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**PROFESSIONAL PAPER**

# Electric vehicle battery safety

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**Abstract:** One of the main contributors to air pollution is road traffic, primarily due to the emission of harmful gases and particles generated by the combustion of fossil fuels. As a professional response to this issue, the development and implementation of electric vehicles, considered an environmentally friendly alternative, is increasingly being promoted. However, despite their growing presence in traffic, certain safety aspects of electric vehicles still remain insufficiently explored. The main challenge associated with these vehicles is the battery, specifically lithium-ion batteries, which are most commonly used in electric vehicles. In addition to their weight and limited capacity, a particularly concerning issue is the risk of fire and the occurrence of thermal runaway within the battery cells, where an uncontrolled heating process takes place. Extinguishing such fires is extremely difficult, as the battery can reignite even after the flames have been suppressed. This paper provides an analysis of the causes leading to fires within electric vehicle batteries. Using previous research studies, the mechanism of fire development is explained — from the initial battery cell damage, the phenomenon of thermal runaway, smoke occurrence, all the way to explosion. The paper also presents both internal and external strategies for improving the safety of electric vehicles, with special emphasis on minimizing human error in order to prevent severe consequences, including battery explosion. To ensure that lithium-ion batteries and their components meet specific safety requirements, numerous safety standards and testing methods have been developed, which are briefly outlined in the paper.

**Key words:** Electric vehicles, batteries, thermal runaway, fire, explosion.

## INTRODUCTION

Lithium-ion batteries, as rechargeable energy-storage systems, represent the dominant technology used in electric and hybrid vehicles, with an estimated market share of approximately 60% to 66% of all installed battery systems worldwide (*IEA Global EV Outlook 2023*). All sub-types of lithium-ion batteries share the same basic structure, consisting of a large number of galvanic cells. Each individual cell contains a cathode, an anode, an electrolyte, and a separator (Figure 1). These subtypes primarily differ in the chemical composition of the active material in the cathode coating, with three variants being the most widely used: lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA). Due to their distinct properties, these variants are used in different categories of vehicles.

The operating principle of all lithium-ion battery types is the same. During charging, an external energy source drives lithium ions ($Li^+$) to de-intercalate from the cathode, diffuse through the electrolyte, pass through the nanopores of the separator, and intercalate into the graphite material on the anode. To maintain electrical balance, electrons simultaneously flow in the opposite direction through the external circuit, from the anode to the cathode. During discharge, $Li^+$ ions spontaneously migrate from the anode back to the cathode, releasing electrical energy to the load. Ion transport during charge–discharge cycling generates significant heat as a result of Joule heating and the chemical processes involved in the cycle.

The heat produced by electrochemical reactions is a normal phenomenon during nominal battery operation and does not pose a safety risk as long as it is dissipated evenly and efficiently. However, during operation, external influences, manufacturing defects, or undesirable charging and discharging conditions may cause excessive heat generation that cannot be removed in a timely manner, leading to safety hazards. Different cell geometries (cylindrical, prismatic, pouch, etc.) exhibit different safety characteristics, with cylindrical cells generally considered the safest.

