

Experimental Investigation of Thermal Runaway Propagation in Lithium-ion Battery Modules for Electric Propulsion Systems: A Comparative Study of Two Packing Configurations

SuHo Yu^{1*}, Yu-Jin Jung^{1**}, Bum-Dong Cho¹, Jun-Uk Kim¹, and Joo-Sung Lee¹

¹*V-AEROSPACE Co., Ltd., Seoul, Republic of Korea*

*E-mail: yoosuh097@gmail.com

**E-mail: rhdehfl9@gmail.com

Abstract

Thermal runaway propagation in lithium-ion batteries is a critical safety concern for urban air mobility and other electric propulsion aircraft. Because pack-level thermal runaway testing involves various practical constraints, this study experimentally analyzed cell-to-cell thermal runaway propagation characteristics at the module level using 14S1P battery modules composed of 90 Ah-class lithium-ion polymer cells. Three module-level tests were conducted under nominally identical trigger conditions but with two different packing configurations: a conventional configuration widely used in ground-vehicle applications (two tests), and an improved configuration incorporating an inter-cell fire-retardant barrier layer together with an aluminum heat-sink structure (one test). Thermal runaway was artificially induced by attaching a resistive heating pad to the centrally located cell of each module, and the temperature and terminal voltage of each instrumented cell were recorded at 1 s intervals. In the conventional configuration, thermal runaway of the target cell occurred at 4 min 35 s and 4 min 53 s respectively, and propagation to the first adjacent cell followed only 12 s and 29 s. In the improved configuration, the target cell entered thermal runaway at 3 min 05 s, whereas propagation to the first adjacent cell occurred at 15 min 28 s from test start, corresponding to a propagation delay of 743 s. Under the tested conditions this represents an increase of approximately 26 to 62 times relative to the conventional configuration and satisfies the 5-minute criterion specified in GB 38031-2020 and UN GTR No. 20. Peak local thermocouple readings reached 885.8 °C on the target cell and 763.6 °C on the first adjacent cell in the improved configuration; several channels exceeded the measurement range during the tests, and the reported values are therefore treated as conservative lower bounds. These results quantitatively characterize cell-to-cell thermal runaway propagation and provide baseline data for the design of thermal management systems and inter-cell insulation of battery modules for electric propulsion aircraft.

Keywords: Electric Propulsion System, Lithium-ion Battery, Thermal Management, Thermal Runaway Propagation, Urban Air Mobility

1. Introduction

Urban air mobility (UAM) and other electric propulsion aircraft rely almost entirely on lithium-ion batteries as their primary energy source. Compared with ground vehicles, these platforms impose a fundamentally different safety requirement.

When a battery fire occurs in a road vehicle, the occupants can normally stop and evacuate within a short time. In flight, however, evacuation is not possible, and the aircraft must remain controllable until a safe landing is completed. A single-cell thermal runaway (TR) event that propagates rapidly through the pack can therefore lead directly to a catastrophic accident.

*Presenting Authors SuHo Yu

**Corresponding Authors Yu-Jin Jung

Nickel-rich NMC chemistries are widely adopted for aviation applications because they offer the gravimetric energy density required for practical flight endurance. The same chemistry, however, releases a large amount of energy once TR is initiated. Feng et al. [1] summarized the chain of exothermic reactions that follows separator failure in nickel-rich cells, and Wang et al. [2] reported that the resulting fire and explosion behavior is significantly more severe than for lithium iron phosphate. Experimental studies on pouch-type modules without any inter-cell barrier have consistently reported very short propagation intervals: Lamb et al. [4] observed that failure consumed an entire pouch-cell battery within 60 to 80 s because a large surface area of each cell was in direct contact with its neighbors, and a recent module-level study on 55.6 Ah NMC-622 pouch cells reported propagation times of 107 s for center initiation and 338 s for edge initiation [5].

