Almost every mobile phone, tablet and laptop PC has a lithium-ion rechargeable battery and larger packs made from similar cells are the main power source for many electric vehicles. This article explains how these batteries actually work and how they're best charged and discharged.

What you need to know about Li-ion Cells & Batteries

by JIM ROWE

In the last few years, lithium-ion based cells and batteries have overtaken all other types of rechargeable power source for portable electronic devices like mobile phones and laptop PCs.

That's because they provide a much higher energy storage density than earlier lead-acid, nickel-cadmium (Nicad) or nickel-metal hydride (NiMH) batteries.

It's also because they can be charged much faster and they withstand repeated charging and discharging cycles better, maintaining more of their capacity for longer.

They're different!

But lithium-ion battery technology is rather different from the earlier battery types and so these cells and batteries need to be treated differently when it comes to charging and discharging.

You can't charge a Li-ion battery using a charger designed for Nicad or NiMH batteries, for example. And although Li-ion batteries don't have any significant memory effect and can hold a charge for much longer than other rechargeables, they do need to be recharged as soon as their terminal voltage drops below a "safe" level.

In this short article, we will try to give you enough understanding of Li-ion cells and batteries to allow you to get the most from them.

Just before we start though, a bit of clarification. Although many people use the terms cell and battery interchangeably, strictly speaking, they don't have the same meaning.

So here we're going to be using the terms according to their strict definitions, using "cell" to refer to a single energy storage element and "battery" to refer to a group of cells connected together in series or parallel, to store more energy and/or provide a higher terminal voltage.

The lithium-ion cell

First of all then, what exactly is a lithium-ion (Li-ion) cell, and how does it work?

The three elements in a basic Li-ion cell are shown in Fig.1: a positive electrode, a negative electrode and an electrolyte layer between them.

Both of the electrodes have a layered structure which is termed "intercalative", meaning that the layers of the material's molecules allow individual molecules or ions to move through the material.

The main component of the positive electrode is usually a layered oxide like lithium cobalt oxide, a "polyanion" such as lithium iron phosphate or a "spinel" such as lithium manganese oxide. The negative electrode is usually formed from graphite (carbon), again in a layered form.

The electrolyte in a common Li-ion cell is usually a mixture of non-aqueous organic carbonates (such as ethylene carbonate or diethyl carbonate), containing complexes of lithium ions.

The latter are usually lithium hexafluorophosphate ($LiPF_6$), lithium hexafluoroarsenate monohydrate ($LiAsF_6$), lithium perchlorate ($LiClO_4$), lithium tetrafluoroborate ($LiBF_4$) or lithium triflate ($LiCF_3SO_3$).

As you can see, there is negligible lithium metal present in the cell, nor is there any water in the electrolyte. This is quite important since the two react strongly (almost explosively) together.

That's also why Li-ion cells have to be sealed securely, to prevent the possible entry of water.

When the cell is being charged, positively charged lithium ions (ie, atoms that have lost an electron) move into the negative electrode and take up positions between its layers (over on the right in Fig.1).

They move there from both the electrolyte and the positive electrode, under the influence of the electric field between the two electrodes created by the charger.

Then when the cell is being discharged, the positively charged lithium ions move back out of the negative electrode. Some of them pass through the electrolyte and enter the positive electrode, while others just move out into the electrolyte.

While this is happening, electrons are flowing between the negative and positive electrodes through the external load circuit, delivering the energy that was stored in the cell during charging.

So that's how the Li-ion cell works. When it comes to construction, many of the most common Li-ion cells are made from electrodes and electrolyte in the form of thin strips, rolled up together in Swiss-roll fashion to produce a cylindrical shape.

This is then sealed inside a cylindrical outer container. A good example of this type of construction is the so-called "18650" cell, used in many laptop computer batteries and in small LED torches (and even electric cars).

