

Consumer Product Safety Commission (CPSC) Staff's Statement on Naval Surface Warfare
Center, Carderock Division's (NSWCCD) Report on "Evaluation of Cell-to-Cell Propagation in
Lithium-Ion Batteries Containing 18650 Sized Cells"
January 2020

The "Report on Evaluation of Cell-to-Cell Propagation in Lithium-Ion Batteries Containing 18650 Sized Cells," presents the results of testing that CPSC funded NSWCCD to execute under CPSC Interagency Agreement. CPSC staff sponsored this interagency agreement to leverage NSWCCD's expertise in the lithium battery failure testing. The objective was to learn more about the catastrophic failures of multi-cell lithium-ion battery packs, such as those used in hoverboards, from a single cell that enters a thermal runaway condition, and to evaluate several methods to isolate the failure to the one cell. This information will support improvements for the voluntary safety standards for electric scooters and e-mobility devices to reduce the severity of fire incidents.

NSWCCD conducted a series of tests forcing a single cell in a multi-cell battery pack into thermal runaway, characterizing the propagation to the remaining cells in the pack and investigating ways to limit the failure to the originating cell, either through spacing cells apart, or using separating materials. NSWCCD conducted tests on commercially available lithium-ion cell battery packs consisting of 10 or 20 18650 cells, as well as custom-built packs that NSWCCD assembled from individual 18650 cells.

NSWCCD's evaluation of the propagation-mitigation techniques showed mixed results warranting further study. CPSC staff funded NSWCCD in FY 2019 for additional evaluation of the materials that showed promise.

Naval Surface Warfare Center Carderock Division

West Bethesda, MD 20817-5700

NSWCCD-63-TR-2020/01

January 2020

Platform Integrity Department
Technical Report

Evaluation of Cell-to-Cell Propagation in Lithium-ion Batteries Containing 18650 Sized Cells

by

Gordon H. Waller, Jonathan K. Ko, Thomas H. Hays, Thomas L. Jiang



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ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Expeditionary and Developmental Power and Energy Branch, (Code 635), at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The work was funded by the Consumer Product Safety Commission (CPSC). The results of this report are not intended as an endorsement of any product.

EXECUTIVE SUMMARY

This document describes the results of an abusive test program conducted on commercially available battery packs utilized in “hoverboard” e-mobility devices, as well as several custom-made battery packs intended to evaluate several possible design changes reported to influence battery safety. “Commercially available” is intended to mean that the referenced battery pack is a component inside a hoverboard product that is available through retail outlets in the United States. Specifically, cell-to-cell propagation is a concern in commercially available battery packs which contain multiple lithium-ion cells in close proximity. The custom-made battery packs included a “close-packed” configuration, analogous to the arrangement found in the commercially available battery packs, as well as packs which included some kind of interstitial packaging material. Packaging materials included a refractory insulating cloth material intended to slow heat transfer between neighboring cells, two insulating materials which utilize the endothermic cooling properties of phase-change material to absorb heat from a cell during thermal runaway, and a simple 2 mm air gap. In one instance, the phase change material was paraffin wax in the form of a wax-graphite composite rigid housing in which cells were inserted. In the second instance the phase change material was a carbon fiber mat with a liquid phase change material enclosed in a flexible pouch which was wrapped between cells. Testing was conducted by driving a single cell into thermal runaway via external heating. Both of the phase change materials were found to delay thermal runaway in the trigger cell. A 2 mm air gap and the refractory cloth material were not found to prevent cell-to-cell propagation. In one of two cases, the wax-based phase change material also prevented cell-to-cell propagation after the trigger cell underwent thermal runaway. In two of two cases, the carbon fiber and liquid phase change material prevented cell-to-cell propagation. For both the phase change materials however, flames and sparks were emitted from the battery pack and high temperatures (>500 °C) were recorded meaning these materials did not prevent single-cell thermal runaway. It can be concluded from the testing in this report that while the likelihood of cell-to-cell propagation can be reduced with appropriate packaging of the battery packs, the underlying mechanism of thermal runaway is still present for individual cells. Furthermore, certain testing conditions such as mechanical or electrical abuse were not evaluated and may change the behavior of the packs. Additional testing on a statistically significant number of battery packs, or using the same packaging materials with different lithium-ion cells (for instance higher capacity cells more likely to undergo sidewall ruptures) is recommended.

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1. Introduction and Background

Lithium-ion batteries (LIB) are commonly utilized in consumer electronic devices as an energy-dense and reliable rechargeable power source. One format which has found broad application from laptops to electric vehicles is the cylindrical “18650” cell, which has dimensions of 18 mm in diameter and 65 mm in length. Cells with the 18650 form factor are manufactured in the billions, mostly in Asia. Several manufacturers produce cells with extremely tight tolerances and reliable performance. However, for devices sold with integrated battery packs, cells from less reputable suppliers or even counterfeit cells are sometimes used, and the quality of integrated cells can be difficult to assess. This can potentially lead to issues with cell capacity balancing or manufacturing defects which can introduce safety issues into the battery pack. Even for well manufactured cells, abusive conditions (i.e. electrical, thermal, or mechanical) outside of the manufacturer specifications can lead to energetic failures of LIB. Media reports have highlighted failures which involved cells venting flaming electrolyte or exploding battery packs, which can be extremely dangerous for people and property.

Typical battery pack designs using 18650 sized cells simply arrange cells in a “close packed” configuration with cells electronically connected in series or parallel as needed using metal tabs. Cell assemblies are controlled using a “battery management system” (BMS) which should limit over voltage, over current, and over temperature conditions from damaging the battery pack, however this is a potential point of failure for poorly designed device-integrated batteries. A major safety issue with LIB is the possibility of a propagating thermal runaway, in which a failure of a single cell releases sufficient energy into neighboring cells to cause a cascade of failures. LIB failures can initiate with very little warning, especially for mass market devices which utilize only rudimentary BMS relative to the sophisticated systems used for electric vehicles. A potential mitigation strategy involves designing battery packs which are passively resistant to a propagating thermal runaway. Generally, this involves containing or directing the heat released from a single cell failure such that adjacent cells are unaffected. While many approaches are available, integrating safety features into a battery design can reduce the energy density of the system by adding mass and volume, and add cost or complexity to the battery assembly process.

In this report, battery packs from commercially available “hoverboard” e-mobility devices were subjected to thermal abuse to determine whether cell-to-cell propagation would occur as a result of a single cell initiation. “Commercially available” is intended to mean that the referenced battery pack is a component inside a hoverboard product that is available through retail outlets in the United States. Hoverboards, which have many manufacturers, were the subject of over a dozen product recalls in 2016 and 2017 due to fire hazards associated with the integrated LIB. The Consumer Product Safety Commission (CPSC) issued a Safety Alert urging consumers to purchase only hoverboards which were compliant with the UL 2272 testing standard. As a comparison to these commercially available battery packs, custom battery packs utilizing similar 18650 LIB to those in the hoverboard packs were assembled and tested at the Naval Surface Warfare Center Carderock Division (NSWCCD). In addition to a “close packed” configuration tested as a control, several designs intended to improve propagation resistance, including some utilizing commercially available cell interstitial packaging materials, were also evaluated.

2. Approach

Testing was performed on two varieties of commercially available hoverboard battery packs featuring 18650 sized cells. The commercially available hoverboard packs, referred to hereafter as “Pack A” and “Pack B” were assembled by different manufacturers and contain different 18650 sized cells. Custom packs, “Pack C” through “Pack G”, containing commercially available 18650 cells were also assembled with an identical electrical and physical arrangement to Pack A, but with and without cell interstitial packaging materials intended to prevent cell-to-cell propagation. Each pack configuration was evaluated twice, except for Pack B, which was tested twice within the aluminum enclosure and once with the cells removed from the aluminum enclosure, and Pack F which involved both an interstitial packaging material and an enclosure. Pack F was tested twice in this configuration, and once with only the enclosure but no packaging material. Table 1 identifies the packs tested and described in this report. Nominal specifications for the 18650 sized cells used in Pack A, C, D, E, F and G are shown in Table 2. The cells found in Pack B were not produced by a recognizable supplier, and an internet search of the part number used in Pack B could not find the specifications for these cells.

Table 1. Battery packs evaluated

Pack ID	Energy (Wh)	Electrical Configuration	Pack Mass	Note
Pack A	90	10S1P	591 g	Commercially available [#] hoverboard's battery pack w/ plastic enclosure
Pack B	96.2	10S2P	1156 g	Commercially available [#] hoverboard's battery pack w/ aluminum enclosure
Pack C	90	10S1P	444 g	Custom 18650 pack w/o insulation (close packing arrangement)
Pack D	90	10S1P	460 g	Custom 18650 pack w/ refractory insulation
Pack E	90	10S1P	761 g	Custom 18650 pack w/ liquid phase change insulation and enclosure
Pack F	90	10S1P	513 g	Custom 18650 pack w/ wax-based phase change insulation
Pack G	90	10S1P	448 g	Custom 18650 pack w/ 2 mm air gap

- Commercially available is intended to mean that the referenced battery pack is a component inside a hoverboard product that is available through retail outlets in the United States.

Table 2. Nominal specifications for cells used in Packs A, C-G

Parameter	Value
Nominal Capacity	2.5 Ah
Nominal Voltage	3.6 VDC
Upper Voltage Cutoff	4.2 VDC
Lower Voltage Cutoff	2.0 VDC
Maximum Charge Current	4 A
Maximum Discharge Current	20 A
Operating temperature range (charge)	0-50 °C
Operating temperature range (discharge)	-20-75 °C
Cell Mass	48 g (~44 g measured)

2.1 Commercially Available Hoverboard Battery Packs

2.1.1 Pack A

Pack A, shown in Figure 1, is comprised of ten 18650 cells electrically connected in series. The battery pack provides 2.5 Ah of capacity at a nominal 36 VDC for 90Wh of energy. There are no known safety devices in the pack, however a pack-mounted electronics board (presumably a battery management system) is included. NSWCCD staff were not provided with any details of the BMS or any safety devices within. Cells in this pack were housed in a plastic enclosure which was cut open to access the individual cells.

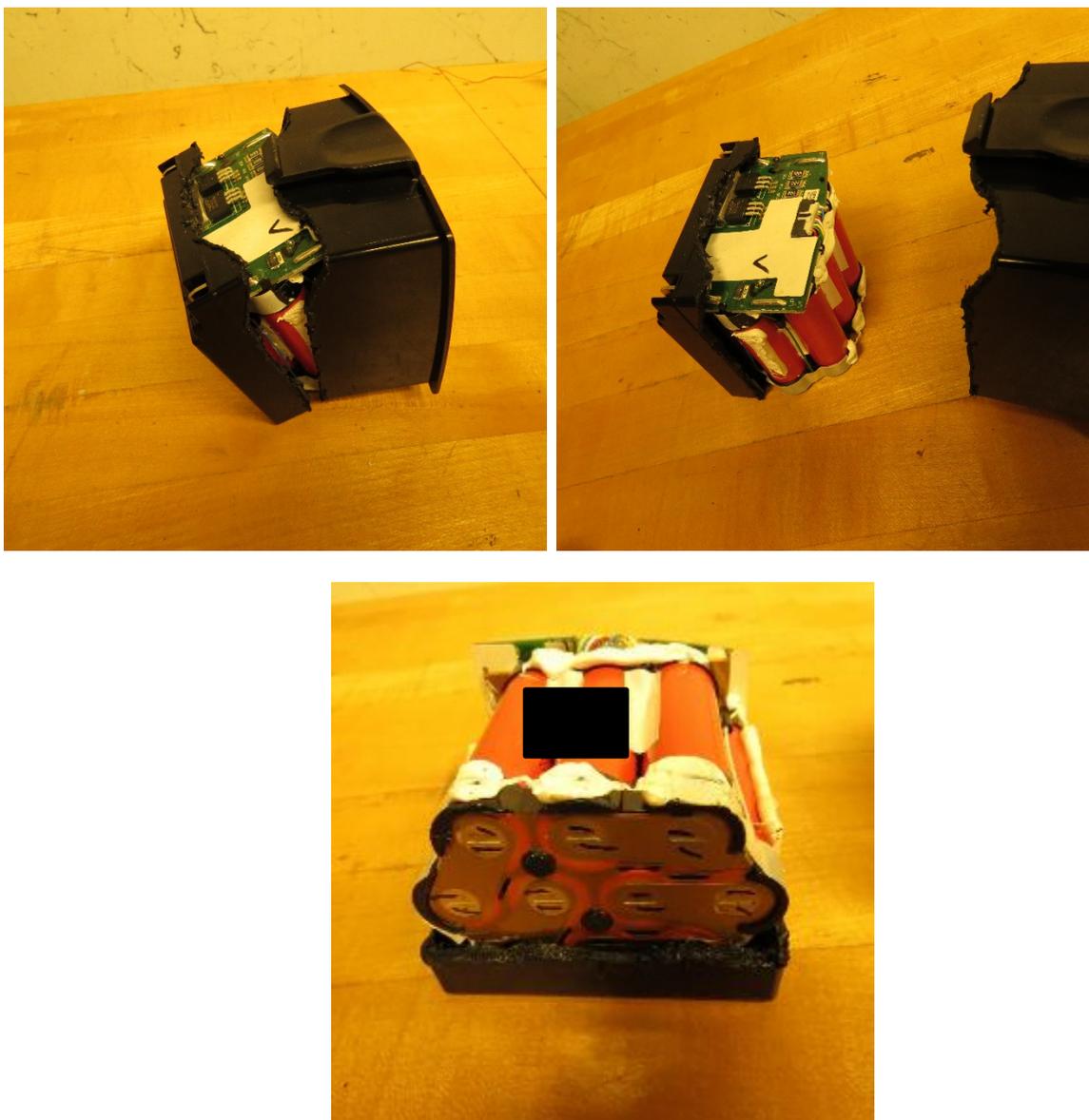


Figure 1. Pack A, comprised of ten 18650 cells in a 10S1P configuration.

Pack A was cycled three times at a rate of $C/5$ (0.5 A) to confirm the rated capacity and placed at 100% state-of-charge for thermal abuse at a rate of $C/5$ (0.5 A), shown in Figure 2. The observed capacity of the commercial pack was 3 Ah, noticeably above the nominal 2.5 Ah of the cell used (Table 2). Given that these cells are rated for high power operation (up to 20 A or a 8C discharge as shown in Table 2), the “extra” capacity could simply be a function of cycling at a lower rate, as increasing rate typically results in less accessible capacity for a given cell. Alternatively, the extra capacity could indicate that the actual cells contained in Pack A are not the cell indicated.

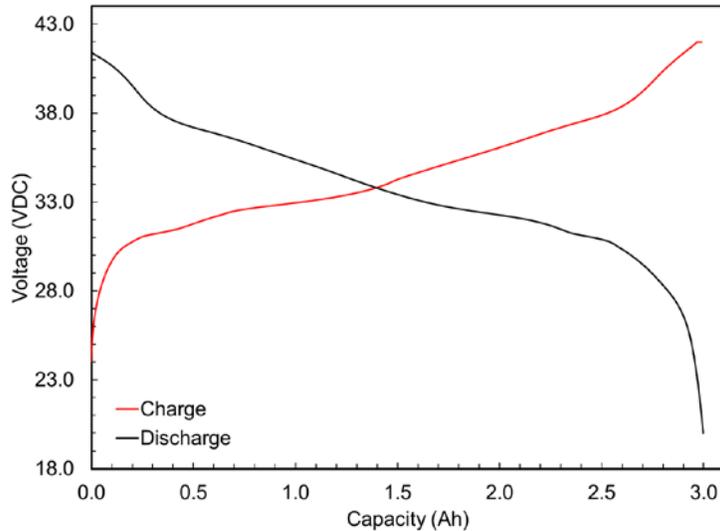


Figure 2. C/5 Cycling of commercial hoverboard “Pack A”.

2.1.2 Pack B

Pack B is similar in design to Pack A in that it contains multiple 18650 cells. However, Pack B utilized twenty cells of a much lower energy density and used pairs of cells in parallel which were then connected in series (10S2P, a total of 20 cells) to achieve a comparable energy content to Pack A (10S1P, a total of 10 cells). Pack B also included an aluminum housing intended to protect the cells and contain any battery failures (Figure 3). A pack-mounted electronics board is also present in Pack B, which as with Pack A is assumed to be a battery management system. However unlike Pack A, which allowed for direct measurement of the pack open circuit voltage (pack OCV) from the pack terminals, the external pack leads of Pack B had to be bypassed in order to determine the pack OCV, which implies the pack mounted electronics may be involved in preventing current flow unless certain external conditions are met. Previously observed failure events for this pack indicated that the aluminum housing can be ruptured as the result of battery failures, and the intention of this evaluation was to determine whether the housing had any influence on observed battery failures. Testing was conducted with and without the aluminum enclosure.



Figure 3. Pack B, comprised of twenty Li-Ion 18650 cells in a 10S2P configuration

Like with Pack A, Pack B was cycled three times at a C/5 rate (0.52 A for the 2.6 Ah nominal capacity of the 10S2P configuration) to confirm capacity and placed at 100% SOC (Figure 4). Additional capacity was also observed for Pack B, which showed nearly a full Ah of additional capacity (3.4 Ah observed). As the exact specifications for the cells used in Pack B could not be obtained, it is difficult to speculate on the rate capability of these cells as an explanation to the extra capacity.

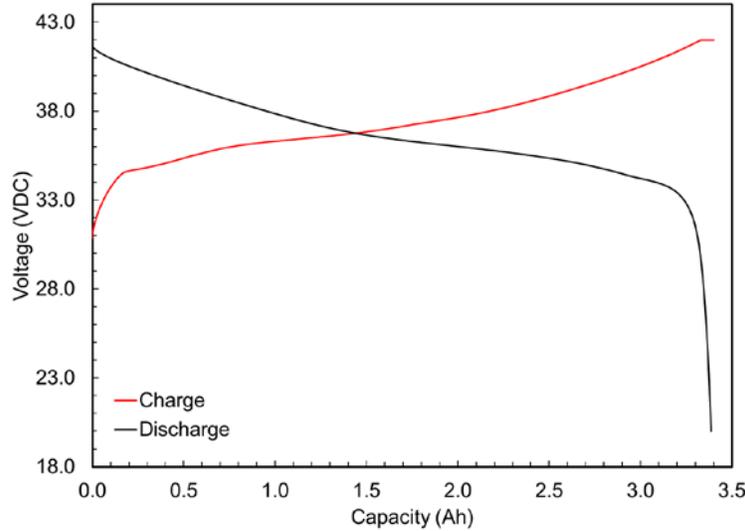


Figure 4. C/5 Cycling of commercial hoverboard “Pack B”

2.2 Customized Battery Packs

Packs C through G were assembled at NSWCCD by connecting ten 18650 cells in a 10S1P configuration analogous to Pack A. Electrical connections were made by spot-welding Ni-tabs from the positive terminal of one cell to the negative terminal of an adjacent cells. Packs were assembled either in a “close packed” configuration with cell walls of nearest neighbors in contact (identical to the spacing shown for Pack A in Figure 1), with interstitial packaging materials included to create a gap of 1-2 mm between adjacent cells, or with spacers near the top and bottom of each cell to create a 2 mm air gap between the cell walls. Top down and isometric views of the 10S1P pack configuration are shown in Figure 5. Two CT scan images of internal cross-section of the cells in Pack C are also provided in Figure 5. Pack C utilized no spacer material (close packed configuration), Packs D, E, and F utilized commercially available insulating materials as interstitial spacing materials, while the spacer “material” for Pack G was simply an air gap.

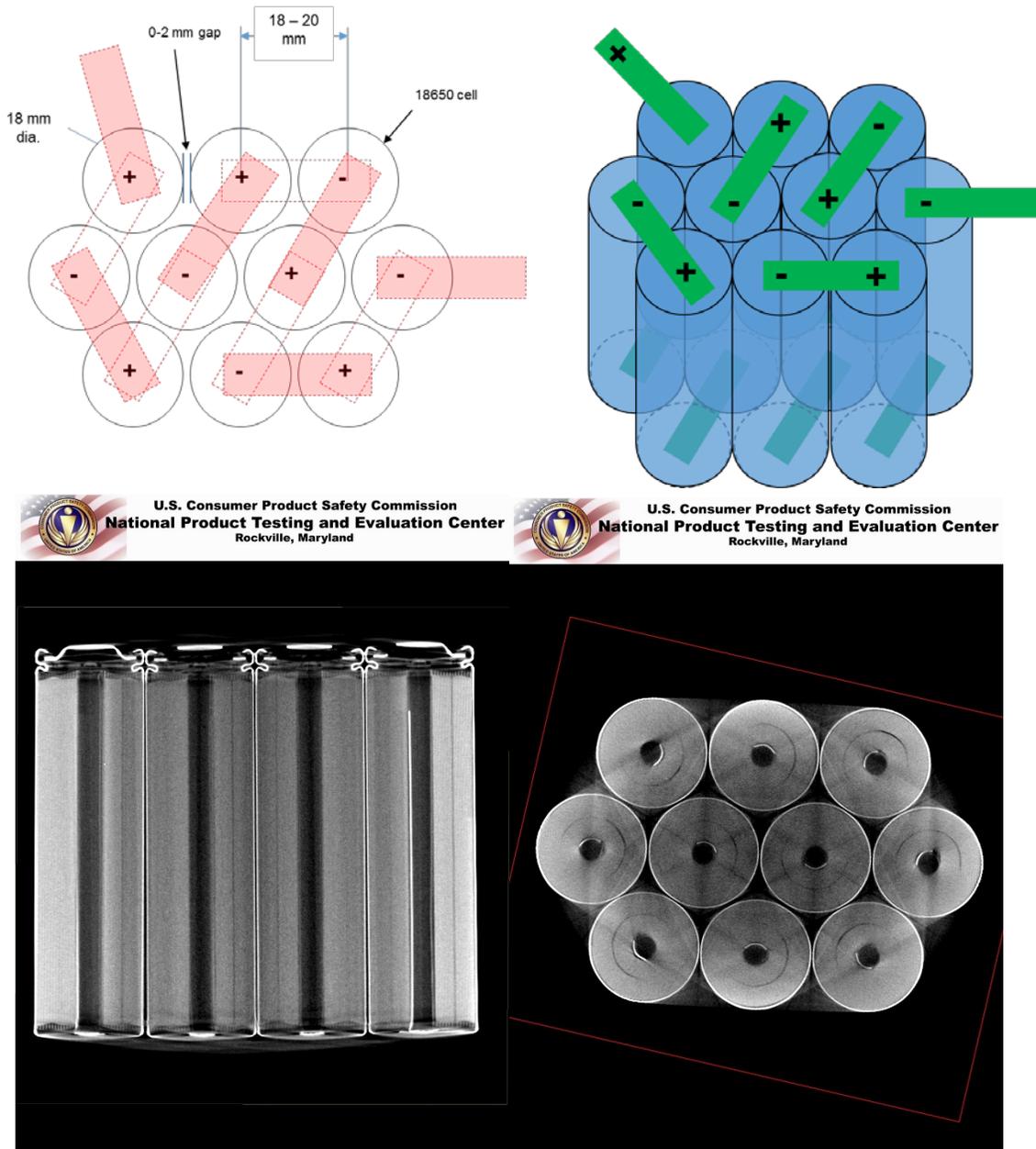


Figure 5. Top down (top left) and isometric (top right) views of 10S1P 18650 pack configuration and cross-sectional cell views, longitudinal (bottom left) and latitudinal (bottom right)

A representative cycling plot conducted at C/5 for Packs C-G is shown in Figure 6. Despite utilizing nominally identical cells to those found in Pack A, the custom fabricated packs reported very little “extra” capacity of 2.55 Ah against a nominal 2.5 Ah.

