Lithium Ion and Battery Safety, what cavers need to know.

General.

A battery is a means of storing electrical energy, if short circuited it can cause fire and injury.

This piece of safety advice is fairly universal, however how many people take the trouble to read it or really think about it? How many non-electrically minded people even fully understand what a “short” actually is? Here we are going to look at the means by which short circuits can arise, their implications, and how Lithium Ion (Li Ion) cells differ from others, and what special considerations they should be given to charging and usage. From the preceding advice ones intelligence should prevent one from carrying any kind of battery uncovered in a pocket together with keys and loose change!

Electricity is a flow of electrons and a circuit is a path along which they can flow and in so doing achieve some kind of work. So electricity is a form of energy that can achieve work, and the circuit is the ‘vehicle’ by which this is achieved. The work is usually in the form of heating, lighting, or motive power, such as from an electric motor. The components included in the circuit present a resistance to the free flow of electricity, as indeed does the ‘wires’ included in the circuit. All electrical conductors have a resistance, and the material and thickness of the wires, or bus system of a Printed Circuit Board (PCB), has to be sufficient for the current flowing through it. If it is insufficient, electrical energy is converted to excess heat, every circuit will generate some heat, but excess heat can be sufficient for the wiring of the circuit to become hot to the degree whereby it can ignite surrounding material.

So in effect a “short circuit” could be regarded as a misnomer, however it is normally caused by accidental contact of high (+) to ground (-), or in the case of a mains supply AC input, the live to either neutral or earth. In effect, this being “short” of the components within the circuit that would normally present a resistance to the flow of electricity. Also, similar effect can be caused by a circuit with wiring or components below the specification required to carry the current, the result being excess heat. From this can be seen that wires contained in cables themselves present a resistance and have to be sufficient for the current they carry.

In either of the above scenarios the eventual outcome will be that part of the circuit will melt causing the circuit to become ‘open’, by reason of the break created. This will always occur at a point in the circuit of smallest sectional area, such as the thinnest wire. This will in effect act as a fuse. However, by this time it may well have caused fire, which is why fuses, which are deliberately designed to act in this way, are a wire enclosed in a non flammable material.

Let us now look at voltage and current. This is most easily explained to the novice by comparison with say the water tap on the kitchen sink. Inside the water pipe water is under pressure, this can be equated with electrical voltage. When the tap is turned on water will flow, (current), and the pressure (voltage) inside the pipe will fall.

We all know that connecting a hose to the tap enables us to say water the garden or fill a water tank. If the tank was tall enough though, there would be insufficient pressure from the hose to reach the top of the tank. But what about connecting a hose directly to the water tank, and for the sake of this explanation, at the bottom of the tank?

Water would indeed flow into the tank which would start to fill, however this would stop at a certain point, assuming the tank was very tall, when the pressure of the water already inside the tank equalled the pressure of water from the tap. Electricity behaves in exactly the same way when a battery is connected to an electrical supply. If a battery has say 10 volts measuring across the terminals, applying a 10 volt supply would do nothing as no electricity would flow, if the battery needed further charging, then the charge voltage would have to be increased. However, if the charge voltage was increased excessively, more current would flow than that which is would be safe for that type of battery, and also the battery would eventually become over charged.

Batteries

Now, as already said, a battery is a means of storing electrical energy. As such there will be a voltage across the terminals. When a circuit is connected, (the load), current will flow, and the voltage of the battery will drop, usually referred to as “voltage drop under load”.

Different types of battery have differing levels of safe charge and discharge, exceeding those can cause damage to the battery, as well as producing fire or explosion. This is especially true with Li Ion. Check the manufacturer’s data sheet for whatever cell you are using.

There are many different types of battery, but for the purpose of this paper we are only really concerned with Lithium Ion. Now be aware that battery chemistry differs, “Li Ion” is a collective term. Lithium Ion Polymer (Li Po) is not the same as other Lithium Ion chemistries and in my opinion is unsuitable for underground use on safety grounds. It can explode if subjected to shock, so for underground use we will stay with the various Lithium Ion chemistries.

