Scale-Up Challenges for Passively Propagation Resistant Batteries: 18650 to 21700

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Abstract

In this study, we present some challenges associated with scaling from 18650 to 21700 batteries while maintaining a passively propagation resistant (PPR) battery architecture. A collaboration between NASA and NAVSEA has achieved PPR battery designs with gravimetric and volumetric energy densities of 166 Wh/kg and 459 Wh/L, respectively. Commercially available 18650 cells were arranged in various electrical topologies to achieve the power requirements for each application. Will those design metrics improve when scaling up with the best commercially available 21700 cell designs? A design, analysis, assembly, and test effort with blast plate composites revealed that the gap for dispersion of the thermal runaway ejecta relied on in 18650 PPR batteries must be increased to allow for sufficient volume when scaling up to a 21700 cell to offer protection between axially stacked battery modules. Furthermore, fractional thermal runaway calorimetry (FTRC) energy yields have shown that the output of high energy cells 21700 cells is 75% more despite an electrochemical energy increase of 50% compared to an 18650 high energy cell design. A thermal analysis model predicts that the interstitial aluminum heat sink webbing thickness, an integral part of the PPR design, would protect the adjacent cells more robustly when increased from 0.5mm to 1mm. Validation by battery PPR testing will be presented.

Keywords: Passive propagation resistance (PPR), lithium-ion, battery, thermal runaway

Introduction

Lithium-ion batteries are critical for storing electrical energy in applications that require high energy and/or power density, such as EVs, grid storage, space vehicles and underwater submersibles. Building and integrating battery packs and modules into battery systems requires rigorous designs and optimization to lower the risk of thermal runaway propagation, provide a uniform pack temperature, absorb shocks or other perturbations, and most importantly, fit within and perform to predetermined operating conditions. Safety is a significant criterion when introducing battery systems into vehicles rated for human use as a single incident, such as a thermal runaway event, can have catastrophic consequences.

Materials and Methods

The objective of the NASA-NAVSEA collaboration effort is to design batteries that can tolerate a single cell thermal runaway event without causing failure to propagate. Four design guidelines were followed:

1. Protecting adjacent cells from possible side wall and/or spin groove breaches of cell undergoing thermal runaway.
2. Provide adequate spacing between cells and an appropriate heat rejection path for the cell undergoing thermal runaway.
3. Individually fuse parallel cells or strings of series cells and prevent bypassing of fuses by conductive ejecta.
4. Protect the adjacent cells from the hot ejecta produced during thermal runaway with appropriate temperature tolerant dissipation gaps.

To achieve a high performance PPR battery, interstitial aluminum heat sinks were utilized between cells as the primary mechanism for dissipating heat generated during thermal runaway. Rapid dissipation of heat away from a failed cell is critical to ensure thermal runaway propagation does not occur in neighboring cells.

Results And Discussion

In 2021, a battery with a 134P-3S electrical topology was designed with commercially available 18650 cells and successfully demonstrated passive propagation resistance. First, a model was utilized to predict cells most vulnerable to propagation during thermal runaway. Twelve cell locations in total were identified for thermal runaway testing. During battery assembly, cells equipped with Internal Short Circuit Devices (ISCD) were installed strategically, following guidance from the thermal modeling. Figure 1 shows a CAD rendering of the “M3” Battery assembly. This design achieved 166 Wh/kg and 459 Wh/L gravimetric and volumetric energy densities, respectively.[1]

