



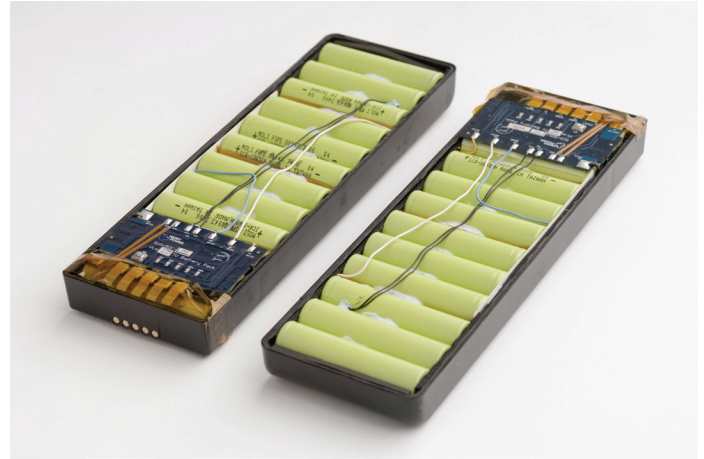
Upgrading to Li-ion from Lead Acid

Both the Lithium-ion (Li-ion) and Sealed Lead Acid (SLA) battery markets are expected to grow over the next several years. Applications with high voltage and capacity requirements are adopting Li-ion technology because of its many advantages- especially the high energy density, small size and low weight that this technology provides. Historically, SLA batteries have had a few superior technical traits, in addition to their extremely low cost, that have kept them leading the majority of the overall battery market. However, recent innovations in Li-ion chemistry has made it extremely competitive in markets that are weight sensitive and inconvenienced by SLA's need for frequent maintenance. Many devices have required batteries for power back-up and these are primed for direct Li-ion replacement of SLA. In the medical market alone, these applications include infusion pumps, ventilators, wheelchairs and workstation carts. This paper will outline the technical and business considerations involved in converting an existing product from SLA to Li-ion.

THE CHEMISTRIES

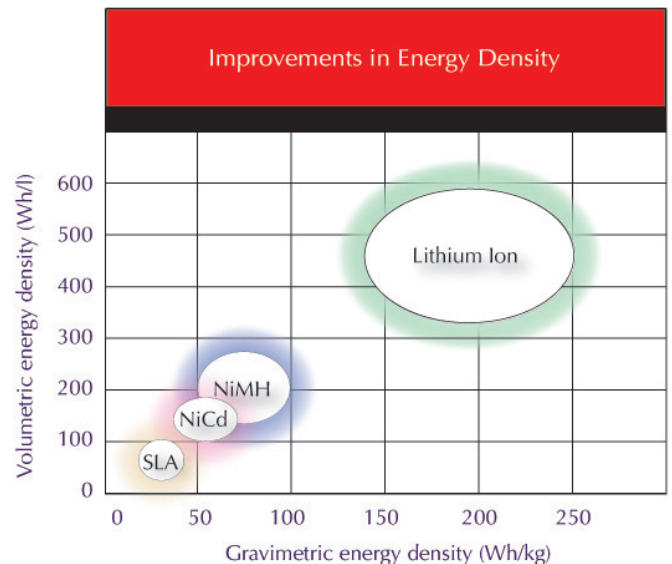
Batteries use a chemical reaction to do work and produce a voltage between their output terminals. The reaction of lead and lead oxide with the sulfuric acid electrolyte produces a voltage in a lead acid battery. An SLA Cell has one plate of lead and another of lead dioxide, with a strong sulfuric acid electrolyte in which the plates are immersed. The characteristic voltage of the creation of lead sulfate is about 2 volts per cell, so by combining six cells you get a typical 12-volt battery.

