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CHARACTERISTICS OF RECHARGEABLE BATTERIES

Introduction

This chapter will highlight the most important electrical and physical characteristics of the three most popular chemistries used in rechargeable batteries:

Nickel-Cadmium (Ni-Cd)

Nickel Metal-Hydride (Ni-MH)

Lithium-Ion (Li-Ion)

Definitions of Terms

A cell is an electro-chemical device capable of supplying the energy that results from an internal chemical reaction to an external electric circuit.

A battery is composed of one or more cells, either parallel or series connected to obtain a required current/voltage capability (batteries comprised of series connected cells are by far the most common).

ESR (Equivalent Series Resistance) is the internal resistance present in any cell that limits the amount of peak current it can deliver.

The Amp-hour capacity of a battery (or cell) is its most important figure of merit: it is defined as the amount of current that a battery can deliver for 1 hour before the battery voltage reaches the end-of-life point.

The "c" rate is a current that is numerically equal to the A-hr rating of the cell. Charge and discharge currents are typically expressed in fractions or multiples of the c rate.

The MPV (mid-point voltage) is the nominal voltage of the cell, and is the voltage that is measured when the battery has discharged 50% of its total energy.

The measured cell voltage at the end of its operating life is called the EODV, which stands for End of Discharge Voltage (some manufacturers refer to this as EOL or End of Life voltage).

The gravimetric energy density of a battery is a measure of how much energy a battery contains in comparison to its weight.

The volumetric energy density of a battery is a measure of how much energy a battery contains in comparison to its volume.

A constant-voltage charger is a circuit that recharges a battery by sourcing only enough current to force the battery voltage to a fixed value.

A constant-current charger is a circuit that charges a battery by sourcing a fixed current into the battery, regardless of battery voltage.

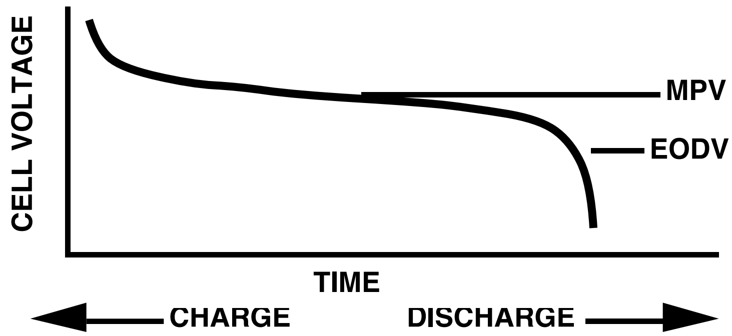

FIGURE 1. BATTERY CHARGE/DISCHARGE CURVE

The Charge/Discharge Curve

The measured terminal voltage of any battery will vary as it is charged and discharged (see Figure 1).

The MPV (mid-point voltage) is the nominal voltage of the cell during charge or discharge. The maximum and minimum voltage excursion from the nominal value is an important design consideration: a "flatter" discharge curve means less voltage variation that the design must tolerate.

When peak charged, the actual cell voltage will be higher than the MPV. When nearing the EODV (end of discharge voltage) point, the cell voltage will be less than the MPV. The EODV is sometimes referred to as the EOL (end of life) voltage by manufacturers.

Basic Battery Characteristics

The electrical characteristics of a battery define how it will perform in the circuit, and the physical properties have a large impact on the overall size and weight of the product that it will power.

The key properties and specifications for Ni-Cd, Ni-MH, and Li-Ion will be presented for easy comparison.

Energy Density (By Weight and Volume)

The energy density of a battery is generally expressed in two ways (see Figure 2):

The gravimetric energy density of a battery is a measure of how much energy a battery contains in comparison to its weight, and is typically expressed in Watt-hours/kilogram (W-hr/kg).

The volumetric energy density of a battery is a measure of how much energy a battery contains in comparison to its volume, and is typically expressed in Watt-hours/liter (W-hr/l).

