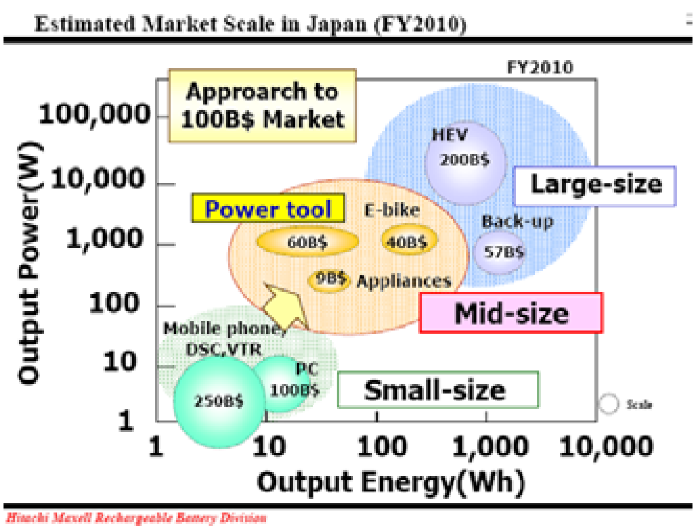
Building Battery Arrays with Lithium-Ion Cells

MICRO POWER

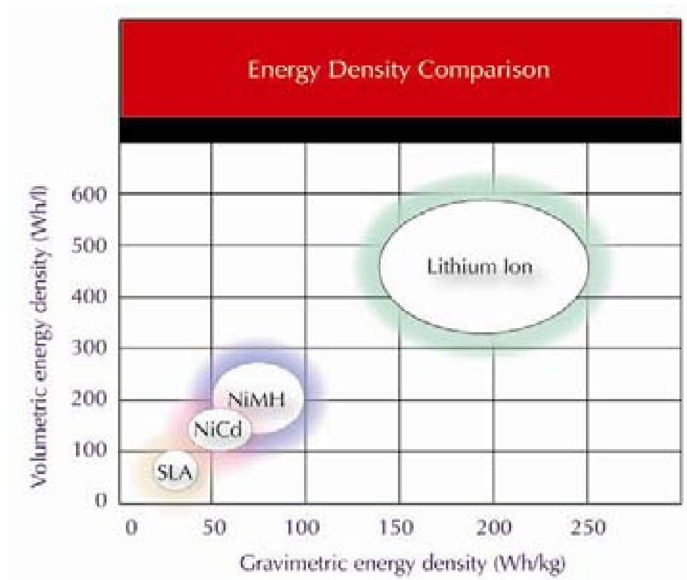
The reasons that many applications have a need for high cell count Li-ion battery packs are many. Large scale arrays based on Li-ion batteries can provide the high voltage, current, and capacity required by many emerging portable markets; however, there are numerous problems facing the designers of larger battery packs including the issues around cell imbalance. Here Micro Power outlines the techniques for achieving high voltage or capacity by building high cell count arrays.

MARKET DEMAND FOR LARGE LI-ION BATTERY ARRAYS

This figure shows the relative power requirements of a variety of battery applications. This figure is specific to the Japanese markets, but it represents the power requirements and relative market sizes of the rest of the world well. The large consumer electronics market which has previously driven the industry's technical progress appears on the lower left side of this graph. Consumer electronics such as cell phones, laptops and PDAs require relatively small, low power batteries. While the consumer electronics markets are still growing in Asia, they are starting to stabilize. The major growth areas for batteries are in electric vehicles and bikes. Also, there is a large drive to convert power tools and back up batteries to Li-ion. These applications, along with industrial, medical and military equipment, require larger battery packs, ranging from 12 cell packs to much larger batteries such as those for electric vehicles.

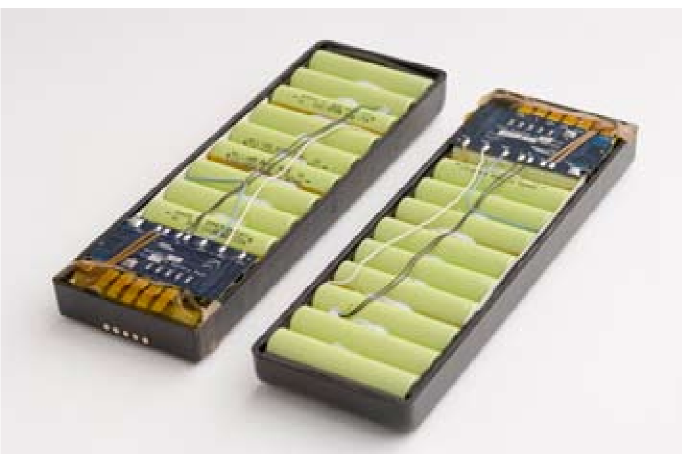


Applications with high voltage and capacity requirements are adopting Li-ion technology because of its many advantages, including good cycle life and improving price points, but most applications are looking for the high energy density and the small size and low weight that this technology provides. A comparison of the energy densities of the various competing rechargeable battery chemistries are shown in this figure. Li-ion cells usually provide an operating voltage of about three and a half volts, but very high voltages require many cells in series. High capacity is achieved with many cells in parallel while high rate capability can be achieved with specially designed cells such as the manganese spinel or nano phosphate or by oversizing the capacity of the battery pack and lowering the effective C-rate.



