USING & CHARGING NI-CAD BATTERIES

The nickel-cadmium or 'NiCad' battery is the most popular type of rechargeable battery in the world today, despite the development of new types offering higher energy storage density. That's no doubt because the NiCad combines relatively low cost with fairly high storage density, the ability to deliver very high load currents on demand and the ability to be recharged very quickly. Providing it is treated in the right manner with regarding to discharging and recharging, it also offers a very long working life.

In short, NiCads make an efficient and very cost-effective source of rechargeable power for a wide range of portable electrical and electronics equipment: cordless power tools and appliances, test instruments, radio transceivers, model boats, cars and aircraft, etc.

The basic nickel-cadmium battery was invented in 1899 by Waldmar Jugner, but the modern sealed type dates from about 1947. It has been used heavily since then by both the military and a wide and growing range of civilian users.

The basic components of a NiCad battery are a positive plate of nickel oxide/hydroxide (on nickel), a negative plate of cadmium metal with cadmium hydroxide, and an electrolyte of potassium hydroxide ('caustic potash'). The construction of a typical NiCad battery cell is shown in Fig.1, and as you can see the two plates are made in the form of long, thin metal foils which are sandwiched between insulating but porous separator films, which are moistened with the electrolyte. The sandwich is then rolled up and packaged in a nickel-plated steel can, with a sealing system built into the positive terminal end. A spring-loaded vent allows electrolyte and/or gasses to be released in the event of a dangerous pressure buildup due to overcharging.

The nominal terminal voltage of a NiCad is 1.2V. In normal use and for the longest working life, manufacturers recommend that NiCads should not be discharged beyond the point where the terminal voltage of individual cells drops below 1.1V, except when they're being 'deep cycled' for reconditioning. (More about this later.)

NiCad batteries typically have an energy storage density of between 40 and 60 watt-hours per kilogram — i.e., up to double that of sealed lead-acid (SLA) batteries. They can be used in virtually any position, and have very low internal impedance so they can deliver high discharge currents. In fact they are generally suitable for applications where the charge capacity of the battery needs to be extracted in periods as small as 30 minutes or less — i.e., at discharge rates of up to and exceeding 2C. This is the highest discharge rate for any readily available rechargeable battery.

Another advantage of NiCads is that with care, they can also be recharged quite rapidly — faster than any other type of commonly available rechargeable, in fact.

However a well-known drawback of NiCads is the 'memory effect'. If a NiCad is not 'worked hard' by being called upon to deliver a reasonable proportion of its stored capacity each time it is recharged, its energy storage capacity gradually drops. This is due to a gradual change in the nickel oxide/hydroxide crystal structure on the surface of the positive plate: initially there's a huge number of very tiny crystals (typically 1um), but these are gradually replaced by much larger (50-100um) crystals, which present a much smaller surface area to the electrolyte.

Some of this growth of larger crystals can also result in the formation of very long needles or 'dendrites', which can pierce the porous separator films and provide localised short-circuits inside the battery. At best this can seriously reduce the capacity of the battery, while at worst it can damage it beyond repair.

In general, the best way to prevent memory effect and the possibility of dendrite growth is to 'work' NiCads fairly hard, discharging them properly before recharging — and also avoiding the temptation to 'top them up on the charger'. Careful recharging using the correct techniques can also be used to reverse crystal growth and shrink dendrites.

Another shortcoming of NiCads is a fairly *high self-discharge rate*. This means that a NiCad loses its stored charge due to internal chemical action, even when not delivering current to an electrical load. Typically it loses around 10% of its charge in the first 24 hours after charging, and then loses it by a further 10% per month. The rate of self-discharge also doubles for a rise in temperature of 10°C. Some NiCads can discharge themselves completely in a period of six months.

All of which tends to mean that NiCads are best suited for applications where batteries are called upon to deliver most of their charge capacity in a relatively short period after being charged. They're less suited for applications where the battery is expected to remain in a charged state for long periods, and only deliver current in an emergency. (SLA batteries are much more suitable for these situations.)

