Rechargeable Batteries
Ni-Cd, Ni-MH, Li-Ion, Li-Ion Polymer

The rechargeable battery has been used for many years to power RC receivers and servos.

As battery technology improves, we are moving toward very high capacity devices in the Lithium Ion and Lithium Ion Polymer battery types.

The cost for these modern types of batteries is equal to or exceeding the cost of a 2-stroke or 4-stroke engine. Rechargeable batteries are a sizable monetary investment that should be maintained in a proper manner.

Improper charging procedures will reduce the life of the battery.

Improper charging procedures can lead to physical harm or fire.

A 2-stroke or 4-stroke engine that is not set up properly or is in need of repair will demonstrate very loudly its "problems". A rechargeable battery has no moving parts and does not make any sound, if it is not working to full capacity.

One can "dead-stick" land an RC model with a motor failure. That is not possible with a discharged battery which cannot operate the plane's servos.

The following report is a summary of many small details about Ni-Cd, Ni-MH, Li-Ion, and Li-Ion Polymer batteries.

The information will be useful for you to take care of and maintain your rechargeable batteries.

Edward Sadok
Whitby AeroModellers
Rev:0 April, 2008

Rechargeable Batteries

Ni-Cd batteries

Cell voltage: **1.2** volts

Internal Resistance: approximately **0.019** ohms (after discharge to 1.0 volts)

Operating temperature range: **-10 ºC to +60 ºC** (available capacity greater than 90%) [2]

Energy Density: **46** watt-hr/kg   (Ratio of energy to mass; the energy is determined by the charge that can be stored and the cell voltage, E=qV)

Ni-MH batteries

NiMH cells were developed to replace Ni-Cd cells because Cadmium (a carcinogenic) is harmful to the environment.

Cell voltage: **1.2** volts

Internal Resistance: approximately **0.025** ohms (after discharge to 1.0 volts)

Operating Temperature range: **0ºC to +50ºC** (available capacity greater than 90%) [3]

Energy Density: **70** watt-hr/ kg (Ratio of energy to mass; The energy is determined by the charge that can be stored and the cell voltage, E=qV)

Comparison between Ni-Cd and Ni-MH batteries [8]

Ni-Cd cells are able to deliver higher currents than Ni-MH cells.

Ni-Cd cells can endure abuse physically and electrically (occasional overdischarges or overcharges and high temperature work) without serious problems. Ni-MH cells are more sensitive in this respect where high temperatures can alter the special structure that the metal-hydride electrode must have.

Ni-MH technology is better than Ni-Cd technology in two aspects: Ni-MH do not contain cadmium which is harmful to the environment, and Ni-MH technology has a higher energy density than Ni-Cd.

Ni-Cd and Ni-MH batteries loose effective capacity due to overcharging, overdischarging, self-discharging, and so on (these loses are often mistakenly attributed to memory effect).

<u>Trickle charging Ni-Cd and Ni-MH batteries</u> [9]

Trickle Charge: A fixed charging current at **0.1C** (where C represents the rated battery capacity) is applied to the battery. This charges the battery in typically **16 to 18 hours**. However, charging beyond this limit can damage the battery.

NiMH cells are more vulnerable to damage than Ni-Cd cells and they get damaged when subjected to extended trickle charging at rate greater than 0.1C.

The trickle charging current for Ni-MH batteries should thus be limited to between **0.033C to 0.05C** to avoid damage to the battery with an upper time limit of **18 – 20 hours**.

<u>Fast Charging Ni-Cd and Ni-MH batteries</u>

A high current during fast-charge of batteries causes an increase in battery temperature and gas production. It is necessary to accurately detect the end of fast-charge, to avoid battery damage, due to overcharging.

Excessive charging rates can result in premature aging of batteries and/or irreversible damage.

"Ni-MH technology is not so robust in comparison to Ni-Cd technology. For Ni-MH, operation in extreme conditions (overcharging, high temperature, high pressure, gas releasing) modifies the special microstructure of the metal hydride active material …so battery performance is seriously affected." [4]

With Ni-MH cells, "a single over-charging event can cause serious battery damage. Therefore, fast re-charging must be carefully monitored to avoid damage to the Ni-NH battery." [7]

(Usual charging rates are typically 0.1C and 0.2C. Trickle charging rates are at less than 0.1C.)

Fast-charging is typically at 0.5C, 1.0C, and 2.0C.

"Tests show that charging rates higher than 2.0C are very inefficient and they can produce a premature aging of the battery (battery temperature increases significantly)." [4]

"Battery temperature increasing is related to inefficiency of the charging process (i.e. a growing portion of the charging current is not dedicated to ionic transference but is converted to heat and {hydrogen} gas production)." [4]

The charging process is essentially complete when hydrogen gas is produced by the battery. Any further charging will only produce more heat and hydrogen gas in the battery, with very little actual charging of the battery.

