1.1 Comparison of Applications Overview

Secondary (rechargeable) battery chemistries in use today include Sealed Lead Acid (Pb Acid), Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), Lithium ion (Li-ion), and Lithium Polymer (Li-Poly). This section of the handbook explains the key advantages and disadvantages of each of the battery chemistries listed.

1.1.1 Nickel Metal Hydride (NiMH)

The rechargeable sealed NiMH cell absorbs hydrogen in the metal alloy makeup of its negative electrode during charge. As the cell is discharged, the metal alloy releases hydrogen to form water. The use of the metal alloy is the underlying reason for the high energy density of the NiMH cell compared to other chemistries (see Figure 1.1 Energy Density Comparison). For more detail description of the chemical reactions within a NiMH cell, see Section 3.1, Principles of Operation.

As shown in the following table, NiMH batteries have a long cycle life (minimum of 500 cycles) and good storage characteristics. Furthermore, the battery can be recharged at any time without experiencing voltage depression (or memory effect). Most importantly, the NiMH battery is an environmentally friendly product.

Table 1.1.1

Advantages	Disadvantages	Typical Application
High volumetric and gravimetric energy density Long cycle life Good storage characteristics No memory effect/voltage depression Environmentally friendly Slow and rapid charge compatible	Overcharge/ over-discharge protection needed	Cellular phones, camcorders, emergency backup lighting, power tools, laptops, electric vehicles

1.1.2 Nickel Cadmium (NiCd)

The Nickel Cadmium (NiCd) cell chemistry is different from NiMH cell chemistry in that the NiCd cell absorbs cadmium where the NiMH cell stores hydrogen. Cadmium is much larger and heavier than hydrogen, which leads to lower volumetric and gravimetric energy densities of the NiCd cell (see figure 1.1, Energy Density Comparison). The NiCd's cycle life and discharge voltage profile are equivalent to NiMH. Also, NiCds can be placed into storage at any state of charge (SOC). Nevertheless, the NiCd battery needs to be completely discharged before it is charged to avoid the occurrence of voltage depression (or memory effect). Furthermore, the primary disadvantage to the use of the NiCd chemistry is the environmental concerns and health risks associated with the use of cadmium.

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Table 1.1.2

Advantages	Disadvantages	Typical Application
Long cycle life Good storage characteristics Rapid charge compatible	Low volumetric and gravimetric energy density Memory effect/voltage depression Environmental and health concerns (e.g. kidney damage, itai-itai (ouch-ouch) disease in Japan, and Mutagenic)	Calculators, power tools, tape recorders, flashlights, medical devices (e.g., defibrillators), electric vehicles, space applications

1.1.3 Lithium ion (Li-ion)

Rechargeable Lithium Ion (Li-ion) cells have a negative electrode (anode) made from lithium compounds. Lithium is a highly reactive material and is much lighter than the hydrogen-absorbing metal alloy of the NiMH negative electrode. This leads to higher gravimetric energy densities for the Li-ion cell (see Figure 1.1 Energy Density Comparison).

As shown in the following table, one of the advantages of Li-ion cells is that they have a self-discharge rate much lower than NiMH cells. As a result, Li-ion cells can stay in storage for 12 months without requiring maintenance. On the other hand, lithium is a very reactive material and it requires special circuitry to control charging as well as preventing over discharge of the cells. If too high of a voltage is applied during charge, a catastrophic failure (e.g. explosion) will occur which may result in damage to the surrounding environment. In addition, a puncture penetrating the electrodes of the cell will also cause catastrophic failure. Furthermore, if the lithium of the negative electrode is exposed to water the negative electrode will spontaneously combust.

The expected cycle life of a Li-ion cell in an application is about 500+ cycles. Storing them fully charged at high temperature significantly degrades the capacity. This is encountered for example, when using a laptop at full charge while plugged into a wall.

Table 1.1.3

Advantages	Disadvantages	Typical Application
Very high volumetric and gravimetric energy density Good storage characteristics	High cost Costly charge and discharge control required Lower rate capability Low high temperature performance Potential health risks/catastrophic failures	Laptops, cellular phones, electric vehicles, digital cameras, camcorders, DVD players

1.1.4 Lithium-polymer (Li-Poly)

Lithium Polymer Ion batteries provide the performance of the Li-ion in a thin or moldable package. They do not use a volatile liquid electrolyte and can sustain significant abuse without explosion or fire. As with all batteries, they should still be handled with care, as there is significant energy stored in the cell. The lithium-polymer uses a polymer soaked with gelled electrolyte to replace the traditional porous

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separator.

Lithium-polymer is not a mature technology and low manufacturing costs have not yet been realized. Lithium-polymer finds its market niche in wafer-thin geometries, such as batteries for credit cards and other such applications. Expected cycle life is about 500 cycles.

Table 1.1.4

Advantages	Disadvantages	Typical Application
Very thin profile Flexible form factor Lightweight Improved safety	Expensive No standard sizes High cost-to-energy	Calculators, digital cameras, pagers, lap tops, phones, PDAs

1.1.5 Sealed Lead Acid (Pb Acid or SLA)

The main attraction for Sealed Lead Acid (Pb Acid) cells is the low cost of lead. This makes the Pb Acid cell very inexpensive per watt-hour. Lead is relatively heavy resulting in low volumetric and gravimetric energy densities (see figure 1.1, Energy Density Comparison). Also, the cycle life of a Pb Acid battery is directly proportional to the amount of energy removed from the battery during discharge. To obtain an equivalent cycle life of a NiMH system, only 30% of the Pb Acids capacity can be used. Another disadvantage to the Pb Acid chemistry is they need to be charged before being placed into storage or they will lose cycle life. Furthermore, there are some environmental concerns regarding the use of lead.

Table 1.1.5

Advantages	Disadvantages	Typical Application
Low cost High rate capabilities	Low volumetric and gravimetric energy density Fair cycle life Must be charged to be stored Environmental and health concerns (e.g. mental retardation, interference with kidney and neurological function, hearing loss, blood disorders, hypertension)	Wheelchairs scooters, golf carts, people movers and UPS

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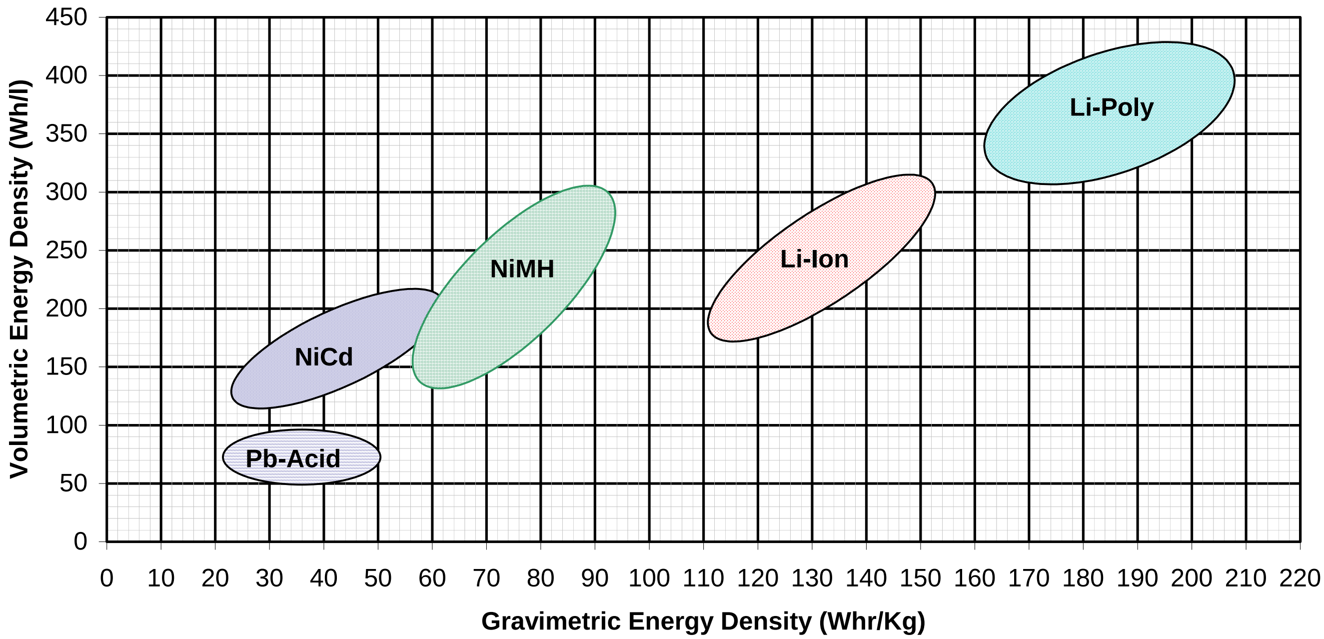
Figure 1.1 Energy Density Comparisons



Note: *Characteristics change according to improvements in chemistry or special niche requirements.*

Figure 1.2 Over All Comparison

Chemistry	Relative Cost	Weight	Temp (ºC)	Cycle Life	Shelf Life (Months)	Volts Per cell
Lead Acid	X	Very Heavy	-15 to 50	180+	6	2.0
Nickel Cadmium	2X	Heavy	-20 to 65	500+	6	1.2
Nickel Metal Hydride	2.5X	Moderate	-10 to 60	500+	12	1.2
Lithium Ion	4X	Light	-10 to 60	500+	12	3.7
Lithium Polymer	5X	Light	-10 to 60	500+	12	3.7

Note: *Characteristics change according to improvements in chemistry or special niche requirements.*

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2.0 Overview

Cells are now widely available in many sizes and designs. Cylindrical cells dominate the rechargeable battery market, but prismatic and button (or coin) cells are used in designs where space available for the batteries are limited.

2.1 Construction

Each cell design (i.e. cylindrical, prismatic, and button) consists of

Four basic internal elements

- Positive electrode
- Negative electrode
- A synthetic separator
- An aqueous solution called electrolyte

Three external elements

- The metal can (or case)
- Vent-cap assembly (with safety vent)
- Polymer gasket

Note: In cylindrical and prismatic cell designs the negative terminal is considered the entire can of the cell and the vent-cap assembly is considered the positive terminal. Button cells the construction is just the opposite; the cap assembly (without a safety vent) is the negative terminal, and the can (or cup in this case) is the positive terminal.

2.1.1 Cylindrical Cells

Cylindrical cells are manufactured by spirally winding two electrodes (positive and negative), with a separator between them, into a bundle. The bundle of electrodes and separator is inserted into a nickel-plated steel can. Electrolyte is then added and absorbed by the electrodes and separator. The positive electrode is welded to a vent-cap assembly, and crimping the can over the vent-cap with a gasket between the can and vent-cap seals the cell. The negative terminal is the can and the positive terminal is the vent-cap assembly with the gasket separating the two. Within the vent-cap is a self-sealing safety vent to prevent excessive pressure building up within the cell. See Figure 2.4 Cylindrical Cell Construction.

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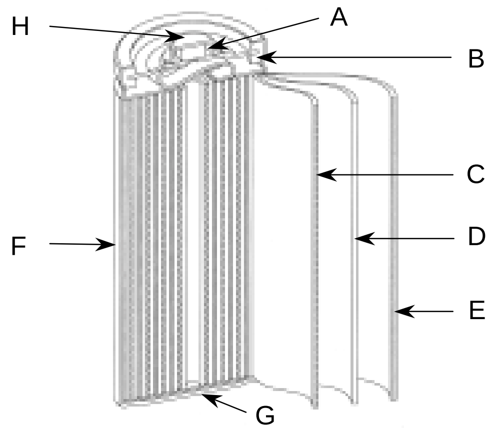
Figure 2.4 Cylindrical Cell Construction

A… Vent-cap Assembly/Safety Vent
B… Gasket
C… Positive Electrode
D… Separator
E… Negative Electrode
F… Can (Negative Terminal)
G… Negative Terminal
H… Positive Terminal

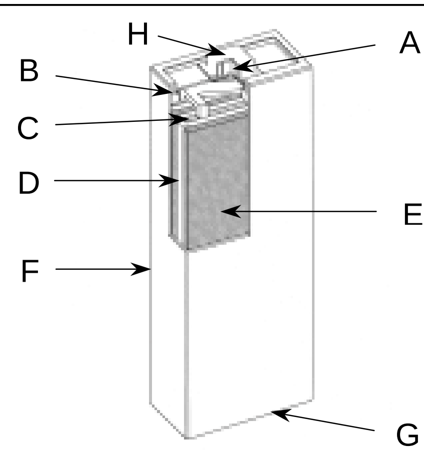


2.1.2 Prismatic Cells

Prismatic cells are manufactured with rectangular electrodes interspaced by separator sheets. The positive electrodes are welded to a vent-cap assembly. The electrodes are then placed in a nickel-plated can and electrolyte is added. Crimping the vent-cap assembly into the can seals the cell. The negative terminal is the can and the positive terminal is the vent-cap assembly with a gasket separating the two. Within the vent-cap assembly is a self-sealing safety vent similar to the one used in cylindrical cells. See Figure 2.5 Prismatic Cell Construction.

Figure 2.5 Prismatic Cell Construction

A… Vent-cap Assembly/Safety Vent
B… Gasket
C… Positive Electrode
D… Separator
E… Negative Electrode
F… Can (Negative Terminal)
G… Negative Terminal



2.1.3 Button Cells

Button cells are manufactured with circular disc of electrodes with a separator sheet in between. The assembly is placed into a nickel-plated cup and electrolyte is added. Crimping a cap into the cup seals the cell with a gasket separating the two. See Figure 2.6 Button Cell Construction.

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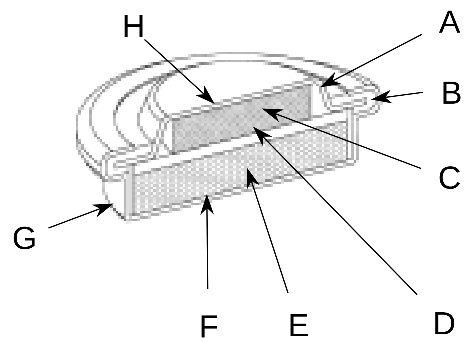
Figure 2.6 Button Cell Construction

A… Cap
B… Gasket
C… Negative Electrode
D… Separator
E… Positive Electrode
F… Cup (Positive Terminal)
G… Positive Terminal



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3.0 Nickel Metal Hydride (NiMH)

3.1 NiMH Principles of Operation

The principles in which NiMH cells operate are based on their ability to absorb, release, and transport (move) hydrogen between the electrodes within the cell. The following sections will discuss the chemical reactions occurring within the cell when charged and discharged and the adverse effects of overcharge and overdischarge conditions.

The success of the NiMH battery technology comes from the rare earth, hydrogen-absorbing alloys (commonly known as Misch metals) used in the negative electrode. These metal alloys contribute to the high energy density of the NiMH negative electrode that results in an increase in the volume available for the positive electrode. This is the primary reason for the higher capacity and longer service life of NiMH batteries over competing secondary batteries.

3.2 Charging Chemical Reaction

When a NiMH cell is charged, the positive electrode releases hydrogen into the electrolyte. The hydrogen in turn is absorbed and stored in the negative electrode. The reaction begins when the nickel hydroxide ($Ni(OH)_2$) in the positive electrode and hydroxide (OH^-) from the electrolyte combine. This produces nickel oxyhydroxide (NiOOH) within the positive electrode, water (H_20) in the electrolyte, and one free electron (e^-). At the negative electrode the metal alloy (M) in the negative electrode, water (H_20) from the electrolyte, and an electron (e^-) react to produce metal hydride (MH) in the negative electrode and hydroxide (OH^-) in the electrolyte. See Figure 3.2 Chemical Equations and Figure 3.3 Transport Diagram.

Because heat is generated as a part of the overall chemical reaction during the charge of a NiMH cell, the charging reaction described above is exothermic. As a cell is charged, the generation of heat may not accumulate if it is effectively dissipated. Extreme elevated temperatures may be experienced if a cell is excessively overcharged. See Section 3.4 Overcharge and 3.5 Overdischarge.