To limit this behavior, regulatory frameworks now specify an explicit survivable interval. GB 38031-2020 [6] and UN GTR No. 20 [7] require that a battery system provide at least five minutes between the onset of a thermal event and the point at which the passenger compartment becomes hazardous. For aviation, RTCA DO-311A [8] specifies a thermal runaway containment test, and EASA MOC-3 to SC-VTOL [9] requires that the containment performance be sufficient for continued safe flight and landing. The revised Chinese standard GB 38031-2025, effective from July 2026, tightens the requirement considerably by mandating no fire and no explosion for at least 120 minutes. Achieving these targets without adding excessive cooling mass is the central design problem for UAM battery packaging.

A practical difficulty in addressing this problem is that pack-level TR testing is expensive, destructive and constrained by facility safety limits, so the number of tests that can be performed is small. Module-level testing with a defined trigger cell is therefore commonly used as a representative and repeatable surrogate. Kovachev et al. [10] demonstrated this approach for a mechanically constrained 41 Ah pouch module and showed that cell terminal voltage provides a more precise indication of TR timing than surface temperature.

The present work follows the same approach and reports three module-level TR propagation tests on 14S1P modules built from 90 Ah-class lithium-ion polymer cells. The distinguishing feature of this study is that the same cell type was assembled into two different packing configurations. The first is a conventional configuration representative of common practice in ground-vehicle modules, in which adjacent cells are stacked in near-direct contact. The second is an improved configuration developed for electric propulsion applications, in which an inter-cell fire-retardant barrier layer is combined with an aluminum heat-sink structure. Because the cell, the trigger method and the instrumentation were kept the same, the difference in measured propagation behavior can be attributed primarily to the packing configuration. The objective is to quantify that difference and to provide baseline data for inter-cell insulation design in electric propulsion aircraft.

2. Experimental Method

2.1. Battery module

The test articles are 14S1P lithium-ion battery modules assembled from 90 Ah-class lithium-ion polymer (LIPB) pouch cells with an NMC cathode. The cells are connected in 14 series with no parallel branch, giving a nominal module voltage of 53.2 V and a fully charged voltage of 58.8 V. Figure 1 shows the exploded view of the module. The stack of 14 cells is enclosed between an aluminum heat-sink structure and a cover, with busbars on the upper face and a mounting bracket at the base. Silicone layers are placed between the cell stack and the surrounding structure, and one face of the housing is designated as the cooling surface. The principal specifications are summarized in Table 1.

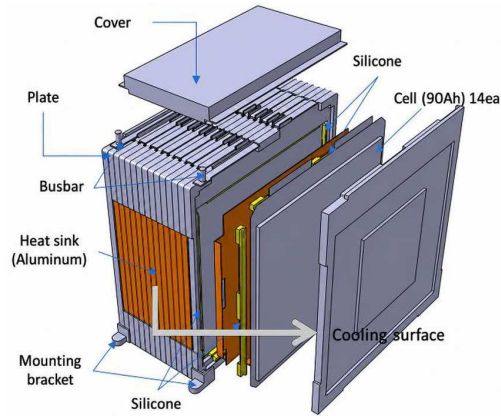


Fig. 1. Exploded view of the 14S1P lithium-ion battery module

Table 1. Principal specifications of the test module

Parameter	Specification
Cell chemistry / format	NMC / Li-ion polymer pouch
Cell nominal capacity	90 Ah
Cell voltage (nominal / max.)	3.80 / 4.20 V
Module Configuration	14S1P
Module voltage (nominal / max.)	53.2 / 58.8 V
Module nominal energy	4.8 kWh

2.2. Packing configurations

Two packing configurations were prepared using the same cell type. In the conventional configuration, which reflects the arrangement commonly adopted in ground-vehicle modules, the cells are stacked so that the large faces of adjacent cells are separated only by a thin compliant interface layer. This arrangement is favorable for volumetric efficiency and for normal-operation heat rejection, because the conduction path between the cell face and the housing is short. Its disadvantage is that the same short path is available to the heat released during a TR event.

In the improved configuration, an inter-cell fire-retardant barrier layer is inserted between adjacent cell faces, and the aluminum heat-sink structure is retained to preserve normal-operation cooling. The intent of this arrangement is to separate the two heat-transfer duties that a module must satisfy. Routine heat generated during charge and discharge is removed laterally through the aluminum structure to the cooling surface, whereas the intense localized heat flux generated during a TR event must cross the barrier layer in the through-plane direction, where the thermal resistance is much higher. This anisotropic strategy is consistent with the design direction reported in the recent thermal-barrier

literature, in which insulation alone has been found insufficient for high-energy cells and a combination of insulation and heat spreading is recommended [11,12].