If the **anode** is *overcharged*, **hydrogen** gas is produced. [10]

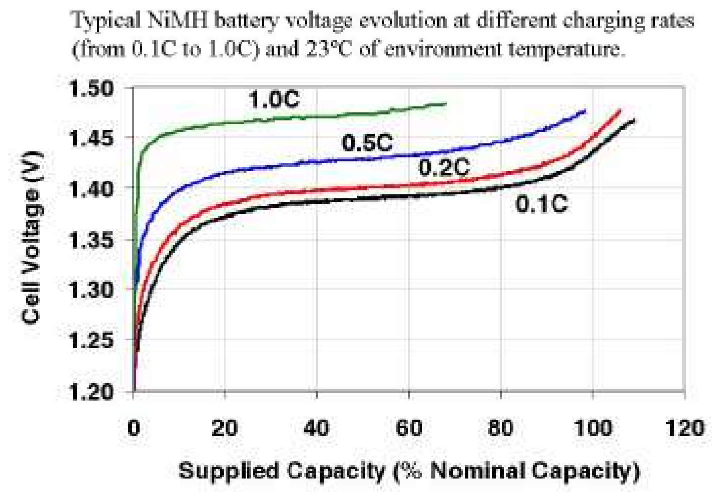
If the **cathode** is *overcharged*, **oxygen** gas is produced. [10]

For battery chargers, the battery voltage is the easiest parameter to measure during the charging process. However, "battery voltage depends not only on battery charge state, ambient temperature, and battery design, but it also depends on charging rate (especially when high charging currents are applied)." [4]

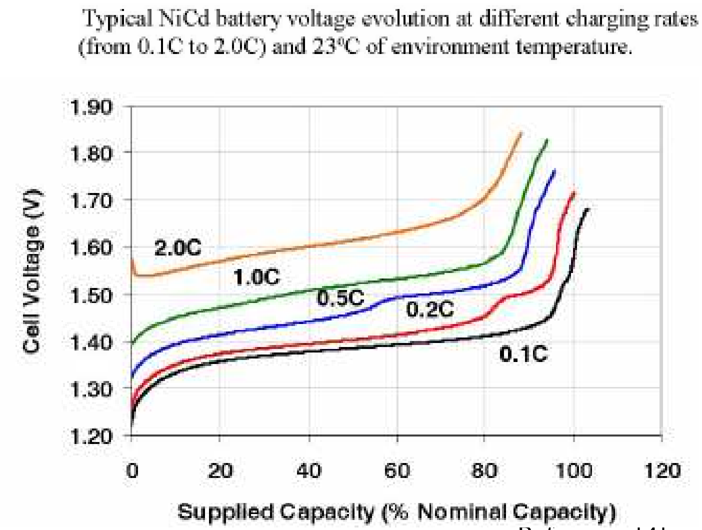
Shown below is the effect of charging rate on battery voltage. Charging was done at a constant current.

The charging process was stopped when the battery started to produce hydrogen gas, which is a sign of overcharging. (This can be seen where each curve ends abruptly on the right of the graph).

Fast charge does not always produce full charge.



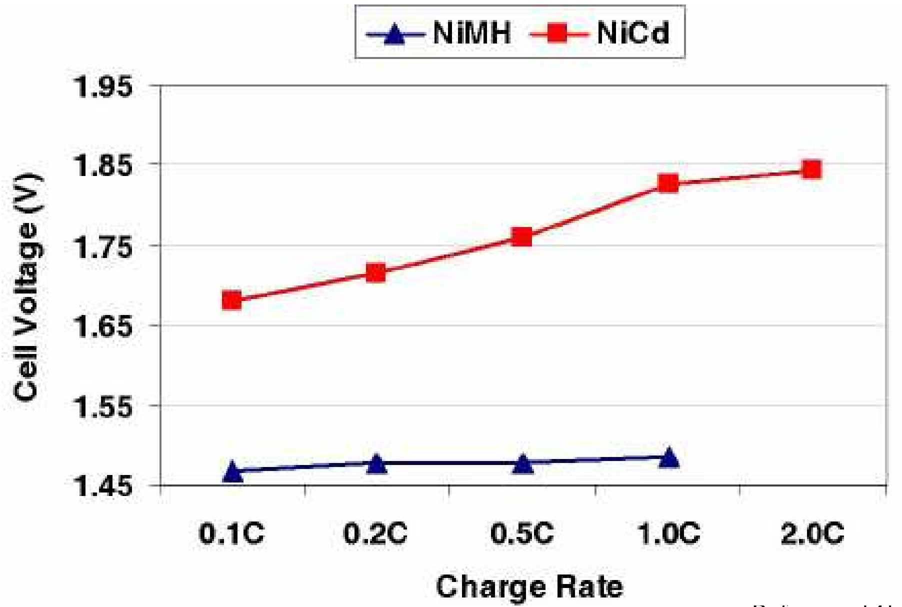
In the **Ni-MH** battery graph shown above, "when a 1.0C rate is applied to Ni-MH batteries, only 68% of nominal capacity can be supplied before overcharging." [4]



Reference: [4]

In the **Ni-Cd** battery graph shown above, "Ni-Cd batteries accept about 90% of nominal capacity when a 2.0C charging rate is applied." [4].

