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Review

Overview of the current state of research on thermal runaway and thermal propagation testing of lithium-ion batteries

Nima Ghandily,[1],* Parthkumar Nakrani,[1] Niklas Kisseler,[1] Heiner Heimes,[1] and Achim Kampker[1]
[1]Chair for Production Engineering of E-Mobility Components, RWTH Aachen University, Bohr 12, 52072 Aachen, Germany
*Correspondence: nima.ghandily@rwth-aachen.de
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SUMMARY

Lithium-ion batteries (LIBs) are becoming increasingly important in the context of climate change, as they are being more widely used in electric vehicles, portable electronics, and grid-scale energy storage systems due to their high energy density, power output, and long service life. Nonetheless, in specific circumstances, thermal runaway (TR) and thermal propagation may occur. These phenomena are characterized by uncontrollable chain reactions, leading to individual cells igniting within the shortest possible time frame. This review examines experimental research focused on TR in LIBs, with particular attention to how test setups reflect real-world conditions. It identifies critical factors such as initiation methods, cooling strategies, thermal insulation, and cell construction that significantly affect thermal behavior during failure events. The analysis reveals a gap between controlled laboratory experiments and the complex conditions encountered in practical applications. By emphasizing the importance of realistic test parameters, the work contributes to improved experimental design and safer battery development, helping to minimize the risk of TR in operational systems.

INTRODUCTION

Globally, increasing attention is being given to the growing issues of environmental pollution and global warming due to high greenhouse gas emissions.[1] Green energy is becoming more prevalent worldwide as a solution to this challenge.[2] Lithium-ion batteries (LIBs) have become among the fastest-growing, promising electric energy storage technologies for effectively storing and utilizing green energy.[3] Due to LIBs' high energy density, extended cycle life, and environmental friendliness, they are becoming more and more common in consumer electronics, electric vehicles (EVs), and energy storage systems (EES).[4] However, safety concerns such as the risk of explosion and fire in LIBs must be carefully considered.[5] To mitigate these risks, preventing thermal runaway (TR) is essential.[6] Once TR is triggered in a single battery, it releases substantial heat along with toxic and flammable gases, significantly increasing the risk of fire or explosion.[7]

In EVs, a high volumetric energy density is essential.[8] To meet the energy demands of EVs, multiple lithium-ion battery (LIB) cells are combined to form a battery system.[9] If TR occurs within this system, the generated heat can spread to adjacent cells, leading to thermal propagation.[10] Many researchers have conducted experiments on battery systems under various conditions to identify the factors that effectively influence thermal propagation and enhance the potential for its prevention. Wang et al.[11] investigated factors such as state of charge (SOC), connection mode, cell arrangement, and battery aging that affect thermal propagation. Additionally, they found that TR is more likely when all the positive terminals of the battery cells are located on the same side. This is because the heat and high-temperature materials ejected from the positive electrodes gather more easily in the same direction, thereby intensifying propagation to adjacent cells. However, other factors like ambient temperature also have a significant impact on thermal propagation. For example, Liu et al.[12] found that thermal propagation intensifies with rising ambient temperatures and SOC. Kim et al.[13] investigated the thermal behavior of 18650 cells with nickel-cobalt aluminum (NCA) as well as the quantity and composition of gases produced during the TR. The amount of oxidizable species (H_2, CO, CH_4, C_2H_4, and C_2H_6) normally increases with the SOC, according to their identification of six key species (H_2, CO_2, CO, CH_4, C_2H_4, and C_2H_6). However, the percentage of generated gases depends on the battery cell material. For instance, in an experimental study, Wang et al.[14] categorized various elements of battery component materials according to how sensitively the smoke deposit affected their valence states. The elements that they discovered to be insensitive are cobalt (Co), copper (Cu), sulfur (S), lithium (Li), and phosphorus (P), while the elements that are sensitive are aluminum (Al), carbon (C), fluorine (F), manganese (Mn), nickel (Ni), and phosphorus (P). Furthermore, insulating materials have a significant impact on TR. As a result, in recent years, new types of insulation materials have been developed to prevent TR. For example, Niu et al.[15] utilized a hollow glass microsphere (HGM) plate as a thermal barrier to prevent TR propagation (TRP) within

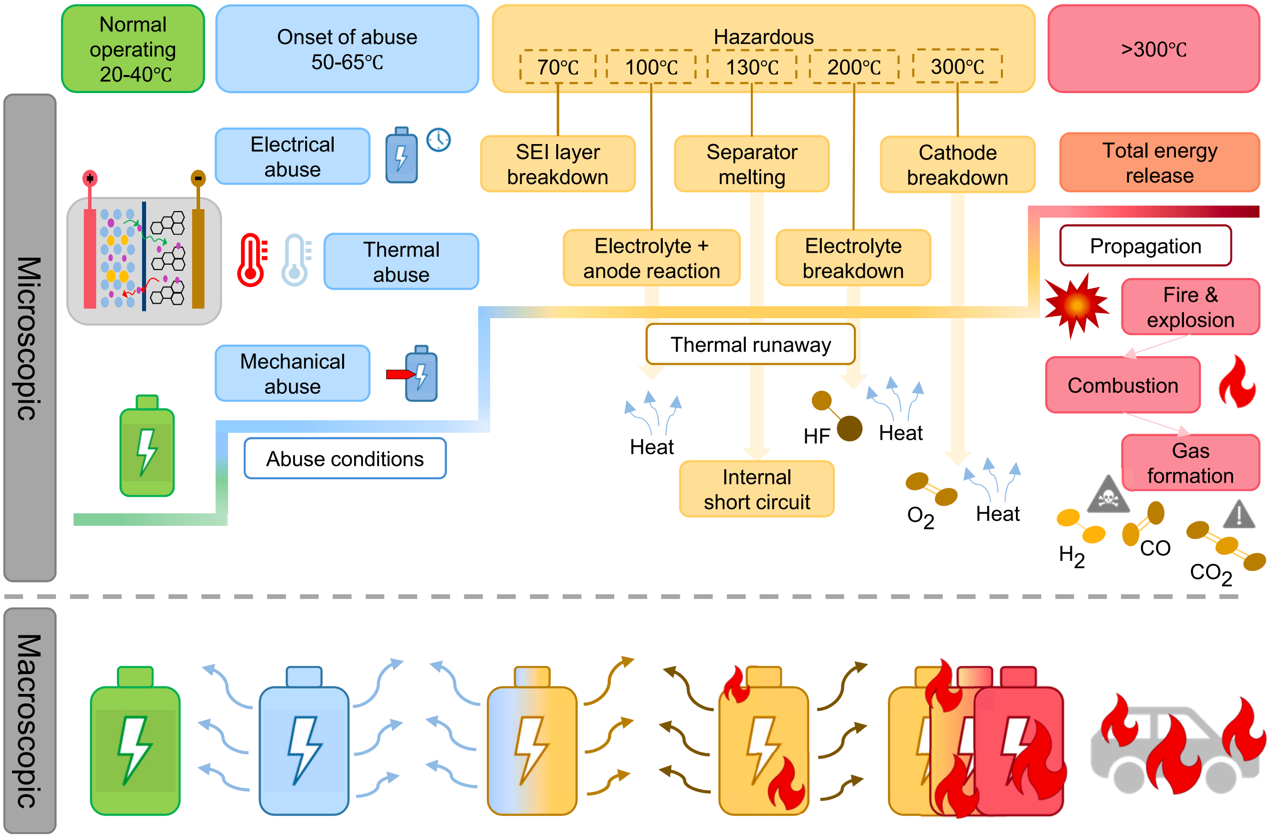

Figure 1. Detailed analysis of TRP in lithium-ion batteries with NMC cathode

a battery module. This plate comprises three main components: raw material, fire retardant, and binding agent. The results indicate that the most effective composition for preventing TRP is an HGM plate with 60 wt % HGM, 25 wt % curing agent, and 15 wt % flame retardants. Although several experimental and simulation research has been conducted, comparability of the different publications is not guaranteed. This is due to the fact that most tests do not fulfill uniform framework conditions. In addition, the number of tests conducted is generally not statistically meaningful. Methods such as the design of experiments (DoE) are mostly not used in the publications analyzed.