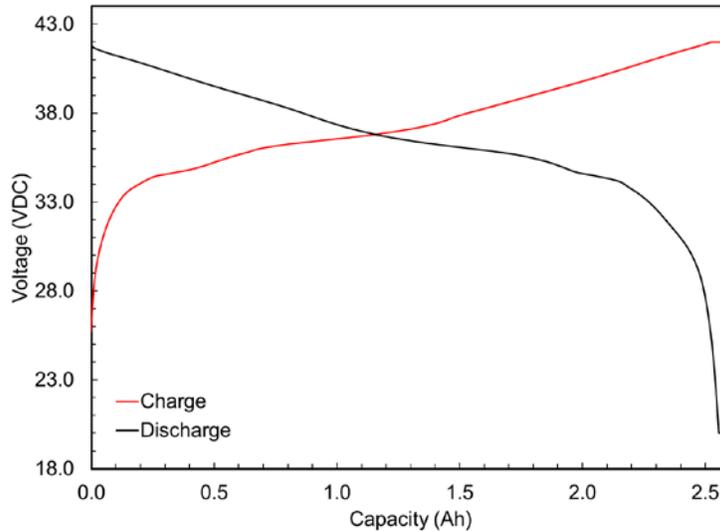


Figure 6. C/5 Cycling of custom 18650 pack used in pack configurations C through G

2.2.1 Pack C

Pack C consisted of ten 18650 cells in a close packed configuration, analogous to the arrangement used in the commercial Packs A and B. No modifications were made to the as-received cells beyond glass fiber tape used to adhere thermocouples and the heater cartridge, a 3D printed ABS plastic (acrylonitrile butadiene styrene) ring to ensure a tight fit between cells, and Ni tabs used to make electrical connections between cells. A digital photograph showing the Pack C assembly is shown in Figure 7.



Figure 7. “Pack C” with close-packed cell arrangement

2.2.2 Pack D

Pack D incorporated refractory cloth insulating material containing primarily SiO_2 and Fe_2O_3 refractory fibers. The commercial product is provided as a flexible felt with a thickness of 1 mm. Individual 18650 cells were wrapped in one layer of refractory cloth which was held in

place with glass-fiber tape. The pack was then assembled in an otherwise “close packed” configuration such that 2 mm of refractory cloth was between the can walls of adjacent cells. Packs were tab-welded into a 10S1P assembly and then wrapped with electrical tape to keep the cells tightly packed. The heater cartridge was mounted directly on the cell, inside of the layer of refractory cloth insulation.

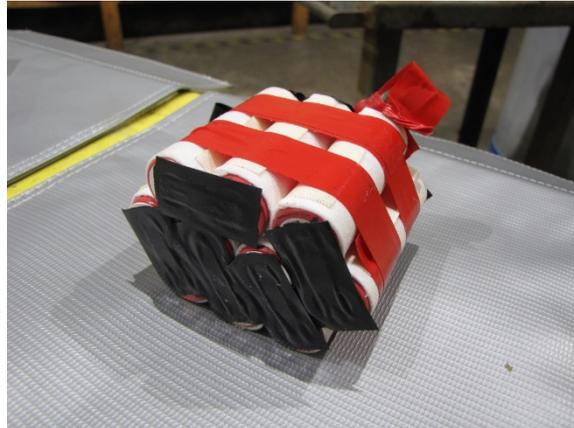


Figure 8. “Pack D” with refractory cloth insulation around individual cell (left) and multiple cells arranged in a pack (right)

2.2.3 Pack E

Pack E utilized a flexible heat-absorbing spacer material. Like the refractory cloth product used in Pack D, the material used in Pack E is a flexible sheet of insulation which creates a separation between adjacent cells in a battery pack. Unlike the refractory cloth material however, the Pack E material also includes a liquid component intended to maintain the battery pack temperature through an endothermic phase change. Special instructions were provided by the material manufacturer for the installation of this product into a lithium-ion battery. First, cells were wrapped with two sheets of the insulating material (indicated as Sheet 1 and Sheet 2 in Figure 9). Cells which were not separated by the insulating material were separated by a phenolic insert. Both the spacer and the insulating material used in Pack E had a thickness of 1.5 mm.

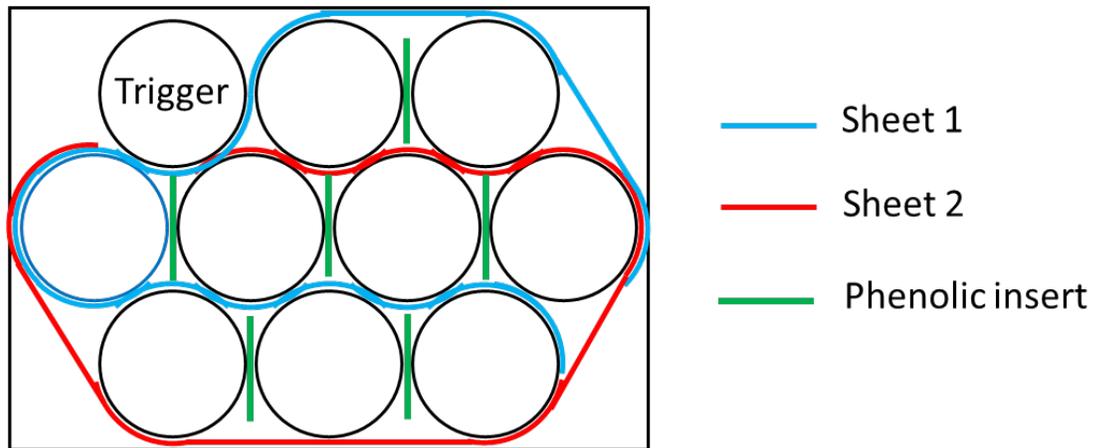


Figure 9. Phase-change insulating material placement for Pack E

The insulating material wrapped cells were then enclosed in a box which featured an “end capture plate” on each end of the battery pack and an additional layer of flexible phase change material outside each end capture plate, which served as a “flame arrestor” to block sparks and flaming electrolyte during a cell failure (Figure 10).

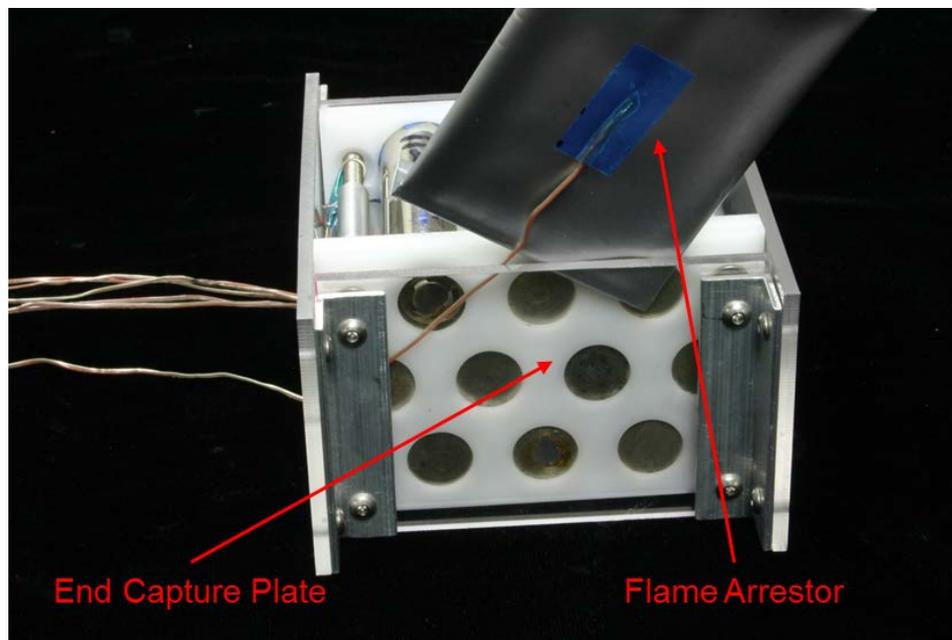


Figure 10. End capture plate and flame arrestor placement in Pack E

The materials used for the end capture plate and battery enclosure were not specified by the manufacturer, however for the testing conducted at NSWCCD, an end capture plate was 3D printed using ABS plastic, and the enclosure was constructed of G10 glass fiber reinforced polymer which was epoxied together on 5 sides and screwed into place on one side. The G10 material has a maximum service temperature of 140 °C and is generally non-flammable, while ABS plastic will soften at temperatures as low as 60 °C and is flammable. In addition to the openings between screw placements on the top of the G10 enclosure, small pass-through holes were machined to allow for thermocouples, voltage sense lines, and heater cartridge power lines

to exit the box. As a result, the box was not air tight. Photographs showing various stages of Pack E assembly are shown in Figure 11.

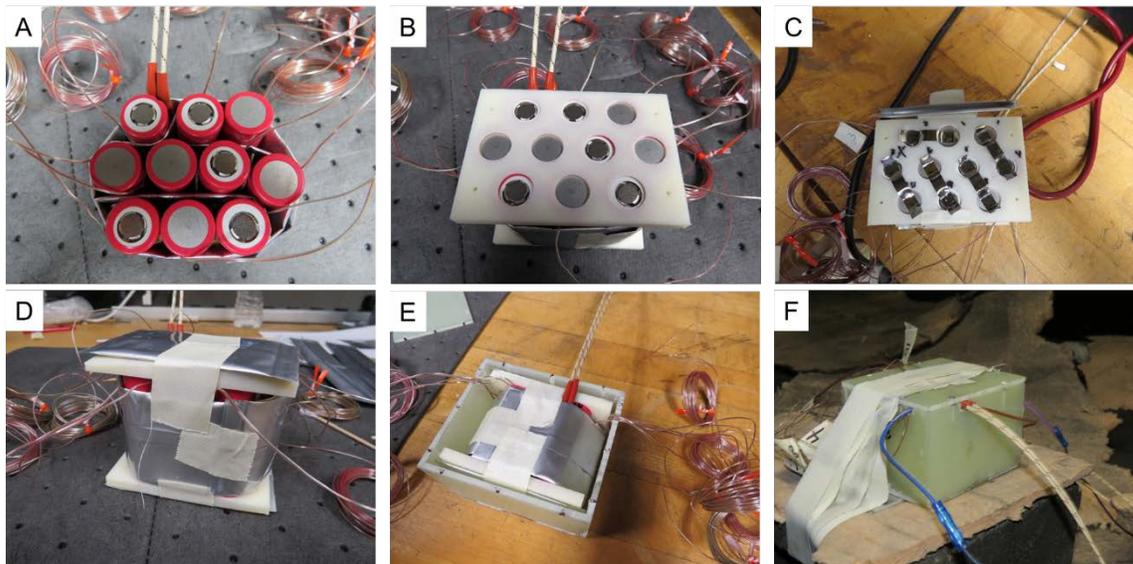


Figure 11. Assembly of Pack E depicting placement of the flexible phase change material (A), the end capture plate (B), tab welding between cells (C), placement of the flame arrester (D), placement of insulating material wrapped pack inside the G10 enclosure (E), and positioning of Pack E for testing (F)

2.2.4 Pack F

Pack F utilized a wax based phase change material which contains graphite for enhanced heat-transfer. Pre-fabricated holes were provided for inserting 18650 sized cells. Like with the insulating material utilized in Pack E, the wax based material used in Pack F undergoes a phase change above a certain temperature ($T_m=55\text{ }^{\circ}\text{C}$ for the materials tested in this report) in order to absorb heat from a cell undergoing thermal runaway. The spacing between cells using the wax based phase change material was 2 mm. The manufacturer of the wax based phase change material produces blocks in a 28 cell and 44 cell configuration, so these were cut down to accommodate a 10S1P pack with minimal additional material. Packs were assembled by first pre-heating the wax based phase change material to $5\text{ }^{\circ}\text{C}$ below the phase change temperature to slightly expand the cell openings. Cells were shrink-wrapped with a layer of clear PVC insulating sleeve and then inserted into the pre-heated wax based phase change material. After the cells had been inserted, the entire pack was wrapped with insulating tape. Photographs of the Pack F assembly are show in Figure 12.

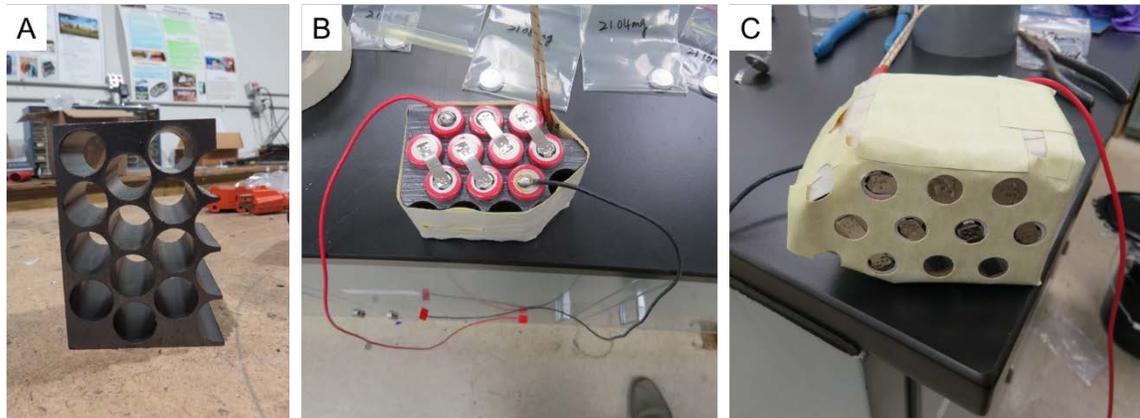


Figure 12. Photograph of Pack F showing starting wax phase change material block (A), pack with 18650 inserted into block (B), and pack covered with insulating tape (C)

2.2.5 Pack G

Pack G utilized a 3D printed spacer ring to separate the 18650 cells by 2 mm (Figure 13). Previous testing conducted by Sandia National Laboratories reported that when a pack containing 2.25 Ah 18650 LIB in a 10S1P configuration with a 2 mm gap between cells, initiation of the center cell into thermal runaway did not lead to a propagating failure (1). However, testing by NASA has reported that air gaps are not sufficient to prevent cell-to-cell propagation, especially when an edge cell with few nearest-neighbors than a center cell is used as the trigger cell (2). In the testing conducted in this report, an edge cell was initiated.

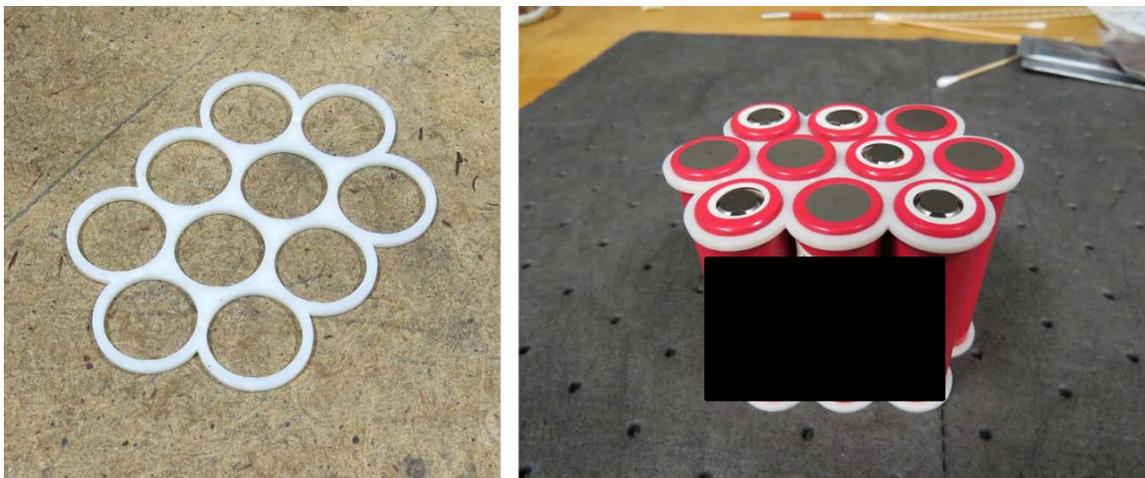


Figure 13. Photograph of Pack G showing 3D printed spacer ring (left) used to create a 2 mm air gap between cells in a pack (right)

2.3 Testing Procedure

A resistance heater cartridge (Watlow Firerod) with a power rating of either 100 W or 150 W was placed on the exterior of a corner cell in the pack (Figure 14). Heater size was selected based on available placement area on the cell can, which for packs A and B was restricted due to the BMS board and casing. Thermocouples were mounted on all accessible cells near the center of the long axis of the cell can for cells on the outside edge of the pack, and on

the negative terminal (vent opening is on the positive terminal) of cells in the center of the pack. For the subsequent data presented in this report, “Cell 1” is referred to as the trigger cell. Cell 2, Cell 4, and Cell 5 were always the nearest neighbor cells to the trigger cell. A depiction of cell labeling used for all 10S1P packs (all packs except Pack B1, B2, and B3) is shown in Figure 14. In some tests, thermocouples were damaged during testing and are not included in the plots for each pack. The trigger cell was heated to failure by supplying power to the heater cartridge using an adjustable AC power supply (Variac). Voltage on the power supply was increased stepwise in increments of 5% of the maximum output voltage every 5 minutes to a cutoff corresponding to ~ 25 W of heater power. In the event that the trigger cell did not activate after 60 minutes at 25 W of heater power, the heater power was increased again in 5% voltage increments every 5 minutes until trigger cell failure. Prior testing of individual cells found that this heating profile is sufficient to initiate thermal runaway, typically prior to reaching 25 W of heater power. Power to the heater cartridge was terminated at the first clear signs of trigger cell failure, namely rapid rise in cell temperature or a cell vent opening with ejected sparks or flames.

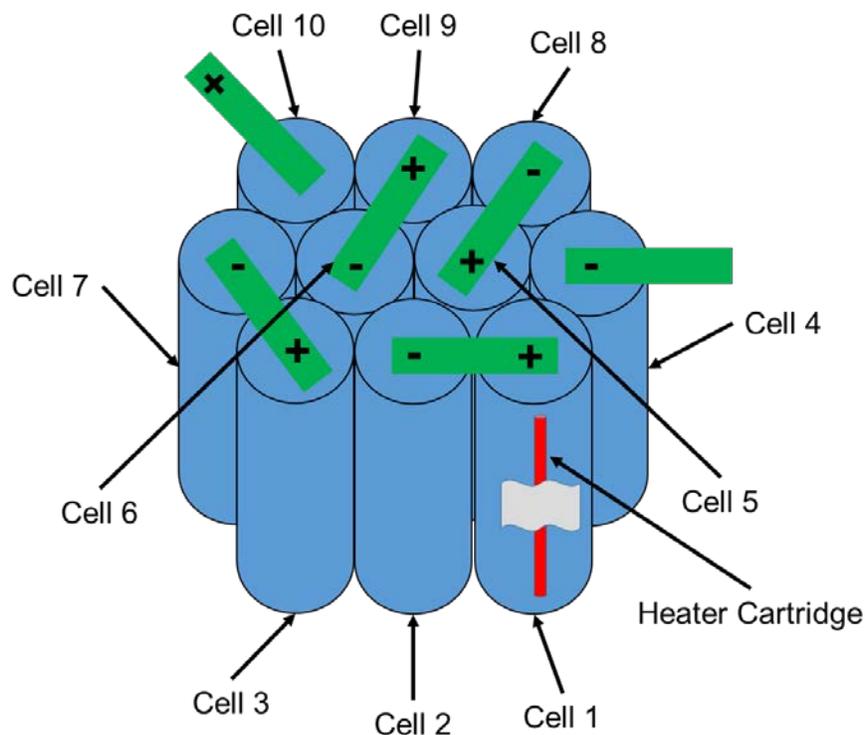


Figure 14. Position of heater cartridge used for thermal abuse of 18650 LIB packs

In addition to thermocouples, the OCV of packs were monitored using voltage sense lines. An additional “render safe” heater plate was included to destroy the battery pack in the event that no propagation or partial propagation occurred after initiating the trigger cell. The render safe heater plate was only used after all cells were observed to cool below 75 °C.

3. Results

Temperature and voltage response of packs subjected to a single-cell thermal abuse are presented in this section. Propagation was deemed to have occurred if any cells beyond the

trigger cell were observed to enter thermal runaway, which was characterized by an energetic vent opening (i.e. sparks or flames observed), or cell temperatures exceeding 200 °C for more than a few seconds. Brief high-temperature excursions could be observed to the initial vent of the trigger cell but did not always indicate thermal runaway of neighboring cells. Audio and video were collected for each test which enabled review of each test to differentiate between single cell failure and multi-cell propagation. A summary of all test results are shown in the Conclusions section, Table 3.

3.1 Pack A

Pack A consisted of commercial hoverboard batteries with a 10S1P configuration. A plastic enclosure was removed prior to testing which could not be resealed. The BMS electronics board and part of the casing which was still attached to the battery pack is visible in the test setup photos (Figure 15). In addition to the thermocouple placements described in section 2.3, a thermocouple was placed on the remaining plastic enclosure, on the BMS electronics board, and on the side of the pack opposite the electronics board in the area of cells #5 and #6 (Figure 14). Cells #8-10 were not accessible due to the remaining piece of plastic enclosure.

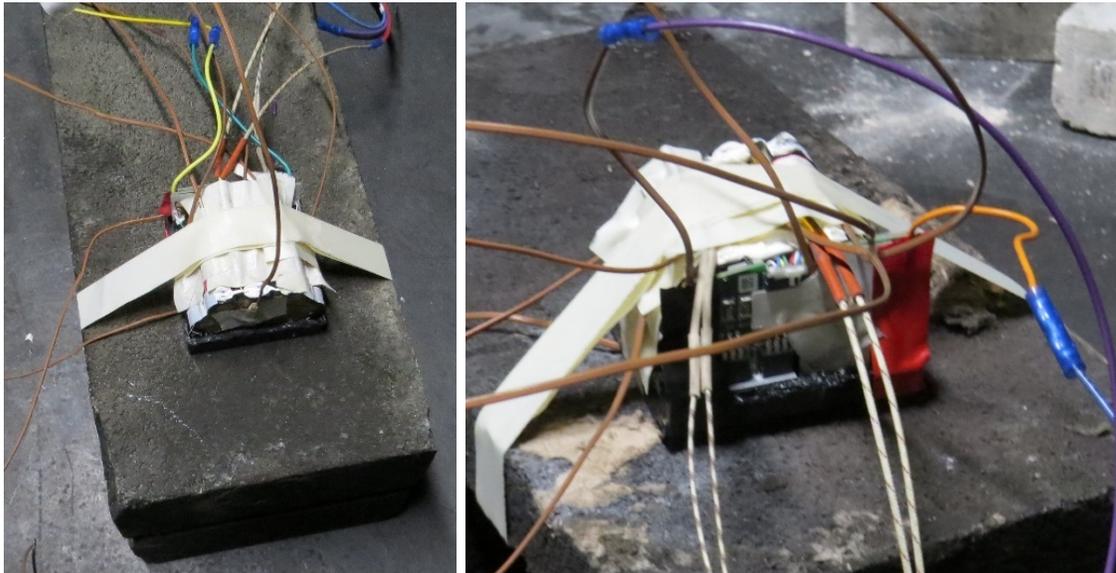


Figure 15. Pack A test setup

The temperature and voltage response of pack A1 are shown in Figure 16. At 17 minutes of heating, a small pop was heard accompanying a partial OCV drop from a starting 40 VDC (100% SOC) to 34 VDC. The temperature of the trigger cell at this moment was 232 °C, while the next highest cell (the nearest neighbor cell #2) was 66.3 °C. The pop and OCV drop are attributed to activation of the current interrupt device (CID) present in these cells, however given the series configuration of these cells a drop to 0 VDC was expected. This may indicate that the CID activation was incomplete, or that the BMS board was capable of bypassing the trigger cell once the CID was activated. A second pop, presumably a vent opening on the trigger cell, was heard at 24 minutes of heating which was accompanied by a brief voltage spike and temperature fluctuation in the thermocouples mounted to the trigger cell as well as the nearest neighbor cell, cell #2. At 30 minutes of heating time and a trigger cell temperature of 385 °C, a rapid

temperature rise in the trigger cell temperature was observed accompanying an energetic vent which was large enough to dislodge the pack from the glass fiber tape restraints. Pack A1 continued to burn with an open flame for approximately 50 seconds without any subsequent vents or explosions, and then self-extinguished. The trigger cell thermocouple reported a maximum temperature of 486 °C, while thermocouples mounted on cells 2, 3, 4, and 7 had maximum temperatures between 100 °C and 400 °C. The maximum pack temperature was recorded from the thermocouple located near cells #5 and #6 (mounted on the electronics board) at 514 °C. However, because all of the thermocouple maximums were observed within a few seconds of the trigger cell event, the recorded thermocouple temperature is most likely from energetic venting, from the trigger cell and not from actual cell temperatures. The BMS board and case mounted thermocouples did not exceed 41 °C at any point during testing.

