy per gram than NiCd batteries. Since Cd is toxic, this higher energy density and greater concenieny has lead to a gradual substitution of NiCd by NiMH batteries.



Retention

Charge retention is another important characteristic. Depending on the battery manufacturer, this parameter can vary greatly. The curve shows that NiC and NiMH batteries have similar retention ratios, which vary according to temperature, but are nevertheless similar. At 20 degrees Celsius the stored charge drops by less than 20% during a month. For other manufacturers, the retention of NiMH batteries is usually worse than for NiCd batteries.

- Self discharge characteristics



Final comparison

The table below compares several different types of batteries. Gravimetric density shows how many watts hour per Kilogram can be extracted from a typical battery for each technology. A 100 Watt light bulb consumes 100 Wh during an hour. While Li-ion has a better energy density, they are difficult to recharge. NiMH has a better energy density than NiCd. However, the internal resistance of NiMH batteries is about 50% higher than for similar NiCd batteries. This means, that when a current flows the heat dissipated in the battery is higher for NiMH than for NiCd batteries. The peak load current for NiCd batteries is 20C. For example, a 600 mAh battery can provide a peak current of 12 Amperes (20 times 0,6 A). The best result is obtained when one C, i.e. 600 mA, is

drained from this battery during continuous use. NiMH batteries can provide a peak current of 5C. This can be an important parameter in the case of autonomous robots, if the motors need to drain several amperes when they start accelerating. If more current is drained, because the robot is stuck and the motors request more and more energy, for example, the batteries get very warm and can be damaged.

The table shows also that NiMH batteries can be recharged, in general, fewer cycles than NiCd batteries.

	NiCd	NiMH	Lead Acid	Li-ion	Li-ion polymer	Reusable Alkaline
Gravimetric Energy Density (Wh/kg)	45-80	60-120	30-50	110-160	100-130	80 (initial)
Internal Resistance (includes peripheral circuits) in mW	100 to 200 ¹ 6V pack	200 to 300 ¹ 6V pack	<100 ¹ 12V pack	150 to 250 ¹ 7.2V pack	200 to 300 ¹ 7.2V pack	200 to 2000 ¹ 6V pack
Cycle Life (to 80% of initial capacity)	1500 ²	300 to 500 ^{2,3}	200 to 300 ²	500 to 1000 ³	300 to 500	50 ³ (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Overcharge Tolerance	moderate	low	high	very low	low	moderate
Cell Voltage (nominal)	1.25V ⁶	1.25V ⁶	2V	3.6V	3.6V	1.5V
Load Current - peak - best result	20C 1C	5C 0.5C or lower	5C ⁷ 0.2C	>2C 1C or lower	>2C 1C or lower	0.5C 0.2C or lower
Operating Temperature (discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C	0 to 65°C
Commercial use since	1950	1990	1970	1991	1999	1992

Figure 1: Characteristics of commonly used rechargeable batteries

6. The Memory Effect

Some kind of rechargeable batteries exhibit the so-called memory effect: i.e. if they are not fully discharged during several cycles, then the amount of power they can deliver diminishes with time. It is as if the battery would “remember” that, for example, only 50% of its capacity has been used many consecutive times and then, when more power is required, it would not deliver more than 50% of the maximum capacity. NiCd batteries can exhibit this effect, NiMH batteries also, but to a much smaller degree.

The memory effect is a chemical transformation of the electrodes. If a battery is not fully discharged several times, then large crystals tend to build up at the electrodes. Large crystals diminish the effectiveness of the chemical reactions in the battery cells. The picture shows an electron photograph of the changes in the electrodes. To the left we can see the corny structure of the electrode in its original state. The porous structure maximizes the surface of the electrode and its contact with the electrolyte. The chemical reactions take place at the normal rate. In the middle we see an electrode in which a large

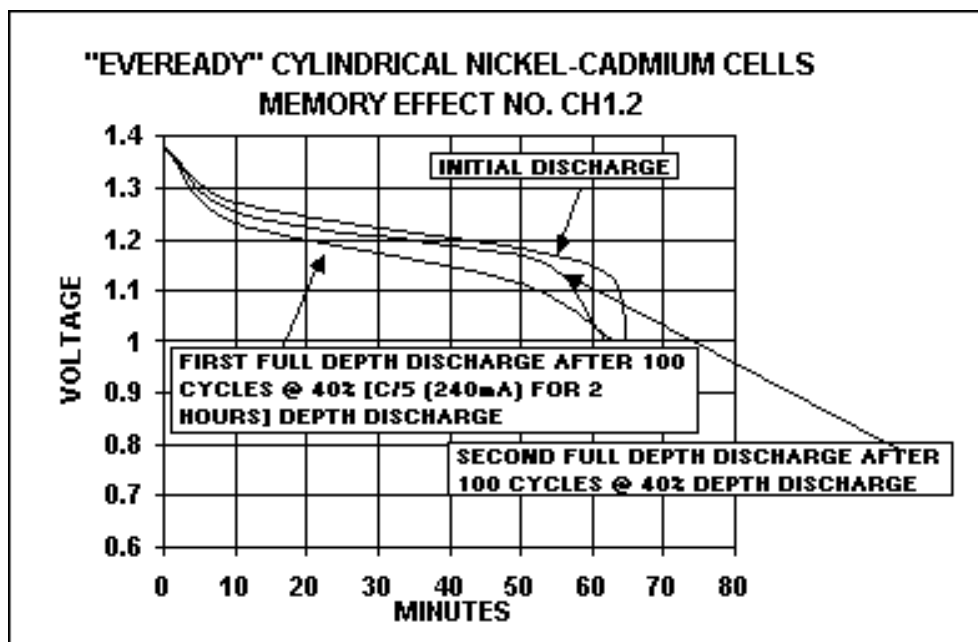
crystal has built up. The effective surface of the electrode has diminished by a large factor and the chemical reactions are impaired. To the right we can see the same electrodes after recovery, which is usually done by subjecting the battery to several cycles of full charge and discharge.



