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Propagation Testing Multi-Cell Batteries

Christopher J. Orendorff, Joshua Lamb, Leigh Anna M. Steele, and Scott W. Spangler

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Christopher J. Orendorff, Joshua Lamb, Leigh Anna M. Steele, and Scott W. Spangler

Power Sources Research and Development Department

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0614

Abstract

Propagation of single point or single cell failures in multi-cell batteries is a significant concern as batteries increase in scale for a variety of civilian and military applications. This report describes the procedure for testing failure propagation along with some representative test results to highlight the potential outcomes for different battery types and designs.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions to this document made by Pete Roth (SNL Retired) and Dan Doughty (SNL Retired, Battery Safety Consulting). We also acknowledge support of this work by David Howell and Brian Cunningham at the Department of Energy's Vehicle Technologies Office (VTO).

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NOMENCLATURE

DOE	Department of Energy
SNL	Sandia National Laboratories
Wh	Watt-hour
Ah	Ampere hour
N	Newton
SOC	State-of-charge
EV	Electric vehicle
OEM	Original Equipment Manufacturer
S	Series electrical connection
P	Parallel electrical connection

1. INTRODUCTION

Lithium-ion battery research and engineering has enabled the increase in lithium-ion battery scale from Ah-sized batteries for portable electronics to cargo container-sized MWh battery systems developed for utility storage. Products are now emerging for transportation (mass transit, military, and personal vehicles) and utility storage (load leveling, integration of renewables); however, lithium-ion cells are not without their challenges with respect to safety. Incidents related to cell safety and product recalls are well documented for the consumer market [1]. There is also a trade-off for these larger battery systems between energy storage capacity and inherent safety. Moreover, as these batteries increase in size and complexity, their failure modes also become more complex and challenging to control.

Of particular concern are failure modes that initiate at the cell level, leading to a thermal runaway condition, which can cascade or propagate through the entire battery system and even spread to the rest of a product or surrounding area. Any propagation of a single point failure (thermal runaway) through an entire battery is an unacceptable outcome in order to ensure system-level safety. While there are propagation testing procedures included in published procedure documents [2, 3], there are no published test results for these procedures, which would be useful in providing context or guidance to developers on how failure propagation can behave. Given the high profile reported incidents that have resulted in failure propagation through battery systems, it is clear that propagation testing needs to be integrated into product design and development by battery developers and original equipment manufacturers (OEMs) [4-7].

This report describes a propagation testing procedure with some practical experimental considerations. In addition, this report includes representative testing results to provide a framework for how failure propagation can take place for different battery designs and configurations.

2. RECOMMENDED PRACTICES FOR PROPAGATION TESTING

The intent of this test is to initiate a single cell thermal runaway under otherwise normal battery operating conditions and evaluate how that failure propagates from cell-to-cell within a battery module or pack. The first step is to experimentally determine a thermal runaway initiation trigger prior to a module- or pack-level test. This initiation trigger may include, but is not limited to, a thermal (direct resistive heating, external heating and conductive heat transfer), electrical (overcharge or cell short circuit), or mechanical (puncture, impact, or crush) abuse condition applied to a cell (see Table 1). It is recommended that this initiation trigger be experimentally evaluated and documented at the cell-level to ensure the initiation results in a typical and reproducible thermal runaway for a given cell type. Another important consideration for a trigger is that it should have the ability to be readily applied in multiple locations within a battery module or pack, while maintaining the attributes of a single cell thermal runaway initiator.

Table 1. Possible Experimental Thermal Runaway Initiation Triggers

Method	Attributes	Challenges
Mechanical deformation/ nail penetration	Limits impact of initiator to only target cell	May be difficult to perform depending on battery configuration
Overcharge	Aggressive test likely to lead to thermal runaway of target	Runaway may be unrealistically severe; may require electrically isolating cell
Short circuit	Relatively easy to perform; initiation would be limited to target cell	Many modern cells are fairly resistant to short circuit failure; may require electrically isolating cell
Thermal/overheating	Aggressive test likely to lead to thermal runaway of target	Will likely require disassembly/reassembly of pack to install heat source; preheating of nearby cells may lead to different result than if cells were at ambient

Once a cell-level initiator has been identified, the next step is to perform the module- or pack-level propagation test. It is recommended that this test be performed on both batteries with active control systems enabled and disabled in order to demonstrate any potential performance improvements with controls in place. Passive controls integrated into the battery design should be left in place for all tests. At a minimum, it is recommended that the cell failure be initiated at a cell located in the center of the battery, at 100% state-of-charge (SOC), and 25 °C. If multiple test articles are available, it is recommended that the test be performed at several locations, SOCs, and temperatures from 25-55 °C. The SOC and test temperature matrix is shown in Table 2. Locations within a battery module or pack should be considered to (1) maximize the number of cells involved in the test and (2) represent any potential design vulnerabilities based on use condition or misuse.

After the initial cell thermal runaway is initiated, the test article should be monitored based on the battery response using a matrix similar to the one presented in Table 2:

- If thermal runaway does not propagate, monitor for 60 minutes after initiation.
- If thermal runaway does propagate, monitor for an additional 60 minutes from the end of the last failure event (cell vent, thermal runaway, fire self-extinguishes, etc.).

Table 2. State-of-charge (SOC) and Test Temperature Matrix for Propagation Test

		Temperature (°C)			
		25	35	45	55
SOC (%)	40				
	60				
	80				
	100				

Recommended data acquisition for the propagation test includes:

- Cell voltage
- Module or pack voltage
- Cell temperature
- Module or pack exterior temperature
- Video/audio
- Still photographs of the test article before and after the test

Post-test, in the event of partial or incomplete propagation or loss of communication or electrical connection to the battery, follow established procedures to put the battery in a safe handling condition to evaluate the state-of-health or stability of the battery as a result of the test.

3. PROPAGATION TEST RESULTS

This study evaluated the propagation behavior of two battery types in different electrical configurations listed in Table 3.

Table 3. Cell and Battery Specifications for Test Articles Used for Propagation Testing

Battery	Chemistry	Geometry	Configuration
2.2 Ah 18650	$LiCoO_2$/Graphite	Cylindrical	10S1P, 1S10P
3.0 Ah pouch	$LiCoO_2$/Graphite	Pouch	5S1P, 1S5P

3.1 Evaluation of Thermal Runaway in Single Cells

The initial runaway initiation trigger used for these experiments is nail penetration [8]. For the cylindrical cells, the penetration is applied axially from the bottom of the cell (away from the header) to cause the maximum amount of damage internal to the cell, shown in Figure 1. For pouch cells, the penetration is applied through the edge of the cell package perpendicular to the tabs, shown in Figure 2.