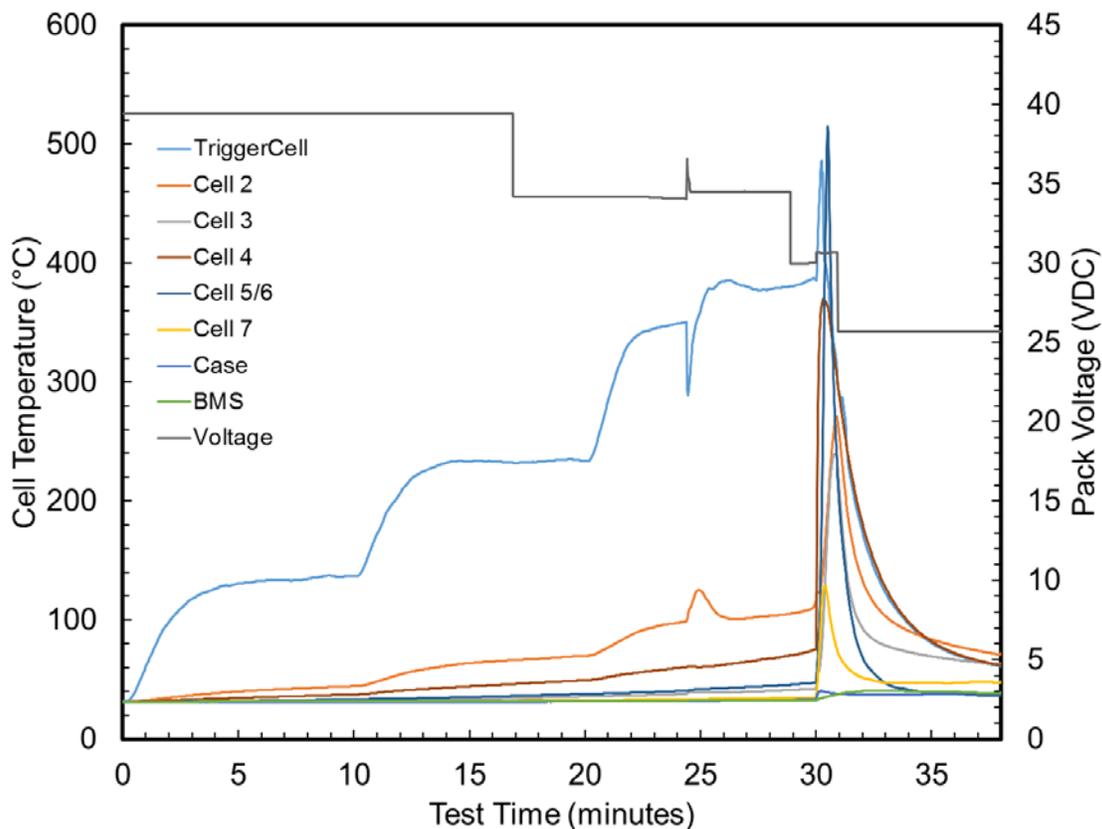


Figure 16. Temperature and voltage plot for Pack A1

Video screenshots from Pack A1 are shown in Figure 17, which are taken immediately before (A), during (B), and after (C) the trigger cell activation. Several live cells were present in the pack after the trigger cell underwent thermal runaway, and the pack OCV remained at 25 VDC after flames subsided.

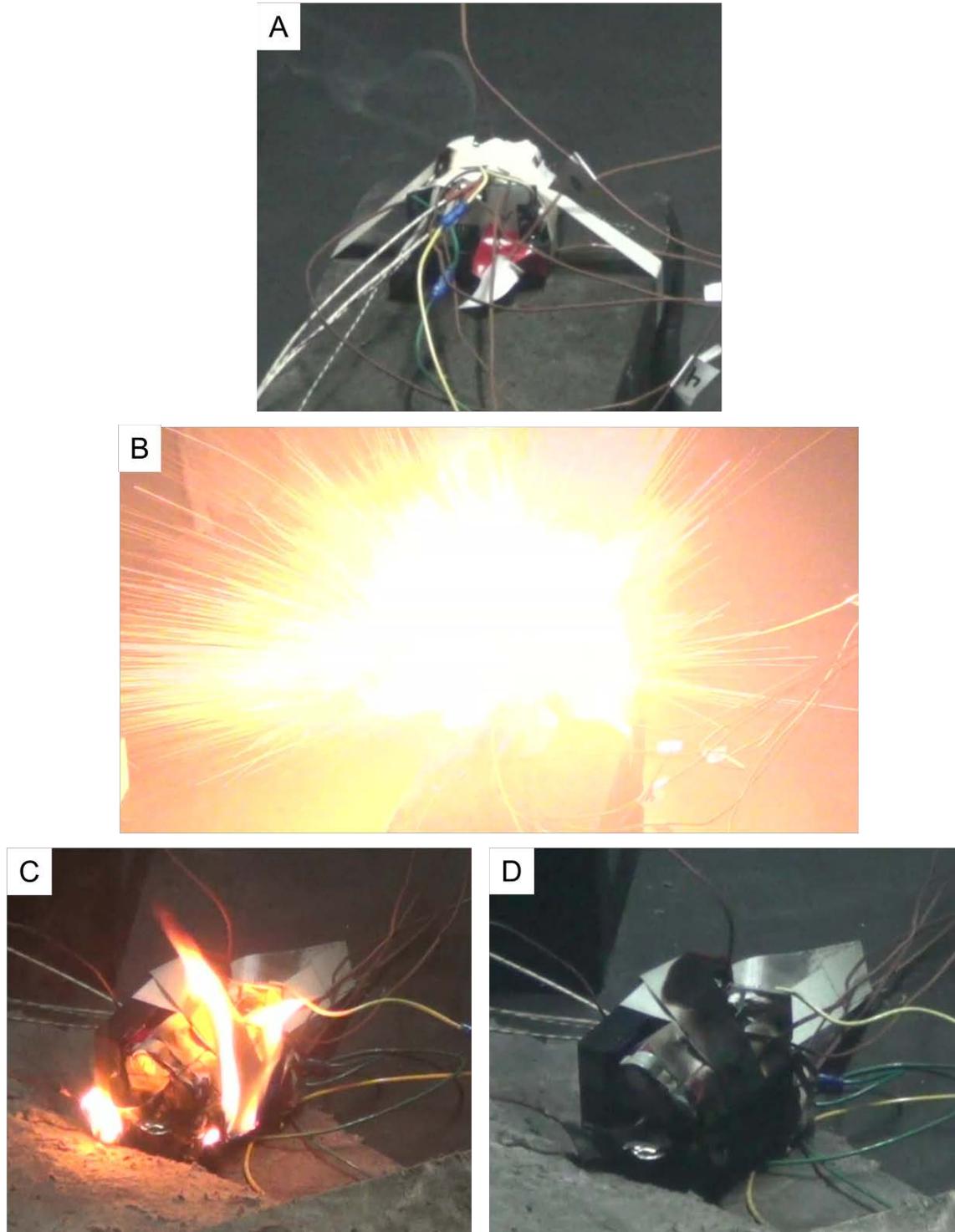


Figure 17. Video screenshots from Pack A1 showing immediately prior to trigger cell failure (A), energetic failure of trigger cell (B), flaming battery pack dislodged from restraints (C), and remaining battery pack after flames self-extinguished (D)

Test results from Pack A2 showed a similar response to Pack A1, namely after the trigger cell was activated the pack was dislodged from the test fixture restraints and no further

propagation was observed. At 26 minutes heating time, a pop and OCV drop was observed with a corresponding trigger cell temperature of 160 °C and a maximum nearest neighbor temperature of 66 °C (cell #2). At 29 minutes heating time, a vent was observed from the trigger cell with a corresponding temperature of 162 °C. Thermal runaway was observed as an explosion of the trigger cell which launched cell components away from the pack. Trigger cell temperature at the moment of the explosion was 266 °C. Following the trigger cell activation, glowing cell components launched in the opposite direction of the pack are observed, and the majority of the pack burns for approximately 50 seconds before self-extinguishing. Temperature and voltage for Pack A2 are shown in Figure 18. The maximum pack temperature for Pack A2 was observed at the trigger cell with a value of 471 °C. Cells 2 and 4 were the only other thermocouple which reported a maximum temperature above 150 °C with maximum values of 220 °C and 421 °C, respectively. As with Pack A1, all of the maximum temperatures were coincident with the trigger cell activation, indicating that cell-to-cell propagation likely did not occur.

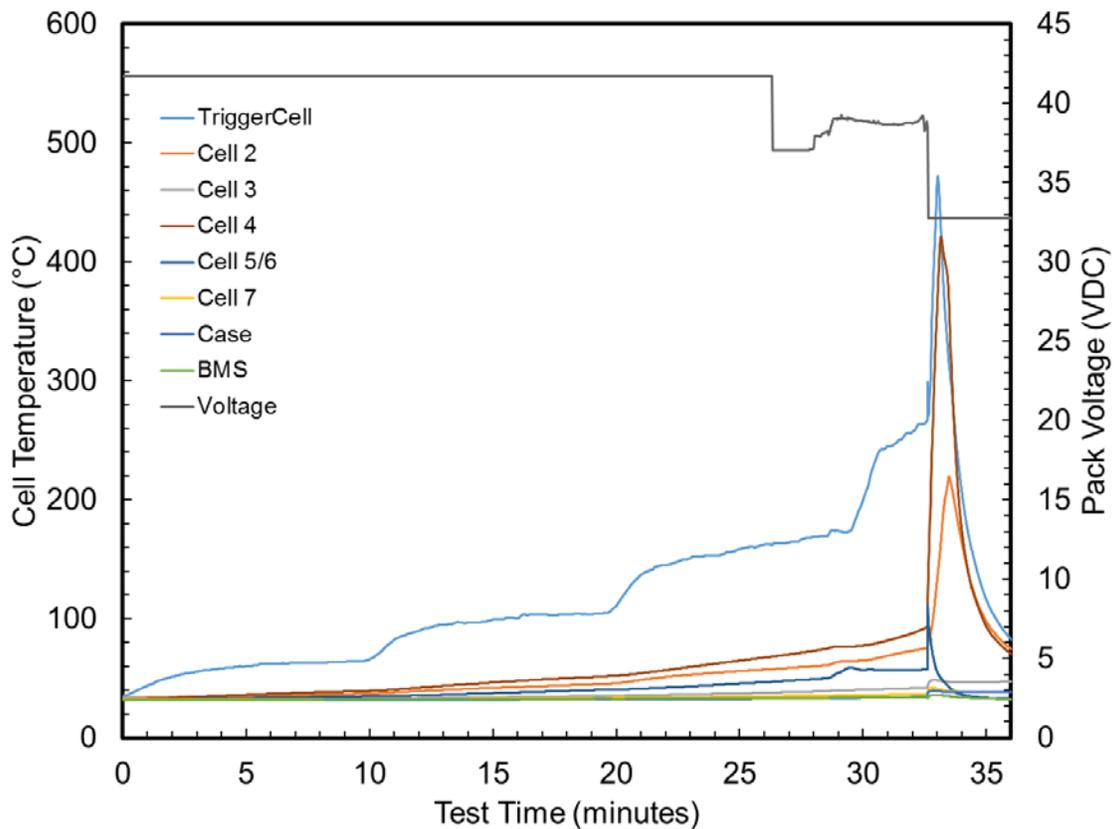


Figure 18. Temperature and voltage plot for Pack A2

Video screenshots from test A2 are shown in Figure 19. As with Pack A1, the trigger cell failure dislodged the battery pack which was left burning for approximately 50 seconds, after which the flames self-extinguished with no additional cell failures. In Figure 19 B, glowing contents ejected from the trigger cell are visible in the top part of the photograph.

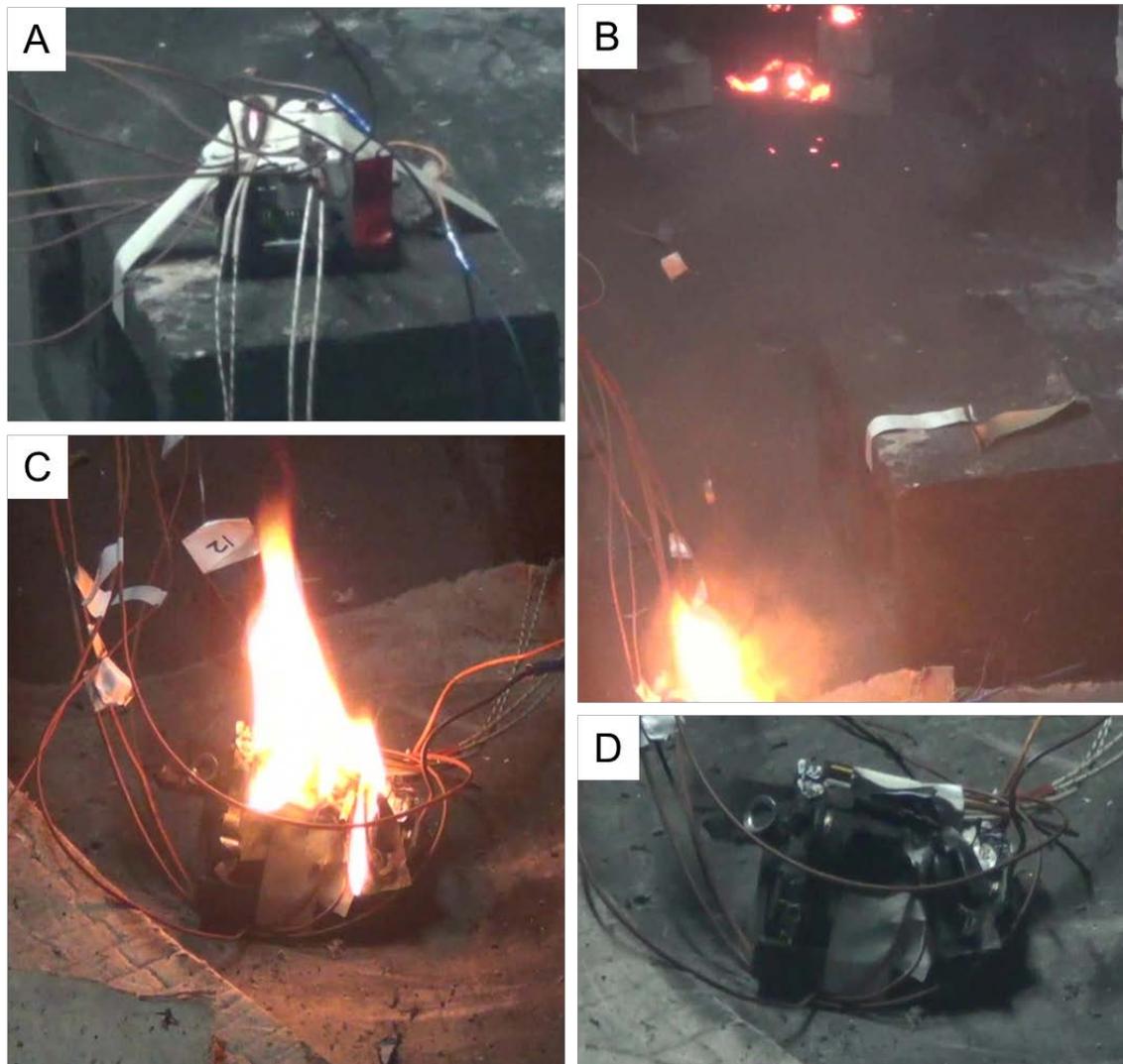


Figure 19. Video screenshots from Pack A2 showing immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in ejected cell contents (B), flaming battery pack (C), and remaining battery pack after flames self-extinguished

3.2 Pack B

Cells for Pack B were removed from their aluminum casing and instrumented with thermocouples and a heater cartridge. Small holes were drilled to accommodate wiring leaving the aluminum enclosure and were then epoxied over to prevent introducing new gas outlets into the case. Even when sealed shut with screws around the perimeter of the lid, the aluminum case was not air tight. The test setup for Pack B with the aluminum enclosure (Pack B1 and B2) and without the aluminum enclosure (B3) is shown in Figure 20.

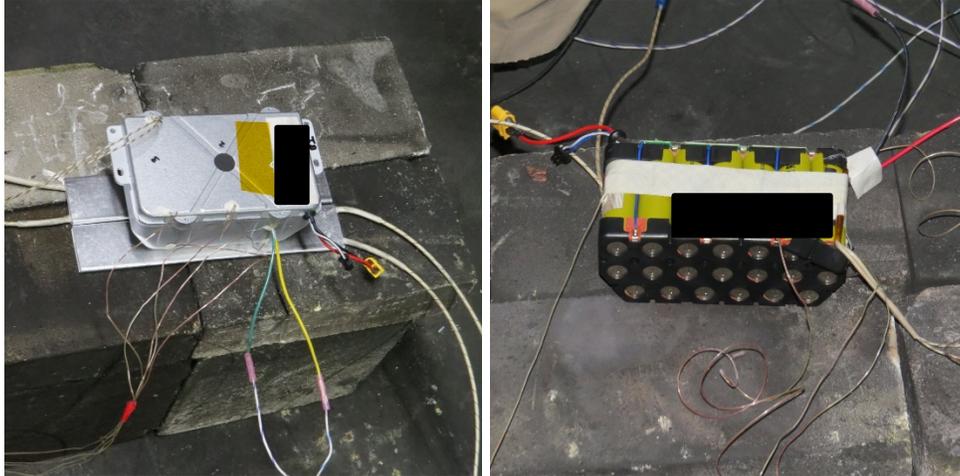


Figure 20. Pack B test setup with aluminum enclosure (left, B1 and B2) and without aluminum enclosure (right, B3)

Temperature and voltage plots for Pack B1 are shown in Figure 21. No response from the pack was observed until 57 minutes of heating at which point an OCV drop, from 41.8 VDC to 37.6 VDC was accompanied by an audible vent pop with sparks ejected from the open rim of the aluminum case, indicating failure of the trigger cell. Trigger cell temperature at this moment was 265 °C, with a temperature of 64 °C recorded at the nearest neighbor. The maximum temperature of the trigger cell was recorded at 764 °C which also caused local maximum temperatures for all other thermocouples in the pack, which was followed by a period of cooling for 3 minutes. While the pack cooled smoke was emitted from the pack lasting for 5 minutes and eventually a cascade of events was observed with open flames and energetic vents for 3 minutes. Over 20 audible vent pops or energetic vents were observed during this time period. Maximum thermocouple temperatures exceeding 1000 °C for a few seconds on cells 2, 3, and 4, while pack temperatures remained above 400 °C for 5 minutes following the onset of propagating thermal runaway.

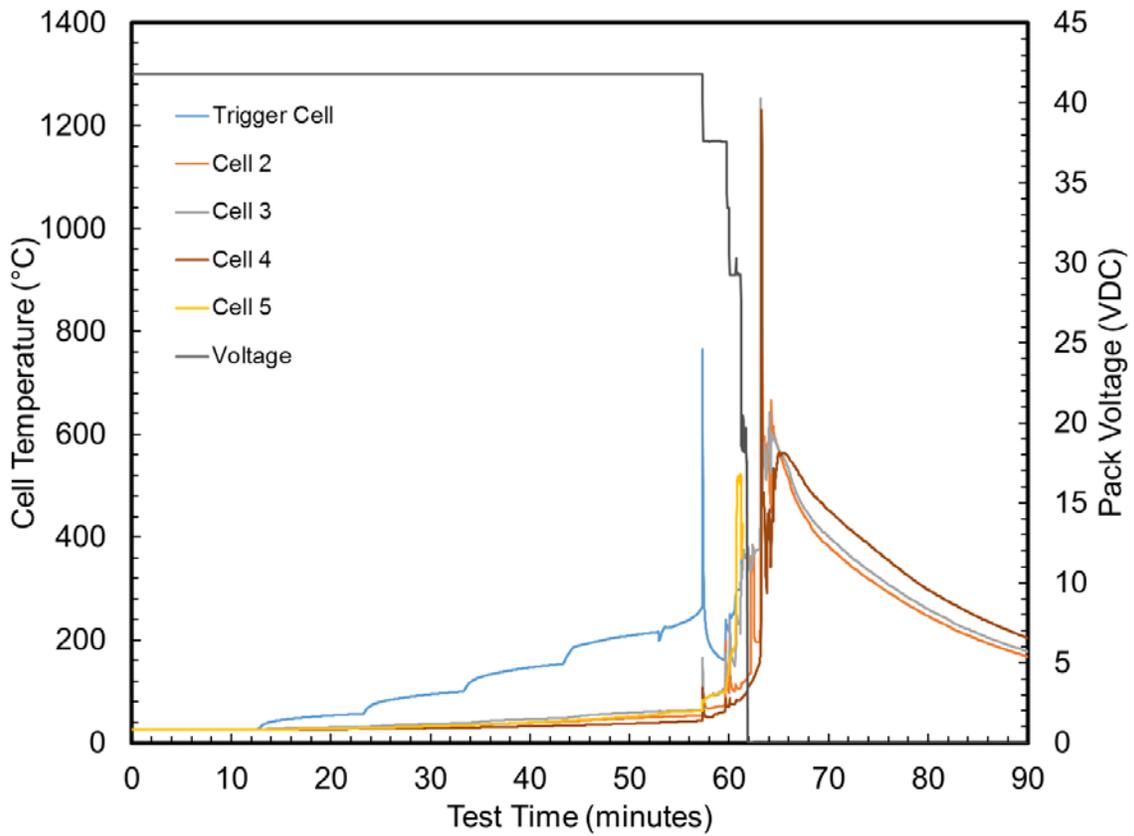


Figure 21. Temperature and voltage plot for Pack B1

Screenshots from Pack B1 showing the initial event, period of smoking while the pack cooled, and propagating thermal runaway are shown in Figure 22.