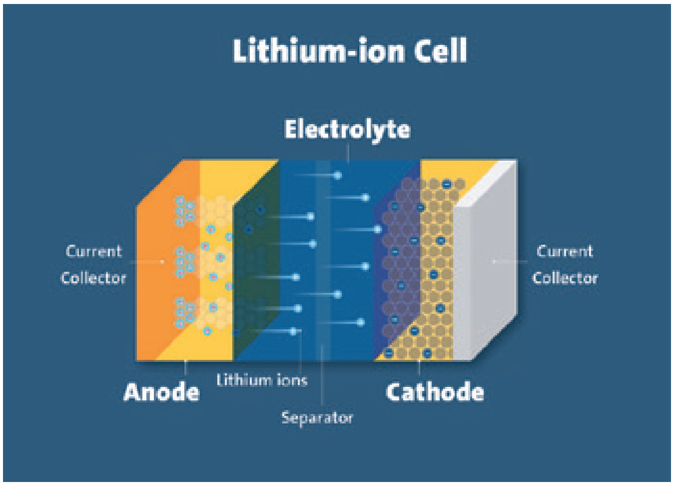


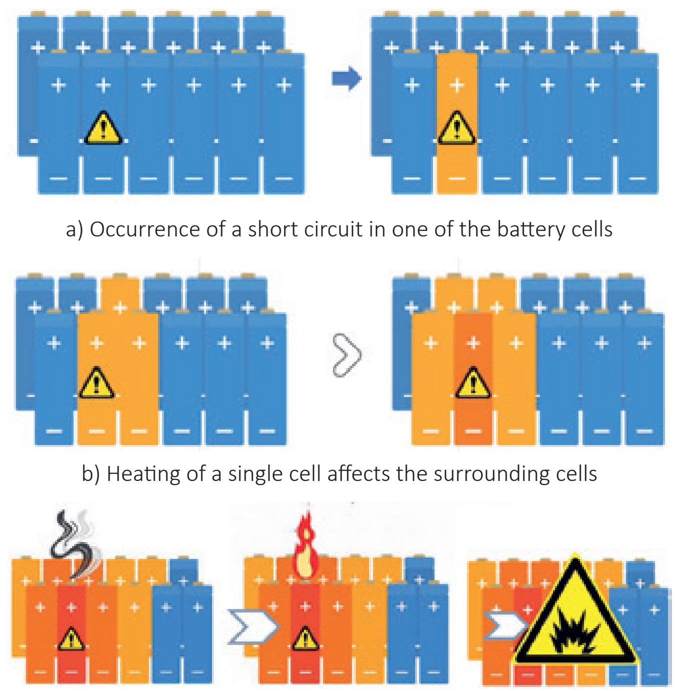

**Figure 1.** Basic element of a lithium-ion battery (https://ul.org/research-updates/what-are-lithium-ion-batteries)

## SAFETY ISSUES IN ELECTRIC VEHICLES

Even under normal operating conditions, the heat generated within a battery cannot be completely removed, particularly in large battery packs and during operation in high ambient temperatures (K. Amine et al., 2010). As the battery temperature increases, additional undesirable parasitic chemical reactions may occur, leading to **thermal runaway**, a state in which the heat generation inside the battery becomes uncontrollable (Wang et al., 2012). The causes of thermal runaway are various forms of battery damage, which are especially likely to occur during traffic accidents. Such damage may include mechanical damage to the battery (housing deformation, compression, puncture, or twisting of cells), electrical damage (overcharging/discharging or short circuits), as well as thermal damage (thermal shock or localized heating), as shown in Figure 2. Understanding battery performance under hazardous operating conditions is essential for improving battery safety during their development and manufacturing processes.

**Thermal Runaway**

Thermal runaway is a phenomenon representing the greatest risk to the thermal stability of lithium-ion batteries (Feng et al., 2017). The stages of thermal runaway development are shown in Figure 3. If any form of internal cell damage occurs, the normal electrochemical reactions are replaced by undesirable chemical processes. Under such conditions, heat accelerates exothermic reactions, resulting in the generation of even larger amounts of heat and the formation of gases. When the abnormal and rapidly increasing amount of heat cannot be dissipated, the materials from which the battery is constructed become chemically unstable and begin to undergo exothermic chemical reactions



