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The Significance of Enhancing the Reliability of Lithium-Ion Batteries in Reducing Electric Vehicle Field Safety Accidents

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In recent years, the frequency of incidents related to the safety of electric vehicles (EVs) due to lithium-ion batteries has seen a troubling uptick, leading to a heightened focus on the safety of lithium-ion batteries (LIBs) as a critical area of research. After thorough analysis, this study contends that the root cause of the majority of safety incidents involving LIBs in the field is predominantly linked to reliability issues within the battery products themselves. This argument offers a more targeted perspective than a broad discussion on the safety concerns of LIBs. Reliability, in this context, is defined as the likelihood that a product will execute its intended function without error over a defined period and under specific conditions. The paper delineates the reasons why current safety testing standards are unable to entirely prevent LIB safety incidents, scrutinizes the multifaceted causes and testing methodologies associated with LIB unpredictive thermal runaways from reliability perspective, and aims to reduce the probability of battery field failure and electric vehicle fire incidents, with an emphasis on mtigating unpredictive fire accidents. This study advocates for a more aggressive research effort into the reliability of LIBs, parallel to the vigorous advancement of safety technologies for these batteries.

1. Introduction

In recent years, there has been a significant uptick in field safety incidents related to lithium-ion batteries (LIBs) in electric vehicles (EVs), endangering the vast array of commercial, environmental, and social benefits that LIBs are poised to deliver. Consequently, ensuring the safety of lithium-ion batteries has taken on urgent importance within the sphere of LIB research and development.[1–19] The majority of safety incidents involving LIBs manifest as thermal runaway, which is initiated by an internal short circuit (typically)[17,20,21] and results in heat generation. Due to the battery's thermal diffusivity, heat buildup increases the battery's temperature. Once the temperature surpasses a certain threshold, it triggers a cascade of chemical reactions within the battery.[13,14,18,19] Thereafter, the battery's temperature continues to rise until the heat release from the internal chemical reactions becomes significant, ultimately overcoming all heat dissipation mechanisms and leading to thermal runaway.[22] This process can be measured using an adiabatic accelerated calorimeter (ARC).[19,23–27] Research has shown that improving the thermal stability of battery materials, through cathode material coating[28,29] and the enhancement of separators[1,3,16,17, 30–33] and electrolytes,[34–40] can substantially enhance battery safety. Moreover, significant improvements in battery safety can be achieved through the refinement of battery and module designs.[18] Through continuous advancements from materials to battery modules, battery safety has seen significant progress. However, despite the efforts of scientists and engineers to effectively evaluate or predict lithium-ion battery failure in thermal runaways, and despite the fact that the systems and designs of these batteries have passed safety standard certifications and the batteries entering the market are considered qualified products, incidents involving lithium-ion batteries, particularly in electric vehicles, are still occurring with troubling frequency in the public eye. Consequently, it is imperative to ask: Why do current safety standards fall short in guaranteeing battery product safety? Are lithium-ion battery failures in thermal runaways preventable? This paper aims to provide a thorough analysis of these questions, with the goal of identifying scientific approaches and research directions to address the thermal runaway failures of lithium-ion batteries.[41]

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2. The Reason that Battery Safety Standards Test Cannot Guarantee Battery Safety

It is well known that the battery safety standard test cannot guarantee battery safety. The battery safety accidents happen frequently. The current safety standards for lithium-ion batteries[42] primarily assess batteries through abuse scenario tests to evaluate the likelihood, manifestation, and destructive potential of thermal runaway. This includes mechanical abuse (compression, puncture, drop, impact, vibration), electrical abuse (external short circuit, overcharging, over-discharge),

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thermal abuse (hot box, simulated fire, thermal shock), and exposure to special environments (salt spray, immersion). Consequently, this detection method is commonly termed "abuse thermal runaway" (safety). Sometimes, test standards can be adjusted. For example, in China, the nail penetration test for Ni-rich cathode based large batteries has been cancelled.