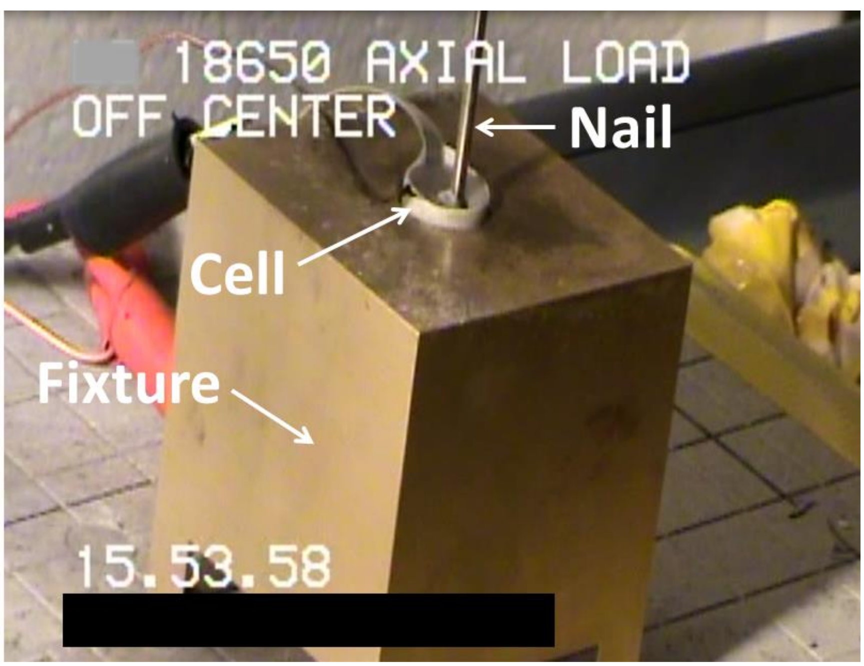

Figure 1. Orientation of nail penetration on single cylindrical 18650 cell.

Figure 2. Orientation of nail penetration on single pouch cell.

Figures 3 and 4 show representative force and displacement (Figure 3) and voltage and temperature (Figure 4) for cylindrical 18650 cells subjected to an axial nail penetration. The cell package ruptures after 10.8 mm of displacement at 840 N. After the package rupture, the cell shorts, indicated by the abrupt drop in cell voltage, and the cell goes into thermal runaway with a peak cell skin temperature of 474 °C. Representative force and displacement and voltage and temperature for edge orientation nail penetration of a pouch cell are shown in Figures 5 and 6, respectively. The cell package ruptures after 5.6 mm of displacement at 492 N. Once the package ruptures, the cell voltage drops immediately, and the cell goes into thermal runaway with a peak cell skin temperature of 200 °C. The thermal runaway response (reactivity and temperature rise) for both cell types to this type of mechanical penetration is reproducible from cell-to-cell.

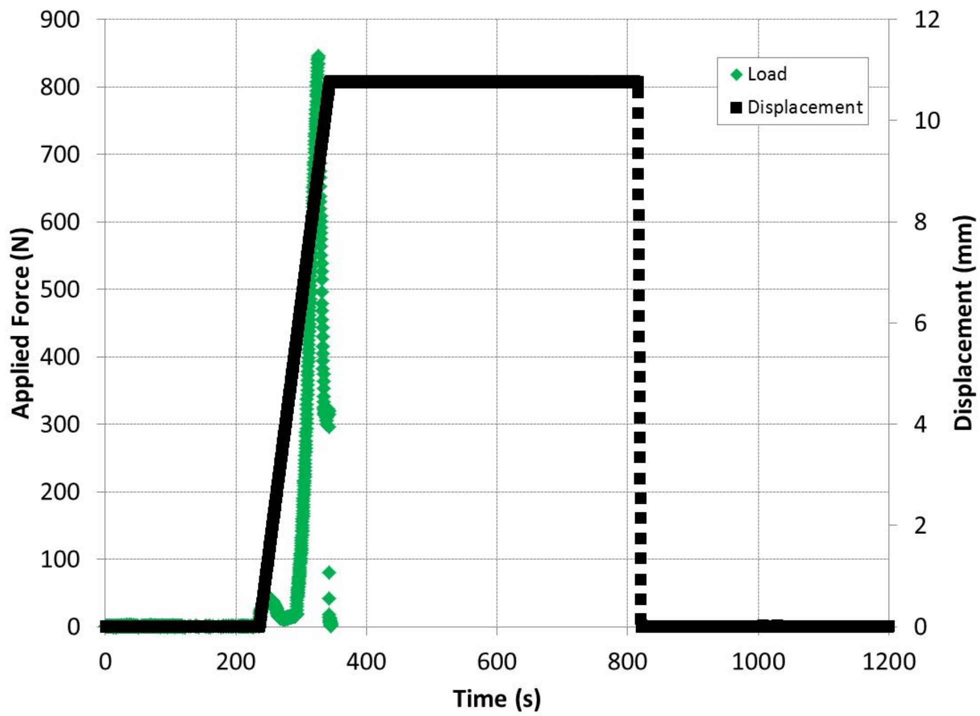

Figure 3. Force and displacement as a function of time during the blunt nail penetration in the axial orientation of a cylindrical 18650 cell.

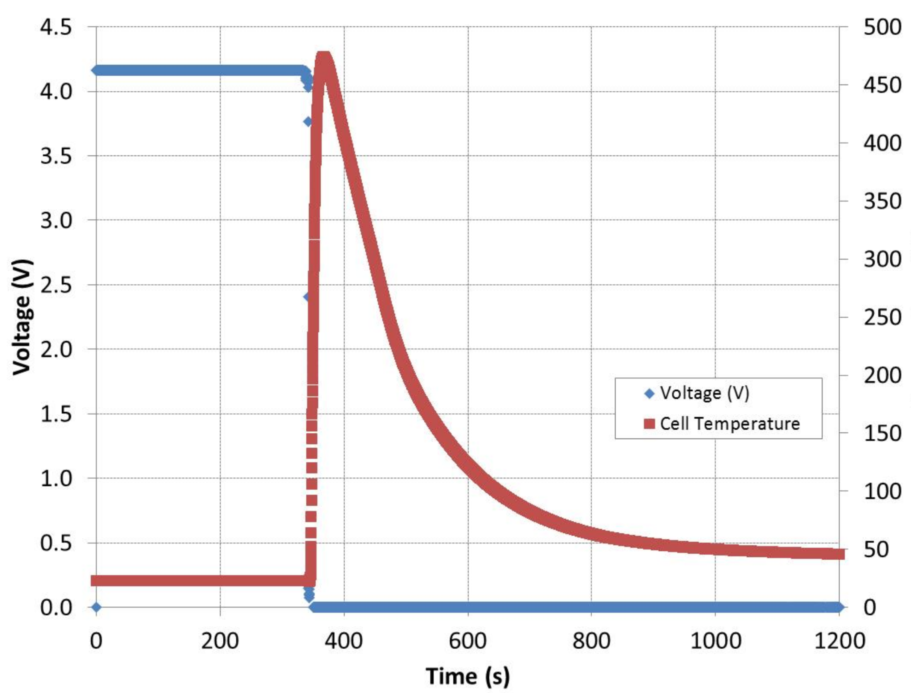

Figure 4. Cell voltage and temperature as a function of time during the blunt nail penetration in the axial orientation of a cylindrical 18650 cell.