a) Occurrence of a short circuit in one of the battery cells

b) Heating of a single cell affects the surrounding cells

c) Onset of thermal runaway accompanied by black and white smoke

d) Ignition or explosion of the cell

**Figure 3.** Stages of thermal runaway development

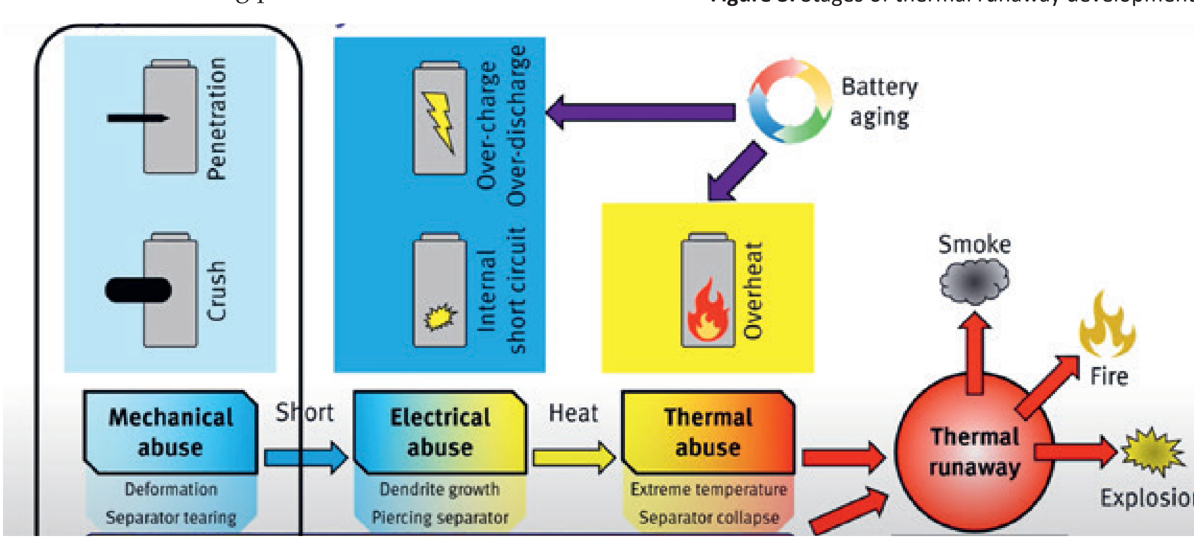



**Figure 2.** Causes of battery thermal runaway (https://www.batterydesign.net/battery-fires/)

These uncontrolled and unstable chemical reactions, which are extremely difficult to bring under control, eventually lead to the breakdown of the separator structure, allowing direct contact between the electrodes. This results in an internal short circuit and a rapid increase in temperature, a phenomenon known as thermal runaway.

In the initial stage, particles of heavy-metal dust from the cathode may appear in the form of dark smoke, followed by the release of a white smoke cloud. The presence of white smoke indicates that the released gases carry fine droplets of the electrolyte solvent. As oxygen from the surrounding environment mixes with this white smoke and heat accumulation continues, the battery cell may ignite, causing the fire to spread to neighboring cells. Ignition typically occurs within a few seconds to a few minutes after the appearance of the white smoke cloud. Under certain conditions, the white smoke cloud—containing toxic and flammable gases—may unexpectedly explode, posing a severe hazard to the surrounding area.

### Problems Caused by Mechanical Damage

As the number of electric vehicles on the roads continues to grow, the likelihood of traffic accidents involving electric vehicles has also increased, thereby raising the probability of mechanical damage to batteries. In a moving vehicle, the battery is subjected to significant forces, which in extreme cases, such as a collision, can cause severe damage. When the battery casing is compromised, air can directly enter the battery system, leading to undesirable reactions with the active components and electrolytes. Due to the high energy density of lithium-ion batteries, such damage can release a significant amount of heat, potentially triggering thermal runaway. Even when the casing is only deformed, the internal components of the battery can be severely damaged: metal current connectors may break, and separators with insufficient flexibility may fail, resulting in direct contact between the electrodes (short circuit). If the heat generated by this short circuit is high, the energy density is sufficient to trigger additional internal short circuits in the surrounding area, inevitably leading to thermal runaway throughout the battery.

The battery casing serves as the first level of protection and must be sufficiently robust to withstand mechanical forces without failure. Its primary role is to ensure that the internal structure of the battery remains intact under certain deformation conditions. The mechanical behavior of the casing represents the most vulnerable point during safety incidents, making it essential to conduct detailed analyses during the design process and the selection of materials for lithium-ion battery enclosures.

### Problems Caused by Electrical Damage

When a battery experiences overcharging, over-discharging, or an external short circuit, it is subjected to electrical stress, which triggers a series of undesirable electrochemical reactions within the cell. The mechanisms of overcharging and over-discharging are similar, while an external short circuit occurs when the cathode and anode of the same cell come into direct contact through a conductor. Overcharging represents the most hazardous type of electrical damage. If the battery management system cannot effectively monitor the voltage of each individual cell, there is a significant risk of overcharging. Since all excess energy is stored within the battery, overcharging is extremely dangerous, leading to a substantial increase in the internal temperature of the battery. Although batteries are typically charged up to a specific **State of Charge (SOC)**, some cells may have a higher SOC at the beginning of the charging process, making them more susceptible to overcharging.

The stages of battery overcharging can be described as follows, as illustrated in Figure 4:

- **Phase I:** The battery voltage steadily rises and exceeds the nominal cutoff voltage, marking the start of the overcharging process (Figure 4a).
- **Phase II:** When the battery is overcharged by approximately 1.2 V above full charge, side reactions begin to occur within the cell (Figure 4b).
- **Phase III:** The battery temperature continues to rise more rapidly, and the battery begins to swell due to gas formation (Figure 4c).
- **Phase IV:** The battery casing ruptures, causing damage to the separator and initiating thermal runaway in the lithium-ion battery (Figure 4d).

