ABC OF RECHAR

Basics, pitfalls & recommendations

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The use of batteries has never been greater. Batteries are becoming smaller and lighter even as they package more and more energy per unit volume. The main driving force for battery development has been the boom in portable equipment such as mobile phones, laptops, camcorders, and MP3 players.

The following brief overview of charging methods and current battery technologies is intended to lend a better understanding of the batteries used in portable devices. It includes discussions of nickel-cadmium (NiCd), nickel-metal-hydride (NiMH) and lithium-ion (Li+) battery chemistries. The article also describes a product for protection of single-cell lithium-ion and lithium-polymer batteries.

Definition of a battery

Calling a battery an energy storage system poses a definition that also includes such things as flywheels and clock springs. In the context of modern technology, however, batteries are usually portable, self-contained chemical systems that produce electrical energy.

Disposable batteries (called non-rechargeable or primary cells) create electricity from a chemical reaction that permanently transforms the cell. Discharging a primary cell leads to a permanent and irreversible change in the cell chemicals. By contrast, rechargeable batteries, also called secondary cells, can be recharged by a charger after having been discharged by the application.

The charge or discharge current is usually expressed (in ampères) as a multiple of the rated capacity (called the C-rate). For example, a C/10 discharge current for a battery rated at one ampère-hour (1 Ah) is 1 Ah/10 = 100 mA. The rated capacity of a cell or battery (in Ah or mAh) is the amount of electricity that it can store (produce) when fully charged under specified conditions. Thus, the total energy of a battery is its capacity multiplied by its voltage, resulting in a measurement of watt-hours.

Defining battery performance

The chemistry and the design of a battery cell together limit the current it can source. Barring the practical factors that limit performance, a battery could produce an infinite current, if only briefly. The main impediments to infinite current are the basic reaction rates of the chemicals, the cell design, and the area over which the reaction takes place. Some cells are inherently able to produce high currents. Shorting a nickel-cadmium cell, for instance, produces currents high enough to melt metals and start fires. Other batteries can produce only weak currents.

The net effect of all chemical and mechanical factors in a battery can be expressed as a single mathematical factor called the equivalent internal resistance. Lowering the internal resistance enables higher currents.

No battery stores energy forever. Unavoidably, the cell chemicals react and slowly degrade, causing degradation in charge stored by the battery. The ratio of battery capacity to weight (or size) is called the battery's storage density. High storage density enables the storage of more energy in a cell of given size or weight.

Table 1 lists nominal voltage and storage density (expressed in watt-hours per kilogram of weight, or Wh/kg) for the major chemistries used in storage batteries for personal computers and cell phones: **Table 2** contains quick comparison data to enable designers to choose the best cell type for a particular application (note that NiCd will be banned soon).

So why not always choose secondary cells, if primary and secondary cells fulfil the same purpose? Secondary cells have drawbacks:

- All practical secondary cells lose their electrical charge relatively quickly, through self discharge.
- Secondary cells must be charged before use.
- Secondary batteries supply less energy at the same volume and weight.

Charging batteries

A new rechargeable battery or battery pack (several batteries in one package) is not guaranteed to be fully

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charged; in fact, it is likely to be nearly discharged. The first thing to do, therefore, is to charge the battery/pack in accordance with the manufacturer's chemistry-dependent guidelines.

Every charging operation applies voltage and current in a sequence that depends on the battery chemistry. Thus, a look at battery-cell chemistries reveals different requirements to be met by the charger and the charging algorithm. The terms most commonly found in battery charging are constant current (CC), used for NiCd and NiMH cells, and constant current/constant voltage (CC/CV), applied to lithium-ion and lithium-polymer cells (**Figures 1-6**). **Table 3** summarizes today's most frequently used charging techniques and the associated parameters per cell type. The methods to determine the very important 'end of charge' moment are listed separately in **Table 4**.

Charging nickel-cadmium cells

NiCd cells are charged by applying a constant current in the range 0.05 C to more than 1 C. Some low-cost chargers terminate the charge by means of absolute temperature. Though simple and inexpensive, that method of charge termination is not accurate. A better choice is to terminate charging when the condition of full charge is indicated by a drop in voltage. The $-\Delta V$ phenomenon is most useful for charging NiCd cells at 0.5 C or greater. The $-\Delta V$ end-of-charge detection should be combined with battery-temperature measurement as well, because aging cells and mismatched cells can reduce the voltage delta.

