INTRODUCTION OF A BATTERY ENCLOSURE THERMAL RUNAWAY MATERIAL SCREENING PROGRAM FOR ELECTRIC VEHICLES

Amanda Nummy
Hyundai Motor Company
Adam Halsband
Forward Engineering North America

Abstract

Early in the design process for high-voltage battery enclosure development, materials engineers must establish a set of pre-qualified materials that can support a capable enclosure design across all load cases and failure modes. One of the most challenging failure modes the engineering team must contemplate is the thermal runaway event. To ensure their product development team continues to have the most capable portfolio of materials to draw from for next-generation electric vehicle platforms, the Materials Development Department at the Hyundai-Kia America Technical Center led the exploration for and development of a state-of-the-art battery enclosure thermal runaway material screening program, with support from Forward Engineering and Underwriters Laboratories (UL). This paper will describe the basis of the technical requirements at a system-level, background on the landscape of test protocols identified, and an outline of the new protocol developed, including results from a cross section of materials using the new test protocol. The results to date demonstrate a repeatable and capable test protocol for material-level screening of thermal runaway performance.

Background and Requirements

Designing battery systems to mitigate thermal runaway (TRA) is necessary to ensure safety of electric vehicle occupants. Several global standards are available to guide the assembly- and vehicle-level performance of battery systems. The latest global standards include specifications for evaluating TRA mitigation when initiated from a variety of methods. The thermal management test protocols for those standards most commonly recognized by automotive industry stakeholders are summarized as follows:

- UL 2580 calls for containment of any fire or explosion, at the pack level, for one hour after initiation of thermal runaway, providing a number of different mechanisms to initiate the event [1].
- GB 38031-2020 requires an alarm that provides five minute warning before any visible fire or explosion to allow for passenger exit, does not specify a means for initiation, and is relevant for the cell, module, pack, and vehicle levels [2].
- ECE R100 (Rev2) verifies internal over-temperature protection during charge/discharge based on stabilization of temperature or inhibition of operation by protection devices, and includes information at the pack and vehicle level [3].
- ECE GTR 20 Addendum similarly requires a five-minute alarm before a thermal propagation hazard for vehicle occupants [4].

The above listed standards primarily focus on system-level performance, evaluating how a pack behaves when exposed to a set of conditions. It is up to each individual producer to determine how these system-level standards translate to their own technical requirements, which guide enclosure design and materials of construction. The materials department at each producer is typically responsible for the qualification of materials for each application on the vehicle. To populate the qualified list of materials for the battery enclosure, the materials department must identify or develop appropriate material-level screening and/or validation tests protocols. These test protocols allow the team to evaluate candidate materials at a plaque or coupon level prior to initiating resource- and time-intensive prototyping and system-level testing.

At the outset of this program, the team considered what conditions would be present in the event of a TRA within a high-voltage battery electric (HV BE) vehicle in order to benchmark existing test protocols against the expected real-world conditions. Focusing on the battery enclosure resistance to a TRA event, the team considered what happens when the energy storage cells/modules enter a TRA condition. It is clear that cell chemistry, format, and energy density will continue to evolve. With this in mind, the primary objective was to identify TRA conditions that are relevant to current technologies, which would inform current product development and provide a relevant and repeatable data point for future analysis.

When commercially available chemical battery cells enter a TRA condition, an exothermic reaction produces a large volume of hot gases carrying particles at high velocity and temperature. If the TRA event is contained, there is the potential to create a significant increase in pressure proportional to the expanding gases and inversely proportional to the available path to atmosphere. Therefore, in order to screen potential materials, the test conditions must include exposure to temperature, pressure, and ablative forces on par with those seen in a real-world TRA event. The team canvased the market, reaching out to testing firms as well as materials and tier suppliers to understand the state-of-the-art for TRA testing. From a cross section of industry stakeholders, it was evident that the topic of TRA testing is of acute interest, and that there was no clear consensus on best practices or examples of test protocols that met the team's requirements.

In general, the plaque-level tests that were identified fell into two categories: torch exposure and torch with media exposure. The torch test methods outline placing an oxy acetylene (or equivalent) torch at a specified distance from a target specimen. The flame temperature is controlled to a target value and the backside of the specimen is monitored for temperature rise and burn through. The torch test with media is a variation including the addition of an ablative media focused at a target area on the specimen. In this test, the flame and media are alternated with different frequencies for a given number of cycles, again with the specimen monitored for temperature on the backside and burn through. While the torch test with media does include both temperature and ablative forces, neither test incorporates the expected increase in pressure on the specimen that would be seen in the real world application.