2.3. Thermal runaway trigger

Thermal runaway was induced by a resistive heating pad attached to the large face of the centrally located cell of each module. The center position was selected because it represents the worst-case initiation location: heat is transferred in both directions simultaneously, and previous work has shown that center initiation produces markedly faster propagation and a higher peak heat release rate than edge initiation [5]. The heating pad was energized from a regulated DC supply and the power was increased until self-sustaining exothermic reaction of the target cell was confirmed. All modules were charged to 100 % SOC before testing, and the tests were conducted in an outdoor test area.

2.4. Instrumentation and definition of thermal runaway

Type-K thermocouples were bonded to the large face of the target cell and of the adjacent cells, and additional channels monitored the heating pad and the ambient condition. The terminal voltage of the target cell and of the adjacent cells was recorded simultaneously. All channels were sampled at 1 s intervals by a waveform recorder.

For consistency across the three tests, the instant of thermal runaway of a given cell is defined in this paper as the time at which its terminal voltage first falls below 1.0 V. This criterion was adopted for two reasons. First, voltage collapse is a direct electrical indication that the separator of that specific cell has failed, whereas a surface thermocouple may respond to heat arriving from a neighboring cell and therefore does not unambiguously identify which cell has failed. Second, the voltage signal is not affected by thermocouple detachment or by ejecta impingement, both of which occur frequently once venting begins. The same reasoning was reported by Kovachev et al. [10], who found the voltage signal to be more precise than temperature for identifying TR timing in constrained pouch modules. The propagation delay is then defined as the interval between voltage collapse of the target cell and voltage collapse of the first adjacent cell.

It should be noted that all temperatures reported in this paper are peak local thermocouple readings at the specific bonding locations, and are not bulk cell temperatures. Internal cell temperatures during TR are known to exceed surface readings by several hundred degrees; Feng et al. [3] reported an internal-to-surface difference of approximately 520 °C at the moment of thermal runaway in a 25 Ah prismatic cell. In addition, several channels in the present tests exceeded the measurement range during the most intense phase of the event. Where this occurred, the highest valid reading before saturation is reported and is explicitly identified as a conservative lower bound.

3. Results

3.1. Conventional packing configuration

Two tests were performed on modules built with the conventional packing configuration. Figures 2 and 3 present the temperature and voltage histories of Test A and Test B respectively.

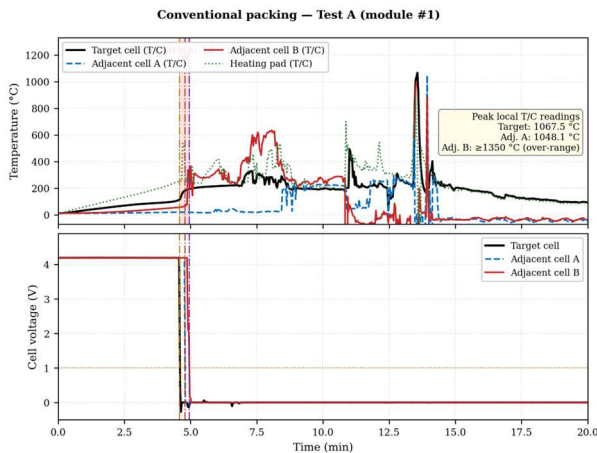


Fig. 2. Temperature and cell voltage histories, conventional packing configuration, Test A

In Test A, the target cell voltage fell below 1.0 V at 275 s (4 min 35 s). The first adjacent cell followed at 287 s and the second adjacent cell at 297 s, so the entire instrumented group of three cells had failed within 22 s of the initial event. The corresponding propagation delay to the first adjacent cell was therefore only 12 s. Peak local thermocouple readings were 1067.5 °C on the target cell and 1048.1 °C on the first adjacent cell; the channel on the

second adjacent cell exceeded the measurement range and its peak is reported as a lower bound.