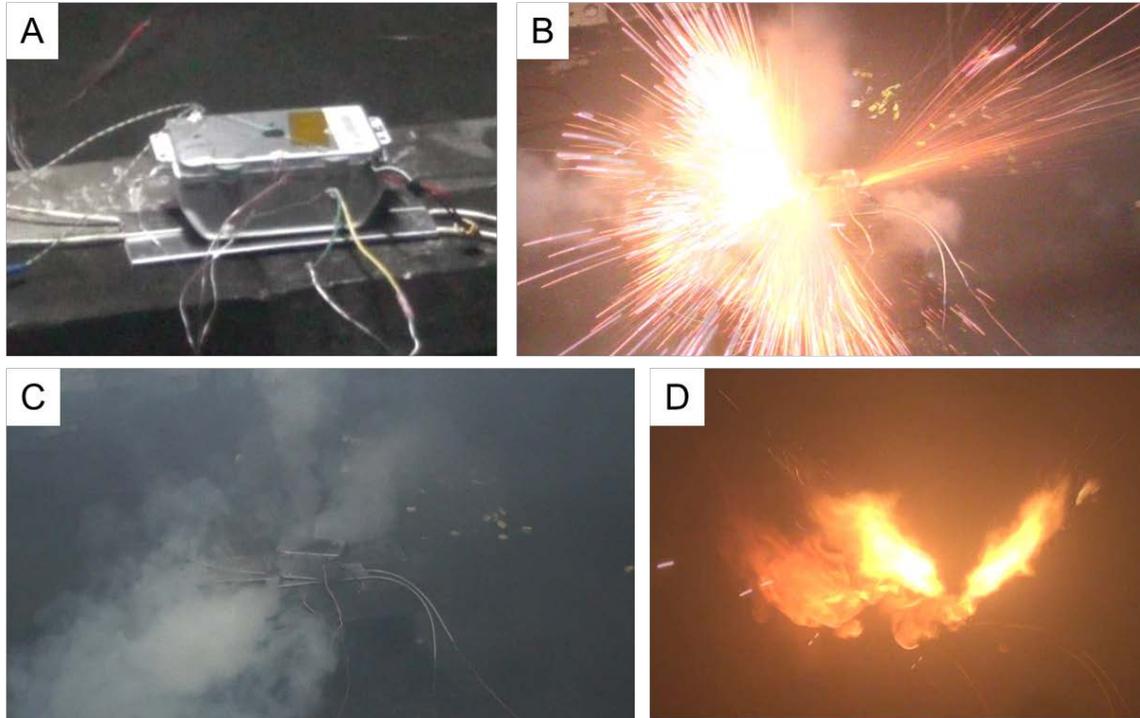


Figure 22. Video screenshots from Pack B1 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame escaping the aluminum enclosure (B), several minutes of smoke emitted from the battery pack (C), and cascading failure of cells with continuous flames ejected from battery pack

Photographs of Pack B1 taken after testing (Figure 23) show that the aluminum case had been melted in several regions, including the location immediately above the vent for the trigger cell. This indicates that even a single cell failure is sufficient to bypass the aluminum enclosure and eject smoke, sparks, or flames.

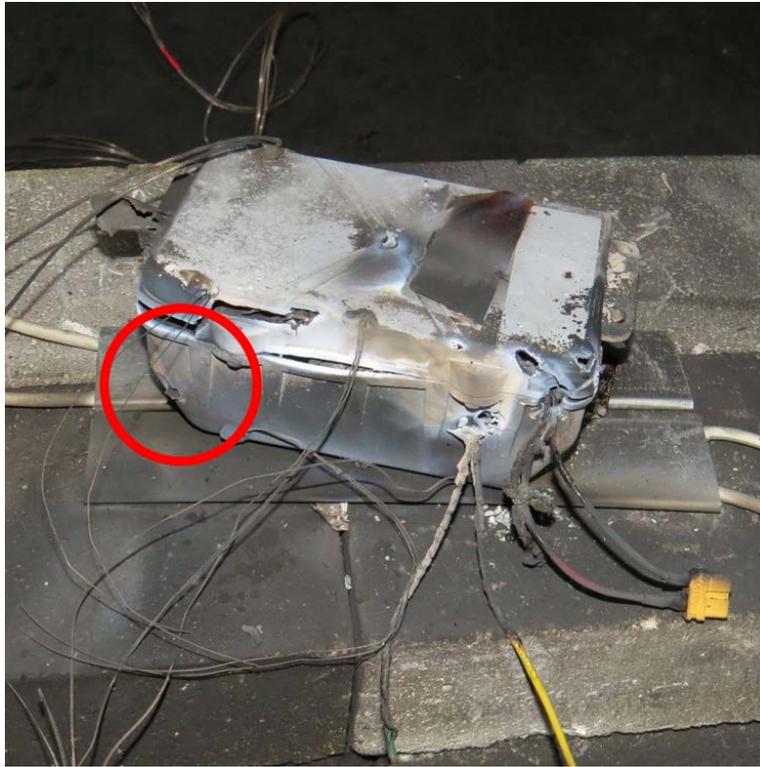


Figure 23. Digital photograph of Pack B1 after testing showing melted regions of aluminum case, position of trigger cell vent is indicated with a red circle

While instrumented and tested in an identical manner to Pack B1, Pack B2 did not undergo propagating thermal runaway. Temperature and voltage plots for Pack B2 are shown in Figure 24. The consistently low temperature of the trigger cell indicates that while the thermocouple was operating properly, it had very likely become physically disconnected from the trigger cell casing, therefore a reliable indicator of the trigger cell temperature at failure is not available. After 44 minutes of heating a sharp increase in temperature is observed for all other thermocouples which corresponded to an OCV drop from 41.7 VDC to 37.5 VDC. Like with Pack B1, sparks were ejected from the aluminum case at the moment of trigger cell activation, however smoke was observed from the pack for less than one minute and no propagation was observed. Maximum thermocouple temperatures did not exceed 200 °C for any cell (pack maximum was 165 °C). After 40 minutes, no thermocouple read above 100 °C and ventilation fans were turned on to clear smoke from the test enclosure, leading to a temperature decrease at approximately 85 minutes of test time.

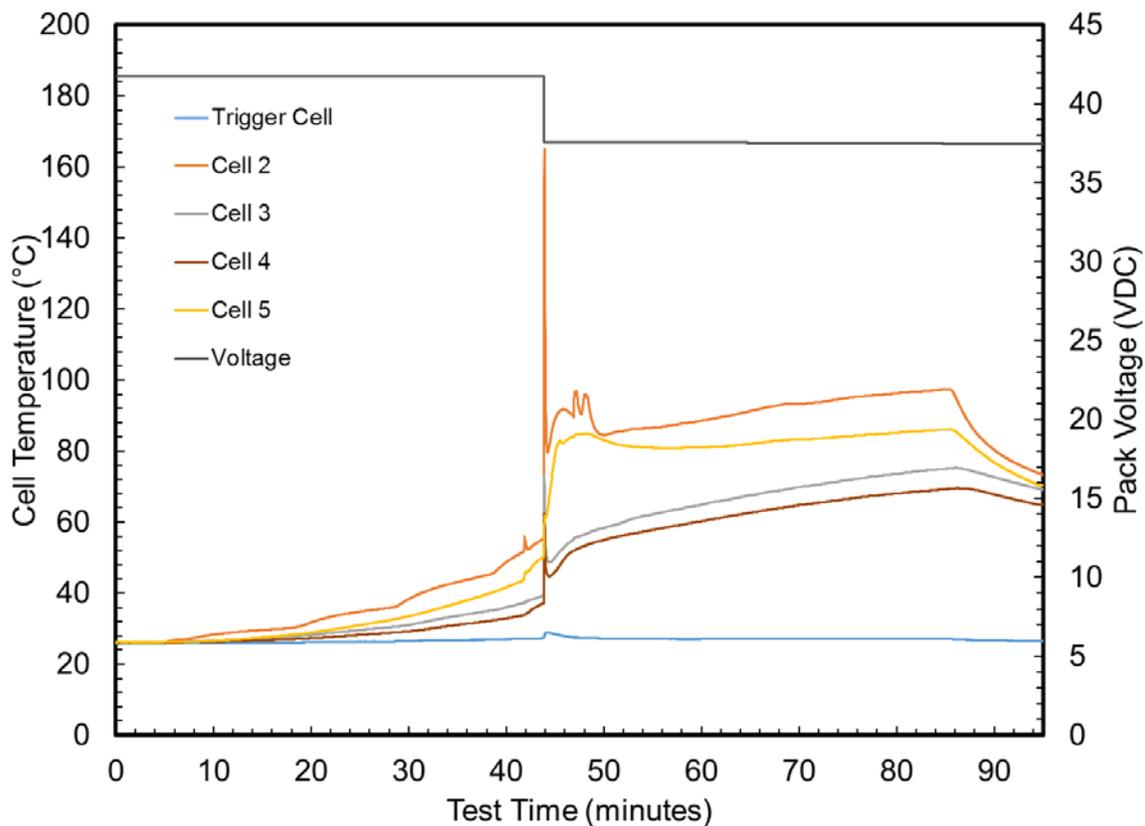


Figure 24. Temperature and voltage plot for Pack B2

Video screenshots from Pack B2 are shown in Figure 25. As with B1, trigger cell activation in Pack B2 ejected sparks from the aluminum case and led to a period of smoking afterward, however the remaining cells did not undergo propagating thermal runaway.

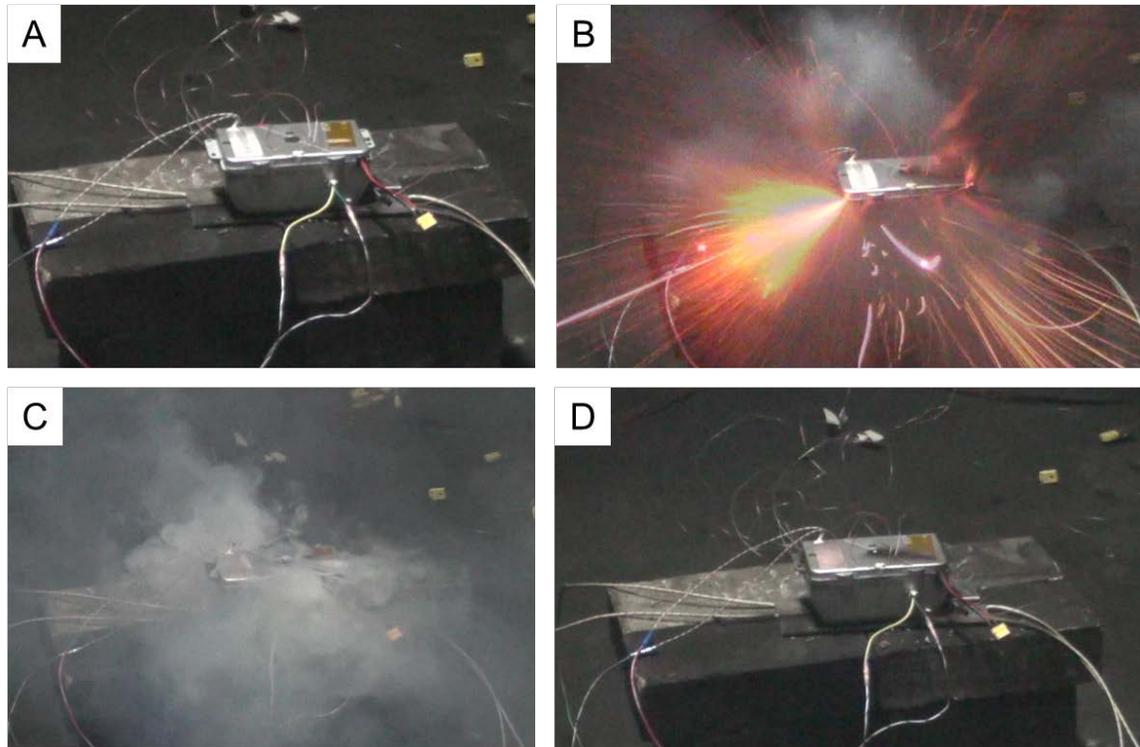


Figure 25. Video screenshots from Pack B2 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame escaping the aluminum enclosure (B), smoke emitted from the battery pack after trigger cell activation lasting less than one minute (C), and remaining pack after trigger cell failure (D)

A final test of the 10S2P hoverboard packs was conducted with the aluminum enclosure removed. As with Packs B1 and B2, a single edge cell was heated to failure within a comparable time period (49 minutes of heating) and trigger cell temperature of 211 °C. Temperature and voltage plots for Pack B3 are shown in Figure 26. Unlike Packs B1 and B2, no OCV drop was observed for the trigger cell activation in Pack B3 despite an apparently comparable response (sparks and flames). The lack of an OCV drop can be explained by the fact that the trigger cell is in parallel with another cell in this 10S2P configuration, which sustains the OCV. Furthermore, neighboring cell temperatures did not exceed 55 °C despite a maximum trigger cell temperature of 626 °C. No propagation to adjacent cells was observed for Pack B3, and the increased temperatures of adjacent cells and OCV drop observed for Packs B1 and B2 suggest that the aluminum enclosure may have in fact retained a significant portion of the heat from the trigger cell, biasing the cells towards failure.

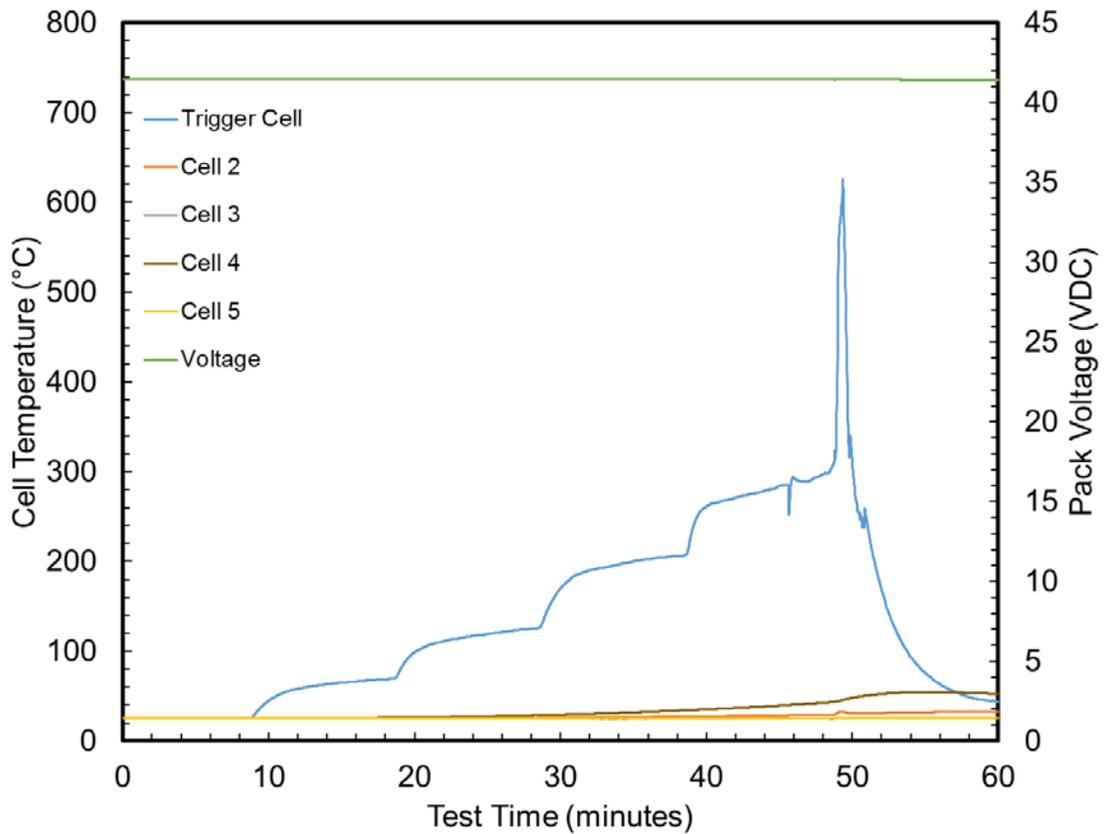


Figure 26. Temperature and voltage plot for Pack B3

Video screenshots from Pack B3 are shown in Figure 27. As was observed for Pack B2, activation of the trigger cell did not lead to a propagating thermal runaway in adjacent cells.

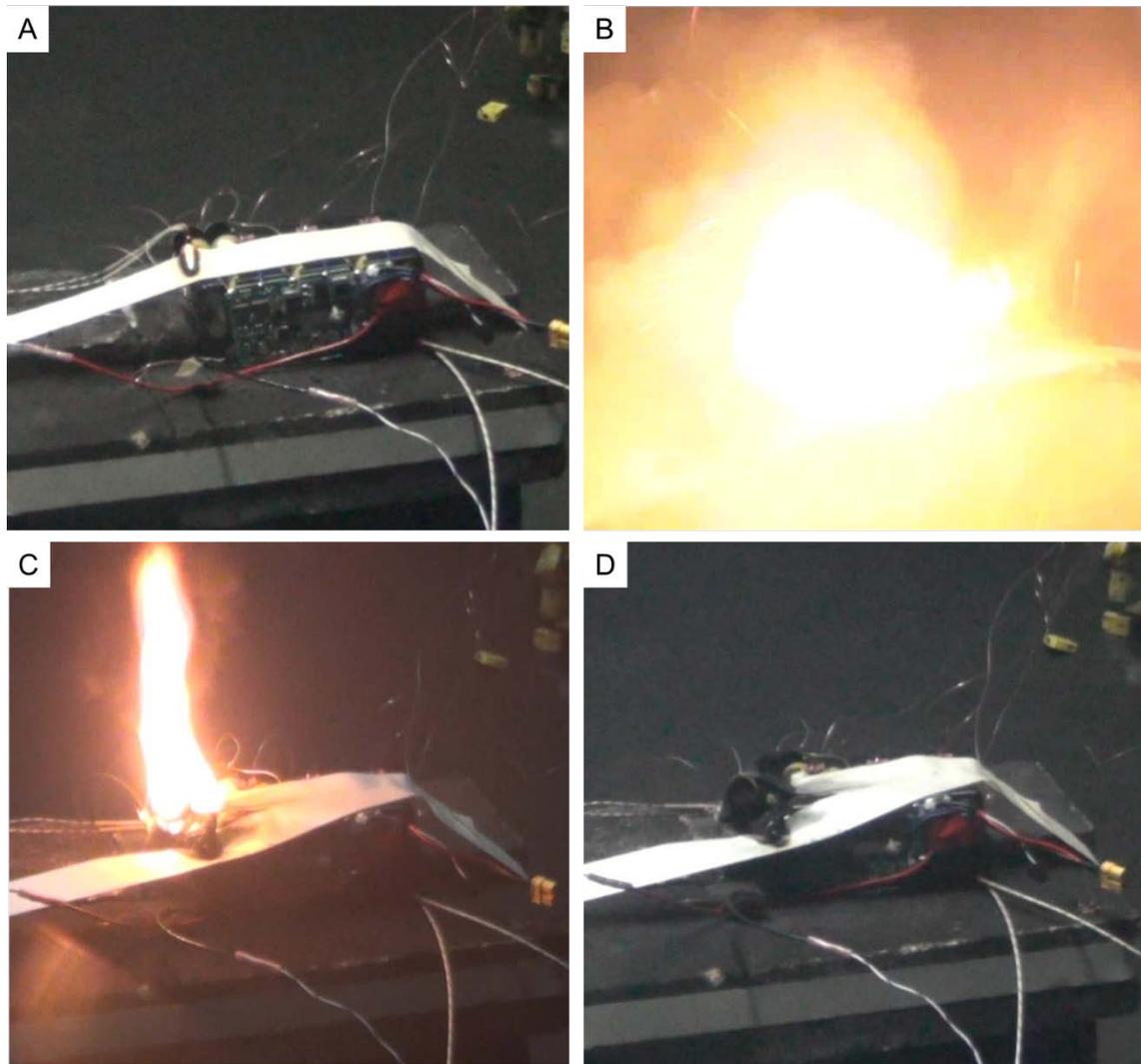


Figure 27. Video screenshots from Pack B3 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), continued burning of trigger cell (C), and remaining pack with no propagating observed (D)

3.3 Pack C

Custom made battery packs, in a “close packed” arrangement, were evaluated by heating an edge cell. The “Pack C” packs were similar to Pack A (10S1P) but lacked the BMS electronics board and part of the plastic enclosure. Pack C cells were physically touching neighboring cells whereas Pack A had a physical airgap using an endcap spacer on each end of the pack. Pack C1 experienced an OCV drop from 41.7 VDC to ~ 1 VDC at 27 minutes of heating and a trigger cell temperature of 119 °C. Voltage and temperature plots for Pack C1 (Figure 28) reveal after a few minutes of additional heating the pack OCV recovered to ~ 38 VDC until thermal runaway of the trigger cell occurred. One possible explanation of this behavior is an expansion of the jellyroll which reconnected the open CID in the can header. At 35 minutes of heating time, a trigger cell temperature of 165 °C, and nearest neighbor maximum temperature of 102 °C, a propagating thermal runaway was observed lasting approximately 3

minutes. Maximum cell temperatures for several cells exceeded 600 °C with an overall pack maximum observed at 828 °C.

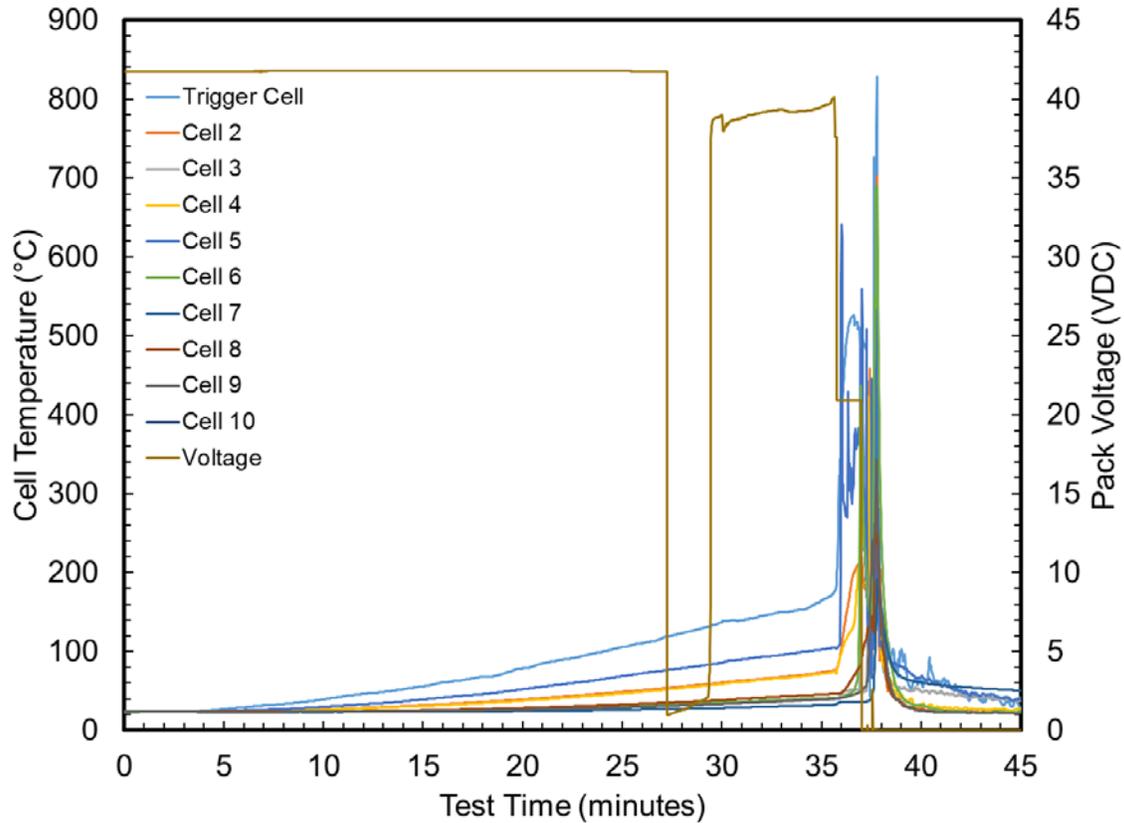


Figure 28. Temperature and voltage plot for Pack C1

Despite the energetic failure of Pack C1, several cells were still intact after being displaced from the test fixture due to an exploding cell. Video screenshots from Pack C1 are shown in Figure 29.