You can achieve a more precise full-charge detection by sensing the rate of temperature increase (dT/dt), and that method of charge detection is kinder to the battery than is a fixed-temperature cut-off. Charge termination based on a combination of $\Delta T/dt$ and $-\Delta V$ cut-off enables a longer life cycle by avoiding overcharge.

Fast charging improves charge efficiency. At 1 C, the efficiency is close to 1.1 (91%), and the charge time for an empty pack will be slightly more than one hour. When applying a 0.1 C charge, the efficiency drops to 1.4 (71%) with a charge time of about 14 hours.

Because the charge acceptance of a NiCd battery is close to 100%, almost all energy is absorbed during the initial 70% of charging, and the battery remains cool. Ultra-fast chargers use this phenomenon to charge a battery to the 70 percent level within minutes, applying currents equal to several times the C-rating without heat build-up. Above 70% the charging continues at a lower rate until the battery is fully charged. Eventually, you top off the battery by applying a trickle charge in the range 0.02 C to 0.1 C.

Charging nickel-metal-hydride cells

Though similar to NiCd chargers, an NiMH charger employs the $\Delta T/dt$ method, which is by far the best

Table 1. Storage density values.

Cell type	Nominal voltage	Storage density (typ.)
Lead Acid	2.1 volts	30 Wh/kg
Nickel Cadmium	1.2 volts	40 to 60 Wh/kg
Nickel Metal Hydride	1.2 volts	60 to 80 Wh/kg
Circular Lithium Ion	3.6 volts	90 to 100 Wh/kg
Prismatic Lithium Ion	3.6 volts	100 to 110 Wh/kg
Polymer Lithium Ion	3.6 volts	130 to 150 Wh/kg

Table 2. Quick comparison chart.

Attribute	Nickel Cadmium	Nickel Metal Hydride	Lithium-Ion
Energy Density	Low	Medium	High
Energy Storage	Low	Medium	Medium
Cycle Life	High	High	High
Cost	Low	Medium	High
Safety	High	High	Medium
Environment	Low	Medium	Medium

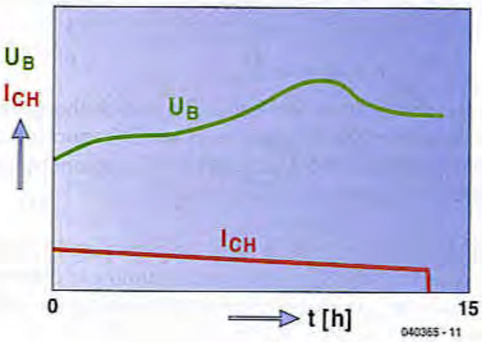

Figure 1. Semi-constant current charging — chiefly used in applications like shavers, cordless phones and toys.

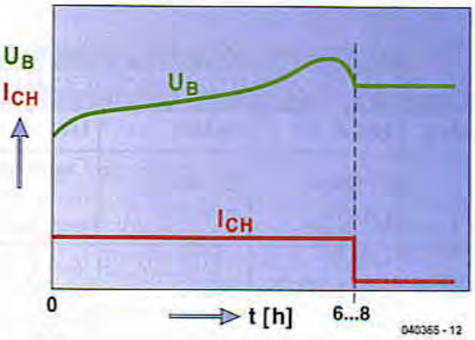

Figure 2. Timer-controlled charging is used mainly in applications like notebooks data terminals, wireless equipment and cellular phones

Table 3. Battery charging methods.