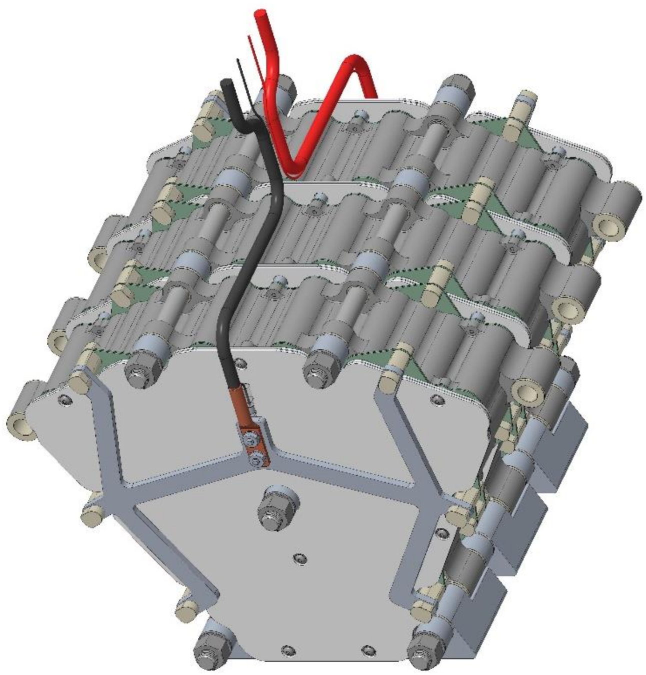

Figure 1: CAD rendering of M3 PPR Battery pack with a 134P-3S electrical topology. This battery successfully demonstrated PPR with 12 individual thermal runaway tests.

The M3 Battery design features an interstitial aluminum webbing thickness of 0.020 inches [~0.5mm] between adjacent cells. The heat sink, designed to match the overall length of the cell, provides the necessary structural support and a heat rejection path in the event of a thermal runaway event. Furthermore, the webbing between cells protects adjacent cells in the event of off-nominal cell failures, such as side wall- and spin-groove ruptures, which may spread hot ejecta to neighboring cells, causing thermal runaway propagation. One out of twelve individual thermal runaway events caused minor pitting in the interstitial aluminum heat sink, demonstrating its robust design.

When combining modules in a battery pack, it is necessary to protect cells in neighboring modules, especially when cells are aligned axially as is the case in the M3 Battery design, with a barrier. This barrier ensures that thermal runaway does not propagate to adjacent modules. A metal-ceramic composite with a 5mm standoff gap, between the cell and barrier, has been tested rigorously and shown to provide sufficient protection in 18650 battery packs. Testing results indicate that a sufficient standoff distance is necessary to allow thermal runaway ejecta to disperse effectively away from adjacent cells.[1] A test setup was conceived to allow cells to be triggered via nail or by heat to determine whether a 5mm standoff gap is sufficient for battery architectures featuring 21700 cell formats. Figure 3 below details the main features of the test apparatus. First, cells are bonded into thin aluminum sleeves, like the procedure used for battery assembly. Simultaneously, blast plate test coupons are prepared by bonding candidate materials to be evaluated onto a rectangular aluminum substrate plate. Nine thermocouples are attached directly onto the back of the aluminum plate in a one-inch array for capturing thermal data. Prior to testing, the cell and blast plate coupon are mounted into the cell chamber and onto the sliding blast plate stage, respectively, followed by adjustment of the sliding stage. The desired standoff distance is achieved adjusting the position of the sliding blast plate stage. Thermal runaway is initiated remotely via nail penetration utilizing the pneumatic actuator or via cartridge heaters installed into the cell chamber.