Measuring battery voltage to detect end-of-charge applies better to Ni-Cd batteries than to Ni-MH batteries. The graph below shows "the relationship between maximum cell voltage (cell voltage at the end of charging process, when hydrogen production is detected) and charge rate applied to {Ni-Cd and Ni-MH batteries}". [4]



Reference [4]

NiCd and NiMH battery voltage at the end of charging process
(average value obtained from statistic data).

"In the **Ni-MH** {battery}, the maximum voltage is about 1.5 volts/cell, independent of charging rate used (from 0.1C to 1.0C)

However, in the **Ni-Cd** {battery}, the maximum voltage increases as charging rate increases (from 1.65 volts/cell at 0.1C to 1.85 volts/cell at 2.0C); always above the values for Ni-MH {batteries}. "[4]

"The charging voltage profile in Ni-MH {batteries} is gentle {and} the rise at the end of the charging process for Ni-MH {batteries} is less pronounced that for Ni-Cd {batteries}." [4]

Battery Temperature

As a battery charges, battery temperature rises.

Battery temperature rise must be limited to minimize premature battery aging or irreversible damage

The maximum operating temperature of a Ni-MH battery should not exceed 50ºC.
The maximum operating temperature of a Ni-Cd battery should not exceed 60ºC.

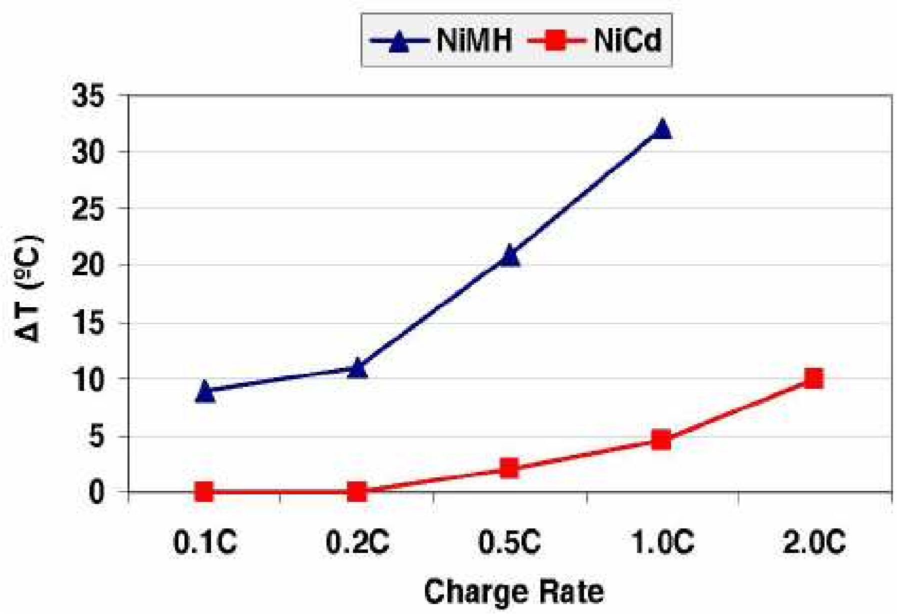
The charging reaction for Ni-Cad cells is endothermic (absorbs heat). [5]
The charging reaction for Ni-MH cells is exothermic (gives off heat). [5]

With a **Ni-MH** battery, the "battery temperature increases from the start of the charge process, even at a 0.1C rate. Moreover, {the rate of change} of temperature… becomes significant from {and above the} 0.2C charging rate. The reason is that electrochemical charge reactions are exothermic in Ni-MH batteries, a significant disadvantage of Ni-MH technology in comparison with Ni-Cd technology." [4]

With **Ni-MH** {batteries} studies show a heavy increase of battery temperature, above ambient temperature, when charging rates higher that 0.5C are used, (an increase of 32ºC at 1.0C rate). [4]
Therefore charging **Ni-MH** batteries at a rate above 0.5C should be done with caution.