Figure 3.2 Chemical Equations

Positive Electrode: $$Ni(OH)_2 + OH^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} NiOOH + H_2O + e^-$$

Negative Electrode: $$M + H_2O + e^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} MH + OH^-$$

Overall Reaction: $$Ni(OH)_2 + M \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} NiOOH + MH$$

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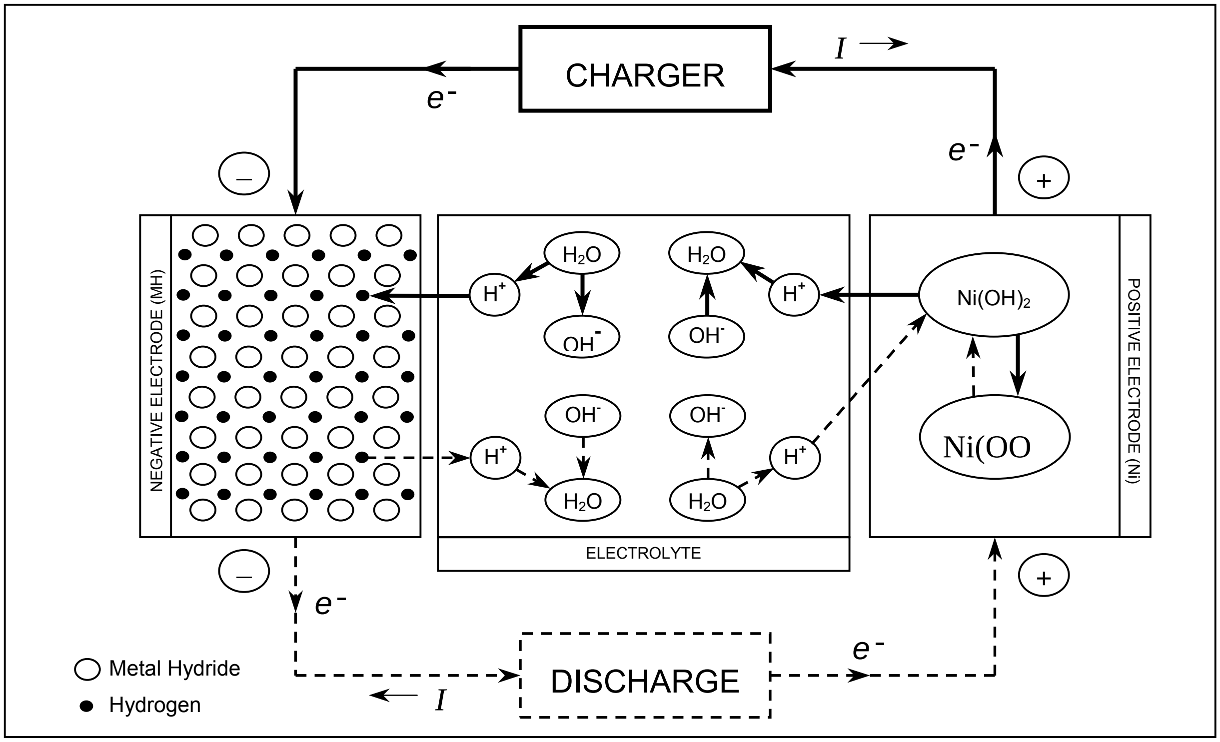
Figure 3.3 Transport Diagram



3.3 Discharge Chemical Reaction

When a NiMH cell is discharged, the chemical reactions are the reverse of what occurs when charged. Hydrogen stored in the metal alloy of the negative electrode is released into the electrolyte to form water. This water then releases a hydrogen ion that is absorbed into the positive electrode to form nickel hydroxide. See Figure 3.2 Chemical Equations and Figure 3.3 Transport Diagram.

For NiMH cells, the process of moving or transporting hydrogen from the negative electrode to the positive electrode absorbs heat and is therefore endothermic. Heat continues to be absorbed until the cell reaches a state of over discharge, where a secondary reaction occurs within the cell resulting in a rise in temperature. See Section 3.5 Over discharge*.*

3.4 Overcharge

Nickel Metal Hydride cells are designed with an oxygen-recombination mechanism that slows the buildup of pressure caused by overcharging. The overcharging of a cell occurs after the positive electrode 1) no longer has any nickel hydroxide to react with the hydroxide from the electrolyte, and 2) begins to evolve oxygen. The oxygen diffuses through the separator where the negative electrode recombines the oxygen with stored hydrogen to form excess water in the electrolyte. If this oxygen-recombination occurs at a slower rate than the rate at which oxygen is evolved from the positive electrode, the result is in a buildup of excess oxygen (gas) resulting in an increase in pressure inside the cell. To protect against the first stages of overcharge, NiMH cells are constructed with the negative electrode having a capacity (or active material) greater than the positive electrode. This helps to slow the buildup of pressure by having more active material available in the negative electrode to effectively recombine the evolved oxygen. See Figure 3.4, Useable Capacity Diagram.

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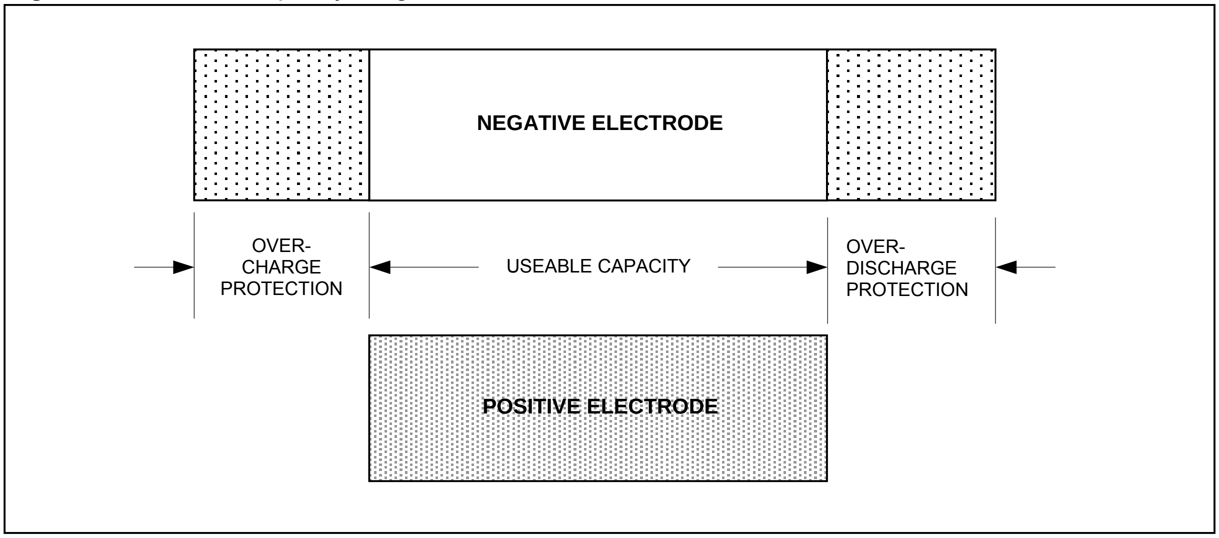
Excessive overcharging of a NiMH cell can result in permanent loss in capacity and cycle life. If a cell is overcharged to the point at which pressure begins to build up, elevated temperatures are experienced and can cause the separator to lose electrolyte. The loss of electrolyte within the separator (or "separator dry out") inhibits the proper transport of hydrogen to and from the electrodes. Furthermore, if a cell is severely overcharged and excessive amounts of oxygen (gas) are evolved, the pressure may be released through the safety vent in the positive terminal. This removes elements from within the cell needed for proper function. To protect against the damaging effects of overcharging, proper charge terminations must be used. See Section 3.8.2 NiMH Charge Termination.

Figure 3.4 Useable Capacity Diagram



3.5 Over Discharge

There are two phases to the over discharging of a NiMH cell. The first phase involves the active material of the positive electrode becoming fully depleted and the generation of hydrogen gas begins. Since the negative electrode has more active material (metal hydride), it has the ability to absorb some of the hydrogen gas evolved by the positive electrode. Any hydrogen not absorbed by the negative electrode begins to build up in the cell generating pressure. The second phase begins when the entire negative electrode is fully depleted of active material. Once both electrodes are fully depleted, the negative electrode absorbs oxygen contributing to the loss of useable capacity.

Extreme over discharge of a NiMH cell results in excessive gassing of the electrodes resulting in permanent damage in two forms. First, the negative electrode is reduced in storage capacity when oxygen permanently occupies a hydrogen storage site, and second, excess hydrogen is released through the safety vent reducing the amount of hydrogen inside the cell. To protect against the damaging effects of over discharging, proper end of discharge terminations must be used. See Figure 3.7.4 NiMH Low Voltage Disconnect or Voltage Cutoff.

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3.6 Rate Capability

The maximum rate a cell is able to achieve for a short burst is dependent on the cell construction, temperature and manner in which it is assembled into a pack. This will be clearer after looking at Section 3.7.1 NiMH Capacity.

3.7 NiMH Discharge Characteristics

The discharge characteristics of NiMH batteries (both cells and battery packs) depend on many factors. These factors include capacity, voltage, discharge rate, discharge termination (or voltage cutoff), matching (of cells within a battery pack), internal resistance, and temperature.

3.7.1 NiMH Capacity

Engineers and designers are usually most interested in how long a battery will supply the current needed to run a piece of equipment or a device. The length of time is directly proportional to the capacity of the battery and discharge rate. Defined as C, capacity is the electric current content of a battery expressed in ampere-hours (Ah) or milli-ampere-hours (mAh). The capacity of a battery is determined by discharging the battery at a known constant current until a predetermined end voltage is reached. The amount of time it takes to discharge a battery to the end voltage multiplied by the rate of current at which the battery was discharged is the rated capacity of the battery. Therefore, a battery would be rated at 1500 mAh if it was discharged at a rate of 150 mA to an end voltage of 1.0 volt per cell and it discharged for 10 hours.

For clarification, the rate of current (charge or discharge) that is applied to a battery is often defined in terms of the rated capacity C of a battery. For example, a battery rated at 1500 mAh that is discharged at a rate of C/2 (or 0.5C) will have 750 mAh discharged from the battery per hour. Thus, a discharge rate of C/2 of a 1500 mAh battery is 750 mA, but this does not mean the battery will last for 2 hours!

<u>One of the biggest misconceptions regarding NiMH cells is that rated capacity is the capacity that will be received by the user.</u> This would only be true if the user charged and discharged at the same rates of current at which the cell was graded.

Rated capacity has been defined by the International Electrotechnical Commission (IEC) in document #61436.1.3.4, as a charge at a rate of 0.1C for a period of 16 hours. This is followed by a discharge of 0.2C to a voltage of 1.00V per cell. However this number sometimes can be convoluted by Maximum, Typical, and Minimum cell ratings. For example, a lot of 1000 cells might range from 1000 mAh to 850 mAh. The maximum capacity would then be 1000 even though only a small number of the cells attain this capacity. The nominal capacity would be 900 mAh, and the majority of the cells tested would attain this capacity. All those cells must conform to the minimum of 850 mAh. We have found that to be considered with other manufacturers, we must also conform to this cell rating procedure

Results derived when testing NiMH technology battery packs for capacity can change dramatically with variation in:

- Temperature
- Charge Rate
- Discharge rate

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- Number of Cells in the Pack / Increase in Voltage Cutoff per Cell

All of these conditions must be taken into to account when a comparison is being made from pack to pack, and cell-to-cell.

Polarizations
When a NiMH technology cell is subjected to a flow of current a chemical change occurs within the cell. The obstacles to current flow are known as polarizations. The polarizations are:

- Ohmic- Ohmic polarization is the internal impedance of the cell against current flow. The impedance has a corresponding voltage drop, which can be seen in the voltage profile of any NiMH cell. During charge current this voltage is added to the overall voltage of the cell. However during discharge this voltage is subtracted from the overall voltage of the cell. The magnitude of the voltage drop will be directly proportional to overall impedance internal to the cell and the rate of current (charge/discharge) the cell is subjected to.
- If a cell has higher impedance, the drop will be greater.
- As the current applied to the cell is increased the voltage drop will increase. This is critical when a predetermined termination voltage is set. If a cell is discharged at a high enough current it can instantly force the cell voltage below 1.00V, even though there is almost 100% capacity remaining.

- Concentration- Concentration polarization is directly proportional to the surface area of the anode and cathode of the cell. The greater the surface area of these active plates, the greater the reduction in this polarization. This is determined during the engineering and manufacturing of the cell itself, and little can be done after that.

- Activation- Activation polarization is the amount of energy expended to cause the chemical reaction. Nothing is 100% efficient, so any chemical change expends energy. At a molecular level temperature has a great effect on the amount of energy it takes to make a reaction transpire. Generally all rating is performed at 20-25°C, as the temperature increases, or decreases the amount of energy on discharge will change.

- Knowing what affects the NiMH chemistry, we can fashion testing to isolate any variable that may cause inconsistent results.

- For example, a cell is charged at a 0.5 C with a –dV termination. When capacity testing is performed at a 0.5C discharge expect to see between 5-7% reduction in cell capacity over the IEC rating. This is explained first by the Ohmic polarization on discharge, and secondly due to the variation in charged energy using a –dV charge regime.

- In order for a –dV to be seen on a NiMH cell it must be subjected to a small margin of overcharge. This overcharge condition forces the voltage depression. It occurs when all of the active material in the cell is chemically reacted, and oxygen evolves and then diffuses into the negative electrode. The negative electrode is designed to be larger than the positive so it accepts a portion of this oxygen diffusion, however pressure is still generated within the cell, which generates heat. The heat then causes the cell voltage to drop. A direct comparison of the energy input during charge and output during discharge cannot be made

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because a portion of the input energy was wasted on oxygen evolution and was never recombined. In order to derive a % of rated capacity, we must calculate the energy received during discharge of our test, with that cell's IEC rated capacity

3.7.2 NiMH Voltage

The discharge voltage profile of a NiMH battery is considered "flat" (see Figure 3.7.2 C/10 Discharge Profile @ 25°C) and varies with the rate of discharge and temperature. As a fully charged battery is discharged the voltage begins at about 1.5 volts followed by a sharp drop to around 1.3 volts. The voltage remains between 1.3 to 1.2 volts for about 75% of the profile until a second sudden drop in voltage occurs as the useful capacity of the battery begins to deplete. At this point is where the discharge current (or load) is terminated at a safe voltage level (see Section 5.4 Low Voltage Disconnect or Voltage Cutoff). With elevated discharge rates, the entire discharge profile is lowered by losses in ohmic polarizations (internal resistance). At high temperatures, the discharge profile is raised by an increase in potential (voltage) between the electrodes. At temperatures below 10°C (50°F), concentration polarization significantly lowers the voltage and the useable capacity. This is caused by an increase in energy required to transport molecules within the battery. See Section 2 Principles of Operation and Construction.

The industry standard for the rated voltage of a NiMH cell is 1.2 volts. This value is the nominal voltage of a cell that is discharged at a rate of C/10 at a temperature of 25°C (77°F) to an end voltage of 1.0 volt. This industry standard is used primarily to call out the rated voltage of battery packs. For example, a battery pack made of three cells in series would be rated as a 3.6-volt battery pack. Figure 3.7.2, C/10 Discharge Profile @ 25°C, shows that the nominal voltage of a Quest® NiMH cell is just above 1.2 volts.

For technical applications and calculations, the nominal voltage of a battery pack provides a useful approximation of the average voltage throughout discharge. The nominal voltage can be simply calculated after the battery has been discharged. To calculate the nominal voltage, divide the batteries energy [watt-hours (Wh)], by the capacity, [ampere-hours (Ah)]. This calculation proves beneficial when a battery is discharged at high temperatures, since nominal voltage will increase under these conditions.