DESCRIPTION OF THE BATTERY PACK

Battery packs can represent a challenge for the designer because they are no longer a simple configuration of cells. They are carefully engineered products with many safety features. The battery packs in this figure are the back up power source for a portable medical device. As illustrated in this photograph 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 printed circuit board, which is blue in this particular battery pack feature the fuel gauge which calculates remaining cell capacity, LEDs that indicate pack or cell status, and a serial data communications bus that provides the status of the pack to the host equipment.



Most importantly, the circuit board provides protection against unsafe operation. The function of the safety circuit is to protect the pack from external stressors and is therefore required for all Li-ion battery packs. When overstressed pretty much any Li-ion technology can be hazardous to a degree. Extra caution must be exercised during the design process to ensure that the cells are being utilized in a manner appropriate to the technology. Essentially, the safety circuit provides the boundaries in which the cells and pack operate. Safe operation occurs within a window that protects against over-charging and over voltage, and this window is reflected in the settings of the safety circuit. For example, usually the highest voltage allowed by the safety circuit is 4.3 V, while the charger constant voltage taper is at 4.2 volts. While for over-discharge, the safety circuit is set just slightly lower than the devices normal operating cutoff, which is usually 3 V per cell. Short circuiting or over-current protection is also necessary and excessively high or low operating temperatures are prevented. Safety circuits are available as off the shelf products appropriate for most consumer types of applications, which operate at room temperature and require relatively low currents; however, issues associated with cell imbalance and other problems can be readily apparent in larger battery arrays. In general, if an application requires high current or more than 12 cells, a custom solution for safety and cell balancing is required.

An example of a large battery for a portable application is shown in this figure; it consists of 42 cylindrical Li-ion cells. Each of these 18mm diameter and 65mm length cells yields 2.6 Ah of capacity. This battery pack is an example of one that might replace a sealed lead acid back-up battery.

The electric vehicle market is driving battery technology to even larger forms. The next picture is of the Tesla roadster's battery. Tesla's Lotus Elise-based car is one of the first electric vehicles on the market using Li-ion technology. In order to provide the cars performance, acceleration from 0 to 60 mph in less than 4 seconds and a top speed of 125 mph with a range that's about 220 miles, Tesla has had to design a custom battery solution. This battery is microprocessor-controlled and consists of almost 7000 individual cells and weighs nearly 1000 pounds. There are 11 modules, each consisting of 9 cells in series and 69 in parallel to produce the 375V and 142Ah capacity. This modular approach is common for electric vehicles.

BATTERY ARRAY DESIGN CHALLENGES

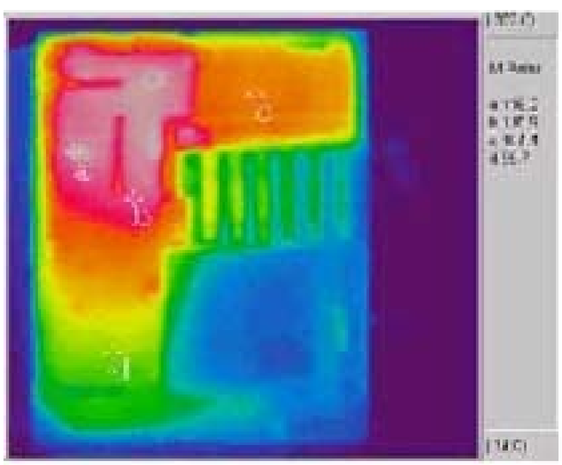
There are many challenges for large battery design. The first to be considered are the practical issues of shipping and vendor support. Many cell vendors do not want their products used in multi-cell packs. This is especially true for prismatic cells, and most vendors limit the size of prismatic packs to 3 or 4 cells. Shipping regulations are also an issue for large batteries in general. Three categories of batteries are defined in the U.S. DOT's rule based on their "size" or Equivalent Lithium Content (ELC). ELC is calculated in grams on a per cell basis to be 0.3 times the rated capacity in ampere hours. Thus, the equivalent lithium content for a battery pack is the rated capacity in ampere hours for a single cell multiplied by 0.3 and then multiplied by the number of cells in the battery pack. Small Li-ion battery packs that have passed the UN testing requirements, including batteries packed with or installed in equipment, can be transported "non-restricted." The battery packs do not have to be shipped as fully-regulated Class 9 hazardous materials. Medium size batteries can be shipped unregulated only by ground, but air shipment requires that they are classified as hazardous material. Larger size Li-ion packs always must be shipped as fully-regulated Class 9 hazardous materials.

