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# LITHIUM-ION TECHNOLOGY: BALANCING INCREASED SYSTEM CAPABILITY WITH THE POTENTIAL FOR EXPLOSION

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## ABSTRACT

The push to increase the capability of satellites has driven significant increases in space battery performance over the past fifty years, progressing to the use of today's state of the art technology: Lithium-ion. To date Lithium-ion batteries have flown on many missions and have demonstrated their tremendous potential to increase the capability of both large and small satellite technologies.

However, recent events in the consumer electronics industry have highlighted the risk of this technology when handled improperly, and several factors are currently combining that increase both the likelihood and hazard of a battery failure: the larger size of spacecraft batteries in general, the push for ever greater energy density, and the shrinking infusion period both for payload and platform technologies. This paper discusses the necessary precautions that must be made to ensure safe use of Lithium-ion technology via the lessons learnt from a fifteen year Lithium-ion space battery program at ABSL. This program has yielded more than fifty successful launches and the space qualification of five Lithium based COTS cell technologies without a single safety incident.

## INTRODUCTION

A major part of the dry mass of a spacecraft must be allocated to batteries to sustain power when solar arrays are in shadow. The push to increase the capability of satellites leads to a desire to reduce the mass of 'housekeeping' systems such as batteries to allow more sophisticated payloads. Thus, the past fifty years of the space industry has seen increases in the energy density of space battery technology from Nickel Cadmium through Nickel Hydrogen through today's state of the art: Lithium-ion.

Recent events in the consumer electronics industry with laptop batteries seemingly spontaneously combusting highlight the risk of this high energy density technology when not handled properly. In the space industry, three factors are combining that increase both the likelihood and hazard of a battery failure: the growing energy levels of spacecraft batteries in general, the push for ever greater energy density, and the shrinking infusion period both for payload and platform technologies. Were a highly energetic failure to occur during integration, on a fuelled spacecraft, or on a stacked launch vehicle, the penalties could extend well beyond substantial programmatic delay to destruction of hardware and injury of personnel.

Within the small satellite community, many groups are exploring or have used Commercial Off The Shelf (COTS) battery technologies. These batteries are attractive to the small satellite community for their performance and scalability, offering tremendous potential to increase the capability of small satellite technology. However, if not designed, handled, and operated properly, such technology presents a safety risk. This paper discusses the inherent risks and corresponding precautions that should be made when utilizing this technology via the lessons learned from a fifteen year Li-ion space battery program at ABSL. This effort has yielded more than fifty successful launches and the space qualification of five Lithium based COTS cell technologies without a single major safety incident.

## LITHIUM-ION CAPABILITIES

To date, Li-ion batteries are a space proven technology that can improve the performance of nearly any satellite. ABSL, the world leader in Li-ion space batteries, has demonstrated the ability to provide high energy density (up to 110 Wh/kg) systems for a variety of missions. More than fifty vehicles have been launched and flown without failure using ABSL batteries, having accrued more than 17,000 flawless cell years of operation in space. They have flown successfully to Mars, Venus, deep space, La Grange Points and have powered the PROBA vehicle for more than 7 years and 40,000 cycles in low Earth orbit (LEO). A new launch vehicle, due to fly in August 2009, is completely powered by ABSL Lithium-ion from Avionics to Pyrotechnic to Flight Termination to 270V Thrust Vector Control Systems. A similar ABSL design is about to become the first man rated high voltage Li-ion battery to fly on the international space station. In addition, a new high energy ABSL Li-ion battery approaching 150 Wh/kg is undergoing qualification to power the tools and life support of NASA astronauts during their space walks.

With such an extensive space heritage, the test data to cover missions exceeding 9 years and 100,000 cycles, and manned flights on the horizon, ABSL can and has provided the performance advantages of Li-ion to the most risk averse customers and missions. However, ABSL has also recognized the attention to safety that must be paid in an industry that is seeing more and more energy packed into smaller and smaller volumes. Throughout their Lithium-ion space battery program, ABSL has had a proactive approach to safety and, over the past 10 years, has completed an extensive investigation to quantify the risks of the various Li-ion chemistries and develop a battery architecture that maximizes performance without sacrificing the necessary levels of protection.

**Figure 1: ABSL has designed and delivered Li-ion batteries for a broad range of space applications**

**LI-ION RISKS**

The Li-ion chemistry is capable of extremely high current delivery. For example, several small format (~1 Ah) high rate Li-Ion cells are capable of delivering more than 60 A. Clearly, when integrated into a large capacity pack, the current delivered when a low resistance circuit is applied to the battery terminals could easily exceed several hundred amps and cause serious damage to hardware and severe injury to technicians.

Furthermore, the uncontrolled release of the large quantities of energy stored in Li-ion cells via thermal runaway often poses a greater risk. Thermal runaway is a condition that can occur in Li-Ion cells in which the cell begins generating heat in a self-sustaining, and even self-accelerating manner (i.e. the cell continues to generate heat regardless of the cell current). This leads directly to an uncontrolled rise in cell temperature that can ultimately result in the forceful venting of electrolyte, fire, and explosion. The onset of thermal runaway is primarily induced by high cell temperatures, but the event is highly sensitive to state of charge (SOC) as well.