Today, lithium-ion batteries are subject to a variety of safety standards across different countries. Table S1 details these safety standards for several countries. It is crucial to understand and evaluate battery safety in light of these varying standards. Table S2 outlines the principal safety tests employed to assess lithium-ion batteries, with each test standard having its corresponding set of safety checks. The detailed descriptions about the standards test are listed in the paper,[43] and put in"Supporting Information" again, which may serve as the background information for readers.

However, a thorough examination of lithium-ion battery safety incidents reveals several telling characteristics: 1) Lithium-ion battery systems and designs at the center of safety incidents had previously met safety standard certifications; 2) Upon leaving the manufacturing stage, the batteries involved in accidents were all considered acceptable products; 3) Staatistics for individual batteries, like the 18650 model used in electric vehicles, suggest an accident likelihood of around one in six million units; 4) In safety incidents, batteries predominantly experience asymptomatic spontaneous combustion, frequently leading to multiple ejections and potentially triggering local explosions. Moreover, these fires have a tendency to spread rapidly, making firefighting efforts largely ineffective. The circumstances surrounding safety incidents are notably concentrated, with exceptions being battery failures caused by water immersion and impacts. Currently, the majority of electric vehicle safety incidents reported in China involve batteries at a high state of charge, primarily occurring during the summer months. In several high-profile international cases of battery self-ignition, post-incident examinations have uncovered varying degrees of internal short circuits, which were not detected in pre-incident battery state assessments. These characteristics indicate that the majority of lithium-ion battery incidents do not arise from abusive conditions but are the result of field failures, likely leading to "self-triggered" thermal runaway. "Self-triggered thermal runaway" is a technical term used by Chinese authors to describe a hazardous occurrence in lithium-ion batteries.[41]

The term "self-triggered" emphasizes the autonomous nature of the process. "Thermal runaway" refers to a condition where the battery's temperature increases become uncontrollable due to excessive heat. If a battery experiences an internal short circuit or localized overheating, it may initiate a chain reaction of reactions that generate additional heat, creating a positive feedback loop that could lead to device damage, ignition, or explosion. In other words, once the temperature reaches a critical level, there is no need for an external trigger; the battery's internal processes alone can sustain the heat generation. In such cases, thermal runaway can originate from internal short circuits, material degradation, or other internal battery failures. The self-triggered thermal runaway is particularly alarming as these batteries can produce substantial heat when overheated, resulting in a rapid decline in performance or, even more dangerously, causing fires or explosions. Therefore, battery design and production incorporate numerous safety features aimed at preventing the occurrence of self-triggered thermal runaway. Extensive engineering experience and accident analysis reveal that many thermal runaways are caused by manufacturing defects, usage conditions, or aging defects, which lead to accidental internal short circuits and subsequent thermal runaway. These manufacturing defects may include loose connections, membrane damage, dust contamination, material selection, electrode coating heterogeneity, electrolyte penetration heterogeneity, and more. The usage conditions may include overcharging, charging at low temperature, vibration, etc.. The aging defects may include lithium metal plating, deformation of electrode,[44] etc., which arises after aging. This phenomenon is termed self-triggered thermal runaway, which distinctly differs from abuse-induced thermal runaway. Given that the external causes of thermal runaway are clear and quantifiable, abuse-induced thermal runaway is characterized by: 1) Predictable and measurable occurrences and outcomes; 2) Effectiveness across all batteries; 3) High reproducibility and the ability to establish safety evaluation standards; 4) The potential to mitigate or eliminate external triggers through protective measures, enhancing safety against battery abuse and thermal runaway.

Self-triggered thermal runaway is primarily caused by random defects that do not produce distinguishable external signal characteristics, such as electrical, thermal, or mechanical signatures. As a result, self-triggered thermal runaway is characterized by the following: 1) The causes of thermal runaway are diverse and do not emit detectable external signals, making prediction methods for such events ineffective; 2) The majority of batteries do not experience thermal runaway, as it is a low-probability random event; 3) The defect formation process shows significant randomness in terms of location, timing, and sequence, and is not reproducible, nor does it lead to changes in external signals. Consequently, these defects cannot be evaluated through testing, and there is no definitive quality management method that can completely eradicate them; 4) Once an explicit external signal appears, such as an increase in battery surface temperature or an abnormal voltage reading, thermal runaway occurs immediately, characterized by a sudden and swift progression; 5) Currently, no safety technology can eliminate the root causes of self-triggered thermal runaway. This unique phenomenon is accordingly referred to as self-triggered thermal runaway.