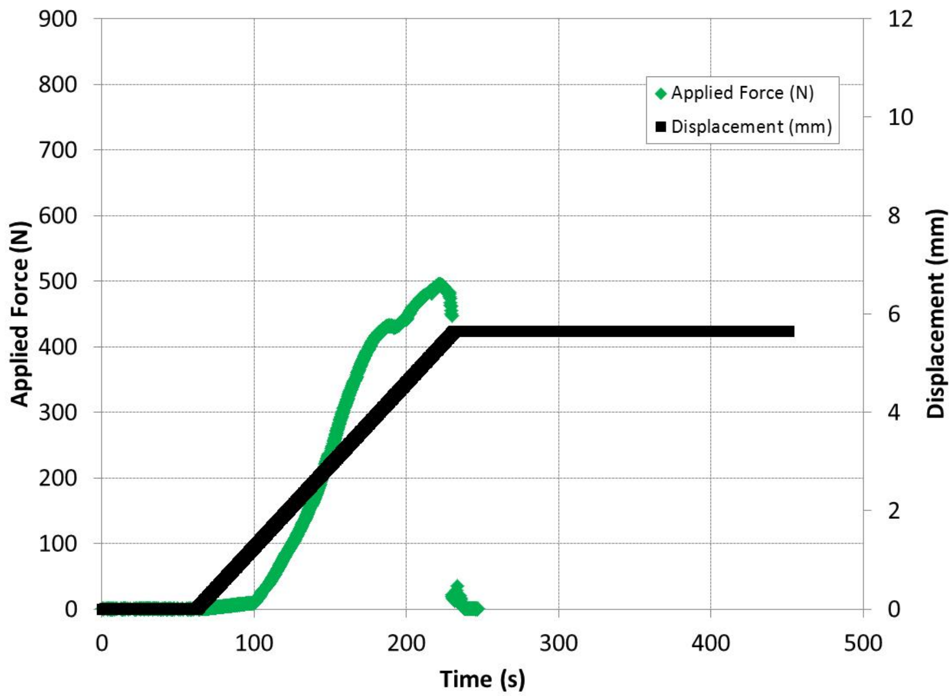

Figure 5. Force and displacement as a function of time during the blunt nail penetration in the edge orientation of a pouch cell.

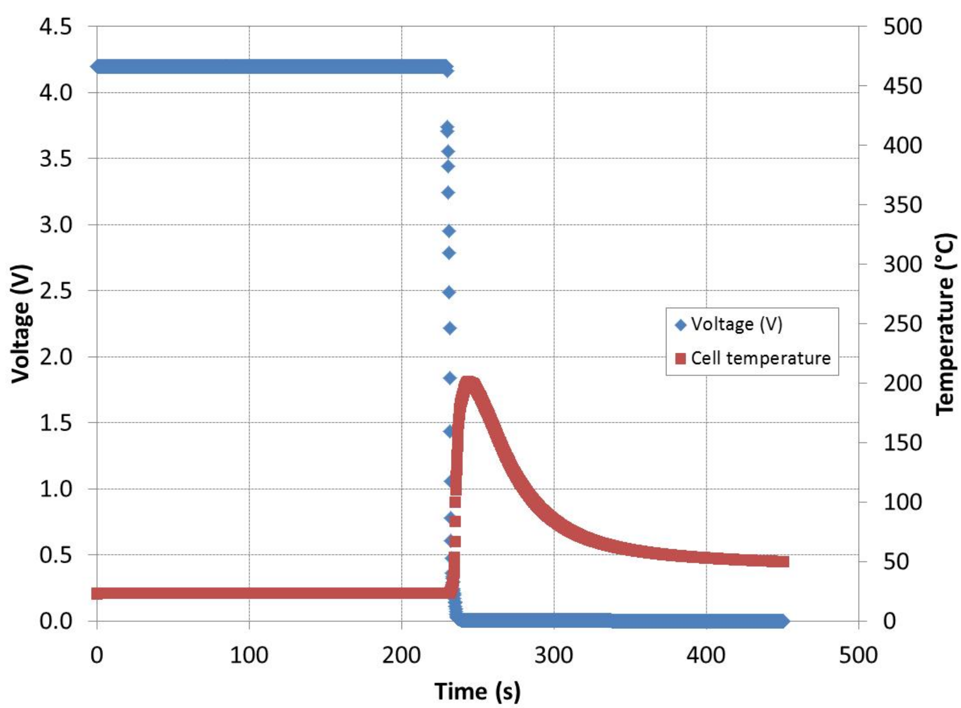

Figure 6. Cell voltage and temperature as a function of time during the blunt nail penetration in the edge orientation of a pouch cell.

3.2 Propagation Testing 10S1P and 1S10P Cylindrical Cell Batteries

Cylindrical cell batteries in the 10S1P and 1S10P configurations were built using commercial-off-the-shelf 2.2 Ah 18650 cells. A picture of a 10S1P battery is shown in Figure 7. All tests are performed at 100% SOC at 25 °C, and failure is initiated at Cell 6 by nail penetration axially through the cell.

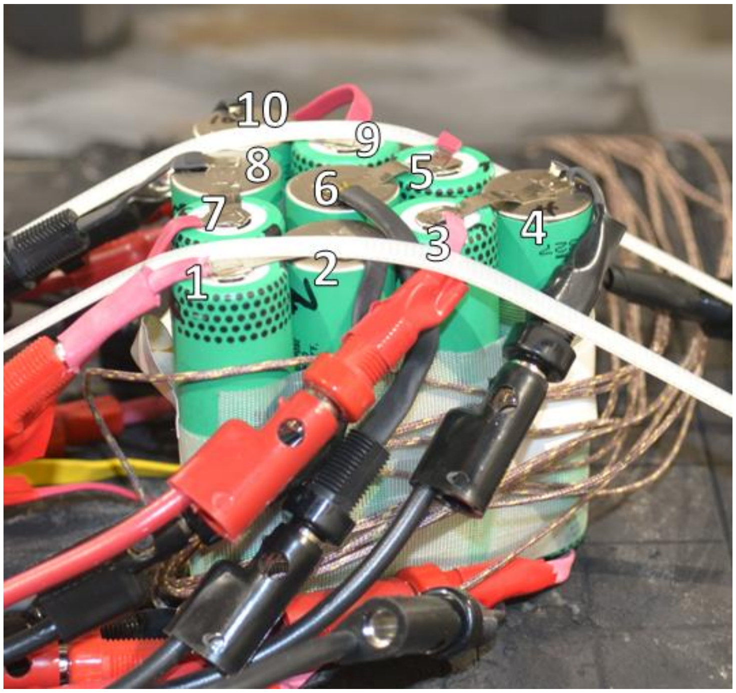

Figure 7. Photograph of a 10S1P battery of 2.2 Ah 18650 cells with each cell numbered.