NiCad charging & chargers

NiCad batteries need to be recharged with a reasonable amount of care, largely because they can be damaged by overcharging. Once a NiCad has been recharged to its full

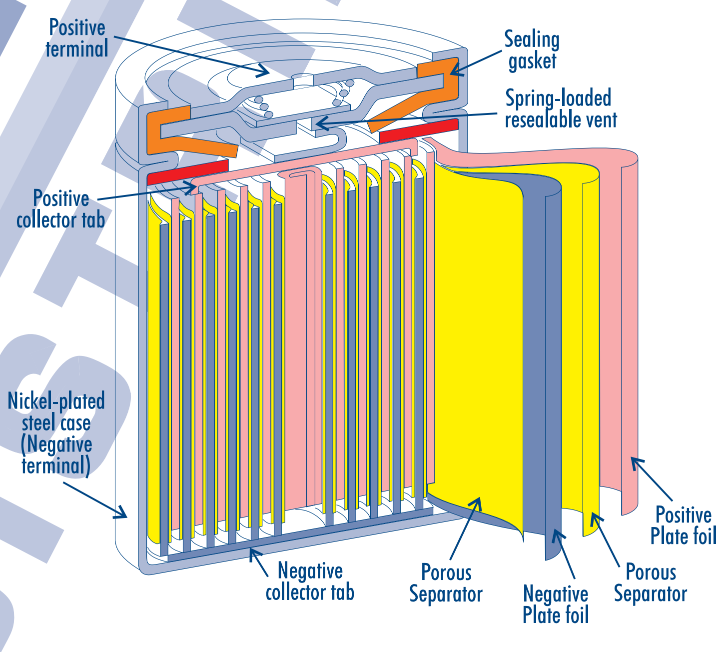

Fig.1: The construction of a typical NiCad sealed battery cell.

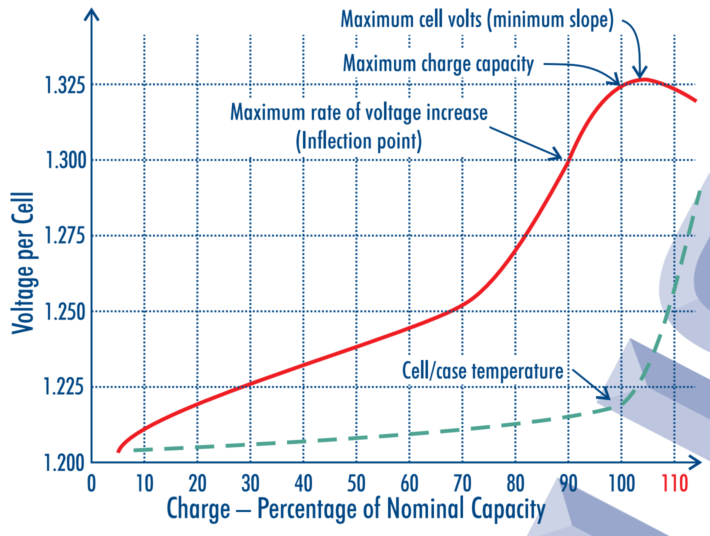

Fig.2: How the terminal voltage of a typical NiCad cell (and also its temperature) tends to vary during charging. Both the inflection point and the voltage peak are used for end-of-charge detection in high-end chargers.

capacity, excess oxygen is generated inside the battery and its internal pressure and temperature both tend to rise rapidly. This can cause the cells to vent and lose electrolyte, and in extreme cases they can even explode.

A number of different types of charger have been developed for NiCads, with varying degrees of complexity and cost. Each type tends to have its own pros and cons, and the choice is often a matter of your particular needs.

The traditional type of NiCad charger, and also the type with the lowest cost, is called the *constant current* or 'CC' type. It uses a fairly simple DC power supply with a current regulating circuit (sometimes just a series resistor) designed to maintain the charging current relatively constant. Usually the current level is set to a value of 0.1C, where C is the nominal battery capacity in Ah or mAh. Allowing for typical charging losses of about 40%, this gives a charging time of around 14 hours for a nominally discharged battery.

With most low cost CC chargers, there is no method of detecting when the battery is fully charged. The user is expected to removed the battery from the battery after 14 hours or so, to prevent overcharging. Providing this is done, and assuming that the NiCads are always discharged to the 1.1V level each time before recharging, this type of charger can be used to achieve a reasonably long battery working life.

More elaborate CC chargers may provide an inbuilt timer, to provide added protection against overcharging. Other types provide a simple system of monitoring the battery case temperature with a thermistor, and a circuit which switches off the charging current when a temperature rise is detected.

Because NiCads do 'live longer' when they're cycled reasonably deeply, some CC chargers also incorporate a *discharger* circuit which can be used to drain the cells down to the 1.1V level before the recharging process begins. With low cost chargers this discharging process is purely manual, but with more sophisticated chargers it can be automatic and arranged so that charging begins as soon as the cell voltage drops to 1.1V.

Again some CC chargers don't totally switch off the charging current when the battery is deemed to be fully charged, but instead switch down to a much lower 'trickle' charge level. This has a very low value — typically less than 0.05C — and is basically designed only to maintain the fully charged state by counteracting the NiCad's own self-discharging.