E. Peter Roth at the Sandia National Laboratory has conducted several studies on the occurrence of thermal runaway in Li-Ion cells[1]. These studies have suggested three generalized phases of thermal runaway:

First is the onset of thermal runaway (typically starting between 80 and 150°C, depending on chemistry and various other factors), characterized by sustained and accelerated self heating. Behavior in this region is highly dependent on SOC, with higher SOCs correlating to lower onset temperatures. Subsequently, a second phase of self heating can occur at higher temperatures where gases generated by chemical reactions within the cell can cause it to vent, thus providing a temporary drop in the self heating rate. Finally, if temperatures continue to increase, a third phase of thermal runaway can be witnessed that is characterized by extremely high self heating rates. This phase sees the final breakdown of the cathode (releasing oxygen) and of the anode passivation layers, as well as an exothermic reaction of the released oxygen with the electrolyte.

The progression of a Li-ion cell through all three phases of thermal runaway typically brings along fire and the destruction of the cell itself, and thus presents considerable hazard. Preventing the occurrence of thermal runaway is therefore of critical importance. This implies limiting the environmental and operational conditions of the battery. Of particular concern are overcharge conditions, in which a cell is charged to extremely high SOCs where self heating rates are exaggerated and thermal runaway is more likely to occur. Operation at high current, either in discharge or charge, can also pose such a risk due to the resultant heating of the cell.

## COTS CELL PROTECTION DEVICES

COTS cells typically have several devices built-in to protect against the above noted risks of Li-ion chemistries. It is important to understand how these devices are designed to work, and perhaps more important to understand their limitations. These points are discussed below along with examples of the performance of ABSL's heritage Li-ion cell, the 18650HC, However, it is important to note that the performance of such devices can change dramatically with other cell models due to differences in design and quality of production.

### *Positive Temperature Coefficient (PTC) Polyswitch*

A PTC is made up of a composite of semi-crystalline polymer and conductive particles as illustrated in Figure 2. At low temperature, the conductive particles form low resistance paths through the polymer. As temperature increase past the polymer's switching temperature, the polymer's crystallites melt and expand, disturbing the low resistance paths and dramatically increase PTC resistance. When the PTC returns to low temperature, it will also return to a low resistance state as the polymer contracts and the conductive pathways are reformed.

Placing a PTC in series with the electrodes, as is done in many COTS Li-ion cells, turns the PTC into a resettable short circuit protection mechanism – high currents induced by a low resistance external path can increase the PTC temperature beyond its switching temperature and activate its high resistance state, which in turn reduces current to a more safe level. If the short circuit is removed, current will stop and eventually the PTC will cool and return to a low resistance state.

Since this thermally driven process takes time, short duration high current pulses are not impeded. This can be a positive from the point of view of mission needs where fuse blowing or pyro activation may be a requirement. However it can also be a negative, in that the temporary application of a low resistance circuit to the battery terminals could result in a current spike that damages hardware or injures operators. Characterizing PTC activation with respect to time, rate, and temperature at the cell level via test is necessary to properly understand the performance and protection of each cell. Example results of such testing for ABSL's heritage 18650HC cell are shown in Figure 3.

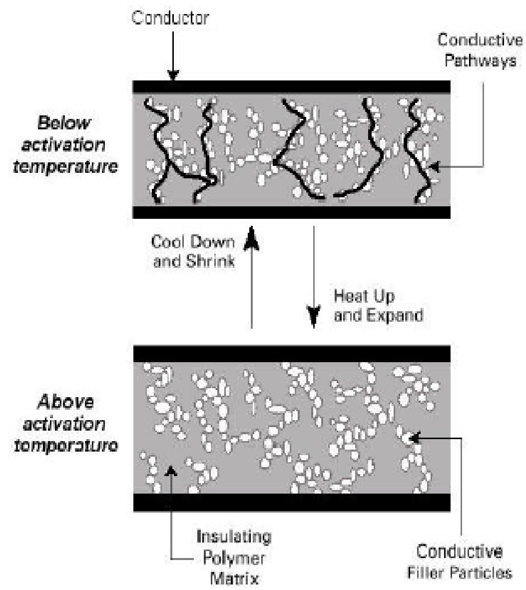


**Figure 2: Positive Temperature Coefficient (PTC) Polyswitch**

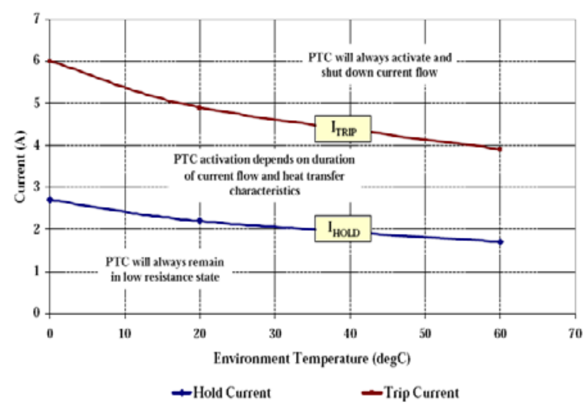


**Figure 3: Response of the PTC in the ABSL 18650HC Li-ion Cell**

Extensive cell testing has shown PTC's to be excellent at limiting current flow with one exception – high voltage applications can cause the PTC to fail permanently to a low resistance state. The battery voltage for which this occurs varies with every cell model. Thus, at a minimum string level testing is required to verify functionality. To this end, ABSL has performed a multitude of string and battery level PTC tests. Two noteworthy cases are illustrated below in Figure 4 and Figure 5, showing the PTC breakdown voltage for the ABSL 18650HC cell is greater than 33.6 V, and thus qualifying the cell for use in 8s, ~28 V assemblies.