This study provides an overview of the current publications in the field of battery TR testing, compares them in terms of test performance, and evaluates their significance. In addition, the relevance and applicability of the DoE methods regarding battery testing are presented.

FUNDAMENTALS OF TR

In LIBs, a phenomenon known as TR may occur when heat production accelerates uncontrollably, causing a sharp rise in temperature. This condition is dangerous because it can lead to fire or explosion.[16] Such events may be initiated by different factors, including prolonged exposure to heat, internal short circuits, mechanical stress, or improper charging.[17] Once the cell moves outside its safe operating range, chemical reactions release additional heat and gases. The resulting escalation can deform the battery and may ultimately lead to fire or explosion.[18,19] Figure 1 illustrates the precise breakdown of TRP in a nickel-manganese-cobalt oxide (NMC) lithium-ion cell at both the microscopic and macroscopic levels.[20]

Abuse condition

Abuse involving mechanical, electrical, and/or thermal components may be the primary cause of TR.[21] The conditions are not identical for all cells. Factors such as cell format, anode and cathode material, and electrolyte composition play a significant role. However, a fundamental distinction is made between three areas. These are mechanical, electrical, and thermal abuse.

Mechanical abuse

Mechanical abuse happens when a battery sustains damage or stress, such as crushing, penetration, or significant impact.[22] The battery's internal structure may be damaged by these actions, which may also distort the electrodes, break the separator, or lead to internal short circuits. Mechanical damage can start a TR by generating concentrated high-resistance areas that quickly generate heat throughout the battery.[23]

Electrical abuse

When a battery experiences significant electrical stress or malfunctions, causing a TR, this is referred to as electrical abuse.[24] This can involve inappropriate usage of the charging

Table 1. Overview of abuse tests aimed at inducing faults or TR in battery systems

Abuse types	Test methods	Observed consequences	Risk of thermal runway
Mechanical abuse[31–33]	drop	superficial damage to the casing	depending on the impact position
	crush	deformation or warping of the casing	high in the event of an internal short circuit
	penetration	potential electrolyte leakage or TR	high due to the punctured separator
Electrical abuse[34,35]	overcharge	voltage irregularities or capacity reduction	high due to overheating
	overdischarge	increased internal resistance	low if performed only once high in the case of dendrite growth
	short circuit	elevated risk of TR	depending on the system resistance
Thermal abuse[36–40]	heating	overheating and damage to cell components	depending on the SOC level
	thermal cycling	localized damage to the cell components	high in the presence of dendrite growth
	temperature fluctuation	decomposition of materials	depending on cell chemistry and the number of cycles

equipment or overcharging, over-discharging, short-circuiting, etc.[25] Overcharging raises the voltage above safe levels, which causes an excessive amount of heat to be produced.[26] A significant voltage drop from overdischarging can result in the creation of metallic lithium and a subsequent TR.[27] Short-circuiting, which happens when the battery's positive and negative terminals are connected directly, results in a sudden surge of current and a tremendous amount of heat, which starts a TR.[28]

Thermal abuse

A battery is abused by the thermal if it is exposed to temperatures that are too high or too low for it to operate safely.[28] The chemical reactions inside the battery are sped up by excessive heat, such as exposure to direct sunshine, fire, or high temperature settings, which increases heat generation.[29] Similar to this, subjecting the battery to extremely low temperatures can impair ion mobility, cause voltage depression, and increase internal resistance, all of which increase the risk of TR when the battery is under high current demand.[30]

Mechanical, thermal, and electrical abuse are primary triggers of TR. To better understand these effects, Table 1 presents the types of abuse tests along with their observed consequences, while Figure 2 illustrates the progression from abuse test to TR. Considering these results is crucial, as various factors can influence, accelerate, or mitigate the onset and development of TR.

TR: Key influencing

To effectively prevent and mitigate TR in LIBs, it is imperative to comprehend the components that contribute to this phenomenon.[41] However, a number of important elements also have a considerable impact on the probability and speed of TR. These include the chemistry and materials of the cell, such as the anode and cathode's composition; the format and capacity of the cell; and the effectiveness of the thermal management systems (TMSs), which include cooling mechanisms, heat dissipation, and thermal barriers.[42] In addition, the battery's SOC, outside factors like the outside temperature or heating, and the precise techniques employed to cause TR all have an essential role to play.[43] Further research into these variables is necessary to improve the safety and reliability of LIBs.

Impact of cell cathode materials

The performance and safety of LIBs in a variety of applications are significantly impacted by the materials that are used in batteries.[44] Anode, cathode, electrolyte, and separator are only a few examples of the components that are essential in determining the features and behavior of the battery under various circumstances.[45]

The battery's overall energy density, cycle life, and thermal stability are all influenced by its various components.[46] However, because the cathode material has a direct impact on the battery's capacity, voltage, and thermal performance, it is particularly important. The thermal stability, safety margins, and energy storage capacity of the battery are all determined by the cathode materials.[8]

Lithium-cobalt oxide (LCO) cathodes are favored in portable electronics for their high energy density but suffer from thermal instability, especially under conditions like overcharging or high temperatures, where oxygen release from the cobalt oxide structure can trigger TR, posing safety risks.[47] In contrast, NMC cathodes offer improved thermal stability over LCO, with variants such as NMC 111 or NMC 622 balancing energy density, cycle life, and safety.[48] This makes NMC cathodes preferred for reliable applications such as EVs and ESSs. However, it is important to note that while NMC 811 provides higher energy density than NMC 111, it comes with lower stability, raising concerns about safety and cycle life. The main challenges are faster degradation, higher safety risks, and more complex production.[49] Meanwhile, lithium iron phosphate (LFP) cathodes are renowned for exceptional thermal stability and safety due to their robust iron phosphate structure, which mitigates risks associated with oxygen release at elevated temperatures and thermal decomposition.[50] LFP cathodes are thus highly preferred in applications prioritizing safety, such as stationary storage and industrial uses.[51]

In summary, while all battery materials affect overall performance, the cathode material plays a dominant role in defining the cell's energy density, safety margins, and thermal characteristics. Consequently, this study focuses on a thorough examination of the cathode material to assess TR behavior.

