Guidelines for Safe, High Performing Li-ion Battery Designs for Manned Vehicles

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Abstract: *New design features and test methods are in development at NASA to take advantage of the newest high power and energy dense commercial Li-ion cell designs and to achieve passively thermal runaway (TR) propagation resistant (PPR) designs for manned missions requiring high power/voltage. The goal is to minimize the parasitic mass and volume of the battery components; thus reaching a balance between high battery specific power (W/kg) and energy (Wh/kg) as well as power (W/L) and energy density (Wh/L). Current 18650 cell designs achieve > 275 Wh/kg, > 725 Wh/L, but present high risks of side wall breaching during TR which can defeat many other safety features resulting in nearly immediate TR propagation. This work seeks to better understand the phenomena of cell side wall breaches and to determine the effectiveness of promising battery design features for achieving safe, high performing battery designs for high voltage/power applications.*

Keywords: Li-ion; thermal runaway propagation; side wall breaches; interstitial heat sinks, battery design guidelines.

Introduction

NASA was successful in establishing guidelines that designers can readily follow for achieving batteries that are passively thermal runaway (TR) propagation resistant (PPR) and prevent flames and sparks from exiting the battery enclosure for low power/voltage applications with low mass/volume penalties.[1]

However, many of NASA's higher power and more energy demanding applications (e.g., Robonaut, RoboSimian, Valkyrie, Mars Chariot Rover and Resource Prospector, and especially NASA electrified aircraft flight projects such as X-57 Electric Airplane) are significantly mass/volume constrained and require more effective thermal management features for both performance and safety. In addition, due to their high voltage, have electrocution and corona discharge hazards. The initial battery designs for Robonaut, Robosimian, and X-57 have been demonstrated (either by intentional test or by catastrophic failure) to not achieve PPR status against a single cell TR event.[2,3]

Why aren't the guidelines and experience from the previous work sufficient?

a) The phenomena and factors driving the propensity of 18650 cell side wall breaches are not well-understood and uncertainty exists about which cell design features mitigate them.[4]
b) Recent calorimetric experiments indicate that introducing a bottom vent feature on 18650 cells reduces total heat output.[5]
c) Risk of side wall breaches with 0.5mm spacing between very high energy-density 18650 cell designs (>700 Wh/L) with an interstitial metallic heat sink was shown to not propagate, albeit with low safety margins for protecting adjacent cells.[6]
d) The solution of adding a snug fitting full length steel sleeve on each cell as structural support has been successfully vetted and adopted for the Orion Command Module battery but comes at significant mass and volume penalties that are too severe for these new applications.[6]
e) Fusible links integrated into the nickel (Ni) bussing sufficiently protects parallel cells in medium and low power applications, but may generate too much heat for high power applications due to their high resistance.[7]
f) The high temperature materials utilized for the cell TR ejecta vectoring protects adjacent cells in the previous assessment, but also presents insufficient safety margins for achieving 0.5mm cell spacing.[6]
g) The current guidelines do not address electrocution and corona discharge hazards.

Prototype Battery Brick Design

The most recently tested heat sink system is depicted in Figure 1. System components include the metallic interstitial bore casing, (50) 18650 lithium-ion cells with mica strips, (25) ceramic bushings, (2) fiberglass capture plates, and (6) nickel bus plates with fusible links in the negative cell weld terminal. Aluminum 6061T6 alloy with an anodized coating as the interstitial heat sink has enabled assemblies achieving > 190 Wh/kg. Substituting to a beryllium-aluminum alloy, with higher conductivity, melting point, and strength and lower density can enable > 200 Wh/kg.[1] The unique geometry of the 50-cell brick shown in Figure 1 allows all cells to have a minimum neighbor limit of three and can also be tessellated in multi-brick systems to yield overall rectangular geometries. Cell-to-cell spacing in the system has been iteratively reduced to the current value of 0.37 mm.

Traditional designs include a mica sleeve around the cells to electrically insulate them from the interstitial material, but thermal analysis suggests the presence of an air gap protects adjacent cells while swelling of the trigger cell and its ejected contents promote heat dissipation to the heat sink.[3] Accordingly, to replace fully circumferential mica sleeves, thin mica strips are wound around cells in a spiral pattern and glued to their surface (Figure 5).