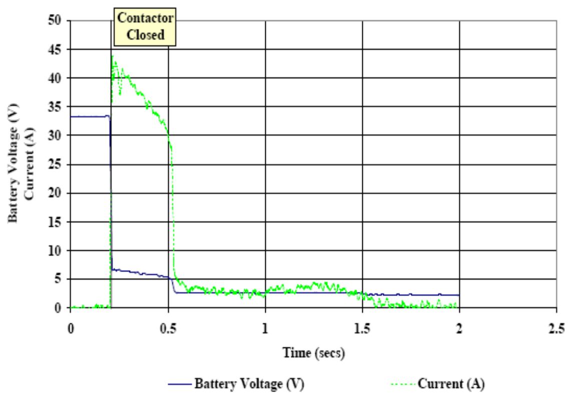


**Figure 4: Response of the PTC on the ABSL 18650HC Li-ion Cell in an 8s pack shows proper PTC operation**

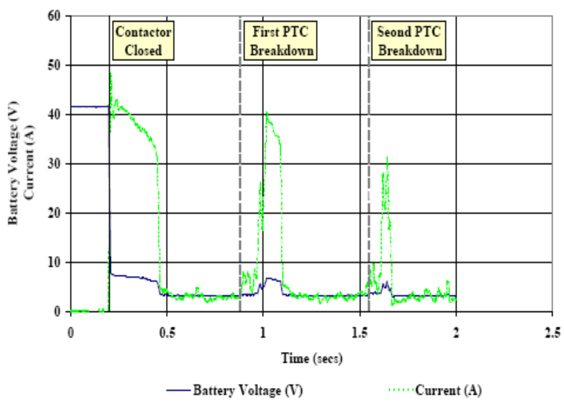


**Figure 5: Response of the PTC on the ABSL 18650HC Li-ion Cell in a 10s pack shows PTC breakdown due to an overvoltage condition**

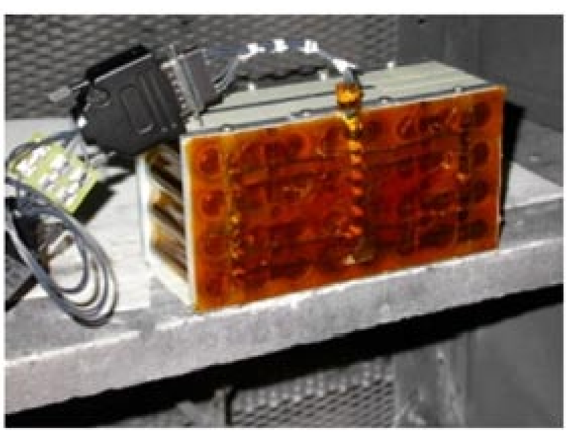

**Figure 6: Thermally insulated battery module used for short circuit protection verification of the ABSL 18650HC Li-ion cell**

Assuming though, that the PTC functions as intended, there is still a risk of catastrophic failure if the PTC is generating enough heat to raise the cell temperature and induce a thermal runaway scenario. Preferably, battery level testing should be performed to ascertain the tolerance of a given cell design to such a scenario in the context of the final battery insulation (thus taking into account the thermal properties of the battery design).

The ABSL 18650HC's safety in this regard has been verified for installations employing ABSL's standard battery architecture and variants thereof via testing of a battery module designed to insulate the cells from the environment (Figure 6). In this manner the test case exhibits temperature increases in excess of those seen in actual practice, and thus be more likely to induce thermal runaway. The results of this test, however, showed a very minimal increase in temperature (~5° C over ambient) and no leaking, venting, or any other catastrophic failures. Thus it was proven that ABSL's standard architecture is tolerant to sustained discharges through tripped PTCs.

### *Current Interrupt Device (CID) & Vent*

A CID responds to the build-up of internal cell pressure which results from high temperature and high SOC (typically much greater than 100%) operation. At some critical pressure, the CID burst disk deforms and breaks the electrical connection of the cell, preventing the flow of further current (Figure 7). Thus the CID is primarily intended to prevent the onset of catastrophic failure via thermal runaway as a result of an external source overcharging the cell.

A large number of cell level tests have shown that the CID reliably acts to electrically disconnect the cell in response to high temperature, high SOC conditions. However, if the cell has reached a sufficiently high temperature prior to CID activation, the self heating rate of the cell can be high enough to continue increasing cell temperature without the influence of an externally supplied current. To at least partially address such situations where cell temperature and internal pressure continue to increase even after CID operation, the burst disk incorporates precise grooves that provide failure points to release the internal pressure in a safe and controlled manner (i.e. not via can explosion, metal fragmentation, and wide debris release). This feature is most commonly referred to as a vent. The vent is designed to activate after the CID burst disk deforms and before the cell can bursts.

Unlike the PTC, neither the CID nor vent is resettable. Once one of these mechanisms is activated, the cell should be electrically considered an open circuit.