CELL TYPE	NI-MH	NI-CD	LI-ION
GRAVIMETRIC DENSITY (W-HR/KG)	55	50	90
VOLUMETRIC DENSITY (W-HR/L)	180	140	210

FIGURE 2. ENERGY DENSITY COMPARISON

In reviewing the data in Figure 2, the Li-Ion advantage in gravimetric density is clearly the most striking, almost doubling the Ni-Cd and Ni-MH figures.

This means that products powered by Li-Ion cells can be made much lighter without sacrificing run time. Alternately, if the battery weight is kept the same, the run time will double if Li-Ion batteries are used. This fact explains the reason that Li-Ion is quickly displacing Ni-MH in top-of-the-line cellular phones and laptop computers.

Cell Voltage/Voltage Stability

The voltage provided to power the load is obviously very important: The Ni-Cd and Ni-MH batteries have a 1.25V nominal cell voltage (their discharge voltages are generally assumed to be identical).

The Ni-Cd/Ni-MH cell voltage is only about one-third of the nominal 3.6V provided by a Li-Ion cell (see Figure 3), which means a designer is required to use three series-connected Ni-Cd or Ni-MH cells to equal the voltage of a single Li-Ion cell.

However, Figure 3 also shows the biggest advantage of Ni-Cd and Ni-MH batteries: their discharge curve is extremely flat, closest to an ideal battery.

This important difference between the battery types means that Ni-Cd and Ni-MH cells are well suited for use with linear regulators, but Li-Ion batteries require switching converters to obtain good energy conversion efficiency in the power supply.

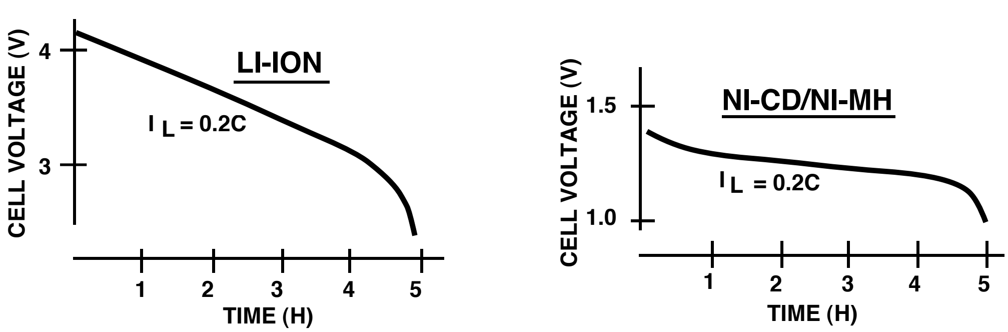

FIGURE 3. CELL DISCHARGE CURVE

Peak Current

The maximum current that a battery can deliver is directly dependent on the internal equivalent series resistance (ESR) of the battery.

The current flowing out of the battery must pass through the ESR, which will reduce the battery terminal voltage by an amount equal to the ESR multiplied times the load current ($V = I \times R$).

More important, the current flowing through the ESR will cause power dissipation within the battery that is equal to the ESR multiplied times the current squared ($P = I^2 \times R$). This can result in significant heating within the battery at high rates of discharge.

Both Ni-Cd and Ni-MH batteries have extremely low ESR values (well below 0.1Ω for a typical "AA" cell), which means that ESR is almost never a limitation for peak discharge current in these cell types.

The Li-Ion battery will typically have a higher ESR (compared to Ni-Cd or Ni-MH), but will probably not be a problem in most applications.

Self Discharge

Self-discharge (which occurs in all batteries) determines the "shelf life" of a battery. Figure 4 shows typical self-discharge rates for the three chemistries, exact values will vary with manufacturer.

In general, Li-Ion is the best of the lot, while Ni-Cd and Ni-MH are fairly comparable to each other. Ni-Cd is typically a little better than Ni-MH, but this may even out as Ni-MH manufacturing technology matures.