3.2.1 10S1P

Figure 8 shows the temperature response of the 10S1P propagation test, initiated at Cell 6. Cell 6 goes into thermal runaway and self-ignites with a peak temperature of 360 °C (initiated at 265 s in Figure 8). The sustained fire causes an initial temperature rise in all of the thermocouples on the cells with the exception of Cell 10, which has a thermocouple that is sufficiently well separated from the fire. Approximately 15 seconds after the initiation, an electrolyte fire ignites from electrolyte that had leaked from Cell 6, which caused a more sustained temperature increase in the Cell 2, 3, and 9 thermocouples. Several cells audibly vent during this test, but there is no evidence of thermal runaway in any cell other than Cell 6.

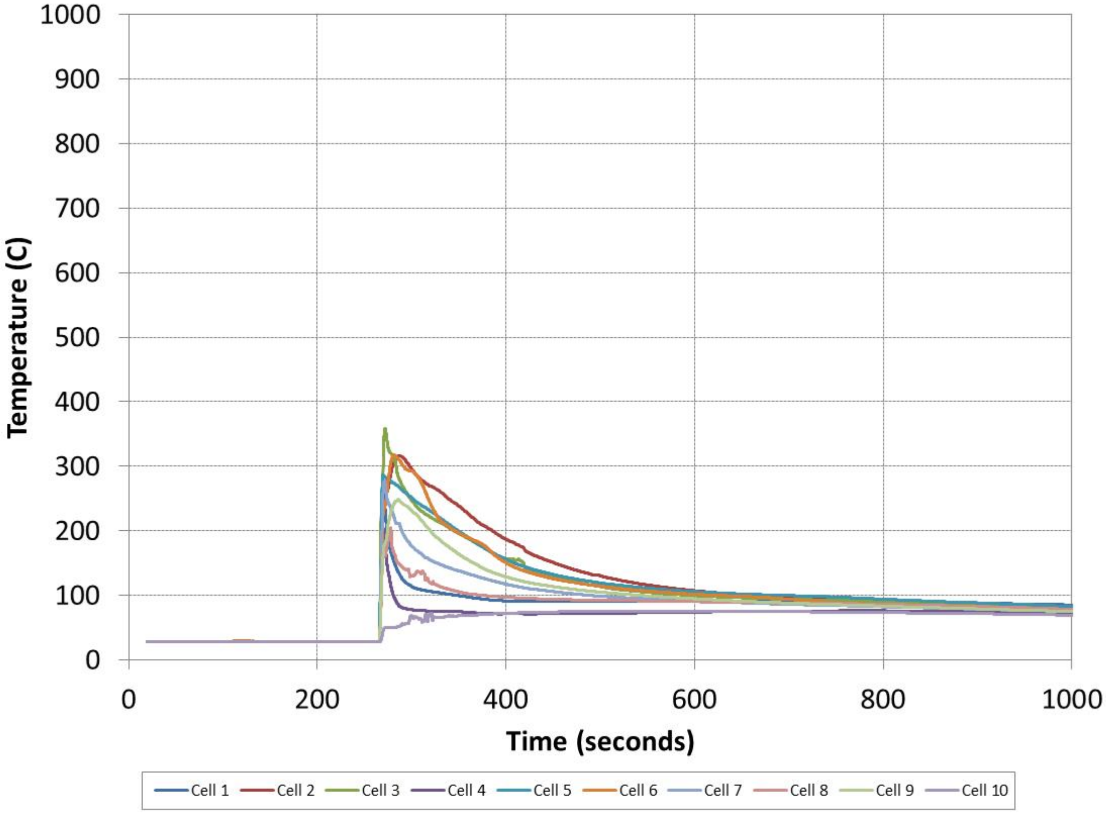

Figure 8. Cell skin temperature as a function of time during the 10S1P propagation test.

The pack and cell voltage responses of the 10S1P battery to the propagation test are shown in Figure 9. After the penetration of Cell 6, the voltages of Cells 1, 2, 3, 5 and 7 also drop, but recover during the test, with the exception of Cell 1. The Cell 8 voltage is also very noisy after the initial Cell 6 failure but settles out over time. The noise on this and perhaps other cell voltage channels could be due to heating from the initial fire that ignited after the Cell 6 failure. Interestingly, Cell 1 voltage is most affected by the Cell 6 failure and not an adjacent cell (5 or 7), but there is no evidence of thermal runaway of Cell 1. Figure 10 shows a picture of the battery after the test, which is completely intact. Thermal runaway failure initiated at Cell 6 clearly impacts the measured voltage of Cell 1, but no thermal runaway propagation to other cells is observed.

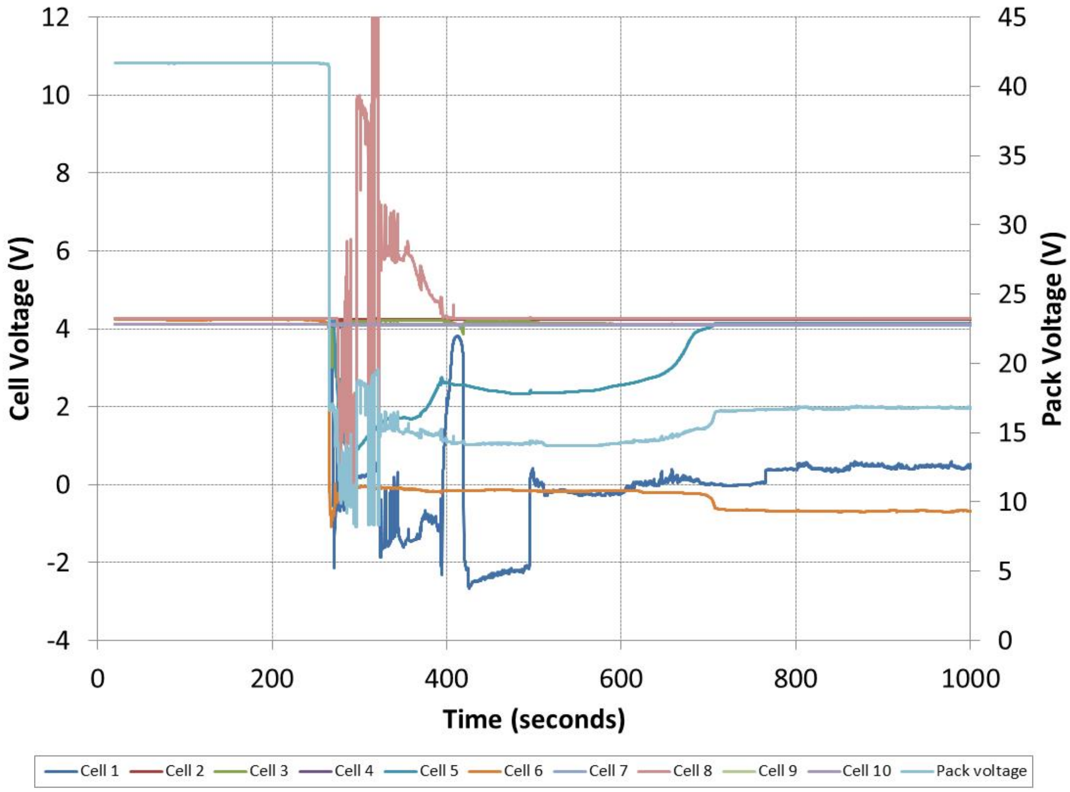

Figure 9. Cell and battery voltage as a function of time during the 10S1P propagation test.