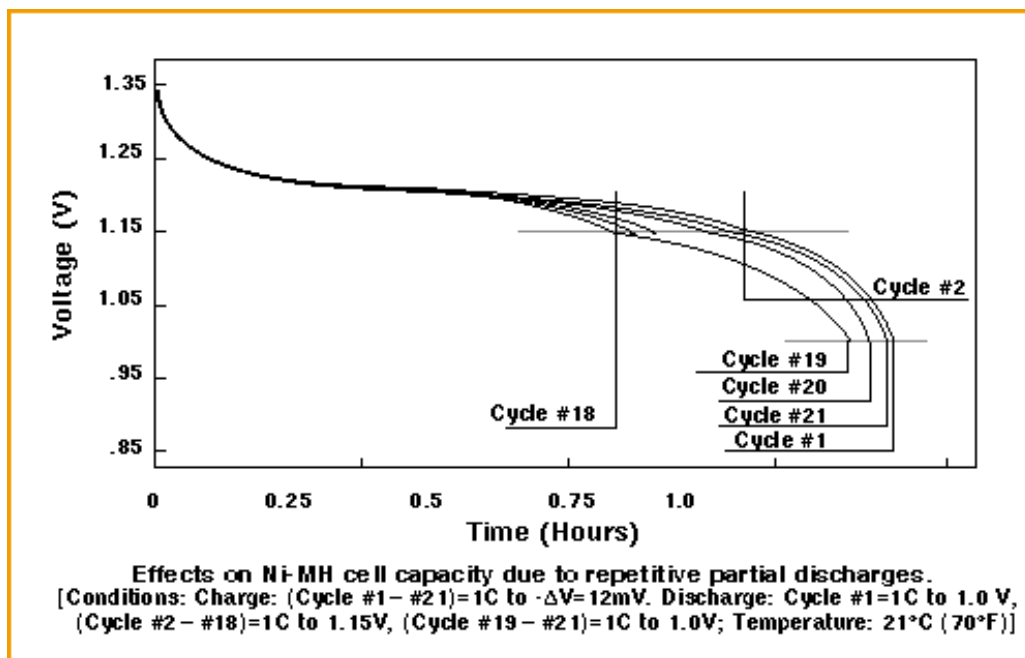
Electron photograph of a NiCd electrode. To the left, original state of the electrode with many cadmium hydroxide crystals. In the center a large crystal has developed and the capacity of the battery has fallen by around 20%. To the right, the state of the reconditioned battery.

The memory effect arises therefore, when not all the active material in the battery is recycled by going through a full charge-discharge cycle regularly. Battery analyzers can help in discharging and charging batteries during several cycles at low currents. The battery need to be fully discharged several times automatically. To avoid the memory effect, it is recommended to fully discharge NiCd batteries at least once a month, and NiMH batteries at least once every three months.

The picture below shows the development of the memory effect for a NiCd battery. The first discharge takes around an hour at the full battery rate (C) before voltage drops below 1.1 V. After 100 cycles of partial discharge, a full discharge leads to a noticeable voltage drop after only 50 minutes. The battery yields now less power as originally. The next full discharge shows that the battery has recovered a little, although it is still not as good as originally.



The next picture shows a small memory effect for NiMH batteries. After 18 cycles of partial discharge (0.75 hours at 1C), the discharge curve has moved down slightly. Several full discharge cycles *19 to 21) bring the curve back near to the original discharge curve (cycle 1).



7. Conclusions

A battery is just a device which transforms chemical energy in an electric current. There are several ways to do this, according to the type of materials used. In general, a redox (reducing-oxidizing) pair of reactions is needed. The negative electrode, the anode, oxidizes and sets electrons free, whereas the cathode reduces and absorbs electrons. The electrons travel from one electrode to another through a motor or a chip or whatever device is connected to the power source.