It is important to note that self-discharge is highly dependent on temperature, increasing as the battery temperature is increased.

Another unpleasant characteristic (I have heard voiced with respect to Ni-MH batteries used in cellular phones and laptop computers) is that the discharge rate is extremely non-linear. A battery which loses 30% in a month may lose 15 to 20% in the first few days (not good if you are taking a couple of spare batteries on a week-long trip, and you don't want to carry the charging station).

CELL TYPE	NI-MH	NI-CD	LI-ION
SELF-DISCHARGE @ 20°C (%/MONTH)	20-30	15-20	5-10

FIGURE 4. RATES OF SELF DISCHARGE

Recharge Time

The amount of time that the typical consumer finds acceptable for battery recharging is highly variable, and depends on the item being powered. Figure 5 shows the typical minimum charging times for slow and fast charging rates of the three battery types.

SLOW CHARGING

"Slow" charge is defined as a charging current that can be safely applied to a battery indefinitely without any kind of monitoring or charge termination method (it is sometimes referred to as trickle charging). A typical Ni-Cd battery will easily tolerate c/10, and some fast-charge Ni-Cd cells will accept up to c/3.

Ni-MH cells are not as tolerant of constant charging, as most will not handle a sustained charging current greater than c/40 (although one manufacturer advertises cells that are rated for c/10 trickle charge rate).

It is important to note that Li-Ion cells will not tolerate trickle charging at all after they are fully charged. If current is continuously forced into a fully-charged Li-Ion cell (even a very minute current) the cell will be damaged. For this reason, Li-Ion cells are charged using constant-voltage (C-V) chargers, and not constant-current (C-C) chargers.

If a product is designed only for slow (overnight) recharging, a user may have to buy a second battery pack, and keep it on "standby" charge (increasing the amount of money he has to spend).

FAST CHARGING

"Fast" charge (usually defined as a 1 hour recharge) requires more complex charging circuitry (again raising the system cost) but gives the customer faster charging time (a very attractive selling point).

The typical Ni-Cd or Ni-MH fast charger simply pumps current into the battery, and waits for the battery to signal when its had enough. Because of the possibility of battery damage and user safety hazards, fast-charge systems must be designed to accurately monitor battery parameters like cell temperature and voltage. In addition, most have back up timers for fail-safe cutoff of the high current charge applied to the battery.

CELL TYPE	NI-MH	NI-CD	LI-ION
TYPICAL SLOW CHARGE TIME (HRS)	12 - 36	4 - 10	(SEE TEXT)
TYPICAL FAST CHARGE TIME (HRS)	1	0.25 - 1 (SEE TEXT)	1.5

FIGURE 5. RECHARGE TIMES

Some consumer products are available with Ni-Cd batteries that recharge in 10 to 15 minutes, requiring very sophisticated and well-designed charge termination circuits. At present, the only batteries which can safely be recharged in 10 minutes are high-rate Ni-Cd cells which are specially designed to withstand the stresses of very fast charging.

However, most battery makers do not give performance specifications for their products when charged at rates that exceed about 1.2c (which is a 1 hour charge time).

In some cases, 15 minute recharging is a necessity: for example, cordless tools aimed at the industrial market would have a competitive disadvantage trying to sell with a 1 hour charge time: 15 minutes (which is the length of a typical coffee break) is much better for these products.

The Ni-MH that are presently cells presently available have a minimum recharge time of 1 hour, which is acceptable for most applications.

The Li-Ion cell has a minimum recharge time of about 1 to 2 hours, but requires a distinctly different charging method than either Ni-Cd or Ni-MH (Li-Ion uses constant-voltage charging only).

Cost

It should be no surprise that the Ni-Cd cell offers the best cost/performance value of any rechargeable battery: it is a mature technology that is being produced in large volumes by many different manufacturers.