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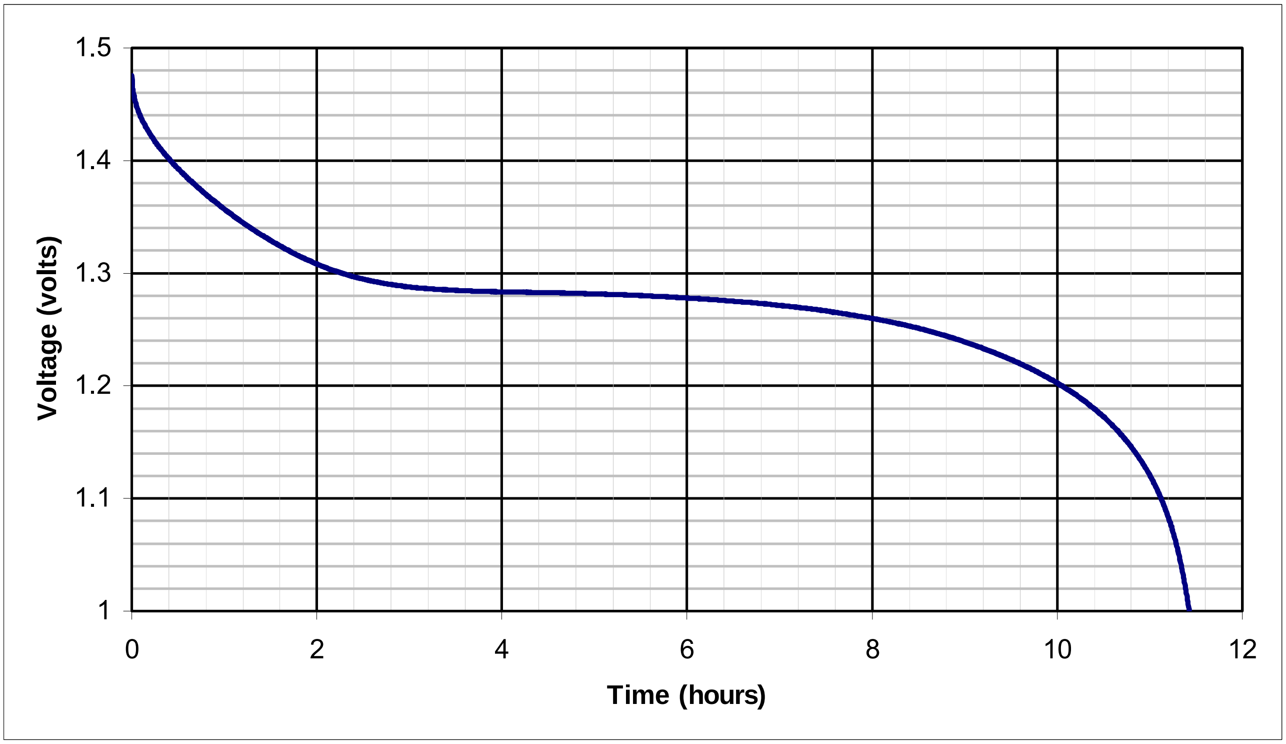
Figure 3.7.2 C/10 Discharge Profile @ 25°C



3.7.3 NiMH Discharge Rate

The delivered capacity and nominal voltage of a battery are dependent on the rate of current at which a battery is discharged. For NiMH batteries, there is no significant affect on capacity and voltage for discharge rates below 1C. A reduction in the nominal voltage occurs for discharge rates between 1C and 3C for all the NiMH cell sizes with the exception of the high rate series of cells.

3.7.4 NiMH Low Voltage Disconnect or Voltage Cutoff

To prevent potential irreparable harm to a battery due to polarity reversal of one or more cells during discharge, the load (discharge current) must be terminated prior to the battery being completely discharged. Damage can be avoided by terminating the discharge at a point where essentially all capacity has been obtained from the battery, but a safe voltage level remains. Removing the load in this manner is referred to as Low Voltage Disconnect or Voltage Cutoff. Capacity of a battery is slightly dependent on the Voltage Cutoff used at the end of discharge. Continuing the discharge to lower end voltages can slightly increase the delivered capacity, yet if the end voltage is set below the recommended Voltage Cutoff the cycle life of the battery will be decreased. The following table gives the Voltage Cutoff recommendations for discharge rates of less than 1C:

Figure 3.7.4 Voltage Cutoff Schedule

Number of Cells in Series	***Low Voltage Disconnect/Voltage Cutoff***
1 to 6	*1 volt per cell*
7 to 12	*[(MPV-150mV)(n-1)]-200mv*

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Where MPV is the single cell midpoint voltage at the given discharge rate (typically 1.3) and n is the number of cells in the pack. For discharge rates greater than 1C the MPV will decrease.

3.7.5 NiMH Matching

Matching refers to the grouping of individual NiMH cells with similar capacities to be used within a battery pack. Typically, the matching of the cells in a battery pack is within 2%. Matching eliminates the potential of reversing the polarity of one or more cells in a battery pack due to the capacity range of the combined cells being too great. Matching becomes more critical as the number of cells in the battery pack increases. This is due to the potential of one cell having a capacity significantly lower than the average capacity of the other remaining cells. As a result, the lowest capacity cell has the potential to reverse polarity while the other cells remain at safe voltage levels before reaching the voltage cutoff. If a battery pack has one or more cells reversed before the Voltage Cutoff is reached, the performance and cycle life will be reduced.

3.7.6 NiMH Internal Resistance

The internal resistance of NiMH cells varies depending on cell size, construction, and chemistry. Different materials are used in various NiMH cells to achieve desired performance characteristics. The selection of these materials also affects the internal resistance of the cell. Since NiMH cells of various sizes, construction, and chemistry are different, there is no one value of internal resistance that can be defined as a standard. The internal resistance for each cell is measured in mΩ at 1000Hz.

3.7.7 NiMH Temperature

To obtain the optimum capacity and cycle life of a NiMH battery, the recommended range of temperature when discharging a standard battery is 0°C (32°F) to 40°C (104°F). Due to the endothermic discharge characteristics of NiMH cells, the discharge performance is increased moderately at higher temperatures, yet the cycle life will be lowered. At lower temperatures, performance decreases more significantly due to the cells polarization. See Section 3.7.7. This is caused by a decrease in transport capabilities (the ability to move ions within the electrodes). For most NiMH batteries, the following chart shows the typical affect of temperature on capacity at a C/5 discharge rate.

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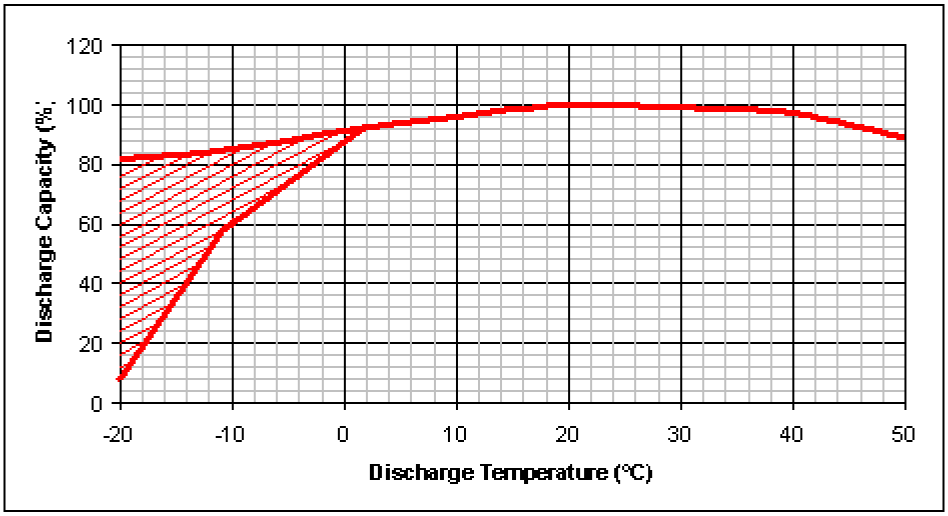
Figure 3.7.7 Discharge Capacity vs. Temperature



3.8 NiMH Charge Characteristics Overview

The charging, or recharging, of NiMH batteries (both cells and battery packs) is the process of replacing the energy that has been removed or discharged from the battery. The performance of the battery, as well as the cycle life, depends on effective charging. The three main criteria for effective charging are:

- Choose the appropriate charge rate
- Select the appropriate charge termination technique
- Control the temperature

3.8.1 NIMH Charge Rates

As the capacity of NiMH cells has increased, so has the demand for faster charging. This leads to higher charge rates, which requires care to ensure a complete charge while minimizing the potential damage of overcharging. Slow charging is still a reliable method, but not all batteries can be slow charged without some type of termination. Some NiMH cell chemistries have higher capacities and are better suited to the more popular fast charging methods.

3.8.2 NIMH Charge Termination

Properly controlling the charging of a NiMH battery is critical to achieving optimum performance. Charge control incorporates proper charge termination to prevent overcharging the battery. The overcharging of a battery refers to the state at which the battery can no longer accept (store) the energy entering the battery. As a result pressure and temperature builds up within the cell. If a cell is allowed to remain in the overcharge state, especially at high charge rates, the pressure generated within the cell can be released through the safety vent located within the positive terminal. This may cause damage to the battery reducing cycle life and capacity.

To prevent damage occurring to the battery, charge termination is one of the most critical elements to be applied to any method of charge control. Charge control may utilize one or more of the following

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charge termination techniques. The three primary techniques of charge termination are time, voltage, and temperature.

3.8.2.1 Time

Time-based charge control techniques terminate charging of the battery after a predetermined length of time. This technique should be used when slow charging to avoid excessive overcharge, and used as a backup secondary termination for all fast charge methods.

3.8.2.2 Voltage

Charge control techniques that are voltage-based are attractive because of the predictable charge voltage profile of a NiMH battery (see Section 3.8.3 Charge Termination Nomenclature). The charge voltage profile of a NiMH battery is consistent regardless of the batteries state of charge. However, the voltage-based charge termination techniques generally occur after a battery has already reached the overcharge state. In addition, the voltage-based techniques may not be applicable at rates below C/4 and are prone to false termination due to RF noise. It is also necessary to include temperature-sensing devices to terminate the charge if the temperature becomes too high. Such devices include thermostats and PTC resettable fuses.

Peak Voltage Detect (PVD)

The recommended technique for voltage-based charge termination is peak voltage detect or PVD. This technique involves sensing the drop in voltage after the battery has reached its peak voltage and becomes overcharged (see Section 3.8.3 Charge Termination Nomenclature). This technique is recommended because it reduces the risks of overcharging from that of other voltage charge termination techniques. To prevent substantial damage to a battery, a maximum drop in voltage of 3 mV per cell before termination is recommended to limit the amount of overcharge on the battery. Additionally, the sampling rate of the charger IC is more frequent to increase sensitivity.

Negative Delta V ($-\Delta V$)

Negative delta V ($-\Delta V$), like PVD, follows the same concept of sensing the drop in battery voltage after the battery has reached its peak voltage. The difference is the change or drop in voltage is increased to 3 to 5 mV per cell before the charge is terminated. This technique allows the battery to be exposed to longer periods of overcharge and is not normally recommended. See Section 3.8.3 Charge Termination Nomenclature

3.8.2.3 Temperature

The exothermic nature of NiMH batteries under charge refers to the generation of heat as the battery is charged especially just before and during overcharge. The temperature-based charge termination senses this temperature rise and terminates the charge when the battery has reached a temperature that indicates when full charge is being approached. This type of charge termination is recommended because of its reliability in sensing overcharge, yet it requires care

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in the selection of set points in the charge circuitry to avoid premature charge termination or failure to detect the overcharge when the battery is exposed to extreme temperature environments.

Change in Temperature (ΔT)

Change in temperature or ΔT is the technique that measures the difference of the rise in battery temperature above the starting (ambient) temperature during charge. The charge is terminated when the rate of change in temperature reaches a predetermined value. See Section 3.8.3 Charge Termination Nomenclature

Change in Temperature/Change in time (dT/dt)

The recommended technique for temperature-based charge termination for all fast-charging methods is dT/dt (see Section 6.3 Charge Termination Nomenclature). This technique monitors the change in temperature T verses the change in time t, and is considered most accurate because it senses the start of overcharge earlier than other techniques. Baseline dT/dt temperature termination is 1°C per minute, but varies according to pack design. When using a dT/dt termination, a top-off charge is suggested in order to fully charge the battery (see Section 3.8.6.5 Top-Off Charge).

Temperature Cut Off (TCO)

Temperature cut off or TCO is a secondary termination required for all fast-charging methods using dT/dt and/or PVD. This technique is based on the absolute temperature of the battery and is recommended only as a fail-safe strategy to avoid destructive heating in case of failure of any or all other charge termination technique(s). See Section 3.8.3 Charge Termination Nomenclature

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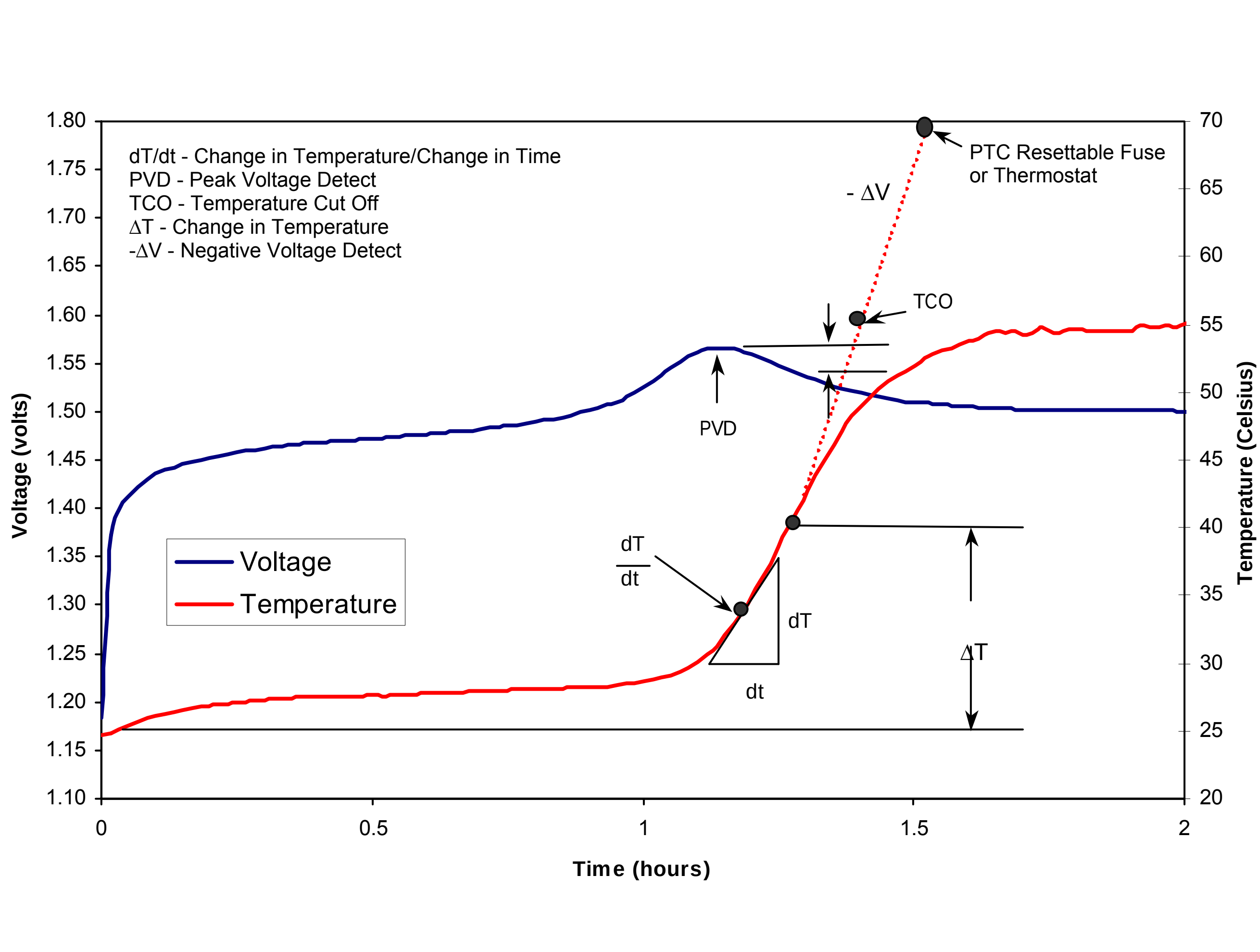
3.8.3 NIMH Charge Termination Nomenclature

Figure 3.8.3 NiMH Charge Termination Nomenclature



3.8.4 NIMH Temperature and Charge Efficiency

The recommended charging temperature is between 10°C (50°F) and 40°C (104°F). If a NiMH battery is exposed to high temperatures (above 40°C, 104°F) due to overcharging or external heat sources, the charge efficiency (increase in stored cell capacity per unit of charge input) will be decreased. In order to avoid decreased charge efficiency, batteries should have charge control methods applied to limit the amount of overcharge heat that is generated. In addition, it is critical to not place batteries in close proximity to other sources of heat or in compartments with limited cooling or ventilation.