Lithium Ion

A lithium Ion cell differs from other types in that it cannot be fully discharged, and to do so is dangerous as well as destroying the cell. Fully discharging lead acid batteries will damage the battery, but Lithium Ion goes a bit further. For this reason some kind of electronic management circuit is essential for its protection in order to prevent over charge, over discharge and short circuit. If short circuited or over current discharged a Li Ion cell can suffer from what is known as “Thermal runaway” whereby it generates an increasing level of heat. I will come back to this later.

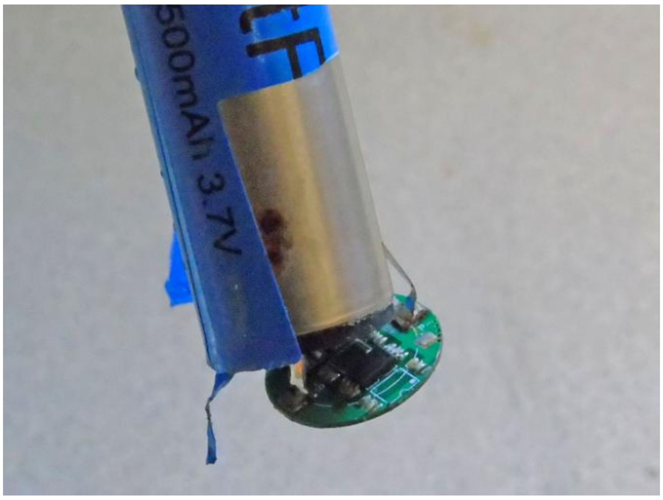
At time of writing a commonly used cell is the Sanyo NCR 18650GA, so we will describe this as an example. The first three letters denote the chemistry, “Nickel Cobalt Rechargeable”. The second is the size, 18mm X 65mm, the third a subtype.

This cell is rated at a nominal voltage of 3.6V, is fully charged at 4.2V, min voltage on discharge is 2.5V, max safe discharge current is 10 amps. An earlier NCR 18650B had a safe max discharge of 8 amps. Please note that if a cell is over discharged down to not less than 2V, it can be recovered by charging at a low current under lab conditions. However, this last piece of information is included in the interests of technical accuracy, I recommend scrapping of any cell that has become over discharged.

The capacity is 3500 mAh, or milli-ampere hours, this is the same as 3.5 ampere hours. For the benefit of clarity, this means that if something electrical was connected to it that drew a current of 1 amp, it would run for 3.5 hours.

The above cell is a “Original Equipment Manufacturer” – OEM product and a retail product based upon this cell will be offered under a variety of brand names, albeit fitted with a protection (Battery management) board fitted to the base and supplied in the retail brand named outer wrapper. See the photograph below.

Obviously the capacity of Li Ion cells has increased with advances in technology. But there are still cells manufactured of lower capacity that are designed for higher discharge rates usually coupled with higher permissible rates of charge, typically for use in power tools. At the time of writing, high capacity is not compatible with high discharge, fast recharge.



On the left is a protected Lithium Ion cell of mediocre quality with wrapper opened up. The little round protection PCB can be seen, this has a connection to the anode of battery (+) by means of the metal strip on the right which has an insulation strip of plastic between itself and the body of the cell which forms the cathode (-). The PCB is insulated from the cell base by a ring of black rubber like material.

The wrapper is marked with the (nominal) voltage and the capacity relative to that voltage.

On the left are three different types of Lithium Ion battery cell. All are OEM (Original Equipment Manufacturer) and as such not intended for retail sale. Usually fitted with a protection board and re-branded, they will have a new outer wrapper with the retail brand on it. Left is the cell described, centre is another 18650 designed for high discharge, as such its capacity is lower at 2600mAh. On the right is a 207000, higher capacity and rated at 15 amps maximum safe discharge.

My advice regarding any lamp that takes loose cells is to always read the lamp manufacturers instruction sheet regarding recommended cells, don’t throw it away. I know that there will be pages of nonsense like not putting it in your mouth, this is a sign of the times were common sense is frowned upon in favour of ‘check box’ mentality, but read all the same. It will likely recommend a type or even best brand of cell, if in any doubt, use good quality protected cells.