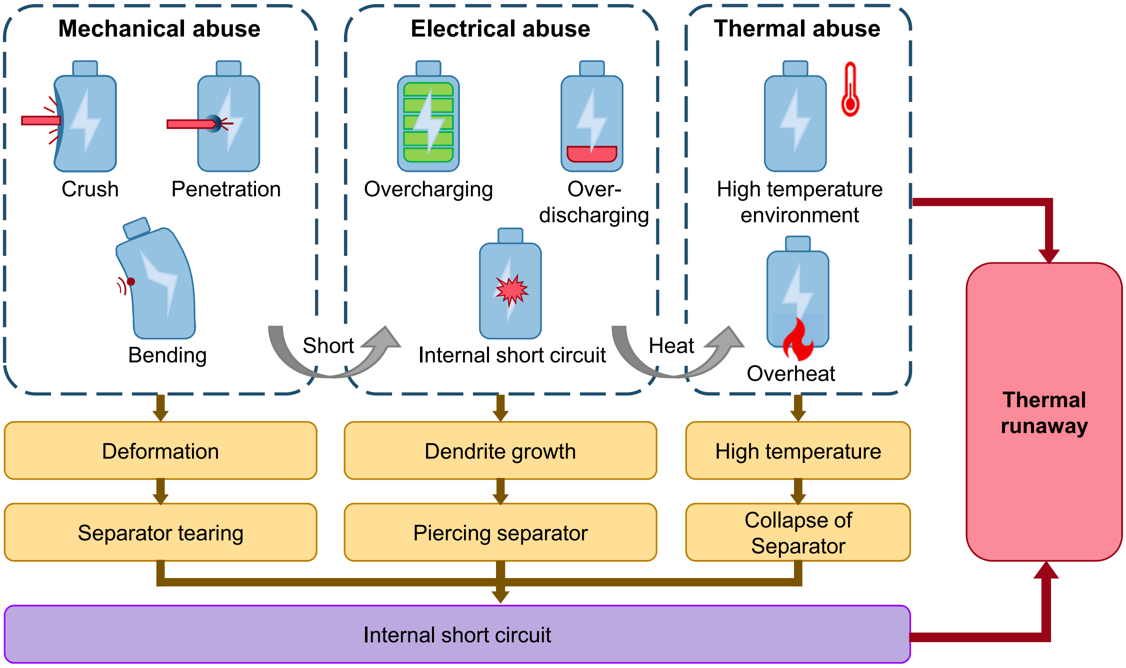

Figure 2. Overview of common causes behind fire incidents in lithium-ion batteries

Cell design

LIB performance, safety, and field usability are all significantly impacted by their design. The choice between cylindrical, prismatic, or pouch cell formats significantly affects the battery's energy density, packing efficiency, and thermal characteristics.[52]

Cylindrical cells are generally considered the most robust format against TR. Their metal casing provides strong mechanical stability, and potting material is often used as a barrier to absorb heat and slow down propagation, thereby localizing failure.[53] Prismatic cells, on the other hand, offer higher capacity per unit volume but are more vulnerable to thermal propagation due to their larger surface area and thinner casing. To mitigate these risks, manufacturers commonly integrate barrier materials such as mica sheets or aerogel layers, which improve thermal insulation but require careful system-level design.[54] Pouch cells provide the greatest flexibility in packaging and energy density, yet their soft casing makes them the most susceptible to TR. As a result, additional protective strategies, including reinforced module structures and advanced barrier layers, are essential to control the safety risks.[55]

Consequently, the selected cell design influences not only the onset of TR but also the extent to which it can propagate.[56] Therefore, during the research for this study, cell design has to be taken into account.

TMS. The TMS enhances the safety and reliability of LIBs by maintaining the cells within their optimal operating temperature range, thereby reducing the likelihood of TR.[57] In order to isolate heat-generating components and stop localized overheating from spreading to nearby cells, which could result in TR, thermal barriers are essential.[58] Thermally conductive materials and heat sinks are examples of effective heat dissipation methods that actively remove excess heat from the cells to keep the battery system's temperature constant.[59] Furthermore, constant active cooling is offered by modern cooling systems, like direct and indirect liquid cooling, which efficiently control the heat produced during high-power operation or rapid cycles of charging and discharging.[60] The TMS can have a significant impact on preventing TR by combining these components: cooling systems to control heat, heat dissipation mechanisms to remove heat, and thermal barriers to contain heat.[61] However, it is also important to note that once TR begins, current TMSs are not capable of stopping it. The underlying cause of this phenomenon is that the cooling systems are engineered to function within a cell temperature range of 20°C–40°C, not to withstand the stresses associated with TR.[62] Therefore, alternative solutions are needed to effectively address this problem.

SOC. In LIBs, the risk of TR is greatly influenced by the SOC.[63] As there is more energy stored at high SOC levels–especially close to full charge–there is a greater risk of TR.[64] The battery cells' internal chemical reactions intensify at high SOC, producing greater heat and raising internal pressure. Thermal instability may result from this state, particularly if the battery is subjected to outside stresses like high temperatures or physical harm.[65] Moreover, increased SOC levels may intensify adverse effects, such as the electrolyte breaking down and releasing heat and combustible gasses.[66] The combined effect of these factors increases the risk of TR. On the other hand, by lowering the overall heat and chemical stress on the battery cells, keeping a moderate SOC range can help alleviate these concerns.[67] Therefore, to improve the safety and dependability of LIBs and avoid situations that could result in TR, thorough SOC monitoring and management are essential.

Table 2. Overview of diagnostic approaches for battery faults across different scales

Scale	Testing context	Diagnostic methods	Key objectives	Potential limitations	Mitigation strategies
Cell level	abuse testing of individual cells in lab settings	● electrochemical impedance spectroscopy ● voltage and temperature monitoring ● smoke and heat release measurement ● monitoring vented gas ● acoustic monitoring ● particle distribution	● provides high accuracy in fault diagnosis ● identifies abnormal behavior and failure mechanisms	● requires advanced sensors and data processing ● susceptible to sensor errors	● use robust battery banagement systems (BMS) ● monitor charge/discharge rates and thermal conditions
Pack level	Testing small packs in controlled environments	● monitoring voltage for each cell ● tracking pack temperature ● checking for pack inconsistencies	● detects critical faults that may lead to large-scale issues ● prevents catastrophic failures	● limited capability for identifying minor faults in individual cells ● increased complexity with higher cell counts	● incorporate thermal barriers and insulating materials ● space cells to limit heat transfer
System level	Testing complete battery systems in real-world conditions	● monitoring overall voltage and current ● system-wide temperature tracking ● analyzing operational data like charge cycles	● identifies major faults affecting the overall system performance ● optimizes control via BMS	● less precise in locating specific faults ● faults may only be detected after significant degradation	● implement active/passive thermal management systems ● use fire-resistant enclosures and early warning systems

External condition

The safety and stability of LIBs are greatly influenced by external factors such as (ambient) temperature, pressure, and ambient conditions, especially with relation to TR.[68] High temperatures have the ability to accelerate chemical reactions in the battery, resulting in a temperature spike and possibly TR. On the other hand, too low temperatures may result in lithium plating on the anode, which increases the risk of TR by causing internal short circuits as the battery warms up.[69]

Important additional considerations include mechanical stress and pressure. Short circuits and localized heating can result from the deformation of the battery case and internal components caused by high-pressure situations or mechanical impacts.[70] This localized heating can lead to the onset of TR. To reduce these dangers, it is crucial to maintain proper pressure conditions and protect batteries from mechanical shocks.[71]

Heat dissipation is influenced by external factors, such as the battery's isolation or exposure to the elements. The risk of TR might increase in remote areas with poor ventilation due to the accumulation of heat produced by the battery.[29] To manage thermal loads and stop TR, protective enclosures and sufficient ventilation are essential. Therefore, it is crucial to specify whether these factors were considered in the experiment.

In this paper, the aforementioned factors will be thoroughly reviewed in the context of existing experimental studies on TR.

Table 2 shows the testing scale at the cell, module, and pack levels. Cell-level testing focuses on the performance and safety of individual cells, while pack-level testing evaluates the interaction of multiple cells in a module or system, including heat generation and failure propagation. System-level testing examines the battery in its full application, assessing thermal management, control strategies, and overall safety. Together, these levels ensure reliability from the smallest unit to the complete system.

In this study, the classification of the papers will primarily be based on cell type, as all the reviewed papers explicitly report the type of cell used in their experiments. This allows for a consistent foundation to compare findings across various studies. However, other classifications, such as SOC and experimental conditions like temperature and pressure, vary significantly between papers. This variability reflects the researchers' focus on understanding TR behavior under diverse setup conditions, tailored to simulate specific real-world scenarios or stress tests. By emphasizing cell type while accounting for these experimental differences, this study aims to provide a structured analysis of TR across various LIB configurations and testing environments.

METHODOLOGY

This section highlights the growing trend in experimental analysis of TR and TRP in LIBs over time. Furthermore, it outlines the criteria used to identify relevant research papers and the key specifications observed during the review. Finally, a summary table of the research papers examined in this study is presented.

