Designs to Mitigate Thermal Runaway Propagation for Cells Packaged for Transportation

Tapesh Joshi and Judith A. Jeevarajan

Electrochemical Safety Research Institute (ESRI)
UL Research Institutes
5000 Gulf Fwy, UHTB, Bldg 4, Rm 230A, Houston, TX 77204
judy.jeevarajan@ul.org

Abstract

Lithium-ion cells may go into failure and thermal runaway due to off-nominal abuse conditions or defects. Incidents during transportation of batteries are causes of major concern due to the hazards from failure. The severity of hazards is magnified when thermal runaway from a single cell is propagated to other cells in a package. Interstitial separation between cells can be effective in preventing the propagation of thermal runaway from a single cell failure to other cells in a shipping package. Materials from different manufacturers were studied to evaluate the efficacy in preventing the propagation of thermal runaway at different state of charge (SOC). Block type material was effective in preventing further propagation of thermal runaway even in the fully charged conditions while other materials also were effective in preventing propagation of single cells at 33 % SOC. Conduction through the tabs resulted in worse outcomes at 33 % SOC for 25P electrically conducted configurations compared to single cells. Design considerations for testing to define the test end conditions and packaging requirements to allow pressure release through venting are also presented.

Keywords

battery safety; thermal runaway; propagation; mitigation; transportation

Introduction

The demand for lithium-ion batteries continues to rise to meet growing needs for powering personal devices to electric vehicles and energy storage systems. Shipment of li-ion cells and batteries is inevitable since these are manufactured in different parts of the world and shipped to end users. This provides safety challenges during shipping to the end-users if proper precautions are not taken. Mechanical, electrical, or environmental hazards occurring in a single cell could lead the cell into thermal runaway and, in worst cases, propagate to neighboring cells in a package or a battery[1]. Hazards such as gas and electrolyte leakage, elevated temperature, fire, and deflagration are possible during thermal runway in lithium-ion batteries[2]. Transportation guidelines and restrictions based on state of charge (SOC) are in place for transporting batteries. Despite transportation guidelines in place, there have been incidents leading to damages resulting from battery failures during shipping[3].

Effective test methods to study the propagation behavior and hazards for batteries in configurations used for shipments can inform improved design requirements for enhancing safety. Additionally, considerations for barrier materials and cell spacing are imperative in mitigating the propagation of thermal runaway. The current study focused on developing test methods and analyzed the effectiveness of several barrier materials to prevent thermal runaway propagation and contain it within the shipping container.

Experimental method and configuration

Commercial 18650 format lithium-ion cells were tested as 25 single cells (unconnected) and 25P electrically connected 5X5 configurations in shipping boxes (4.25” x 4.25” x 3.125”) as shown in Figure 1. The center cell was heated using a 40W tape heater with a target heating rate of 10 °C/min until the trigger cell went into thermal runaway or reached 200 °C. Cells were placed inside corrugated packaging box and tested at 100 % and 33 % state of charge (SOC) to test the worst-case scenario and maximum allowable SOC for shipping, respectively. Interstitial materials from different manufacturers were used to separate the cells from neighboring cells. Materials having different properties were tested in addition to a baseline case with air separation of 2 mm between cells. Testing was also conducted with secondary shipping packages resembling available shipping methods.

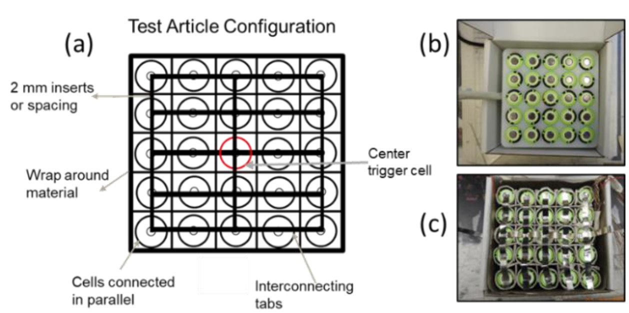

Figure 1. (a) Test article configuration showing the arrangements of 25 cells with trigger cell at the center of the configuration with inserts around each cell, (b) block-type phase change material and (c) combination of tubes and insert materials to separate 25P electrically connected cells in a shipping package.

Results and Discussion

Thermal runaway propagation at different SOC and test configurations and the effectiveness of the interstitial materials in mitigating these hazards are summarized in Table 1. For different materials, the expected trends of increasing hazards with increase in cell SOC were observed[2].

Baseline: Single cells separated by packaging paper inserts and 25P electrically connected cells separated by 2mm air were tested at 33 % SOC as baseline tests. Thermal runaway in the trigger cell was followed by no subsequent propagation for single cell configuration with no fire or charring on the outside of the packaging box. For the 25P electrically connected configuration, full propagation of thermal runaway with fire was observed as the worst-case scenario.