At temperatures below 10°C (50°F) charge efficiency will also decrease resulting in an increase in the amount of time need for charging. Low temperatures inhibit transport capabilities (the ability to move ions within the electrodes) causing the low charge efficiency (see Section 3.7.1, NiMH Capacity and Construction; Rate Capability). Charging below 0°C (32°F) is not advisable

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3.8.5 NIMH Charge Methods

Not all charge methods are recommended for all NiMH cell chemistries, seeing they are not designed the same. Different materials are used in various NiMH cells to achieve certain desired performance characteristics. The selection of these materials also affects the charging characteristics of the batteries. Therefore, any method that could cause problems with some batteries has been noted for each charge method. See Figure 3.8.5 Charge Method Specifications for recommended charge currents and charge terminations.

Figure 3.8.5 Charge Method Specifications

Charge Method	Charge Current	Charge Termination	Comments
Slow	0.02-0.1C	1. None[1] or Timer	Timer rated at 160%C.
Standard	0.1C	1. Timer	Timer set for 16 hours.
Time	0.1-0.2C	1. Timer, and 2. TCO = 55°C	Timer rated at 160%C @ 0.1C to 120%C @ 0.2C.
Rapid[2]	0.25-0.5C	1. PVD, or dT/dt, or ΔT, and 2. Timer, and 3. TCO = 55°C	PVD = -ΔV of 3-5 mV/cell dT/dt = ~1°C/1 min rise. Timer rated at 140%C @ 0.2C to 120%C @ 0.5C.
Fast[2]	0.5-1.0C	1. PVD, or dT/dt, or ΔT, and 2. Timer, and 3. TCO = 55°C	PVD = -ΔV of 3-5 mV/cell dT/dt = ~1°C/1 min rise. Timer rated at 125%C.
Maintenance	0.002-0.008C	1. None	5-10%C per day at C/128 to C/512 pulse recommended.
[1] Not all batteries can be charged without a termination. [2] See Rapid/Fast Charging Procedure (Section 3.8.6).			

3.8.5.1 Slow Charge

When charge time is not an issue and maximum rechargeable capacity is desired, the slow charge method is often used. This method uses a charge that is less than 0.1C and for more than 16 hours (see Figure 3.8.5 Charge Method Specifications). Yet, with the recent developments of some NiMH cell chemistries to be better suited to faster charging methods, slow charging is not recommended for all NiMH batteries.

3.8.5.2 Standard Charge

This method can be used for most of the NiMH cell chemistries. The standard charge is a simple system using a charge rate of 0.1C for 16 hours (see Figure 3.8.5 NiMH Charge Methods). Since the charge rate is low and the charge is terminated after 16 hours, there is less risk of overcharge and increased temperatures. The downside to this method is the inability to detect how much charge a battery has at the time charging begins. Thus, a battery that is at a 60% depth of charge (DOD), or 40% state of charge (SOC), which is charged using this method will see the same amount of charge as a fully discharged battery. This leads to the overcharging of the partially discharged battery before the time termination occurs.

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3.8.5.3 Time Charge

For the faster timed charge method, batteries can typically be charged in 6 to 16 hours. This method of charging NiMH batteries requires the most attention before selection. Since this method uses higher rates of current (see Figure 3.8.5 Charge Method Specifications), two methods of termination are needed: timed and TCO. The later of the two terminations would require the battery to include a thermistor to detect the temperature during the charge cycle. If only a timed charged termination was used, the battery may be pushed into overcharge, especially if a partially discharged battery was charged using this method. For some NiMH cell chemistries this would significantly deteriorate battery performance.

3.8.5.4 Rapid Charge

The Rapid Charge method is good for applications needing a faster charge time, but the battery compartment does not allow for good heat dissipation. Rapid charge methods typically charge in 2.5 to 6 hours using charge rates of 0.25C to 0.5C (see Figure 3.8.5 Charge Method Specifications). This method of charging uses PVD, - ΔV, dT/dt or ΔT with time backup. For further charging details see Section 3.8.6 Rapid/Fast Charging Procedure. This system usually uses a temperature backup to ensure against overcharging.

The advantage of this charge method is the ability to safely charge batteries that are at any state of charge. In other words, a partially discharged battery can be charged without the risk of being overcharged. The disadvantage to this type of system is the added complexity and expense of the charger.

3.8.5.5 Fast Charge

When time is a limited resource and there is good heat dissipation, Fast Charge methods are the best approach. Fast Charge methods will charge batteries in 2.5 hours or less. Like the Rapid Charge method, this method has increased charge rates and requires three separate charge terminations (see Figure 3.8.5 Charge Method Specifications). Some of the higher capacity NiMH batteries will not handle a constant 1.0C charge rate. Presently, a good rule to follow is no constant charging above 1.0C or 3.0Amps. For further charging details see Section 3.8.6 Rapid/Fast Charging Procedure.

As with the Rapid Charge, the advantages of the Fast Charge method is the ability to safely charge batteries that are at any state of charge in a short period of time. The disadvantages are, again, the added complexity of the charger and expense.

3.8.5.6 Maintenance Charge

Unlike the previous six methods the Maintenance Charge method is not considered a means of charging a discharged battery to full capacity. Rather, this method is used to counteract the occurrence of battery self-discharge when the battery is not in use. See Section 3.9 Battery Storage.

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3.8.6 NIMH Rapid/Fast Charging Procedure

The following procedure outlines the six steps for fast or rapid charging a NiMH battery. These steps will provide insight into what the charger chip manufacturers have tried to incorporate into their chips.

3.8.6.1 Initialization Charge

Before fast or rapid charging a battery, a trickle charge rate is recommended. Starting with a pulsed C/10-C/50 trickle charge is good for two reasons. First, to bring up the temperature if the batteries are cold, and second, to verify there are no problems with the batteries or charging circuitry.

3.8.6.2 Temperature Measurement

Before fast or rapid charging can begin, the temperature must be between 10°C and 40°C. This is done as part of the trickle charge step. If a battery has been exposed to lower temperatures, the battery temperature must be brought up to above 10°C before fast charging can begin. Furthermore, take note that the dT/dt parameters will be reached at the beginning of a fast charge on a cold battery, thus resulting in the premature termination. Many chargers incorporate a "low temperature inhibit" to nullify this event.

3.8.6.3 Pack Voltage Measurement (PVM)

The measurement of the battery pack voltage is also part of the trickle charge step. A pack voltage measurement (PVM) can be used to verify that the battery is at the proper voltage level and to verify there is current available for charging. Time (few seconds to 10 minutes) and voltage (1.1 volts x # of cells) are dependent on the type and number of cells used. If the voltage of the battery is not reached in the set time (usually about 20 minutes) the charge is terminated. For PVM a pulse charge at a rate of C/10 to C/50 is recommended, but a constant charge rate of C/10 to C/50 can be used.

3.8.6.4 Rapid/Fast Charge

Rapid charge or fast charge methods require three modes of termination:

1. PVD, or $-\Delta V$, or dT/dt, or ΔT
2. Timer
3. Temperature Cut Off (TCO).

See Table 3.8.5 Charge Method Specification for charge rate information.

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3.8.6.5 Top-Off Charge

Top-off charging is only used if the fast charge or rapid charge does not fully charge the batteries. This occurs with some dT/dt and ΔT terminations. Before using a dT/dt or ΔT fast charging, the charging and termination parameters need to be tested inside the device. Since a constant current top-off charge has a tendency to remove energy, the top-off charge is best to be done as a pulse charge. The top off charge is terminated by time and is C/10 to C/40 of the rapid charge rate.

3.8.6.6 Maintenance

A maintenance charge will retain a full charge on the battery until it is removed from the charger. During the first 24 hours after a battery has been charged, it will lose about 5% of its energy caused by the battery's self-discharge. A standard maintenance charge at a C/128 rate is designed to counter this self-discharge. Some NiMH chemistries are able to handle maintenance charge rates up to a C/64 rate. Continuous charging at low rates is not very efficient, therefore, pulse charging is recommended.

3.9 NiMH Battery Storage Overview

Over time capacity and voltage of NiMH rechargeable batteries will decrease when stored or left unused. This is caused by a chemical reaction that takes place within the cells, commonly referred as self-discharge. The affects of self-discharge will be minimized if unused batteries are properly stored. Proper storage of NiMH batteries requires both temperature control and inventory management.

3.9.1 NiMH Storage Temperature and Battery Cycling

Temperature is the major factor affecting the rate of self-discharge of an unused battery. As storage temperatures increase, the self-discharge rate increases thus causing the maximum storage time of a battery to decrease. It is best to store batteries in a temperature-controlled environment so that the maximum storage time can be accurately determined. Figure 3.9.1 Storage Temperature vs. Storage Time shows the range of storage temperatures that NiMH batteries can be stored and the maximum length of time a battery can be left unused before having to be cycled.

Figure 3.9.1 Storage Temperature vs. Storage Time

Storage Temperature	***Maximum Storage Time (Frequency of Cycling)***
40°C to 50°C (104°F to 122°F)	*Less than 30 days*
30°C to 40°C (86°F to 104°F)	*30 to 90 days*
-20°C to 30°C (-4°F to 86°F)	*180 to 360 days*

The energy storage capability of a battery will be decreased if the battery is allowed to completely self-discharge. The affects of self-discharge can be corrected if the batteries are subjected to cycles of charging and discharging. On the initial charge/discharge cycle, the battery will achieve approximately 95% of rated capacity. Full capacity will be achieved on the second and third cycles.

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3.9.2 NiMH State of Charge

The state of charge (SOC) of an unused NiMH battery has no influence on the required storage temperature or the maximum storage time (see Figure 3.9.1 Storage Temperature vs. Storage Time). A fully discharge battery will last in storage as long as a fully charged battery. Therefore, NiMH batteries can be stored at any state of charge.

3.9.3 NiMH Storage Guidelines

The key to properly storing NiMH rechargeable batteries is establishing good inventory management practices. To prolong the cycle life and maintain battery performance adhere to the following five guidelines:

1. Practice FIFO (First In First Out) inventory rotation.
2. Never store batteries under load.
3. Store batteries in a temperature-controlled environment (see Figure 3.9.1 Storage Temperature vs. Storage Time).
4. Cycle batteries (see Figure 3.9.1 Storage Temperature vs. Storage Time).
5. Store batteries at 65% (±20%) humidity.

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4.0 NiCd Batteries

4.1 NiCd Principles of Operation

In the uncharged condition the positive electrode of a nickel-cadmium cell is nickelous hydroxide, the negative is cadmium hydroxide. In the charged condition, the positive electrode is nickelic hydroxide, the negative metallic is cadmium. The electrolyte is potassium hydroxide. The average operating voltage of the cell under normal discharge conditions is about 1.2 volts.

4.2 NiCd Charging Discharging Chemical Reaction

Figure 4.1 NiCd Chemical Equations

Positive Electrode: $$Ni(OH)_2 + OH^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} NiOOH + H_2O + e^-$$

Negative Electrode: $$Cd(OH)_2 + 2e^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} Cd + 2OH^-$$

Overall Reaction: $$Cd(OH)_2 + 2Ni(OH)_2 \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} Cd + 2NiOOH + 2H_2O$$

4.3 NiCd Charge Chemical Reactions

During the latter part of a recommended charge cycle and during overcharge, nickel-cadmium batteries generate gas like Nickel Metal Hydride batteries. Oxygen is generated at the positive (nickel) electrode after it becomes fully charged and hydrogen is formed at the negative (cadmium) electrode when it reaches full charge. These gases must be vented from the conventional nickel-cadmium system. In order for the system to be over chargeable while sealed, the evolution of hydrogen must be prevented and provisions made for this reaction of oxygen within the cell container. These things are accomplished by the following:

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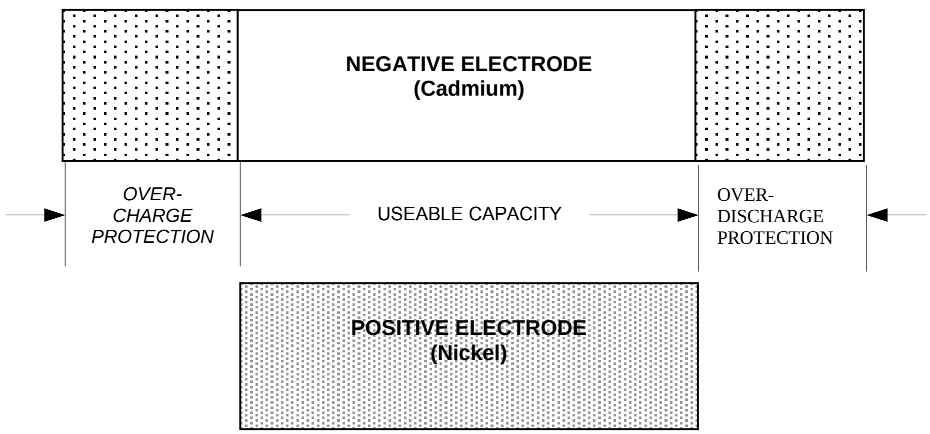
4.3.1 Overcharge Protection

Figure 4.2 Useable Capacity Diagram



- The battery is built with excess capacity in the negative cadmium electrode
- This causes the positive electrode to reach full charge before the negative electrode and it starts to give off oxygen. Since the negative electrode has not reached full charge it will not give off hydrogen.
- The oxygen is absorbed by the nickel fast enough to offset input energy. This keeps the cell in equilibrium.

4.4 NiCd High Current Discharge

High rate nickel-cadmium cells will deliver exceedingly high currents. If the cells are discharged continuously under short circuit conditions, self-heating may do irreparable damage. The heat problems vary somewhat from one cell type to another, but in most cases internal metal strip tab connectors overheat or the electrolyte boils. In some instances, both events occur. General overheating is normally easy to prevent because the surface temperature of the battery can be used to determine when to rest, for cooling, is required. In terms of cutoff temperature during discharge, it is acceptable practice to keep the battery always below 60°C (140°F). The overheated internal connectors are difficult to detect. This form of overheating takes place in a few seconds or less, and overall cell temperature may hardly be affected.

Harding Energy recommends paying close attention to the heat generated by the pack. In special cases, where cooling of the cell or battery is likely to be poor, or unusually good, special tests should be run to check the important temperatures before any duty cycle adjustment is made. Output capacity that is composed of pulses is difficult to predict accurately because there are infinite combinations of current, "on" time, rest time, and endpoint voltage. Testing on a specific cycle is the simplest way to get a clear understanding of temperature issues for a pack design.

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4.5 NiCd Over Discharge

When cells are connected in series and discharged completely, small cell capacity differences will cause one cell to reach complete discharge sooner than the remainder. The cell, which reaches full discharge first, might be driven into reverse by the others. When this happens in an ordinary nickel-cadmium sealed cell, oxygen will evolve at the cadmium electrode and hydrogen at the nickel electrode. Gas pressure will increase as long as current is driven through the cell and eventually it will vent. This condition is minimized in some sealed nickel-cadmium cells by special construction features. One technique uses a reducible material in the positive in addition to the nickel hydroxide, to suppress hydrogen evolution when the positive expires. Discharging to the point of reversal should be avoided.

4.6 NiCd Voltage Depression (Memory Effect)

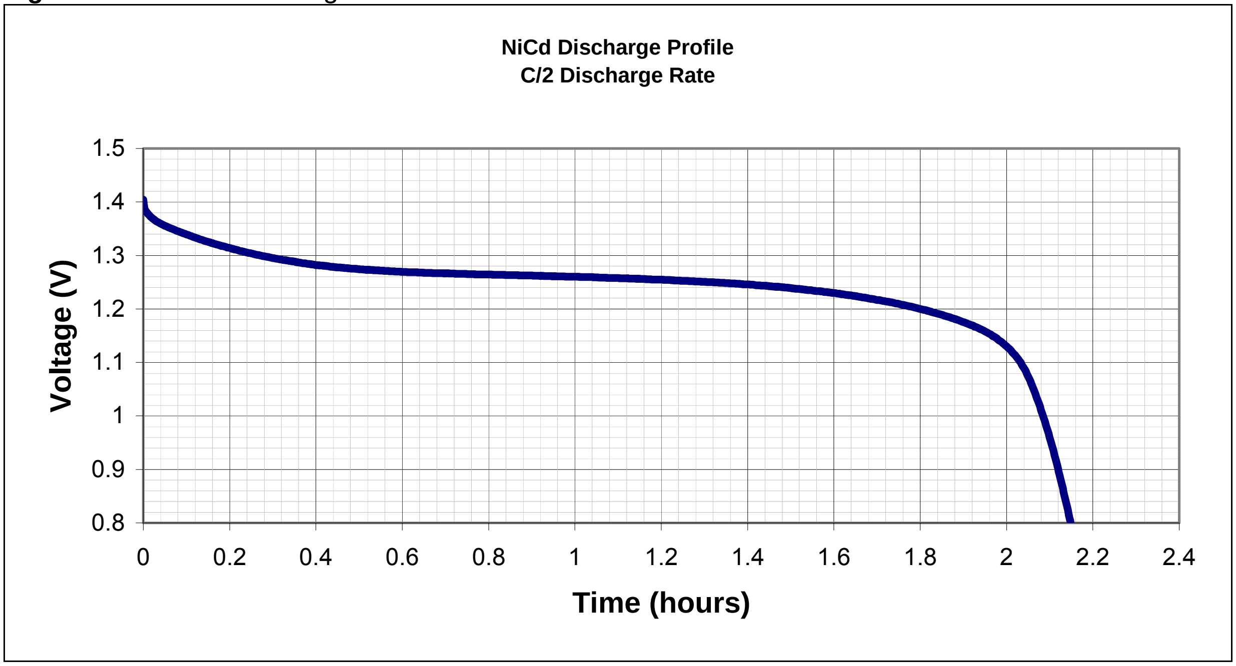
Voltage depression is the characteristic attributed to nickel-cadmium cells wherein the cell retains the characteristics of the previous cycling. After repeated shallow depth discharges the cell will not provide a full depth discharge. The cell remembers the level of discharge and the voltage of the cell emulates that of a fully discharged cell. This is reversible by conditioning the cell with several deep discharges.