Li-ion is a type of rechargeable battery in which lithium ions move from the negative electrode (cathode) to the positive electrode (anode) during discharge, and from the cathode to the anode when charged. The three primary functional components of a lithium-ion battery are the anode, cathode, and electrolyte, for which a variety of materials may be used. Commercially, the most popular material for the anode is graphite, but some manufacturers use coke. The electrolyte is a non-aqueous solution of a lithium salt. The cathode is generally one of three materials: a layered oxide (such as cobalt oxide), one based on a polyanion (such as iron phosphate), or a spinel (such as manganese oxide). Depending on the choice of material for the anode, cathode, and electrolyte, the voltage, capacity, life, and safety of a Li-ion battery can change dramatically. The electrochemical reaction produces about three and a half volts depending on the chemistry and brand, so four cells in series can produce a range of nominal voltages from 12.8 to 14.8. Battery packs made with Li-ion are not a simple configuration of cells. They are carefully engineered products with many safety features. The main components of a battery pack include; the cells, which are the primary energy source, the printed circuit board, which provides the intelligence of the system, the plastic enclosure, external contacts, and insulation. The internal features of a battery pack are shown in the first picture (right).



LI-ION ADVANTAGES

Li-ion batteries offer many attractive advantages for portable equipment over the older rechargeable technologies. Li-ion battery characteristics include a nominal voltage of 3.6 V, thousands of duty cycles per lifetime, a less-than-three-hour charge time, a typical discharge rate of approximately ten percent per month when in storage. This accompanying graph illustrates that Li-ion technology offers a pronounced energy density advantage by both volume and weight.



It's also important to note the size of the Li-ion bubble; it represents the many flavors of Li-ion available on the market. The specific characteristics of each Li-ion cell chemistry, in terms of voltage, cycles, load current, energy density, charge time, and discharge rates, must be understood in order to specify a cell that is appropriate for

an application.

Li-ion battery systems are a good option when requirements specify lower weight, higher energy density or aggregate voltage, or a greater number of duty cycles. Conventional Li-ion chemistry, designed for portable applications like lap-tops and cell phones, is designed to offer the highest energy density by size and weight. Typically, these applications do not have high current requirements and are relatively price sensitive, so conventional Co-based Li-ion cells are appropriate for applications that need to be smaller and lighter. Newer Li-ion chemistries are optimized around the power tool and electric vehicle markets. These Fe-phosphate based cells have remarkable cycle life and current delivery capability, but their volumetric energy density is less and upfront cost is greater. They are more amenable to direct use of an SLA charger and are appropriate for replacement of SLA when total cost of ownership and weight reduction are the primary objectives.

DIRECT REPLACEMENT OF SLA WITH LI-ION

Making a direct comparison of lead acid batteries and Li-ion batteries is difficult. The operation of the cells is so fundamentally different that direct replacement and comparison is hard. SLA Runtime is determined by not only capacity, but is also highly dependent on rate. We'll see the effect of rate on recognized capacity in a few slides. In addition, SLA batteries cannot be fully discharged. The voltages are not well matched for the two chemistries.

The chart below presents a comparison of li-ion battery packs made with traditional Co oxide chemistry cells and SLA batteries.

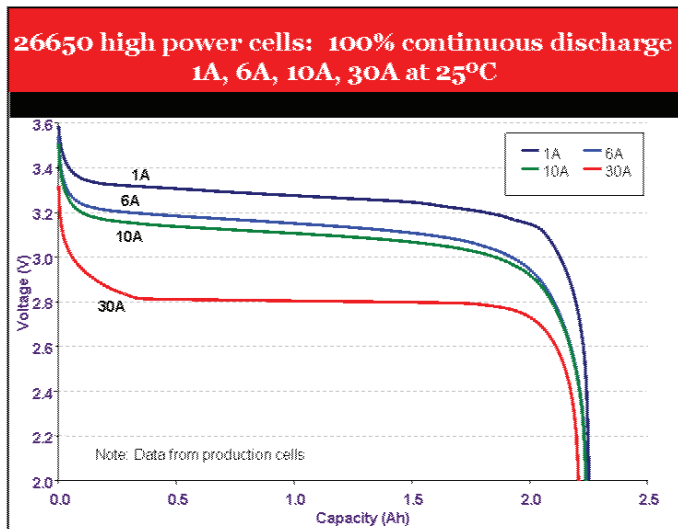
The first column is 6 sealed lead acid batteries in series and 2 in parallel. The following 2 columns are 2 Li-ion configurations of Li-ion 18650 cells: 4s 2p and 3s 6p designed to give similar performance and runtimes to the SLA. The series configuration determines the voltage and paralleled cells determine the capacity. The runtimes are similar, yet the Li-ion batteries occupy about one fifth the volume and about one seventh the weight. Unfortunately, packs made from conventional chemistry are not compatible with SLA chargers.