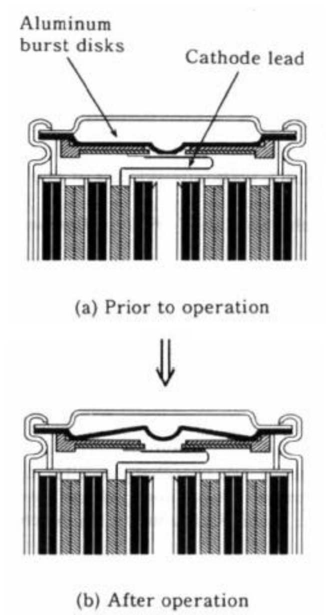


**Figure 7: Current Interrupt Device (CID)**

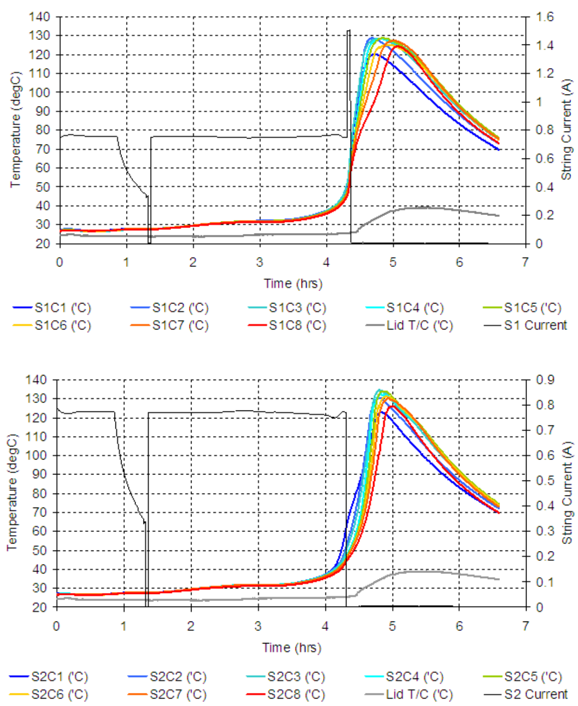


**Figure 8: Results of overcharge testing on a thermally isolated 8s2p module**

This sequence of events is demonstrated by an overcharge test conducted previously by ABSL. This module was constructed to minimize thermal conductivity to the environment and encourage high cell temperatures, much like the previous module for PTC testing discussed above. As can be seen in Figure 8, the study showed that a CID activated properly to shut down the current, but cell temperatures did not peak until approximately 30 minutes afterwards. The temperatures in excess of 120° C induced venting in several cells, but no flame or explosions occurred. Subsequently the cell temperatures were seen to decrease back to safe levels, due to (1) the absence of continued charge current due to CID activation, (2) the increase in heat dissipation rate from the pack to the environment due to increased temperature, and (3) the cessation of internal self heating due to the evacuation of electrolyte and possible melting of the separator.

### *Shutdown Separator*

In some cases the venting of the internal cell gases will decrease the self heating rate and impede further internal reactions sufficiently to stop thermal runaway, but this is not always the case. The final level of protection built-in to COTS cells is a shutdown separator placed between the anode and cathode. This porous separator nominally allows the transfer of ions between the electrodes, but at high temperatures the separator begins to melt and the pores close shut. With ion movement restricted, further self heating reactions are also halted.

Separator shutdown can be an effective means of preventing catastrophic cell failures; however, they are not resettable, they often activate after cell venting (which itself can be catastrophic if vent gases ignite), and their melting can lead to voids in the electrical insulation between the anode and cathodes, creating an internal short. Because of these reasons, it is recommend that one not rely on shutdown separators for protection, but rather to treat them as a reserve line of defense and to make every effort to control hazards adequately and prevent the need for the use of this device.

## BATTERY LEVEL PROTECTION STRATEGIES

As discussed in the previous section, individual COTS cells often include several safety devices that can impede the onset of hazardous conditions (such as a thermal runaway scenario) as a result of abusive operation (e.g. application of a short circuit, overcharging the cells, etc.). However, when multiple cells are assembled to build a battery, failure modes become more complex. Therefore it is important to consider the safety implications of how such cells are assembled into a battery and take advantage of opportunities to improve safety and fault tolerance when available.

***Topology***

The topology of a battery defines the basics of how multiple cells are electrically connect to provide the desired capacity and voltage levels required by the system. Typically, one of two basic approaches is elected. In the first option (P-S), cells are first paralleled together to build high capacity, low voltage cell banks (often called "virtual cells"). Then multiple cell banks are connected in series to achieve the desired voltage. This topology is illustrated in Figure 9.

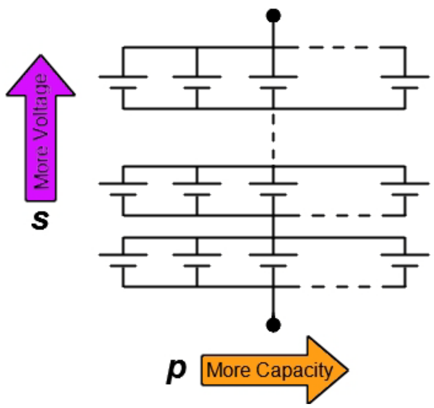


**Figure 9: P-S Topology**

The principle advantage of employing a P-S topology is its friendliness to supplementary protection and balancing electronics. Such electronics can provide the ability to disconnect and bypass an entire bank of cells (if the presence of a fault requires it) and / or actively equalize the voltage of each bank (as can be necessary to prevent overcharging or overdischarging individual banks). With this topology only one active channel is necessary per bank to provide such control; thus a typical 28V battery (eight banks of cells in series) requires only eight control channels regardless of the size of the cell bank.