Ni-Cd is also a product that is continuing to improve in performance, primarily due to the competition of the Ni-MH battery. Utilizing a new technology called foamed nickel substrate, modern Ni-Cd cells can offer volumetric/gravimetric energy density that nearly doubles the best Ni-Cd cells offered a few years ago. For example, the standard "AA" Ni-Cd cell is typically rated at about 600 mA/hr, but cells are now available in "AA" size with >900 mA/hr capacity.

These "high energy" Ni-Cd cells offer energy density that is within 10% to 20% of the capacity offered by the more expensive Ni-MH cells. This added performance makes Ni-Cd an even better dollar value.

However, because the Ni-Cd battery contains Cadmium, it is less eenvironmentally friendly than Ni-MH. This means that alternate battery types (like Ni-MH) may take over some of Ni-Cd's market share. The discharge voltage of the Ni-MH battery is considered identical to the Ni-Cd, which allows it to drop into most applications using Ni-Cd.

Although typically 50 to 100% higher than Ni-Cd in price, the Ni-MH battery is presently displacing Ni-Cd in products such as cellular phones and laptop computers, where expensive battery packs are tolerated by the consumer without serious complaint. A computer that sells for $4k can afford to carry a $200 battery (although you might find consumers aren't happy about it, they probably won't change brands because of it).

In "low-end" consumer products like flashlights and toys (where Ni-Cd is unchallenged), the Ni-MH cell will probably never come down in price sufficiently to become economically feasible.

The Li-Ion battery is the most expensive of the types listed, presently appearing only in high end products where performance is the primary consideration.

Reliability

Battery makers (and common sense) tell us that most of the problems with rechargeable batteries can be traced to misuse:

NI-CD and NI-MH: HOW CELLS ARE DAMAGED

Sustained high-current overcharge and cell polarity reversal (during discharge) are the main killers of Ni-Cd and Ni-MH batteries:

If a high charge rate is used, it is essential to terminate charge when the cell is full. If this is not done, the temperature and pressure within the cell will rise quickly as the charging current is dissipated as heat.

Both Ni-Cd and Ni-MH cells have internal vents which will open to allow gas to escape and prevent explosion of the cell. In the case of Ni-Cd, the gas released is oxygen, while a Ni-MH cell will vent hydrogen.

The gas that is lost can never be replaced, which means that the lost cell capacity which results from a severe overcharge is not recoverable.

It is never wise to rely on the cell's vent as a failsafe, because they often corrode over time and can not be assumed to be absolutely reliable.

Avoiding abusive high-current overcharge can only be ensured with a well-designed charging system that responds to the signal the battery gives when fully charged.

Cell polarity reversal is a potential problem with any series-connected string of cells: as the battery is discharged, the cell that goes down to zero volts first will continue to have current forced through it by the other cells. When this occurs, the voltage across the fully-discharged cell is reversed.

A cell that has current forced through it with a reverse voltage across it will heat up very quickly and vent gas in a similar mode to that described for the sustained overcharge, with the same resultant damage.

LI-ION: HOW CELLS ARE DAMAGED

The biggest problem with the Li-Ion battery is the ease with which it can be damaged during use:

The Li-Ion battery carries a very large amount of energy in a small package. Combined with the fact that the internal resistance is fairly high, you have the potential for a very dangerous product: If the cell is accidentally shorted, it could get hot enough to burn a user (and possibly explode).

The makers of Li-Ion cells handle the explosion threat by designing the case of the cell so that it will "die with honor", and not explode in someones pants pocket if the battery hits their car keys. More important, the actual battery terminals are simply never allowed to reach the outside world.

The only manufacturer presently shipping Li-Ion batteries for consumer products does not sell single cells, only battery packs. Contained within the pack is circuitry that isolates the battery power leads from the outside world if excessive current is sensed, preventing battery damage and protecting the user.

