ANALYZING THERMAL RUNAWAY BEHAVIOR OF LITHIUM-ION BATTERIES IN FULL-SIZE ELECTRIC VEHICLES
A Comparative Study of Extinguishing Agents

by

Umit SENYUREK[a]*, Raja Mazuir Raja Ahsan SHAH[b], Hakan Serhad SOYHAN[c], and Cenk CELIK[d]

[a] Institute of Science and Technology, Kocaeli University, Kocaeli, Turkey
[b] College of Engineering and Technology, University of Doha for Science and Technology, Doha, Qatar
[c] Department of Fire Safety and Mechanical Engineering, Sakarya University, Sakarya, Turkey
[d] Department of Mechanical Engineering, Kocaeli University, Kocaeli, Turkey

Original scientific paper
https://doi.org/10.2298/TSCI2504977S

Lithium-ion batteries are commonly used in electric vehicles and other electrical devices. However, their thermal behavior can pose safety challenges. Thermal abuse can lead to fires, known as thermal runaway, with high heat release rates and the emission of toxic gases. This paper discusses thermal runaway in lithium-ion batteries during electrical vehicles production, emphasizing the need for early fire intervention. Five experiments were conducted to validate lithium-ion batteries thermal runaway and assess organic and inorganic-based extinguishing agents. The inorganic quenching agent could rapidly cool the lithium-ion batteries surface temperature to 75 °C within just 50 seconds, delaying the onset of thermal runaway. The organic-based extinguishing agent failed to extinguish the lithium-ion batteries fire even after three interventions in the thermal abuse test. However, the inorganic-based extinguishing agent successfully extinguished lithium-ion batteries fires that had entered thermal runaway with only one portable extinguisher. Fire blankets can also be effectively used in electric vehicles fires. Unlike organic extinguishing agents, a single tube of the inorganic quenching agent is sufficient for thermal runaway.

Key words: *thermal runaway, electric vehicle, extinguishing agent, battery testing, battery thermal management system*

Introduction

Fire incidents occur when abuse conditions break the boundary of the lithium-ion batteries (LIB) electrochemical system, such as thermal runaway [1]. Thermal runaway is a severe issue in LIB due to chemical reactions leading to uncontrollable internal temperature rises, causing deformation of the SEI layer [2], redox reactions between electrolyte-electrode [3], or reactions between electrode-binder [4]. Understanding this phenomenon requires identifying deformation scenarios of all electrode, electrolyte, and solid electrolyte interphase elements [5]. During thermal runaway, the temperature inside LIB can rapidly exceed 1000 °C, releasing toxic gases [6]. A common cause of thermal runaway is the melting of the polyole-

* Corresponding author, e-mail: umitsenyurek@yahoo.com

fin separator, causing an internal short circuit [7]. Even though electrolytes and separators are relatively light, burning these substances accounts for approximately 80% of the heat released during a fire [8]. Thermal runaway progresses through stages. Stage I: Safe operational temperature range, Stage II: Onset of irreversible damage, which can be mitigated by cooling, and Stage III: Total cell destruction, followed by rapid energy discharge. During thermal runaway, gases such as hydrogen, H_2, CO, CO_2, and various hydrocarbons, CH_4, C_2H_4, *etc.*, are released, and the ignition of these gases could potentially create an explosion [9]. This risk is significant in closed areas due to gas accumulation. According to Fan *et al.* [10], the decomposition of electrolyte material mainly produces the released gases. The components of the electrolyte determine the combustion parameters. One method to prevent thermal runaway in LIB is by continuously circulating Novec 1230 gas, which is effective due to its significant cooling effect compared to the heat generated that can cause thermal runaway [11]. Yu *et al.* [12] studied the quenching effect of prismatic-shaped $LiFePO_4$ LIB with perfluorohexanone, an environmentally friendly gas. Their study has established that perfluorohexanone gas effectively prevents thermal runaway due to its quenching and cooling effects. However, this effect may not be suitable for NiCoMn (NCM) LIB. Zhang *et al.* [13] experimented with the extinguishing effects of $C_6F_{12}O$, CO_2, and HFC-227ea and their combination with water mist in terms of extinguishing time, peak temperature, mass loss, and heat release rate. Their findings suggest that multiple extinguishing agents are more effective than just one. The optimal combination for both extinguishing and cooling was $C_6F_{12}O$, while CO_2 had a longer duration for extinguishing. Interestingly, HFC-227ea did not extinguish the fire but weakened its intensity. Liu *et al.* [14] studied the impact of extinguishing agents on LIB. According to their research, varying pressure levels (1-3 MPa) significantly impacted the efficacy of extinguishing agents like $C_6F_{12}O$ and water mist. Higher pressure led to a reduction in peak temperature. They also revealed that adding substances like $KHCO_3$ and $K_2C_2O_4$-H_2O improved the cooling and quenching abilities of water mist, while others like $C_{18}H_{29}NaO_3S$ and $F(CF_2)_6CH_2CH_2CH_2O(CH_2CH_2O)$ had the opposite effect. Additionally, higher state-of-charge levels resulted in the production of more hazardous gases. Sun *et al.* [15] investigated the effectiveness of HFC-227ea, $C_6F_{12}O$, and water mist as extinguishing agents for LIB. They found that the cooling mechanism was the most crucial parameter for extinguishing fires indoors. The heat absorption capacities of the three agents varied greatly, with HFC-227ea absorbing 24.8 kJ, $C_6F_{12}O$ absorbing 111 kJ, and water mist absorbing a substantial 459.8 kJ. The HFC-227ea was ineffective in extinguishing the fire, while $C_6F_{12}O$ could not prevent thermal runaway formation. However, $C_6F_{12}O$ could reduce heat in LIB and delay thermal runaway formation. Ultimately, water mist was the most effective agent, preventing thermal runaway and possessing the best cooling ability.