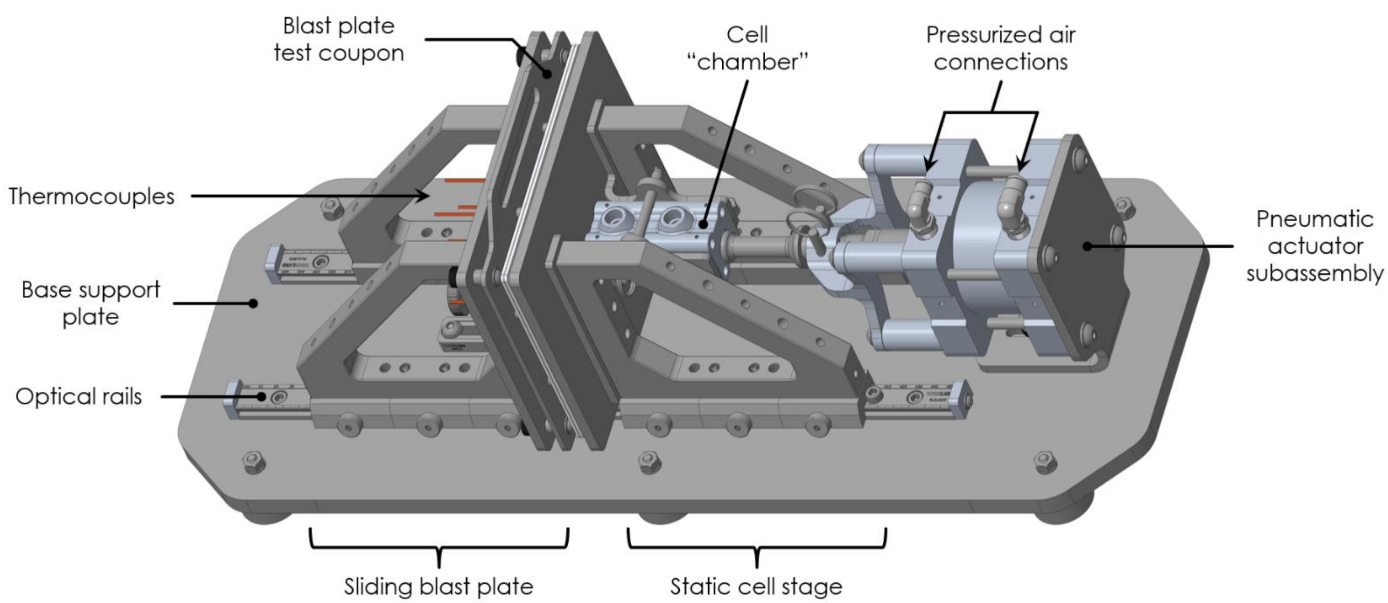

Figure 2: Blast Plate Test Stand (BPTS) designed to evaluate various blast plate materials at a fixed distance from the cell header. Cells are driven into thermal runaway in the cell chamber via axial nail penetration or cartridge heaters.

Several thermal barrier materials were tested including ones manufactured by Morgan Advanced Materials, Zircar, and Oerlikon. The purpose of these materials is to protect a 1/32 inch [~0.8mm] aluminum substrate plate from perforating by thermal runaway ejecta from the cell. An additional success criterion for a selected standoff distance is to ensure that accumulation of ejecta mounting onto the surface of the blast plate does not touch the trigger or neighboring cells. Tests in which ejecta was observed touching the trigger cell were considered unsuccessful and deemed to have inadequate spacing for dispersion of ejecta. Accumulation of hot ejecta near the adjacent cells may result in thermal abuse and potential failure and potential shorting or discharge of cells.