The charging rate is often the most significant factor influencing the risk of overcharging. The current density during overcharging directly determines the rate of heat generation resulting from chemical reactions within the battery: the higher the current, the greater the amount of heat produced per unit time, thereby increasing the risk of uncontrolled battery behavior.

### Problems Caused by Thermal Damage to Batteries

Thermal damage to a battery occurs when the battery

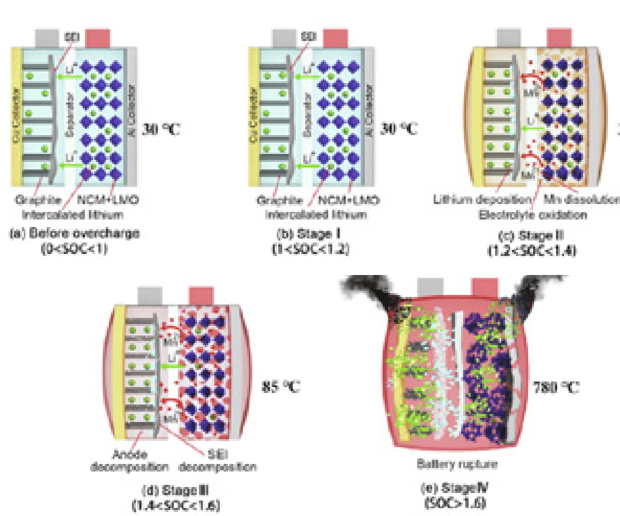



**Figure 4.** Stages of lithium-ion battery overcharging, (Chen et al., 2021)

reaches high temperatures or experiences thermal shock, potentially leading to fire (Wang et al., 2019). Battery fires can occur during the charging of electric vehicles, as described in the previous section, or as a result of exposure to flames—for example, if nearby vehicles are on fire or if flammable materials such as highly combustible pollen, seeds, flowers, or leaves are present in the air. These materials may ignite when in close proximity or in direct contact with a heated or malfunctioning battery.

In theory, normal cycling of a battery cannot cause safety incidents, as the heat generated during standard anodic and cathodic reactions is insufficient to trigger a sudden temperature rise. However, in practice, the rate of heat release from the electrodes often exceeds the rate at which heat can be dissipated (cooling). Poor battery design can lead to uneven heat transfer and non-uniform temperature distribution, increasing the risk of thermal shock. Localized high temperatures can trigger exothermic reactions, potentially leading to battery explosions. Heat transfer within a battery primarily depends on the external surface area and the battery's geometry.

### Electric Vehicle Fires

The causes of fires in electric vehicles (EVs) are diverse and complex. Statistics from Australia indicate that approximately **15% of all EV battery fires occur while the vehicles are connected to a charger or within one hour after disconnection from charging**. It is important to emphasize that battery charging itself cannot be considered the primary cause of these fires, even though EVs spend a significant portion of their operational life connected to a charger. Research has shown that most fires of this type occur due to **pre-existing battery damage**, rather than a failure of the charger or overcharging.

The main factors leading to battery damage, and consequently to potential fires, include:

- **Collision:** Traffic accidents can cause significant damage to the battery. Additionally, driving over sharp objects on the road can physically damage the battery.
- **Water immersion:** Prolonged exposure of the vehicle to water, particularly saltwater or floodwater, can lead to corrosion and internal short circuits within the battery system. Seawater is especially hazardous due to its conductivity, which can trigger chemical reactions and lead to thermal runaway.
- **Manufacturing defects:** If manufacturers later identify issues in a battery that could potentially cause thermal runaway, they are required to recall these products, as the risk of fire in such vehicles is significant.
- **External fire:** If the vehicle is exposed to an external fire, flames can spread to the vehicle and involve the battery.

Less common causes of fires include faulty cables, defective charging cords, or failures in the electrical system.

Although there are some similarities with fires in internal combustion engine vehicles, lithium-ion battery fires in EVs present additional challenges, as shown in Figure 5:

- The release of a toxic cloud of flammable gases, posing both respiratory and explosive hazards,
- The occurrence of thermal runaway, which complicates extinguishing the battery fire,
- The risk of **re-ignition** even after the fire appears to be extinguished, and
- EV battery fires are still not fully understood, requiring emergency response teams to receive specialized training for handling fires in electric vehicles.