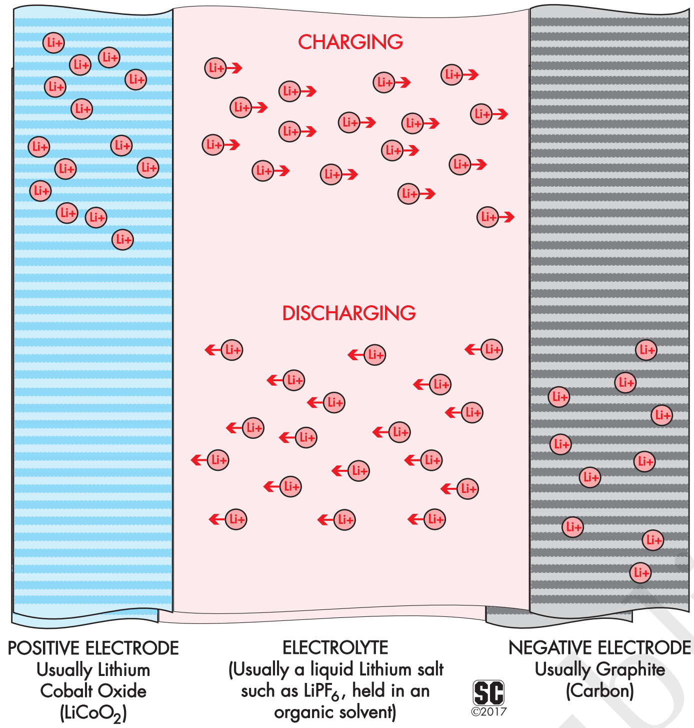


Fig.1: this diagram shows the basic elements of a Lithium-ion cell, and how lithium ions move between the electrodes and through the electrolyte in one direction or the other, during charging and discharging.

The name 18650 is a contraction of its physical size, 18.6mm in diameter and 65.2mm long. Typically, the 18650 Li-ion cell has a capacity of between 1500 and 3000mAh, with the maximum being about 3700mAh.

Claims for 18650 cells with much higher capacities (up to 10,000mAh or more) are simply fraudulent; it just isn't possible with present-day technology.

Another approach is to flatten the roll into a thin rectangular form, to make it suitable for use in smaller portable equipment like mobile phones.

One common cell of this type measures 56mm long by 42mm wide by only 4mm thick, with a rated capacity of 1000mAh.

What about LiPo cells?

Before we go any further, we should look at how lithium-polymer (LiPo) cells differ from Li-ion cells.

Essentially, LiPo cells are just another form of lithium-ion cell and strictly speaking, they should be called lithium-ion polymer cells.

That's because the main difference between a LiPo cell and a standard Li-ion cell is that instead of a liquid or gel electrolyte between the two electrodes, a LiPo cell has a solid polymer electrolyte (SPE) such as polyethylene oxide (PEO), polyacrylonitrile (PAN), polymethyl methacrylate (PMMA) or polyvinylidene fluoride (PVDF).

The so-called solid electrolyte is typically one of three types: dry SPE, gelled SPE and porous SPE. Or it may be a combination of two of these, with the porous element being a separator formed from a microporous film of polyethylene (PE) or polypropylene (PP).

Some LiPo cells have a PVDF polymer binder in both of the electrodes themselves, plus an additive to improve electrical conduction.

Despite these differences in construction, LiPo cells operate in exactly the same way as standard Li-ion cells, as shown in Fig.1.

The main differences are in terms of physical construction; many LiPo cells are sealed in a flexible foil-type (polymer laminate) pouch, rather than a rigid metal case. This allows them to be about 20% lighter in weight than equivalent cylindrical cells of the same capacity.

They can also be made in more complex shapes, to fit the available space inside an electronic device (eg, a tablet computer), allowing the device to use a higher capacity battery than would be possible if it had to be a rectangular prism or cylinder.

Having said that, most of the LiPo cells and batteries you will come across will be rectangular and in most cases, they will also be shrink-wrapped, likely along with some protection circuitry; see the section below titled "Battery pack protection".

Electrical characteristics

Lithium-ion cells tend to have a much higher energy storage capacity than other types of rechargeable cells like the lead-acid, Nicad and NiMH type, for a given size and weight.

But just as these types differ from one another, lithium-ion cells have their own particular characteristics.