Most studies on thermal runaway have focused on single-size LIB, with minimal research on vehicle-sized LIB. The fire risks from LIB at electric vehicles (EV) production facilities have yet to be examined. Thermal runaway during production can disrupt production continuity, jeopardize EV safety, and tarnish the company's reputation. The EV LIB are either externally sourced, ready-made, or assembled in a dedicated area [16]. The area where LIB are assembled poses a significant fire risk [17]. Therefore, rapid intervention in the event of a LIB fire is necessary for swift cessation of thermal runaway reactions, prevention of the spread of the reaction to neighbouring LIB, and rapid removal of heat from the environment [18]. To achieve this, EV manufacturers equip their facilities with advanced fire suppression systems, such as automated water mist systems and specialized extinguishing agents tailored for LIB fires [19]. Understanding LIB health monitoring and early detection of potential issues through intelligent sensor technology is crucial in preventing catastrophic incidents [20]. The probability of LIB fires in EV production facilities can be evaluated by considering three primary triggering scenarios: mechanical damage to LIB cells during handling or assembly can lead to electrolyte leakage and subsequent ignition, thermal runaway due to internal short circuits or overcharging poses a significant risk, and manufacturing defects in LIB components, such as separator misalignment or electrode contamination, may compromise LIB structure integrity and increase the likelihood of thermal runaway [21, 22]. Understanding these triggering mechanisms is essential for implementing preventive measures and ensuring the safety of EV production facilities. It aims to fill research gaps and provide valuable insights into this area. Extinguishing the fire during thermal runaway is crucial before it progresses and spreads. Based on this study, selecting the appropriate type and weight of portable fire extinguishers is essential to minimize the risk of reignition and delay the fire. Another test method examined practical and fast extinguishing possibilities, including organic and inorganic extinguishers.

Methodology

Two types of LIB (HV and PHEV) architectures were used in the experiments to represent the actual LIB architectures in the EV production facilities based on $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC 622) chemistry: fig.1(a) – three modules that consist of twenty-four LIB cells per module and fig. 1(b) – four full-sized EV vehicle LIB pack. Each full-sized LIB pack comprises twenty-eight LIB modules, with 2-series and 56-parallel arrangement.

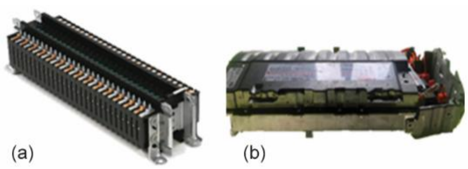


Figure 1. The LIB Module and EV LIB

The specifications of the LIB cell, module and full-sized pack are shown in tab. 1, respectively.

Table 1. The LIB specifications

Type	Full-sized battery pack	Module
Dimensions [mm]	830 × 220 × 370	392 × 112 × 111
Unit weight [kg]	31.5	6.5
Nominal cell voltage [V]	201.6 V	88 V

Understanding the factors that can cause LIB to experience thermal runaway is crucial. To achieve this, researchers typically subject LIB to one of three abuse conditions: external heating, electrification, or mechanical impact. Among these conditions, the most effective method of simulating thermal abuse is through external heating, which involves uniformly heating the entire LIB to accelerate the formation of the thermal runaway mechanism and its spread to other LIB cells. In many studies, simple electric or propane heating systems accomplish this goal, as they can heat LIB uniformly. However, due to its high thermal value, some researchers have used a mixture of gasoline and diesel fuel to simulate thermal abuse. Interestingly, experiments have shown that the gasoline and diesel fuel mixture burns after initiating the thermal runaway. This indicates that the experiment will not be affected once the fire starts.

Experiment set-up

The experimental set-up included a mixture of gasoline and diesel (50% gasoline and 50% diesel) as accelerator agents to heat the LIB and trigger a thermal runaway [23]. The set-up included a metal sheet fire pan and a thermal measurement camera (Testo 868 model). Two types of extinguishing agents were used: organic-based and inorganic-based. According to the material safety data sheet, the inorganic-based extinguishing agent contains 98% water, 1% disodium metasilicate, and 1% boric acid disodium salt. The organic-based extinguishing agent combines detergents, polyvalent compounds, and hetero-organic substances. It has a 1.02 g/mL density and a pH value of 7.5. Two experimental set-ups for LIB were prepared in a closed experimental room with an A1 fire resistance class material (EN 13501 standard) to ensure that the effect of external factors such as wind and rain was negligible during the experiment. The experimental layout is shown in fig. 2.