Manufacturers A, C, G: Interstitial materials were ineffective in preventing cell-to-cell thermal runaway propagation from the trigger cell to the neighboring cells. In all tests with materials as interstitial separators, full propagation of thermal runaway with fire occurred at 100 % SOC. Fire following the trigger cell thermal runaway and immediate propagation of the thermal runaway to all of the cells in the package was observed, as seen in Figure 2 for material from manufacturer G. Ejection of the jelly roll and sidewall rupture were also evident.

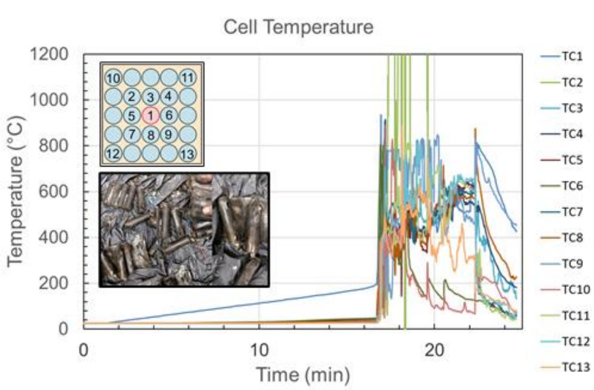

Figure 2. Cell temperatures and thermocouple layout for 100 % SOC test with interstitial material from manufacturer G. Inset shows post-test cell pictures with sidewall rupture.

At 33 % SOC for single cells and 25P electrically connected tests, the propagation of thermal runaway from the trigger cell to neighboring cells were prevented. The trigger cell went into thermal runaway and charring around the trigger cell location along with electrolyte leak was observed.

Manufacturer B: Structural support and the heat dissipation provided by the block material were effective in preventing further propagation of thermal runaway. Tests with and without an ejecta-control pouch placed on the top of the cell yielded no propagation of thermal runaway from the trigger cell to the neighboring cells. The pouch captured ejecta released from the trigger cell (inset Figure 3). For all 100 % SOC tests, the cells maintained pre-test voltage after the completion of the tests.

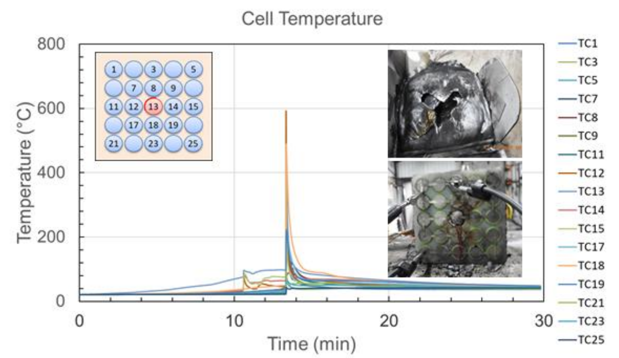

Figure 3. Cell temperatures and thermocouple layout for 100 % SOC 25P connected test with block material from manufacturer B.

Tests at 33 % SOC with the block material prevented full propagation of thermal runway from trigger cell to all of the cells in the package. For single cells test, there was no propagation from the trigger cell to the neighboring cells. Thermal runaway on the trigger cell was followed by the ejection of the jelly roll and fire, but no further thermal runway was observed. In case of 25P connected test, heavy gas and electrolyte release was observed. Although full propagation was prevented, some of the neighboring cells went into thermal runaway.

Manufacturer D, H: Interstitial materials configured in interlocking grid-pattern from manufacturers D and H showed volume expansion during tests, but the propagation of thermal runaway and fire was not mitigated. The materials charred and burned lacking structural support. Full propagation of thermal runaway with ejected contents and sidewall rupture was observed.

Single cell tests as barrier between the cells prevented full propagation of thermal runaway in case of single cell, however, full propagation of thermal runaway occurred in 25P electrically connected case. Heavy gas and electrolyte release was observed for 25P electrically connected test and the conduction through the tabs led to worse outcome compared to the single cell configuration.

Secondary containers: Inherently safe packaging design with mitigation materials that can prevent the propagation of thermal runaway from cell-to-cell in cases of off-nominal abuse and incidents are ideal. In transportation, secondary containers that can withstand cell failures and contain the ejecta, fire, and heat within the package are desired. Tests with three such packaging designs highlighted successful packaging design and failure modes.

Table 1. List of materials, SOC and configurations for the different tests and propagation outcomes.