Faster charging

As already mentioned the charging time using a traditional CC charger is typically around 14 hours, which is fairly long. In fact it's far *too* long for many applications, and that's why faster charging techniques have been developed.

Generally fast charging is quite feasible with NiCads, because the electrochemistry of this type of cell actually responds better to faster charging than slow or trickle charging. However the faster the charging is done, the more care needs to be taken to prevent overcharging and its subsequent risk of damage. So 'fast' NiCad chargers generally have to incorporate a system of reliably detecting the fully charged condition, and abruptly stopping the charge process as soon as it's reached.

There are a number of ways of detecting the fully charged condition, all based on an understanding of the way a NiCad cell behaves during the charging process. In particular, on the behaviour of either the cell's terminal voltage or its case temperature.

The graph of Fig.2 shows how the terminal voltage of a typical NiCad tends to vary as it's being charged. Until about 70% of its charge capacity has been reached, the voltage rises relatively slowly. It then begins rising somewhat faster, reaching a maximum rate of increase at about 90% of capacity. This point is called the 'inflection point', because the rate of change then begins slowing down. In fact it slows down quite dramatically, reaching a peak (i.e., zero slope) just beyond the point where the battery has reached full charge. Then the voltage actually starts *dropping*, as oxygen starts building up inside the battery and it enters the overcharge danger zone.

As you can see from the dashed plot in Fig.2, the battery temperature tends to remain relatively low during charging until the 100% capacity point is reached, after which it rises fairly rapidly. So case temperature can be used as a way of detecting the fully charged condition, although the detection circuitry needs to be quite sensitive and to measure temperature change rather than absolute temperature.

Most modern chargers designed for fast NiCad charging actually use terminal voltage monitoring to detect full charge. They generally do this using an analog-to-digital converter and a microcontroller, using either of two methods.

One way is to monitor the terminal voltage itself, and

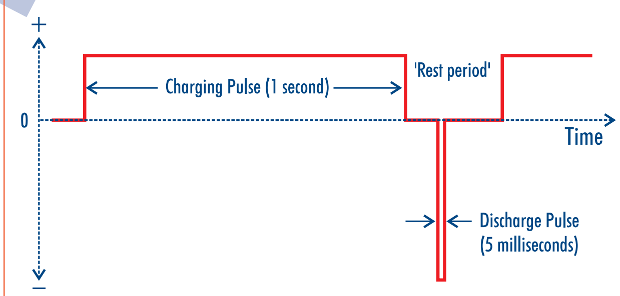

Fig.3: The type of charging current waveform used in pulse chargers, and especially those using discharge-pulse 'burping'.

detect when this has just reached the peak and begun to fall again. This is known as the **negative delta voltage** or '-ΔV' (-DV) method, and its only disadvantage is that because the voltage peak actually occurs just *after* full charge, it can allow a small amount of overcharging to occur. This is particularly true with very fast chargers, and at relatively high ambient temperatures.

The other method is to have the microcontroller monitor not the cell's terminal voltage itself, but the voltage's *rate of change* instead. This allows it to detect the maximum rate of change, or the point of inflection — corresponding to about 90% of full charge. This is known as the **positive delta voltage** or '+ΔV' (+DV) method, and has the advantage that it very definitiely avoids overcharging. In fact there's a risk of slight under-charging, although most chargers using the +ΔV method don't *stop* charging when the point of inflection is reached — they merely change down to a somewhat lower charging current, and continue at this rate until the voltage peak is reached.

Fast NiCad chargers using either -ΔV or +ΔV end-of-charge detection can be arranged to charge at rates of 0.5C or higher, giving the ability to recharge batteries in two hours or less. In fact specialised and sophisticated fast chargers can recharge a NiCad in less than an hour, if required.

Like traditional CC chargers, fast chargers can simply use regulated DC as the actual charging current. In this case it's simply a somewhat higher current level. However some of the more sophisticated chargers use a different technique, and one that has actually been shown to increase the working life of NiCads by reducing the risk of crystal growth and dendrite formation.

Pulse and 'burp' charging

A lot of work done by battery researchers in recent years, particularly by the US military, has shown that NiCads respond better to a *pulsed* charging waveform than to a steady DC current. By applying the charge current in one-second pulses with brief 'rest' periods between them, ions are able to diffuse over the plate area, and the cells are better able to absorb the charge efficiently.

This is particularly true at the higher charge rates used in fast chargers. In these chargers the 'rest' period between the charging pulses can also be used by the microcontroller and its A-to-D converter to sample the battery terminal voltage, free from any noise or hum which may be present in the charging current.