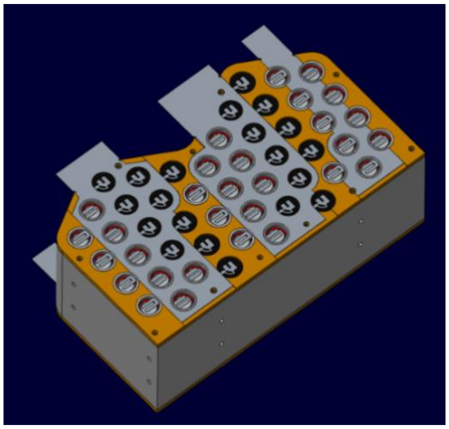

Figure 1. Battery Brick Assembly. CAD model depicting the interstitial bore casing, cells, ceramic bushings, capture plates, and nickel bussing plates in a 5s10p configuration.

Figure 2. Photo of battery brick as prepared for testing.

Prototype Battery Brick Verification

The battery brick assembly shown in Figures 1 and 2 contained three 'trigger' cells implanted with internal short circuit devices[4] for initiating thermal runaway. The key component of the device is a wax disc inside which melts when heated > 57 ℃, inducing a hard internal short between anode active material and cathode current collector, which initiates thermal runaway. Previous tests have shown that heating normal cells into thermal runaway while inside interstitial aluminum heat sink is extremely difficult due to its very facile heat dissipation.[3] The locations of the trigger cells included a corner cell, side cell, and middle cell, which can be seen in Figure 2 where heater wires stem from the system. Three separate experiments were conducted by charging the battery to 100% state-of-charge and initiating a thermal runaway event in each trigger cell with a small custom bottom heater. The temperature of the cells neighboring the trigger cells and the temperature of the test article at key locations was measured with K-type thermocouples, and the voltage of each trigger cell bank was recorded during each experiment. A snapshot of the third test (corner trigger cell) during the thermal runaway event is depicted in Figure 3.

Thermal runaway propagation from cell to cell was not observed in any of the three single cell trigger events conducted. Instantaneous temperatures as high as 450 and 750 ℃ were recorded at the terminals of neighboring cells during thermal runaway events initiated by the edge and middle trigger cells, respectively. These high temperatures stemmed from direct contact of thermocouple junctions with combusting ejecta, or with flames, or due to diagnostic cables exposed to the ejecta. Nevertheless, the temperature readings quickly decreased due to rapid heat dissipation throughout the system. The open-cell voltage (OCV) of each bank dipped and immediately recovered which indicates effective electrical isolation of the trigger cell by the cell fusible link designed into the negative cell termination connection of each nickel bus plate. The lack of thermal runaway propagation and open circuit voltage bounce-back serve as verification of the current metallic interstitial system and its corresponding design parameters. However, post-test examination capacity cycling of the adjacent cells indicated a few of the 12 total cells would not accept a charge suggesting low margins against propagation. These cells were located next to the side and corner trigger cells.

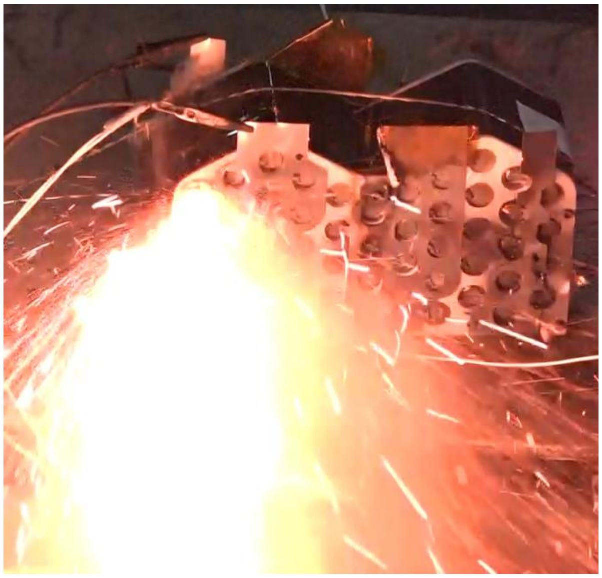

Figure 3. Video snapshot of the battery brick assembly during the single cell thermal runaway event.