Manufacturer	**Medium**	**SOC/Configuration**	**Propagation**
Baseline	Interlocking paper insert	33 % (single)	N
Baseline	Air	33 % (25P)	Full
A	Interlocking separator	100 % (25P)	Full
B	Block	100 % (single)	N
B	Block	100 % (25P)	N
B	Block	33 % (single)	N
B	Block	33 % (25P)	Partial
C	Interlocking separator	100 % (25P)	Full
C	Tubes	100 % (25P)	Full
C	Interlocking separator+ tubes	100 % (25P)	Full
C	Tubes	33 % (single)	N
C	Tubes	33 % (25P)	N
D	Interlocking separator-2mm	100 % (25P)	Full
D	Interlocking separator-4mm	100 % (25P)	Full
D	Interlocking separator-2mm	33 % (single)	N
D	Interlocking separator-2mm	33 % (25P)	Full
D	Interlocking separator-4mm	33 % (single)	N
D	Interlocking separator-4mm	33 % (25P)	Full
D	Interlocking separator	33 % (single)	N
E	Interlocking paper insert (Secondary box)	100 % (single)	N
F	Cell sleeves, separators (Secondary box)	100 % (25P)	Full
G	Interlocking separator-2mm	100 % (25P)	Full
G	Interlocking separator-4mm	100 % (25P)	Full
G	Interlocking separator-2mm	33 % (single)	N
G	Interlocking separator-2mm	33 % (25P)	N
H	Interlocking separator	100 % (25P)	Full
I	Silica granules (Secondary box)	100 % (25P)	Full
I	Silica granules	33 % (single)	N
H	Silica granules	33 % (25P)	Full

Thermal runaway propagation and hazards were mitigated for manufacturer E. For manufacturer F, delayed thermal event after more than 5.5 hours since the beginning of the test was noted (Figure 4a). The dangers of delayed propagation of thermal runaway and the need to design test completion criteria to account for stranded energy and to ensure safety of personnel and equipment is highlighted from this test. In Figure 4b, the secondary package from manufacturer I did not contain pressure relief vents for releasing excess gas build-up within the container. As gases accumulated after cell failures due to thermal runaway in the package, deflagration and fire resulted in the package.

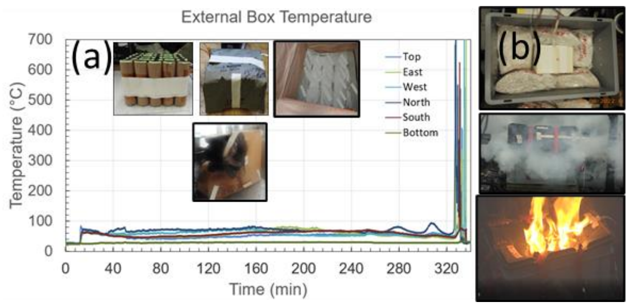

Figure 4. (a) External box temperature showing delayed thermal event within the box. Inset shows test article preparation and placement within secondary container and fire at the end of the test. (b) Pictures showing placement of test article within the secondary container and pressurized gas release and fire due to a lack of venting mechanism in the secondary box.

Table 2 lists the material properties of the interstitial materials used in the tests. These properties were shared by the manufacturers and the missing property values were not reported or shared.

Conclusions

Mitigation materials from different manufacturers were tested to study the efficacy in preventing the propagation of thermal runaway to neighboring cells in a shipping package configuration. Interstitial material with a block/ mold design that provided structural support to the cells and effectively dissipated excess heat prevented thermal runaway propagation for worst-case scenario at 100 % SOC. Single cell configurations tests with materials from all manufacturers were tolerant to abuse and prevented propagation of thermal runaway and fire at 33 % SOC. For 25P electrically connected configuration at 33 % SOC, tab-conduction contributed to worse outcomes including full propagation for some manufacturers. For tests including secondary containers, manufacturer E was effective in preventing propagation while the other manufacturers underwent full propagation with fire. Because of the nature of the hazards present, a combination of fire retardation, insulation, and heat dissipation is desired to effectively prevent the propagation of thermal runaway.

Table 2. List of material properties for interstitial materials used in the tests.

Materials	**Thermal Conductivity (W/m.K)**	**Phase Transition Temperature**
Manufacturer A (Kaowool)	0.06 (260 ºC) 0.12 (538 ºC)	-
Manufacturer B Block/Mold	0.65	122 ºC
Pouch	0.74 (xy plane)	95-110 ºC(Thermal Dissipation – 1600 -2000 J/g)
Manufacturer C Flexible Mica Tubes	0.04 (22 ºC); 0.15 (816 ºC)	-
Flexible Flame Barrier	0.2 (200 ºC); 0.35 (400 ºC)	-
Manufacturer D Intumescent cell separators	0.54	Expansion Temp: 200 ºC
Intumescent flat sheets	0.54	Expansion Temp: 200 ºC
Manufacturer G	0.024 (0 ºC) 0.054 (600 ºC)	-
Manufacturer I	0.06 (20 ºC)	-

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References

1.Jeevarajan, J. A.; Joshi, T.; Parhizi, M.; Rauhala, T.; Juarez-Robles, D., Battery Hazards for Large Energy Storage Systems. *ACS Energy Letters* **2022,** *7* (8), 2725-2733.

2.Joshi, T.; Azam, S.; Lopez, C.; Kinyon, S.; Jeevarajan, J., Safety of Lithium-Ion Cells and Batteries at Different States-of-Charge. *Journal of The Electrochemical Society* **2020,** *167* (14), 140547.

3.Kapp, E. A.; Wroth, D. S.; Chapin, J. T., Analysis of Thermal Runaway Incidents Involving Lithium Batteries in U.S. Commercial Aviation. *Transportation Research Record* **2020,** *2674* (11), 584-592.