4.7 NiCd Discharge Characteristics

4.7.1 Voltage

The voltage output curve on NiCd Cells nearly is identical to the NiMH. See Figure 4.7.1. The only difference is the knee of the NiCd voltage profile tends to be steeper.

Figure 4.7.1 NiCd Discharge Profile



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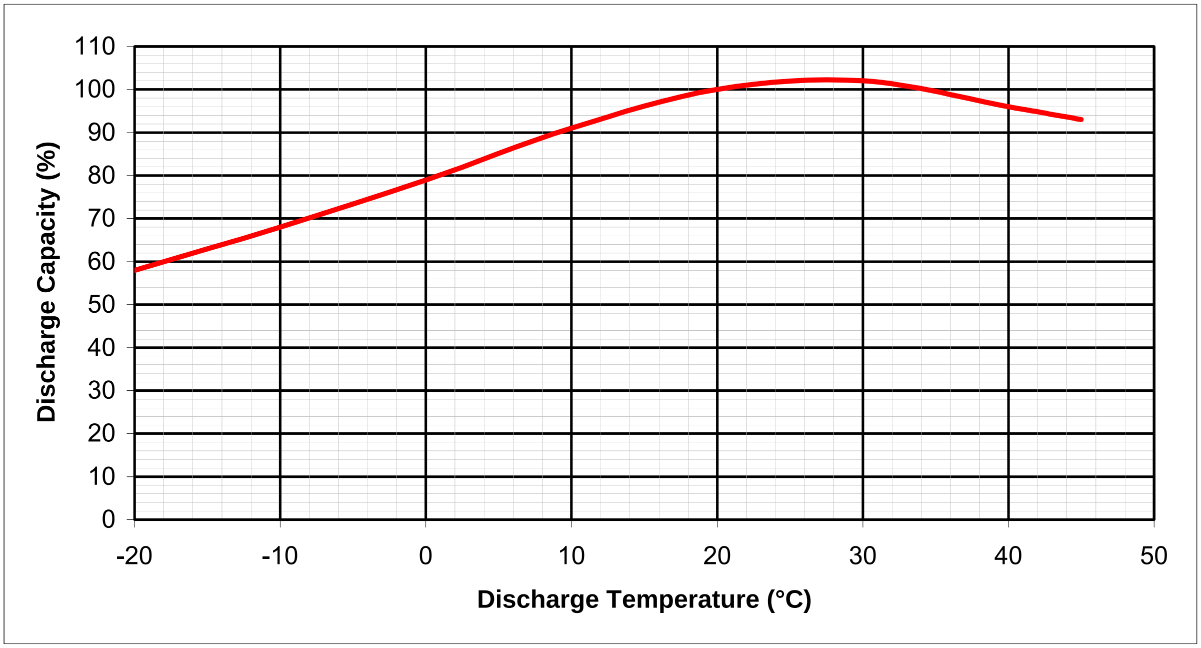
4.7.2 Temperature

The affect of temperature on NiCd cells is not as dramatic as on NiMH but it is still a significant factor as can be seen in the Figure 4.7.2. This is for a 0.2C discharge rate.

Figure 4.7.2



4.8 NiCd Charge Characteristics Overview

Constant current charging is recommended for sealed nickel-cadmium cells. The C/10 rate should not be exceeded unless overcharge is acceptable. The recharge efficiency of sealed nickel-cadmium cell is dependent on a number of things, but it is most important to remember that charging becomes more difficult as temperature increases and charge rate decreases. It is possible, under certain conditions, to charge at rates much higher than the C/10 charge rate, but control devices which prevent high rate over-charge are typically required.

The nickel-cadmium battery can be trickle charged but floating and constant voltage charging are not recommended. For maximum performance in situations of long term trickle charge, the current required to keep the battery fully charged is approximately C/30 to C/50.

4.8.1 Charging Temperature requirements

<u>C/7 to C/10 Charge Rate</u>
- Cells should not be charged below 0°C
- At 45°C charge efficiency will be about 50%

<u>C/1 to C/3 Charge Rate</u>
- Cells should not be charged below 15°C at the 1 hour rate
- Cells should not be charged below 10°C at the 3 hour rate
- At 45°C efficiency will be about 90%

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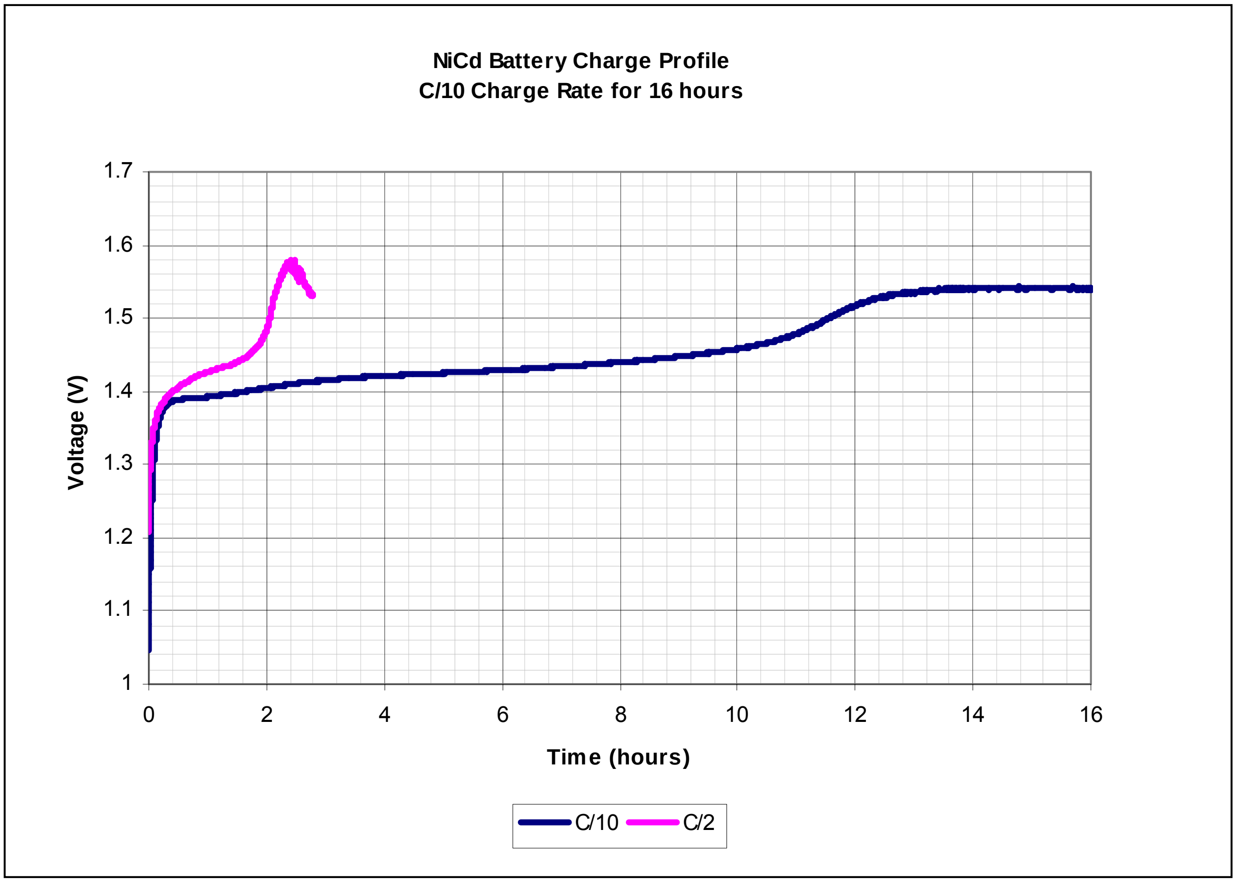
Figure 4.8.1 Typical NiCd Charge Curve



4.8.2 *NiCd Charge Termination*

Properly controlling the charging of a NiCd battery is not as critical to achieving optimum performance as in NiMH. Charge control incorporates proper charge termination to prevent overcharging the battery. The overcharging of a battery refers to the state at which the battery can no longer accept (store) the energy entering the battery. As a result pressure and temperature builds up within the cell. If a cell is allowed to remain in the overcharge state, especially at high charge rates, the pressure generated within the cell can be released through the safety vent located within the positive terminal. This may cause damage to the battery reducing cycle life and capacity.

To prevent damage occurring to the battery, charge termination is one of the most critical elements to be applied to any method of charge control. Charge control may utilize one or more of the following charge termination techniques. The three primary techniques of charge termination are time, voltage, and temperature.

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4.8.2.1 Time

Time-based charge control techniques terminate charging of the battery after a predetermined length of time. This technique should be used when slow charging to avoid excessive overcharge, and used as a backup secondary termination for all fast charge methods.

4.8.2.2 Voltage

Charge control techniques that are voltage-based are attractive because of the predictable charge voltage profile of a NiCd battery (see Section 4.8.3 NiCd Charge Termination Nomenclature). The charge voltage profile of a NiCd battery is consistent regardless of the batteries state of charge. However, the voltage-based charge termination techniques generally occur after a battery has already reached the overcharge state. Depending on charge rate, it may also be necessary to include temperature-sensing devices to terminate the charge if the temperature becomes too high. Such devices include thermostats and PTC resettable fuses.

Negative Delta V (-ΔV)

Negative delta V (-ΔV), senses the drop in battery voltage after the battery has reached its peak voltage. The change or drop in voltage is to 10 to 15 mV per cell before the charge is terminated. This technique allows the battery to be exposed to longer periods of overcharge and is not normally recommended. See Section 4.8.3 Charge Termination Nomenclature

4.8.2.3 Temperature

The temperature-based charge termination senses this temperature rise and terminates the charge when the battery has reached a temperature that indicates when overcharge has begun. This type of charge termination is recommended because of its reliability in sensing overcharge, yet it requires care in the selection of set points in the charge circuitry to avoid premature charge termination or failure to detect the overcharge when the battery is exposed to extreme temperature environments.

Change in Temperature (ΔT)

Change in temperature or ΔT is the technique that measures the difference of the rise in battery temperature above the starting (ambient) temperature during charge. The charge is terminated when the rate of change in temperature reaches a predetermined value. See Section 4.8.3 NiCd Charge Termination Nomenclature

Change in Temperature/Change in time (dT/dt)

The recommended technique for temperature-based charge termination for all fast-charging methods is dT/dt (see Section 4.8.3 NiCd Charge Termination Nomenclature). This technique monitors the change in temperature T verses the change in time t, and is considered most accurate because it senses the start of overcharge earlier than other techniques. Standard dT/dt temperature termination is between 0.5 to1°C per minute depending on pack

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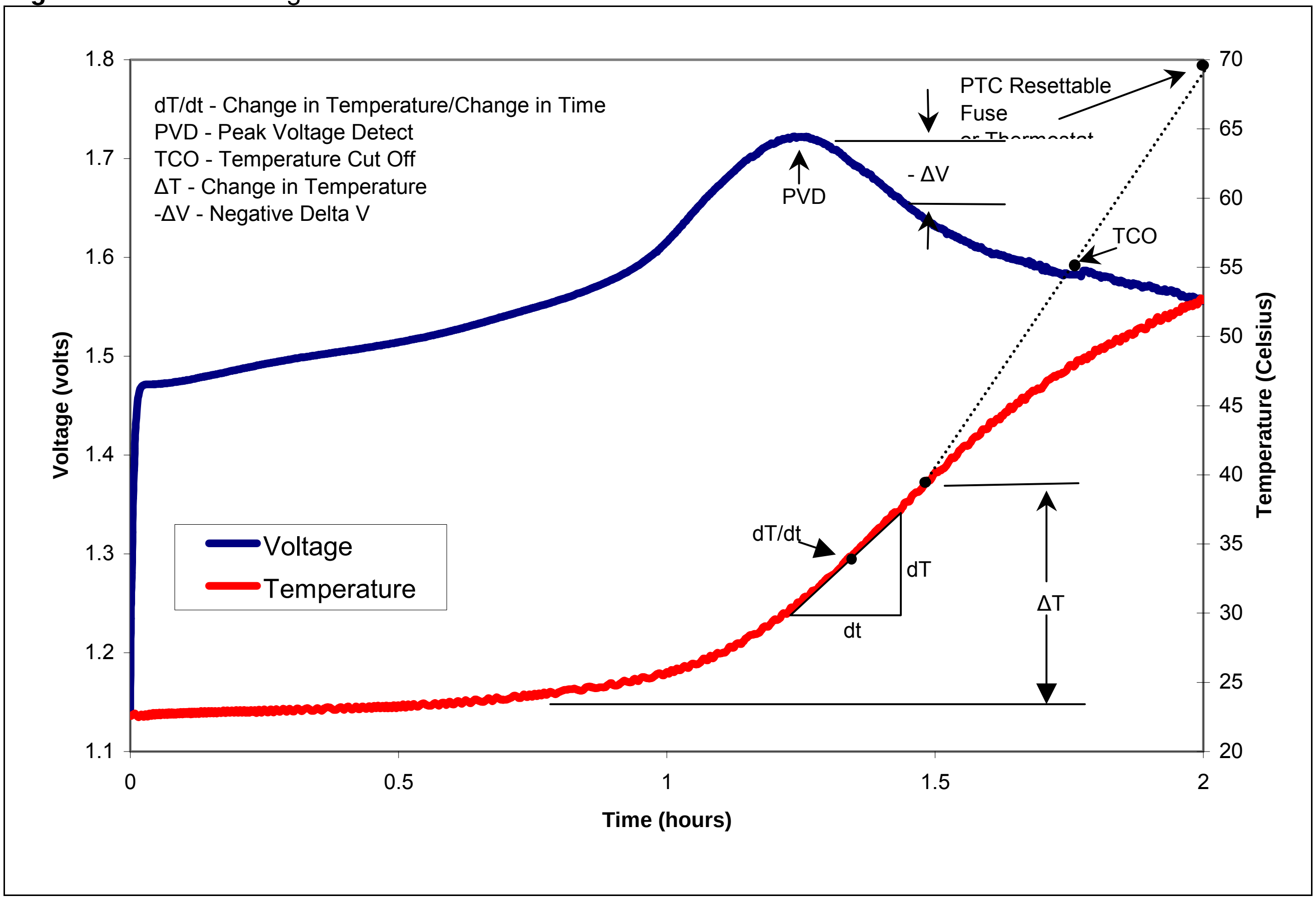
configuration and charge rate. When using a dT/dt termination, a top-off charge is suggested in order to fully charge the battery (see Section 4.8.6.5 Top-Off Charge).

Temperature *Cut Off (TCO)*

Temperature cut off or TCO is a secondary termination required for all fast-charging methods using dT/dt or -ΔV. This technique is based on the absolute temperature of the battery and is recommended only as a fail-safe strategy to avoid destructive heating in case of failure of any or all other charge termination technique(s). See Section 4.8.3 NiCd Charge Termination Nomenclature

4.8.3 NiCd Charge Termination Nomenclature

Figure 4.8.3 NiCd Charge Termination Nomenclature



4.8.4 NiCd Temperature and Charge Efficiency

The recommended charging temperature is between 10°C (50°F) and 40°C (104°F). If a NiCd battery is exposed to high temperatures (above 40°C, 104°F) due to overcharging or external heat sources, the charge efficiency (increase in stored cell capacity per unit of charge input) will be decreased. In order to avoid decreased charge efficiency, batteries should have charge control methods applied to limit the amount of overcharge heat that is generated. In addition, it is critical not to place batteries in close proximity to other sources of heat or in compartments with limited cooling or ventilation.