In order to address these shortcomings, an enclosed specimen-level test method was developed that allows for repeatable testing of materials under the combined effects of temperature, ablation, and pressure. The goal of the newly developed test method was to quantify material endurance to representative real-world conditions in order to inform pack design. By having an early material screening program, design and assembly considerations can be made to enable new materials, balancing system cost and weight while maintaining performance. This method also allows quick iterations to evaluate many different materials, as small test panels can be used rather than full prototypes. Furthermore, it is more accessible to material suppliers and can therefore aid in next-generation material development compared to the resources needed for system-level testing.

Materials and Method

As highlighted above, the team recognized that battery cell chemistry is, and would be, continuously evolving. With that in mind, they sought to select a representative and capable proxy for the battery cell in the new test protocol. Due to a number of factors, including relative energy density, commercial availability, consistency, and expected long-term availability, the team selected 18650 lithium ion (Li-ion) cells to build this test apparatus.

A test apparatus consisting of a 5-sided welded plate steel box with bolted perimeter flange was designed and fabricated, as illustrated in Figure 1. A test panel of 200 mm x 200 mm x 2 mm is secured to the top of the box and retained by a plate steel bolted flange. The actual chamber area the samples are exposed to is 100 mm x 100 mm. A sample thickness of 2 mm was selected based on relevant application design values and provides a capable plaque size to work with. A 5 x 5 array of 18650 Li-ion cells are enclosed within the box. The resulting free volume and energy density of the test assembly corresponds to typical designs across the industry.

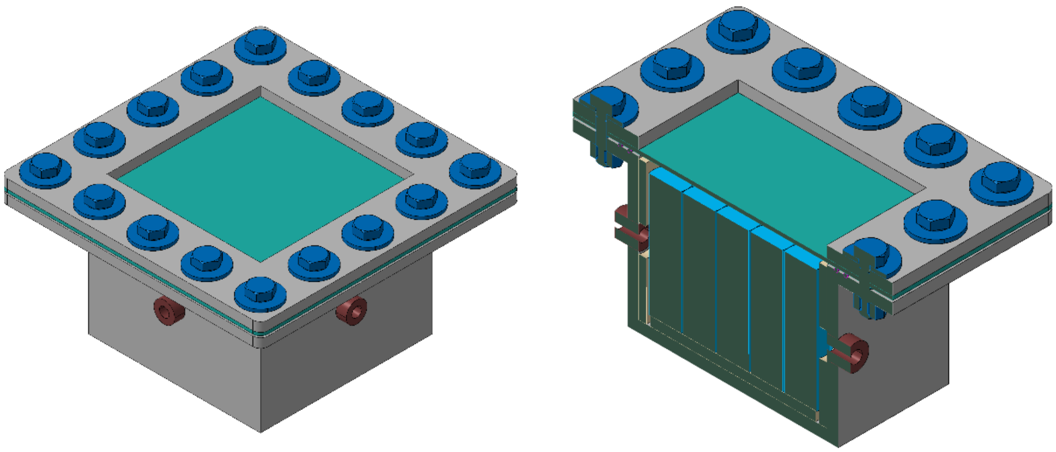

Figure 1: Test apparatus (left) and cross section showing battery array (right). Source: Forward Engineering.

To safely emulate different pressure levels potentially seen in an HV BE, a key challenge for the test development was designing a means to repeatably and capably control pressure within the enclosure to a representative level. After much consideration, and debate around target pressures, the team selected a static flat plate orifice to control the peak pressure in the test enclosure. By fabricating plates of several orifice sizes that can be interchanged on the test apparatus, a series of tests can be run at different pressures to comprehensively populate a materials portfolio for design engineers. Calculations were made based on the expected gas release from the 18650 Li-ion cells to estimate orifice sizes to realize a range of target pressures. A series of trials were run with different size orifices to confirm appropriate orifice sizes for the relevant enclosure pressures. The tests run to date demonstrate that a repeat of three specimens is able to bracket the targeted pressures for each of the selected orifices. The selected orifice sizes and nominal pressures are listed in Table I below.

Table I: Summary of test pressures and corresponding orifice sizes.

Nominal Peak Pressure	Orifice Size
250 kPa	16.0 mm
500 kPa	10.7 mm
1 MPa	10.0 mm

To achieve the objective of a controlled and repeatable initiation of TRA, the team selected to employ thermally induced runaway. To accomplish this, two resistive heaters were wired in series and wrapped around the two centermost cells in the array. The cells are heated at a rate of 6 °C per minute until the TRA event is initiated, when the rate of temperature rise exceeds the heating rate. A control unit with P&ID control algorithm modulates power to the heaters, using feedback from a thermocouple placed on the center most cell to ramp the cell temperature up at the target rate, progressively reducing power to the heaters as the runaway event is detected.