For example, the nominal voltage of

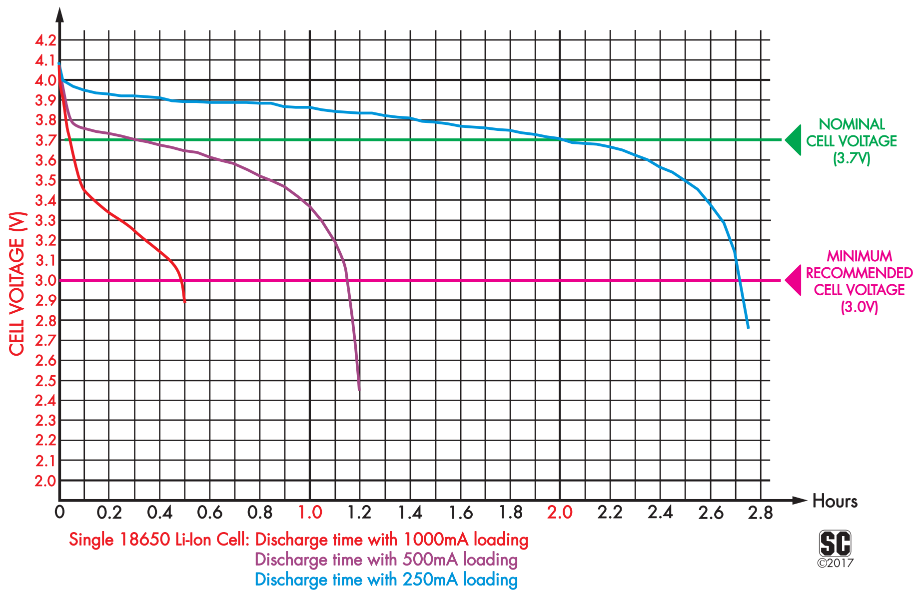


Fig.2: discharge curves for a rather poor quality 18650 Li-ion cell being discharged at current levels of 1000mA (red), 500mA (purple) and 250mA (blue).

a Li-ion cell is around 3.7V but during charging this can rise to around 4.1-4.2V. Then during discharge, the voltage first drops quite rapidly to around 3.7-3.9V, after which it falls more slowly when delivering most of its charge, before finally dropping to below 3.0V at the end of discharge.

(In some cases, discharge is terminated at a higher voltage, resulting in less degradation for each charge/discharge cycle.)

You can see this typical behaviour in the curves shown in Fig.2, which shows the voltage of a rather poor quality 18650 cell discharging at three different current levels: 1000mA (red curve), 500mA (purple curve) and 250mA (blue curve).

Also shown in Fig.2 are the nominal cell voltage of 3.7V (green horizontal line) and the minimum recommended cell voltage of 3.0V (magenta horizontal line). The latter is the voltage below which further discharging may cause the useful life of the cell to be significantly reduced.

Many Li-ion cells have a small electronic "cut-out" or protection circuit included inside the case, to disconnect the load when the cell voltage drops below 3.0V.

Cell capacity

We should mention here that like many other cell types, the nominal storage capacity (C) of a Li-ion cell is usually defined in terms of the discharge current in milliamps it can provide for one hour before the cell voltage drops to the 3.0V level.

So the particular 18650 cell used to provide the curves shown in Fig.2 would be described as having a capacity of about 575mAh, as revealed by the purple curve.

This is a bit disappointing, considering that 18650 cells are supposed to have a capacity of between 1500 and 3000mA, but I admit it was an "Asian cheapie".

And as the blue curve shows, it can still deliver a current of 250mA for just on 2.7 hours; not bad at all for a cell measuring only 18 x 65mm. It would be OK for powering a piece of electronic gear drawing less than 250mA.

Varying voltage

Bear in mind that the voltage output of a Li-ion cell during discharge does vary over a fairly wide range, as shown in Fig.2. While this may not be a problem when it's used to power a LED torch or even a small radio receiver, it would be a potential problem when you want to power something that needs a fairly constant 5V or 3.3V.