Chemistry	Charging Method	Feature	# of terminals	Charge time	Charge Current	Trickle Current	Charge level at End of charge	Figure
Nickel based (NiCd & NiMH)	Semi-constant current charging.	Most typical system Simple and low cost.	2	15 Hours	0.1 C mA	—	—	1
	Timer Controlled charging	More reliable than semi-constant current system. Relatively simple and low-cost	2	6-8 hours	0.2 C mA	1/20-1/30 C mA	Approx. 120%	2
	-ΔV cut-off charging	Most popular More complex	2	1-2 hours	0.5-1 C mA	1/20-1/30 C mA	Approx. 110-120%	3
	DT/dt cut-off charging	More costly but over-charging can be avoided enabling longer life cycle than the others	3 or 4	1-2 hours	> 1 C mA	1/20-1/30 C mA	Approx. 100-110%	4
	Trickle charging	Simple and low cost Applicable for continuous charging	2	15 hours	0.1 C mA	—	—	5
Lithium based	**Constant Current – Constant Voltage** (CCCV)	Not recommended for the main charge control system for NiCd /NiMH batteries. Prevailing charge method for Li-ion and Li Polymer Relatively complex charger design	2	1-3 Hours	1C mA	—	Approx. 100%	6

method for charging NiMH cells. The end-of-charge voltage decrease for NiMH batteries is smaller, and for small charge rates (below 0.5 C, depending on temperature) there may be no voltage decrease at all.

New NiMH batteries can show false peaks early in the charge cycle, causing the charger to terminate prematurely. Moreover, an end-of-charge termination by -ΔV detection alone almost certainly ensures an overcharge, which in turn limits the number of charge/discharge cycles possible before the battery fails.

Table 4. End-of-charge detection.

Chemistry	NiCd	NiMH	Li+
Charging	Constant current	Constant current	Constant current / constant Voltage
Full charge detect	–ΔV/dt and/or ΔT/dt	ΔV/dt = 0 and/or ΔT/dt	I_{charge} = eg 0.03C and/or time

It seems there is no available –dV/dt algorithm that works well for charging NiMH batteries under all conditions: new or old, hot or cold, and fully or partly discharged. For that reason, don't charge a NiMH battery with a NiCad charger unless it utilizes the dT/dt method for end-of-charge termination. And because NiMH cells do not absorb overcharge well, the trickle charge must be lower (about 0.05 C) than that recommended for NiCd cells.

Slow-charging a NiMH battery is difficult if not impossible, because the voltage and temperature profiles associated with a C-rate of 0.1 C to 0.3 C do not provide a sufficiently accurate and unambiguous indication of the full-charge state. The slow charger must therefore rely on a timer to indicate when the charge cycle should be terminated. Thus, to fully charge a NiMH battery you should apply a rapid charge of approximately 1 C (or a rate specified by the battery manufacturer), while monitoring both voltage (ΔV=0) and temperature (dT/dt) to determine when the charge should be terminated.

Charging lithium-ion and lithium-polymer cells

Whereas chargers for nickel-based batteries are current-limiting devices, chargers for lithium-ion batteries limit both voltage and current. The first lithium-ion cells called for a charge-voltage limit of 4.10 V/cell. Higher voltage means greater capacity, and cell voltages as high as 4.2 V have been achieved by adding chemical additives. Modern Li-ion cells are typically charged to 4.20 V with a tolerance of ±0.05 V/cell.

Full charge is achieved after the terminal voltage has reached the voltage threshold and the charging current has dropped below 0.03 C, which is approximately 3% of I_{charge} (**Figure 6**). The time for most chargers to achieve a full charge is about three hours, though some linear chargers claim to charge a Li+ battery in about one hour. Such chargers usually terminate the charge when the battery's terminal voltage reaches 4.2 V. That kind of charge determination, however, charges the battery only to 70% of its capacity.

A higher charging current does not shorten the charge time by much. Higher current lets you reach the voltage peak earlier, but then the topping charge takes longer. As a rule of thumb, the topping charge will take twice as long as the initial charge.

Protection modes

Overvoltage: If the cell voltage sensed at V_{DD} exceeds the overvoltage threshold V_{OV} for a period longer than the overvoltage delay t_{OVD}, the DS2720 shuts off the external charge FET and sets the OV flag in the protection register. The discharge path remains open during overvoltage. The charge FET is re-enabled (unless blocked by another protection condition) when the cell voltage falls below the charge-enable threshold V_{CE}, or discharging causes $V_{DD} - V_{PLS} > V_{OC}$.

Undervoltage. If the cell voltage sensed at V_{DD} drops below the undervoltage threshold V_{UV} for a period longer than the undervoltage delay t_{UVD}, the DS2720 (see inset) shuts off the charge and discharge FETs, sets the UV flag in the protection register, and enters sleep mode. After the cell voltage rises above V_{UV} and a charger is present, the IC turns on the charge and discharge FETs.