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At temperatures below 10°C (50°F) charge efficiency will also decrease resulting in an increase in the amount of time need for charging. Low temperatures inhibit transport capabilities (the ability to move ions within the electrodes) causing the low charge efficiency (see Section 2.1.5, Principles of Operation and Construction; Rate Capability). Charging below 0°C (32°F) is not advisable.

4.8.5 NiCd Charge Methods

Not all charge methods are recommended for all NiCd cell chemistries, since they are not designed the same. Different materials are used in various NiCd cells to achieve certain desired performance characteristics. The selection of these materials also affects the charging characteristics of the batteries. Therefore, any method that could cause problems with some batteries has been noted for each charge method. See Figure 4.8.5 Charge Method Specifications for recommended charge currents and charge terminations.

Figure 4.8.5 Charge Method Specifications

Charge Method	Charge Current	Charge Termination	Comments
Slow	0.02-0.1C	1. None[1] or Timer	Timer rated at 160%C.
Time	0.1-0.2C	1. Timer, and 2. TCO = 55°C	Timer rated at 160%C @ 0.1C to 120%C @ 0.2C.
Rapid[2]	0.25-0.5C	1. dT/dt, or ΔT, and 2. Timer, and 3. TCO = 55°C	-ΔV of 10-15 mV/cell dT/dt = ~1°C/1 min rise. Timer rated at 140%C @ 0.2C to 120%C @ 0.5C.
Fast[2]	0.5-1.0C	1. dT/dt, or ΔT, and 2. Timer, and 3. TCO = 55°C	-ΔV of 10-15 mV/cell dT/dt = ~1°C/1 min rise. Timer rated at 125%C.
Maintenance	0.002-0.008C	1. None	5-10%C per day at C/128 to C/512 pulse recommended.
[1] Not all batteries can be charged without a termination. [2] See Rapid/Fast Charging Procedure (Section 6.6).			

4.8.5.1 Slow Charge

When charge time is not an issue and maximum rechargeable capacity is desired, the slow charge method is often used. This method uses a charge that is less than 0.1C and for more than 16 hours (see Figure 4.8.5 Charge Method Specifications). Yet, with the recent developments of some NiCd cell chemistries to be better suited to faster charging methods, slow charging is not recommended for all NiCd batteries.

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4.8.5.2 Time Charge

For the faster timed charge method, batteries can typically be charged in 6 to 16 hours. This method of charging NiCd batteries requires the most attention before selection. Since this method uses higher rates of current (see Figure 4.8.5 Charge Method Specifications), two methods of termination are needed: timed and TCO. The later of the two terminations would require the battery to include a thermistor to detect the temperature during the charge cycle. If only a timed charged termination was used, the battery may be pushed into overcharge, especially if a partially discharged battery was charged using this method. For some NiCd cell chemistries this would significantly deteriorate battery performance.

4.8.5.3 Rapid Charge

The Rapid Charge method is good for applications needing a faster charge, but the battery compartment or housing does not allow for good heat dissipation. Rapid charge methods typically charge in 2.5 to 6 hours using charge rates of 0.25C to 0.5C (see Figure 4.8.5 NiCd Charge Methods). This method of charging uses - ΔV, dT/dt or ΔT with time backup. For further charging details see Section 4.8.6 Rapid/Fast Charging Procedure. This system usually uses a temperature backup to ensure against overcharging.

The advantage of this charge method is the ability to safely charge batteries that are at any state of charge. In other words, a partially discharged battery can be charged without the risk of being overcharged. The disadvantage to this type of system is the added complexity and expense of the charger.

4.8.5.4 Fast Charge

When time is a limited resource and there is good heat dissipation, Fast Charge methods are the best approach. Fast Charge methods will charge batteries in 2.5 hours or less. Like the Rapid Charge method, this method has increased charge rates and requires three separate charge terminations (see Figure 4.8.5 Charge Method Specifications).

As with the Rapid Charge, the advantages of the Fast Charge method is the ability to safely charge batteries that are at any state of charge in a short period of time. The disadvantages are, again, the added complexity of the charger and expense.

4.8.5.5 Maintenance Charge

Unlike the previous methods the Maintenance Charge method is not considered a means of charging a discharged battery to full capacity. Rather, this method is used to counteract the occurrence of battery self-discharge when the battery is not in use. See Section 4.9 NiCd Storage Guidelines.

[1] Contact Harding for listing of current items in stock

4.8.6 NiCd Rapid/Fast Charging Procedure

The following procedure outlines the six steps for fast or rapid charging a NiCd battery. These steps will provide insight into what the charger chip manufacturers have tried to incorporate into their designs.

4.8.6.1 Initialization Charge

Before fast or rapid charging a battery, a trickle charge is recommended. Starting with a pulsed C/10-C/50 trickle charge is good for two reasons. First, to bring up the temperature if the batteries are cold, and second, to verify there are no problems with the batteries or charging circuitry.

4.8.6.2 Temperature Measurement

Before fast or rapid charging can begin, the temperature needs to be above 10°C. Furthermore, take note that the dT/dt parameters will be reached at the beginning of a fast charge on a cold battery, thus resulting in the premature termination. Many chargers incorporate a low temperature inhibit to nullify this event.

4.8.6.3 Pack Voltage Measurement (PVM)

The measurement of the battery pack voltage is also part of the trickle charge step. A pack voltage measurement (PVM) can be used to verify that the battery is at the proper voltage level and to verify there is current available for charging. Time (few seconds to 10 minutes) and voltage (1.1 volts x # of cells) are dependent on the type and number of cells used. If the voltage of the battery is not reached in the set time (usually about 20 minutes) the charge is terminated. For PVM, a pulse charge at a rate of C/10 to C/50 is recommended, but a constant charge rate of C/10 to C/50 can be used. Pack temperature must be raised to between 10°C and 40°C. This is done as part of the trickle charge step.

4.8.6.4 Rapid/Fast Charge

Rapid charge or fast charge methods require three modes of termination:

1. $-\Delta V$, or dT/dt, or ΔT
2. Timer
3. Temperature Cut Off (TCO).

See Table 4.8.5 Charge Method Specification for charge rate information.

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4.8.6.5 Top-Off Charge

Top-off charging is only used if the fast charge or rapid charge does not fully charge the batteries. This occurs with some dT/dt and ∆T terminations. Before using a dT/dt or ∆T fast charging, the charging and termination parameters need to be tested inside the device. The top-off charge is best to be done as a pulse charge. The top off charge is terminated by time and is some fraction of the rapid charge rate.

4.8.6.6 Maintenance

A maintenance charge will retain a full charge on the battery until it is removed from the charger. During the first 24 hours after a battery has been charged, it will lose about 5% of its energy caused by the battery's self-discharge. A standard maintenance charge at a C/128 rate is designed to counter this self-discharge. Some NiCd chemistries are able to handle maintenance charge rates up to a C/10 rate. Continuous charging at low rates is not very efficient, therefore, pulse charging is recommended.

4.9 NiCd Storage Guidelines

There are no detrimental effects of storing between –20 °C and 40°C. However, above 32°C self-discharge will be considerably higher than at room temperature. It is recommended that batteries be stored at 21°C (70°F) or lower for this reason.

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5.0 Lithium Ion (Li-Ion)

5.1 Li-Ion Principles of Operation

The lithium Ion battery employs a metal oxide material (such as lithium cobalt oxide $LiCoO_2$), or a material with a tunneled structure (such as lithium manganese oxide $LiMn_2O_4$) as its positive electrode. The negative electrode is typically a graphitic carbon. During the charge and discharge processes, lithium ions are inserted or extracted from interstitial space between atomic layers within the active material of the battery.

5.2 Charge/Discharge Chemical Reaction

During charge, the positive material is oxidized and the negative material is reduced. In this process, lithium ions are de-intercalated from the positive material and intercalated into the negative material. (Intercalated – a reaction where lithium ions are reversibly removed or inserted into a host without a significant structural change to the host) The reverse process is present during a discharge cycle.

Figure 5.2.1: Charge/Discharge Chemical Reactions

Positive: $$LiXXO_2 \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} Li_{1-x}XXO_2 + Li^+ + xe^-$$

Negative: $$C + xLi^+ + xe^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} Li_xC$$

Overall: $$LiXXO_2 + C \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} Li_xC + Li_{1-x}XXO_2$$

XX= Various Combining elements including Cobalt and Manganese

5.3 Overcharge/ Over Discharge

A strict charging regime is necessary to properly and safely charge lithium ion batteries. Most batteries contain a protective circuit to prevent overcharge and over discharge. This circuit limits the charge voltage to a maximum 4.3 volts, and 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. The Lithium Ion batteries permanently lose capacity when exposed to elevated temperature greater than 65 °C.

The protective circuit also limits the discharge voltage to between 2.7 and 3.0 volts per battery. In spite of these preventative measure, over discharge may still occur. If a lithium battery has dwindled to a voltage of less than 1.5 volts per battery, recharge should be avoided. Copper shunts may form inside the battery, causing a partial or total short circuit. In this case, the battery becomes unstable, charging the battery would cause excessive heat, and safety cannot be assured.

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5.4 Rate Capability

Table 5.4.1: Charge/Discharge Chemical Reactions

Typical Performance Characteristics of Lithium Ion Batteries	
Operational Battery Voltage	4.2 to 2.7 Volts
Specific Energy	100 to 158 W/kg
Energy Density	245 to 430 W/L
Continuous Rate Capability	Typical: 1C High Rate: 5C
Pulse Rate Capability	Up to 25C
Cycle Life at 100% DOD	Typically 500
Calendar Life	3 - 5 years
Self Discharge Rate	0.3% / month
Operable Temperature Range	-20 °C to 60 °C
Memory Effect	None

Note: Characteristics can change according to improvements in chemistry or special niche requirements.

5.5 Discharge Characteristics

At a constant current discharge rate, the lithium ion battery maintains a relatively flat voltage discharge profile with a steep decrease in the profile near the end of discharge. The battery should not be discharge to less than 3.0 volts per battery.

5.6 Charging Characteristics

Operating temperatures for charging are –10 °C to 60. The lithium ion batteries require a controlled charge regime to properly charge the battery and prevent overcharge during the charge cycle. The two-stage charge cycle must be performed to fully charge the battery. This is called a CC/CV charge cycle.

- 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.

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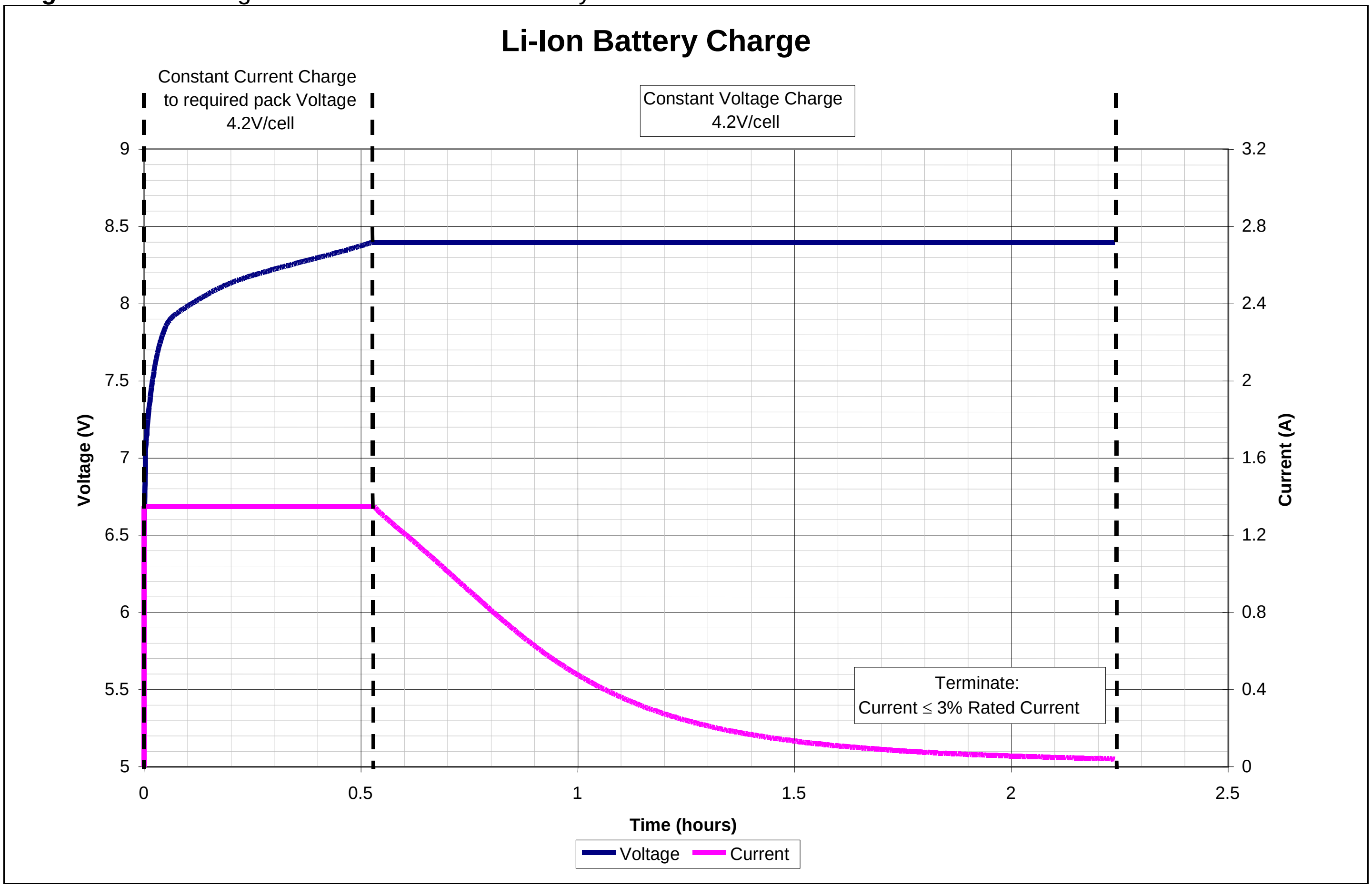
Figure 5.6.1: Charge Profile of Lithium Ion Battery Pack



5.7 Li-Ion Battery Storage Guidelines

Batteries should be stored at 15 °C (59 °F) with a 30% to 50% state of charge

5.8 Li-Ion Cell Nomenclature

5.8.1 Pack Nomenclature

When Lithium ion cells are assembled into packs of series and parallel, the arrangement is specified in the form NSXP. Where N is the number of cells in series and X is the number of cells in parallel. For example a 3S4P pack of 1500 mAh cells would be built of four, three-cell series packs in parallel. The nominal voltage for this pack would be 11.1 V and the total capacity would be 6000 mAh.