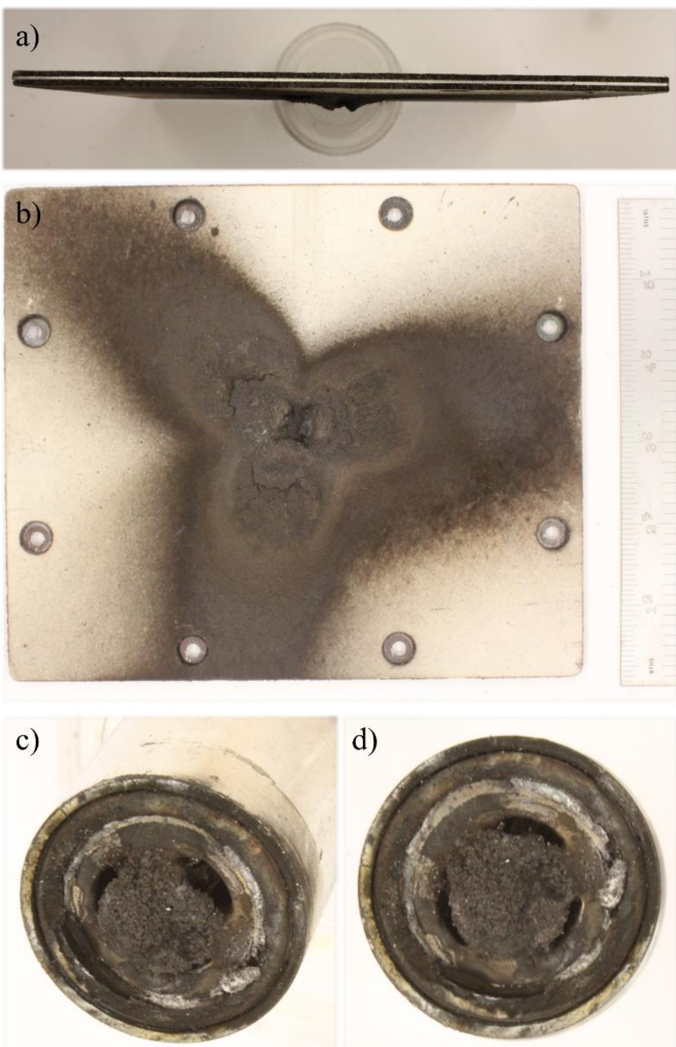

Figure 3: Post-test images of blast plate and cell a) top view of blast plate test coupon after testing with view of ejecta mounting, b) front view of the blast plate showing the uniformity of ejecta dispersion, c) angled view of a Samsung 50S cell following a blast plate test at 8mm standoff distance and d) top view of cell showing the activation of all three vent holes and a nominal failure.

In total, four blast plate materials, three standoff (gap) distances, two cell types and two trigger methods were evaluated. Each test condition (material, gap, cell, and trigger method) was repeated a minimum of six times. Our test result revealed that for two 21700 cell designs (LG INR21700 M52V and Samsung INR21700 50S) triggered via nail penetration, a standoff distance of 8mm is required to provide for adequate ejecta dispersion. Various levels of damage and ablating were observed on the blast plate shielding materials, however, no perforations in the aluminum substrate was observed in any of the tests performed with nail penetration. Figure 3a and b show the top and front views of a blast plate test coupon reinforced with Morgan Advanced Material shielding. This test was performed at an 8mm standoff distance. Note the symmetry of ejecta spread corresponding to the activated vent holes of the Samsung 50S cell shown in Figures 3c and d.

A series of heater confirmation runs were performed at 8mm which resulted in severe bending and some perforation of the blast plate test coupons. Thermal energy added to the cells to initiate thermal runaway causes a much more kinetically energetic output. Since our design objective is to prevent cell propagation, the thermal trigger is likely an over test and therefore not representative of a defect induced field failure thermal runaway event. However, the test results were informative of the potential damage that a battery system may sustain if propagation does occur; successive cell failures are more severe than the defect that induced the initial thermal runaway event. Subsequent testing with ISCD implanted 21700 trigger cells will be performed with our selected barrier composite material and standoff distance to simulate a field failure and verify the barrier's ability to protect adjacent cells. Cells with implanted ISCD require a thermal activation temperature just above 60°C to active; significantly less thermal energy compared to a normal cell.

Fractional Thermal Runaway Calorimetry (FTRC) testing of the newest 21700 cell designs has revealed that the total thermal runaway energy output can be as much as 75% higher than the incumbent 18650 Molicel M35A despite only providing 50% more electrochemical energy. The plot in Figure 4 provides a comparison of overall and cell body energy releases for three cells: Molicel INR18650 M35A, Samsung INR21700 50S and LG INR21700 M52V with various activation mechanisms including heat trigger, ISCD heater trigger and nail penetration. Our thermal analysis predicts that increasing the thickness of the interstitial aluminum webbing between cells from 0.020 inches [~0.5mm] to 0.040 inches [~1.0mm] will reduce the maximum temperature of the adjacent cells by 15°C with our maximum calorimetric output for a 21700-cell determined by FTRC.[3]

The results of PPR tests and with 19-cell subscale batteries will be presented along with analysis anchored by the thermal runaway test results.