The analysis highlights that contemporary safety testing concentrates on "abuse conditions," whereas actual safety incidents involving lithium-ion batteries occur under "self-triggered conditions" that do not involve abuse. The battery failures in thermal runaway, whether triggered by abuse or spontaneously, are concomitant rather than causative. As such, safety standard testing alone cannot guarantee the comprehensive safety of lithium-ion batteries. This observation is depicted in Figure 1.

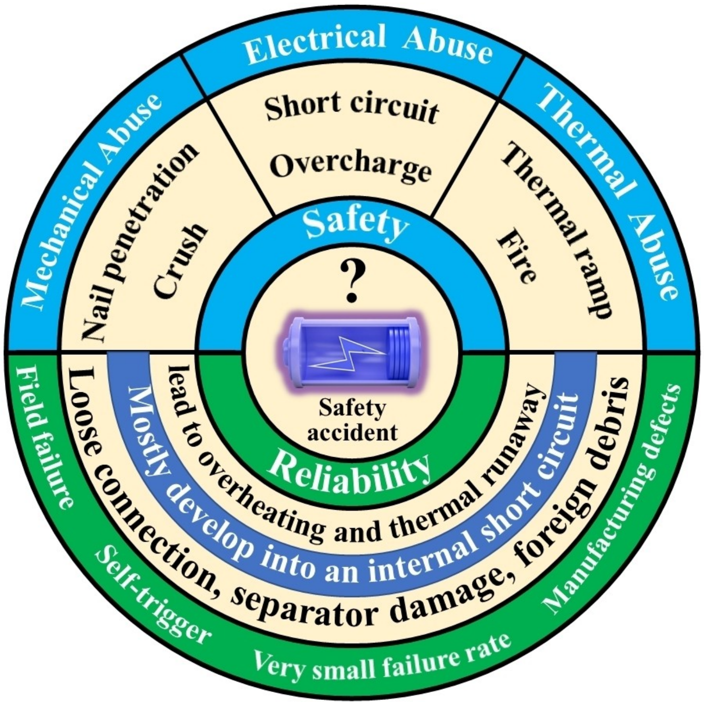

Figure 1. Differences between standard safety tests and safety accedents.

The repercussions of self-triggered thermal runaway on lithium-ion battery applications are profound, characterized by uncertainty and unpredictability. Given the etiology and progression of its underlying causes, embracing a reliability-based approach to comprehend lithium-ion battery safety incidents is deemed more precise. Both reliability failures and "self-triggered thermal runaway" share attributes of uncertainty and unpredictability.

3. Differences between Safety and Reliability Issues of Lithium-Ion Batteries

Figure 2 illustrates the distinct characteristics between standard safety tests and safety accidents in electric vehicles (EVs). The features of safety accidents in EVs suggest a stronger correlation with reliability issues rather than being confined to mere safety concerns.

Drawing from various definitions,[3–10,12,32,33,45–61] reliability is broadly understood as the product's ability to execute specified functions without failure under defined conditions and within a determined timeframe. In the realm of product attributes, higher reliability is universallydesirable, as it guarantees a longer operational period free from malfunctions. In the context