There are also design challenges for packs with many cells in parallel, i.e. high-capacity packs. High current circuit design is non standard and diodes are used between the cells. The placement of the diodes in the parallel string is question to be debated by the electronics designer. Fuel gauge limitations are also likely to be encountered. Off the shelf solutions often don't exist that accommodate high current. The few solutions available use out-dated coulomb counting technology. Some solutions exist or are in development for many of these problems. For example, bigger cells and modules are in development. These modules can have the advantage of providing an off the shelf built in solution to some of the problems like thermal management. However, they are typically built around a specific application so they may not meet everyone's needs well or adequately. For example, a module from Electrovaya consisting of pouched prismatic cells delivers 1.5kWh, and is equivalent in capacity to 166 standard cobalt 18650s or 356 nano iron phosphate 18650s.The scale up to a larger system such as those required for an electric vehicle is easier when you start with these larger modules. Heat sinks and active cooling can be used during charging and discharging for thermal management, and large ICs can be used to accommodate the current.

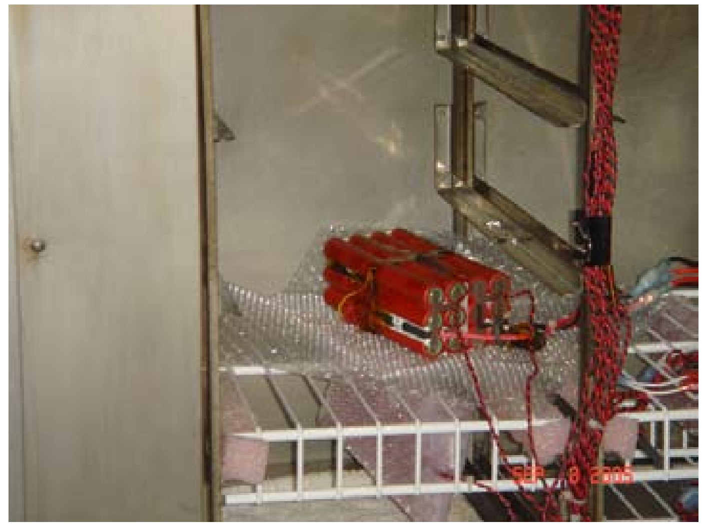
To deliver a given wattage high series cell counts or high voltage is more effective than high parallel cell count so high series design challenges are more prevalent. While, thermal management issues are similar, the issue of balancing the cells becomes more challenging. Pack reliability and cycle life can be compromised by cells going out of balance. The pack will perform to the lowest common denominator cell, and cell imbalance will grow over multiple charge and discharge cycles. Self discharge, especially due to uneven heating, will exacerbate the problem. High voltage chemistries are sometimes explored as an alternative. Commercially available cells deliver 3.3 to 3.7 volts. The potential difference between the lithium based anode material and the cathode's oxide insertion material determines the cell's voltage. Unfortunately the list of potential candidates is limited to delivering maximum charge voltages of about 5 volts- far from the hundreds of volts necessary for an electric vehicle or even the 14 volts for a motor. This is because the electrolyte has a fundamental operating window. If the voltage difference is greater than this window, the electrolyte will decompose.