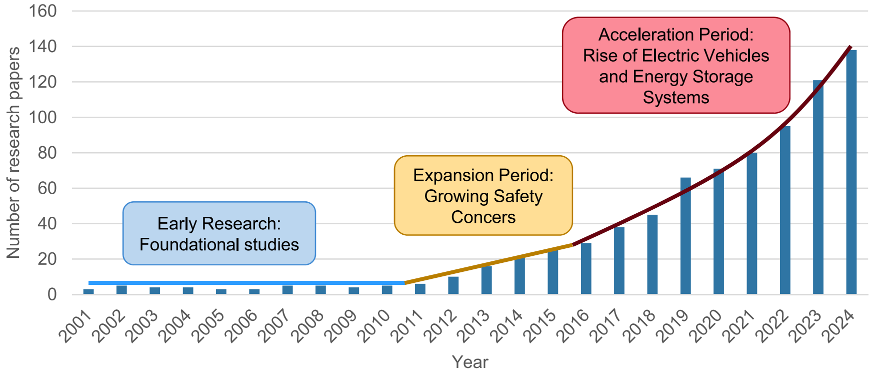

Figure 3. Rising trend of publications on TRP over the years

Trend of TR

The issue of TR has been extensively studied over the last two decades, particularly as battery technology has evolved and its applications have expanded. Incidents like the Boeing 787 Dreamliner battery fires (2013), Tesla Model S fires, and Samsung Galaxy Note 7 explosions (2016) have highlighted the global urgency for improved understanding and mitigation of battery failures.[27,72]

Since 2000, research into TR has grown exponentially, driven by safety concerns, regulatory demands, and advancements in LIB technology. Scientists have conducted experiments at the cell, module, and pack levels to investigate the causes, mechanisms, and prevention techniques for TR. Computational modeling and machine learning are now also being used to predict and mitigate risks in real-time applications.[73]

This article explores the trends in TR research from 2000 to 2025, examining how the number of studies has increased, what factors have influenced this growth, and what types of experiments have been performed at different battery scales.

Early research (2000–2010): Foundational studies

Before 2010, research on TR was limited, with most studies focusing on the chemical and electrochemical processes leading to thermal instability, such as electrolyte decomposition, separator failures, and dendrite formation.[74] Experiments were primarily conducted at the cell level using small cylindrical and prismatic batteries. As safety concerns grew, regulatory agencies began setting safety standards, prompting more studies into battery abuse testing, including overcharging, overheating, and mechanical damage.[75]

Expansion period (2011–2015): Growing safety concerns

Between 2011 and 2015, growing safety concerns, particularly after high-profile incidents like the **Boeing 787 LIB fires**, led to a significant increase in TR research.[76] Studies shifted beyond just analyzing the onset of TR to investigating **thermal propagation,** examining how a failing cell could trigger failures in adjacent cells, potentially leading to catastrophic failures in battery packs.[75] Research expanded to the **module level**, focusing on **thermal management strategies, fire suppression methods, and protective barriers** to prevent cascading failures. This period also saw increased regulatory scrutiny, pushing manufacturers to implement stricter safety measures in battery design and testing.[77]

Acceleration period (2016–2024): Rise of EVs and EESs

With the rapid rise of EVs from 2016 to 2024, there was a surge in demand for safer and more reliable battery designs to prevent TR incidents.[78] Researchers focused on TRP in large battery packs, studying how failures could spread and how to prevent large-scale hazards.[14] Computational models and finite element simulations were developed to predict TR behavior under various conditions, improving the understanding of heat generation and gas release during failure events. In response, battery manufacturers introduced new safety features, such as thermal barriers, improved cooling systems, pressure relief vents, and fire-resistant materials, to enhance battery safety and performance.[79] This period marked a shift from small-scale experimental studies to large-scale pack-level safety strategies, driven by industry demand, regulatory requirements, and real-world fire incidents.

Figure 3 illustrates the number of research papers published annually from 2001 to 2024, focusing on experimental investigations of TR. A significant increase in publications has been observed, particularly after 2015, with exponential growth seen from 2018 onward.

These data have been derived using the Web of Science database, where specific keywords related to “experimental investigation of TR for LIBs” have been applied. The number of papers retrieved is strongly dependent on the choice of keywords, meaning different search terms could yield varying results.

This trend suggests that TR mechanisms, safety improvements, and experimental methodologies have become major research areas, with intensified focus in recent years.

Figure 4A represents data for the year 2024 and consists of two pie charts. The first chart illustrates the level of testing, indicating that cell-level testing is the most common, accounting for 51%. However, obtaining sufficient information about TR from this type of testing is challenging, as real-world scenarios predominantly involve battery modules or battery packs. As shown in the chart, only 6% of the studies focus on pack-level testing, likely due to the higher complexity and cost associated with it compared to module-level and cell-level testing. Consequently, 41% of researchers conduct testing at the module-level to obtain more relevant data and ensure a closer representation of real-world conditions.

Figure 4B illustrates the types of battery cells used in these research papers. The choice of cell form varies depending on the specific research objectives, highlighting the diverse approaches taken in battery testing.

Study categorization and classification

The categorization and classification of studies on TR in LIBs are essential to systematically analyze the diverse range of research

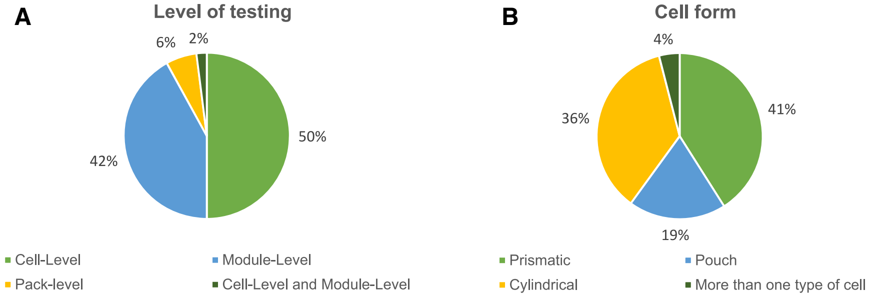

Figure 4. Distribution of testing levels and cell designs in experimental studies on lithium-ion batteries

(A) Testing is primarily conducted at the cell and module levels, with fewer studies at the pack level.

(B) Prismatic and cylindrical cells dominate experimental designs, while pouch cells and mixed-format approaches are less common.

in this field. LIBs, widely used in applications such as electric vehicles, consumer electronics, and EESs, exhibit varying TR behaviors influenced by their design, chemistry, and operating conditions. This variability necessitates a structured approach to grouping and comparing studies, enabling researchers to draw meaningful conclusions and identify patterns across different experimental setups and methodologies.

Table 3 presents a comprehensive overview of the various factors influencing TR in batteries.

Figure 5 illustrates the process used to select research papers for this review. Specifically, it includes all potential papers published between 2015 and 2024 that meet the outlined criteria. While some studies focus solely on simulation-based analyses, these are not included in this review, as simulation studies often differ from real-world experimental results due to environmental factors and uncontrolled conditions. Instead, this paper prioritizes research that includes experimental validation to ensure more accurate insights.

Additionally, key aspects such as cell configuration (cell, module, or pack level), trigger methods (electrical, mechanical, or thermal abuse), and test setups (housing, insulating sheets, and environmental conditions) are considered. Some researchers incorporate TMSs in their test setups to enhance realism, utilizing methods such as air cooling, liquid cooling, and phase-change materials (PCM). However, due to the complexity and high costs associated with these setups, only a limited number of studies have investigated them experimentally. Ultimately, only papers that align with the criteria outlined in this chart will be reviewed in this study.