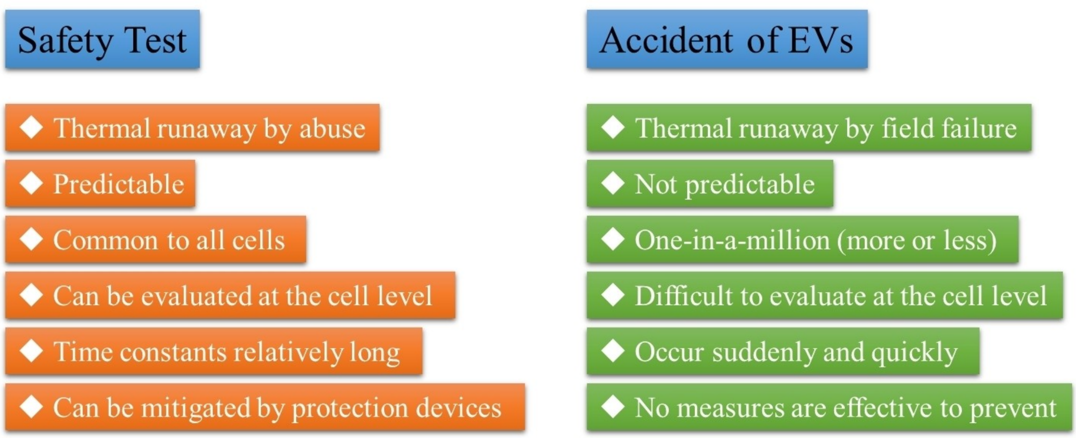

Figure 2. Characteristics of standard safety tests and safety accedents.[11]

of lithium-ion batteries, the prevention of thermal runaway is a reliability concern that has a direct and significant impact on their safety.

Quality, with a focus on functionality, encompasses several key features: 1) It involves a description of the product's operational functionality; 2) It utilizes sample mean management for quality control purposes; 3) It includes the capacity to test and assess product quality. Reliability, at its core, is a measure of how product quality stands the test of time. Its traditional definition hinges on the probability that a product will perform its intended functions satisfactorily under specified conditions within a defined time period. Reliability is characterized by the following: 1) It reflects the duration of a product's normal operational life; 2) Its management is predominantly grounded in probability theory and mathematical statistics; 3) Product failures are considered random probability events, with reliability being quantified through the "failure rate."

The failure rate serves as a critical metric for assessing reliability, representing the probability that a product will fail within a specified time frame after having operated without failure up to that point. In the context of lithium-ion batteries, the occurrence of safety incidents, manifesting as thermal runaway failures, can be seen as a measure of their failure rate. Therefore, the self-initiated thermal runaway process is a significant reliability issue.

As high-density energy storage devices, lithium-ion batteries store energy predominantly as chemical energy within their electrode materials. It is impractical to achieve a completely safe battery through extremely high chemical stability across all materials. However, the safety design of such a product can significantly enhance its application potential. This analysis suggests that lithium-ion battery safety standards are intended to assess the effectiveness of the safety design in these products, focusing on whether the design is properly implemented during production and maintained throughout the product's lifespan – a fundamental aspect of reliability research. To date, research into the reliability of battery safety, particularly in the context of lithium-ion batteries, is relatively scarce.

The causes of failure in thermal runaway events within lithium-ion batteries are classified into two broad categories: "safety design issues" and "reliability issues." Safety design issues pertain to the inherent safety characteristics of each battery, while reliability issues are concerned with the probability of failure in the form of thermal runaway, reflecting the execution of safety designs. Thus, just as the flammability of gasoline does not prevent its safe use in cars, the safety of lithium-ion batteries cannot be judgments solely based on thermal stability. The safety of these products largely depends on the effectiveness and durability of their safety designs, which are paramount to reliability. The introduction of the reliability concept offers a novel perspective for research into lithium-ion battery safety, with the potential to open up new avenues in this field.

4. Possible Causes of Field Failure in Thermal Runaway for Lithium-Ion Batteries

There are numerous potential causes for safety incidents resulting in field failures of lithium-ion batteries, and determining the precise cause of an incident becomes difficult once the battery has been destroyed by fire. Therefore, the identification of the cause must be inferred by considering possible explanations for the thermal runaway events in lithium-ion batteries. As illustrated in Figure 3, the author outlines six primary possible causes: thermal instability, metallic lithium plating on the negative electrode, contamination of the positive electrode with foreign metallic particles, separator defects, design and manufacturing flaws, and electrode deformation.