Another important discovery was that paradoxically, the charging process actually improves even further if during the 'rest period' between charging pulses, the cells are subjected to very brief *discharging* pulses — with an amplitude of about 2.5 times the charging current, but lasting for only 5ms (milliseconds) or so.

It seems that these short discharge pulses actually dislodge oxygen bubbles from the plates, and help them diffuse during the rest period. As a result, the use of these brief discharge pulses is known as 'burping', or 'burp charging'.

Many of the high-end fast pulse chargers for NiCads therefore use a charging current waveform like that shown in Fig.3. The main charging is via the one-second main pulses, while the rest periods between them and the 5ms discharge 'burp' pulses are to achieve the highest possible charging efficiency.

Tests by both the US military and NASA have shown that NiCads charged using fast chargers employing the burped pulse system tend to last up to twice as long as those charged using traditional CC chargers. In other words, fast charging using the kind of pulsed waveform shown in Fig.3 actually tends to *increase* NiCad working life, and quite significantly.

Reconditioning

Although NiCads do tend to lose their capacity due to the memory effect when they're lightly cycled for extended periods, this doesn't necessarily mean that they have to be discarded. A technique known as *reconditioning* can often be used to reverse the crystal and dendrite growth, and restore the NiCad to almost-new capacity.

Reconditioning is essentially a sequence of very deep discharge-charge cycles. After discharge to the 1.1V level at the 1C rate the battery is slowly discharged even further, to a somewhat lower terminal voltage than usual — typically 0.6V or less — which tends to shrink the crystals on the surface of the plates and dissolve any dendrites that may have formed. It is then fully charged again, and this sequence is repeated a few times to get the battery used to 'working out'.

This reconditioning process won't achieve much if the battery's porous separators have been seriously damaged by dendrite growth, but in many cases it can be used to bring NiCads which have lost most of their capacity 'back to life'.

Some of the high-end microcontroller based NiCad chargers incorporate a reconditioning algorithm which automates the process, allowing batteries to be reconditioned at the touch of a button.

Multi-cell batteries

There are a few complications with *multi-cell* NiCad batteries like the small '9V' single-ended rectangular type (usually 8.5V) and many of the integrated battery packs used in cordless phones, cordless power tools and camcorders.

The main complication with these batteries is that internally they have six, seven, eight or more individual NiCad cells connected in series, and inevitably some of these cells age at different rates to the others. This means that they gradually develop different charge capacities, and as the battery as a whole is charged and discharged repeatedly, these differences are accentuated — a kind of 'survival of the fittest' process occurs.

The nett result is that during discharge, some 'weak' cells can be discharged well below the 1.1V level, and even driven into reverse charge, before the others reach the fully discharged state. Then during recharging, the same cells tend to absorb most of the charge and overheat, while the others (which were perhaps not properly discharged) are improperly recharged and tend to suffer increased crystal growth.

In short, multi-cell NiCad batteries tend to have a somewhat shorter working life than separate cells, and tend to be much harder to recondition or even cycle adequately. Unfortunately this is the price you pay for their convenience.

NiMH BATTERIES

The nickel-metal hydride or 'NiMH' battery is in many ways a development from the NiCad, although they're also related to the hydrogen-nickel oxide batteries used in communications satellites. They basically evolved from the work done in the 1970s into the storage of hydrogen gas in metallic hydrides, but only became practical about 1990.

The construction of most NiMH batteries is almost identical to that of NiCads, so the diagram in Fig.1 of this data sheet also applies to NiMH cells. Like NiCads the positive plate is of nickel with nickel oxide/hydroxide, and the electrolyte is potassium hydroxide. However in the NiMH battery the negative electrode is made from a hydrogen storage alloy such as lanthanium-nickel or zirconium-nickel.

NiMH batteries have up to 30% higher energy storage density compared with NiCads, but still display some memory effect. They're not as happy with deep discharge cycles, though, and tend to have a shorter working life. The self-discharge rate is also about 50% higher than NiCads.

Charging NiMH batteries

Unlike NiCads, NiMH batteries tend to dissipate heat during all of the charging process — not just following the full charge point, as with NiCads. This tends to mean that NiMH batteries can only be charged at about half the rate of NiCads, unless temperature sensing is used to limit charging current.

Broadly speaking, though, most of the charging techniques described in this data sheet can be used with NiMH batteries. The main difference is that although the charging voltage characteristic of a NiMH cell has the same basic shape as that shown in Fig.2, the actual voltage levels are different. So chargers for NiMH cells must usually be arranged to sense the terminal voltage rate of change, and use the positive delta voltage (+ΔV) method of end-of-charge detection.

Many modern pulse-type chargers are designed to charge either NiCad or NiMH cells, and can automatically sense which type is present — adjusting their charging characteristic to suit.