"The endothermic reaction of electrochemical charge reactions in **Ni-Cd** batteries improves their behaviour under fast charging. Tests show that battery temperature increases only when the battery is near to full charge, if charging rates below 0.5C are applied. The endothermic nature of charging reactions is cancelled at charge rates above 0.5C and battery temperature increases as soon as charging starts." Even so, charge rates until 2.0C can be supplied to..{**Ni-Cd**} batteries without excessive heat problems……[4]

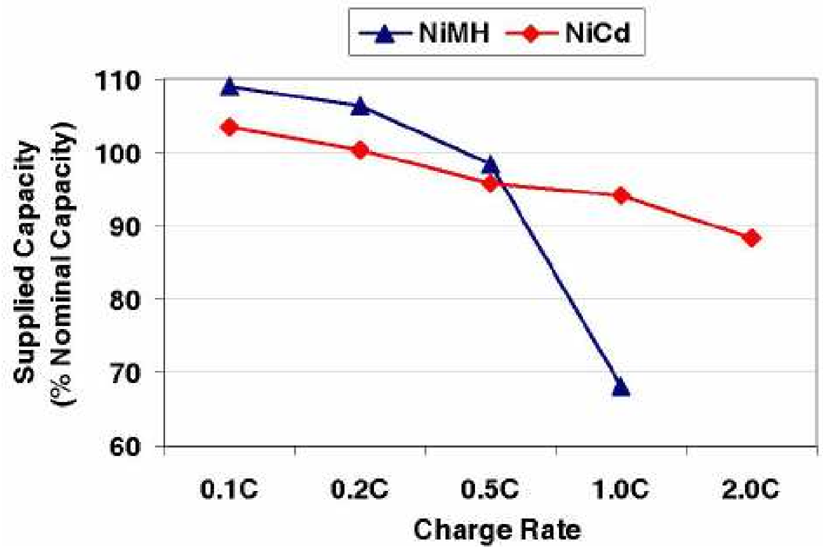
With **Ni-Cd** batteries, "battery temperature increasing becomes significant at charging rates above 1.0C. Therefore, charging rates higher than 1.0C should be done with caution.



In figure above, Ni-NH and Ni-Cd battery temperature increase above ambient temperature (23ºC) at the end of charging process. (average value obtained from statistic data) [4]

Charge Acceptance/Charge Efficiency

A battery is considered fully charged only if the effective capacity is above 90% of nominal capacity. (A battery is considered discharged, if its effective capacity is below 80% of nominal capacity).



Supplied capacity to Ni-Cd and Ni-MH batteries during charging process at different rates and 23ºC of environment temperature Reference: [4]

For "Ni-MH {batteries}, the capacity that can be supplied efficiently to {Ni-MH} batteries decreases heavily at charging rates higher than 0.5C. For example, supplied capacity at 1.0C is lower than 70% {for Ni-MH batteries}.

The highest charge acceptance is obtained at 0.5C (near to 95% in Ni-Cd technology and 98% in Ni-MH technology." [4]

For both Ni-Cd and Ni-MH batteries, "above 0.5C, charge acceptance decreases due to increasing battery temperature." [4]

<u>Ni-Cd and Ni-MH Battery Chargers</u>

Charging Ni-Cd batteries and Ni-MH batteries must be done with care to avoid *excessive* temperature increase in the battery.

Recall the maximum operating temperature for a **Ni-Cd** battery is **60ºC**. Therefore, if room temperature is 20ºC, the Ni-Cd battery temperature can only increase another 40ºC, during charge, before it will suffer damage.

For **Ni-MH** batteries, the maximum operating temperature is lower. It is **50ºC**. Therefore, during a charging operation, at 20ºC room temperature, the Ni-MH battery can experience only an additional 30ºC rise in temperature, before the battery will suffer damage.

A well designed battery charger will contain:

a battery temperature sensor (for Ni-Cd and Ni-MH batteries)

a method to measure the slope or inflection of battery voltage (for Ni-MH batteries)

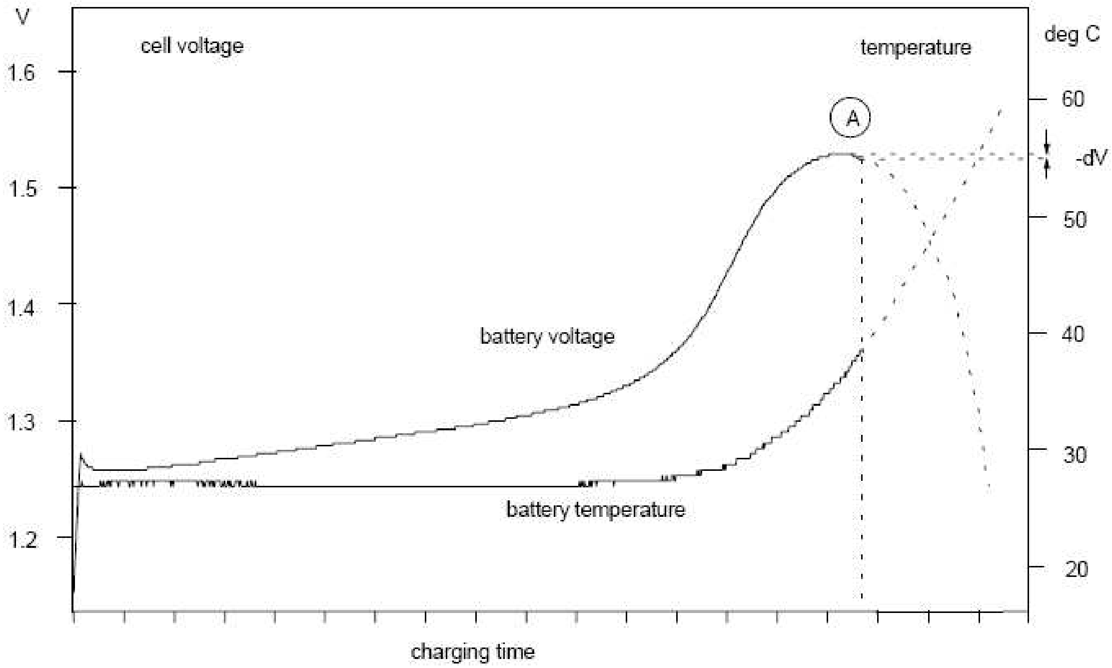
a method to measure a negative voltage dip or [-ΔV] (for Ni-Cd batteries)