The thermal stability of lithium-ion batteries can be thoroughly evaluated by means of Accelerated Rate Calorimetry (ARC) testing,[19,23–27] which serves as a critical instrument for

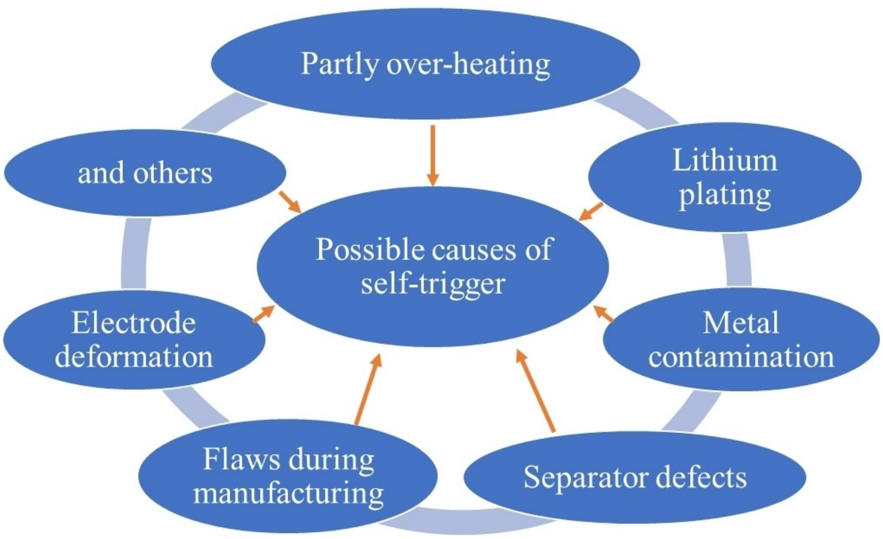

Figure 3. Possible causes of self-trigger safety in field failure accident of EVs.

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assessing the safety of these batteries. Improved thermal stability leads to a prolonged thermal runaway sequence in lithium-ion batteries, diminishes the severity of thermal runaway, or could even terminate it altogether. Given that thermal runaway inherently involves chemical interactions among the battery's internal components, enhancing the thermal stability of these materials, for example, through the application of coatings to positive electrode materials, can substantially bolster battery safety and reduce the severity of safety incidents.[19,24,25,62]

Metallic lithium plating on the negative electrode is considered a significant safety concern for lithium-ion batteries. Conditions such as high-rate charging, charging at low temperatures, or inconsistencies in electrode coating during the manufacturing process can lead to the formation of metallic lithium plating on the negative electrode. Due to the high reactivity of metallic lithium and its tendency to generate heat during reactions, the energy required to trigger chemical reactions within the battery is reduced, potentially enabling safety hazards.[20,63,64]

During the charging process, impurities of foreign metals within the positive electrode undergo electrolysis, converting into metal ions. These ions then migrate to the negative electrode, where they are reduced, resulting in the formation of dendrites or highly reactive nanoscale metal deposits on its surface. This process increases the risk of internal short circuits or lowers the activation energy for exothermic reactions, consequently raising the probability of thermal runaway in the battery. Therefore, from the production of battery materials to the assembly of the final batteries, it is crucial to exercise vigilant control over potential foreign metal contamination to mitigate the occurrence of battery accidents.

Historically, separator defects have been less prioritized in battery research and development. The uniformity of micropores within the separator membrane is challenging to verify through quality control processes associated with the finished product. Instead, it can only be reliably confirmed by evaluating the battery's performance during its manufacturing phase.[42,65,66] For instance, identifying a clogged micropore can be particularly difficult. Nonetheless, a localized blockage of the separator holes (or an increase in local impedance) can result in the local formation of lithium metal plating, which could potentially lead to safety incidents.[67] Localized imperfections within separators have the potential to create concentrated areas of heightened electrochemical activity, which may result in lithium plating. Flaws that restrict local transport, such that general macroscopic defects within a cell could unexpectedly trigger lithium plating, represent a significant risk. Particularly concerning are defects that entirely block lateral transport in the negative electrode, such as the detachment of the negative electrode from the current collector, which could lead to even more severe localized effects.