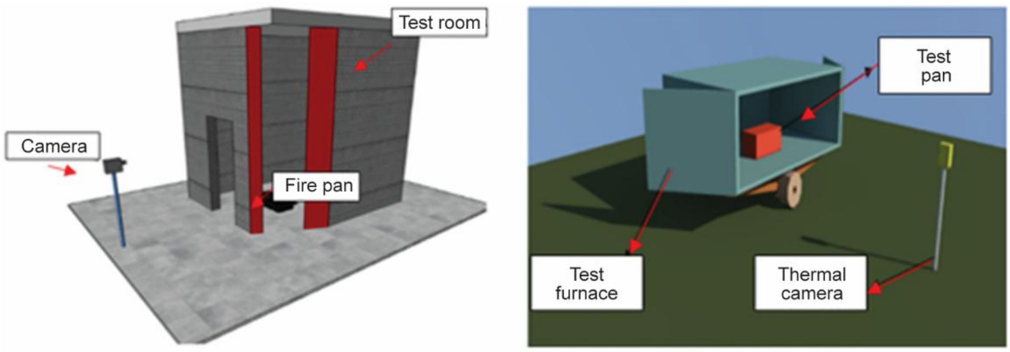


Figure 2. Experimental furnace set-up

Abuse experiment

Five abuse experiments were conducted to observe thermal runaway and the effects of extinguishing agents with retardant specifications. Before conducting the experiments, the top cover of each LIB module was opened to access the insulated protection cover to measure the external temperature using the Testo 868 model portable thermal measurement device. The LIB were positioned on a steel construction stand within a closed test room during the heat abuse experiments. A 3 L mixture of 50% diesel and 50% gasoline accelerator was poured into the fire pan to initiate thermal runaway. The experiments were initiated by igniting the accelerator, and the thermal camera recorded each stage of the fire, thermal runaway, and extinguishing processes.

The EN 1. The experimental set-up was prepared by placing three LIB modules on a fire tray, as shown in fig. 3(a). At the 23rd second, white smoke was observed emerging from the modules, as shown in fig. 3(b). This phenomenon continued, with the white smoke increasing and spreading. At the 118th second, the plastic materials holding the module started melting and dripping sounds into the fire tray were heard. Three temperature measurements were recorded: 623 °C at the 237th second, 649 °C at the 254th second, and 652 °C at the 265th second. The first explosion sound was heard at the 271st second, as shown in fig. 3(c).

Along with the explosion, a burst of flame was observed, and pieces fell from the LIB modules into the fire tray. It was identified that the fallen pieces were LIB cells and that the frame structure holding the LIB modules together had started to disintegrate. Up to this

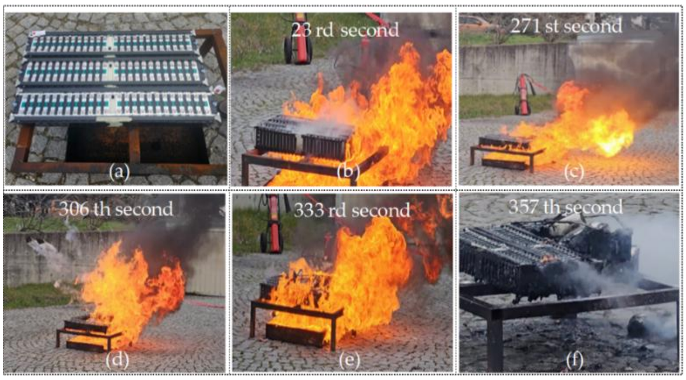


Figure 3. (a) Experiment set-up, (b) intensive white smoke, (c) first explosion, (d) cathode and anode foils extraction by an explosion, (e) LIB module frame lost its strength, LIB cells fell into the pan, and (f) LIB modules condition after extinguishing

point, the emission of white smoke had been continuous, but it suddenly ceased. Subsequently, between the 275th and 280th seconds, the exploded module began to swell, and the frame holding the LIB modules was observed to deform. At the 280th second, two more explosions occurred in the deformed and swelling module. Between 280 and 284 seconds, a sound of expansion was heard from the frame structure, which disintegrated and lost its form. At the 294th second, the first module exploded again, this time more violently. The sound of pressurized gas release accompanied the explosion. The disintegration of the LIB modules caused the cathode and anode to separate within the LIB cells. Another intense explosion occurred at the 304th second, and the temperature was measured at 663 °C at the 309 second. Following this significant explosion, at the 306th second, another explosion occurred within the LIB module, ejecting numerous cathode and anode foils, as shown in fig. 3(d). Another explosion occurred at the 323rd second, accompanied by the sound of pressurized gas release, with flames spreading more laterally. At the 333rd second, another explosion occurred with a pressurized gas sound, causing some LIB cells to fall into the tray, as shown in fig. 3(e). The explosion that compromised the frame structural integrity was intervened at the 337th second with a fire extinguisher containing an inorganic-based extinguishing agent. The fire was extinguished at the 357th second (after 20 seconds of total intervention), as shown in fig. 3(f). Smoke emission continued until the 399th second. The stages of this experiment can be divided into three parts. In the first stage, the temperature rapidly increased, and white smoke emission occurred. In the second stage, seven explosions occurred, and the propagation of the thermal runaway to other LIB cells was observed. In the third stage, the inorganic liquid was implemented, and the temperature was rapidly reduced, thereby terminating the thermal runaway. The highest temperature measured during the thermal runaway was 663 °C. The total extinguishing process lasted for 20 seconds, and after the extinguishing action, intense smoke emission was observed for another 42 seconds. The stages are shown in fig. 4.