Once all potential research papers are selected, they are systematically categorized based on key aspects to ensure a thorough analysis of TR in LIBs. One of the primary classification criteria is battery cell type, which includes cylindrical, prismatic, and pouch cells. Each of these cell formats exhibits unique structural characteristics that influence heat dissipation, mechanical stability, and the likelihood of TRP. Additionally, the classification extends to battery chemistry, with a focus on LFP, NMC, and LCO. By considering both cell format and chemistry, this classification enables a more detailed comparison of thermal safety across various battery designs.

Beyond cell type, the studies are further classified by trigger mechanisms such as electrical, mechanical, and thermal abuse, as well as by testing methodologies including experimental setups and computational models. This systematic classification not only provides a comprehensive framework for understanding the factors influencing TR but also helps identify research gaps, ultimately guiding future investigations to enhance LIB safety.

Table 4 provides an overview of the papers, including the categories used in this review.

In most scientific studies focused on battery safety, researchers use several standard trigger methods to initiate TR, a dangerous and rapid release of heat and gases from a battery cell. One of the most common is cell triggering, which includes techniques like heating the cell with a coil or inducing an internal short circuit, mimicking internal malfunctions. Another method is the use of an external heater, which gradually increases the cell temperature until failure occurs, simulating high-temperature environments. The nail penetration test physically pierces the cell, causing an internal short and simulating mechanical damage such as accidents. Overcharging pushes the cell beyond its voltage limits, stressing internal components and mimicking faults in battery management systems. Each method has its advantages, limitations, and relevance in replicating real-world TR events.

Table 5 presents a comparison of various trigger methods for TR. Each method of triggering TR in LIBs offers unique insights into different failure scenarios. While methods like internal triggering and overcharging closely replicate real-world causes of TR, techniques like nail penetration and crushing are essential for simulating the effects of mechanical damage.[71,104–107]

COMPARATIVE ANALYSIS

This section provides a detailed analysis of all the papers listed in Table 4, categorized by cell type, and discusses their potential advantages and research gaps in comparison to others.

Based on cylindrical cells

Kim et al.[13] conducted a simulation to study the ventilation gases during TR of cylindrical cells in two phases: cell breach and venting. The first phase had little impact on propagation, while the majority of reactive gas generation occurred during the second phase. The release of gases like H_2, CO_2, and CH_4 increased with SOC, and the pressure inside the cell casing also rose, reaching up to 4.25 bar at 100% SOC, potentially causing a breach. The issue with this analysis is that it relies on simulation data, which may not fully capture the complexities of real-world scenarios. While simulations can account for many factors, there are variables, such as internal short circuits, that are difficult to predict and incorporate into the model. As a result, the findings

Table 3. Analysis of multiple factors involved in the onset and propagation of TR

Specification	Importance	Categories/values
Battery cell type	TR behavior varies significantly between cell types due to design and material differences	● cylindrical ● prismatic ● pouch
Trigger method	identifies the primary cause of TR for each study	● mechanical abuse ● thermal abuse ● electrical abuse
Cathode material	different chemistries have varying thermal stability and runaway characteristics	● lithium-cobalt oxide (LCO) ● lithium-iron phosphate (LFP) ● nickel-manganese-cobalt (NMC) ● nickel-cobalt-aluminum (NCA)
State of charge (SOC)	SOC significantly influences TR onset temperature and severity	● low SOC ● medium SOC ● high SOC
Propagation behavior	describes how TR spreads within a battery pack or module	● none (isolated) ● mild (limited spread) ● severe (entire pack/module)
Safety features	indicates built-in safety measures and their effectiveness	● venting mechanisms ● thermal fuses ● flame-retardant materials
Test setup	provides insight into how the study was conducted and its reproducibility	● lab-scale ● real-world simulation ● computational modeling ● housing
	environmental conditions that specifically affect the runaway behavior	● ambient temperature ● humidity ● pressure
	Effect of thermal management system	● air cooling ● liquid cooling ● PCM cooling ● hybrid cooling

from this simulation study may not be as reliable or applicable when compared to real-world testing, where unexpected conditions and failures can have a significant impact on the results. Therefore, this simulation study cannot be directly compared to or considered a substitute for actual experimental testing.

Conversely, Jia et al.[90] conducted a simulation study alongside experimental testing, producing results that more closely reflect real-world scenarios compared to studies relying solely on simulations. The study identifies two modes of TRP in battery modules: mode I, where local overheating accelerates TR through short circuits, and mode II, where heat spreads slowly, triggering TR at a critical temperature. It also finds that smaller pack sizes and higher temperatures increase TR speed. However, factors such as the distance between cells, cell design, environmental conditions, and charging conditions can influence TR. Therefore, such studies may not produce results that accurately reflect real-world scenarios.

Some researchers have performed experimental tests considering these factors to gain a better understanding of TR in real-world scenarios. For example, Chen et al.[84] investigated mass loss rates during TR using different module sizes (6 × 6 and 10 × 10). This study offers valuable insights into the thermal failure and fire propagation of primary lithium batteries, emphasizing key factors such as thermal failure temperature, mass loss rate, and combustion efficiency. Furthermore, Hu et al.[85] conducted a thorough investigation of TR in 18650 LIB modules under various charging conditions, emphasizing the accelerated impact of high charging rates on TR onset temperature and propagation time. Undercharging C-rate, Wang et al.[86] conducted experimental tests to investigate the significant impact of spacing on TR. The study reveals that increasing triggering temperature and battery spacing, along with reducing the charging C-rate, can effectively reduce TRP in LIB modules.

Beyond charging conditions, the effect of cylindrical cell diameter on TR is also significant. To investigate this, Wang et al.[87] conducted experimental tests and analyzed the TR process of four types of LIBs with varying diameters, revealing that both the propagation time and rate increase with battery diameter. Additionally, elements in the air, particularly oxygen, can accelerate the TR rate. Weng et al.[88] conducted experiments showing that reducing oxygen concentration from 21% to 12% significantly delays TRP and weakens its severity. Furthermore, both nitrogen and argon dilution gases effectively slow down TR, with nitrogen providing a more cost-effective solution, while lower oxygen levels reduce the overall hazards associated with battery fires. However, it is important to note that the research mentioned in the previous two paragraphs used a heater as the triggering method, which simulates external thermal stress but does not account for internal faults. This means the experimental results may vary when compared to real-world scenarios.