Consequently, battery cells can be made safer, more reliable, and longer-lasting by considering the impact of defects on cell design and material selection. Furthermore, inspecting batteries for macroscopic defects could serve as a pragmatic approach for providing an early warning of potential failures within battery storage systems.

A multitude of defects or flaws, stemming from the design and manufacturing processes, such as burrs produced by slicing that could precipitate internal short circuits, lithium plating resulting from uneven local capacity distribution between the positive and negative electrodes due to coating variations, internal short circuits caused by the powder shedding of the battery cell jelly roll, and short circuits at the electrodes' edges due to manufacturing discrepancies, among others, are detectable through process inspection during production. These represent preventable safety incidents.

In the context of module and pack manufacturing, widespread safety concerns include loose wiring terminals that can lead to overheating, foreign particles puncturing the insulation protection layer of prismatic cell casings, and localized overheating within modules or packs. These issues are detectable through effective process control.

Defects associated with battery aging also necessitate attention to prevent safety accidents. Particularly for jelly roll and cylindrical cells, the volume changes of the electrodes during charging and discharging can cause relative displacement between the positive and negative electrodes, potentially puncturing the separator and leading to internal short circuits. In high-capacity cylindrical cells, the substantial winding stress on the electrodes may exacerbate electrode deformation, increasing the risk of internal short circuits and severe battery safety accidents.

5. Perspectives

The spontaneous and unmanageable thermal runaway of lithium-ion batteries serves as a pivotal factor in electric vehicle safety incidents. To enhance battery safety, it is imperative that our focus transcends the inherent thermal stability of battery materials and passive protection mechanisms. We must prioritize the augmentation of the safety reliability of lithium-ion batteries, endeavoring to counteract the potential triggers of field failures during thermal runaways. By refining battery materials and the manufacturing process, taking into account the likely triggers of field failures in lithium-ion batteries, we can lessen the likelihood of thermal runaway incidents occurring.

Over the past two decades, researchers have dedicated substantial effort to tackling safety concerns in lithium-ion batteries. These efforts have included the development of cathode coatings to enhance thermal stability, the use of electrolyte additives to stabilize the cathode-electrolyte interface (CEI), the adoption of fluorine-rich electrolyte solvents and flame-retardant additives to decrease flammability, and the implementation of ceramic coatings on separators to improve their thermal resilience. Additionally, the introduction of new separator materials, such as polyimide (PI), has been pursued to enhance performance at high temperatures.,[16,30,31] The field has also seen the development of novel electrolyte additives and lithium salts to stabilize the solid-electrolyte interphase (SEI) of

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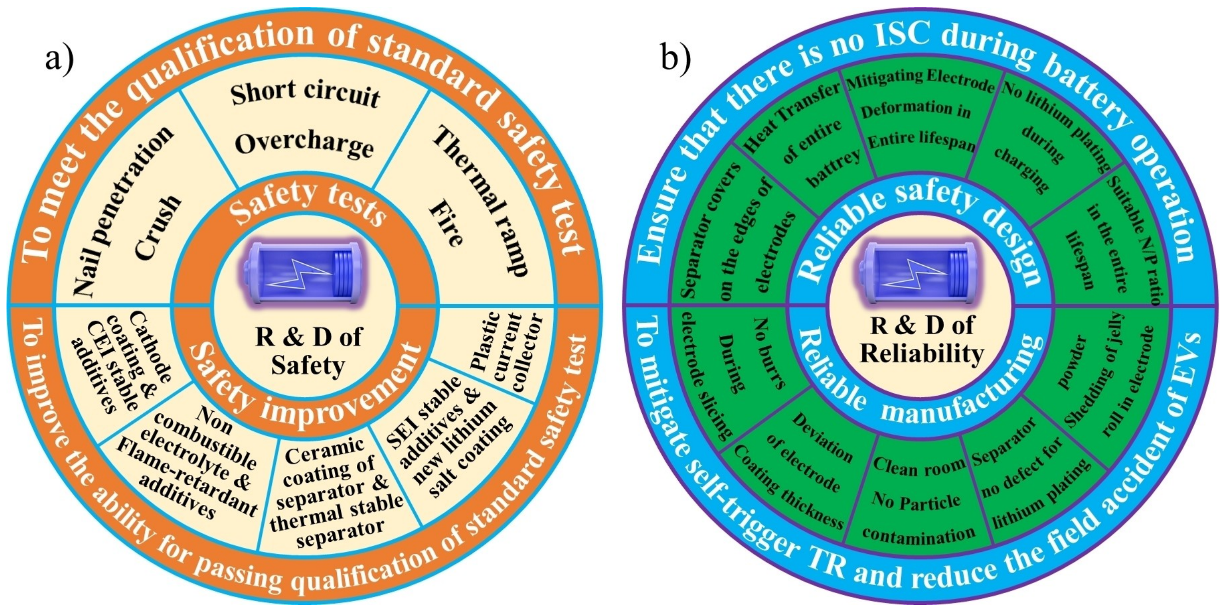