The EN2. During the experiment, at the 110th second, the fire pan temperature was at 258 °C, while the external temperature of the full-sized LIB pack was at 275 °C. After 20 seconds, the first spark appeared due to a short circuit in the full-sized LIB pack, as shown in fig. 5(a).

Then, a series of sparks followed in fig. 5(b), which continued until the 216th second, when the sound of a pressurized gas outlet was audible for 7 seconds. There were more short circuit-induced burst sounds, and at the 235th second, the cable connector experienced the first thermal runaway, as indicated in fig. 5(c). Thermal runaway formation continued to worsen at the 250th second. Thermal runaway continued from the melting surface due to the short circuit

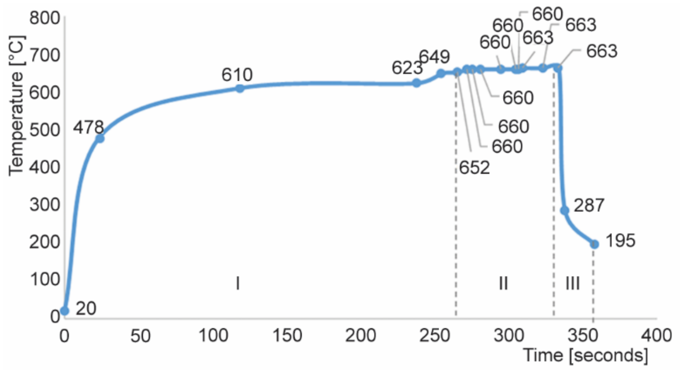


Figure 4. Thermal runaway occurrence sequence and breaking of the reaction attempted by inorganic liquids; *I – first reactions, heat up, white smoke, and plastic mount melted, II – 7 explosions, gas vent, scattering of the cell, losing its form, thermal runaway and propagation of thermal runaway to other cells, and III – breaking the thermal runaway reactions by inorganic material and quick cooling*

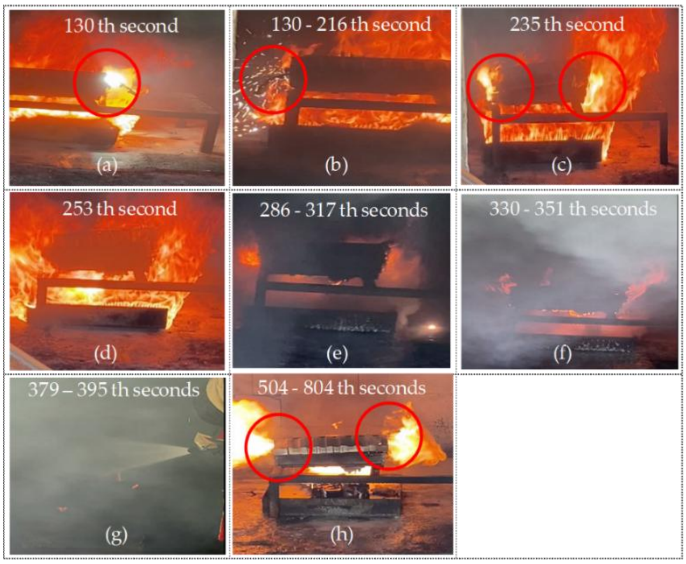


Figure 5. (a) Initial spark occurrence due to short circuit, (b) series of spark, (c) first thermal runaway occurrence, (d) bottom cap explosion, (e) first intervention organic extinguishing agent, (f) second intervention, (g) third intervention, and (h) thermal runaway reoccurrence

at the bottom cover. At the 253rd second, an explosion forcefully opened the bottom cover, and some LIB cells fell into the fire pan, as shown in fig. 5(d). At the 262nd second, the smoke layer began to thicken, and another short circuit burst and pressure gas was released at the 266th second. An intervention was initiated, which lasted for 31 seconds, using an organic-based extinguishing agent, as shown in fig. 5(e). At the end of the first extinguisher, the external full-sized LIB pack temperature dropped to 300 °C, but the fire continued. At 330th second, there was a second intervention for 21 seconds, but it failed to stop the fire as the thermal runaway was reinstated, as shown in fig. 5(f). The third intervention began at the 379th second and lasted for 16 seconds, as shown in fig. 5(g), managing to reduce the external full-sized LIB pack temperature to 200 °C. However, at the 452nd second, the external full-sized LIB pack temperature again increased to 380 °C. Following this, the flame length remained constant for 52 seconds, and the external full-sized LIB pack temperature subsequently dropped to 290 °C. A thermal runaway was again observed at the end of this duration, as shown in fig. 5(h).

The reactions in the full-sized LIB pack can be classified into five stages, as shown in fig. 6. At the first stage, the internal heat increases. At the second stage, the gas outlet starts, and the burnable gases catch fire. The maximum temperature was measured as 667 °C before applying the organic liquid. While the first tube was used, the temperature decreased from 667 °C to 417 °C. At the end of the second tube, the temperature decreased to 200 °C, but it was not enough to break the thermal runaway reactions. The temperature increased again to 370 °C. Similarly, the third tube reduced the temperature to 380 °C, but not enough to break the thermal runaway reactions.