With the exception of the specified flat plate orifice, the enclosure is sealed. All thermocouple wires and heater power lines are routed through a sealed pipe pass through. Redundant pressure transducers (200 psi and 500 psi) are connected to the enclosure through pipe fittings. These sensors are oriented at 90 degrees to the cells in the enclosure to avoid damage to the transducers. A flat silicone gasket is placed between the specimen and enclosure top flange. The flange bolts are torqued to spec in a uniform fashion to ensure proper sealing of the specimen panel.

The test apparatus is instrumented with thermocouples to measure temperature during the test at three locations. One thermocouple is located at the side of the trigger cells in the center of the array and a thermocouple probe is mounted to the side of the enclosure through the pipe fittings to provide a measure of internal temperature. Another thermocouple is taped to the center of the top surface of the test specimen to provide external surface temperature. A linear variable differential transducer (LVDT) is also placed at the center of the test specimen to measure vertical displacement. The LVDT is mounted on a frame secured to the base of the enclosure, and the tip of the LVDT is placed on the surface of the test specimen. High-speed data is collected throughout the initiation of TRA and for at least five minutes following TRA initiation. High-definition video is recorded throughout the test, and pictures of the samples are taken before and after, including of the top and bottom side of the test specimen.

For the initial series of tests to explore the potential of this new method, a variety of test materials were selected including conventional steel as well as polymer composites. The polymer composite materials included both baseline reinforced resins as well as production-intent materials integrated with electromagnetic interference (EMI) shielding strategies. A high-level overview of the materials tested are outlined below in Table II.

Table II: Materials demonstrated for development of new thermal runaway screening test protocol.

Material	Reinforcement
Steel	None
Thermoplastic	Discontinuous Glass Fiber
	Continuous Glass Fiber
Thermoset	Discontinuous Glass Fiber
	Continuous Glass Fiber
Metal/Polymer Sandwich	Discontinuous Glass Fiber
	Continuous Glass Fiber

Results

Calibration testing was conducted at a targeted peak pressure of 1 MPa. Based on initial observations, it was determined additional iterations at lower pressures would provide value, to develop a more robust set of data for enclosure design. For a second round of testing, the starting point for the targeted peak pressure was 250 kPa. If specimens did not yield, a second set of panels were tested at a targeted peak pressure of 500 kPa.

Qualitative and quantitative assessments were made during and after testing. During the test, panel yield is evident by the emission of flames or plasma from the top side of the test assembly, as shown in Figure 2. Post-test disassembly was performed for a qualitative assessment of the panel surface, inspecting for areas where the panel yielded or was near yield, as well as observing effects of temperature, pressure, and ablation on the material and reinforcement, as shown in Figure 3.

Figure 2: Evidence of panel yield during test.

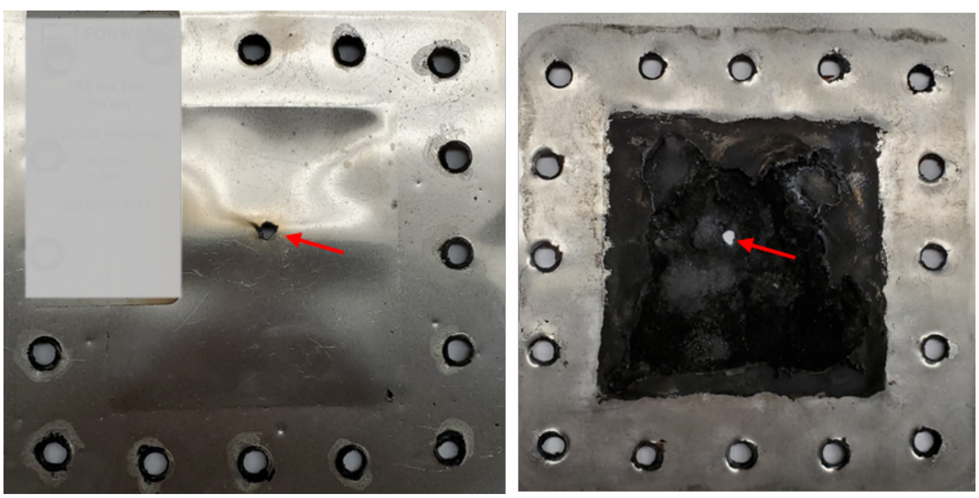

Figure 3: Panel yield, indicated by arrow, on top (left) and material degradation on bottom (right) sides of specimen.

Summary and Next Steps

To organize test results and provide the design team with the sought-after set of screened materials, the materials department prepared and maintains a TRA test performance matrix, as illustrated in the redacted Table III below. This tool allows the design team to choose from capable materials and constructions across a range of performance requirements based on each application's unique requirements.

Table III: Example of test performance matrix.