as an option, a timer to turn off charger unit (for trickle charge)

A charger designed <u>**only**</u> for Ni-Cd batteries <u>should not</u> be used for charging Ni-MH batteries.

A charger designed for Ni-MH batteries <u>can</u> be used for charging Ni-Cd batteries.

Ni-Cd Battery charger: using the [-ΔV] method [5]



"When a Ni-Cd battery reaches full charge, its voltage decreases slightly, -dV, as shown in the figure above.

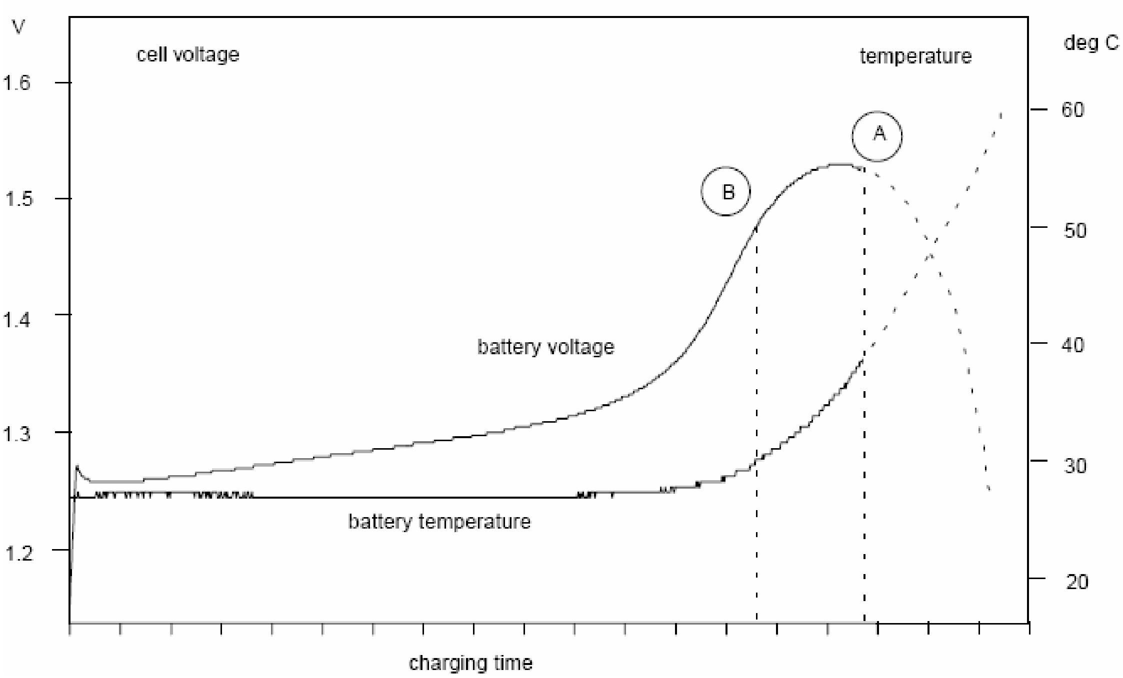
(Some types of Ni-MH batteries do not exhibit a significant voltage drop when reaching their full capacity. Hence, the [-ΔV] method is not suitable for charging Ni-MH batteries)

The negative delta voltage method [-ΔV] consists of stopping the charge, as soon as the voltage slope versus time, becomes negative. This charge termination technique is optimized to fast charge a Ni-Cd battery to its full capacity.

In fact, a Ni-Cd battery charged with the [-ΔV] method is slightly overcharged. The figure above shows that the battery temperature has substantially increased at point **A,** when charge is terminated, which may decrease the life-time of the battery." [5]

Before point **A** is reached, there is a portion of the charge current that is not converted into active battery charge, but into heat.

Ni-MH battery charger: inflexion point method [5]



"In the battery charging curves shown above, most of the battery current between point **B** and the negative voltage drop at point **A**, is not directly converted into active battery charge, but into heat.