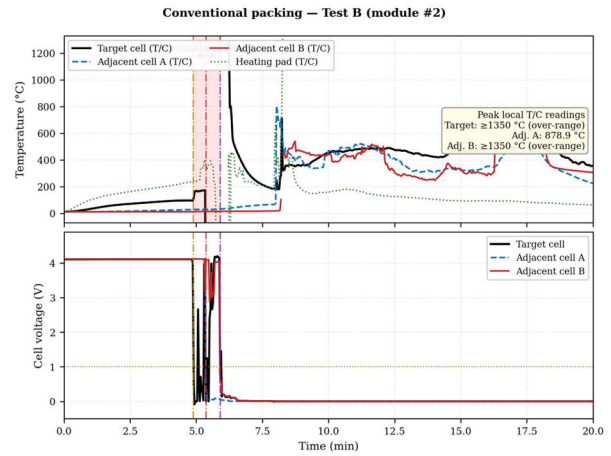


Fig. 3. Temperature and cell voltage histories, conventional packing configuration, Test B

Test B showed the same qualitative behavior with slightly longer intervals. The target cell failed at 293 s (4 min 53 s), the first adjacent cell at 322 s and the second adjacent cell at 354 s, giving propagation delays of 29 s and 61 s respectively. The peak local thermocouple reading on the first adjacent cell was 878.9 °C, while the target-cell channel and one further channel exceeded the measurement range.

In both tests the cascade was effectively continuous. The interval between successive cell failures was of the same order as the sampling resolution of a typical battery management system, and considerably shorter than any plausible detection-and-response sequence. Under the tested conditions, neither module satisfied the five-minute criterion of GB 38031-2020 [6] or UN GTR No. 20 [7]. The measured values are, however, consistent with the published baseline for pouch modules without an inter-cell barrier, in particular with the 60 to 80 s complete-consumption interval reported by Lamb et al. [4], which supports the view that the two tests represent normal rather than anomalous behavior for this configuration.

3.2. Improved packing configuration

Figure 4 presents the temperature and voltage histories obtained with the improved packing configuration under nominally identical trigger conditions.

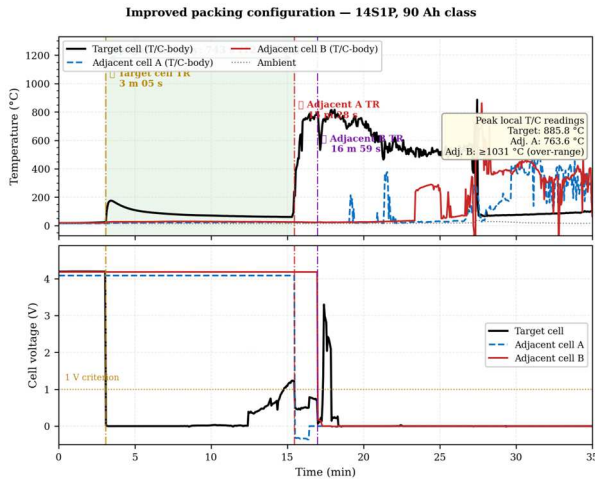


Fig. 4. Temperature and cell voltage histories, improved packing configuration incorporating an inter-cell fire-retardant barrier and aluminum heat-sink structure

The target cell entered thermal runaway at 185 s (3 min 05 s), which is earlier than in either conventional test. This is expected and is not a deficiency of the configuration: because the barrier layer restricts lateral heat loss from the heated cell into its neighbors, a larger fraction of the applied trigger energy is retained within the target cell itself, so the target cell reaches its self-heating threshold sooner. The same mechanism has been noted in barrier studies, where improved isolation can slightly accelerate failure of the initiating cell while strongly delaying its neighbors [11].

The first adjacent cell did not fail until 928 s (15 min 28 s) and the second adjacent cell until 1019 s (16 min 59 s). The propagation delay to the first adjacent cell was therefore 743 s, or 12 min 23 s. Peak local thermocouple readings were 885.8 °C on the target cell and 763.6 °C on the first adjacent cell. The channel bonded to the second adjacent cell exceeded the measurement range during the most intense phase; the highest valid reading before saturation was 1031 °C, which is reported here as a conservative lower bound.

