Smart Batteries and Lithium Ion Voltage Profiles

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Abstract: This paper addresses how the Smart Battery System Specifications facilitate battery interchangeability in light of differences in battery chemistry. Specifically it addresses differences among LiIon battery manufacturers as well as differences between nickel metal hydride and lithium ion batteries. Examples of some of the "Smart Battery System" functions are given.

Introduction:
Historically batteries intended for a specific device were known to have a particular chemistry, and as a result had a specific operating voltage range. The idea of interchangeable referred to exchanging the original battery with one that had the same voltage range. A simple example of this is the use of alkaline primary batteries in the same applications that initially used zinc carbon. Although differing in chemistry the alkaline voltage profile could easily be used in applications that were designed to be powered by zinc carbon cells.

In rechargeable batteries nickel metal hydride has replaced nickel cadmium in many applications. One of the factors helping drive this replacement is the ease of exchange -- the voltage profiles are very similar. The charging requirements are also nearly identical, making it virtually a drop in substitution.

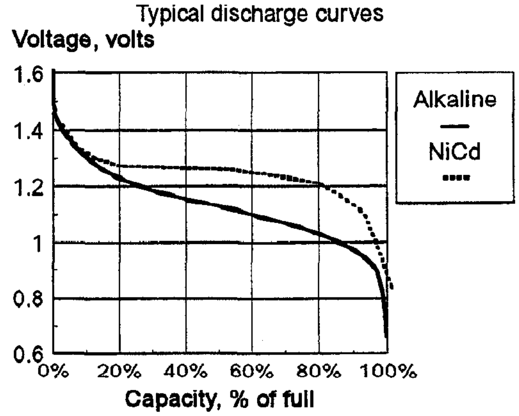
The most recently developed system to achieve wide spread commercialization is lithium ion . It is a battery system that is a premium performer at a premium price. In the same volume lithium ion provides more energy and is lighter in weight than nickel based batteries. These features are highly desirable, and many portable electronics manufacturers, particularly notebook computer manufacturers, have been willing to pay two to three times the nickel metal hydride cost for.

The move to lithium ion is a significant departure from nickel metal hydride or nickel cadmium. The operating voltages, charging requirements and safety concerns are all very different. Additionally different manufactures of lithium ion batteries use different electrode materials which can have a significant effect on operating voltage ranges.

In recent years lithium ion has rapidly become state-of-the-art battery choice for the portable computer, but due to limited supply and high cost has only made it into higher end units. For the same reason device manufacturers have been looking to dual chemistry solutions that allow the use of both nickel metal hydride and lithium ion in the same device.

In order to accommodate the variety of potential battery chemistries and operating voltages a uniform system is needed that allows the OEM/ODM designers to plan for interchangeability. This uniform system is provided in a series of published standards -- Smart Battery System Specifications (SBS). This

Figure 1
Typical discharge curves



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paper describes how the use of SBS compliant smart batteries can lead to greater freedom of choice for the device designer when it comes to handling the variety of differences between NiMH and different lithium ion chemistries.

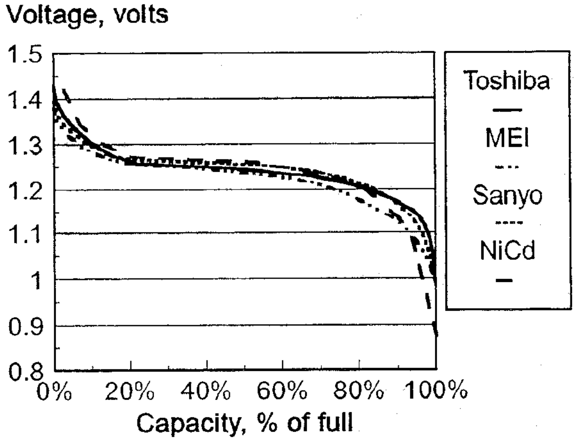
Battery interchangeability

As previously stated an early example of interchangeable battery chemistries is zinc|carbon and zinc|MnO_2 (alkaline primary). Add to these rechargeable NiCd and rechargeable alkaline. They make up a variety of batteries each having there own value tradeoffs that can power a whole range of low cost consumer applications, flashlights, radios, portable tape players, etc.. Within certain rate limits a device that takes AA cells can work over a voltage range of 1.5 to 1.0 volts/cell can use any of these battery types. The reason that the different cells are easily interchangeable between devices is that the voltages match well, see figure 1. Multiple batteries provide the consumer flexibility.