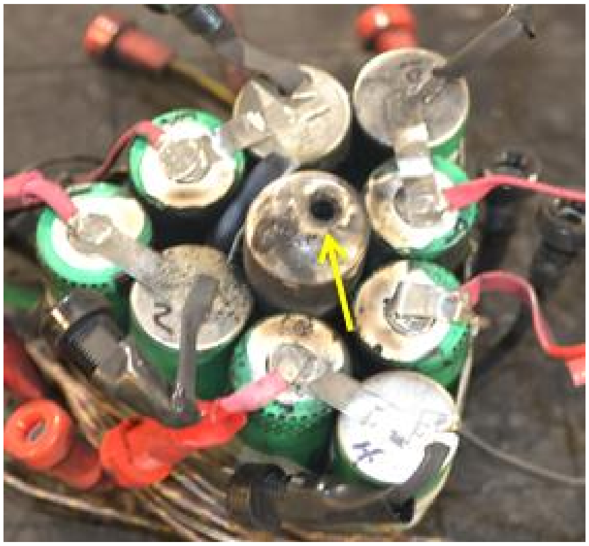

Figure 10. Photograph of the 10S1P battery post-propagation test showing the penetration of Cell 6.

3.2.2 1S10P

Figure 11 shows the cell skin temperature and Figure 12 shows the battery voltage during the 1S10P propagation test. Failure is initiated at Cell 6, which results in self-ignition and relatively small sustained electrolyte fire. This sustained electrolyte fire continues as cells vent and leak electrolyte over the course of several minutes. While there are elevated temperatures recorded by the thermocouples on the skin of each cell, there is no evidence of thermal runaway at times less than 400 s. Pack voltage is lost at approximately 200 s (Figure 12). At approximately 420 s, Cells 2 and 9 go into an energetic thermal runaway, and this failure quickly propagates through the rest of the battery (approximately 290 s after the initiation at Cell 6). Skin temperatures of the cells measured during the runaway are between 600-900 °C, with some thermocouples reading saturation at 1,270 °C (likely destroyed in the fire). Figure 13 shows the significant damage to the battery post-test. Unlike the 10S1P configuration, the failure of Cell 6 propagates completely through the 1S10P battery. This difference is attributed to the good thermal conductivity and heat transfer through the parallel connections of the copper current collectors of the 1S10P battery. The short created within Cell 6 in the parallel configuration also provides an external short to all other cells of the battery. This allows self-heating to occur within cells due to the sudden rapid discharge of the cells.

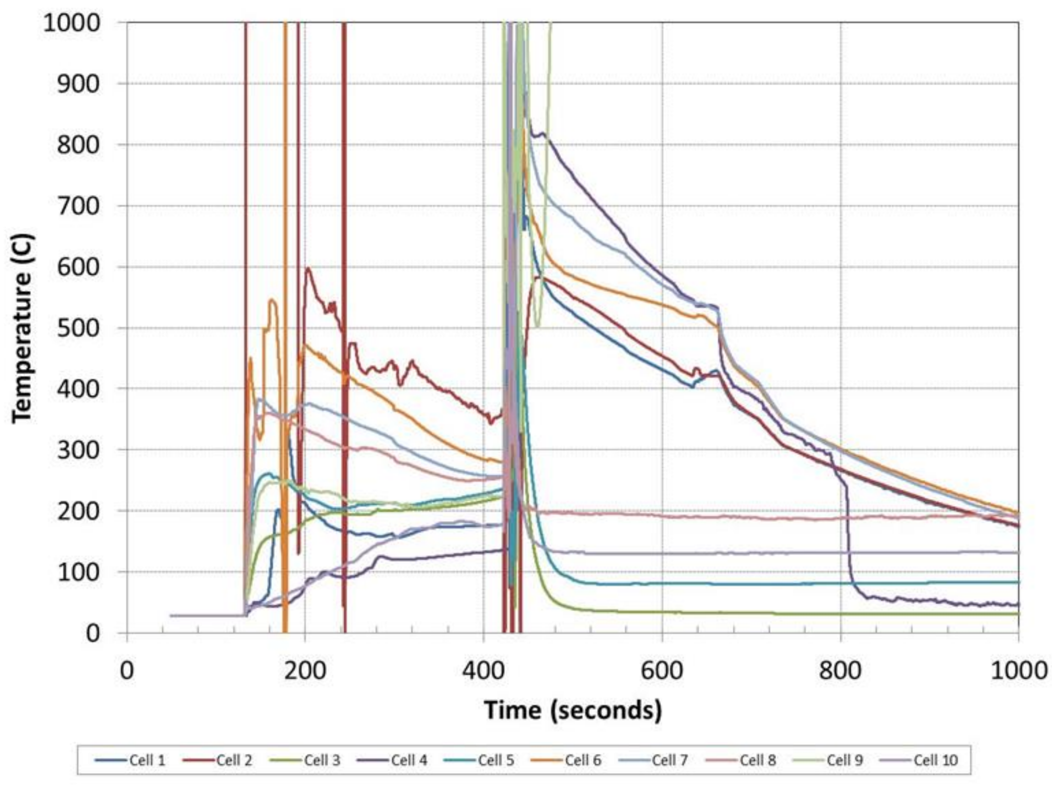

Figure 11. Cell skin temperature as a function of time during the 1S10P propagation test.