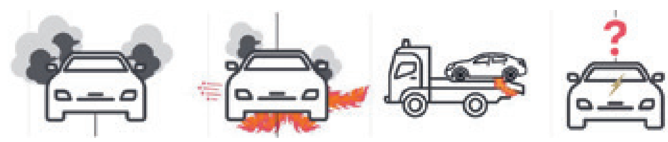


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**Figure 5.** Challenges for emergency response teams

During thermal runaway in electric vehicle batteries, three main hazards are present:

- **Gas release** – Rapid heating of lithium-ion cells causes electrolyte evaporation, resulting in the release of a toxic and flammable gas cloud.
- **Ignition** – After gas release, the flammable gases can ignite. The vapor pressure escaping from the battery often forms a directed jet flame, making extinguishing difficult and allowing the fire to spread rapidly.
- **Explosion** – When gases cannot escape from the battery pack (e.g., due to a sealed casing or blockage), they can accumulate under high pressure, creating a risk of an explosion of the entire gas cloud, which can have catastrophic consequences for both the vehicle and its surroundings.

When handling, transporting, or repairing electric vehicle batteries, the following points should be considered:

- **Lower State of Charge (SOC) reduces fire risk:** Batteries with a lower SOC have a lower likelihood of fire. A battery with a SOC below 50% has a reduced probability of entering thermal runaway, although gas release without ignition may still occur. Therefore, for transport purposes, it is recommended that electric vehicle batteries be charged to **30% SOC or less**.
- **No lithium-ion battery is fireproof:** All batteries used in electric vehicles can experience thermal runaway, regardless of chemical composition or form. While design and chemistry can influence the likelihood or rate of thermal runaway propa-

gation, they cannot fully prevent it.

- **Battery behavior during fire varies:** The chemical composition and shape of the battery can affect the volume of smoke, flame intensity, and the potential for explosion.
- **High risk to emergency responders:** In the event of an electric vehicle fire, first responders face significant hazards. It is therefore critical that emergency personnel identify the vehicle as electric upon arrival at the scene.

## STRATEGIES FOR IMPROVING THE SAFETY OF ELECTRIC VEHICLE BATTERIES

The safety of lithium-ion batteries is one of the key factors determining the future widespread adoption of electric vehicles. Improving the safety of lithium-ion batteries involves:

- **Internal strategies**, which focus on the materials and design of the battery to prevent excessive heat generation.
- **External strategies**, which relate to the efficiency of cooling and cell balancing, both of which are essential for enhancing battery safety and longevity.
- **Battery testing and monitoring systems,** which are critical for ensuring safe operation under various service conditions.

### Internal Strategies

Enhancing active materials, separators, and electrolytes can significantly improve safety performance. This is determined by a range of factors, including the chemical composition of the active material, the type of electrolyte, the efficiency of heat generation and dissipation, and tolerance to external mechanical stresses. The most easily controlled factors within the battery itself include the percentage of active electrode materials, electrolyte composition, and separator characteristics.

Cathode materials in lithium-ion batteries must exhibit chemical and structural stability to ensure safe operation throughout charge–discharge cycles. Separators are crucial for preventing short circuits in batteries and must maintain thermal stability and mechanical integrity. In anodes, lithium plating presents significant safety risks, particularly under potential thermal and electrical damage. The flammability and stability of the electrolyte are also critical factors. Organic carbonate-based liquid electrolytes are highly flammable and can lead to combustion or explosions under adverse conditions. Improving the flash point or decomposition temperature of the electrolyte can greatly enhance safety. Solid-state electrolytes are being developed to eliminate many of the undesirable effects associated with liquid electrolytes.

### External Strategies

Effective cooling strategies and cell voltage balancing are essential for improving the safety and longevity of batteries.

Balancing the voltage between cells is crucial for minimizing differences within the battery pack. Both passive and active equalization methods are used to maintain cell balance. Passive balancing can dissipate excess energy from overcharged high-capacity cells within the battery, but it cannot supply energy to undercharged low-capacity cells. The circuit structure used in passive balancing systems is relatively simple, and the energy-consuming components can continuously dissipate energy. Active balancing, on the other hand, involves the use of various circuit topologies and control strategies that non-dissipatively transfer energy between different cells and modules, thereby equalizing the system (storing energy from high SOC cells and charging low SOC cells). Active methods demonstrate higher efficiency.