The most pronounced disadvantage of this topology is its poor ability to handle a cell that has failed as a short circuit. Such a failure could be due to factors creating an external short across the cell terminals, of the repeated overdischarge of the cell or a manufacturing fault leading to a short circuit internal to the cell. Mathematically, either case can be represented by the addition of a resistor (representing the short) in parallel to the affected cell bank in Figure 9. It is clear from this representation that all of the energy stored in said cell bank will be discharge through the short of the failed cell. At best, the cell bank in its entirety will be lost, removing a large fraction of the open circuit voltage and capacity of the battery. At worst, temperatures of the failed and / or parallel cells could become dangerously high during the discharge and pose a risk of thermal runaway. The precise outcome depends on the impedance of the short and the battery configuration.

In the alternative topology option (S-P), cells are first connected together in series to build high voltage, low capacity cell strings. Then multiple cell strings are connected in parallel to achieve the desired capacity. This topology is illustrated in Figure 10.

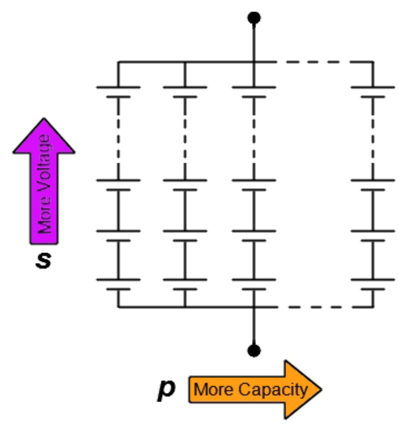


**Figure 10: S-P Topology**

The S-P topology is not often amenable to the addition of external protection or balancing electronics. This is because one control channel is necessary for every cell, and given that aerospace batteries can contain several hundred cells, the complexity, mass, volume, and cost penalties quickly become excessive.

Fortunately, the improved passive fault tolerance of the S-P topology can negate the need for these external aides. By first connecting cells in series, the redundancy of the built-in protection devices is maximized. For example, in a 28V battery with each string consisting of eight series connected cells, there are eight serial connected CIDs and PTCs to protect against overcharge and short circuit faults. Note that since only one of these devices needs to function to protect the string, up to seven protection mechanisms could fail and the system could still be safe.

The S-P option is also more effective at handling short circuit cell failures. Again, the fault can be mathematically interpreted as a resistor in parallel with the affected cell. In comparison with the same failure in a P-S topology, the resultant current flow through the affected cell is reduced due to the resistance of the other cells in that same string limiting current flow from parallel strings. This means it is much less likely that excessive temperatures and thermal runaway will result from a short circuited cell in an S-P topology than in a P-S topology. And furthermore, subsequent to the occurrence of the fault, the affect on battery level performance is minimized. The affected string could continue to function for some time without noticeable affect at the battery level; however, the remaining cells in said string will be operating at a much higher voltage, and it is likely that one or more CIDs will eventually activate to disconnect the string. Afterwards, though, the battery will only suffer a small capacity loss, with little to no degradation in voltage levels.

The fault handling effectiveness of the S-P topology has been demonstrated by test and practice on several occasions. One excellent example is the following case of indirect overcharge. In addition to direct overcharge events, the possibility of indirect overcharge exists even when the total battery level voltage does not impose a blatantly obvious overcharge state. This is due to the presence of voltage dispersion among the cells of a string. As is illustrated in Figure 11, a single cell can be charged to a dangerously high level while the average voltage remains within recommended levels. Thus, if excessive voltage dispersion is present, charging a string or battery to its nominal EOCV could result in the activation of a CID.

Such a situation occurred repeatedly on two flight like life test batteries (connected in parallel). In this test, the batteries had undergone 1800 cycles of 40% DOD LEO cycling with minimal dispersion and thus no indirect overcharge. However, during integration operations following a capacity measurement at the 1800 cycle mark, an operator inadvertently applied a hard short. Following the short event, this battery resumed LEO cycling at 30% DOD. The hard short had increased the magnitude and growth rate of voltage dispersion within the batteries, resulting in the indirect overcharge of many cells within the system over time. 2250 cycles later, the effects thereof had accumulated and caused the nominal activation of a CID. CIDs in subsequent strings safely activated afterwards due to the same indirect overcharge condition as shown in Figure 12 until it was decided to stop the test.

Note that as strings were safely being shut down, capacity of the overall assembly degraded gradually, without extreme temperature rises, venting, or catastrophic results. Such graceful degradation provides confidence that even if a system level power anomaly induced a hard short on orbit, flight operations could potentially be continued for some time even after such a dramatic event.

Detailed investigation of the battery after the test also revealed that one cell in the system had suffered a short circuit failure. This likely resulted from continued overdischarge of the cell during cycling due to high voltage dispersion levels. However, no anomalous temperature increases, sharp voltage or capacity drops, venting, or other catastrophies had been noticed during testing corresponding with this event. Furthermore, the string containing the cell was still functional. This string was then electrically isolated and cycled at 100% DOD. After an additional 68 cycles, a CID in an adjacent cell in this string activated and shut the string down open circuit thusly proving the ability of the architecture to safely handle short circuited cells.