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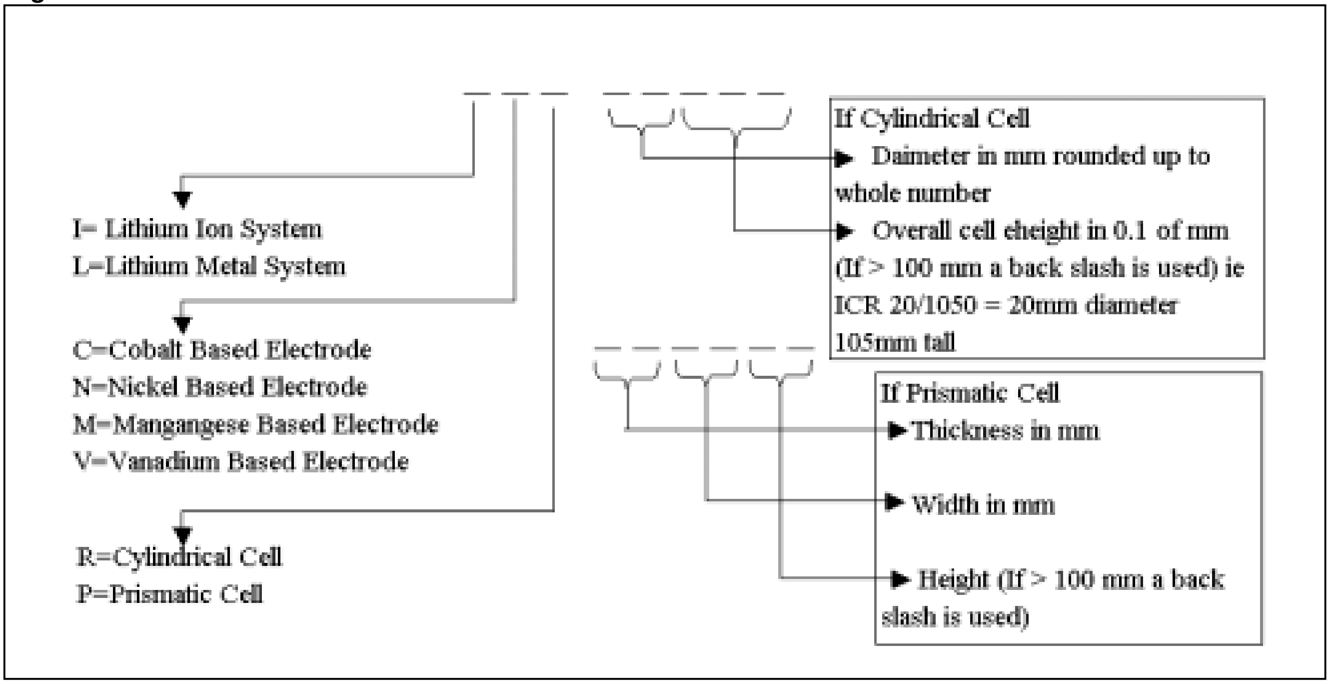
Figure 5.8.1: Li-Ion Cell Nomenclature



5.9 Li-Ion Cautions

<u>Lithium Ion Batteries and packs that are abused may get hot, explode, or ignite and cause serious injury!</u>

- 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
- Do not install the battery/ pack backwards
- Charge only with charger specified by equipment manufacturer

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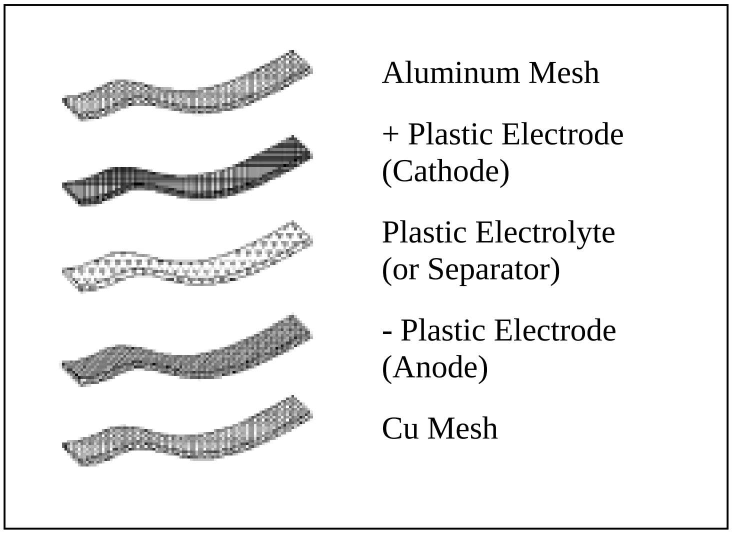
6.0 Lithium Polymer (Li-Pol)

A Lithium polymer is technically a lithium-ion polymer battery. It is very similar to the lithium ion battery but without some of the shortcomings. It can sustain a significant amount of abuse. For example a fully charged Lithium Polymer battery can be punctured with a nail without explosion or fire.

It originally used a plastic anode material and SPE (Solid Polymer Electrolyte) as the electrolyte. This comparatively new technology is rapidly evolving and improving. Currently we use a gelled electrolyte and separator. The data below is based on the current technology at the time of publication.

Figure: 6.0 Lithium Polymer Cell Construction



6.1 Lithium-Polymer Principles of Operation

The lithium-polymer electrochemistry currently covers a wide range of active materials such as $LiCoO_2$, $LiNiO_2$, and its Co doped derivatives. Harding uses $LiCoO_2$ chemistry.

Rather than the traditional metal can used by other small rechargeable cells, Lithium Polymer Batteries employ a thin (110 µm), polymer-based packaging material to contain the electrochemical materials. This allows the system to have a flat thin (2 to 5 mm) form factor. It is also possible to make the footprint of the cell large (e.g. 70mm by 100mm), this being ideally suited to handheld devices such as PDA's.

Since the case of the cell starts as a sheet of polymer-laminate, changing the footprint of the cell is cost effective. Also, if the Lithium Polymer cell uses a 'stacked' construction, adjusting the electrode/electrolyte structure is also easy. In this way, Lithium Polymer cells exhibit flexibility in their mechanical properties and flexibility in their construction.

[1] Contact Harding for listing of current items in stock

6.2 Charging Chemical Reaction

When Lithium Polymer cells are first charged, lithium ions are transferred from the layers of the lithium cobaltite to the carbon material that forms the anode.

Figure 6.2 Initial Charge

$$LiCoO_2 + 6C \rightarrow Li_{1-x}CoO_2 + Li_xC_6$$

Subsequent discharge and charge reactions are based on the motion of lithium ions between anode and cathode.

6.3 Discharging Chemical Reaction

Figure 6.3

$$Li_{1-x}CoO_2 + Li_xC \longleftrightarrow Li_{1-x+dx}CoO_2 + Li_{x-dx}C$$

During charge/discharge Li+ ions are transported back and forth between two insertion electrodes

6.4 Overcharge

A strict charging regime is necessary to properly and safely charge Lithium 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.

6.5 Over Discharge

Cell should cutoff at 3.0 Volts.

6.6 Discharge Characteristics

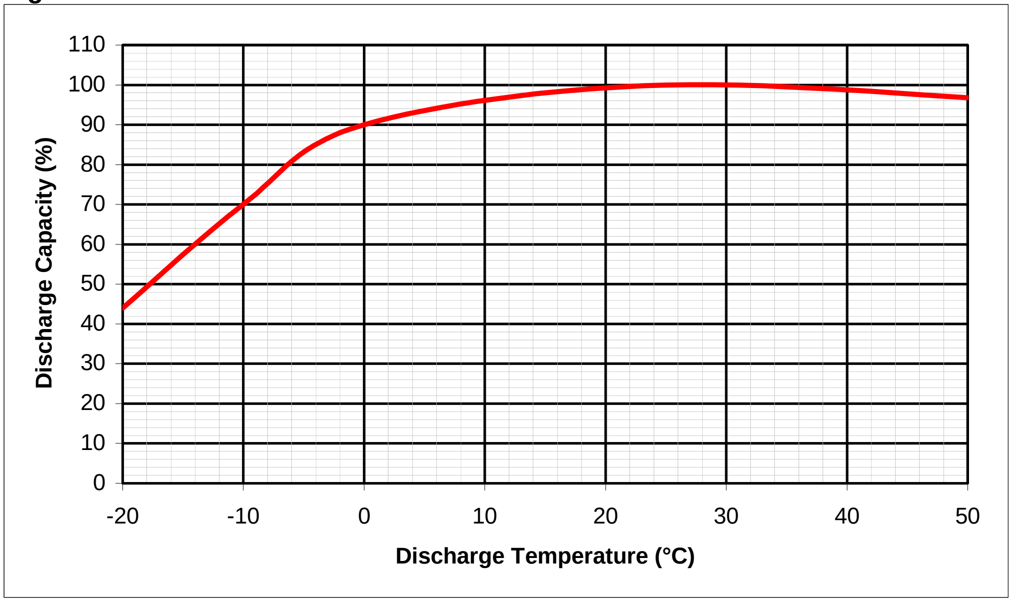
Operating temperatures for Discharging are -10°C -60°C

6.6.1 Temperature

Temperature is a significant factor on available capacity as shown on Figure 6.6.1.

[1] Contact Harding for listing of current items in stock

Figure 6.6.1



6.7 Charging Characteristics

- 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

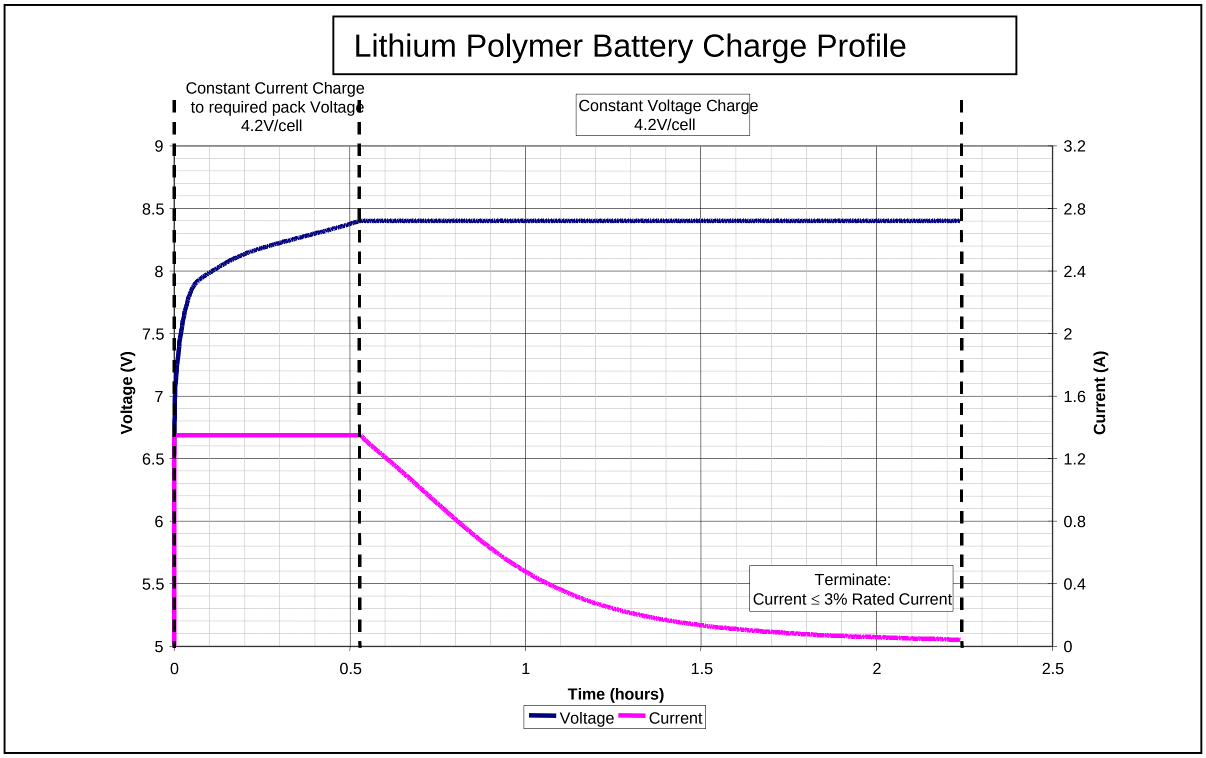
6.7.1 Charge Cycle

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.

[1] Contact Harding for listing of current items in stock

Figure 6.7.1: Charge Profile of Lithium Polymer Battery Pack



6.8 Lithium Polymer Storage Guidelines

- 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.

6.9 Protection Circuit

Malfunction may be caused by the unstable Lithium Polymer battery structure when it is overcharged or over discharged. Accordingly, a protection circuit is necessary to fend off this malfunction. By monitoring voltage of each battery, charging or discharging is limited by breaking the current when the monitored voltage deviates from normal levels. The flow of current is cut off in the case when the current flow is excessive. This is done with an IC, FET, Fuse and/or PTC Thermal Fuse.

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6.10 Lithium Polymer Cautions

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

[1] Contact Harding for listing of current items in stock

7.0 NiCd and NiMH Battery Pack Design Overview

NiCd and NiMH fall into a different design category than Lithium based batteries. This section is about Nickel based packs. Battery pack describes any grouping of individual cells physically connected to one another to achieve the dimensional and electrical characteristics desired. Many of today's NiMH battery packs are assembled as "drop-in" replacements for NiCd's, but many custom batteries are being developed as new portable products are introduced. A Nickel battery pack can be designed to fit into most compartments, cases and enclosures, as long as the physical dimensions match that of electrical requirements. For all new product designs battery packs should be designed before the area in which it will be enclosed. This will ensure all aspects of the battery pack have been established before costly tooling is made for the battery enclosure.

Before a battery pack can be designed and assembled, both electrical requirements and physical parameters need to be determined. The following sections identify key factors in designing a battery pack best suiting the requirements of a given application and ensuring cost effective reproducibility.

7.1 Electrical Requirements

Typically, the electrical requirements needed to run a device or application are already known when the battery pack is to be designed. The primary elements regarding battery pack design are:

- Pack voltage
  - Nominal
  - Maximum
  - Minimum
- Capacity (or runtime)
  - Maximum Current
  - Average Current
  - Temperature
- Charging
  - Required Charge Time
  - Temperature during charge and ability to dissipate heat

As previously discussed in previous sections, both the voltage and capacity of a battery pack are dependent on the conditions in which the battery is discharged and charged. Therefore, the discharge and charge requirements of a device need to be identified.

7.1.1 Discharge Requirements

- Nominal Voltage
  The pack voltage is based on the number of cells in the battery pack. The industry standard for the rated voltage of Nickel based cells are 1.2V. Thus, five cells of 1.2V each connected together in series would result in a battery pack with a pack voltage of 6.0 Volts.

- Maximum Voltage
  It is important to know the discharge rate in order to design a battery pack with the appropriate voltage, capacity and electrical components. For all sizes of Nickel based batteries, there is no significant effect on voltage and capacity for discharge rates below 1C. A reduction in the nominal voltage occurs for discharge rates between 1C and 3C for most Nickel based batteries.

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- Minimum Voltage
  Equally important is the identification of the voltage cutoff or discharge termination to protect against damage occurring to the battery pack at the end of discharge.

- Temperature
  At high discharge rates the over heating of the battery could cause derating of the capacity. The pack should be designed to dissipate heat if high current draw is required.

7.1.2 Capacity (or Runtime)

The amount of capacity, or runtime, that a battery pack will have is dependent on many factors.

- Cell size
  Determines the amount of capacity a battery pack will have, and is directly associated to the amount of room there is in the battery compartment/enclosure (See www.hardingenergy.com for Cell Specification Data Sheets for capacity and dimensional information).

- Discharge rate
  Has an influence on the amount of capacity/runtime that a battery pack will deliver (see Section 3.7. NiMH Discharge Characteristics and 4.7 NiCd Discharge Characteristics).

- Charge method
  See Section 3.8 NiMH Charge Characteristics Overview and 4.8 NiCd Charge Characteristics Overview.

- Environment
  The environment in which the battery pack is used, and the electrical configuration (series/parallel) of the battery pack will also have some affect on the capacity of a battery.

To determine the runtime for a battery in an application, divide the battery's rated capacity, C, by the discharge rate for the application. For example, a battery with a capacity of 1500 mAh discharged at 750 mAmps (with proper discharge termination) would have a runtime of 2 hours.

7.1.3 Charge Requirements

The charging of a battery pack will have some influence on performance, but does not need to be in place at the time that a battery pack is first designed. Yet, consideration of the basic methods of charging NiMH batteries needs to be done to ensure the designed battery pack and battery enclosure will be compatible with the charge method(s) that may be desired (see Section 3.8 & 4.8 Charge Characteristics). This includes the dissipation of the heat generated by the battery when charged. This is especially true just before and during the event of the battery being overcharge. In addition, it is critical not to place batteries in close proximity to other sources of heat or in compartments with limited cooling or ventilation.

[1] Contact Harding for listing of current items in stock

7.2 Battery Pack Construction

After the electrical requirements have been determined, the designing of the battery pack can begin. The areas that need to be considered in battery pack design include:

1. Battery Pack Configuration
2. Protective Devices
3. Connectors
4. Packaging
5. Labeling

With the rising demand for portable battery packs, the materials and technologies for battery pack assembly have become more advanced and refined. The basic materials used in the construction of a battery pack can be seen in battery pack assemblies from around the world. The following three figures illustrate the basic construction materials and components as well as some of the specialized devices of a battery pack assembly to be discussed.