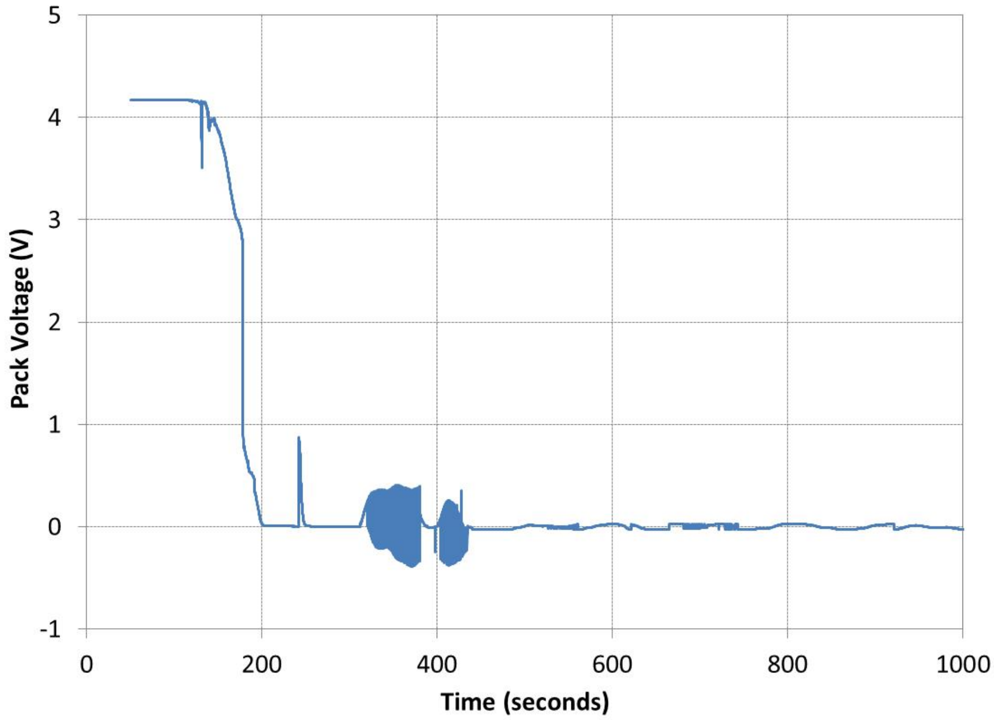

Figure 12. Battery voltage as a function of time during the 1S10P propagation test.

Figure 13. Photograph of the 1S10P battery post-propagation test.

3.3 Propagation Testing 5S1P and 1S5P Pouch Cell Batteries

Pouch cell batteries in the 5S1P and 1S5P configuration were built using commercial-off-the-shelf 3.0 Ah pouch cells. All tests were performed at 100% SOC at 25 °C with batteries constrained in fiber board fixtures to minimize swelling and deformation during the test. Failures were initiated at the center cell (Cell 3) and at the end of a cell string (Cell 1).

3.3.1 5S1P

The propagation test of the 5S1P pouch cell battery is initiated by a nail penetration at the edge of Cell 3. Thermocouples are placed between cells (labeled C1-2 for the thermocouple between Cells 1 and 2) and on the outside ends of the battery (Cells 1 and 5). Figure 14 shows the cell skin temperature and battery voltage as a function of time during the propagation test. Figure 15 shows the battery and individual cell voltages during the 5S1P propagation test. Nail penetration of Cell 3 results in a short circuit and a thermal runaway with a sharp temperature rise of the C2-3 thermocouple and a loss in the Cell 3 voltage. The failure propagates outward from Cell 3 to Cell 2, Cells 4 and 1, and finally Cell 5 with a full thermal runaway of the battery over the course of approximately 60 s. Figure 16 shows a picture of the 5S1P battery post-propagation test.

Results from the pouch cell and cylindrical cell batteries in the series configurations are notably different. The failure quickly propagates completely through the pouch cell battery but not in the cylindrical cell battery. This suggests that in the series pouch cell battery, propagation of failure is dominated by heat transfer from cell-to-cell because of the good thermal contact over the largest surface area of the cells.

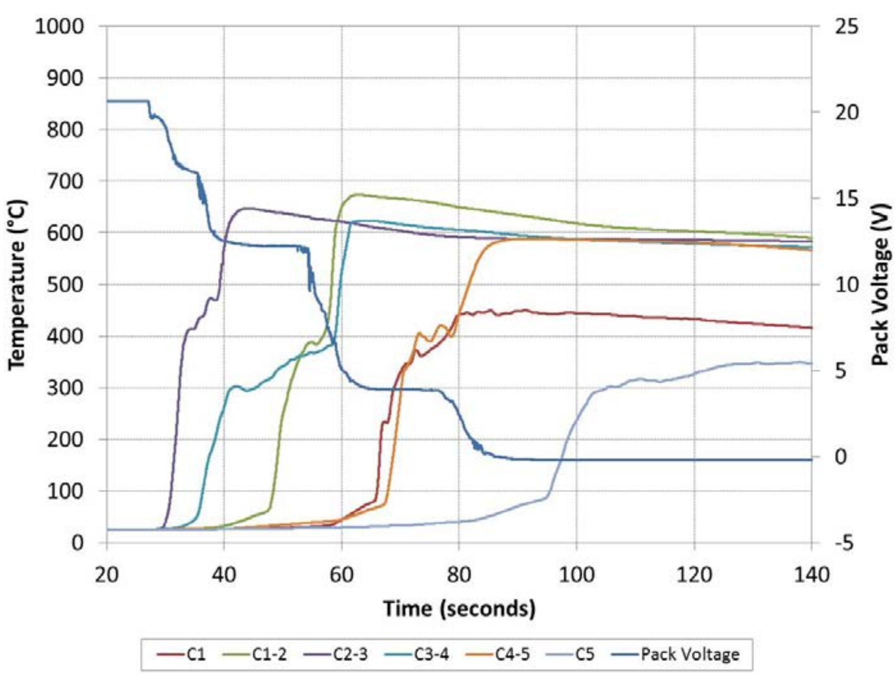

Figure 14. Cell skin temperature and battery voltage as a function of time during the 5S1P propagation test initiated at the center cell (Cell 3).

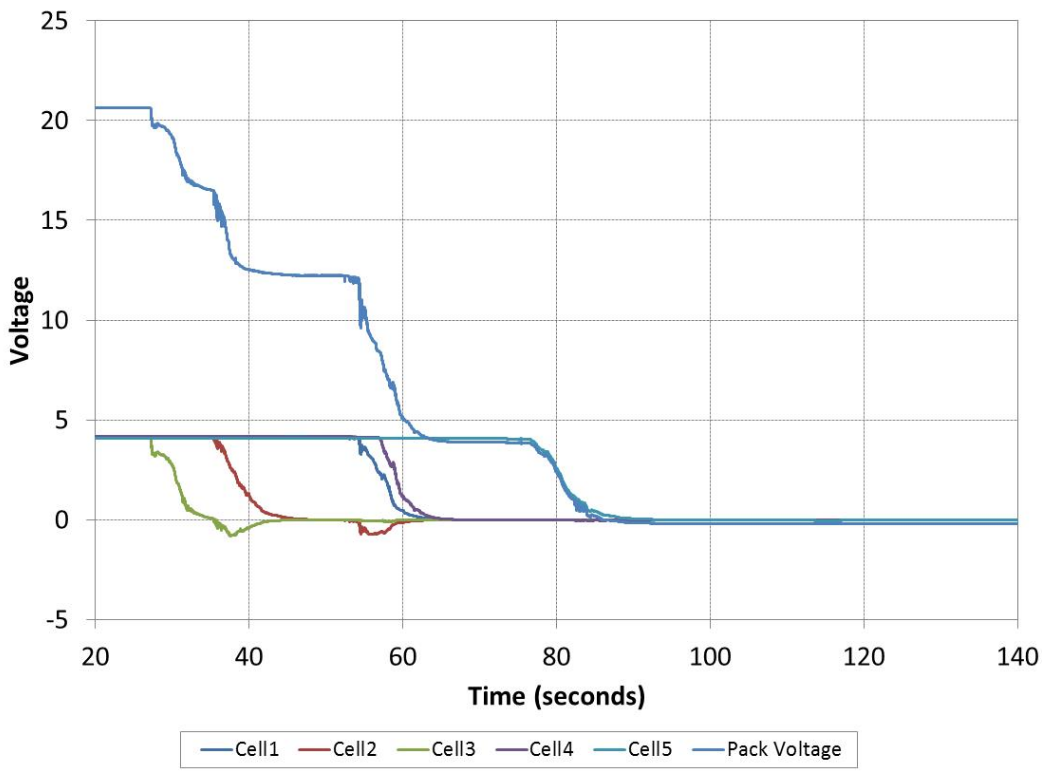

Figure 15. Battery voltage and cell voltages during the 5S1P propagation test initiated at the center cell (Cell 3).