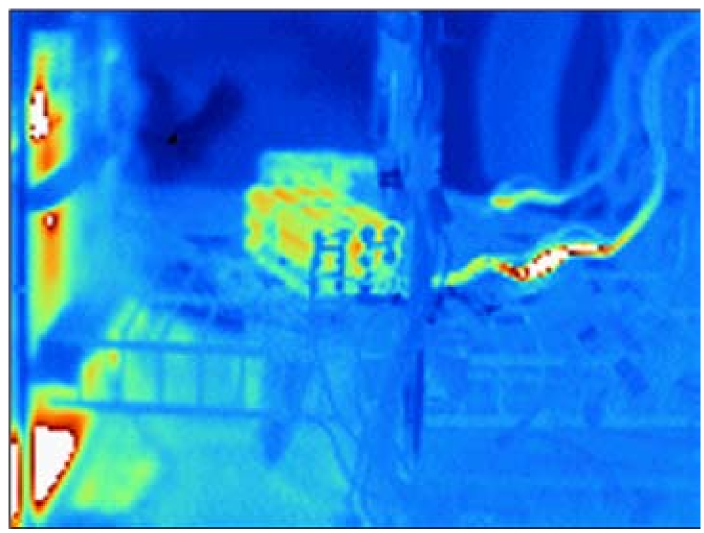
THE CHALLENGE OF CELL IMBALANCE

To conquer the challenge of designing a high voltage pack the problem of cell imbalance must be understood. Poor cell capacity matching can cripple a battery pack right off the manufacturing floor. First, cells must be matched so that the pack does not start out of balance. A quality battery pack manufacturer will test all incoming lots and should reject lots of cells with high variance. Impedance and chemical efficiency variations in the cells can have a similar effect to poor capacity matching; thus, packs should never be assembled using more than one manufacturer or even more than one lot. Regardless, heat can cause the pack to unbalance over time even if cells are well matched at the start of use. Non-uniform thermal stress is a common problem and is often part of poor design of the batteries host device. Because self discharge doubles for each 10° C rise in temperature, even heat from a microprocessor can cause radical differences in self discharge across a multi-cell battery pack. In this picture one can see the non-uniform cell heating in a laptop. Proximity to the processor increases the cell temperature.



Non-uniform electrical loading of the pack causes the same uneven discharge and high discharge rates can exacerbate all of these issues. Temperature becomes a great factor in very large battery arrays simply because the gradients are larger, and also the physical cell arrangement can influence the temperature gradients and pack effects. Active cooling may not evenly affect the cells so careful pack design is important. The next image is a four cells in series, six in parallel battery pack. Accompanying the picture of the experimental set-up is a real thermal image of the battery pack in operation.





Clearly the cells are heating unevenly some cells remain at 40 or 45° C while the hottest cells are about 60 to 65° C. While these are safe operating temperatures for all the cells, the 20 degree difference can quadruple the self discharge rate making an active balancing system necessary. Another feature to notice in this thermal image is the connector to the right of this pack. It is white hot and well over 70° C. Obviously connector design and placement is an important consideration when a pack is delivering significant current as it can confound the problems.

Pack design should minimize the gradients that cells are exposed to, but this may not be sufficient in very large packs. The solution then is to employ cell balancing. There are a couple strategies to implement cell balancing, but their ultimate purpose is the same: to deliver as much energy during discharge as possible and extend the cycle life of the battery pack by minimizing the difference in energy stored in each cell. The techniques fall into two basic categories bypass or active redistribution. Bypass is also known as bleed balancing and in this technique an alternative current path to a cell that is out of balance to other cells in series is provided. This is the traditional, simple technique and is the least expensive for low current. Bleeding off excess energy represents a fundamental tradeoff between energy conservation in the long run and energy delivered. It is recommended to balance during charge cycle, and there are duty cycle limitations; the amount of energy moved is limited to by time, temperature and current. There is a trade-off in the cost of the high current resistors and low ohm FETs and the technique is thermally challenging at high temp portions of pack life.

A newer strategy is to use active balancing, or charge redistribution, which actually moves charge from higher charged cells to lower charged cells in series. It is basically a method for energy transfer between adjacent cells and the circuitry moves energy where and when its needed to minimize global imbalance. The current path is outside of the charge and discharge path. Unlike the bypass strategy, active balancing can be implemented during charge, idle and discharge periods. There are a couple topology choices, capacitive and inductive. For capacitive, there is a switch capacitor across higher cell to lower cell and it is a simple higher voltage to lower voltage measurement and shuttle of energy. Unfortunately, this technique only works during times of peak voltage, at the end of the cycle. There is maximum fifty percent efficiency. The inductive method stores energy from the higher cell before delivering it to the lower cell. There is a FET capacitor and inductor used to create a mini dc/dc boost converter and bi-directional transfers energy efficiently between adjacent cells. Redistribution is allowed anywhere in pack. The system moves energy where and when it is needed to minimize global imbalance and is not as efficiency challenged at mid-capacity levels. The downside of the inductive method is that it has a higher part count and cost.

Large battery arrays represent unique challenges for the pack designer. Yet, they enable new markets to employ the lighter, smaller and more efficient Li-ion technology. Fortunately, the huge potential in this market has prompted the development of new, innovative solutions. The most recent and meaningful attacks the issue of cell imbalance due to thermal and electric gradients.

ABOUT MICRO POWER ELECTRONICS INCORPORATED

Micro Power Electronics, Inc. is ISO 13485 and 9001:2008 certified, as well as ITAR and FDA registered. Micro Power supplies custom battery systems to the portable medical, handheld Automatic Identification and Data Collection (AIDC) and commercial military markets. As a pioneer in the development of Lithium battery systems, smart battery packs, chargers, power supplies and docking stations, Micro Power has more than 20 years of experience developing battery solutions. With a proven track record of technical excellence, quality solutions and award-winning service, Micro Power has become the fastest growing supplier of custom battery systems in North America. For more information, please visit www.micro-power.com or call 800-576-6177.