NiCd batteries have been traditionally used for small robots, since they have been in commercial use since the 1950s. Their advantages are:

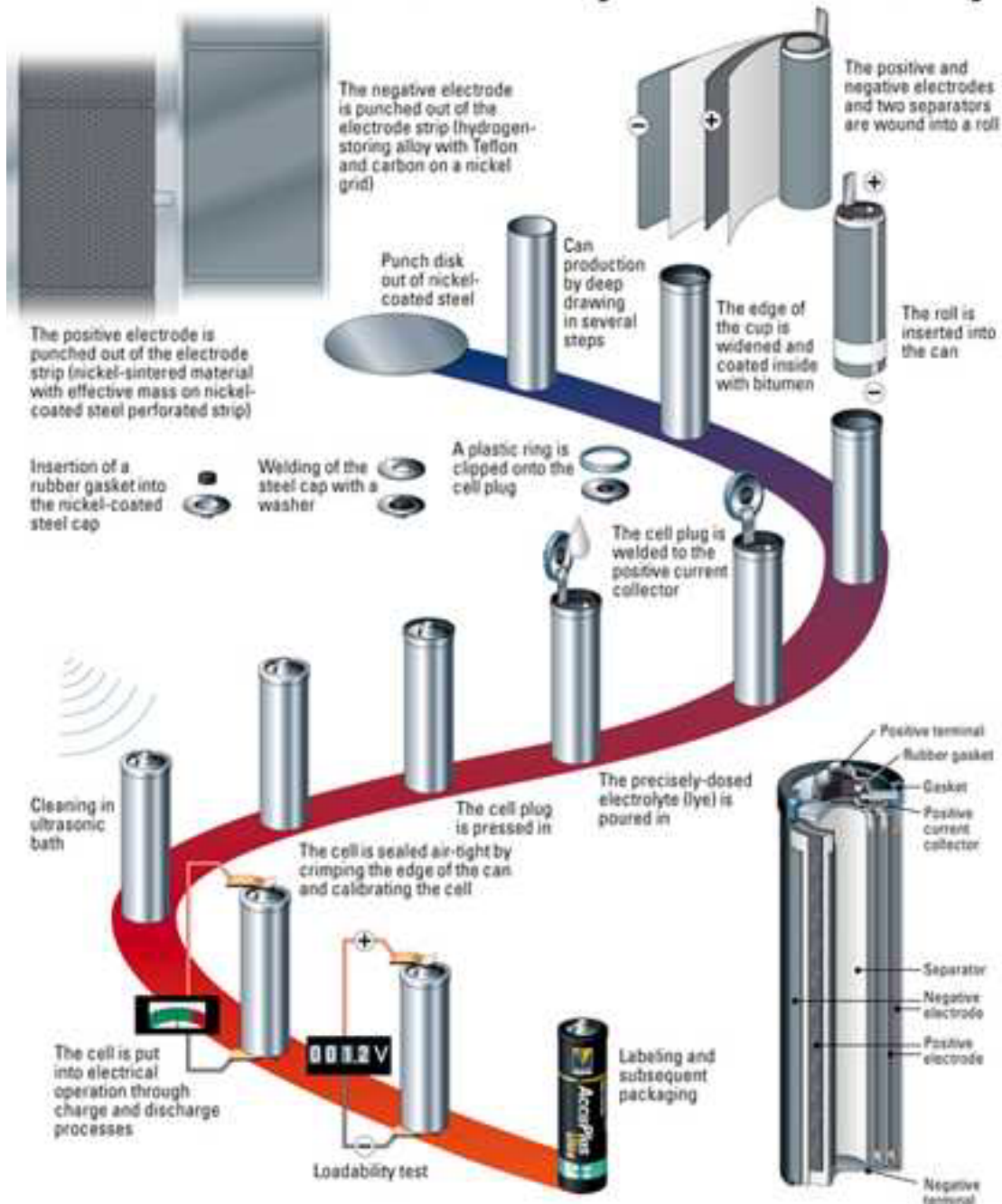
- fast and simple to recharge
- can service high peak loads

- survive many recharge cycles
- economical, rugged and with long shelf-life

Their disadvantages are their lower energy density compared to NiM batteries and their toxicity for the environment.

NiMH batteries are replacing NiCd batteries due to their higher energy density, but have a shorter life (in terms of charge-discharge cycles). They cannot deliver as much energy as NiCd for peak loads, and this can be a disadvantage if a robot occasionally drains much concentrated energy. They are less prone to suffer the memory-effect than NiCd batteries.

Assembly and Construction of a Nickel-Metal-Hydride Battery



Nickel-metal-hydride batteries can be recharged up to 1000 times. Their key features include high capacity and environmental compatibility (0% lead, 0% mercury, 0% cadmium). Nickel-metal-hydride batteries can be used in mobile telephones, cordless telephones, camcorders, notebooks and audio equipment.

VARTA
THE BATTERY EXPERTS