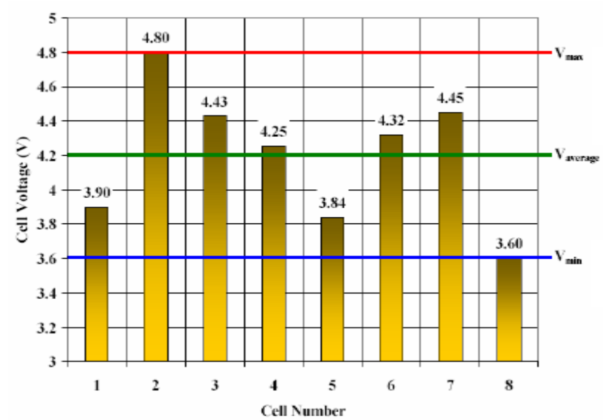


**Figure 11: Indirect Overcharge**

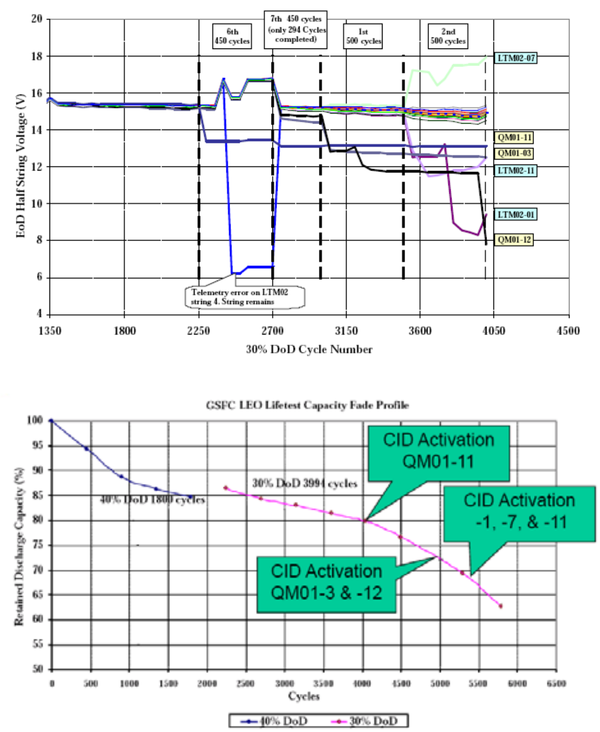


**Figure 12: Graceful degradation of flight like battery modules in response to LEO cycling following abusive conditions**

### *Cell Size*

Cell size is an important factor in determining the safety of a battery for two main reasons: segmentation of energy and the ability to reject heat.

Segmentation of energy is important to protect against the effects of faults affecting single cells (such as an internal short circuit, for example). In such cases it is often impossible to prevent the fault from propagating through the entirety of the cell; if the result of this fault is thermal runaway, the entirety of the cell's energy may be hazardously released. For example the energy contained in a single ABSL 18650HC cell is19.5kJ compared to 1.3MJ for a typical 100Ah cell. Constraining catastrophic failure to a single small cell is plausible; the inevitable cascade effect across multiple large cells in a space battery would be devastating.

Heat rejection is important to control the thermal response of the cell to faults. As discussed earlier, thermal runaway is facilitated by the generation of heat within the cell and accelerates at higher temperatures. By maximizing the ability to extract a cell's heat, lower peak temperatures will result during all nominal and off-nominal operations, thereby reducing the chance of entering a thermal runaway state.

With regard to both of these factors, smaller cells are safer. Smaller cells contain less total energy, and thus a single cell fault will result in less catastrophic results. In addition, it is easier to extract heat from smaller cells, due to higher surface area to volume ratios and shorter distances from the center of the cell to the exterior where heat can be removed.

Smaller cells also add fault tolerance benefits, in that if a single cell (or string of cells) is lost there is a lesser impact to the entire system. For example, comparison of small and large cell options in a 28V 100Ah system with respect to the loss of a single cell shows that the loss of one large cell will induce the loss of 12.5% of both voltage output and total stored energy, whereas the loss of a single small cell in a typical ABSL design would only result in a 1.5% loss of capacity and energy, with almost no effect on voltage levels. However, in practice one must consider the effect to overall performance as well – the use of smaller cells can entail higher parasitic mass fractions, and thus lower overall energy density. But even this point can often be offset by the ability to fine tune the size and shape of a small cell solution, minimizing the inclusion of excess capacity not needed by the system.

### *Thermal Management*

In addition to driving the selection of cell size, the ability to reject heat in pursuit of reducing peak cell temperatures and avoiding thermal runaway scenarios must be considered at the battery level. Here, three safety objectives are sought: (1) the ability to reject heat from the entire battery in response to faults that affect the entire cell array, (2) the ability to remove heat from a single cell (or subset of cells) in response to moderate faults that affect only said cell (or subset of cells), and (3) the ability to isolate the thermal runaway of a single cell in response to extreme faults that affect only said cell.

Clearly, the latter two objectives are conflicting in many cases. The most practical means to prevent the thermal runaway of a single cell in response to a fault affecting only that cell is to design a structure that shares heat quickly between all of the cells. In this manner, a fault that in isolation might cause a cell to increase in temperature by 100° C and induce a thermal runaway event, could instead cause 100 cells to increase in temperature by only 1° C with perfectly benign results. Conversely, however, the implementation of a battery with high inter-cell conductivity means that if a cell were to enter a thermal runaway scenario, the heat transfer to surrounding cells could be sufficient to induce thermal runaway in those cells as well.