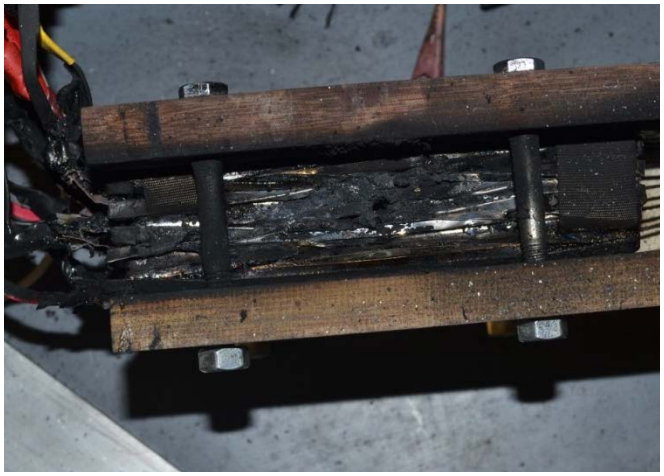

Figure 16. Photograph of the 5S1P battery post-propagation test initiated at the center cell (Cell 3).

With heat transfer through the surface area of the cells dominating the propagation process, initiation at the center of the battery is likely to be the most severe test condition. Failure propagation through the 5S1P pouch cell battery is also evaluated with initiation at the end of the battery (at Cell 1), which is expected to be a less severe condition. Figure 17 shows the cell skin temperature and battery voltage of the 5S1P propagation test initiated at Cell 1. Figure 18 shows the battery and individual cell voltages for this test. Nail penetration of Cell 1 results in a short circuit, a loss of cell voltage, and a thermal runaway of Cell 1, where the skin temperature is measured to be greater than 200 °C on the outside of the cell (C-1) and greater than 600 °C on the inside face of the cell (C1-2). Just as observed for the Cell 3 initiation experiment, failure propagates through the entire 5-cell battery when failure is initiated at Cell 1, resulting in full thermal runaway of the battery. The total propagation time is approximately 80 s, which is longer than observed for the propagation event when initiated at Cell 3. Since propagation takes place serially from one end of the battery to the other, it is rational to expect the duration of the propagation event to be longer than if initiation is triggered in the center of the battery. Even for initiation at the end of the battery, the heat transfer through the contact surface area between cells is still sufficiently high to cause the failure to propagate completely through the 5S1P battery. Figure 19 shows the remains of the battery after the 5S1P test initiated at Cell 1.

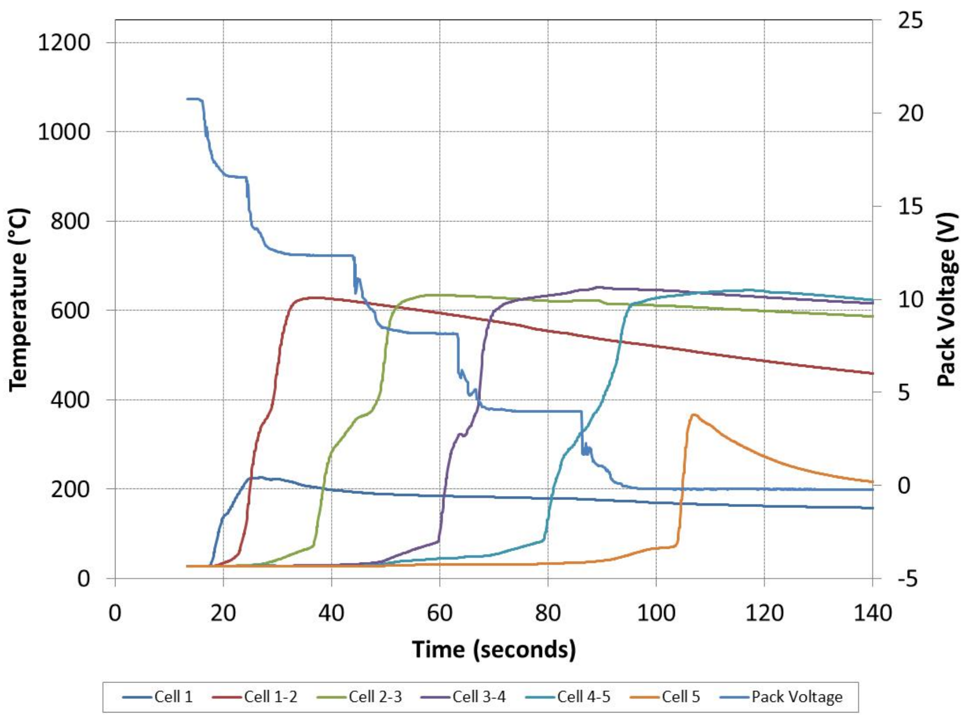

Figure 17. Cell skin temperature and battery voltage as a function of time for the 5S1P propagation test initiated at Cell 1.