SUPPLIER	TYPE	Sample Description	"250 kPa" (16.0 mm)	"500 kPa" (10.7 mm)	"1 Mpa" (10.0 mm)	Ignition[1]	Notes
	TPGF	3mm TPFRP Sample #8	G*	G*	Yield	Yes	Yield recording peak pressure of 550 kPa, ignition from yield and radient heat of cells
	SMC	2mm TSFRP Sample #11	G*	Yield		No	Yield recording peak pressure of 414 kPa
	SMC	2mm TSFRP Sample #14	G*	Yield		No	Yield recording peak pressure of 379 kPa
	SMC + GFRT	2mm TSFRP Sample #12	G	G	G	No	Peak recorded pressure of 861 kPa
	SMC + GFRT	2mm TSFRP Sample #13	G	G	G	No	Peak recorded pressure of 958 kPa
	TP OS GFRT	2mm TPFRP Sample #15	Yield	Yield		No	Gas permeation/venting began mid way through TRA event (see video), recorded peak pressure of 496 kPa
	TP OS GFRT	2mm TPFRP Sample #16	Yield	Yield	Yield	No	Gas permeation/venting began mid way through TRA event (see video), recorded peak pressure of 758 kPa
	TPGF/AL	2mm Sandwich Sample #17 - Repeat 1	Yield			No	Peak recorded pressure of 168 kPa
	TPGF/AL	2mm Sandwich Sample #18 - Repeat 2	Yield			No	Complete perforation through sandwich, recording peak pressure of 132 kPa
	TPGF/AL	2mm Sandwich Sample #19 - Repeat 3	Near Yield			No	Partial peforation through lower 2/3rds of sample, recording peak pressure of 253 kPa
	TPGF/AL	2mm Sandwich Sample #20	Yield*	Yield		No	Complete perforation through sandwich, recording peak pressure of 218 kPa
	Al/TSGFRT	2mm Sandwich Sample #21 - Repeat 1	G			No	Peak recorded pressure of 338 kPa
	Al/TSGFRT	2mm Sandwich Sample #22 - Repeat 2	G			No	Peak recorded pressure of 189 kPa
	Al/TSGFRT	2mm Sandwich Sample #23 - Repeat 3	G			No	Peak recorded pressure of 215 kPa
	Al/TSGFRT	2mm Sandwich Sample #24 - Repeat 1	G*	Yield		No	Delamination of sandwich, peak recorded pressure of 786kPa
	Al/TSGFRT	2mm Sandwich Sample #25 - Repeat 2	G*	G		No	Peak recorded Pressure of 646 kPa
	Al/TSGFRT	2mm Sandwich Sample #26 - Repeat 3	G*	G		No	Peak recorded Pressure of 744 kPa

1) Ignition - Does sample ignite during test as a function of TRA event and/or post TRA residual energy
*Projected based on results from higher-pressure test condition

These preliminary results demonstrate a capable and repeatable test protocol as an effective screening tool for a variety of battery enclosure material specimens. Since the first series of tests were conducted in 2020 the team has, along with industry suppliers, completed TRA testing on a broad mix of sample materials and formats using this new protocol. The results to date have provided visibility to those sample materials and formats which are candidates for HV BE applications and those that are not viable candidates for the test conditions defined.

Thanks to the successful trials and response from the industry, the UL team has fabricated three new test apparatuses to incorporate lessons learned which allow the tests to be run more efficiently. Looking forward, the team will use insights gathered from the tests executed to date to help guide supplier partners with the preparation of relevant candidate materials for testing, and continue to expand the performance matrix as a design tool. By understanding the TRA performance representative of real-world conditions, considerations can be made in material development and enclosure design to enable new opportunities in material selection.

Acknowledgements

The author wishes to thank the team at Underwriters Laboratories and Forward Engineering for their expertise and efforts in developing this new test method. Additionally, the author would like to acknowledge the Materials Development Department at the Hyundai- Kia America Technical Center and the Exterior Plastics and Powertrain Team at the Namyang R&D Center for their support.

Bibliography

1. Underwriters Laboratories. “Batteries for Use in Electric Vehicles.” *UL Standards*, Standard 2580, Edition 3, 2020.
2. State Administration of Market Supervision (SAMR), Standardization Administration of the People’s Republic of China. “Electric vehicles traction battery safety requirements.” *National Standard of the People’s Republic of China*, GB 38031-2020, 2020.
3. United Nations Economic Commission for Europe (UNECE). “Uniform Provisions Concerning the Approval of Vehicles with Regard to Specific Requirements for the Electric Power Train.” *Official Journal of the European Union*, Regulation No. 100 (R100). Revision 2, 2013.
4. UNECE. “Global Technical Regulations on Electric Vehicle Safety.” *United Nations Global Registry*. Global Technical Regulations (GTR), Regulation No. 20. 2018.