Batteries in arrays

This will commonly be encountered in an off the shelf, purpose designed lamp for underground use, but may also be encountered in a lamp or torch which is designed to take loose cells. It may be in the form of a sealed battery pack such as the Stenlight or my lamps, or cells contained in an outer wrapper whereby the whole assembly is designed to fit into a battery case such as with the Scurion or Rude Nora. In this case there are no special considerations other than following the manufacturer's instructions. This arrangement however, may also be used by the DIY lamp or battery pack builder. In this case it is important for a builder to fully understand the issues involved.

The understanding a few basic facts will also be necessary for product evaluation, as well as the implications of DIY conversions, and the possible pitfalls of using products that take loose cells if no specific instructions are included.

Batteries in an array can be connected either in parallel or in series, however they are connected the capacity of the array will be the same in real terms. If one takes an example of two cells, if connected in parallel, positive to positive, negative to negative, then the output voltage will remain the same and the indicated capacity of each cell doubled. Connecting them in series, positive of one to the negative of the other will double the available voltage, but the capacity is same as a single cell, however the available voltage has doubled. But in real terms the capacity is still double that of one single cell. In electrical terms we measure power in watts, and this is arrived at by multiplying the voltage by the current. So the capacity of a battery is better stated in terms of watt hours, this is a lot more meaningful and more useful for the comparison of competitive products.

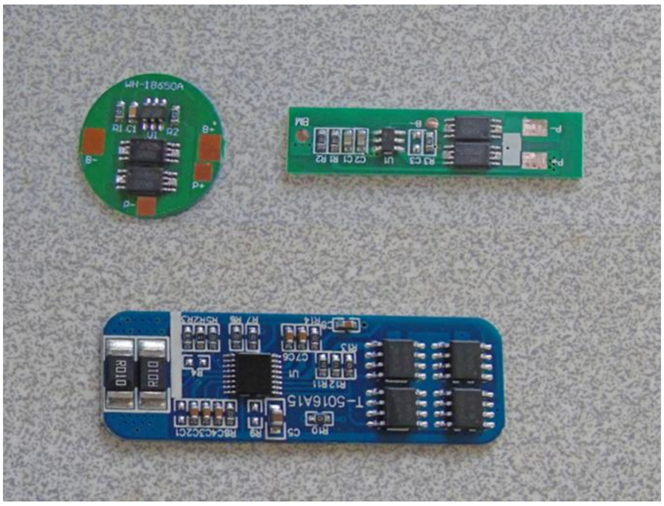
The implication of this is that stating the capacity of a battery pack that contains an array of cells is meaningless without giving the nominal voltage, and is more accurately expressed anyway as Watt Hours.

So taking our two series lithium Ion pack, fresh off charge it will have a voltage of about 8.4V, and minimum safe voltage of 5.4V, however a management circuit, would have to evaluate each individual cell.

Battery Management

All Lithium Ion cells, or arrays of cells such as will be contained in a battery pack, will need some form of electronic battery management, sometimes referred to as a "Protection Board" as in the single cell example previously described. This will disconnect the cells in event of short circuit, and prevent overcharge and over discharge.

Now battery management for serial arrays of cells has to relate to each individual cell, otherwise one cell could become over charged and the other undercharged and together still have an overall voltage meeting the maximum criteria of 8.4V. Below illustrates some typical management circuit boards together with their properties. As said before, always refer to the manufacturer's data sheet. You will need to know the charge cut off voltage, the discharge cut off voltage, the maximum discharge current, and the max charge current. All of these will need to be suitable for the battery pack that you are constructing.



On the left can be seen a selection of Li Ion battery management modules. Top left is the kind that is mounted on the base of a single cell and enclosed within the wrapper. Top right is a type designed to manage two cells in series with an off charge voltage of 8.4V. Note the similarity between components. Both utilise a dedicated chip manufactured by Seiko Industries. These are rated at 2 amps so are mounted in pairs to handle 4 amps.

Bottom one is a different kind of beast. This is designed for three cells in series, 12.6V off charge and is also designed to handle a larger output current of 8 amps.

Charging Li Ion cells.

Different types of battery present different types of charging requirements, but all require the application of a voltage over and above the voltage of the battery before current will flow. As McCoy said to Captain Kirk, “You can’t change the rules of physics Captain”.