Figure 5 shows the module before the test and after propagation was complete. Although the propagation was delayed

substantially, the cascade was not ultimately prevented, and the module sustained severe structural damage. The peak local readings exceed the melting point of aluminum, 660 °C, which is consistent with the deformation visible in the post-test photograph.

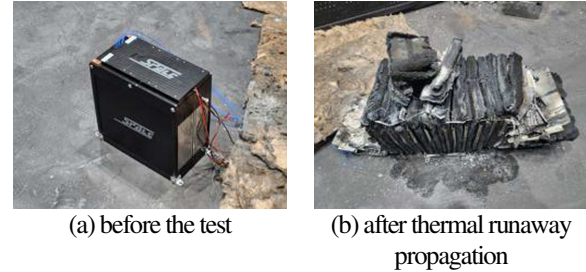


Fig. 5. Lithium-ion battery module used in the thermal runaway propagation test: (a) before the test and (b) after thermal runaway propagation

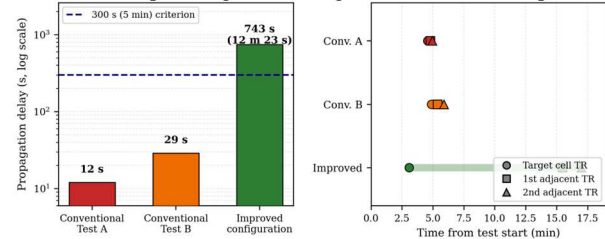
3.3. Comparison of the two configurations

Table 2 summarizes the three tests and Fig. 6 presents the comparison graphically. A logarithmic scale is used in Fig. 6(a) because the propagation delays differ by nearly two orders of magnitude.

Table 2. Summary of thermal runaway propagation results for the three module-level tests

Parameter	Test A (conventional)	Test B (conventional)	Test C (improved)
Inter-cell barrier	-	-	Applied
Time to TR (s)			
Target cell	275	293	185
1 st adjacent cell	287	322	928
2 nd adjacent cell	297	354	1019
Propagation delay (s)			
Target cell to 1 st adjacent cell	12	29	743
Target cell to 2 nd adjacent cell	22	61	834
Peak Temperature (°C)			
Target cell	1067.5	> range	885.8
1 st adjacent cell	1048.1	878.9	763.6
2 nd adjacent cell	> range	> range	1031

Peak local thermocouple readings at the bonding locations, not bulk cell temperatures.



(a) cell-to-cell propagation delay

(b) TR event timeline

Fig. 6. Comparison of the two packing configurations: (a) cell-to-cell propagation delay on a logarithmic scale, and (b) thermal runaway event timeline for the three tests

Relative to the conventional configuration, the improved configuration increased the propagation delay from 12 s and 29 s to 743 s, corresponding to a factor of approximately 62 and 26 respectively. The measured delay of 743 s exceeds the 300 s criterion of GB 38031-2020 [6] and UN GTR No. 20 [7] by a factor of about 2.5. It is also comparable with the best passive results reported in the barrier literature; Mao et al. [12] extended the propagation interval of a large-format prismatic module from 368 s to 1294 s using a 1 mm aerogel barrier, which places the present result within the same performance band.

4. Discussion

4.1. Propagation mechanism and the role of the barrier

The results indicate that the dominant heat-transfer path in the conventional configuration is direct conduction across the large faces of adjacent cells. Because a pouch cell presents a large, flat and closely coupled contact area, the thermal resistance between neighboring cells is low, and the energy released by the failing cell reaches the adjacent cell almost immediately. This explains why the measured intervals of 12 s and 29 s are of the same order as those reported by Lamb et al. [4] for a geometrically similar arrangement.

The inter-cell barrier interrupts this path. Two effects act together. The first is a purely thermal resistance effect: the barrier has a much lower through-plane conductivity than the cell stack it replaces, so the heat flux reaching the adjacent cell is reduced. The second is an endothermic effect associated with decomposition of the barrier material at elevated temperature, which absorbs part of the incoming energy rather than transmitting it. Sensitivity analysis reported by Liu et al. [11] indicates that both the specific heat and the degree of anisotropy of the barrier are influential design parameters, with an increase in specific heat of 60 %

producing an increase in propagation delay of approximately 26 %.