Latest Design Methods

Numerous cell and pack level features are being developed and incorporated in new batteries for improved TR performance and greater energy density.

Previous generations of high performance battery packs were built using highly insulating interstitial materials that limited energy transfer to adjacent cells; newer development designs tend to favor a highly conductive and diffusive pack featuring a solid metal conductive heat sink as an intercell interstitial material.

The goal in using these conductive heat sinks is to allow heat (from either TR or nominal cycling) to be dissipated away quickly from the target cell and distributed evenly across the other healthy cells in the pack, while simultaneously removing this energy from the pack itself via thermal links to the case and vehicle structure itself. The solid metal heatsink also serves to prevent expansion of the cells and contain side-breach events during TR.

The latest of these designs featuring aluminum interstitial material couples this with a hexagonal packing arrangement (Figure 4).

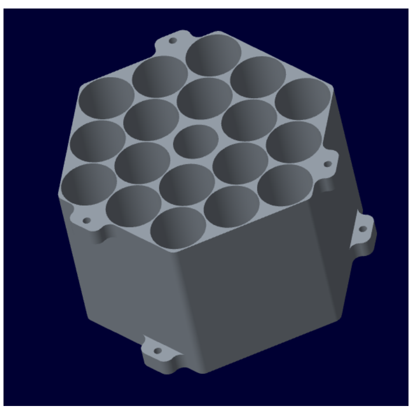

Figure 4. Hexagonal aluminum interstitial heat sink.

The hexagonal packing offers the tightest possible arrangement of cylinders in a plane, while also being able to be tessellated infinitely to allow larger batteries to be constructed from these smaller interlocking modular banks. The design also allows for stacking of modules in "decks", giving even more options for use.

In an 18650 cell, the entire cell can is polarized negative, which creates a short risk to chassis when cells are embedded in these conductive heat sinks. To prevent this electrical shorting, the surface is hard-anodized, and several additional processes are performed on the cells themselves.

The cells are coated with a thin paraxylene layer approximately 1 thousandth of an inch thick via chemical vapor deposition. This coating is abrasion resistant, inert, and electrically isolating, and is too thin to impact normal vent and burst operation of the cell.

In addition to the paraxylene, the cells are wrapped with a helical strip of mica paper. The mica is both electrically and thermally isolating, and retains its mechanical strength up to 900˚C. The helical wrap serves a double function: it lightens the pack by using less material than a full sleeve, and serves to create a critical dead air gap in between the cells and the heat sink. As shown in Figure 5 the cell mica paper wrapping that ensures the air gap and is less likely to be damaged when inserting the cell assembly in the snug fitting bores of the heat sink.

Figure 5. Spiraling mica paper wrapped around an 18650 cell.

These features combine to make the heat sink effective at wicking away heat during nominal operations as well as TR, but insulating enough to prevent damage to adjacent cells during a single-cell TR event. In addition to nominal TR protection, the design must be prepared against abnormal venting and failure.

In certain high energy cells, can breaching is occasionally observed in the spin groove below the positive terminal of the cell. This failure results in hot ejected material being sprayed diagonally in an uncontrolled manner and impinging upon neighboring cells. To mitigate the consequence of this failure, a number of features are being developed.

Offsetting the positive end of the 18650 cells from the negative end of adjacent cells helps protect the neighboring cells from being exposed to direct contact with ejected material from the failed cells. It is worth noting that this is only effective in modules in which cells are oriented with their positives faced both up and down in banks; if positives faced the same direction, the lower cell would always be able to impinge on the higher cell.

As seen in Figure 6, the spin groove is raised far away from adjacent negative ends, preventing direct impingement. This is sufficient if cells are packed in a checkerboard pattern with adjacent positive terminals spaced far away from each other, but the increased safety comes at a cost of space efficiency and interstitial mass.

In a hexagonal packed structure, it is inevitable there will be adjacent positive cell headers, making additional controls necessary (see Figure 7.) To address this concern, short and thin stainless steel tubes are placed over the spin groove, acting as a blast shield for ejecta, redirecting it upwards in a safe direction (Figure 8.)