Li Ion cells are charged at a constant voltage of 4.2V per cell. The nature of the cell is such that as charge progresses the voltage of the cell will increase with its internal resistance. A cell at its lowest state of discharge, such as 2.7V, will present the lowest resistance within the charging cycle, therefore the current that flows must be regulated so as not to exceed the cells maximum safe charging current, again ‘data sheet’. As a general rule, this will be 0.5C where “C” = Capacity. However, some cells are manufactured for high discharge/fast recharge. Again, refer to data sheet. In any event, as recharge progresses and the batteries internal resistance increases, the charging current will become governed by the battery. For this reason charging to half capacity will be a darn sight quicker than the final phase of charging. Something to remember if you come out from underground with an almost depleted lamp and only have an hour to recharge it, it will take a lot more charge in the hour that you would think!

Now if one is constructing a battery pack using multiple cells it’s important to consider charging implications. To simplify matters we will consider just two cells.

If connected parallel, as stated before, the nominal voltage will remain the same but the capacity relative to that voltage is doubled. In effect we have combined two cells together to make a single cell that will have voltage same as a single cell. However the capacity of two, say 3500 mAh cells will now be 7000 mAh, so one half of C will be 3500 mAh, therefore 3500 mA would be a permissible charge current. The charger voltage required being the same a single cell, Output 4.2V.

However connecting the two in series will double the voltage to a nominal 7.4V, also the maximum ‘off charge’ voltage will have doubled to 8.4V, but the maximum charge current will 0.5C of a single cell. So the correct charger will be 8.4V output, with a maximum output current of 1750 mA.

Here are two different charger types; however they both have an indicated output voltage of 8.4V which makes them suitable for charging 2 series Li Ion battery packs. However they differ in other ways. The one on the left has an output of 1 amp, so is fairly universal. A battery with multiple cell arrays will just take a fraction longer to charge. This example is not specifically marked as a Li Ion charger however, although it is. Both have charging (red) to Fully Charged (green) LED indicators.

The one on the right is marked at 2 amps, so should only be used on battery packs where the manufacturer indicates that this rate of charge is suitable. It also a 2 pin plug, this is OK; the one on the left has an earth prong which is a dummy. However the one on the right needs an adaptor. Whichever way it's plugged into the adapter makes no difference.

Another consideration when charging Lithium Ion cells is the ambient temperature. The manufacturer's data sheet for the Sanyo cells I have used in the paper as an example gives a range of 10 to 40 degrees Celsius, and charging should be done within this range. It is a general rule however that Li Ion cells should not be recharged in sub zero temperatures such as would be found in a garden shed in winter. If you do this expect a reduced burn time in use and possible cell damage.

Torches

Now lets just consider loose cells such as would be fitted into a torch.

A fairly standard torch will usually not have any kind of battery management electronics; therefore unless you are instructed otherwise by the manufacturer, they should only be used with what are called "Protected cells" as described previously. These have a small circular printed circuit board mounted in the base and fully enclosed by the cell wrapper, as previously described. This will cause the torch to go out when the battery is depleted down to its safe maximum discharge limit, the cells minimum safe voltage. However, do read the instructions and use whatever the manufacturer recommends.

So what happens if a Li Ion battery is over discharged?

Well, basically it's trashed, but there are some more serious implications. Over discharge can cause internal breakdown where internal short circuits can be created. This may not be immediate, but can occur when the battery is being recharged. For this reason dedicated Lithium Ion battery chargers that meet quality standards will not charge a cell if it registers a voltage below a safe limit.

On the face of it, the above sounds serious, it is. However there is a condition that can arise that is even more serious. This is that of a 'battery to battery' short circuit.

Referring to what I have previously written regarding cells connected in series, there are actually two ways this will be encountered, end to end such as some torches taking loose cells, and side by side as usually encountered in sealed rechargeable torches such as the Imolent DX80.

Batteries connected in series side by side will usually be connected together by metal tags. Beauty of this is that in the event of a short circuit, the metal tag would act in the same way as a fuse. This is the way that the better quality sealed rechargeable torches such as the above example are constructed. Also disassembly has demonstrated that there is no contact between the bodies of the cells and the torch outer case, and that there is cell between cell insulation.