Because of this, most of the USB Power Bank type devices sold to allow recharging of mobile phones and tablet PCs include a switch-mode DC-DC boost converter, to provide a regulated 5V DC output from the varying output from the Li-ion cell or cells inside.

Charging a Li-ion or LiPo cell

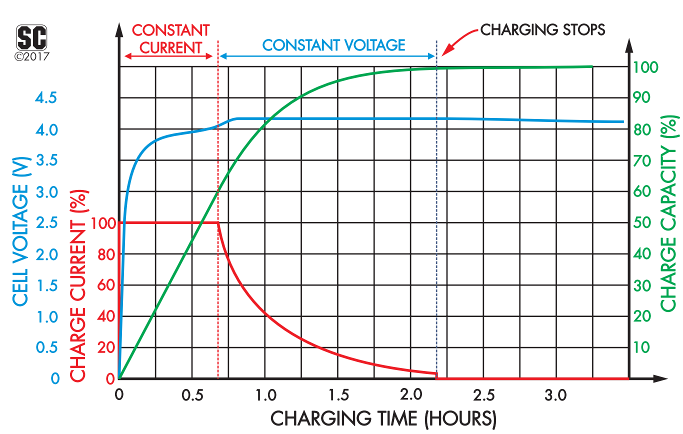
Because Li-ion and LiPo cells can be easily damaged by overcharging, a "safe charging protocol" has been established for them. This defines the best way to charge one of these cells both safely and in close to the shortest practical time. The protocol can be summarised like this:

1. First, the cell is charged with a constant current (CC) until its voltage rises to 4.0V. This corresponds to about 60% of its final charge. (If the cell voltage is much below 3.0V, a smart charger will use a much lower charge current until the cell comes back up to 3.0V, before resuming the full CC charging rate. This is to limit damage from swelling.)

2. Then the charger switches over to constant-voltage (CV) charging, with a charging voltage of around 4.1-4.2V. This second phase continues until the charging current drops to around 5-10% of the initial charging current level, whereupon the charger stops charging altogether since the cell will now be charged to more than 98% of its full capacity.

You can see a graphical representation of this protocol in Fig.3. Here the red curve shows the charging current, and as you can see this remains constant during the initial CC mode. Then when the cell voltage (blue curve) rises to 4.0V, the charger switches to CV mode. The charging current then starts

Fig.3: graphs showing the safe charging protocol recommended for single Li-ion cells and batteries with the cells connected in parallel.



Part of disassembled 18650 Li-ion cell, with a section of the "Swiss Roll" cut away to show the inside construction.

to fall, while the cell voltage rises only a little further before staying constant at around 4.1-4.2V.

The CV mode continues until the current falls to around 5% of the CC level, signifying that the cell has reached very close to its full capacity (green curve). Then the charger turns off, to prevent overcharging.

It might seem a little complex but as you'll see in another article in this issue, there are now low-cost ICs which take it in their stride. You'll find these ICs used in many of the low-cost Li-ion/LiPo chargers and modules.

If the charger remains powered, it can continue to monitor the cell voltage and if it drops very much (by say 100mV from the fully charged voltage), it can go back to CV mode to "top up" the cell. Repeated top-ups should bring it very close to 100% of its design capacity.

Multi-cell batteries

Li-ion/LiPo cells can be used alone, as in most mobile phones, but they're also commonly used in multi-cell batteries, with the cells connected either in parallel to provide a higher current capacity, or in series to provide a higher voltage (or both). For example, many USB Power Banks have two, three or four low-cost 18650 cells in parallel to provide extra "grunt", while some of the Li-ion batteries used in portable power tools may have three, four or five cells in series to provide a higher voltage.

It's easy to pick the batteries which have the cells connected in parallel because they still have the same terminal voltage as a single cell; nominally, around 3.7-3.9V. In contrast, any Li-ion battery which has a higher terminal voltage than this (like 7.6V, 11.4V, 15.2V or 18.5V) must have the cells in series.

When it comes to charging, you can treat batteries which have the cells connected in parallel in exactly the same way as a single cell. This means you can use the same kind of charger; it'll simply take longer to charge the battery than it would with a single cell.