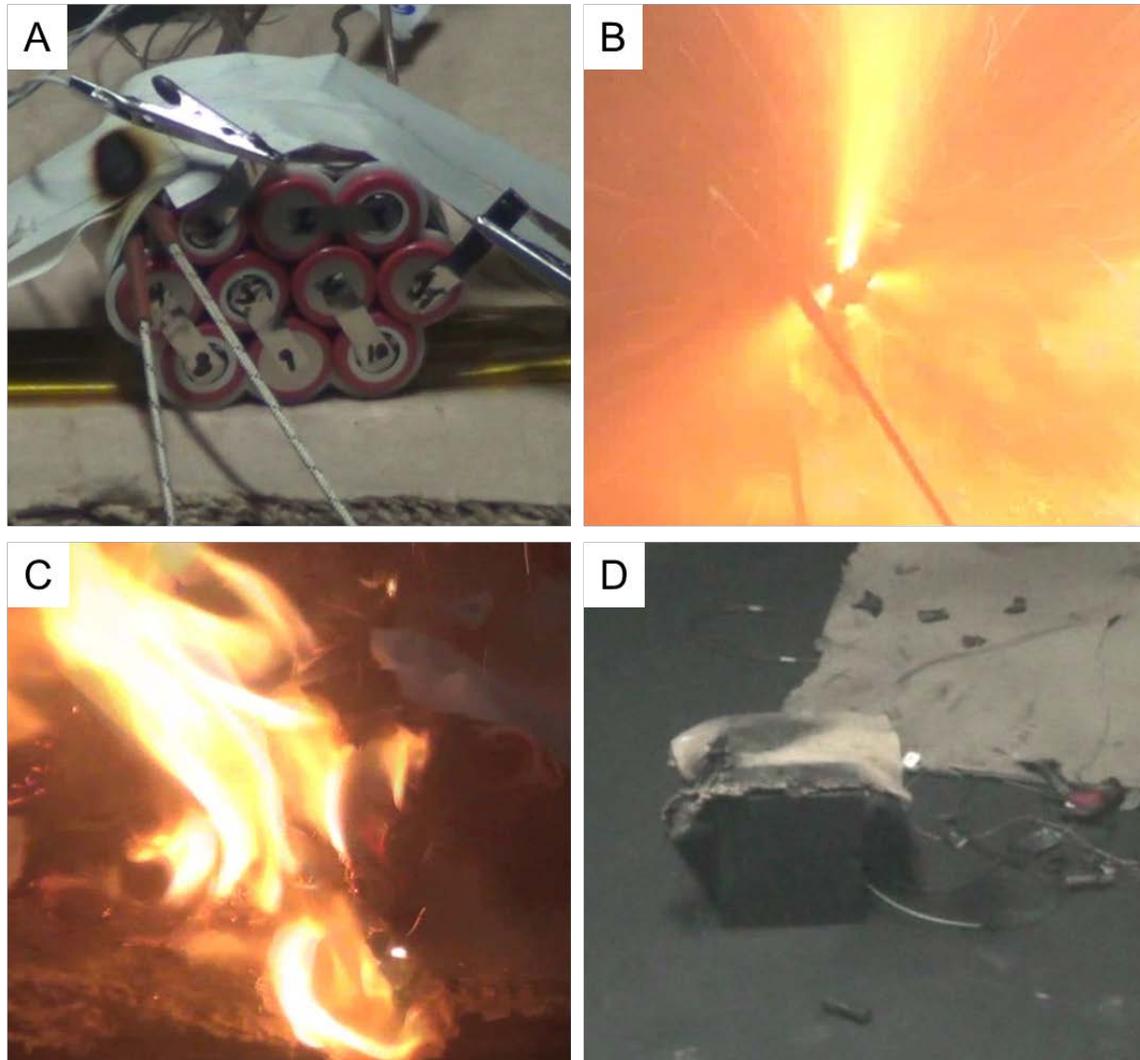


Figure 29. Video screenshots from Pack C1 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), flames and pack disassembly associated with propagating thermal runaway (C), and remaining cells scattered from test fixture (D)

Pack C2 showed comparable results to Pack C1. An initial OCV drop was observed after 26 minutes of heating corresponding to a trigger cell temperature of 142 °C and was followed a few minutes later by a recovery of pack OCV until thermal runaway occurred. After 35 minutes of heating the trigger cell entered thermal runaway at a temperature of 201 °C with a nearest neighbor temperature of 76 °C. All cells in Pack C2 underwent thermal runaway within a few minutes of the trigger cell, with maximum cell temperature for every cell exceeding 500 °C and a pack maximum temperature of over 1000 °C.

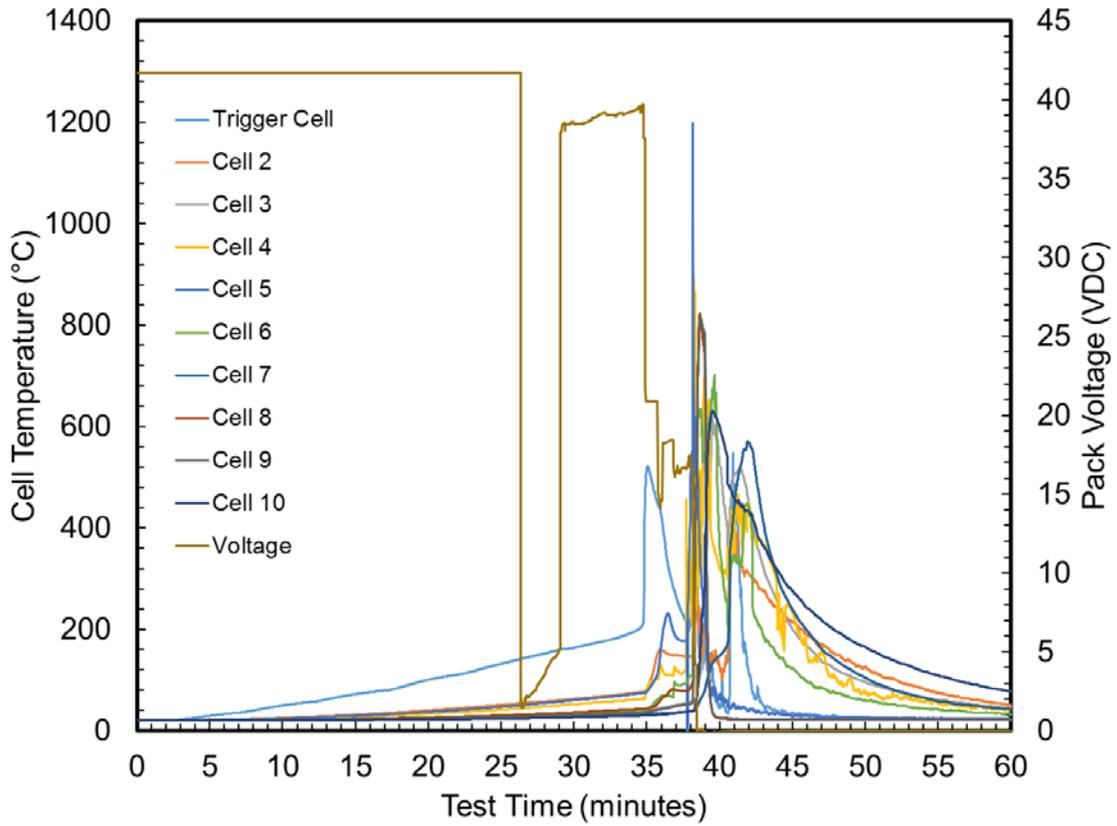


Figure 30. Temperature and voltage plot for Pack C2

Video screenshots from Pack C2 are shown in Figure 31.

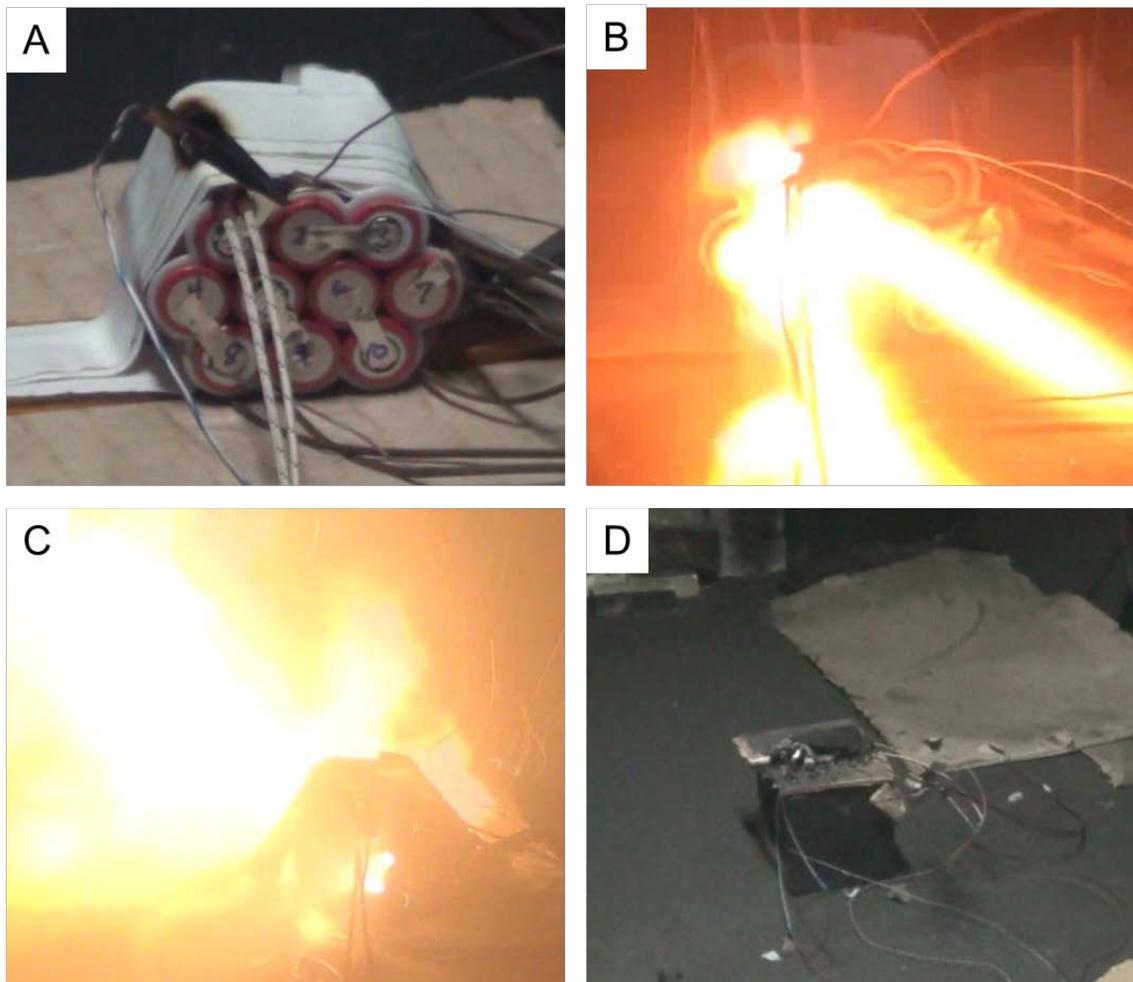


Figure 31. Video screenshots from Pack C2 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), flames and pack disassembly associated with propagating thermal runaway (C), pack remnants following thermal runaway (D)

3.4 Pack D

Cells in Pack D1 and D2 were individually wrapped with a 1 mm thick layer of refractory cloth insulation. The heater cartridge was located directly on the trigger cell (i.e. inside the insulation) and therefore the activation of the trigger cell was not expected to be delayed. Plausibly, the insulation could have contributed to an increased heat retention of the trigger cell and less temperature biasing of the adjacent cells. For Pack D1, an OCV drop to 0 VDC was observed after 38 minutes of heating with a trigger cell temperature of 92.5 °C and a nearest neighbor temperature (cell #4) of 82 °C. Six minutes after the OCV drop the trigger cell underwent thermal runaway at a temperature of 141 °C with a vent opening ejecting sparks and flames. Between the initial OCV drop and the failure of the trigger cell, the pack OCV was observed to fluctuate to a great degree and recovered to 37.5 VDC for two minutes. All cells in the pack entered thermal runaway and achieved maximum temperatures ranging from 425 °C to 560 °C within twenty minutes of the trigger cell activation. Temperature and voltage plots for Pack D1 are shown in Figure 32. Note that the thermocouple response for Cell 9 never rose

significantly above the ambient temperature and may have been dislodged (i.e. removed from physical contact of the cell) during one of the prior cell activations.

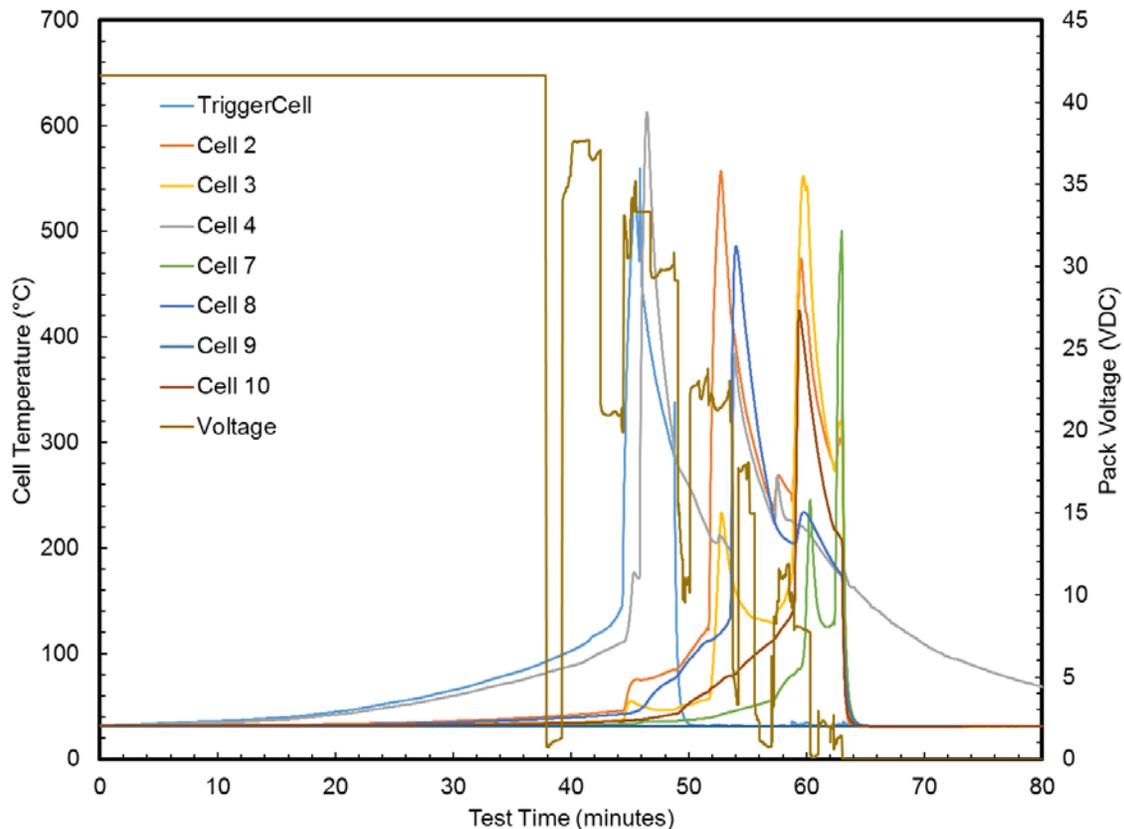


Figure 32. Temperature and voltage plot for Pack D1

Video screenshots of Pack D1 are shown in Figure 33.

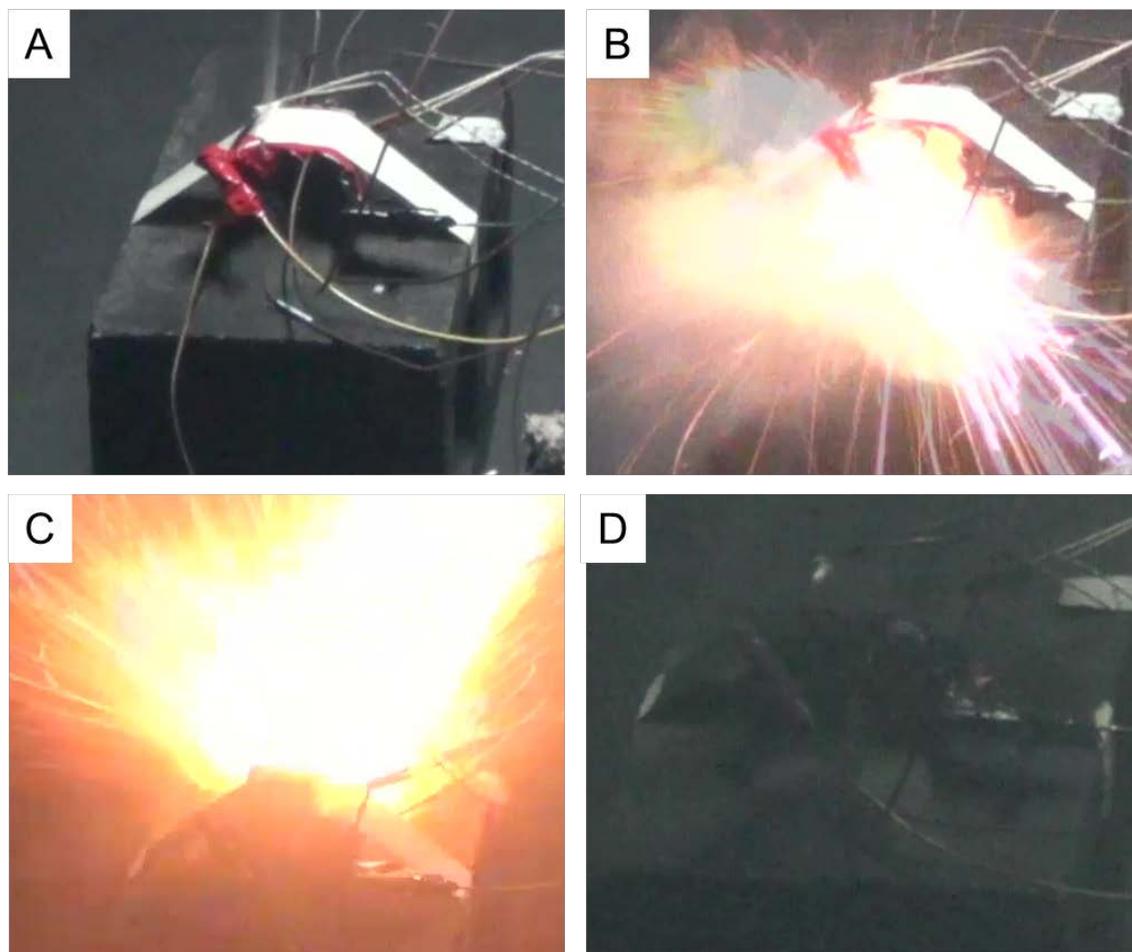


Figure 33. Video screenshots from Pack D1 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), additional flaming vents with propagating thermal runaway (C), pack remnants following thermal runaway (D)

Pack D2 initially showed similar behavior to Pack D1. An OCV drop was observed after 32 minutes of heating with a trigger cell temperature of 100 °C and a nearest neighbor (cell #4) temperature of 66 °C. After an additional 4 minutes of heating and a trigger cell temperature of 152 °C and cell 4 temperature of 86 °C, the trigger cell underwent an energetic vent opening that launched the cell away from the pack, tearing the Ni tabs and heater cartridge away in the process. The temperature of the remaining cells in the pack dropped rapidly and no subsequent thermal runaway occurred. Maximum temperatures for the remaining cells did not exceed 47 °C. Temperature and voltage plots for Pack D2 are shown in Figure 34.

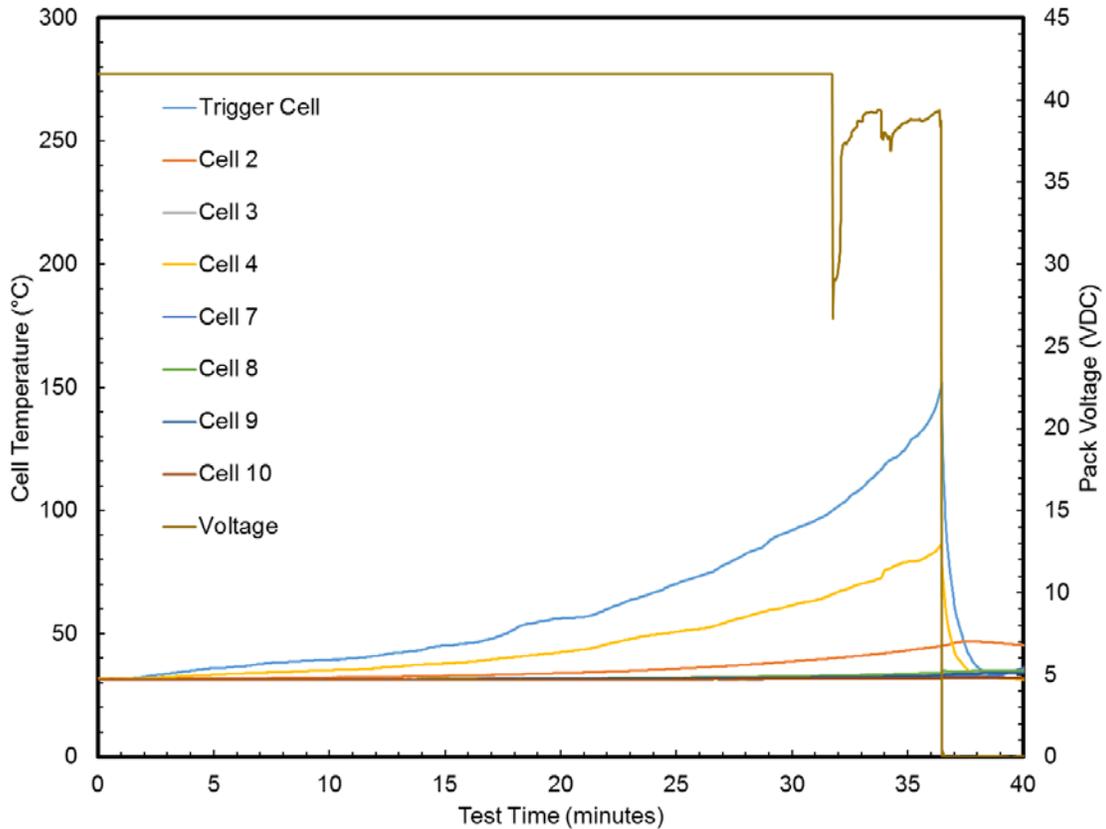


Figure 34. Temperature and voltage plot for Pack D2

Video screenshots of Pack D2 are shown in Figure 35. As can be seen in Figure 35C, activation of the trigger cell led to the trigger cell contents being ejected from cell can. The remaining can was hot enough to be seen glowing after the trigger cell contents were ejected, however the remaining heat in the trigger cell was not sufficient to cause a propagating thermal runaway in adjacent cells.