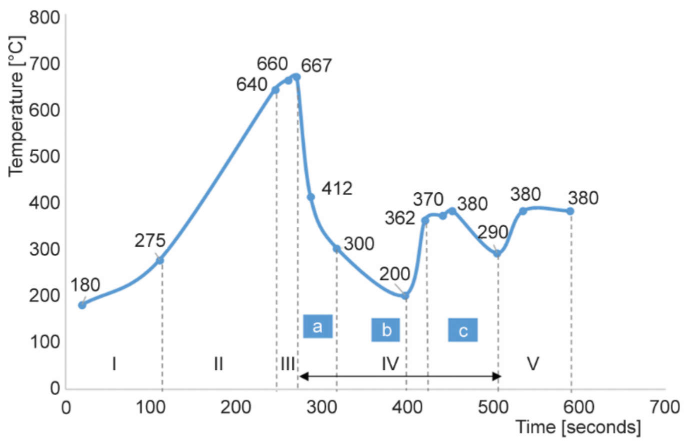
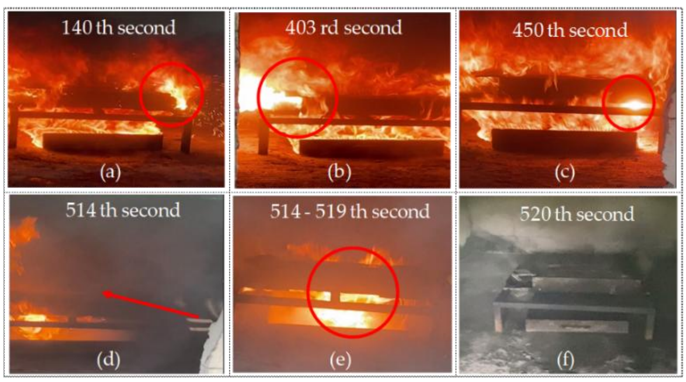


Figure 6. Thermal runaway occurrence sequence and breaking of the reaction attempted by organic liquid; *I – first reactions, heat up, II – gas blow and explosions, III – thermal runaway flames, and IV – thermal runaway reaction break trial by extinguishing material: (a) first tube, first attemption, (b) second tube, second attemption, (c) third tube, third attemption, and V – thermal runaway continue*

The EN3. At the 42nd second after the ignited accelerator, the full-sized LIB pack reached an external temperature of 547 °C. Melted plastic, including upper covers and cable isolators, fell to the fire pan in the 89th second. By the 113th second, the external full-sized LIB pack temperature had reached 615 °C. At the 140th second, there was a loud explosion related to an internal short circuit, as shown in fig. 7(a), followed by pressurized gas released at the 236th second.



Figire 7. (a) Short circuit caused serial explosions in LIB, (b) thermal runaway and explosion from the left side of LIB, (c) explosion causes by a short circuit destroyed LIB bottom plate, (d) intervention from the left side of LIB using inorganic extingushing agent, (e) flames from LIB bottom cover, and (f) fire extinguished

An explosion occurred from the right side of the full-sized LIB pack where the cables were located at the 336th second, followed by another explosion at the left side of the full-sized LIB pack at the 403rd second, resulting in a thermal runaway, as shown in fig. 7(b). These short circuit-related explosions continued for 47 seconds, with explosions also observed in the bottom cast plate of the full-sized LIB pack, releasing pressurized gas and flame that pierced the full-sized LIB pack upper and lower protection metal covers. Figure 7(c) shows an explosion caused by a short circuit during the piercing of the bottom plate. An inorganic-based extinguishing agent intervened in the explosion and the thermal runaway. The extinguishing process began at the right side of the full-sized LIB pack at the 507th second. Although the flames were smaller, they were more severe than *EN1* and swept from the left side of the full-sized LIB pack. The extinguishing process lasted 7 seconds, from the right to the left side of the gap, as shown in fig. 7(d). Flames came out from the right side of the full-sized LIB pack cavity and all other spaces, but with a reduced size. The extinguishing intervention continued for 6 seconds from the full-sized LIB pack left to right side. As the extinguishing agent penetrated the full-sized LIB pack, the flame's intensity decreased, and it disappeared when the extinguishing intervention occurred in both the full-sized LIB pack cavities. However, the fire continued down the floor cover holes due to the full-sized LIB pack short circuit, as shown in fig. 7(e). The first extinguisher continued to work for 45 seconds before the second fire extinguisher. The flames spontaneously extinguished 7 seconds after the first extinguisher was applied, as shown in fig. 7(f), and there was no need to use a second extinguisher. During the extinguishing process, the heat removal property of the extinguishing agent was observed. After the 13th second of extinguishing, the external full-sized LIB pack temperature decreased to 270 °C and reduced to 216 °C in the 87th second of extinguishing. The external full-sized LIB pack temperature dropped to 190 °C, 177 °C, and 168 °C at the 123rd second, 138th second, and 164th second of the extinguishing process, respectively.

The reactions in the full-sized LIB pack can be classified into five stages, as shown in fig. 8. At the first stage, the internal heat increases; at the second stage, the gas outlet starts, and the burnable gases catch fire. The maximum temperature was measured at 670 °C before applying the inorganic liquid. During the application, the temperature decreased suddenly from 670 °C to 270 °C while the thermal runaway reactions were suppressed. Then, the temperature measurements continued in stage V, the cooling stage. A massive amount of liquid vaporized from the surface, and the heat was taken from the full-sized LIB pack. The rapid removal of heat from the surface effectively broke the thermal runaway.