Figure 7.2.1 Basic Battery Pack Components

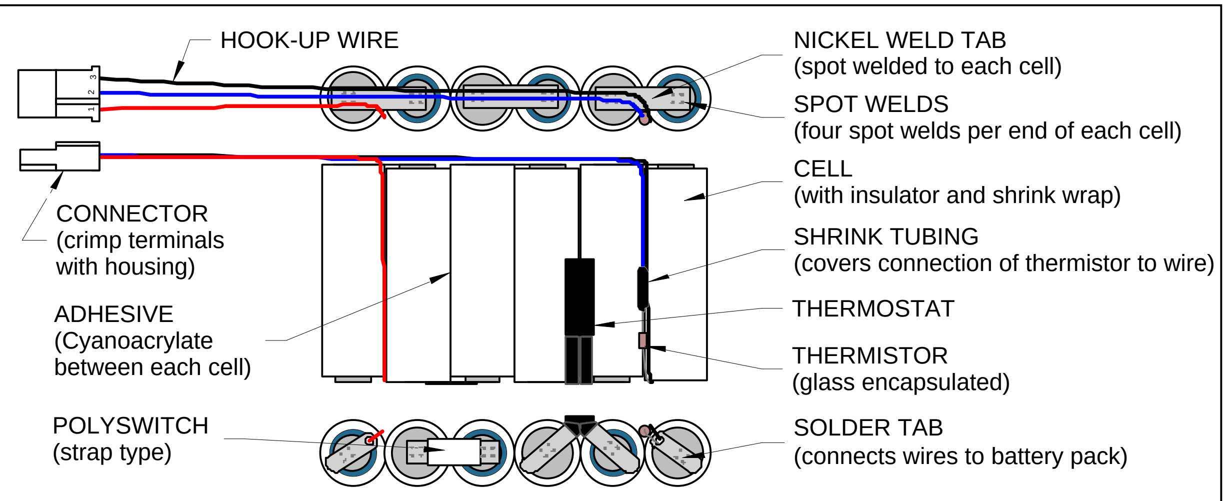

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Figure 7.2.2 Insulative Battery Materials

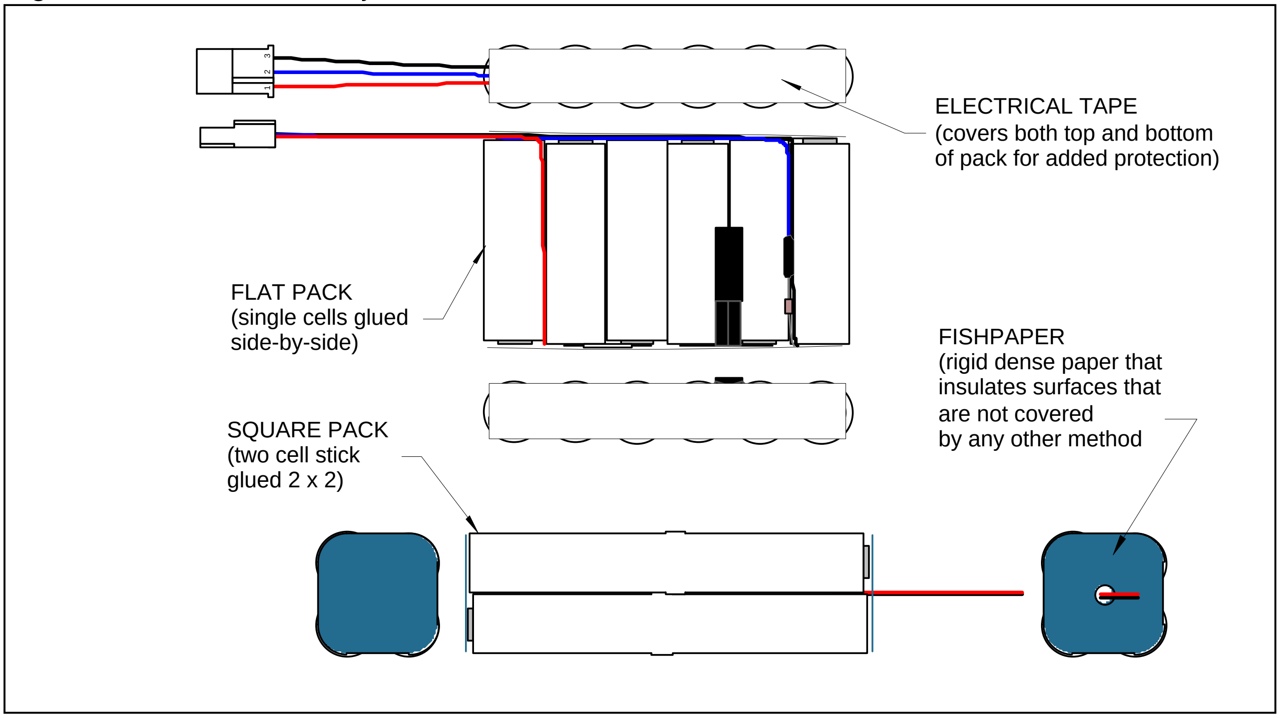
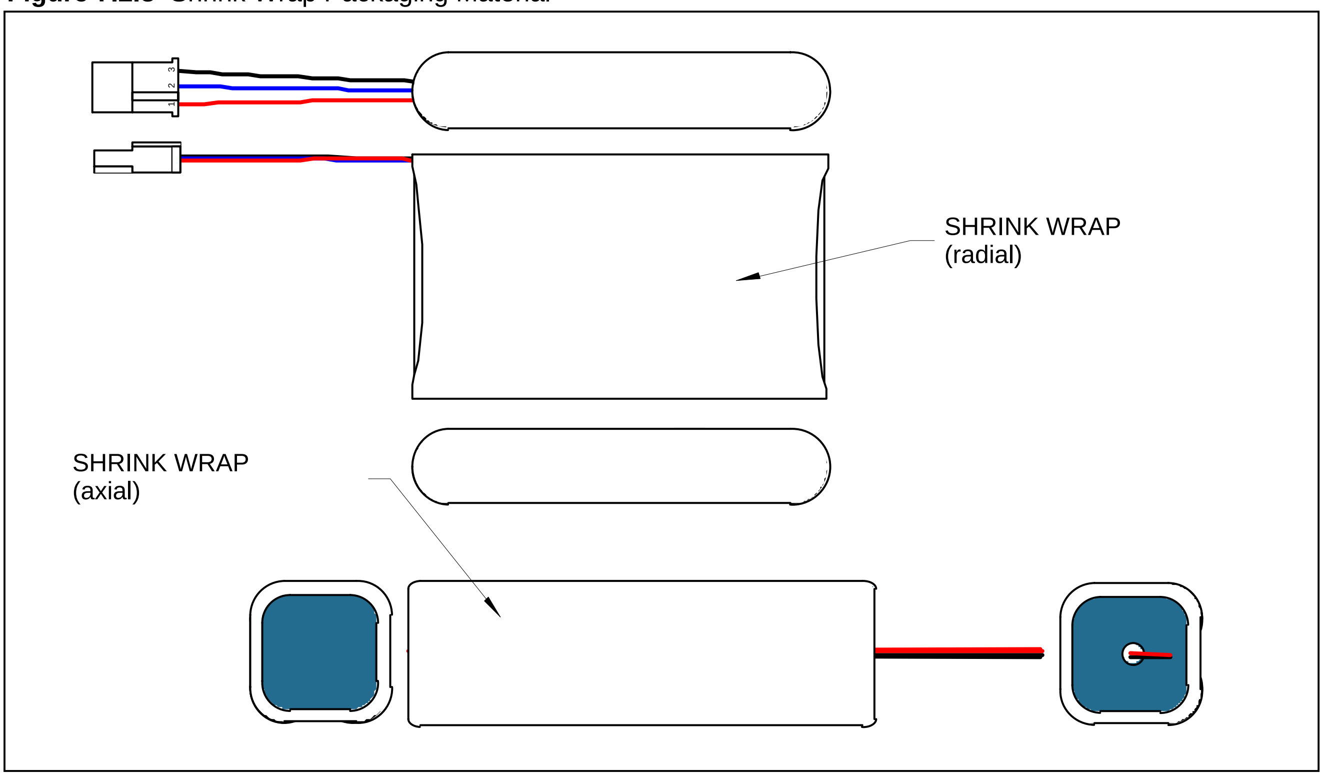


Figure 7.2.3 Shrink Wrap Packaging Material



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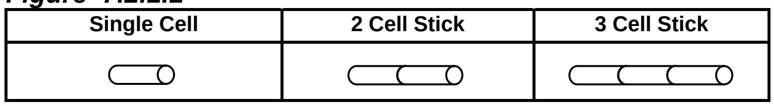
7.2.1 Nickel Battery Pack Configuration

Based on the electrical requirements and size (dimensional) restrictions, the actual physical construction or battery configuration can be determined.

Figure 7.2.1.1



Cell Type (Size)

The type, or size, of the cells to be used in the battery pack is determined once the pack voltage, capacity, and dimensional requirements have been identified. The list of cell sizes and designs is continually growing as the market for NiMH batteries becomes more diverse (see www.hardingenergy.com for Quest® NiMH cell sizes available).

Cell Configuration

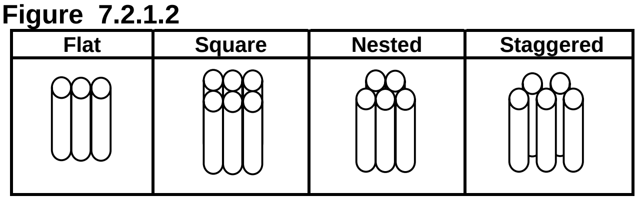
The cell configuration refers to the way an individual cell is assembled into a battery pack. The common cell configurations are either a "single" individual cell or an assembled "stick" of two, three, or more cells welded together end-to-end as shown in Figure 7.2.1.1

The "single cell" or "cell sticks" are then assembled into the desired battery pack configuration. (Note: the "cell stick" configurations are sometimes considered as a finished battery pack)

Pack Configuration

The battery pack configuration is the way the cell configurations are assembled together. Typical pack configurations are shown in Figure 7.2.1.2. Packs can be assembled in configurations listed in Figure 7.2.1.2 using cells configured in the "single" or "stick" configurations listed in Figure 7.2.1.1.

Figure 7.2.1.2



The "flat" battery pack configuration is the most common because of its ease of assembly. Next are the "square" and then the "nested" battery pack configurations. The "staggered" configurations are not common and more difficult to assemble, but will sometimes work for battery packs with restrictions in depth.

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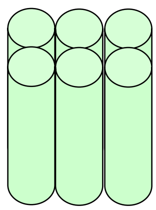
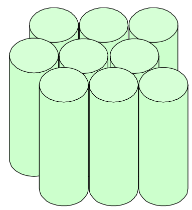
The configuration of a battery pack is almost limitless, yet designing a battery pack that is considered "non-typical" is usually not as cost effective. A "non-typical" battery pack often incorporates a mixture of cell configurations as well as locating cells at various directions to one another that would inhibit the ease of assembly. To ensure the efficient reproduction of a battery pack, the above cell and pack configurations are recommended.

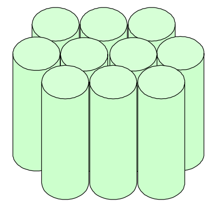
The size of a flat pack is D x nD x H where D is the diameter of the cell, n is the number of cells, and H is the height of the cells.

<u>Square</u>

There are two ways to start assembling them. One could be called the square, and the other nested.







nD x mD x H	L = (m +½)D W = [0.86(n-1)+1] D	L = mD W = [0.86(n-1)+1] D

Where D is the cell diameter, m is the number of cells in the longest layer, and n is the number of layers.

7.3 Protective Devices

Electrical components of a battery pack refer to the devices incorporated into the battery pack to increase functionality. These components protect a battery pack from damage that may otherwise occur if they are not used.

This first group of protective devices includes a variety of ways to sense and protect a battery pack from damage. The following list describes most of the commonly used protective devices.

7.3.1 Thermistor

Used primarily with the more sophisticated methods of charging NiMH batteries, this device senses temperature throughout the charging of the battery, which is then analyzed by the charging circuitry. Thermistors are thermally sensitive resistors that exhibit a large, predictable and precise change in electrical resistance when subjected to a corresponding change in temperature. The thermistors typically used in battery packs are negative temperature coefficient (NTC) thermistors. This means that they exhibit a decrease in electrical resistance when subjected to an increase in temperature.

Thermistors come in various types, but the most commonly used and the preferred type is a 10K 1% glass encapsulated with axial leads. Other thermistors used are the epoxy bead type thermistors, but are less desired due to the increased difficulty to assemble into the battery packs.

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7.3.2 PTC Resettable Fuse

The most commonly used component in the assembly of battery packs is the strap-type polymeric positive temperature coefficient (PTC) device. Strap-type polymeric PTC resettable fuses are easily installed in series with the cells inside the battery pack with only a small addition (~1 mm) to the overall dimensions of the battery pack. PTC resettable fuses limit the flow of dangerously high current during fault conditions, which includes accidental, short-circuits of battery. Providing over-current protection as well as over-temperature protection, the polymeric makeup of the PTC resettable fuse latches into a high-resistance state when a fault occurs. While only allowing a small amount of current through the battery, this high-resistance state will remain until the fault is removed. Once the fault and power to the circuit are removed, the PTC resettable fuse will then automatically reset, ready for normal operation. See section 7.6 for Harding's standard components.

7.3.3 Thermostat

The other commonly used circuit protection device used is the bi-metallic thermostat or circuit breaker. This type of resettable fuse also protects against short-circuit but using an entirely different technology than the PTC resettable fuse.

Thermostats use a bi-metal disc that senses both heat and current from the battery pack. When the temperature reaches a predetermined temperature, the disc snaps open the contacts, thus completely breaking the path of the current. When the battery returns to normal operating temperature, the thermostat resets. See section 7.6 for Harding's standard components.

7.3.4 Thermal Fuse

The one-time use thermal fuse is less common. These fuses open at elevated temperatures caused by run-away current. They are a fail-safe measure since the battery will become inoperative once the fuse has opened. These fuses are recommended, if absolute termination of current is needed for safety concerns only.

7.4 Gas Gauge

Obvious advantage is available with the use of a gauge to inform the user on the available capacity of the battery. Voltage sensing is not accurate for nickel based batteries. There are several variables to take into consideration in determining the state of charge of a pack (SOC). These variables include environmental temperature, discharge rate, self-discharge, and time. The electronics that must be installed on the pack also require the use of the battery so if the pack is stored on the shelf for an extended period of time, the gas gauge losses its memory or pulls the pack down below the recommended storage level.

Harding does carry standard gas gauge boards and has capabilities to meet most custom requirements. However, the standard gas gauge boards must be configured for each specific pack.

[1] Contact Harding for listing of current items in stock

7.5 Connectors

This diverse group of components provides an easy and efficient means of connecting the battery pack to device. The most commonly used methods are described in the following:

7.5.1 Crimp Terminal and Crimp Terminal Housing

This connector system uses a terminal that is crimped onto the stripped ends of each wire leading from the battery pack. The crimp terminals are then inserted into the crimp terminal housing. These connectors can be used to connect battery lead wires to wires leading to the device, or to the printed circuit board of the device.

Crimp terminal connectors may have a number of positions from 2 to over 20 depending on the connector style chosen. Also, these types of connectors have many optional features that aid in the connection of a battery to a device. In addition, a wide range of wire sizes (28 AWG to 12 AWG) can be used, as well as a wide range of connector sizes and styles.

7.5.2 Quick Connect/Fast-on Connectors

This connector style uses a tab-to-tab type connection with the female tab having rolled edges that receives the flat tab of the male connector. This type of connector is also a crimp type connection to each wire lead of the battery, but is only a single position connector with an optional protective cover or housing.

7.5.3 Contacts

Some battery pack assemblies have been designed without the use of wires and connectors. As an alternative they use metal contacts designed within the battery pack to mate directly with the device and charger. The contacts are typically heavy gauge nickel tabs placed on and/or around the battery pack that line-up with corresponding springs or tabs in the battery compartment of the device and charger. This method of connection can be effective depending on the location of the contacts and overall design of the battery pack. If the contact connection method is preferred, it is recommended to make the contacts on or near the positive and negative ends of the battery pack for ease of assembly.

7.5.4 Other Connector Types

- Molded cable assemblies
- Insulation displacement termination (IDT)
- Mass termination assemblies (MTA)
- Low voltage DC assemblies
- 9V snap-on connectors
- Watertight connection systems.

Many of these connection methods (e.g. molded cable assemblies, 9V snap-on, and watertight) are more expensive and complex to assemble. With this in mind these connector types are not the most cost effective battery pack assemblies.

[1] Contact Harding for listing of current items in stock