The retention of the aluminum heat-sink structure is equally important and should not be interpreted as being in conflict with the barrier. The module must satisfy two different thermal duties. During normal charge and discharge, heat must be removed continuously and the aluminum structure provides the necessary lateral conduction to the cooling surface. During a TR event, heat must be prevented from crossing between cells, which is the function of the barrier in the through-plane direction. It should nevertheless be recognized that a metallic structure can also act as a bypass path around a barrier if the two are not designed together, and the geometry of the heat sink in the vicinity of the barrier therefore requires careful attention in future iterations.

4.2. Implications for electric propulsion aircraft

For a UAM aircraft, the practical value of a propagation delay is that it converts an unmanageable event into a manageable one. A delay of 12 s, as measured in the conventional configuration, is shorter than the time required for a battery management system to confirm an anomaly, announce it to the crew and for the crew to initiate a diversion. A delay of 743 s is of a different character: it is comparable with the time needed to complete a descent and landing from a typical UAM cruise altitude, and therefore aligns with the continued safe flight and landing philosophy expressed in EASA MOC-3 to SC-VTOL [9].

A second observation concerns detection. In the improved configuration the target cell voltage collapsed at 185 s, whereas the first adjacent cell did not fail until 928 s. A monitoring function capable of detecting a single cell falling below 1 V within a 14-series string would therefore have had more than twelve minutes of warning before the event escalated. This suggests that voltage-based single-cell monitoring and passive inter-cell barriers should be regarded as complementary rather than alternative measures.

Finally, it must be emphasized that the improved configuration delayed but did not prevent propagation. The post-test condition shown in Fig. 5(b) confirms that the cascade eventually consumed the module. Under the revised GB 38031-2025 requirement of no fire and no explosion for 120 minutes, a

delay of 743 s would not be sufficient, and complete suppression rather than delay would be required. Reported approaches that have achieved full suppression generally combine a barrier with an active or latent heat-absorbing element [11,12], and this represents the natural direction for further work.

5. Limitations

The following limitations should be taken into account when interpreting the results.

- (1) Each configuration was evaluated in a single test, and the improved configuration was evaluated only once. Thermal runaway propagation is sensitive to small variations in heater placement, contact pressure and cell-to-cell manufacturing tolerance, and the statistical spread of the reported delays has not been quantified. Repeat testing is required before the values are used as design margins.
- (2) Instrumentation was limited to the target cell and two adjacent cells. The behavior of the remaining cells of the 14S1P module, and in particular whether the cascade would eventually have been arrested at some point in the stack, could not be determined from the present data.
- (3) All reported temperatures are peak local thermocouple readings at specific bonding points and are lower bounds on the true cell temperature. Several channels exceeded the measurement range during the most intense phase of each test, and thermocouple detachment or ejecta impingement cannot be excluded.
- (4) The tests were conducted at ambient pressure. Reduced pressure at altitude is known to alter both the venting behaviour and the composition of the released gas, so the results are not directly transferable to in-flight conditions without further verification.
- (5) The results do not constitute certification evidence. Formal compliance with GB 38031, RTCA DO-311A or EASA MOC-3 to SC-VTOL requires pack-level testing under an accredited procedure, which has not been performed.

6. Conclusions

Three module-level thermal runaway propagation tests were performed on 14S1P modules built from 90 Ah-class lithium-ion polymer cells, using two different packing configurations with the same cell type and the same trigger method. The main findings are as follows.