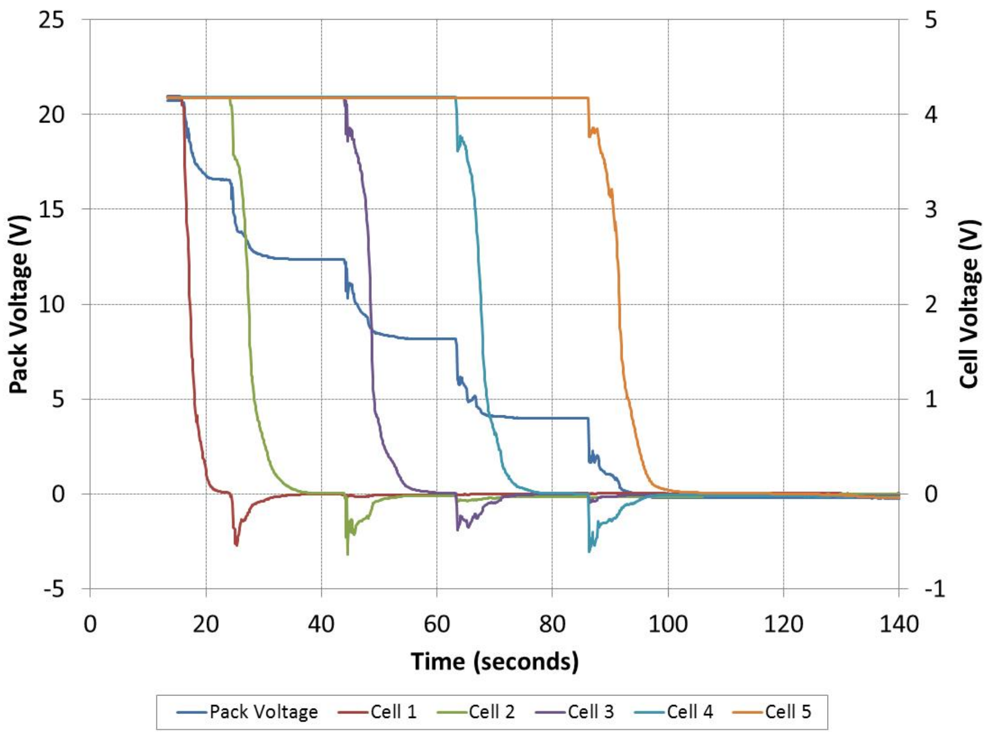

Figure 18. Battery and cell voltages for the 5S1P propagation test initiated at Cell 1.

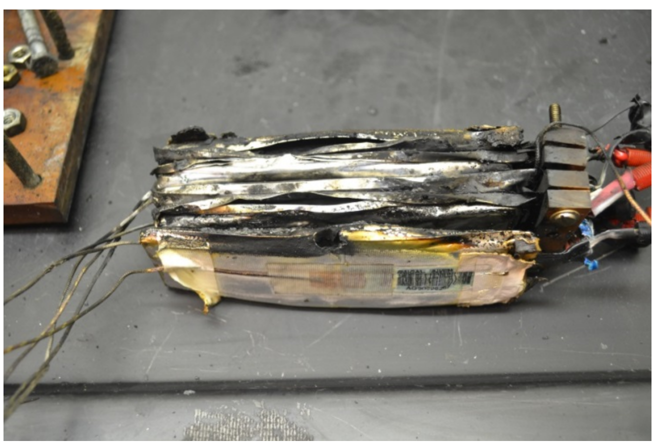

Figure 19. Photograph of the 5S1P battery post-propagation test initiated at Cell 1.

3.3.2 1S5P

Pouch cell battery failure propagation is also evaluated for batteries in the 1S5P configuration, where failure is initiated by nail penetration at the center of the battery (Cell 3). Figure 20 shows the cell skin temperatures and battery voltage for the 1S5P propagation test. As observed in the 5S1P experiments, failure propagates completely through the 1S5P batteries. Since the thermal conductivity through the copper current collectors of the 1S5P battery is better than that in the 5S1P configuration, one might expect the propagation to take place faster through the 1S5P battery. However, the propagation times through both batteries are comparable (approximately 50-60 s). This suggests that for relatively small batteries, the propagation behavior is controlled more by heat transfer through the surface area contact than by the electrical configuration.

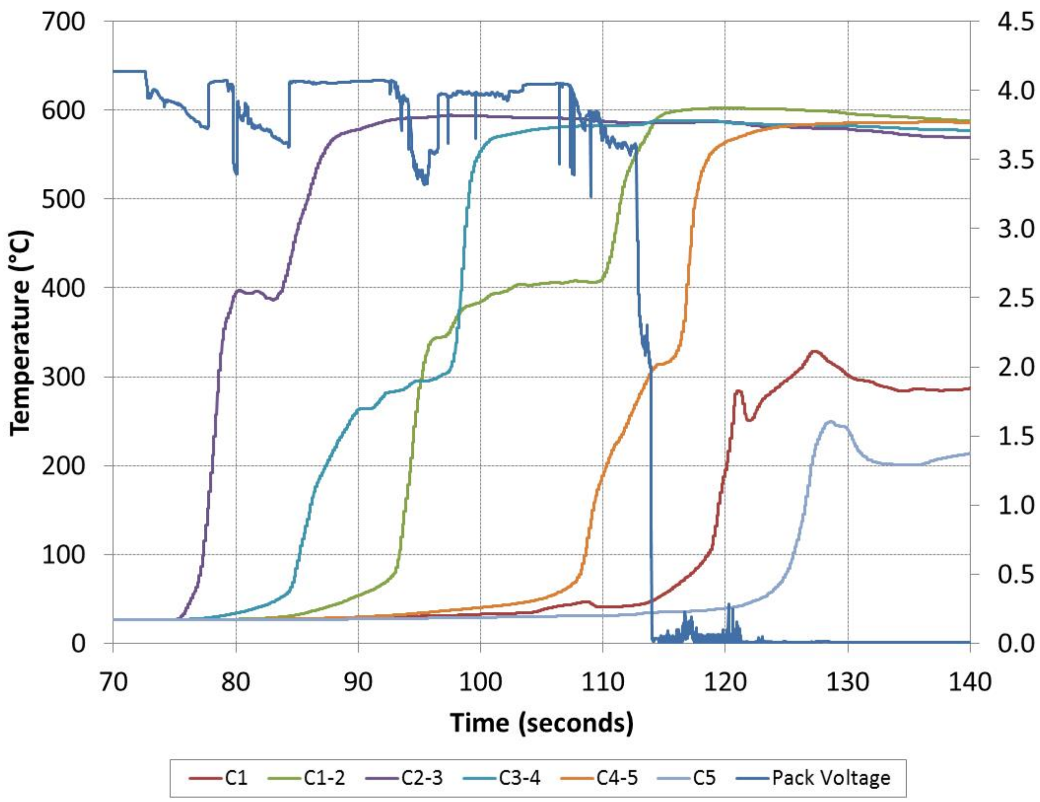

Figure 20. Cell skin temperatures and battery voltage for the 1S5P propagation test initiated at Cell 3.

4. SUMMARY

This report describes a test procedure for failure propagation in multi-cell lithium-ion batteries. In this procedure, it is important to select a failure initiation trigger based on cell-level empirical data that gives a reproducible thermal runaway failure response. It is also important that this initiation trigger be easily applied to cells packaged in a module or pack and that cells are accessible at different locations for testing.

This report also includes testing results on representative batteries of different cells types and electrical configurations. For cylindrical cell batteries, failure propagation is governed primarily by heat transfer through the electrical connections within a battery. Failure propagation is observed for parallel configured batteries with good thermal conductivity through the copper current collectors and not observed for the series battery analog. For pouch cell batteries, failure propagation is observed for all configuration types and for initiation at both the end and in the center of the battery. Results for pouch cell batteries suggest that propagation is dominated by heat transfer through the large surface area contact between cells.

Future work in this area will continue to evaluate failure propagation using other experimental initiation triggers; studying different cell types, sizes, and chemistries; evaluating more sophisticated battery designs (with passive and active controls); and simulating the propagation events for selected battery types and configurations.

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