Additionally, the first seemingly simple objective of total ability to reject heat typically can compete with both safety and performance objectives. First, a high total conductivity means that the cells are not well insulated from their environment, and thus extreme increases in environmental temperature could drive a thermal runaway event. On the other hand, performance objectives often require that total battery conductivity is low in satellite applications. This is because the battery interface panel is often colder than the cells' optimal operating temperature. Under these conditions it is beneficial to insulate the cells from the cold interface and allow the waste heat generated by nominal electrical operation to keep cell temperatures above the interface temperature.

To best meet all of these objectives, detailed thermal analysis is required to identify the optimal thermal design. This must entail thorough knowledge of the cell's thermal response to nominal and off-nominal operations, as well as accurate consideration of the battery structure and thermal pathways therein. Thanks to the broad availability and low cost of COTS Li-ion cells, ABSL has been able to conduct a large number of abusive tests on the cells it employs and build accurate electrical and thermal mathematical models therefore. This in turn allows ABSL to design in the necessary thermal management features to confidently provide the necessary level of protection while maintaining the necessary level of performance.

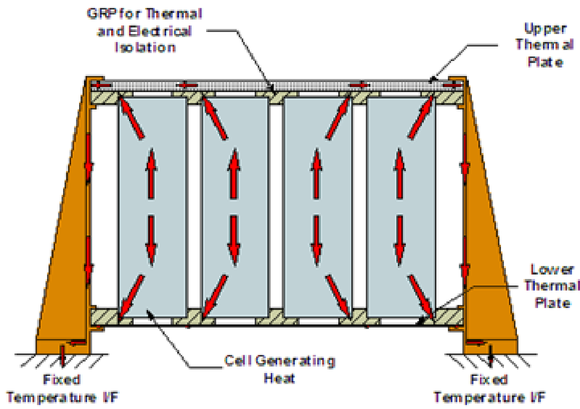


**Figure 13: Example Thermal Management Strategy**

Abuse testing at the full module level has been performed by ABSL to verify the levels of safety provided by its designs. For example, overcharge testing on a flight like battery module (Figure 14) has validated both CID operation in highly parallel configurations and the thermal management techniques employed. Results showed the complete battery was shutdown via the CIDs, that maximum cell temperatures did not exceed ambient temperature by more than 35° C, and that no venting, fire, or other form of catastrophic failure occurred.

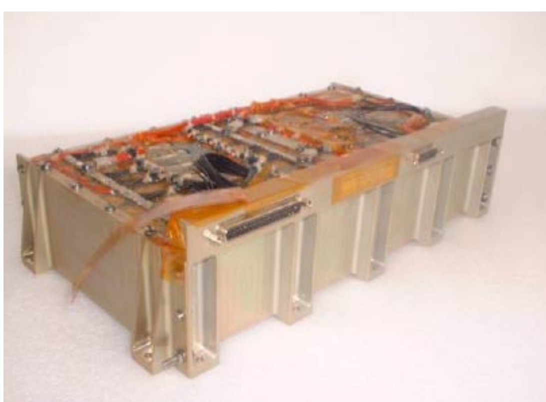

**Figure 14: Flight-like battery module employed for overcharge testing**

In addition, the indirect overcharge case discussed earlier in which a similar flight like battery design experienced the overcharge, overdischarge, and short circuit failure of several individual cells within the modules showed no notable temperature spikes of individual cells and certainly no cases of venting or other catastrophic failures. Thus this case demonstrated the inter-cell thermal conductivity of the architecture, and has shown the sharing of heat of individually faulted cells with nominal ones to be an effective strategy for limiting the propagation of faults to non-catastrophic levels.

### *Additional Protection Mechanisms*

As noted earlier, P-S topologies are often paired with external protection electronics. At their best, these systems can electrically isolate any cell in the battery if it appears at risk of a catastrophic failure. However, in batteries with a large number of cells, the monitoring requirements to do so can become excessive. Furthermore, there are always scenarios that such systems cannot respond to, such as internal cell faults.

The safety of either topology can be further augmented with other "add-ons", from simple battery level fuses to address short circuits, to complex diode-based networks to prevent PTC failures in high voltage systems. However, ABSL's testing of batteries using its 18650HC has demonstrated that in most cases such design features are not required to provide adequate levels of safety.

## OPERATIONAL PROTECTION STRATEGIES

Regardless of which cell and battery level protection mechanisms are physically employed in the system, there are several operational safeguards which should always be employed:

*Limiting Voltage Range:* Li-ion chemistries are highly sensitive to over- and under-voltage conditions. Subjecting a battery to voltages above their maximum recommended voltage (typically 4.2 V per cell) increases degradation and susceptibility to thermal runaway. Conversely, discharge of a battery below its minimum recommended voltage (typically 3.0 V per cell) also increases degradation and could result in a short circuit failed cell. Ensuring that voltage ranges are not exceeded is therefore critical.

*Limiting Charge/Discharge Currents:* Battery operation above specified maximum charge or discharge rates can result in accelerated degradation and high cell temperatures. This can pose a risk of thermal runaway. Charging at high rate is of particular concern due to reactions within the cell and the fact that the combination of high temperature and SOC is more likely to occur, increasing the cell's sensitivity to thermal runaway. Limiting the maximum operational rate is therefore highly recommended and this consideration should remain forefront in mission planning as more complex operational scenarios, particularly in LEO and SSA applications looking for rapid recharge capability.

*Limiting Environment Temperature:* Excessively high environmental temperatures will increase the risk of thermal runaway by elevating the maximum cell temperature seen during operation. Long term storage at high temperature will also accelerate degradation.