This "heat" can be seen in the temperature curve shown above. The point **B** corresponds to the inflexion point of the battery voltage curve versus time". [5] (At point **B**, the slope of the battery voltage curve changes from a steep positive slope to a more shallow positive slope).

The Ni-MH battery should not be charged beyond point **B**. At point **B**, the battery temperature is about 30ºC and if the ambient room temperature is 20ºC, the Ni-MH is already at its maximum operating temperature of 50ºC.

Therefore the inflexion point method should be used for charging Ni-MH batteries. (And can be used for charging Ni-Cd batteries as well).

(Detection of the inflexion point of the voltage curve with a microprocessor computer unit requires the evaluation of the first derivative (i.e. slope) of the battery voltage curve versus time, to detect the change in slope at point **B**). [5]

Trickle charging can be used to finish off the charging of the Ni-MH battery.

Damage Recovery of Ni-Cd or Ni-MH Battery

"Battery damage is detected by measuring the open-circuit battery voltage.

A voltage of less than 1V/cell shows an over-discharged battery. In this case, a trickle charge (C/10) is recommended until the battery is recovered (that is, the battery voltage is increased to 1.3 V/cell)

If the voltage remains lower than 1.25V/cell after five minutes, the C/10 charging process can be stopped because the battery is irreversibly damaged." [7]

Internal Resistance of Ni-Cd and Ni-MH batteries

Think of a battery as a pure voltage source in series with a resistor.

This resistor is the internal resistance of the battery.

The value of internal resistance is determined by the battery chemistry and by the physical construction of the battery.

The internal resistance of a **Ni-Cd** cell is typically 19-milliohm (i.e. 0.019 ohms). [1], [2]

Therefore, a 9.6 volts Ni-Cd battery (eight cells in series) will have an internal resistance of approximately 0.152 ohms (i.e. 8 x 0.019 ohms)

The internal resistance of a **Ni-MH** cell is higher, typically 25-milliohms (i.e. 0.025 ohms). [1], [3]

A 9.6 volts Ni-MH battery will have an internal resistance of approximately 0.2 ohms.

Internal resistance influences the magnitude of current that the battery can supply. A battery with a low internal resistance can supply more current than a battery with higher internal resistance.

As a battery discharges, its internal resistance increases so that less and less current can be supplied to the load.

Ni-Cd batteries have a lower internal resistance than NiMH batteries. Hence, in high current drain applications (such as when using a high torque servo) the Ni-Cd battery is more suitable than a Ni-MH battery.

Lithium Ion batteries and Lithium Ion Polymer batteries are very similar.

Since no metal battery cell casing is needed for the Lithium Ion Polymer battery, it can be lighter and it can be specifically shaped to fit the device it will power.

Li-OH batteries

Lithium-Ion cells are typically made with aluminum cases a for reduced weight and increased capacity. The cells come in low profile, high energy density packages with capacities ranging from 190 mAh to 1800 mAh.

Lithium Ion Cell Specification		
Nominal Voltage		3.7V
Nominal Capacity		190mAh to 1800mAh
Charge	Method	Constant Current (CC) / Constant Voltage (CV)
	Max. Current	1C
	Max. Voltage	4.2V†
Discharge	Max. Current	1C
	Termination	3.0V†
Operating Temperate	Charge	0ºC to +45ºC
	Discharge	-20ºC to +60ºC
Storage	3 months	-20ºC to +45ºC
	12 months	-20ºC to +25ºC
Life Expectancy	Minimum	>300 cycles (80% rated capacity)
	Typical	500 cycles
Notes:		
† Charge termination and discharge termination required.		

Reference: [11]

Energy Density: **150 - 200** watt-hr/kg (Ratio of energy to mass; the energy is determined by the charge that can be stored and the cell voltage, E=qV) [12]

Li Ion Polymer batteries

The Lithium Ion Polymer cells come in low profile, high energy density packages for fitting into those tightest of spaces. With this technology advance, cells have been made lighter providing reduction in the overall end product weight, with capacities ranging from 100 mAh to 4500 mAh.

Lithium Polymer Cell Specification		
Nominal Voltage		3.7V
Nominal Capacity		100mAh to 4500mAh
Charge	Method	Constant Current (CC) / Constant Voltage (CV)
	Max. Current	1C
	Max. Voltage	4.2V†
Discharge	Max. Current	2C
	Termination	3.0V†
Operating Temperate	Charge	0ºC to +45ºC
	Discharge	-20ºC to +60ºC
Storage	1 months	-20ºC to +45ºC
	6 months	-20ºC to +30ºC
Life Expectancy	Minimum	>300 cycles (80% rated capacity)
	Typical	500 cycles
Notes:		
† Charge termination and discharge termination required.		