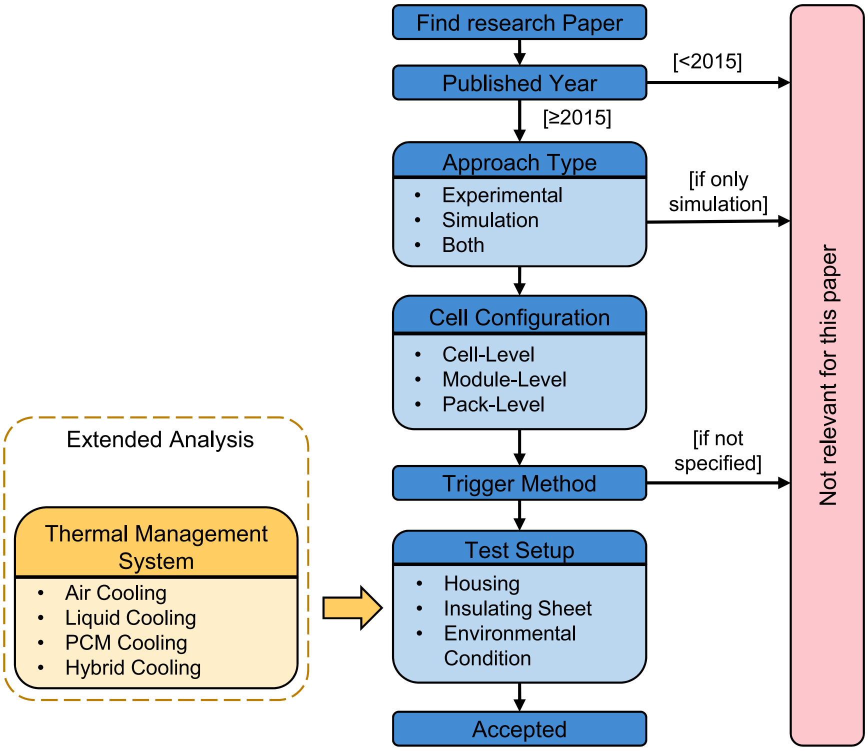

Figure 5. Approach to research paper selection with emphasis on relevant factors

For example, a few experiments have used a triggered cell as the initiation method. Liu et al.[12] conducted TR tests under low pressure, revealing that TRP in modules is more aggressive in parallel-connected configurations and influenced by ambient pressure and temperature. While low pressure has minimal impact in real-world scenarios due to relatively stable surface pressure on Earth, ambient temperature and SOC can have a significant effect on TR. Niu et al.[80] investigated TRP in 18,650 LIB modules under varying SOCs, connection methods, and ambient temperatures, revealing that higher SOC and temperature increase propagation speed, with flat-tab connections accelerating propagation and non-flat-tab connections increasing explosion risk. Along with the influence of SOC, Wang et al.[11] also investigated the impact of connection mode and battery arrangement on TR propagation and showed that venting behavior and, consequently, the amount of energy released vary depending on the SOC. TR propagation is more likely when battery positives are aligned in the same direction, while a higher number of parallel structures shortens the TR interval. A high level of SOC has been shown to result in enhanced venting and combustion. Consequently, the remaining battery mass was also lower than with a lower SOC. This resulted in a variation in the proportions of the types of heat release (heat conduction, convection, and radiation) depending on the SOC. A lower SOC resulted in less intense venting and, consequently, a higher remaining battery mass, which manifested itself in the form of heat conduction to neighboring cells.

Besides SOC, ambient temperature, and pressure, the distance between cells and their arrangement also play a crucial role in TR. Some researchers have explored these factors through the triggered cell method. For instance, Wang et al.[81] conducted experiments on TR with spacing in open environment and closed space and different configurations. They discovered that the risk of TRP is higher in a confined space than in an open environment. Furthermore, propagation is more likely in a vertical arrangement than in a horizontal one. Additionally, Ouyang et al.[108] investigated the impact of discharging treatment on thermal failure propagation in battery modules with various shapes (cell arrangement). Their results demonstrate that discharging treatment accelerates thermal failures, leading to faster propagation and greater mass loss. The failure process varied across different phases depending on the module shape, with discharging treatment significantly increasing the overall risk of TRP in battery modules under operation.

Although the aforementioned paper focused on various potential factors, such as SOC, temperature, cell spacing, and cell arrangement, which significantly impact TR, additional factors like housing and the cooling system should also be considered. Including these elements would provide results that are more relevant to real-world scenarios. Some studies, such as the research by Yuan et al.,[82] have experimentally evaluated the effectiveness of interstitial materials in mitigating TRP in battery modules. Their study incorporated proper housing for the battery module, allowing assessment and modification of TR behavior based on the thermal conductivity of different materials. While air proved ineffective, aluminum extrusion provided the highest level of protection, followed by graphite composite sheets. These findings are particularly relevant for cylindrical LIBs and contribute to the development of safer battery module designs. Furthermore, Ke et al.[89] examined TR behavior in a serpentine channel liquid-cooling system, finding that the primary cause of TR propagation is the high-temperature electrolyte ejected from the battery's positive end. Increasing the coolant flow rate can slow down TR, while minimizing coverage over the battery's positive end in battery TMS (BTMS) designs can further enhance safety.

Some researchers have conducted experimental tests under various conditions, specifically focusing on cooling systems, housing, and insulation. These studies offer valuable insights and enhance the understanding of real-world scenarios. For example, Ouyang et al.[83] investigated thermal failure propagation by analyzing the effects of battery gap, SOC, and PCM cooling systems. Their findings show that increasing the battery gap effectively delays or even halts failure propagation, while

Table 4. Analysis of research papers based on methods and investigated key parameters

Cell format	Triggering method	Cathode material	Test level	Cooling system	Housing	Purpose
Cylindrical	Triggering cell	NMC	module	☐	☐	TR under low atmospheric pressure[12]
		NMC	module	☐	☐	TR at different ambient temperatures[80]
		NMC	module	☐	☐	TR with different cell arrangements in the module[80]
		NMC	module	☐	☐	experiment with different SOC and connection type[11]
		NMC	module	☐	☐	effect of cell spacing on TR[81]
		NCA	module	☐	■	effect of different interstitial materials on TR[82]
	Heater	LCO	module	■	■	experiment with different SOC and different distance between cells[83]
		NMC	module	☐	☐	investigate the mass loss rate in 6 × 6 and 10 × 10 cell arrays[84]
		NMC	module	☐	☐	TR under charging condition[85]
		NMC	module	☐	☐	experiment with different C-rate and different distance between cells[86]
		NMC	cell to pack	■	■	pack-level experiment with liquid cooling system[14]
		NMC	module	☐	☐	influence of battery diameter on TR[87]
		NMC	module	☐	☐	effects of oxygen level and diluent gas[88]
		NCA	module	■	☐	investigated the retarding effect of liquid cooling on TR[89]
	nail	LFP	module	☐	☐	the test was carried out at low and high equivalent thermal resistance[90]
	ignored	NCA	module	☐	☐	investigated the gas generation mechanism during TR[13]
Prismatic	triggering cell	LFP	module	■	☐	effects of thermal insulation[91]
	heater	LFP	module	☐	☐	experiment with different SOC[92]
		LFP	module	☐	■	TR under inclined ceilings[93]
		LFP	module	☐	■	experiment with different cell connections[94]
		NMC	module	☐	☐	experiment with hollow glass microsphere plates[15]
		NMC	module	☐	☐	influence of characteristic thermophysical parameters[95]
	gas burner (Fire)	NMC	Ppck	☐	■	experiment with two active battery modules and six dummy modules[96]
	nail	NMC	module	■	☐	optimization of interstitial heat-absorbing thermal barriers[97]
	overcharging	LFP	cell	■	■	experiment with an oil immersion cooling system[98]
		NMC	cell	☐	☐	internal and external temperature sensing[99]

(*Continued on next page*)

Table 4. *Continued*

Cell format	Triggering method	Cathode material	Test level	Cooling system	Housing	Purpose
Pouch	heater	NMC	module	☐	☐	effect of heating power and heating energy[100]
		NMC	module	☐	■	effects of heating position[101]
	nail	NMC	cell	☐	☐	experiment with mica sheets[102]
		NMC	module	☐	☐	insert a different heat-resistant layer between adjacent batteries[10]
	tab heater	NMC and LFP	module	☐	☐	influence of tab overheating on TR[103]

higher SOC exacerbates propagation, resulting in faster failure and higher peak temperatures. Furthermore, traditional PCM negatively affects thermal management by trapping heat and causing excessive accumulation. These insights help improve battery module safety and thermal management strategies. A promising study under realistic conditions was conducted by Wang et al.,[14] who examined the TRP characteristics of a cell-to-pack (CTP) battery system. The research identified three main propagation patterns: ordered, synchronous, and disordered, with synchronous propagation causing the most damage. It was found that liquid cooling plates do not prevent propagation between modules, whereas larger gaps help reduce it. The study also analyzed temperature changes and flame spread during TR and identified key sensitive elements in smoke deposits, offering valuable insights for enhancing battery safety and thermal management.

Based on prismatic cells

Huang et al.[96] carried out a sensitivity analysis of TR propagation on a battery module. The simulation model showed a minimal deviation from the real test. GT-SUITE 2021 was used as simulation software. A gas flame was used as the triggering method, which is uncommon. The sensitivity analysis showed that the TR start temperature and the heat capacity of the cell have the greatest influence on the TR process. It was not explained why an entire pack was used for the test if the simulation was only carried out at the module level. In addition, no thermal barrier materials or gap pads were used between the prismatic cells at the module level, which is also uncommon in a real-world scenario.