Another easy way to destroy an Li-Ion battery is by discharging it too far. The Li-Ion cell should never be allowed to drop below about 2.4V, or an internal chemical reaction will occur where one of the battery electrodes can oxidize (corrode) through a process which can not be reversed by recharging. If this occurs, battery capacity will be lost (and the cell may be completely destroyed).

A similar process will occur if an Li-Ion cell is charged to too high of a voltage. If current is continually forced into a fully charged cell, internal corrosion can take place which will reduce cell capacity (possibly completely).

For this reason, Li-Ion cells can not be trickle charged for extended time periods without cutting off the current when full charge is reached. Sustained charge currents (even a few μA) can damage the cell if allowed to run continuously.

AGE-RELATED FAILURE MODES

Ni-Cd: After a period of time, the insulator within a Ni-Cd battery often develops holes which allow the cell to grow crystalline "shorts" that provide a conduction path between the positive and negative electrodes of the cell (which basically shorts out the cell).

If this happens, you may have to blow open this short with a high current pulse before the cell will again accept charge (a process sometimes referred to as "zapping").

A leaky Ni-Cd cell will always have a high self-discharge rate and will re-grow internal shorts if left on the shelf without some kind of trickle charge. The annoyance factor of batteries that go dead quickly often prompts users to throw away leaky Ni-Cd batteries, even though they may still be able to give nearly full A-hr capacity during discharge.

Ni-MH: The Ni-MH cell (according to the manufacturers) is not supposed to be prone to developing internal shorts like a Ni-Cd battery. User feedback (so far) on Ni-MH has been good, with no major problems reported.

Li-Ion: The Li-Ion battery got off to a weak start, as there were many failures in the first batteries shipped. However, the addition of the internal protection circuitry inside the battery (and increased knowledge about the failure modes) has improved this.

At present, there are no known problems which appear significant enough to prevent Li-Ion from successfully penetrating the high-end consumer market.

Operating Temperature

Batteries are acutely sensitive to operating temperature with respect to their charging characteristics and A-hr capacity. Most well-designed chargers have temperature sensors to assure that the battery temperature is within the allowable "window" for charging (if not, the charger will not turn on the current source).

NI-CD/NI-MH

Battery makers generally recommend 0-50°C as the maximum operating limits for Ni-Cd and Ni-MH batteries, and typically restrict the allowable range to about 10-40°C for fast charging of the batteries.

These batteries work best at temperatures close to 25°C, as their characteristics change very quickly when the temperature deviates from this "ideal" point.

At elevated temperatures, the cell experiences two undesirable effects:

a) The A-hr capacity of the cell reduces, meaning the cell will simply not deliver as much energy after being fully charged.

b) The cell gets "reluctant" to accept charge (the charging efficiency gets very bad) which makes it harder to fully charge the cell. This means that at high (>40°C) temperature, the charging efficiency can be so poor that 200 to 300% of the battery's total energy may have to be pumped in to it before it gets fully charged.

At low temperatures, the maximum safe charging current that the cell can tolerate is lower because the gas does not recombine as readily within the cell. For optimum battery life, a charger should sense the temperature and reduce to maximum charge current at low temperatures.

There is also a loss of cell capacity at low temperatures, although the effect is not nearly as pronounced as the reduction seen at high temperature.

LI-ION

The Li-Ion cell (as advertised by the few manufacturers presently making it) can be safely charged at temperatures between 0-45°C.

The operating temperature range during discharge is specified as -20 to 60°C.

The small amount of information in published curves on the Li-Ion cell indicate that it is superior to Ni-Cd/Ni-MH in its performance over temperature.

The Li-Ion cell does not suffer a significant capacity loss at high temperatures, as the discharge curves at 20°C and 60°C are virtually identical.

There is a progressive loss of capacity at low temperatures, with the 0°C delivered energy being about 90% of the 20°C amount, and at -20°C the cell delivers about 70% of the capacity that is delivered at 20°C.

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