But Li-ion batteries which have the cells connected in series should be handled in a different way for charging. For a start, these batteries need a higher voltage from the charger because otherwise, they won't receive any charge at all; as with other batteries, the various transition and cut-off voltages are simply multiplied by the number of cells in series.

In addition, a series string of Li-ion cells ideally isn't charged in exactly the same way as a single cell because the individual cells may not charge at exactly the same rate, due to variations in cell capacity and internal resistance. The result is that by the time the battery has reached its full charge voltage, some cells may not yet be fully charged while others may be overcharged. These over-charged cells may be damaged, especially if over-charged repeatedly.

Because of these problems, series-string Li-ion batteries are normally charged using a different kind of charger. This type of charger has a third balancing mode in between the CC and CV modes, where the charging current is either reduced or cycled on and off while the state of charge of the individual cells is brought to the same level by a balancing circuit. This continues until all the cells are charged equally, after which the charger switches to the CV mode until the full charge level is reached.

We published a circuit to balance a Li-ion or LiPo battery pack with 2-8 cells in the March 2016 issue (**www.siliconchip.com.au/Article/9852**).

This small module uses a PIC and some analog SMD components to constantly monitor and compare the voltage across each cell during charging and/or discharging and it slightly discharges the cell with the highest voltage, until they all exhibit the same voltage (within a fairly tight tolerance).

Note that while it's a good idea to balance a Li-ion/LiPo battery pack each time it is charged or discharged

While we have been concentrating on cells and batteries, Li-ion cells are found in a huge range of consumer equipment; at left is a typical 2900mAh phone battery, while above is a pack from Master Instruments specifically intended to start your car or truck when its battery won't! It will supply several hundred amps for a short time.

Li-ion Cell and Battery Protection

The most common anode material used in Li-ion cells is lithium cobalt oxide, because this gives the best energy density.

However, cells of this construction also have a worrying habit of exploding and/or bursting into flames when overcharged. For this reason, loose Li-ion cells and even made-up packs are now banned in many cargo flights; indeed, there are now also some restrictions on carrying devices such as laptop/tablet computers and phones powered by Li-ion batteries on passenger aircraft.

This is despite the fact that many (but definitely not all!) Li-ion cells and battery packs incorporate protection electronics, usually consisting of a tiny PCB with a high-current Mosfet and voltage-sensing circuitry which prevents the cell/battery from being charged if the cell voltage exceeds say 4.25V/cell. Normally, charging will stop at 4.2V/cell or less so this will not be activated unless a faulty or incorrect charger is used.

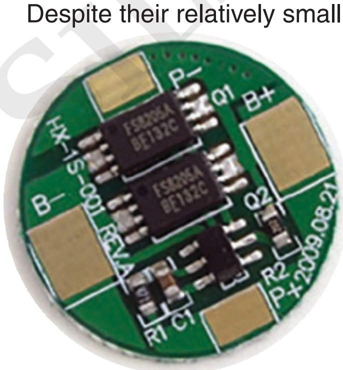
Cells and packs without protection are normally cheaper, but given the dangers, we would not recommend using them in most circumstances. Basically, to use an unprotected cell or pack, you need 100% confidence that your charger both uses the correct charging method and also cannot fail in such a way as to over-charge the battery.

Many of the protection circuits available will also prevent battery pack destruction due to over-discharging. This works similarly to the over-charging protection, except that it uses a second Mosfet to prevent the pack from discharging any further once its voltage drops below a threshold of usually between 2.7-3.0V per cell.