Due to the growing demand for storage systems as buffer storage, more and more tests are being carried out that are focused on the so-called ESS. For example, the group of Wang et al.[92] carried out an extensive investigation of the TR and propagation behavior of 105 Ah LFP cells. Here, a single cell was first brought to TR via overheating in order to determine the heat emitted. This makes it easier to correlate the results with the propagation behavior and to compare different publications with each other. This was carried out for 0%, 50%, and 100% SOC. Further experiments were carried out in a module setup of up to four cells to investigate the propagation behavior. In addition, the modules were placed on top of each other to investigate propagation to another module level. Unfortunately, no information is available about the distances between the modules or the isolation between each layer. Another disadvantage was the large volume of the test room. The influence of the escaping gases can be estimated to be small because of the large volume of the test room.

The group led by Zhai et al.[93] investigated different ceiling angles for the battery modules in an ESS. Large-format LFP cells with 243 Ah were used, which were heated to initiate a TR. The aim was to investigate the influence of the ceiling angle on propagation, as not only flammable gases escape upward during TR but also particles that can cause heat transfer to neighboring cells and cause a TP. It is worth mentioning the use of an experimental design with a single parameter change that represented the ceiling angle. A horizontal ceiling, which is currently the most widely used in ESS, represented the most unfavorable orientation. A 10°–30° angle is better in order to transport the escaping gas away from the adjacent cells as much as possible. This publication shows how important gas routing is in a TR event and how minor changes can lead to safety optimization.

Another approach to stop propagation is the use of intensive cell cooling. The use of immersion cooling is one such approach, which was investigated by the group of Bai et al.[98] Here, a 125 Ah LFP cell was brought to TR via overcharging. Three different cooling methods were investigated: Air cooling, static, and dynamic immersion cooling. With the help of dynamic immersion cooling, the TR time was reduced by 30 s. Overall, a more homogeneous cell temperature could also be realized during charging and discharging processes, as the cell was cooled all around with oil, which was used as a cooling liquid. Further studies should be carried out with module structures to investigate the effectiveness of immersion cooling regarding TP.

There are a large number of cell parameters that have an influence on TR. The group led by Wang et al.[95] has carried out a detailed study to analyze these parameters and their influence. Among other things, thermocouples were used in prismatic cells with different cathodes (NMC111, NMC523, and NMC622) in order to obtain even more precise measurement results. This was followed by precise measurements with a calorimeter and propagation tests with four real cells and a heating plate with the geometry of a neighboring cell. The following findings were obtained: A higher self-heating temperature T1 has a significant influence on the TR trigger temperature and the propagation speed. The trigger temperature T2 is even higher. An increase in this can extend the propagation time by more than 200%.

On the other hand, Kisseler et al.[99] investigated the timing delay between external and internal temperature sensors. Their

Table 5. Overview of trigger methods used in previous research studies

Trigger method	Advantages	Disadvantages	Suitability for real-world scenarios
Heat coil	● simulate internal failures accurately ● useful for studying early thermal events ● targets specific cell areas	● hard to reproduce exactly ● complex setup may be needed	high
Heater	● easy to control ● reproducible ● safe and simple setup	● high space requirements ● less realistic compared to heat coil ● may not reflect internal causes	high
Nail penetration	● triggers realistic internal short circuit ● clear failure point	● hard to control and reproduce ● local damage only	moderate
Overcharging	● simulates common electrical faults ● useful for BMS failure tests	● ay not always trigger runaway ● abnormal reaction due to excessive energy content	low

study showed that integrating thermocouples into large-format prismatic NMC811/C lithium-ion cells allows reliable internal temperature monitoring without significantly affecting cell performance. The internal sensors detected the onset of TR earlier (21 s) than surface measurements and revealed pronounced temperature gradients inside the cell. These findings underline the importance of internal sensing for early warning and enhanced safety in high-energy automotive batteries. However, it is also important that the temperature sensor material remains chemically inert with the internal cell components to avoid any impact on performance.

Another factor in propagation is the electrical connection of the cells. Zhou et al.[94] examine the influence of parallel contacting on propagation. Due to the short circuit, which occurs after the TR of the first cell, current flows from the neighboring intact cells through the short-circuited TR cell. Prismatic cells with 200 Ah were used for this purpose. Four cells and one heater were used per module. Four tests were carried out. Without parallel contacting and with contacting, as well as the same setup with aerogel as a thermal insulator between the cells. A significantly higher heat dissipation was measured due to the parallel connection. This was 400 W per cell with a parallel connection. The TR cell was 16°C warmer due to the connection, which shows no significant influence. The use of aerogel prevented propagation despite the parallel connection and reduced the thermal output of the cell from 400 to 35 W. The greatest influence on propagation is therefore the heat conduction between adjacent cells and lesser the electrical contact between the cells. Future investigations should nevertheless be carried out in order to be able to make a statistical statement, as only one test per setup was carried out here.

A similar approach was pursued by the group of Niu et al.[15] only without the use of cell contacting. They investigated the use of HGM plates as a propagation-inhibiting material. This material has a low density, which can be important when used in a battery system in order to save as much space and weight as possible. Prismatic cells with a capacity of 51 Ah and an NMC 811 cathode were used in the test. Nine different HGM plates with different material ratios (raw material, fire retardant, and binding agent) were tested to identify the ideal ratio. Five real cells were used per test setup and brought to TR by means of overheating. It was shown that the propagation could be stopped at a thickness of 3 mm.

Important components, such as the cooling system, are often neglected in propagation tests. These are used in battery EVs (BEVs), for example, to realize a homogeneous battery temperature under a wide range of ambient conditions and charging rates. The cooling system, which is a cooling plate or a hose-type cooling system, is often used and can influence the propagation behavior. These components should therefore be considered in tests in order to validate a system that is as close to reality as possible. This approach was chosen by the team around Merz et al.[97] They tested propagation tests with prismatic cells in PHEV2 format with 50 Ah capacity and 811 NMC cathode, using an aluminum plate on the underside of the cells to symbolize a cooling system. Tests were carried out with insulation materials of varying thicknesses and the middle cell in a three-cell setup was triggered using a nail. A 1.5-mm-thick barrier material (hydrogel) was used to stop the propagation. A housing around the three cells was not used to investigate the influence of the emitted gases.

Based on pouch cells

Most research on TRP has been conducted at the module or pack level to better understand the real-world scenarios. However, some studies have focused on the cell level. For instance, Zhang et al.[102] investigated the TRP behaviors of large-format LIBs, introducing the concept of the TR front (TRF) to characterize the TRP process. Their experimental data revealed that the TRF progresses symmetrically along the cell's central axis, with an average velocity of approximately 24.14 $\mathrm{mm \cdot s^{-1}}$, influenced by key thermophysical properties. Their findings suggest that modifying the cell's thermal conductivity and reaction speed could delay the TRP process, offering valuable insights for TR prevention in future battery designs. However, experiments at the single-cell level may yield different results than module or pack-level setups, making it harder to evaluate cell-to-cell interactions.

As mentioned above, trigger methods are crucial in the occurrence of TR, yet some studies, including Lyu et al.'s,[103] lack specific details on these methods. Lyu et al.'s study provides valuable insights into tab connection methods using an electrothermal and lumped TR model, demonstrating that higher current densities can induce TR due to tab overheating and that LFP batteries perform better thermally than NCM batteries. However, it does not address the triggering methods themselves or consider spatial and thermal factors, such as the role of the battery enclosure. Due to this lack of information, it is essential to incorporate these aspects in future research, especially when aiming for results that more closely reflect real-world scenarios.