Camcorders, cellular phones, notebook computers and other items have created a huge market for higher power rechargeable batteries. Initially powered by NiCd battery packs, in the early part of the 1990's NiMH began displacing NiCd batteries in these applications. Although somewhat higher in cost NiMH batteries were typically higher in capacity and more environmentally friendly, features which seemed to easily justify the cost to most device manufacturers.

Figure 2

Typical NiMH C/5 room temperature discharge curves



Any transition from NiCd to NiMH was very easy to manage due to the similarities in operating voltages and charging methods. Both batteries system have a 1.2 volt nominal voltage and similar discharge endpoints. The charging method for NiCd is compatible with NiMH with the exception of the need to minimize overcharge of NiMH batteries. Although there are some specific differences from one manufacturer to another the chemistries of either the two systems remains basically the same. Interchangability between NiCd and NiMH chemistries and different manufactures is an easy matter to handle again due to voltage compatibility. Figure 2 shows a comparison of Sanyo, MEI and Toshiba NiMH cells and a Panasonic NiCd. The voltage behavior is almost identical. One manufacturers battery pack can easily replace another.

Lithium Ion Batteries:

Lithium Ion batteries have become the state-of-the-art preference in notebook computers and high end electronic devices. They are both higher in capacity and lighter in weight than the best NiMH cells on the market. Unfortunately there are few similarities to NiMH, and the move to lithium ion is a major point of departure for those device manufacturers. Table 1 shows a comparison of some of the differing features in battery implementation between LiIon and NiMH.

Despite the significant differences between the two chemistries dual battery systems are desirable. LiIon demand is high and the supply is limited. A manufacturer of a notebook computer that is dual chemistry (NiMH - LiIon) does not have to worry about the supply of lithium ion batteries if the device can also ship with a NiMH battery. An alternate incentive for dual chemistry is that a manufacturer can ship a device with a lower cost nickel metal hydride battery, and the lithium ion battery can be offered as an upgrade. However, in contrast to the nickel rechargeable batteries which vary little from manufacturer to manufacturer there are a variety of LiIon chemistries on the market.

Table 1

	NiMH	LiIon
Nominal voltage	1.2 v	3.5 to 3.7 v
Maximum voltage	~1.6v	4.1 to 4.25 v
discharge endpoint	1.0 v	2.5 to 2.8 v
charging method	constant current	constant voltage
Overcharge	tolerant of overcharge	overcharging can result in fire or explosion and must be prevented
Safety devices	Thermal fuse and current limiting devices	Safety electronics required to prevent overcharge and overdischarge

Lithium Ion Intra-chemistry issues:

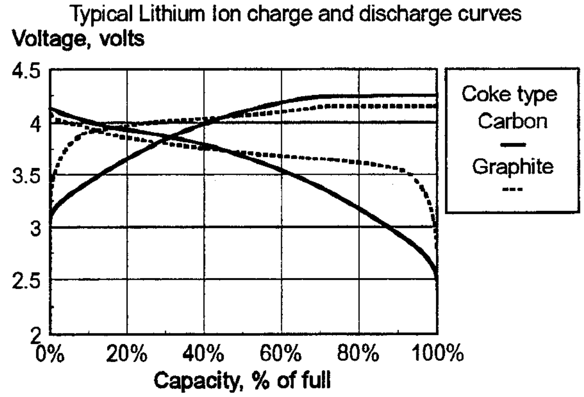
Lithium Ion batteries come in many different types varying from manufacturer to manufacturer. Differences can be seen by examining the various electrode and electrolyte materials that are used in present and potential commercial cells.

- **Negative electrode**
  - Carbons
    - Graphite (Panasonic)
    - Advanced Carbon
    - Coke, hard carbon (Sony)
  - Tin composite oxide (Fugifilm Celltec)
- **Positive Electrode**
  - Cobaltite (Sony, Duracell, Panasonic)
  - Lithium Nickelate (Saft)
  - Spinel $LiMn_2O_4$ (Moli Energy)
- **Electrolyte**
  - Standard ethylene carbonate based organic liquid (most)
  - Polymer (Bellcore, Valence, Ultralife)

Just considering these elements there are 24 different combinations of positive electrode | electrolyte | negative electrode.