Figure 35. Video screenshots from Pack D2 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), ejection of cell contents from trigger cell (C), remaining cells intact after trigger cell ejection (D)

3.5 Pack E

Pack E featured the most thermal protection of any of the packs evaluated for this report in terms of added mass. Cells were separated by 1.5 mm using an “end capture plate”, interwoven with the flexible phase change material and phenolic spacers, featured a “flame arrester” (additional sheet of flexible phase change material), and were enclosed in a non-flammable container. To evaluate the contribution of the flexible phase change material alone vs

the cell separation and enclosure, a third test was conducted with only the end capture plate and non-flammable container. For Pack E1, an OCV drop was observed after 33 minutes of heating, corresponding to a trigger cell temperature 114 °C and a nearest neighbor temperature of 90 °C (cell 4). Heater power was held constant at 25 W for 60 minutes after the OCV drop with no apparent thermal runaway behavior observed, however a vent pop was audible at a trigger cell temperature of 120 °C. Prior to the vent pop, OCV was observed to slowly rise up from 0 VDC to ~34 VDC and then changed rapidly after the vent pop. After 90 minutes of heating the trigger cell remained at 120 °C while all other cells in the pack were between 92 °C and 102 °C. Temperatures measured on the flame arrestor on the opposite side of the cells and the outside of the pack enclosure were at 68 °C and 92 °C, respectively, at the same moment. In order to activate the trigger cell, power supplied to the heater cartridge was increased from 25 W to 40 W over the course of 10 minutes. Trigger cell temperatures rose in response to the increased heater cartridge power and smoke was observed to escape the pack enclosure at a trigger cell temperature of 149 °C. Shortly after smoke was observed, a single eruption of flames from the lid of the pack enclosure caused cells near the trigger cell to show maximum temperatures in excess of 500 °C lasting less than one minute (trigger cell Tmax=506 °C, pack Tmax=527 °C for cell 8). While cell 8 is not a “nearest neighbor” cell as shown in Figure 14, the maximum temperature observed in this test is expected to be from the vent opening within the G10 enclosure rather than thermal runaway of cells beyond the trigger cell. Thermocouples mounted to other cells in the pack showed minimal temperature rise, while the flame arrestor and case exterior had maximum temperature of 422 °C and 161 °C, respectively. Temperature and voltage plots for Pack E1 are shown in Figure 36, and a close up of the trigger cell activation is shown in Figure 37.

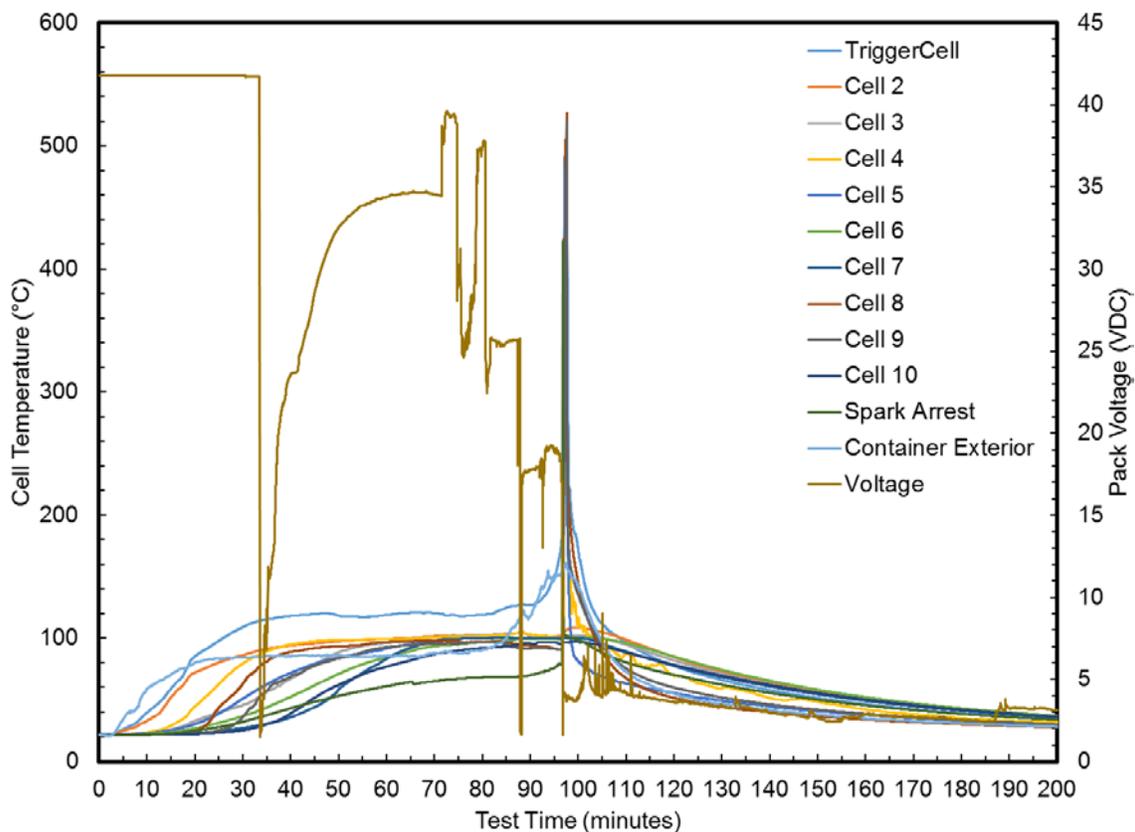


Figure 36. Temperature and voltage plot for Pack E1

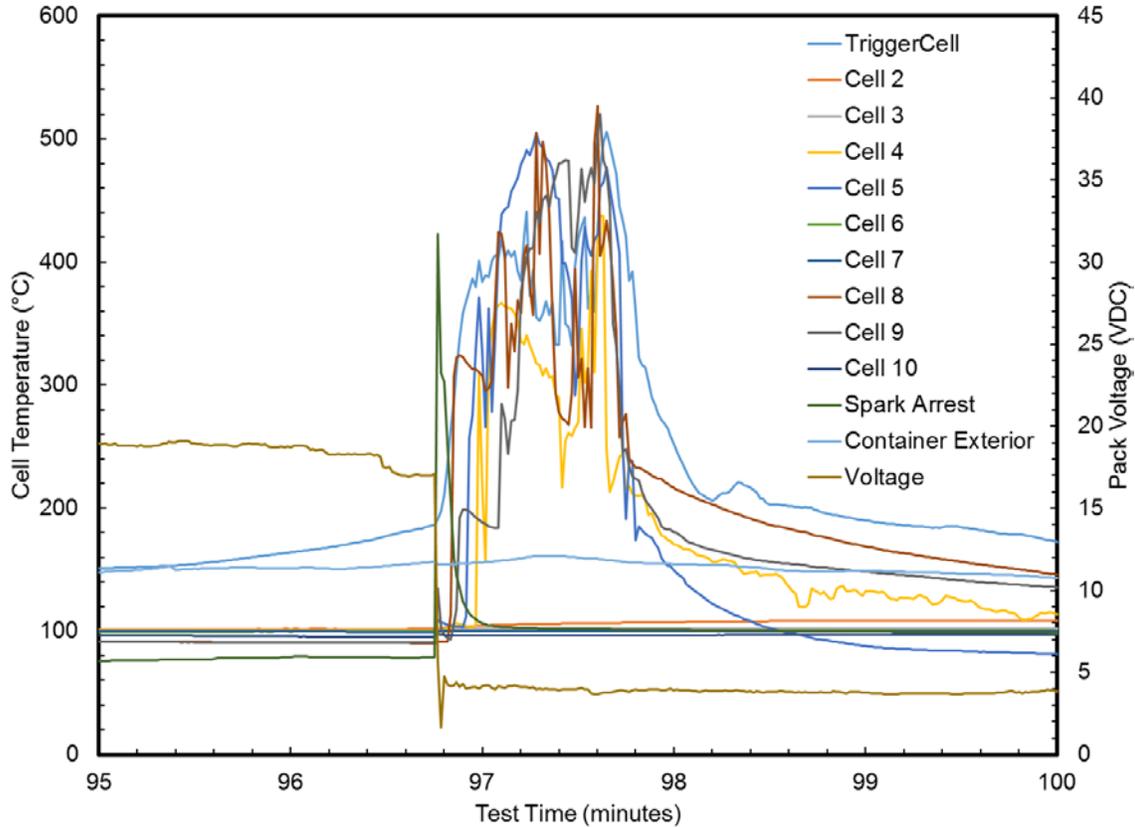


Figure 37. Selected region of temperature and voltage plot for Pack E1 highlighting trigger cell activation

Video screenshots from Pack E1 are shown in Figure 38. While an initial energetic vent resulted in sparks and flames escaping the cell enclosure, open flames were observed for approximately one minute and no propagation to neighboring cells occurred. Shortly after the trigger cell activation some of the flames observed appear to be burning electrolyte vapor escaping the enclosure, however the majority of the open flames shown in Figure 38 are attributed to the adhesive in the glass fiber tape.

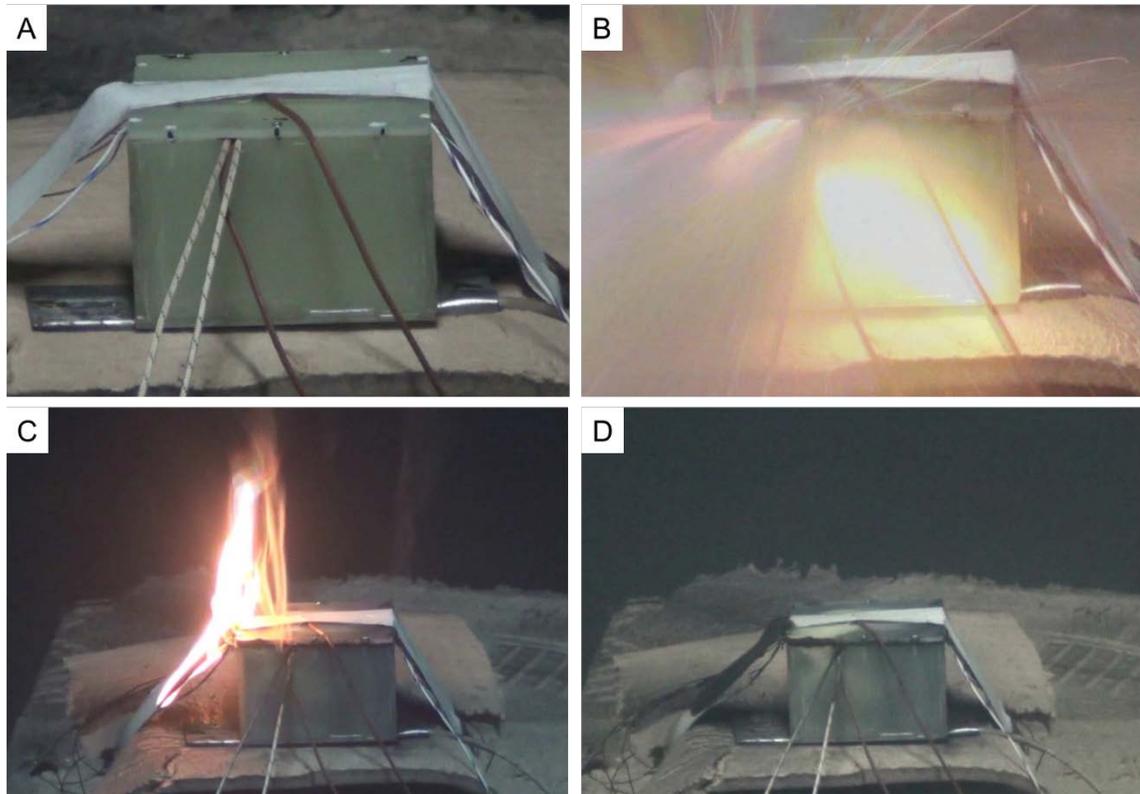


Figure 38. Video screenshots from Pack E1 showing immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), burning electrolyte vapor and glass fiber tape (C), remaining intact enclosure after trigger cell activation (D)

Test results for Pack E2 were comparable to Pack E1. After an OCV drop 27 minutes into heating (trigger cell temperature of 117 °C) an audible vent pop was heard three minutes later (trigger cell temperature of 135 °C). As with Pack E1, the vent pop led to a recovery of the pack OCV above the 0 VDC observed due to CID activation. Pack E2 showed no signs of thermal runaway for 60 minutes at a heater power of 25 W, trigger cell temperature of 145 °C, and pack temperatures between 73 °C and 101 °C. Analogous to Pack E1, thermal runaway of the trigger cell was only observed when power to the heater cartridge was increased, but a smaller increase to 30 W was required. At a trigger cell temperature of 168 °C a single burst of flames was observed to escape the pack container. Only the trigger cell and one adjacent cell (cell 2) showed temperatures above ~100 °C with the maximum temperature of the trigger cell reaching 479 °C and cell 2 reaching a maximum temperature of 664 °C in response to the trigger cell failure. Maximum temperatures of all other cells ranged from 89 °C to 102 °C, while maximum temperatures of the flame arrestor and container exterior reached 500 °C and 155 °C, respectively. Temperature and voltage plots for Pack E2 are shown in Figure 39, and a selected region of the same plot showing the trigger cell activation as shown in Figure 40.

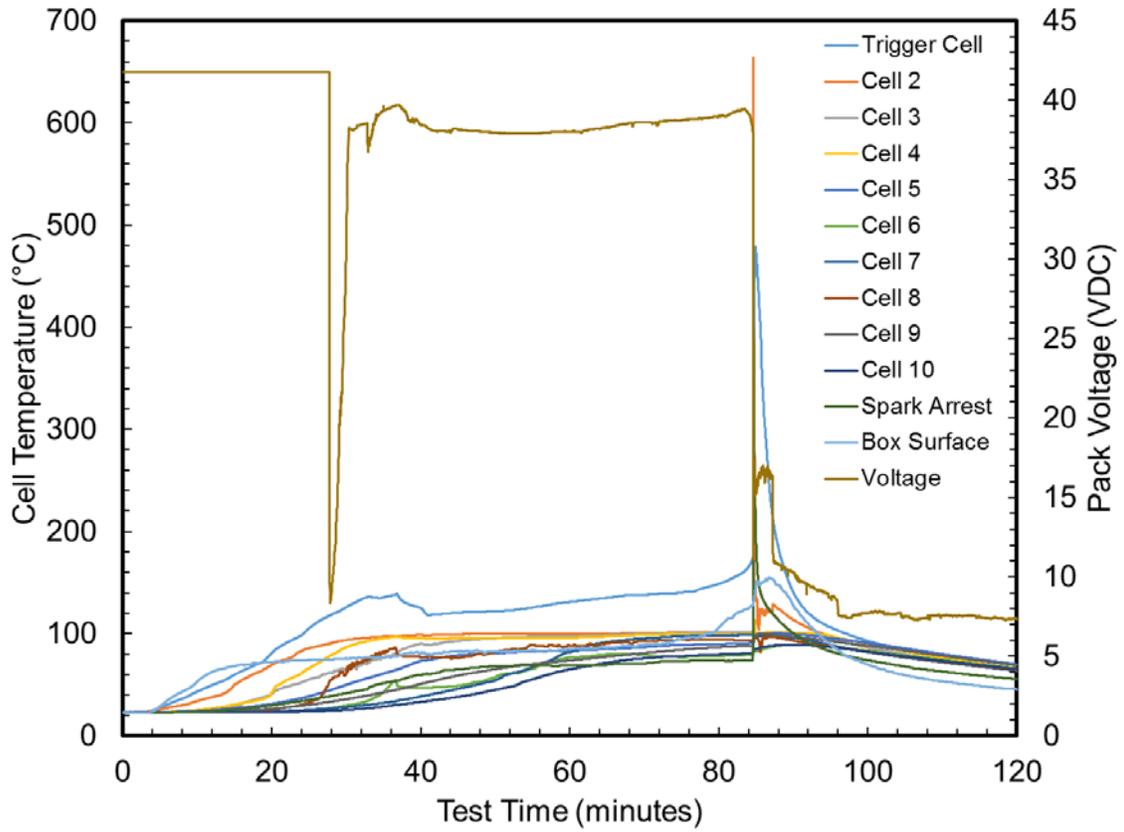


Figure 39. Temperature and voltage plot for Pack E2

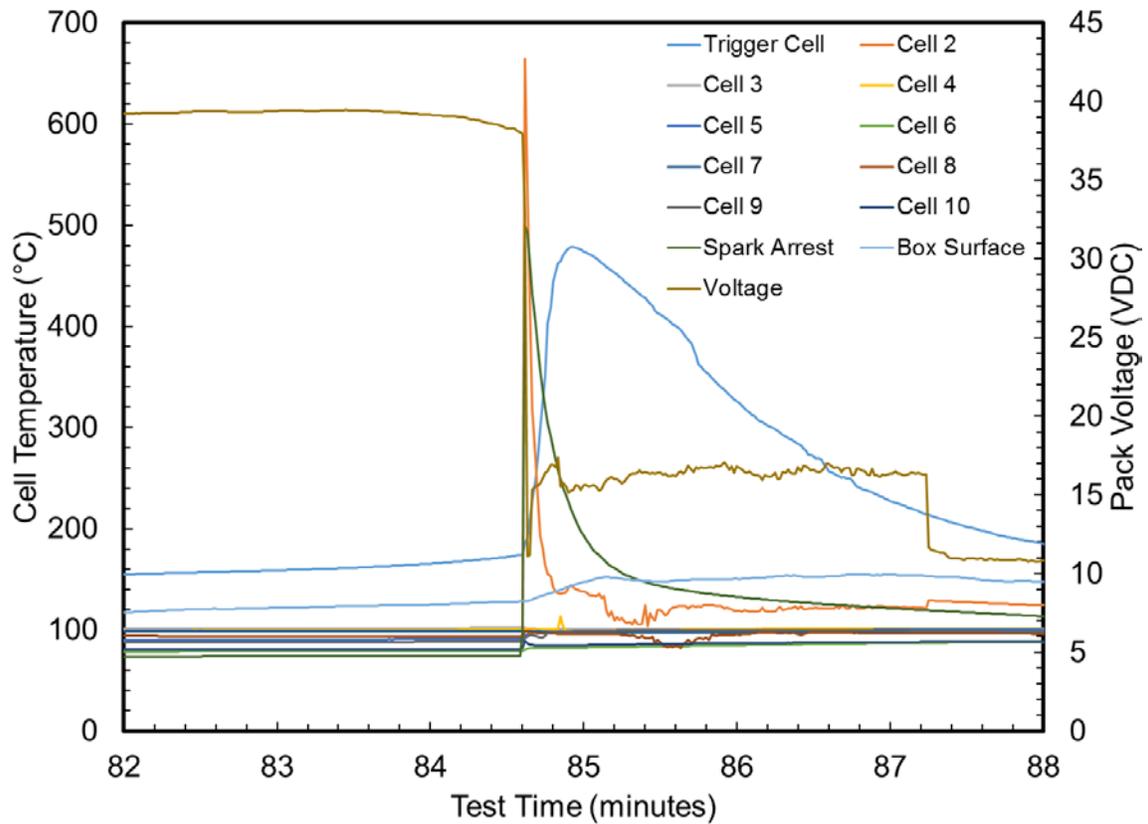


Figure 40. Selected region of temperature and voltage plot for Pack E2 highlighting trigger cell activation

Video screen shots from Pack E2 are shown in Figure 41. As with Pack E1, the trigger cell activation caused sparks and flames to escape the pack container and ignite the glass fiber tape used to restrain the pack, however propagating thermal runaway was not observed.

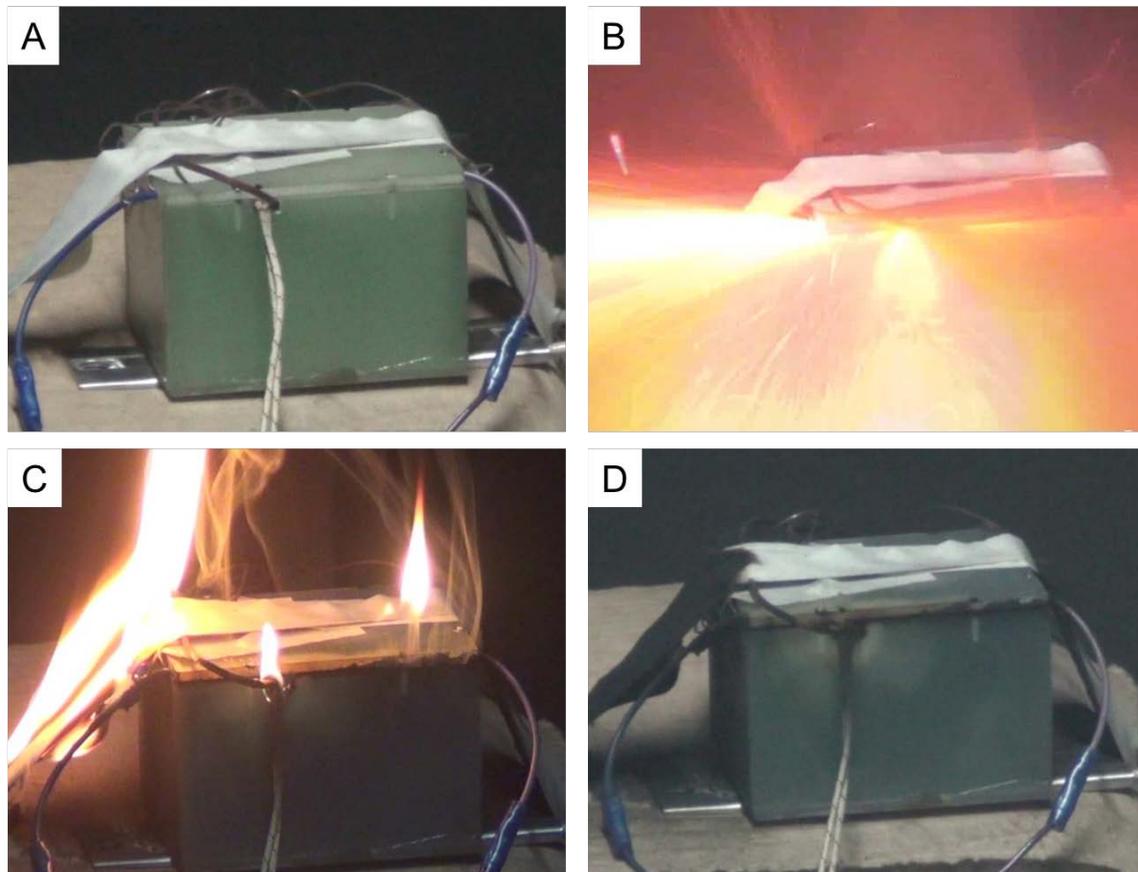


Figure 41. Video screenshots from Pack E2 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), burning electrolyte vapor and glass fiber tape (C), remaining intact enclosure after trigger cell activation (D)

Pack E3, which had an identical format to Packs E1 and E2 except for the exclusion of the flexible phase change material between the cells (spark arrests were included), had a markedly different response to trigger cell activation. After 20 minutes of heating the pack OCV dropped from 41.8 VDC to ~4VDC, corresponding to a trigger cell temperature of 105 °C. Two minutes after the OCV drop, a vent pop was heard at a trigger cell temperature of 132 °C and the pack OCV recovered to ~37 VDC. One minute after the vent pop was heard (23 minutes of heating with a trigger cell temperature of 162 °C) a propagating thermal runaway was observed with open flames and energetic vents observed over a 15-minute period. All cells reached maximum temperatures of 400 °C and above, with a pack maximum of 970 °C. Temperature and voltage plots for pack E3 are shown in Figure 42.