*Preventing Short Circuits:* With high quality of manufacture, inclusion of adequate protection mechanisms, and employment of the above operational limitations, the risk of catastrophic failure via thermal runaway should be negligible. However, the risk of damaging hardware and personnel via human error cannot be completely mitigated. Given that Li-ion chemistries are capable of extremely high rate discharges, and that they still contain considerable energy and voltage when fully discharged, such risks should not be taken lightly.

These risks are highest during manufacture, when the insulation and protection features of the battery are not yet in place. ABSL carefully controls its manufacturing procedures to provide the necessary safety, and does not recommend anyone but trained professionals pursue such endeavors.

Interfacing with the battery, either for test or integration on the spacecraft, poses the next greatest risk. Improperly mating connectors and / or harnesses can create a short. Particular care must be taken when connecting multiple batteries in parallel. It is ABSL's recommendation that all battery interfacing be performed with the batteries fully discharged to their minimum voltage, that the battery connectors be mated last (i.e. the harness should be mated to the power management electronics before being mated to the batteries), and, when possible, fused connector savers be employed during test to provide protection if an accidental short were to occur.

During the course of all battery handling, all metallic items worn by the technician (jewelry, cufflinks, etc.) should be removed and insulative rubber gloves should be worn to further reduce the risk of short circuiting the battery.

## ON THE VARIABILITY OF COTS CELLS

ABSL has serviced spacecraft and launch vehicle programs around the world using a variety of COTS cells chosen for their optimal attributes to serve particular applications. Four COTS cells have been space qualified, three have flown with another to fly this year. This may suggest that qualifying COTS cells is relatively straightforward. However, these statistics do not reveal the fact that in the last decade hundreds of other COTS cells have been rejected by ABSL for space use.

COTS cell suppliers vary enormously in terms of build quality and consistency, both between different models and batches of the same model. The needs of space customers does not mesh with or drive the market demand for COTS cells. As a result, cell build standard, chemistry, production location, material and component supply chain, and a multitude of other factors that can effect performance are not necessarily fixed. Subtle changes that might not affect a consumer product needing 500 cycles for a year in a cell phone might have a dramatic effect to a battery needing to reach 5,000 cycles in a year of LEO operation.

ABSL has privileged relationships with commercial cell suppliers and invests years understanding not just production, quality, materials and cell performance issues, but also the business plans of companies on specific cells prior to investing in full space qualification. Once a cell is qualified, cells are purchased in very large quantities, the batch quality is verified by extensive lot acceptance testing, all cells are thoroughly screened to catch anomalous cells and enable close matching within battery builds, and large reserves are stockpiled to assure the availability of high quality cells (inconjunction with last time buy arrangements)to meet the needs of future demand. This general philosophy, which ABSL has found to be necessary to delivering safe, high quality, high reliability batteries for space applications, is practical for an entity like ABSL producing batteries on a large scale. The stockpiling aspects also mesh perfectly with Responsive Space needs to ensure availability.

On university cubesat programs and other low-cost missions, budgets are extremely tight and COTS cells appear to be an attractive lightweight battery fix that can be implemented at low cost. Yet it is not often feasible for low cost and one-off battery build efforts to implement a comprehensive approach to ensuring the highest levels of safety, reliability, and quality as ABSL does. Alternative small scale attempts using COTS cells must be approached with extreme caution, however. This is especially true when a single, small batch of cells are procured, where the risk of battery performance falling short due to cell to cell differences is a minor issue compared to the potential for safety problems due to poor selection of cell model or batch wide performance defects. Subpar production quality, for example, has led to several incidences of metallic contamination within cells, leading to internal shorts and thermal runaway as seen in laptop fire incidents. Furthermore, it is ABSL's experience that the effectiveness of protection devices can vary greatly between cell suppliers. Indeed, testing of some COTS cells has revealed some batches of cells do not even contain the protection devices they are advertized to employ. Therefore the possibility of catastrophic thermal runaway event happening on cubesats and other low-cost missions is real.

## SUMMARY AND RECOMMENDATION

Despite the proven performance benefits possible with the use of Li-ion chemistries for space applications, the use of energy storage technologies with increasing energy density carries increased safety risk. ABSL has proven a safe approach to yielding high energy density batteries via the use of COTS cells. However, the significant likelihood of catastrophic failure, such as a thermal runaway event, via the use of custom cells, especially large format ones, or the improper use of COTS cells is apparent. During spacecraft integration and test, such an event could lead to costly damage or injury of personnel. However, the effects of an incident propagating to a fuelled spacecraft and/or launch vehicle are potentially devastating.

As the small satellite community continues to make strides to increase the utility of smaller and smaller spacecraft, it is crucial that Lithium-ion batteries do not cause a safety incident to set back the industry. Currently, cubesats and other low budget spacecraft ride along with larger spacecraft with budgets orders of magnitude greater. Thermal runaway of one of these batteries leading to damage to a more primary payload would be hugely detrimental to the industry.

The small satellite community must therefore be particularly aware of the potential risks of not treating Li-ion batteries with the respect they deserve. ABSL performs a tremendous amount of testing at cell and battery level to ensure the safety of its COTS based products. The small satellite community must be prepared to be equally thorough if they are to avoid a safety incident.

## REFERENCES

1. Roth, E.P, “Li-Ion Safety: New Material and Cell Performance,” 2007 Space Power Workshop, Los Angeles, CA, April 2007