Operating at high temperatures significantly accelerates battery aging, which directly leads to safety issues such as thermal runaway. Therefore, a well-designed and integrated cooling system is a critical safety factor for these batteries, enabling precise temperature control. The optimal operating temperature range for lithium-ion batteries is between **15 °C and 35 °C** (Chen et al., 2021). An efficient cooling system must be capable of maintaining this temperature range, thereby extending battery life and reducing maintenance costs.

Some of the battery cooling systems are:

- **Air cooling system** – the simplest and least expensive option; less efficient and suitable for smaller battery packs.
- **Liquid cooling system (water, glycol)** – the most widely used method in electric vehicles due to its high efficiency and precision.
- **Phase change material (PCM)-based cooling system** – these materials absorb heat by changing their phase, providing passive cooling; still under investigation for mass application.
- **Heat pipe-based temperature management system** – heat pipes use phase transitions of the working fluid for highly efficient heat transfer and are also under study for future application.

Among all these systems**, liquid cooling** is the most widely used in electric vehicles due to its significant advantages:

- **High specific heat** – absorbs significantly more heat per unit mass, making the system much more efficient.
- **Better thermal conductivity** – transfers heat more effectively compared to air.
- **Good temperature control** – maintains battery temperature within the optimal range, directly extending battery life, improving vehicle performance, and ensuring safety.
- **Even temperature distribution** – liquids provide more uniform cooling of all cells within the bat-

tery pack.

- **Design adaptability** – although requiring more components than other systems, it can be efficiently integrated into the vehicle design.

### Battery Testing and Monitoring Systems

Before being installed in a vehicle, every lithium-ion battery must undergo a rigorous series of tests to determine its safety. Safety standards and tests ensure that the battery and its components meet the prescribed criteria, particularly for commercial production. Electric vehicle batteries must be certified in accordance with relevant safety standards before mass production and sale. Testing of certified and standardized batteries provides customers with assurance that the risk of thermal runaway under specified conditions is minimized.

A large number of countries and international organizations have developed safety-oriented standards for electric vehicle batteries, including: the Chinese standard **GB/T 31485,** the **Society of Automotive Engineers (SAE) Standard 2464,** the **International Electrotechnical Commission (IEC) Standard IEC62133 Edition 2.0,** the **United Nations (UN) Standard UN38.3,** the **Japanese Industrial Standard (JIS) C8714,** the **Underwriters Laboratories (UL) Standard UL2580 Edition 2.0,** and the **International Organization for Standardization (ISO) Standard ISO 16750–2.** In addition to standard tests, each standard includes specific testing methodologies (Chen et al., 2021).

The main tests that every lithium-ion battery must undergo include:

- **Test 1 (electrochemical performance):** overcharging, over-discharging at high and low temperatures, external short circuit, and forced discharge.
- **Test 2 (mechanical properties):** drop test, high-impact test, nail penetration.
- **Test 3 (thermal performance):** heating, thermal shock, and spark exposure.
- **Test 4 (environmental conditions):** low pressure, high altitude, and vehicle submersion.

Laboratory testing conditions are generally more severe than real-world driving conditions to ensure maximum safety during vehicle operation. Although the tests are extremely rigorous and batteries undergo complex procedures during certification, battery fires still remain a challenge for electric vehicles. Therefore, continuous optimization and improvement of pre-installation testing procedures are necessary to ensure the highest possible safety of batteries before they are integrated into vehicles.

## CONCLUSION

In recent years, energy and environmental issues have become increasingly prominent, and electric vehicles powered by lithium-ion batteries have demonstrated significant potential and advantages in addressing these challenges. Compared to other battery types, lithium-ion batteries offer high specific energy, high energy density, good durability, low self-discharge, and a long lifespan.

However, battery temperature management has become a significant challenge for manufacturers. At high temperatures, lithium-ion batteries can experience thermal runaway, leading to short circuits, combustion, explosions, and other safety hazards. At low temperatures, lithium dendrites may form, causing short circuits, failure to start, and other operational malfunctions.

The solution lies in careful design, efficient temperature management, and rigorous battery testing. Batteries must be designed to maintain their performance under various operating conditions that may occur during their service life. Continuous improvement of cooling systems, along with ongoing optimization of safety standards and testing procedures, is imperative for enhancing battery safety and reliability.

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