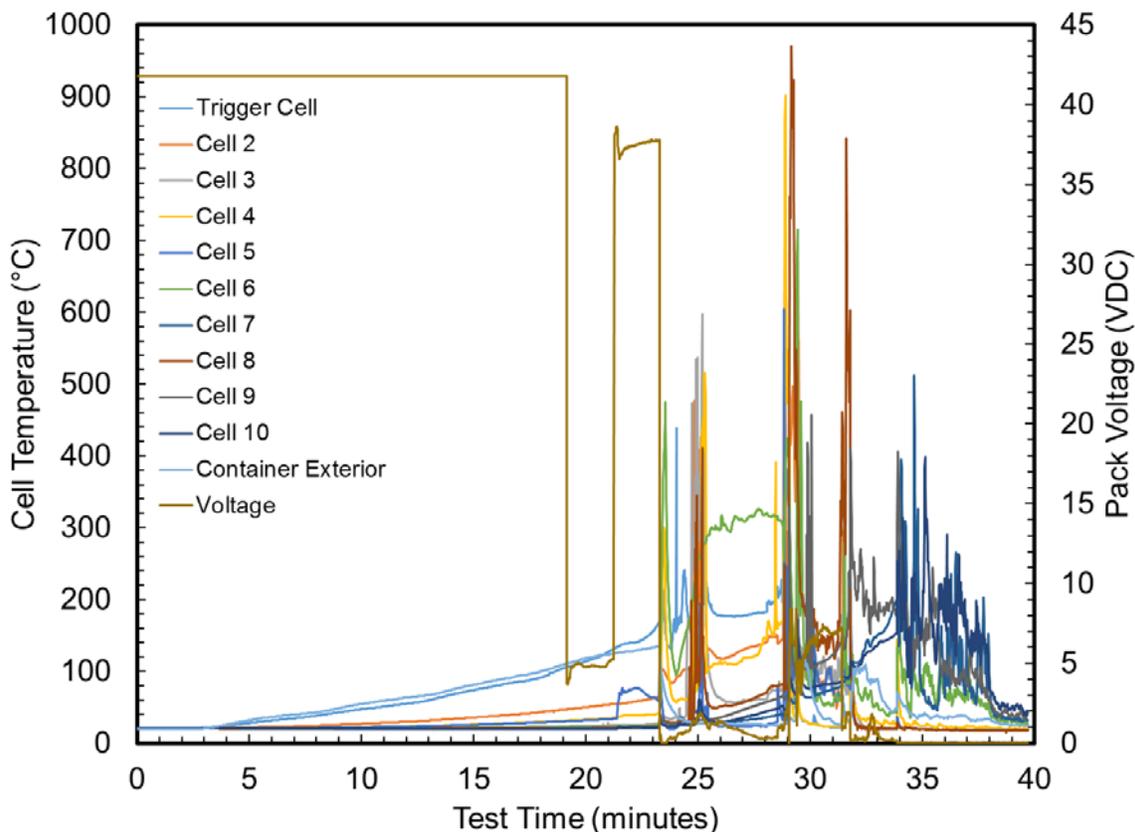


Figure 42. Temperature and voltage plot for Pack E3

Video screenshots from Pack E3 are shown in Figure 43, which compared to Pack E1 and E2 shows that without the flexible phase change material between the cells, propagation was seen despite the incorporated 1.5 mm cell spacing and pack enclosure. A digital photograph of Pack E3 after testing (Figure 44) shows that one side of the enclosure was blown off during the thermal runaway process, and fragments of the destroyed flexible phase change sheets used as the spark arrest are also visible as black carbon fibers.

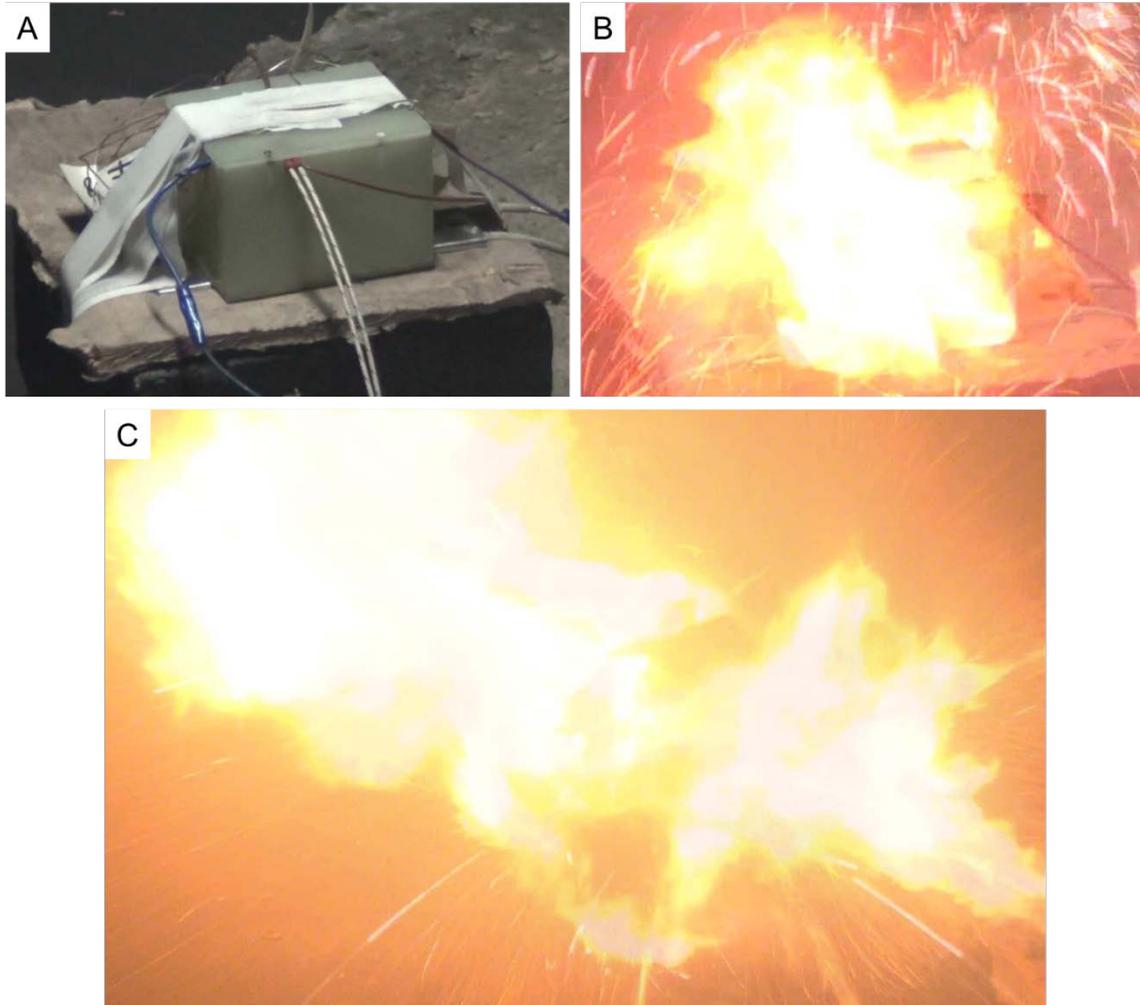


Figure 43. Video screenshots from Pack E3 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), explosions and flames due to propagating thermal runaway (C)



Figure 44. Digital photograph of Pack E3 following propagating thermal runaway

3.6 Pack F

Pack F was constructed using the wax based phase change material. An audible CID pop and pack OCV drop was observed for Pack F1 after 60 minutes of heating, corresponding to a trigger cell temperature of 92.5 °C and a nearest neighbor temperature of 75.5 °C (cell 2). Some voltage recovery was observed after the initial OCV drop, and the OCV was observed to fluctuate prior to the vent pop possibly indicating a loose connection. At 90 minutes of heating (trigger cell temperature of 98 °C and nearest neighbor temperature of 81 °C) a vent opening on the trigger cell dislodged the voltage sense line, causing the pack voltage to drop to 0 VDC for the remainder of the test. Heater power was increased shortly after the vent opening to 40 W. After 117 minutes of heating and a trigger cell temperature of 138 °C and a nearest neighbor temperature of 112 °C the trigger cell entered thermal runaway with a flaming vent. Within 2 minutes of the trigger cell activation, all cells underwent thermal runaway and the wax based phase change material block was destroyed. Maximum cell temperatures ranged from 550 °C to 1000 °C. The temperature and voltage plot for Pack F1 is shown in Figure 45, while a selected region of the temperature and voltage plot centered on the failure event is shown in Figure 46. Video screenshots from Pack F1 are shown in Figure 47.

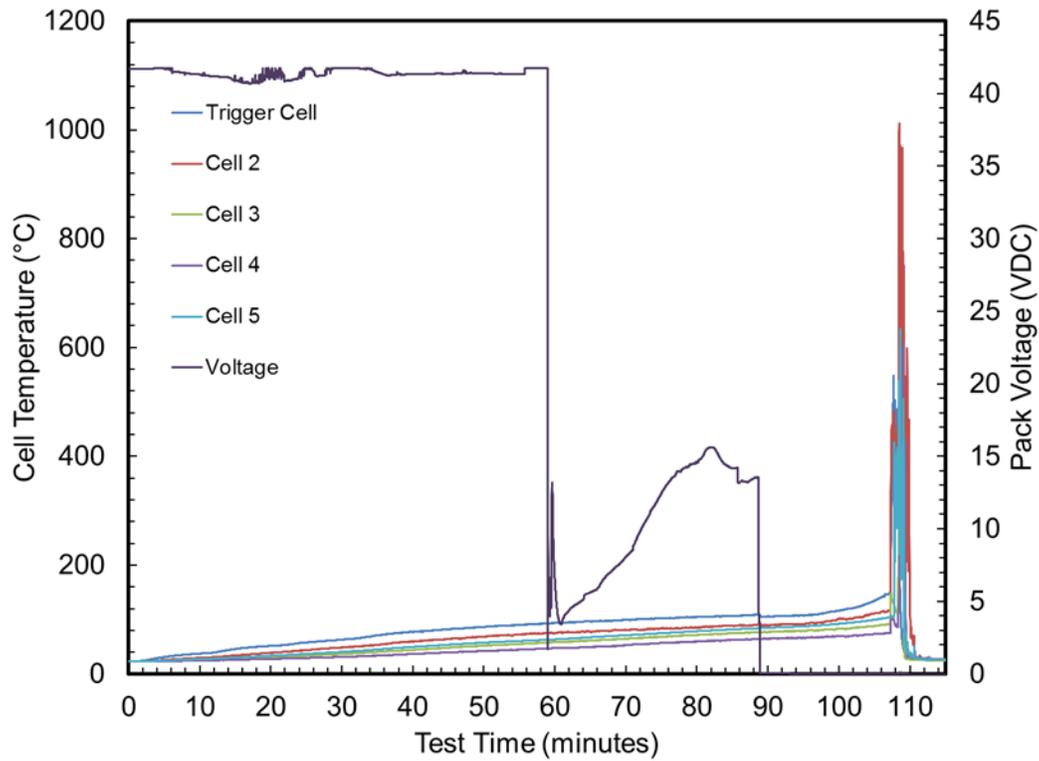


Figure 45. Temperature and voltage plot for Pack F1

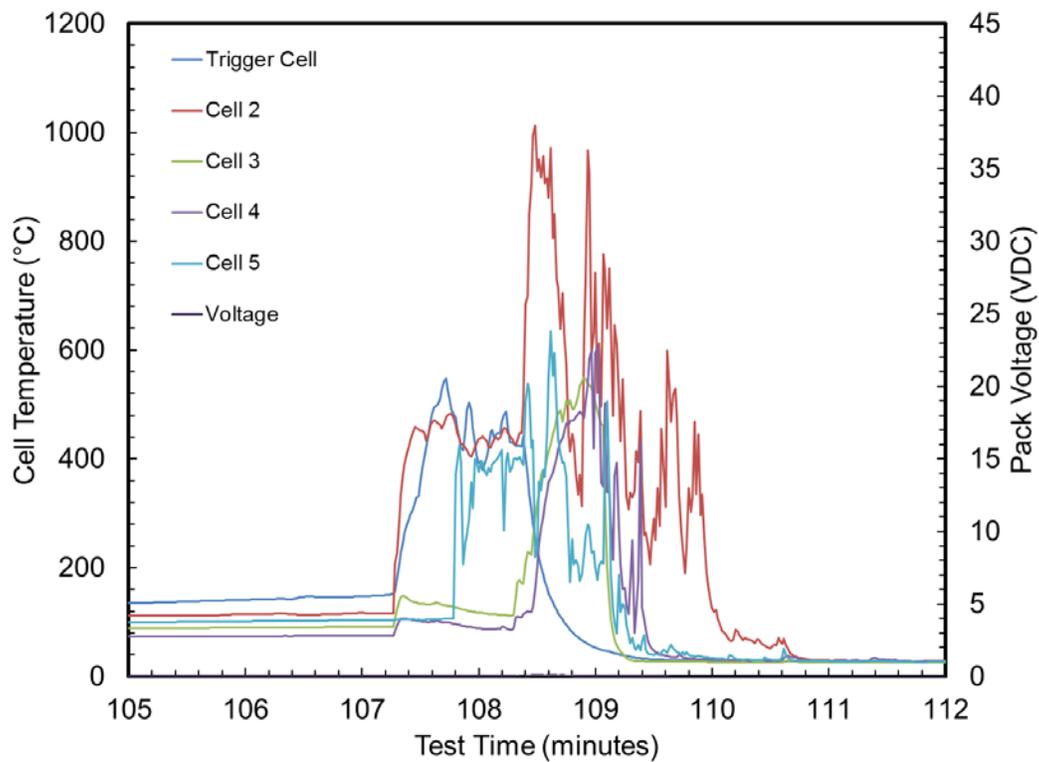


Figure 46. Selected region of temperature and voltage plot for Pack F1 highlighting trigger cell activation

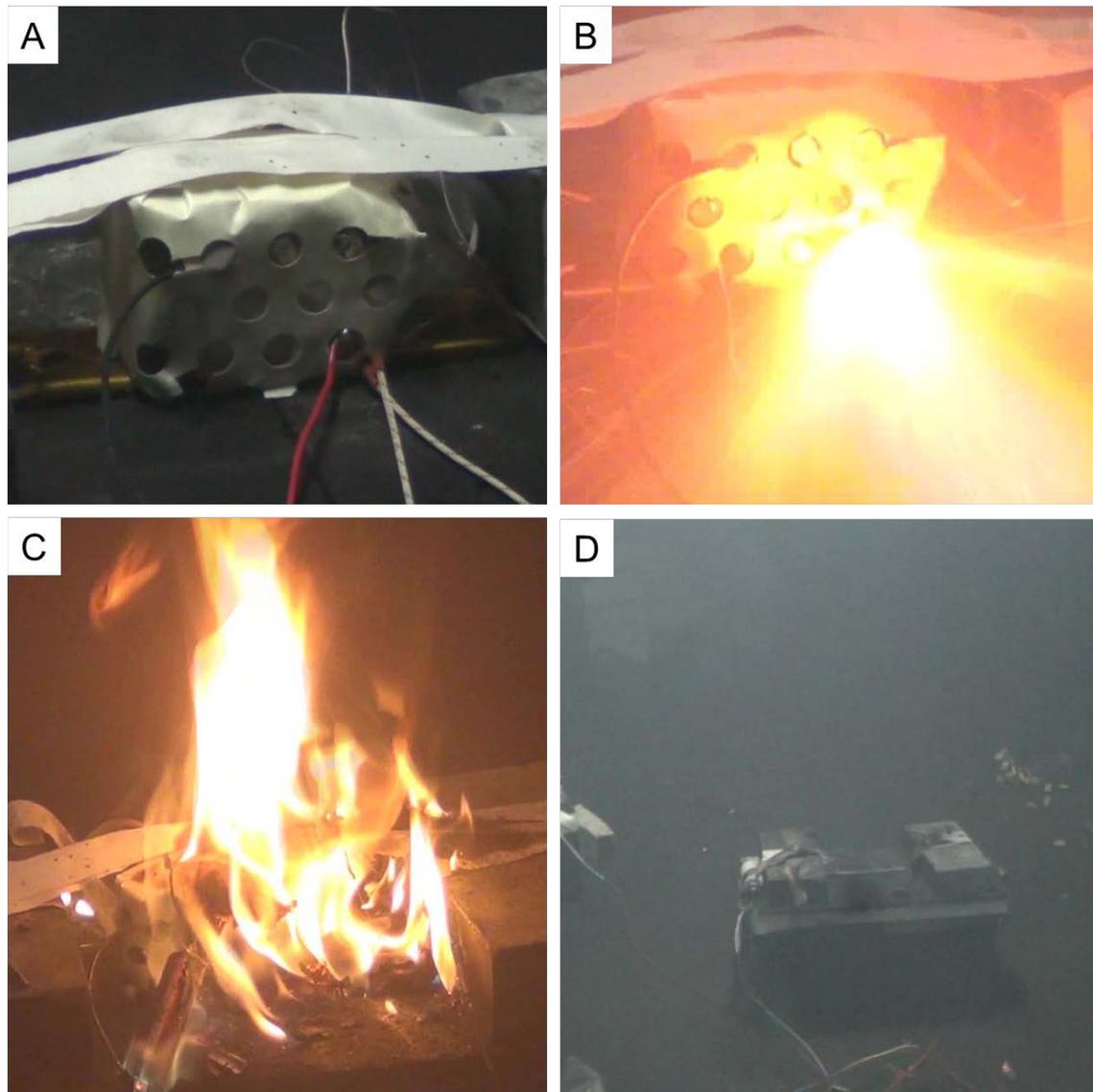


Figure 47. Video screenshots from Pack F1 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), propagating failure (C), post testing showing scattered cells and destroyed wax based phase change material block (D)

Like Pack F1, Pack F2 also required extensive heating to induce thermal runaway in the trigger cell. At 77 minutes of heating and a trigger cell temperature of 81 °C, the pack OCV dropped from 41.5 VDC to ~1 VDC and then steadily recovered. Heater cartridge power was increased after 60 minutes at 25 W to 40 W over ten minutes until thermal runaway was observed after 115 minutes of heating time with a trigger cell temperature of 116 °C and a nearest neighbor temperature of 101 °C. Like with Pack F1, the trigger cell ejected sparks and flames and reached a maximum temperature of 559 °C. A single neighboring cell (cell 2) also underwent thermal runaway and open flames were observed on the pack for several minutes, however these eventually self-extinguished and the pack remained intact. Temperature and

voltage plots for Pack F2 are shown in Figure 48, with a selected region near the thermal runaway event shown in Figure 49.

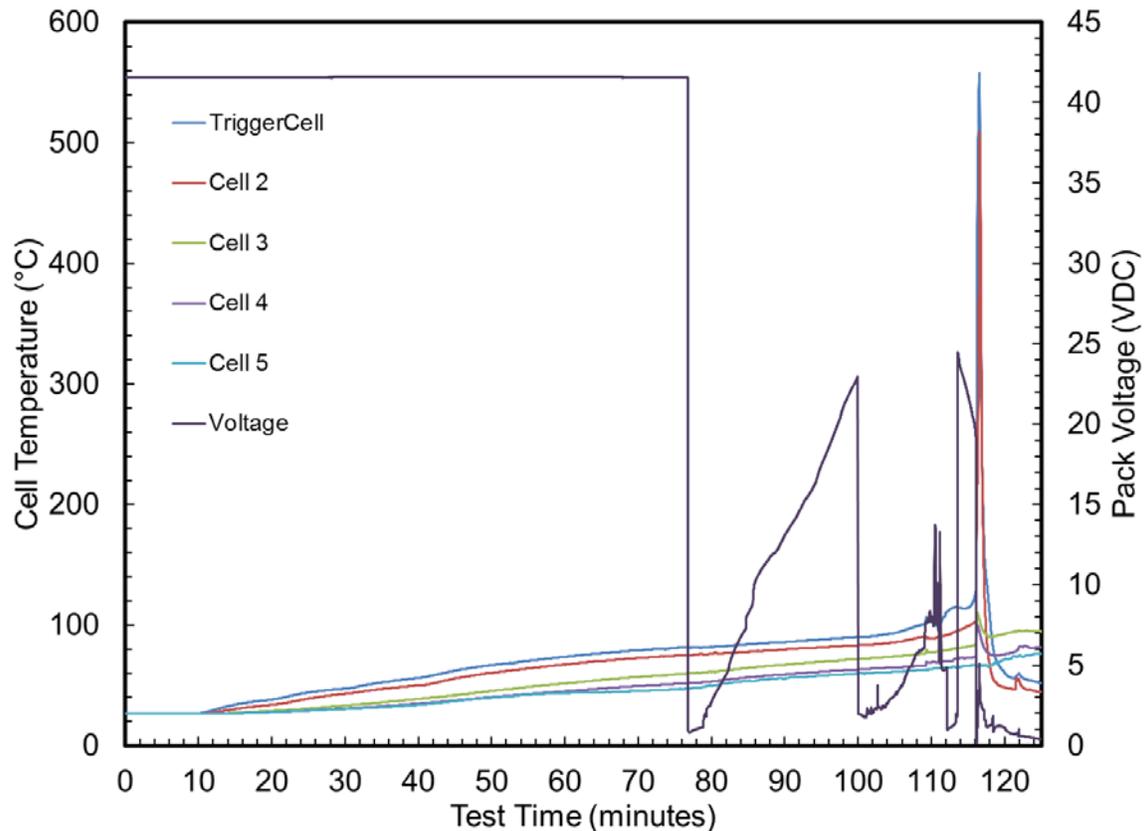


Figure 48. Temperature and voltage plot for Pack F2

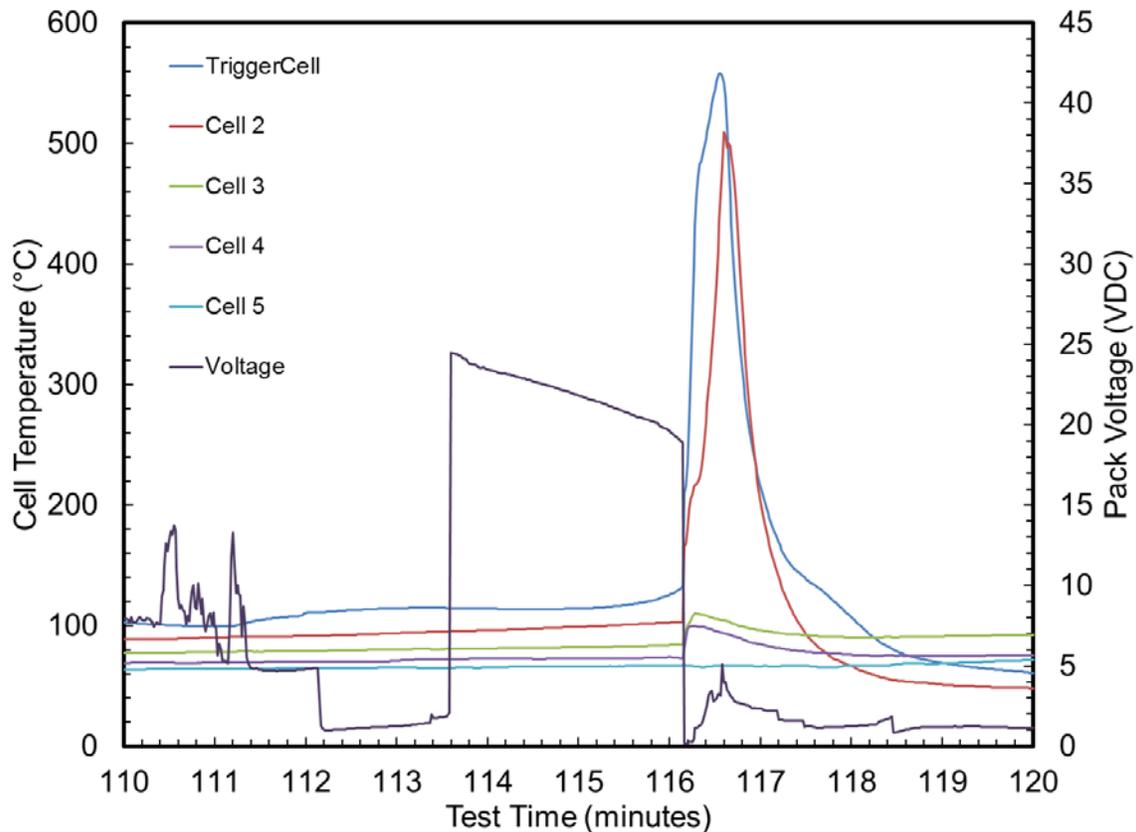


Figure 49. Selected region of temperature and voltage plot for Pack F2 highlighting trigger cell activation

Video screenshots from testing of Pack F2 are shown in Figure 50. Figure 50 also highlights a small but potentially significant difference between Packs F1 and F2, namely the position of the trigger cell. In Pack F1, the trigger cell was located on the bottom of the pack, while in Pack F2 the trigger cell was located at the top of the pack. Both trigger cells are in the same edge position with the same number of nearest neighbors, however it is plausible that less of the heat release due to the failed trigger cell was transferred into the neighboring cells for Pack F2, in which much of the flames produced by the trigger cell activation and subsequent propagation to a single neighboring cell were not in contact with the remaining pack. All of the testing in this report involved heating a trigger cell located on the outside edge of the pack, however the location at the top or bottom of the pack was at the discretion of the test engineer and not deliberately modified.