Short Circuit. If the cell voltage sensed at V_{DD} drops below the depletion threshold V_{SC} for a period of t_{SCD}, the DS2720 shuts off the charge and discharge FETs and sets the DOC flag in the protection register. The current path through the charge and discharge FETs is not re-established until the voltage on PLS rises above V_{DD}–V_{OC}. The DS2720 provides a test current through internal resistor R_{TST} (from V_{DD} to PLS) to pull up PLS when V_{DD} rises above V_{SC}. This test current allows the DS2720 to detect removal of the offending low-impedance load. In addition, it enables a recovery charge path through R_{TST} from PLS to V_{DD}.

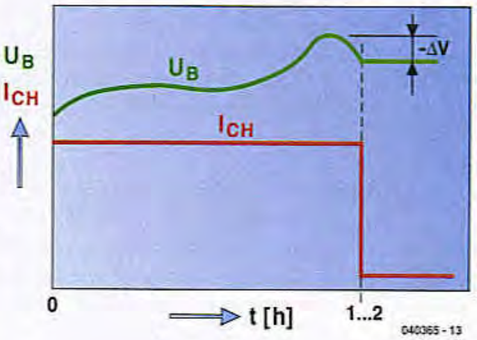

Figure 3. Charging is terminated via –ΔV cut-off in applications like notebooks, dat terminals, camcorders, wireless equipment, and ce lular phones.

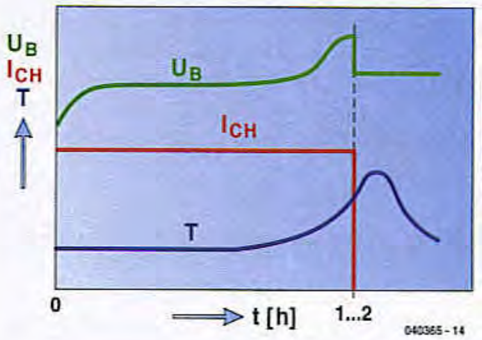

Figure 4. Charging is terminated via –dT/dt cut-off in applications like power tools and electric tools.

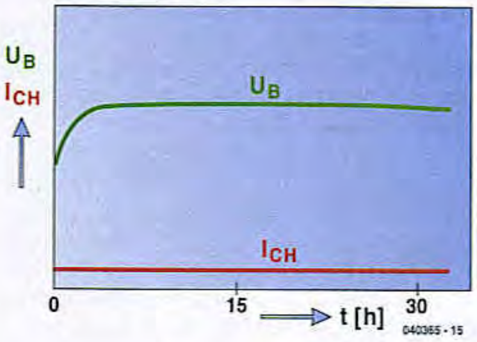

Figure 5. Trickle charging is mainly used in applications like emergency lights, guide lights, and memory backup.

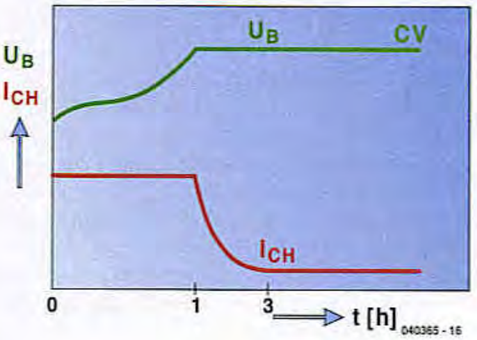

Figure 6. Constant-current, constant-voltage charging is used in application like cellular phones wireless equipment and Notebook PCs.

Overcurrent: If voltage across the protection FETs (V_{DD}–VPLS) is greater than V_{OC} for a period longer than t_{OCD}, the DS2720 shuts off the external charge and discharge FETs and sets the DOC flag in the protection register. The current path is not re-established until the voltage on PLS rises above V_{DD}–V_{OC}. The DS2720 provides a test current through internal resistor R_{TST} (from V_{DD} to PLS) to detect removal of the offending low-impedance load.

Overtemperature. If the DS2720 temperature exceeds T_{MAX}, the device immediately shuts off the external charge and discharge FETs. The FETs are not turned back on until two conditions are met: cell temperature drops below T_{MAX}, and the host resets the OT bit.