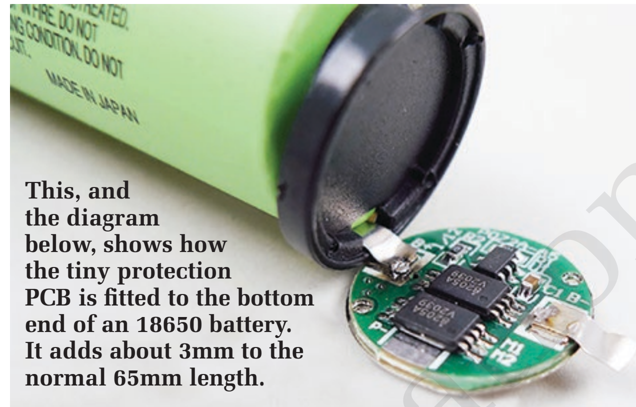
This may complicate charging should the protection kick in, as the charger may no longer be able to properly sense the pack voltage. However, the application of a small amount of current will normally allow the cell voltage to rise into the normal range, disabling the protection and normal (fast) charging can then resume. Some chargers will detect and handle this case by themselves; others may need user intervention.

Packs which lack over-discharge protection can easily have cells rendered useless if current continues to be drawn once they are flat. The pack would then require cell replacement or in the worst case, total replacement. Depending on the size of the battery, this could be an expensive proposition. Hence over-discharge protection is always recommended for Li-ion batteries, whether it is built into the pack or the load.

Despite their relatively small size, 18650 cells are available with built-in protection circuitry. The adjacent photos show how a small disc-shaped PCB is sandwiched at the end of the cell, with a connection back to the opposite terminal and so all current passes through this PCB. It typically contains two SMD Mosfets plus a control circuit to switch them off if the cell voltage is too low or high. The whole thing is then shrink-wrapped to hold it together.



This 18650 protection PCB is shown about three times life size for clarity: it's actually about 18mm in diameter.



This, and the diagram below, shows how the tiny protection PCB is fitted to the bottom end of an 18650 battery. It adds about 3mm to the normal 65mm length.

So 18650 cells with protection are slightly longer than those without; usually around 69-70mm compared to the nominal 65.2mm and that's one way to tell if a cell has protection. However, the outside packaging of the cell will usually make it quite clear that it has protection, since this is a major selling feature. As a result, most readers would be well advised to stick to using this sort of cell in their own projects.

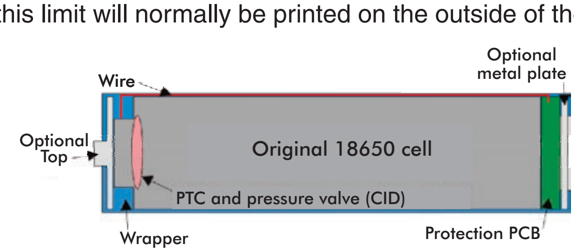
Incidentally, you can buy Li-ion protection PCBs incredibly cheaply from such places as ebay – for example, the PCBs pictured here are as low as 10 for $AU2.00 – pack and post included! Many other sizes and shapes are also easily obtainable, in a range of currents. If you have a project which uses unprotected cells, you'd be wise to avail yourself of a few!

You should also be aware that many (unscrupulous) manufacturers have branded non-protected cells as protected, some even going to the trouble of packing them to increase their length to that of protected cells.

There are countless videos (eg, on YouTube: siliconchip.com.au/l/aaeb) showing the disassembly of "protected" branded cells revealing . . . no protection! There are also videos which show how easy it is to check if a cell really is fitted with this vital safety aid.

There is an enormous variety of videos (particularly on YouTube) showing just how dangerous Li-ion batteries (and in particular 18650 cells) can be when not handled properly. There's a huge amount of energy in those little packs just waiting to get out (with the smoke)!

Finally, besides the extra cost and size, one other difference with protected cells is that the charge/discharge current may be lower than that for a cell by itself, as the Mosfets in the protection module will have their own current limit. If so, this limit will normally be printed on the outside of the cell.



for the best possible lifespan, in practice it takes multiple cycles for a damaging imbalance to build up. Fast and/or deep charging/discharging exacerbates this effect.

So one possible approach is to use a non-balancing charger to recharge a battery "in the field" as long as it is periodically re-balanced back at the home/office/depot.

This approach is safest if the battery is never fully discharged nor fully charged, except for when it is connected to the balance charger, since that minimises the chance of any single cell becoming over-discharged or over-charged.