- (1) In the conventional packing configuration, thermal runaway of the target cell occurred at 4 min 35 s and 4 min 53 s in the two tests, and propagation to the first adjacent cell followed after only 12 s and 29 s respectively. Neither test satisfied the five-minute criterion of GB 38031-2020 or UN GTR No. 20.
- (2) In the improved packing configuration, incorporating an inter-cell fire-retardant barrier together with an aluminum heat-sink structure, the target cell entered thermal runaway at 3 min 05 s and the first adjacent cell at 15 min 28 s, giving a propagation delay of 743 s. Under the tested conditions this satisfies the five-minute criterion with a margin of approximately 2.5 times.
- (3) The improvement in propagation delay was a factor of approximately 26 to 62 relative to the conventional configuration. Since the cell, the trigger method and the instrumentation were identical, the difference is attributed primarily to the packing configuration.
- (4) Peak local thermocouple readings reached 885.8 °C on the target cell and 763.6 °C on the first adjacent cell in the improved configuration, with several channels exceeding the measurement range. These values exceed the melting point of aluminum and indicate that structural containment must be designed for temperatures well above that level.
- (5) The barrier delayed but did not prevent the cascade. Complete suppression, as required by the forthcoming GB 38031-2025, will require further development beyond passive delay alone.

Future work will address repeat testing to establish statistical confidence, full 14-cell instrumentation to determine whether the cascade can be arrested within the stack, optimization of the barrier

thickness against the resulting energy-density penalty, and verification under reduced-pressure conditions representative of flight.

Acknowledgement

This work was supported by the Institute of Information & Communications Technology Planning & Evaluation (IITP) grant funded by the Korean government (MSIT) (Grant No. [RS-2024-00400712]).

References

- [1] F. Xuning, O. Minggao, L. Xiong, L. Languang, X. Yong and H. Xiangming, "Thermal runaway mechanism of lithium-ion battery for electric vehicles: A review," *Energy Storage Materials*, Vol. 10, pp. 246-267, 2018.
- [2] W. Qingsong, P. Ping, Z. Xuejuan, C. Guanquan, S. Jinhua and C. Chunhua, "Thermal runaway caused fire and explosion of lithium-ion battery," *Journal of Power Sources*, Vol. 208, pp. 210-224, 2012.
- [3] X. Feng, M. Fang, X. He, M. Ouyang, L. Lu, H. Wang and M. Zhang, "Thermal runaway features of large format prismatic lithium-ion battery using extended volume accelerating rate calorimetry," *Journal of Power Sources*, Vol. 255, pp. 294-301, 2014.
- [4] J. Lamb, C. J. Orendorff, L. A. M. Steele and S. W. Spangler, "Failure propagation in multi-cell lithium-ion batteries," *Journal of Power Sources*, Vol. 283, pp. 517-523, 2015.
- [5] S. Na, "Thermal runaway propagation in pouch-type lithium-ion battery modules: Effects of state of charge and initiation location," *Batteries*, Vol. 11, No. 11, Art. 398, 2025.
- [6] Standardization Administration of China, "Electric vehicles traction battery safety requirements," *GB 38031-2020*, SAC, Beijing, China, 2020.
- [7] United Nations Economic Commission for Europe, "Global Technical Regulation No. 20: Electric vehicle safety," *ECE/TRANS/180/Add.20*, UNECE, Geneva, 2018.
- [8] RTCA, "Minimum operational performance standards for rechargeable lithium batteries and battery systems," *DO-311A*, RTCA Inc., Washington DC, 2017.
- [9] European Union Aviation Safety Agency, "Means of compliance with the special condition VTOL," *MOC-3 to SC-VTOL*, Issue 2, EASA, Cologne, 2023.
- [10] G. Kovachev, C. Ellersdorfer, G. Gstrein, I. Hanzu, H. M. R. Wilkening, T. Werling, F. Schauwecker and W. Sinz, "Analysis and investigation of thermal runaway propagation for a mechanically constrained lithium-ion pouch cell module," *Batteries*, Vol. 7, No. 3, Art. 49, 2021.
- [11] Y. Liu, X. Wang, H. Chen and Q. Wang, "Thermal barrier for preventing battery thermal runaway propagation: Sensitivity analysis of material properties," *Journal of Energy Storage*, Vol. 132, 2025.
- [12] T. Mao, Y. Xiao, X. Cheng, J. Wang and H. Zhang, "Effects and mechanisms of thickness-tunable aerogel thermal barriers on suppression of thermal runaway propagation in large-format prismatic lithium-ion batteries," *Materials Today Energy*, Vol. 53, Art. 101996, 2025.