Figure 3

Typical Lithium Ion charge and discharge curves



Identifying the correct voltage ranges for lithium ion are particularly important. Safety mandates strict adherence to upper and lower voltage limits which typically require safety electronics inside the battery pack. Maximum cell voltage limits on charge range from 4.10 to 4.25 volts per. Typical operating voltages can range from 3.4 to 3.7 volts. Discharge end point voltages vary form 3.0 volts to 2.4 volts. Figure 3 shows differing voltage profiles on charge and discharge comparing coke and graphite type electrodes. The maximum voltage limit on charge can be 100 mV different between cells that use the cobaltite type positive, but different carbons in the negative. These upper cell voltage limits need to be controlled within less than 50 mV. Overvoltage protection is required for safety concerns, but stopping charge at voltages too much below the upper limit will result in reduced capacity.

Discharge endpoint voltages can vary by up to 500 mV. Although less of a safety concern than the upper voltage limit, there are performance considerations. Terminating discharge of the coke type cell in figure 3 at the end point for the graphite type electrode results in less capacity. On the other hand continually driving the graphite type cell to the lower voltage end point of the coke will reduce cycle life of the that cell.

The battery system for the device:

When designing a battery system it is important to consider the operating ranges for the device. The designer (OEM/ODM) of a device that cannot accommodate the variety of operating voltages and limits presented by the various lithium cell manufacturer will find themselves tied to a sole source of supply in a scarce market. So in addition to interchangeability with NiMH it is also important to consider interchangeability of a lithium ion cell that uses a graphite|cobaltite chemistry with another manufacturer that might use coke|$LiMn_2O_4$ spinel or other combinations. With this in mind there are several issues to consider when designing for interchangability between different chemistries and different manufacturers.

- A common form factor
- A common connector -- electrical interface
- Voltage compatibility
- Battery information -- data/communications

Although shape and connector issues are a must for interchangeable batteries, they will be considered outside the scope of this paper.

Voltage compatibility:

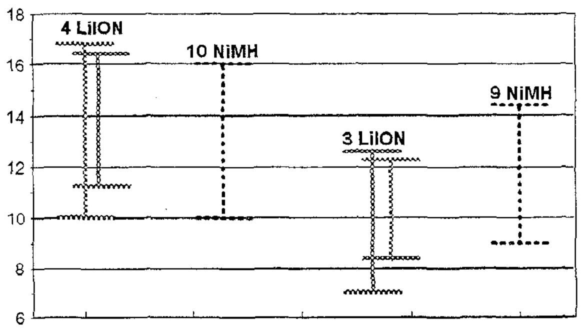
It is important to consider the operating voltage ranges for all the battery chemistries that the device is being designed to accommodate. With all this in mind there are several issues to consider when designing for interchangeability of NiMH and various lithium chemistries:

- The typical operating voltages of LiIon and NiMH are a factor of 3 to 1. but the maximum and end point voltages are very different.
- Different LiIon types have different voltage limits. To maintain safe operation and optimal performance the correct cell voltage limits for a particular battery chemistry must be adhered to.
- The cells are going to be configured in packs and a 3 to 1 or 5 to 2 cell ratio of lithium ion cells to nickel metal hydride cells should be maintained.

Figure 4 shows how battery pack voltages match up for typical cell string configurations. Lithium Ion cells are typically connected in parallel first then in series strings to give the desired pack voltage and capacity to be compatible with nickel metal hydride packs.

The considerations for powering a device from any combination of cells are relatively easy. Power supplies in devices can generally operate over a wide range of input voltages. The problem becomes determining the appropriate end point

Figure 4



Charge & Discharge Voltage Limit Comparisons

trigger. The power supply can operate over the battery's entire range, but the device must make a logic level decision to suspend or shut off before the voltage of the battery drops below the recommended end point. Somehow the device must determine the appropriate end point for the battery powering it.