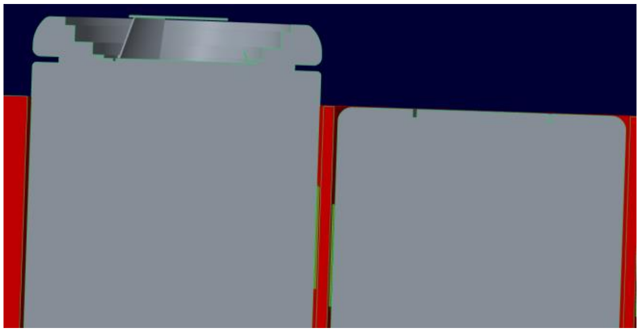

Figure 6. Offset alignment of adjacent cells as protection against spin groove breaches during TR.

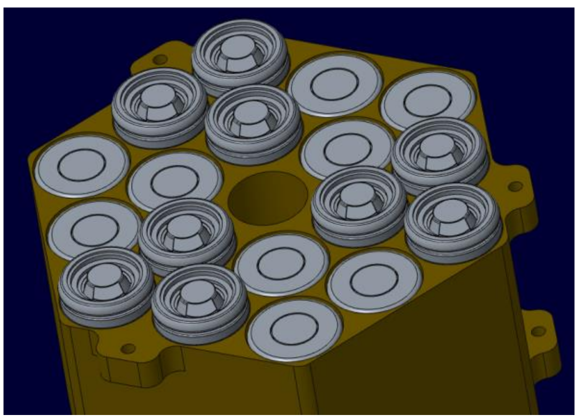

Figure 7. Battery packaging showing groups of cells with the vulnerable spin grooves in very close proximity.

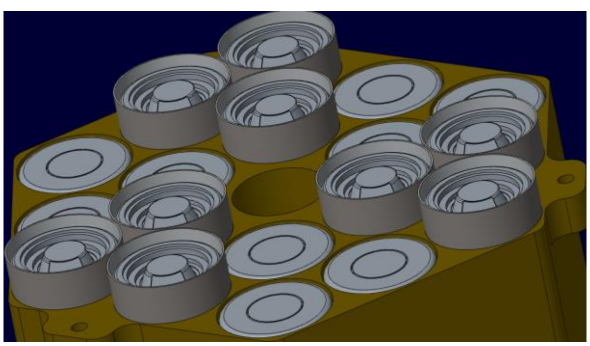

Figure 8. Short steel tubes protecting the spin groove area of a TR cell from impinging on adjacent cells.

There is concern that when axial compression of the cells leading up to and during TR events is sufficient to prevent the free expansion of the header crimp, the resultant higher burst pressures create greater energy release and consequently a more violent TR than nominal conditions. To fasten cells in place securely while minimizing the amount of header compression, a frangible tab has been built into the capture plates for the modules, covering the positive button of the cell. A plastic washer is sandwiched between the top of the cell and the capture plate; this applies uniform pressure to the tabs during TR by providing a buffer between the cell buttons and the tabs themselves. During TR the header attempts to swell and lengthen, causing the washer to shear off the tabs, giving the header the room it needs to expand (see Figure 9).

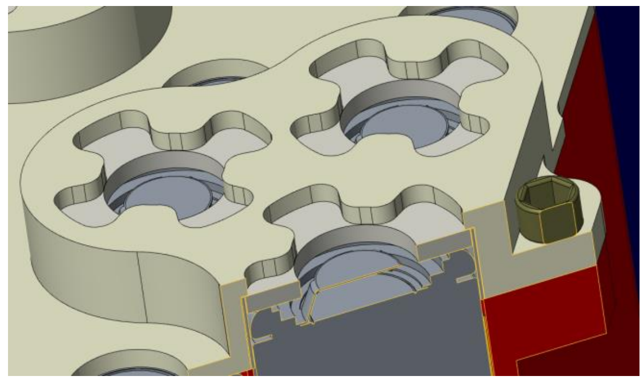

Figure 9. Plastic washer and frangible tabs in capture plate.

Conclusions

Safe, high performing (>160 Wh/kg) battery designs are possible with metal interstitial heat sinks.

Acknowledgements

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