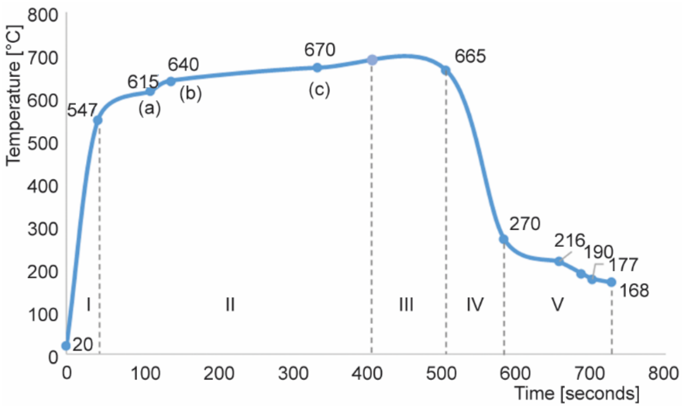


Figure 8. Thermal runaway occurrence sequence and breaking of the reaction attempted by inorganic liquid; (a) first explosion, (b) pressurized gas outlet, and (c) serial explosions: *I – first reactions, heat up, II – gas blow and explosions, III – thermal runaway flames, IV – thermal runaway reaction break by extinguishing material, and V – cooling*

The EN4. The full-sized LIB pack plastic components began melting and dripping only 38 seconds after the accelerator was started, as seen in fig. 9(a). At the 146th second, a burst sound from a short circuit was heard for the first time, followed by consecutive bursts at the 211th second, as shown in fig. 9(b). When the inorganic-based extinguishing agent intervention started at the 215th second after ignition, the flames increased in the direction of the extinguishing action sweep, as shown in fig. 9(c). The flames were extinguished within 54 seconds. Between the 269-379th second, smoke was visible, and the external full-sized LIB pack temperature was measured at 75 °C. The peak temperature was 665 °C before the inorganic extinguishing material applied as shown in fig. 10.

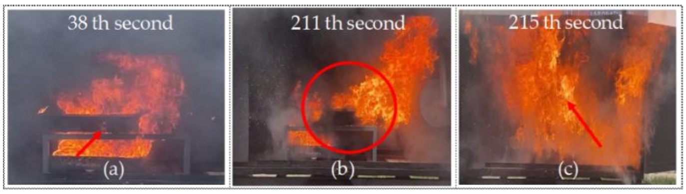


Figure 9. (a) The LIB plasctic components melted, (b) series explosions caused by short circuits, and (c) intervention from the left side of LIB

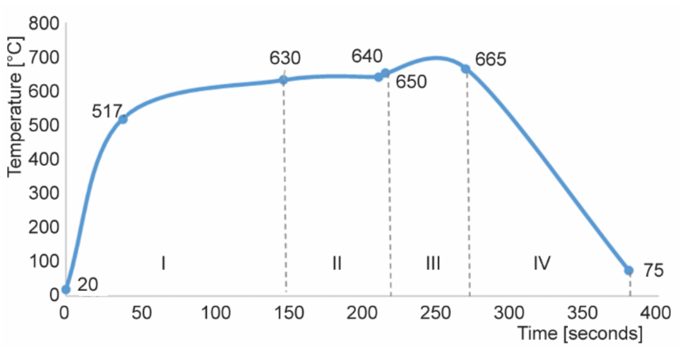


Figure 10. Thermal runaway occurrence sequence and breaking of the reaction attempted by inorganic liquid; *I – first reactions, heat up, II – gas blow and serial explosions, III – thermal runaway reaction break by extinguishing material, and IV – cooling*

The EN5. After the ignition, the plastic components of the full-sized LIB pack started to liquefy and drip into the container within a minute, producing a sizzling noise. The 228th second saw white smoke from the cable cavity of the full-sized LIB pack, indicating gas production, as shown in fig. 11(a). By the 253rd second, the external full-sized LIB pack temperature had risen to 445 °C. At the 274th second, a short circuit triggered an initial explosion that lasted until the 286th second, as seen in fig. 11(b). Most of the burnt material was the plastic components of the full-sized LIB pack. At the 330th second, four short circuits co-occurred, followed by the release of pressurized gas at the 440th second, accompanied by a distinct sound, signifying the beginning of thermal runaway, fig. 11(c). Thermal runaway continued for another 14 seconds, but the sound of the flame and gas pressure decreased gradually. At the 454th second, the thermal runaway intensified, increasing the output of pressurized gas and causing the flame to grow stronger. Thermal runaway happened at both ends of the full-sized LIB pack and quickly worsened in severity, accompanied by a burst of short-circuit sounds, as shown in fig. 11(d). The external full-sized LIB pack temperature reached 420 °C at the 547th second, and the stable flame length lasted for 19 seconds, giving the impression that it was self-extinguishing. However, at the 566th second, thermal runaway started again, worsening the situation further, as depicted in fig. 11(e). During thermal runaway, the compressed gas outlet produced a noticeable sound that became more severe over time. The flame was pressurized and flared from both ends of the full-sized LIB pack, causing the plastic to flow in liquid form from the cable inlet cavity. At the 654th second, the flame appeared to be going out but then became loose again, with four consecutive short-circuit burst sounds. At the 663rd second, the flame intensity increased again, accompanied by burst sounds induced by short circuits. At the 675th second, the thermal runaway caused downward pressure output at the cast bottom cover. By the 820th second, the flame height and thermal runaway severity decreased, and the inorganic liquid extinguishing agent was used for 13 seconds to put out the fire. During this time, the external full-sized LIB pack temperature was measured at 220 °C, dropping to 160 °C after 7 seconds and 51 °C after the extinguishing action was completed, as shown in fig. 11(f). Smoke was seen between the 269-379th second, and the external full-sized LIB pack temperature was measured at 75 °C.