Charging at high and low temperatures. Efforts should be made to charge at room temperature. Nickel-based batteries should only be fast-charged between 10°C to 30°C (50°F to 86°F). Below 5°C (41°F) and above 45°C (113°F), the charge acceptance of nickel-based batteries is drastically reduced. Li-ion batteries offer reasonably good charge performance throughout the temperature range, but below 5°C (41°F) the charge rate should be less than 1 C.

Conclusion

NiMH chargers can accommodate NiCd batteries, but not the other way around. Chargers dedicated to NiCd batteries will overcharge a NiMH battery. The cycle life and performance of nickel-based batteries are enhanced by fast charging because it reduces the memory effect due to formation of internal crystals. Nickel- and lithium-based batteries call for different charge algorithms.
Li+ batteries need protection circuitry to monitor and protect against overcurrent, short circuits, over- and undervoltage, and excessive temperature. Remember to remove a battery from its charger when the battery is not used regularly, and apply a topping-charge before use.

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Lithium-ion safety — meet the DS2720

Because overcharging (or overdischarging) a Li-ion cell can cause it to explode and injure people, safety is a major concern in handling this type of storage cell. As a result, commercial Li-ion battery packs contain a protection circuit such as the DS2720 (**Figure A**), which provides all electronic safety functions required for applications involving rechargeable Li+ batteries: protecting the battery during charge, protecting the circuit against excess current flow, and maximizing battery life by limiting the level of cell depletion.

DS2720 ICs control the conduction paths for charge and discharge currents with external switching devices such as low-cost n-channel power MOSFETs. The IC's internal 9-V charge pump provides high-side drive to the external n-channel MOSFETs, yielding lower on-resistances than do the same FETs operating in a more common low-side protection circuit. FET on-resistance actually decreases as the battery discharges (**Figure B**).

The DS2720 lets you control the external FETs from the data interface or from a dedicated input, thereby eliminating the redundant power-switch controls otherwise required in a rechargeable Li+ battery system. Through its 1-wire interface, a DS2720 provides the host system with read/write access to the status and control registers, instrumentation registers, and general-purpose data storage. A factory-programmed 64-bit net address allows each device to be individually addressed by the host system.

The DS2720 provides two types of user memory for battery-information storage, EEPROM and lockable EEPROM. EEPROM is a true non-volatile (NV) memory whose contents (important battery data) remain unaffected by severe battery depletion, accidental shorts, or ESD events. When locked, a lockable EEPROM becomes a read-only memory (ROM) that provides additional security for unchanging battery data.

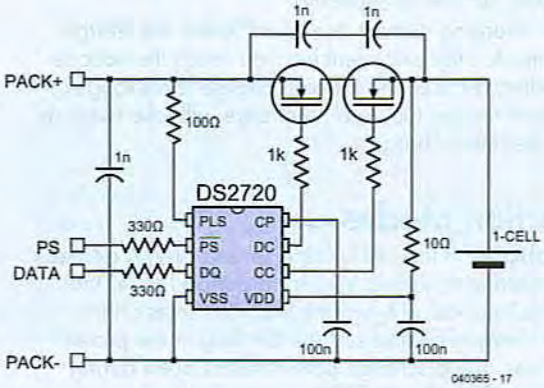

Figure A. Typical application diagram for the DS2720 lithium-cell protection IC.

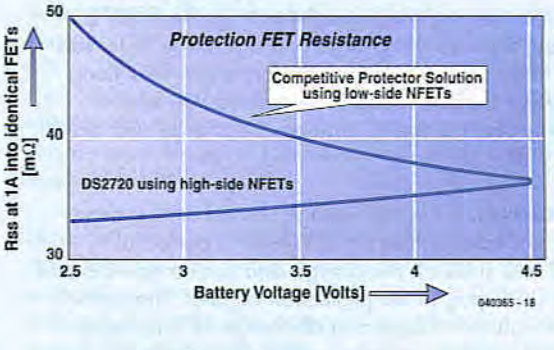

Figure B. The resistance of protection FETs controlled by the DS2720 ('high-side mode') is lower than FETs operating in the traditional low-side mode. FET resistance-controlled by the DS2720 actually drops with battery voltage.