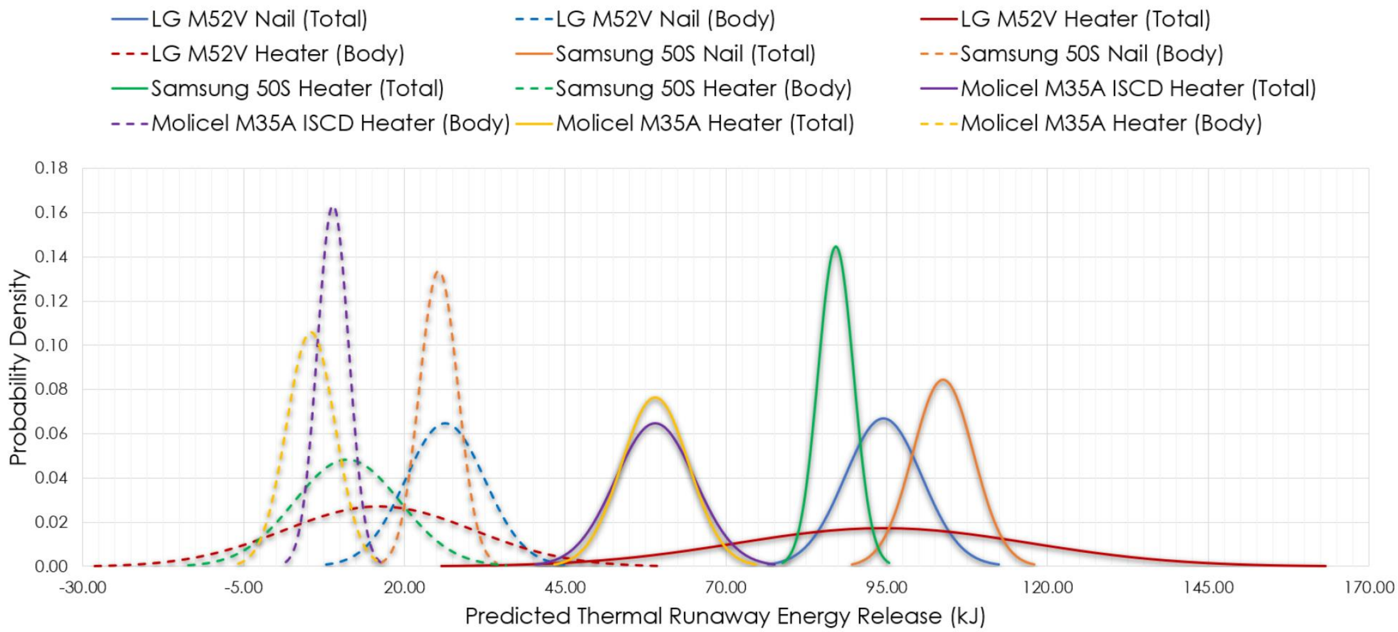

Figure 4: Energy yields of three select cells: Molicel INR18650 M35A, Samsung INR21700 50S and LG INR21700 M52V for selected trigger mechanisms. Overall and cell body energies are plotted as a function of trigger and cell type.

Conclusion

This study is part of a broader collaborative effort between NASA and NAVSEA with the primary objective of designing passively propagation resistant batteries for application in human-rated vehicles. We present challenges associated with up-scaling lithium-ion PPR battery architectures from 18650 to 21700 cell formats, namely the results from a blast plate testing campaign as well as preliminary PPR testing results form subscale batteries. These results will be used to inform future designs of full-scale PPR battery architectures featuring 21700 cells.

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