The full-sized LIB pack coated with inorganic liquid in the previous experiment was re-ignited. The time required for the thermal runaway was prolonged, and the highest temperature at which the thermal runaway occurred was measured at 445 °C. The thermal runaway reaction was terminated in as short as 13 seconds, as shown in fig. 12.

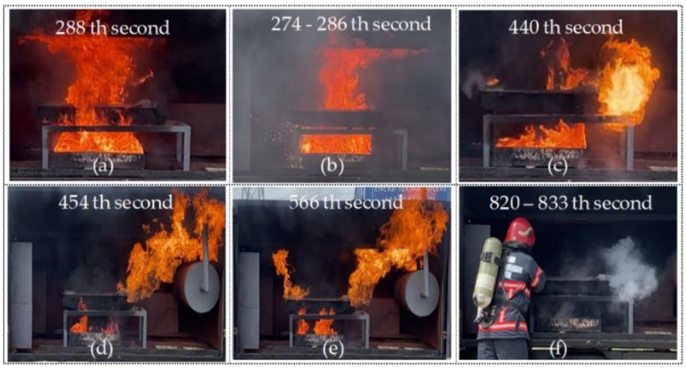


Figure 11. (a) Gas venting, (b) first explosion, (c) initial thermal runaway, (d) thermal runaway accompanied by bursting sound and flame stabilized, (e) thermal runaway reinstated at both ends of LIB, and (f) intervention using inorganic extinguishing agent stop the fire

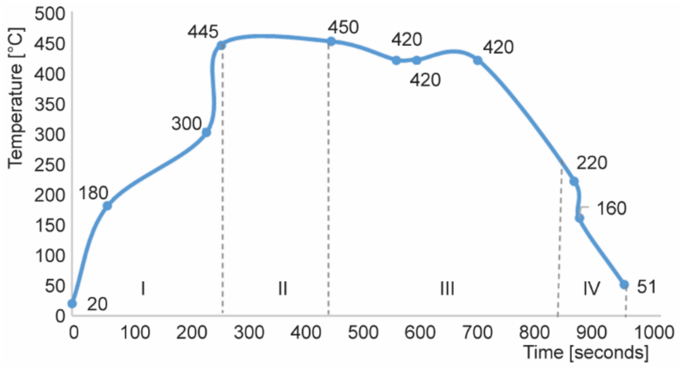


Figure 12. Thermal runaway occurrence sequence and breaking of the reaction attempted by inorganic liquid; *I – first reactions, heat up, II – gas blow and explosions, III – thermal runaway flames, IV – thermal runaway reaction break by extinguishing material, and V – cooling*

Discussions and conclusions

Five experiments have successfully validated the thermal runaway of LIB and identified the performance of two extinguishing agents. These experiments exhibit high repeatability, as they can be replicated with the same materials and under identical conditions, yielding consistent results that other researchers can reproduce. The LIB cells disintegrated in two of three LIB modules during *EN1*, while one did not initiate thermal runaway. At the 284th second, the anode and cathode foils from the exploded LIB cells were violently ejected with flames. The highest temperature measured during the experiment was 663 °C. The extinguishing process prevented thermal runaway in the single LIB module and was completed in 20 seconds. In *EN2*, the potential damage to separator material caused short circuits, leading to increased heat due to the decomposition of electrolytes and thermal runaway within 502 seconds and with a maximum external full-sized LIB pack temperature of 380 °C. The organic-based liquid extinguishing agent did not stop thermal runaway and only slightly reduced the heat. Effective intervention and extinguishing of the formation of short circuits before the start of thermal runaway are essential in preventing fire spread. In *EN3*, due to the short circuits during thermal runaway, explosions occurred, causing pierces on the protection cover. The maximum external full-sized LIB pack temperature reached 615 °C within 113 seconds. Using only one portable extinguisher, the inorganic-based extinguishing agent successfully put out the fire, which had entered the thermal runaway stage. As a result of the application of the extinguishing agent, the external full-sized LIB pack temperature decreased to 102 °C. The application of the liquid agent provided suppression of the gas release. The extinguisher was applied to the short-circuit sparks at the onset of thermal runaway. Applying the inorganic liquid in *EN4* successfully prevented the ingress of the full-sized LIB pack into thermal runaway and extinguished the fire. Following the application of the extinguishing fluid, the external full-sized LIB pack temperature decreased to 75 °C in just 50 seconds. The application of the relevant liquid also resulted in the suppression of the gas outlet. Compared to the previous test conducted without the same condition extinguishing agent, there was a significant delay in starting thermal runaway in *EN5* when the inorganic liquid was applied. The inorganic liquid could delay the onset of thermal runaway while retaining its long-term retardant feature. However, it was unable to completely prevent the formation of thermal runaway. The severity of thermal runaway varied, which is believed to have been influenced by the applied liquid. Despite this, the inorganic-based extinguishing fluid successfully extinguished the full-sized LIB pack fire, where thermal runaway continued. Prior to the onset of thermal runaway, the full-sized LIB pack swelled, which led to short-circuit sparks. These short circuits continued to occur throughout thermal runaway. Protecting those intervening in the fire is crucial due to the risk of electricity and sparks. Even after the extinguishing action was completed, gas output continued, resulting in toxic effects during the period of gas poisoning. The gas outlet continued accordingly.