Figure 4. Research and development of lithium ion batteries. a) safety; b) reliability. Researchers pay a lot of efforts to solve the safety problems. Most of them have been in the direction of conventional safety pholosophy, to improve the battery safety for passing the standard safety test by abuse triggered thermal runaway. This is not enough to mitigate the safety accidents of electric vehicles. We should pay more attention to reliability of self-triggered safety issues in field accident of EVs.

the anode. More recently, innovative solutions like plastic current collectors have been designed to enhance safety during nail penetration tests.[1,2,22,68–71]

However, while these conventional safety measures aim to improve battery safety and pass standard thermal abuse safety tests, they are not sufficient to address the safety accidents associated with electric vehicles. It is the reliability of self-triggered safety issues in the field accidents of electric vehicles (as illustrated in Figure 4) that necessitates greater attention. The objective of this paper is to advocate for a shift in focus towards the reliability of lithium-ion batteries, with the aim of reducing the occurrence of safety failures in electric vehicles.

Manufacturers can initiate proactive measures to tackle potential lithium-ion battery hazards right from the beginning. They should develop a risk-conscious battery safety strategy that enhances performance while progressively reducing risks at every phase. Particularly crucial is the management of fires associated with these batteries as they can lead to catastrophic environmental impacts. Smart batteries, equipped with advanced sensors, are emerging as the standard solution for monitoring battery health. They provide accurate and timely data on key parameters such as temperature, pressure, and impedance. Their sophisticated perception systems enable the integration of physical and chemical signals, which supports the development of effective active control strategies. The inherent unpredictability in diagnosing and forecasting lithium-ion battery failures demands a practical approach. It is essential to recognize that even high-precision models may not be flawless. This poses a significant challenge in creating diagnostic models that reflect real-world engineering conditions. Domain adaptation, in particular, has proven its effectiveness in extracting and combining domain-invariant features. It significantly aids in the detection of faults under real-world conditions. A nuanced understanding of uncertainty can result in more reliable predictions of battery safety, thereby enhancing overall system reliability. To mitigate electric vehicle fire accidents related to lithium-ion batteries, the following approaches are recommended: firstly, identifying potential causes of field failure in lithium-ion battery safety is crucial. Secondly, establishing testing protocols for the self-triggered safety probability of lithium-ion batteries is essential. Lastly, implementing appropriate measures to mitigate the potential causes of field failure in lithium-ion battery safety can help avoid or reduce fire risks.

Currently, the majority of academic researchers focus their inquiries on comprehending battery safety and related materials, such as flame-retardant electrolytes, thermally stable cathode materials, and robust SEI films. However, the issue of battery reliability is often overlooked. There is a dearth of systematic research dedicated to understanding and mitigating electric vehicle fires through the lens of reliability. As a result, the pace of addressing battery fire-related issues is disappointingly slow. This article underscores the need for a shift in focus, encouraging a growing contingent of researchers to prioritize the study of self-triggered thermal runaway in electric vehicles from a reliability-centric perspective.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interests

The authors declare no conflict of interest.

Keywords: lithium-ion battery · safety accident · reliability · thermal runaway · field failure

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