	SLA 2 x LC-RA127R2P	Li-ion 18650s	
Configuration	6S-2P	4S-4P	3S-6P
Volume [l]	1.85	0.34	0.38
Weight [kg]	4.94	0.67	0.76
Thickness [cm]	6.5	3.4	3.4
Voltage range [V]	10.5 –13.7	11.0 – 16.8	8.25 – 12.6
Run time at 12 W [hrs:min]	7:12	6:30	7:18
Run time at 14 W [hrs:min]	6:06	5:34	6:15
Run time at 16 W [hrs:min]	5:15	4:52	5:28

The benefits of new high rate Fe-phosphate cell chemistries both include; increased safety, low impedance and high discharge rates and a voltage that matches well with SLA at 12 and 24V increments. These design features allow use of a conventional SLA charger. In the fourth figure, one can see the performance of the A123 cells, an example of the high rate cells.

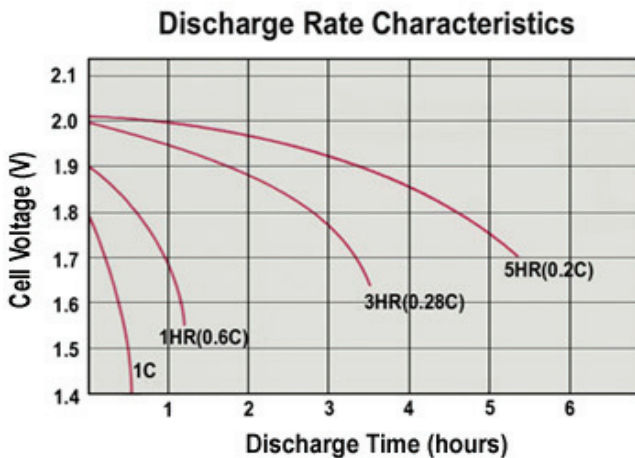
As the load increases, the discharge time suffers because some battery energy is lost due to internal losses. This results in the battery heating up. The efficiency of a battery is expressed in the Peukert number. In essence, the Peukert number reflects the internal resistance of the battery. A value close to 1 indicates a well-performing battery with little losses. A higher number reflects a less efficient battery. SLA batteries are stressed the most if discharged at a steady load to the end-of-discharge point. An intermittent load allows a level of recovery of the very chemical reaction that produces the electrical energy. Because of the rather sluggish behavior, the quiescent rest period is especially important for lead acid. There is an advantage. The advantage of this curve is a simple voltage measurement can be used for fuel gauging.

Traditional fuel gauges for Li-ion either monitored the voltage or the capacity, and the accuracy was quite limited. This is due to that flat discharge curve we saw earlier. New gas gauges monitor the number of coulombs being transferred and opportunistically calibrate with the open circuit voltage of the Li-ion pack. These features allow the end-user to intelligently manage device use and avoid unexpected failures or shutdowns.



The cells deliver virtually full capacity at a high rate of 30A. Here we can see how flat the discharge voltage of a L-ion cell is; this represents a challenge for fuel gauging.

Figure 5 is a discharge curve for SLA- note the almost linear downward slope. The relationship between the discharge times (in amperes drawn) is reasonably linear on low loads.



CHARGING ISSUES

There are several charging methodologies for SLA batteries. Due to the versatility of the SLA battery chemistry, charging electronics are simple and cheap, and numerous options exist, including:

- Trickle: charging at a rate equivalent to its self-discharge rate.
- Float: the battery and the load are permanently connected in parallel across the DC charging source and held at a constant voltage.
- Taper: either constant voltage or constant current is applied to the battery through a combination of transformers, diodes, and resistance. The current diminishes as the cell voltage increases.
- Constant Voltage Charging with Current Limit: constant voltage charging method, with current limiting, applies the maximum allowable charge voltage, but has a current limit to control the initial absorption current.
- Three Phase Charging: the most advanced charging method for SLA batteries. The first phase is bulk charging. When the preset voltage has been reached, the charger switches into the constant voltage phase and the current drawn by the battery will gradually drop. The final phase is the float phase.