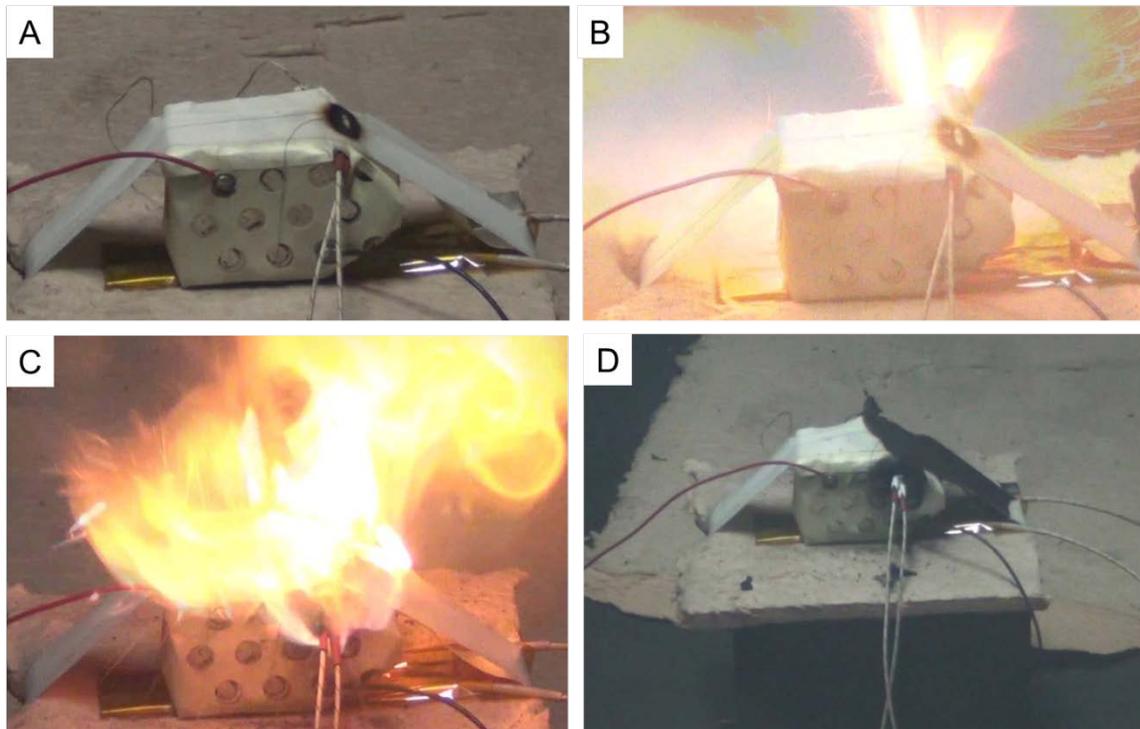


Figure 50. Video screenshots from Pack F2 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), open flames following second cell thermal runaway (C), post testing showing a mostly intact wax based phase change material block (D)

3.7 Pack G

Pack G featured the simplest method of preventing cell-to-cell propagation, namely an increased distance between adjacent cells. In the case of Pack G, a 2 mm gap between the sides of two cells was established using a 3D printed holder. This method however offers no protection to the trigger cell itself, and therefore thermal runaway was observed in a time frame comparable to packs containing close-packed cells. For Pack G1, OCV drop was observed after 28 minutes of heating and a trigger cell temperature of 141 °C. After 37 minutes of heating the trigger cell was observed to vent at a temperature of 168 °C, cool slightly, and enter thermal runaway a few minutes later. The air gap does seem to have some influence on the neighboring cell temperatures, as even at the moment of thermal runaway the next highest cell temperature is only 65 °C. Temperature and voltage plots for Pack G1 are shown in Figure 51, which shows a maximum pack temperature of 830 °C.

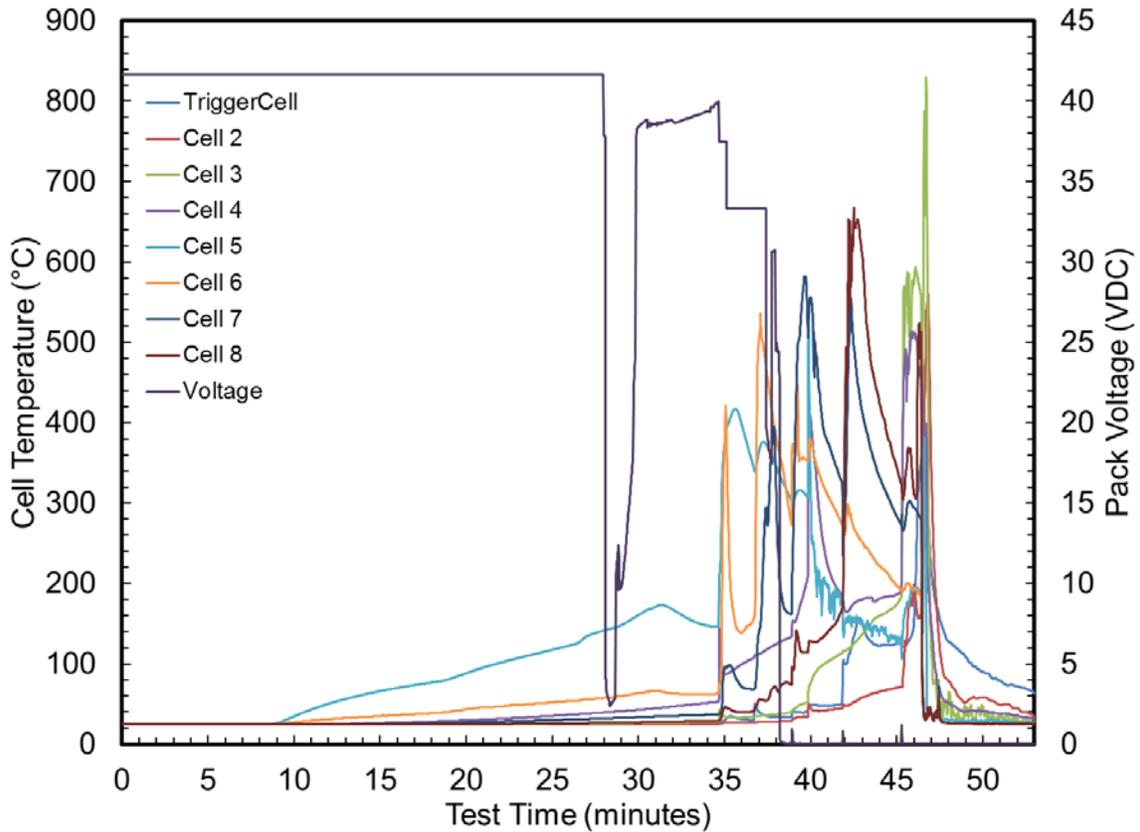


Figure 51. Temperature and voltage plot for Pack G1

Video screenshots from the evaluation of Pack G1 are shown in Figure 52. Note that for Pack G1, there were time periods between cell failures in which no open flames were present and heat transfer between neighboring cells was still sufficient to cause propagating thermal runaway.

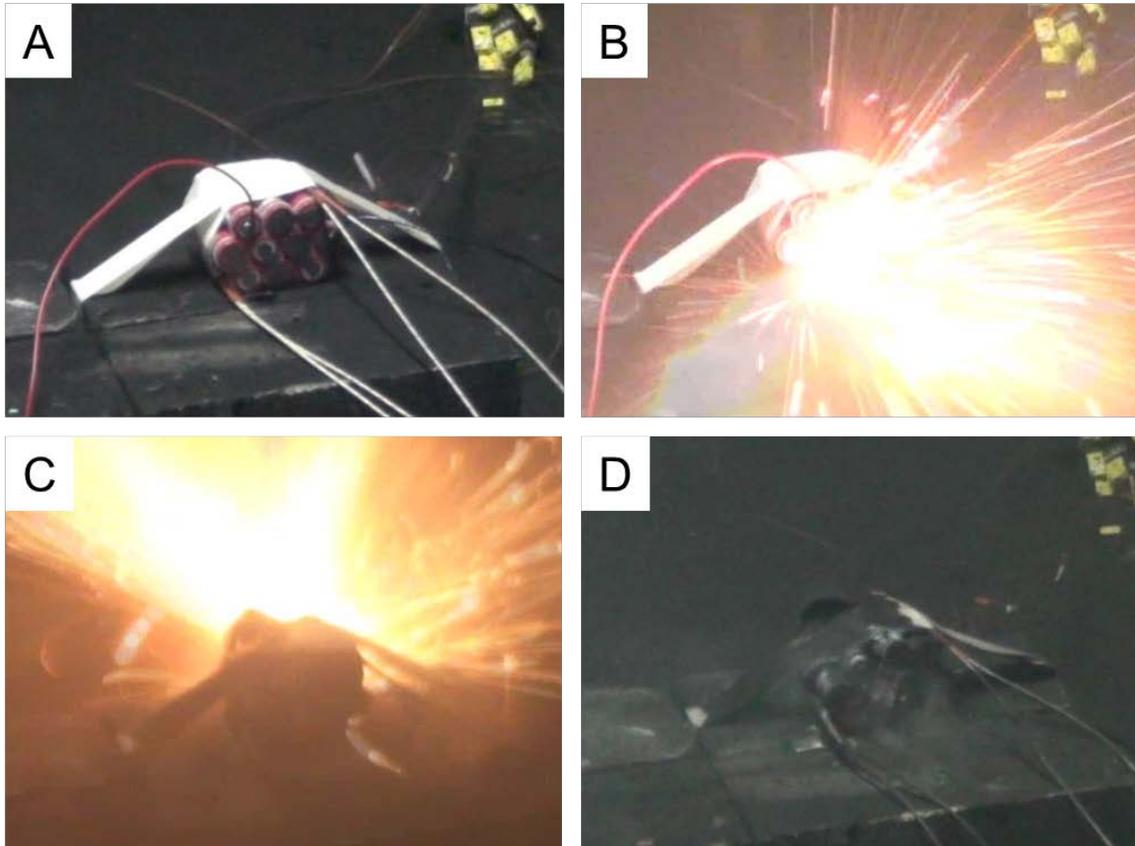


Figure 52. Video screenshots from Pack G1 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), subsequent failure of neighboring cells (C), post testing showing all cells have been consumed (D)

Full propagation was also observed for Pack G2, with an initial OCV drop occurring after 23 minutes of heating, a trigger cell temperature of 143 °C, and a nearest neighbor maximum temperature of 57 °C. At 25 minutes of test time a cell vent was observed with a trigger cell temperature of 171 °C and the heater cartridge power was terminated in anticipation of thermal runaway, however the trigger cell then began to cool for 25 minutes. At this point power was restored to the heater cartridge and thermal runaway began with a trigger cell temperature of 217 °C and a nearest neighbor maximum temperature of 76 °C. Temperature and voltage plots for Pack G2 are shown in Figure 53. Maximum pack temperatures during thermal runaway exceeded 1000 °C for some cells.

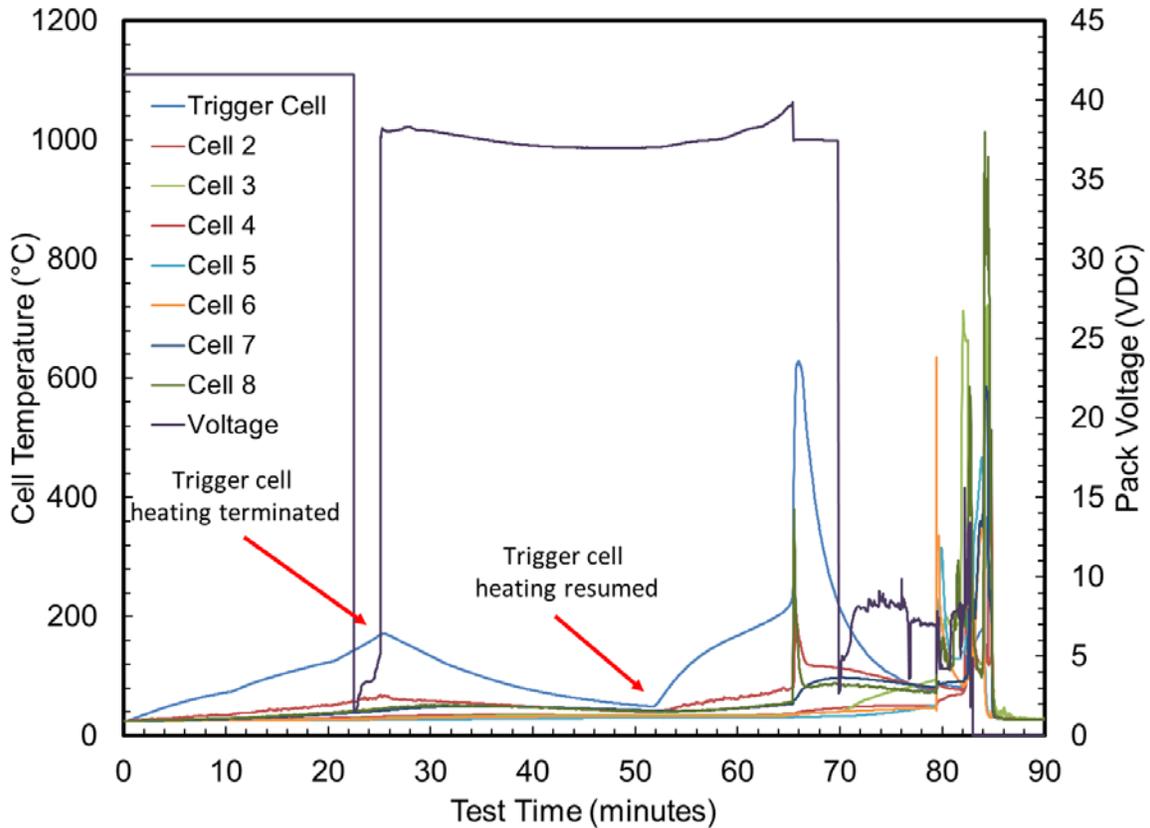


Figure 53. Temperature and voltage plot for Pack G2

Screenshots from the testing of Pack G2 are shown in Figure 54. Note that during the activation of the trigger cell the pack became dislodged from the test fixture and is blocked by a stack of fire bricks, however individual cell failures could still be identified on the live video feed. As with Pack G1, there were periods of time during the propagating failure observed in Pack G2 in which no open flames or other signs of “active” thermal runaway were apparent.

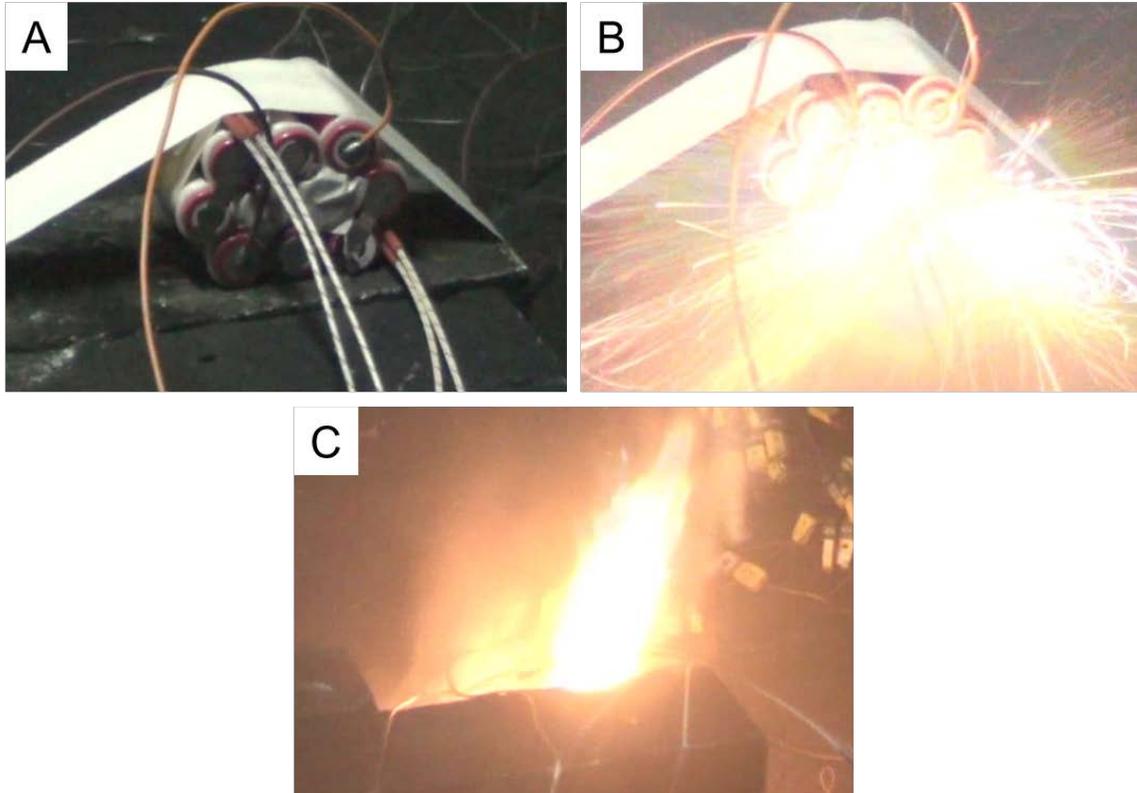


Figure 54. Video screenshots from Pack G2 immediately prior to trigger cell failure (A), energetic failure of trigger cell resulting in sparks and flame (B), subsequent failure of neighboring cells after pack had been knocked from test fixture (C)

4. Conclusions

This report describes the thermal propagation results of battery packs containing 18650 sized lithium-ion cells by conducting thermal abuse of a single trigger cell. Trigger cells were located on the exterior of each battery pack and selected at a corner to minimize the number of nearest neighbor cells. Thermal abuse was conducted by using a small resistance heater, initially with a maximum power output of 25 W, which was increased for certain test configurations in which 60 minutes of heating at 25 W did not force the trigger cell into thermal runaway. Explicitly evaluated in this report was the propagation behavior of commercially available “hoverboard” battery packs, and whether certain commercially available interstitial packaging materials could prevent neighboring cells from entering thermal runaway.

A summary of all test results is presented in Table 3, which includes the time and maximum temperature (T_{max}) at which a drop in pack open circuit voltage was observed, indicating a CID activation, the time and maximum temperature at which thermal runaway (TR) was observed, and the overall maximum pack temperature.

For the commercial hoverboard battery packs tested (Pack A and Pack B), both variations showed signs of propagation from the trigger cell to neighboring cells. For one commercial hoverboard battery design (Pack B), an aluminum case was included to contain LIB failure. Pack B was evaluated with and without the aluminum case, and while propagating thermal runaway was only observed in one test, the presence of the aluminum case was not sufficient to prevent sparks, flames, and smoke from exiting the battery pack.

Custom made battery packs with a variety of configurations were also evaluated. Packs containing close-packed cells (Pack C), cells wrapped in ceramic fiber insulation (Pack D), or cells separated by a 2 mm air gap (Pack G) all exhibited propagating thermal runaway with minimal differences in onset temperatures or time to failure. Packs which contained the flexible phase change material (Pack E) or the wax-based phase change material from (Pack F) showed a delayed initiation of the trigger cell and required heating above 25 W before the trigger cell underwent thermal runaway. The Pack E material in this configuration showed some indication of preventing cell-to-cell propagating failure, however activation of the trigger cell still caused sparks, flames, and smoke to escape the battery enclosure. While a battery design incorporating the Pack E material would likely be more thermally robust than a battery without, the possibility for cell failure still exists and the possibility of a single cell failure causing injuries or fires when applied in a consumer electronic device still exists.

Table 3. Summary of test results from thermal abuse of 18650 LIB packs

Pack ID	Time and T_{max} @ OCV drop	Time and T_{max} @ TR	Pack T_{max}	Propagation?
Pack A1	17 min., 232 °C	30 min., 385 °C	514 °C	N
Pack A2	26 min., 160 °C	33 min., 266 °C	472 °C	N
Pack B1	57 min., 265 °C	57 min., 265 °C	>1000 °C	Y
Pack B2	44 min., 60 °C*	44 min., 60 °C*	165 °C*	N
Pack B3	No OCV drop	49 min., 300 °C	626 °C	N
Pack C1	27 min., 119 °C	35 min., 165 °C	828 °C	Y
Pack C2	26 min., 142 °C	35 min., 201 °C	>1000 °C	Y
Pack D1	38 min., 92.5 °C	44 min., 141 °C	560 °C	Y
Pack D2	32 min., 100 °C	38 min., 152 °C	N/A	N*
Pack E1	33 min., 114 °C	97 min., 149 °C	527 °C	N
Pack E2	27 min., 117 °C	85 min., 168 °C	664 °C	N
Pack E3	20 min., 105 °C	23 min., 162 °C	970 °C	Y
Pack F1	60 min., 92.5 °C	117 min., 138 °C	>1000 °C	Y†
Pack F2	77 min., 81 °C	115 min., 101 °C	559 °C	N
Pack G1	37 min., 141 °C	37 min., 168 °C	830 °C	Y
Pack G2	23 min., 143 °C	65 min., 217 °C‡	>1000 °C	Y
* Trigger cell was ejected from test pack preventing cell-to-cell propagation † Additional heating of trigger cell required to initiate propagation ‡ Trigger cell heating terminated after vent w/o thermal runaway and was restarted				

5. References

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8. **Orendorf, Christopher J, Lamb, Joshua and Steele, Leigh Anna M.** *Recommended Practices for Abuse Testing Rechargeable Energy Storage Systems (RESSs)*. s.l. : Sandia National Laboratories, 2017. SAND2017-6925.