But end to end, this condition has the potential to be a lot more serious. Generally torches are of anodised aluminium construction, aluminium being a very good conductor of electricity. Anodising produces a dyed and sealed oxide coating that is non conductive, but generally the contained cells will have a ground (-) to the torch body by means of a metal spring set into the base. It's fairly few torches designed in this way nowadays, but a few years back there was a mass of cheap low quality but high powered torches available on the market following this design. These basically consisted of an aluminium tube to hold the batteries, and a head into which the manufacturer could cram as many LEDs as possible driven by some cheap generic driver system. The output would be grossly exaggerated as a 'sell' and maybe even doubled again for effect, in order to dupe the unknowing prospective purchaser. In this design, a short circuit between the high side (+) of the batteries and case of the torch would produce what I call a "solid", i.e. non fusible short circuit. Remember also, that the positive(+) of cell no 2 is the negative(-) of cell no 1 and so on. Also, if Lithium Ion batteries are short circuited, refer to my earlier text, they can suffer from what is known as "thermal runaway".

If you look at a cell you will see that the cap has a vent. The cell does not normally 'breath', this is in effect an anti explosion valve. So if you take a cheap low quality high powered torch that takes two, three, or even four cells, unscrew the tail cap and fit unprotected battery cells, and when you screw down the tail cap you are in effect making a sort of pipe bomb.

The term "pipe bomb" above is possibly an over exaggeration, as any comparison with a real pipe bomb containing high explosive is nonsense. In the case of an internal non fusible short circuit, hot gasses would be produced which would exert a pressure on the body of the torch. The aluminium would rupture and split probably at the base, and a jet of hot burning gasses would erupt. This is bad enough to cause serious damage and injury.

DIY Considerations and pitfalls.

There are a lot of cavers and mine explorers who have, or will, either attempt to build their own lamp typically using say and Oldham GT headset, or modify a lamp designed to run on some other battery type to run on Lithium Ion. Here I attempt to describe the considerations and second guess possible pitfalls.

The design of lamps is outside of the scope of this paper, but most DIY lamp builders will likely be using an 'off the shelf' driver for their LEDs, in this respect the same consideration regarding battery voltage will apply as to a conversion for a pre existing lamp. The first thing will be to get the input voltage range of the driver or lamp. If it's someone else's lamp this information should be in the lamps instruction sheet or maybe off their website. As I have said, the voltage of a Li Ion cell fresh of charge will be a fraction below 4.2V, this is obviously the voltage to consider and not the nominal voltage marked on the cell. You also need to consider cell management, a circuit board will not only prevent over discharge, but also over charge and short circuit.

Some lamps will be designed to run off battery types that can be fully discharged, such NiMH, the commonly found AA and AAA type. If so, a well designed lamp will utilise a boost circuit of some kind to get every last drop of power from the cells. Converting to Li Ion and using unprotected cells would be a disaster and possibly make work for the local Fire and Rescue.

Recharging will also need to be done with a dedicated Li Ion charger. One of the cheap mains adaptor chargers with possibly a different connecting plug fitted in place of usual jack plug may well do the job. But the original supplied charger will not be suitable and if used would be downright dangerous.

It will also require one to check the current output of whatever charger you are considering and decide whether this is suitable for the battery pack you are constructing. Too low a charge rate will do no harm, and most people put lamps on charge overnight. However if you are using cells that are designed for high discharge, fast recharge, something could be gained by using a charger that delivers a higher current output. Refer to above photo and description.

I advise against any kind of amateur battery pack of higher voltage containing three or more Li Ion cells connected in series. The considerations here are a lot more complicated and most certainly require management electronics that evaluate each individual cell, and as such need a much deeper understanding of electronics that can reasonably be expected of the average hobbyist.

In constructing a battery pack or indeed anything electrical, consideration has to be given to the cable and its ability to carry the current required.

Spring loaded battery holders are best avoided as they can be unreliable in use. A sudden shock can cause a momentary disconnect that could cause a lamp to change mode.

Water ingress is another factor to consider. With regard to the cells themselves it would just induce corrosion of the steel bodies; however its effect on electronic management circuits would be destructive.

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