The bottom line is that higher voltage, series-connected Li-ion batteries should normally be charged using a specially designed charger. That's part of the reason why power tools which use Li-ion battery packs come with a matching charger.

9800mAh and 10,000mAh Li-ions? Unbelievable!

The 18650 Ultrafire Li-ions at left and the unbranded cell at right are regularly offered for sale on ebay at very attractive prices (eg, 6 for $13 including postage!). But if you look closely, you'll see the Ultrafires are rated at 9800mAh. The unbranded cell is even "better" at, wait for it, 10,000mAh (ie, 10Ah!). This is amazingly powerful for an 18650 cell, considering the highest rating 18650s currently being manufactured are about 3700mAh! Many online tests confirm this brand, and many like it, are totally bogus and may not even reach a tenth of their claimed rating! Anything above 3700mAh (and even many below it in some brands!) should not be believed. They are frauds. By the way, $13 is not a bad price for ONE legitimate brand 18650 (eg, Panasonic, Sanyo, etc).

Safer lithium chemistries and functional differences

We mentioned near the start of this article the various different compounds that can be used to form lithium-ion cell anodes but we didn't describe their relative advantages and disadvantages.

As explained in the June 2013 article titled "Get a LiFe with LiFePO4 Cells" by Stan Swan (www.siliconchip.com.au/Article/3816), cells which use lithium iron phosphate in the anode (ie, LiFePO4 cells) have somewhat different properties to the more familiar lithium cobalt oxide (Li-ion/LiPo) cells.

The major benefit of LiFePO4 cells is that they are much more tolerant of being over-charged or rapidly discharged (eg, with the terminals shorted) and even if they are damaged from excessive over-charging, don't tend to fail destructively. They also have a much flatter voltage discharge curve.

On the flip side, they have a lower energy density (ie, lower watt-hour capacity for the same size/weight of cell) and they also have a lower terminal voltage, which means LiFePO4 chargers must operate differently from other Li-ion chargers (some chargers can be switched between different modes to suit either type).

As stated earlier, a fully charged Li-ion cell is about 4.2V, nominal operating voltage is around 3.7-3.9V and a discharged cell is around 3.0V. By contrast, a fully charged LiFePO4 cell is around 3.6V, nominal operating voltage is 3.2-3.6V and 2.5V when fully discharged.

Also, when a Li-ion/LiPo cell is charged to 4.2V, it will remain at that voltage for a long time (months/years) if untouched.

By contrast, LiFePO4 cells charged to 3.6V drop back to around 3.3V a short time after charging ceases. This is similar behaviour to other cell chemistries such as lead-acid and NiMH.

$LiFePO_4$ cells are also claimed to survive more charge/discharge cycles, especially deep discharges, compared to Li-ion.

Because they are non-flammable, protection circuitry isn't as critical for LiFePO4 cells but is still a good idea to minimise the chance of cell damage due to over-discharge.

Lithium ion manganese oxide and lithium nickel manganese cobalt oxide (anode) cells appear to offer similar properties to $LiFePO_4$ cells, ie, they are safer than traditional Li-ion cells, however, they do not appear to be as popular as $LiFePO_4$ at the moment. SC

We visit Australia's largest battery importer, distributor and packager: Master Instruments

At the time of preparing this feature, we took the opportunity to visit Master Instruments Battery Engineering at their new (and huge 5500m^2) premises in Milperra, Sydney.

A third-generation, family owned Australian company, they've grown from primarily making panel meters for the defence forces during WWII to a major player in the Australian electrical and electronics industry with offices in four states.

They're not only the largest importer of cells and batteries in the country, they also manufacture batteries for a huge variety of equipment, either to special order for OEMs or for the wholesale and retail market.

They have a large production area packaging and preparing cells into the shapes and sizes required – and to back this up, they carry Australia's largest inventory of cells and batteries of every shape and size – many you would never have heard of. There are over 8000 individual stock lines in vast racks in the new warehouse.

But they also offer support, including R&D if required, for industrial and commercial battery users who need specialised batteries for their equipment – including mining, distribution, medical, transportation, defence and many more.

See the Master Instruments story at their website: www.master-instruments.com.au