Reference: [11]

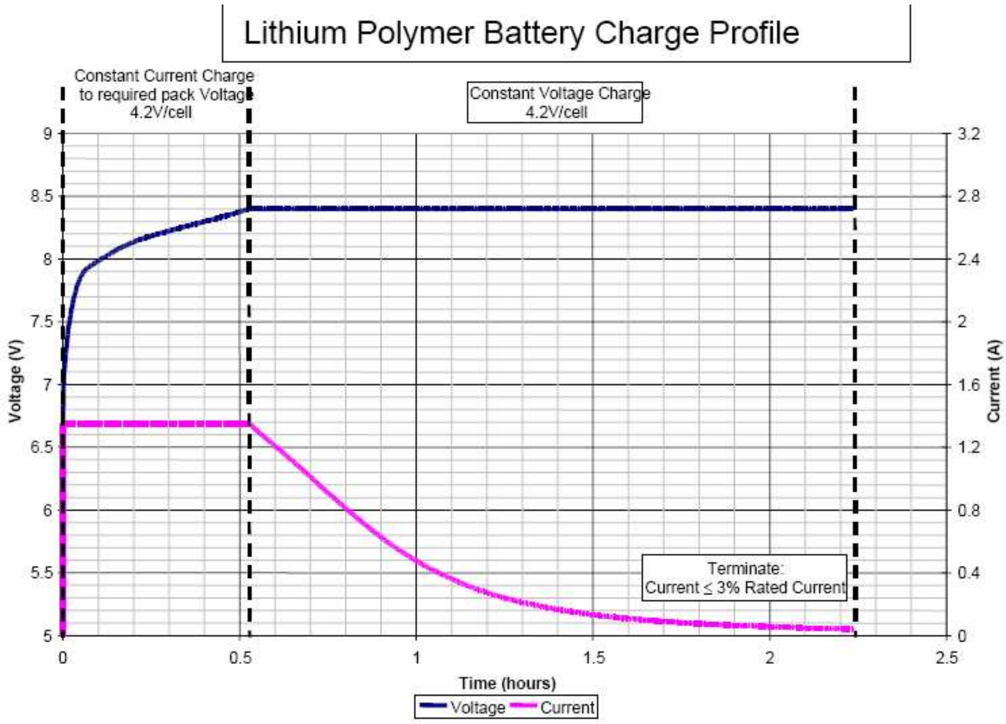
Energy Density: **180 - 240** watt-hr/kg (Ratio of energy to mass; the energy is determined by the charge that can be stored and the cell voltage, $E=qV$)

Since no metal battery cell casing is needed, the battery can be lighter and it can be specifically shaped to fit the device it will power. Because of the denser packaging without intercell spacing between cylindrical cells and the lack of metal casing, the energy density of Li-poly batteries is over 20% higher than that of a classical Li-ion battery. [13]

(Recall that the energy density of a Ni-Cd cell is 46 watt-hr/kg and 70 watt-hr/kg for a Ni-MH cell).

Charging Li Ion and Lithium Ion Polymer batteries

Shown below is a 2-cell battery (i.e. 2 x 4.2 volts = 8.4 volts). [Reference: 15]



Reference: [15]

- You must use a charger designed for Lithium Polymer Batteries. Do not use a charger intended for NiCd/NiMH batteries - you will damage the cells permanently.
- Lithium Polymer cells cannot be "fast charged". Never charge at a mA higher than the capacity of the battery (1C max charge rate). For best charging, low charge rates should be used when possible. You must not over discharge your Lithium Polymer cells or they may become permanently damaged
- Charge at a constant current until the battery voltage reached the 4.2 voltage limit at which time the current is reduced to maintain 4.2 volts.
- Operating temperatures for charging are 0°C to 45°C

The Charge cycle called a CC/CV two-stage charge cycle must be performed to fully charge the battery.

- The first stage of the charge cycle is a Constant Current charge until the battery voltage reaches 4.1 to 4.2 volts.
- Upon reaching this peak voltage, a Constant Voltage charge is initiated until the charge current reduces to 3% of the rated current. Upon completing charge, a top off charge may be used to insure to counteract the self-discharge of the battery and protective circuit. This top off charge may be initiated when the open circuit voltage of the battery reaches less than 4.05 volts and terminate upon reaching the full charge voltage of 4.1 to 4.2 volts. Depending on the battery, this top off charge may be repeated once every 20 days.

It is important to note that trickle charging is not acceptable for lithium batteries. The Li-ion chemistry cannot accept an overcharge without causing damage to the cell, possibly plating out lithium metal and becoming hazardous. [14]

Overcharge Reference: [15]

A strict charging regime is necessary to properly and safely charge Lithium Ion Polymer batteries. Most batteries contain a protective circuit to prevent overcharge and over discharge. This circuit limits the charge voltage to a maximum 4.2 Volts. The circuit also contains a thermal sensor, which disconnects charge if the temperature reaches 90 °C (194 °F).