Feng et al.[10] conducted experiments under various setups to analyze TRP. One test used the nail penetration method on a battery module to simulate faults like punctures, while another involved thermal-resistant layers between cells to assess their effectiveness in limiting TR spread. Their analysis proposed four key TR prevention strategies: raising the trigger temperature, reducing internal short-circuit energy, improving heat dissipation, and adding thermal barriers. Additional tests conducted within enclosed housing structures offered more realistic insights, reflecting real-world battery module conditions; however, since these tests were performed on single cells, their relevance to full module or pack-level scenarios is limited.

In the aforementioned paper, the nail penetration method was used as the trigger, which is effective for simulating accident scenarios such as physical damage. However, in typical real-world situations, TR is more commonly caused by factors like overheating or overcharging. Therefore, some studies have adopted heater-based triggering methods to better replicate these conditions. For example, Jin et al.[100] investigated the effect of heating power and energy on TRP in LIB modules using a heater as the trigger method. The study showed that while heating power influences TR initiation, heat flux accumulation is more critical for TRP speed, with low power causing a preheating effect that accelerates propagation. A fast-heating method (1700 W or 12.6 W/cm^2) at the battery's maximum operating temperature is recommended to better simulate real-world conditions. However, this study was not conducted within a battery housing, which may limit its accuracy in reflecting real-world module conditions.

On the other hand, Li et al.[101] conducted experiments using proper housing with a heater as the trigger method. Li et al. investigated the impact of heating position (inside vs. outside the battery enclosure) on TR and its propagation in pouch lithium-ion cells. The results indicate that while external heating delays the onset of TR, it accelerates its propagation and increases the maximum cell temperature, raising overall risks. To mitigate these effects, it is crucial to install temperature sensors and cooling systems in both the battery module and enclosure, prevent jet flames, and reduce heat conduction by lowering the enclosure's thermal conductivity or using effective insulation. However, a TMS, such as a cooling system, should be used to counter TRP and obtain more realistic results.

DISCUSSION

Ensuring the safety of LIBs is a major concern, especially with their growing use in EVs and energy storage. TR, caused by internal faults and chemical reactions, can lead to dangerous incidents. Research now focuses heavily on its modeling, prediction, and prevention to support safe battery applications. This comprehensive review focuses exclusively on experimental studies to provide a realistic understanding of TP in LIB systems. While simulations are valuable for initial assessments, their complexity and the significant computational resources required often lead to necessary simplifications that limit accuracy to specific scenarios. Moreover, the rapidly evolving dynamics of the TR introduce additional challenges for modeling, as intense energy releases occur within very short time frames. Due to these limitations, they were excluded from this review in favor of experimentally validated data that better reflects actual operating conditions. Furthermore, there are only a few publications that have carried out both a simulation and a practical validation. Most validation tests were only used to optimize the simulation model and not to provide a holistic view of the propagation.

To bridge the gap between laboratory results and real-world performance, several key experimental parameters must be carefully designed and reported.

1. Trigger method: the choice of trigger method has a profound impact on the relevance of TRP data. Methods such as heater-based triggers, nail penetration, and overcharging simulate different real-world failure modes. For realistic modeling, heater-based triggers with controlled power and position should be prioritized, especially when simulating internal faults and heat accumulation.
2. SOC: a recurring theme across nearly all studies is the significant influence of SOC on TR initiation and propagation speed. Higher SOC leads to faster and more violent TR events, making it essential to test across a full SOC range (0%–100%) and to report SOC clearly in all TRP studies.
3. Cell spacing and arrangement: cell-to-cell distance, module configuration (vertical vs. horizontal), and alignment (positive-to-positive or mixed) directly impact heat transfer and gas flow during TRP. Experiments must control and report these design factors to understand their influence on propagation severity.
4. Connection method and electrical configuration: parallel connections and flat-tab designs accelerate TR propagation due to current backflow. Testing different connection types and monitoring current flow during TR are vital to identify electrical pathways contributing to propagation.
5. Ambient conditions (temperature and pressure): external temperature and pressure affect TR behavior. Although low pressure has minimal impact under Earth's surface conditions, ambient temperature significantly increases TR risk. Studies should include thermal chambers or climate-controlled setups to account for environmental variability and comparability.
6. Cell type and form factor: TR behavior varies significantly across different lithium-ion cell formats. In particular, cylindrical, prismatic, and pouch cells each show distinct TR characteristics. Larger cell diameters and prismatic formats generally propagate TR faster due to larger thermal mass and surface area. Hence, cell geometry must be matched to the intended real-world application.

7. Housing and insulation materials: the presence and design of housing can significantly alter gas containment, heat accumulation, and flame spread. Studies incorporating realistic module housing and interstitial materials provide better correlation with operational conditions. Materials like aerogel and HGM plates have shown strong potential in stopping propagation with minimal added mass.
8. Cooling systems and thermal management: active and passive cooling systems (e.g., PCM, immersion cooling, and serpentine liquid channels) influence TR onset and spread. Experimental designs should integrate cooling elements and monitor their interaction with heating profiles and gas generation for more accurate thermal modeling.
9. Gas flow and venting behavior: vent gas composition, pressure rise, and directionality (e.g., through ceiling angles or jet flames) critically affect neighboring cells and the overall risk. TRP studies should include gas sensors, pressure monitoring, and gas flow management strategies to evaluate containment and suppression methods.
10. Scale and test environment: module- and pack-level experiments yield more applicable results than isolated cell tests, though both are necessary for parameter isolation. Large test rooms may dilute gas effects and distort data. Thus, chamber size and airflow must be optimized to simulate realistic confined environments like battery enclosures in EVs or ESSs.

It is important to note that interactions between the ten points mentioned are also present. These phenomena can be quantitatively analyzed through a combination of experimental tests and simulation models. The influencing factors, such as trigger method, cell type and materials, as well as the cooling system, vary considerably from one application to another. Consequently, it is not possible to make a general statement about the interactions between these factors, as this depends heavily on the respective system.

RECOMMENDATIONS FOR FUTURE EXPERIMENTS

Achieving reliable and comparable results in TR and TRP studies requires a consistent and well-structured experimental design. Despite the availability of numerous publications, identifying the safest setup or cell type remains challenging due to substantial variation in cell formats, system configurations, and individually developed test setups. To enable more meaningful and transferable findings, future studies should adopt standardized criteria that reflect realistic system components, including battery TMSs, enclosures, triggering methods, and electrical connections. Recommended criteria for such standardization include.

- Apply triggering methods that reflect operational failure modes, such as overheating under load or internal short circuits. In particular, when triggering the cell, the geometry of the heating element should match or replicate the cell's form factor to ensure even heating across all sides of the cell.
- Standardize reporting of test conditions (cell type, SOC, housing, trigger method, etc.) to allow data comparison across studies.
- Vary key parameters systematically, such as SOC, spacing, and connection type, to evaluate their individual and combined impact.
- Use real enclosures and cooling systems, not open-air tests, to assess thermal containment and venting.
- Monitor temperature, voltage, pressure, mass loss, and flame behavior with suitable sensors.
- Include a full module configuration, even if simplified, to observe chain reactions and boundary conditions.
- Conduct tests under controlled, but realistic environmental conditions, including temperature and humidity.
- Incorporate safety materials (insulators and thermal barriers) in the configuration to validate their effectiveness.

As EVs and EES systems have become increasingly widespread, standardizing test methods with these critical parameters will be essential to ensure real-world safety and robust thermal management of LIBs.

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AUTHOR CONTRIBUTIONS

Conceptualization, N.G. and P.N.; data curation, N.G. and P.N.; funding acquisition, H.H. and A.K.; methodology, N.G. and P.N.; visualization, N.G. and P.N.; writing – original draft, N.G. and P.N.; and writing – review and editing, N.G., P.N., and N.K. All authors have read and agreed to the published version of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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