For Li-ion batteries, constant current - constant voltage, or CC/CV, is the only universally accepted Li-ion charging method. A constant current equal to or lower than, the maximum charge rate is applied to the battery until the maximum charge voltage is reached. At that point, the operating mode turns to constant voltage output, which is maintained until the charge termination criterion is satisfied. A Li-ion battery is fully charged when the maximum charging voltage has been reached and the falling value of the charge current is below a certain fraction - usually 1/30 to 1/10 - of the battery's maximum charge rate. There is a very good chance the SLA charge regime already embedded into the device or charging platform will not charge a Li-ion battery while maximizing safety, the capacity of the battery, or the cycle life of the battery.

When a device manufacturer considers migrating from SLA to a Li-ion battery, they have several options for placement of charge control electronics. If the customer base for the device will allow a wholesale change with the charger, the simplest way is to totally replace the SLA charge

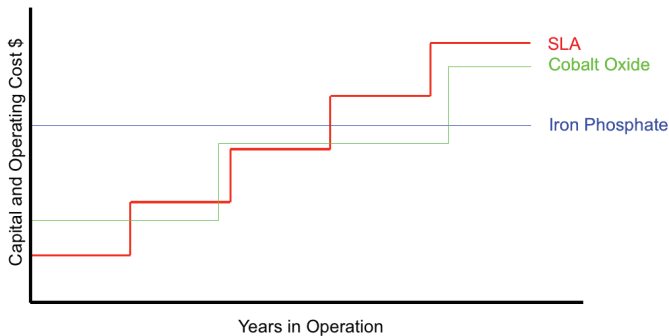
electronics with Li-ion charge electronics within the charging bay. The new Li-ion charger is backwards compatible with the SLA batteries, but the old SLA charger is not forward compatible with the new Li-ion battery. Lithium iron phosphate provides a nice compromise for migration from SLA, as it will operate with most of the SLA charging methods. The notable exception with lithium iron phosphate is that unchecked trickle charge will overcharge the cells.

BUSINESS CONSIDERATIONS AND TOTAL COST OF OWNERSHIP

In addition to the technical performance benefits, there are additional reasons to switch to Li-ion from SLA. One is that Li-ion is more environmentally friendly. There is no over arching law regarding the recycling of batteries in North America, but Federal law requires that used Ni-Cd and lead acid batteries to be managed as Universal Waste and 38 states have bans on the disposal of lead batteries, while Li-ion can be disposed of normally in most areas and can easily be recycled. Europe is leading the way in enforcing environmental regulation. They have several relevant pieces of legislation. The most relevant piece of legislation is the EU Battery Directive, which sets maximum quantities of chemicals and metals in batteries. It requires proper waste management of these batteries, including recycling, collections, "take-back" programs, and disposal; it sets the financial responsibility for programs.

Most Li-ion ion battery packs are custom made for each application. Off the shelf battery packs can be purchased but they are specifically made for high volume lap tops, cell phones, cameras, and other consumer electronics. Industrial, medical, and military equipment almost always use custom Li-ion products. It's important to choose a battery pack supplier with experience in the design, development and manufacture of batteries for your industry. SLA batteries in contrast are almost always off the shelf products there are several common voltages and capacities and these can be purchased from many brands at many retail locations.

This final graph conveys the economic tradeoff between SLA and 2 Li-ion chemistry solutions.



One might imagine an SLA battery for a product with a 10 year lifetime. Over this lifetime the SLA would need to be replaced 5 times. A cobalt oxide pack with similar capacity would cost roughly twice as much but its cycle life is almost twice as much also. The upfront cost would be more, but over the lifetime of the product the total cost may be lower. With an iron phosphate Li-ion pack would likely be about 3 to 4 times the upfront cost, but the cycle life is so long that the solution will almost certainly have a lower cost over the life of the product. Of course, there are many details that go into this economic model, for example shipping cost and how remote or difficult to replace the battery, so it is important to vet out the specifics before making a decision.

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