If a cell is inadvertently overcharged, the cell may heat up and vent with a flame.

Over Discharge Reference: [15]

Cell should cutoff at 3.0 Volts.

Discharge Rate

For LiPo cells, the discharge rate, in mA-hr is based on a 5-hour discharge rate. Lithium cells do not lose their capacity when discharged quickly, as much as lead-acid do. However, when the discharge rate gets to a few minutes LiPo cells do lose some capacity. Some data sheets will have the capacity versus discharge time.

Lithium polymer cells differ in their design. Some are designed for rapid discharge for the RC industry and some are designed for a slower discharge in other applications. In the case of fast-discharge (10C to 20C or 3 to 6 minutes) batteries, the trend is to give the capacity at fast discharge, since the 5 hour discharge rate capacity is irrelevant to these users. Reference: [14]

Lithium Polymer Storage Guidelines Reference: [15]

Store the cell in a dry location between –20°C and 30°C.
Keep out of direct sunlight.
When storing for an extended period, store between 10°C to 30°C
Store at 40% of capacity.
When charging the first time after long-term storage it may take several cycles to achieve original performance

Lithium Polymer Cautions Reference: [15]

Lithium Polymer Batteries and packs that are abused may cause damage to the pack or the device resulting in personal injury.

Do not expose the battery to extreme heat
Do not short circuit battery
Do not puncture or modify the battery or pack
Do not immerse the battery pack in water
Never reverse charge the battery
Charge only with charger specified by equipment manufacturer
Never connect cells in parallel and/or series that are not designed for that purpose. A cell mismatch may cause overcharge and venting with flame.
Never leave the battery unattended while under charge or discharge.
Pay special attention when using an unknown brand. Not all brands contain intrinsic safety features that protect the cell when stressed.

Reference

[1] Sanyo battery specs: http://us.sanyo.com/batteries/specs.cfm

[2] http://sanyo.wslogic.com/pdf/pdfs/KR-1100AAU.pdf

[3] http://sanyo.wslogic.com/pdf/pdfs/HR-3U-2300.pdf

[4] NiMH vs NiCd Batteries under High Charging Rates
J.C. Viera; M. Gonzalez; J. C. Anton; J.C. Campo; F.J. Ferrero; M. Valledor
Telecommunications Energy Conference, 2006. INTELEC apos;06. 28th Annual International
Volume, Issue, Sept. 2006 Page(s):1 - 6

[5] N. F u r u k a w a , "Development and commercialization of nickel-metal hydride secondary batteries", *Journal **of** **Power Sources,***vol. 51. 1994, PD. 45-59.

[6] ST6 - From **Nickel-Cadmium** to Nickel-Hydride fast battery charger
Page 1. From **Nickel-Cadmium** To Nickel-Hydride Fast Battery Charger J. NICOLAI, L. WUIDART **...** FROM **NICKEL-CADMIUM** TO NICKEL-HYDRIDE FAST BATTERY CHARGER 2/16 Page 3. **...**
www.st.com/stonline/products/literature/an/2074.pdf - 2007-05-02

[7] New intelligent Ni-Cd and Ni-MH battery fast-chargerGonzalez, M.; Perez, M.A.; Diaz, J.; Campo, J.C.; Horta, S. Industrial Electronics, 1997. ISIE apos;97., Proceedings of the IEEE International Symposium on
Volume 2, Issue , 7-11 Jul 1997 Page(s):501 - 506 vol.2
Digital Object Identifier 10.1109/ISIE.1997.649001

[8] Ni-Cd and Ni-MH battery optimized fast-charge method for portable telecommunication applications
Gonzalez, M.; Perez, M.A.; Diaz, J.; Ferrero, F.J.
Telecommunications Energy Conference, 1996. INTELEC apos;96., 18th International
Volume , Issue , 6-10 Oct 1996 Page(s):522 - 529
Digital Object Identifier 10.1109/INTLEC.1996.573385

[9] **An Innovative Battery Charger for Safe Charging of NiMH/NiCd Batteries**
Tanvir Singh Mundra Kumar, A.
Indian Inst. of Technol., New Delhi;
This paper appears in: **Consumer Electronics, IEEE Transactions on**
Publication Date: Aug. 2007
Volume: 53, Issue: 3
On page(s): 1044-1052
Location: Rosemont, IL, USA,
ISSN: 0098-3063
INSPEC Accession Number: 9624252
Digital Object Identifier: 10.1109/TCE.2007.4341584

[10] Wikepedia: Nickel-Cadmium Battery

[11] http://www.ibt-power.com/Battery_packs/Li_Ion/Lithium_ion_tech.html

[12] Wikepedia: Lithium-Ion Battery

[13] Wikepedia: Lithium-Ion Polymer battery

[14] http://www.powerstream.com/index.html "Lithium Ion Charging"

[15] http://www.hardingenergy.com/pdfs/LiPolymer.pdf