References

[1] Lu, L., *et al*., A Review on the Key Issues for Lithium-Ion Battery Management in Electric Vehicles, *Journal of Power Sources, 226*, (2013), Mar., pp. 272-288
[2] Wang, H., *et al.,* Experimental Study on the Cell-Jet Temperatures of Abused Prismatic Ni-Rich Automotive Batteries under Medium and High States of Charge, *Applied Thermal Engineering, 202,* (2022), 117859
[3] Chen, J., *et al*., Designing an Intrinsically Safe Organic Electrolyte for Rechargeable Batteries, *Energy Storage Materials, 31* (2020), Oct., pp. 382-400
[4] Park, S.-Y., *et al*., Observation and Modeling of the Thermal Runaway of High-Capacity Pouch Cells due to an Internal Short Induced by an Indenter, *Journal of Energy Storage, 72* (2023), 108518
[5] Duan, J., *et al.,* Building Safe Lithium-Ion Batteries for Electric Vehicles: A review, *Electrochemical Energy Reviews, 3* (2020), 1, pp. 1-42
[6] Golubkov, A. W., *et al.,* Thermal Runaway of Commercial 18650 Li-Ion Batteries with LFP and NCA Cathodes – Impact of State of Charge and Overcharge, *RSC Adv., 70* (2015), 5, pp. 57171-57186
[7] Wang, E., *et al.,* Safety Assessment of Polyolefin and Nonwoven Separators Used in Lithium-Ion Batteries, *Journal of Power Sources, 461* (2020), 228148
[8] Ghiji, M., *et al.,* A Review of Lithium-Ion Battery Fire Suppression, *Energies, 13* (2020), 19, 5117
[9] Jin, Y., *et al.,* Explosion Hazards Study of Grid-Scale Lithium-Ion Battery Energy Storage Station, *Journal of Energy Storage, 42* (2021), 102987
[10] Fan, R., *et al.,* Numerical Analysis on the Combustion Characteristic of Lithium-Ion Battery Vent Gases and the Suppression Effect, *Fuel, 330* (2022), 125450

[11] Said, A. O., Stoliarov, S. I., Analysis of Effectiveness of Suppression of Lithium Ion Battery Fires with a Clean Agent, *Fire Safety Journal, 121* (2021), 103296
[12] Yu, D., *et al.,* Fire extinguishing test of lithium-ion battery case in electric bus, *Proceedings,* 9th International Conference on Fire Science and Fire Protection Engineering (ICFSFPE), Chengdu, China, 2019, pp. 1-5
[13] Zhang, L., *et al.,* Experimental Study on the Synergistic Effect of Gas Extinguishing Agents and Water Mist on Suppressing Lithium-Ion Battery Fires, *Journal of Energy Storage, 32* (2020), 101801
[14] Liu, Y., *et al.,* Experimental Study on a Novel Safety Strategy of Lithium-Ion Battery Integrating Fire Suppression and Rapid Cooling, *Journal of Energy Storage, 28* (2020), 101185
[15] Sun, H., *et al.,* Experimental Study on Suppressing Thermal Runaway Propagation of Lithium-Ion Batteries in Confined Space by Various Fire Extinguishing Agents, *Process Safety and Environmental Protection, 167* (2022), Nov., pp. 299-307
[16] Sun, P., *et al.,* A Review of Battery Fires in Electric Vehicles, *Fire Technology, 56* (2020), 6, 1361-1410
[17] Hassan, M. K., *et al.,* Fire Incidents, Trends, and Risk Mitigation Framework of Electrical Vehicle Cars in Australia, *Fire, 6* (2023), 8, 325
[18] Zhang, G., *et al.,* Study on the Suppression Effect of Cryogenic Cooling on Thermal Runaway of Ternary Lithium-Ion Batteries, *Fire, 5* (2022), 6, 182
[19] Wang, K., *et al.,* Early Warning Method and Fire Extinguishing Technology of Lithium-Ion Battery Thermal Runaway: A Review, *Energies, 16* (2023), 7, 2960
[20] Cai, T., *et al.,* Early Detection for Li-Ion Batteries Thermal Runaway Based on Gas Sensing, *ECS Transactions, 89* (2019), 1, 85
[21] Kethareswaran, V., Moulik, S., Electric Vehicles and the Burning Question: Reasons, Risks, Ramifications and Remedies – An Indian Perspective, *Fire Technology, 59* (2023), 6, pp. 2189-2201
[22] Tran, M.-K., *et al.,* a Review of Lithium-Ion Battery Thermal Runaway Modeling and Diagnosis Approaches, *Processes, 10* (2022), 6, 1192
[23] Kang, S., *et al.,* Full-Scale Fire Testing of Battery Electric Vehicles, *Applied Energy, 332* (2023), 120497

Paper submitted: November 10, 2024
Paper revised: April 23, 2025
Paper accepted: April 28, 2025