Considerations for charging are more complicated. Nickel metal hydride charging and charge termination is much simpler than lithium ion. Some differences are listed below

Nickel metal hydride:

- **constant current or constant power supply.**
- **Slow charging can be done based on a time (or capacity) limit.**
- **somewhat tolerant of overcharge.**
- **Fast charging, less than 2 hours, requires detecting a change in the temperature slope (dT/dt) or a change in the voltage characteristic.**
- **There is no maximum voltage limit**

Lithium Ion:

- **constant voltage, current limited charging.**
- **charge termination is based on the charge current diminishing while the cells are held at the upper voltage threshold..**
- **The upper voltage threshold varies based on the particular LiIon chemistry**
- **Charging above the upper voltage threshold cannot be tolerated.**
- **In battery packs individual cell voltages must be monitored.**

Battery Intelligence:

Battery manufacturers can solve for voltage and charging issues by adding on-pack electronics with a data interface to the device and charger. "Smart Batteries" can provide all the necessary information about the battery to the device and charger. Smart battery solutions can either be proprietary or based on an open standard. The concept of dual chemistry interchangeability lends itself extremely well to standard solutions.

Proprietary dual chemistry schemes are possible, but have some short comings. Until recently dual battery solutions have been device specific. Now there are a wide variety of lithium ion products coming on the market with significant differences between them. To insure compatibility system designers would have to deal with specific vendors of like lithium ion chemistries, further limiting sources of supply. In addition there is a California consumer law will require manufactures to be able to supply replacement battery for up to seven years. With a standardized smart battery an end user with be able to buy a replacement battery with the latest technology. The device manufacturer does not have to worry about stocking batteries for older machines if their devices can be serviced by a standard size, standard intelligence battery.

The "Smart Battery System Specifications" provide a standard architecture, data bus and data messaging. The Smart Battery System are actually a set of five complimentary specifications:

- **The System Management Bus (SMBus) specification defines the data interface.**
- **The Smart Battery Data Specification (SBD) defines standard messaging.**
- **The Smart Battery Charger Specification**
- **The SMBus BIOS specification**
- **The Smart Battery Selector specification**

Per these specifications, the information a device requires about the battery is supplied by the battery itself. The battery, charger and device make up the main components of the Smart Battery System. These components exchange information via the SMBus protocol during operation and emergency situations. The strength of the system is that it is designed to be chemistry independent. Each battery is the source the information about how it should be used, and changing batteries brings an automatic change in information.

The Smart Battery Data specification defines 34 data elements that a smart battery provides for the power management system in the device and the charger. Together with the Smart Battery Charger specification a smart charging method is defined. The smart battery provides the charging current and charging voltage information to the smart charger. The Smart Battery also alarms the charger when it detects that it is fully charged or if there is a problem. Effectively the battery becomes its own charge controller, and the smart charger is a slave to the battery. This is fundamental to the idea of smart interchangeable batteries. The information about the battery is contained in the battery rather than in the device or the charger. As long as a smart battery is compliant to the SBS specifications and fits in the device's cavity it will work in the device.

The Smart Battery Data specification also provide solutions for the differing discharge voltage endpoints. Capacity and time remaining information provided by the smart battery can replace traditional voltage level cut off values. The device's power management system can make decisions based on predicted time remaining. In particular using a set of functions described as AtRate() functions in the specification a device can write an expected drain requirement to the smart battery. The smart battery will then return the time in minutes that it can sustain that drain. Rather than relying on voltage based cut off which can vary widely between batteries, the device can take low battery actions based on the actual amount of energy remaining in the battery.

Conclusion - Benefits of SBS

With the growing number of battery choices and the appeal of rechargeable standard smart batteries the Smart Batteries System Specifications define the data interface, standard messaging and physical architecture that facilitate chemistry and manufacturer exclusive battery designs. The fundamental concept is that the battery itself contain the information required for its correct use, and any SBS compliant device can utilize any SBS compliant battery regardless of chemistry or manufacturer.

The Smart Battery System specifications have gained wide industry acceptance. In October 1996 ten leading companies in the computer, battery and semiconductor industries announced an agreement to share ownership of the Smart Battery System specifications. Operating system level support fo these specifications is expected to accelerate the current trend toward open standards for Smart Batteries.

More information on the SBS specifications can be found at http://www.mediacity.com/~sbs

References

1. Smart Battery System Specifications, Revision 1.0, Benchmarq Microelectronics Inc. et al, 1996.
2. Duracell Technical Note, "Chemistry Interchangeability: NiMH and LiIon Batteries," November 1995.