POLITECNICO DI TORINO

Master's degree Course in Energy and Nuclear Engineering

Master Thesis

# Risk analysis of thermal runaway of electric vehicles in closed spaces


Relatore:
Prof. Davide Papurello

Candidato:
Tarek Fakhran

ID: S282089


June 2023

# Table of Contents

# Abstract

This thesis presents a risk analysis of thermal runaway of electric vehicles in closed spaces. The use of electric vehicles has increased significantly in recent years due to their environmental benefits. However, the lithium-ion batteries used in these vehicles have the potential to cause thermal runaway, resulting in fires that can be difficult to extinguish. This risk is amplified when electric vehicles are stored or charged in closed spaces, such as underground parking garages or warehouses. This thesis investigates the potential risk of thermal runaway events occurring in electric vehicles (EVs) in closed spaces, such as garages or tunnels. Thermal runaway is a phenomenon where the battery cells in an EV rapidly heat up and release flammable gases, leading to a self-sustaining fire. The objective of this research is to provide a comprehensive risk analysis of thermal runaway events in closed spaces, considering various factors such as battery chemistry, charging behaviour, and environmental conditions. The results of this study provide insights into the potential risk of thermal runaway events in closed spaces, and the effectiveness of different mitigation strategies. The findings can be used to inform the development of safety guidelines and regulations for the use of EVs in closed spaces, as well as to guide the design of EVs and associated charging infrastructure to minimize the risk of thermal runaway events.

# List of Figures

# List of Tables

# 1. Introduction

## 1.1 Background and context of the study

The use of electric vehicles has been increasing rapidly in recent years due to their environmental benefits, such as reducing greenhouse gas emissions and improving air quality. However, the lithium-ion batteries used in electric vehicles have the potential to cause thermal runaway, which can result in fires that can be difficult to extinguish. This risk is particularly pronounced when electric vehicles are stored or charged in closed spaces, such as underground parking garages or warehouses.

As the popularity of electric vehicles grows, the risk of thermal runaway in closed spaces is becoming an increasingly important concern for public safety. Therefore, a risk analysis of this issue is necessary to identify and evaluate potential hazards and propose appropriate mitigation measures. This thesis aims to address this issue by systematically analysing the potential risks associated with thermal runaway of electric vehicles in closed spaces and proposing mitigation measures to reduce the risk. The study includes a review of relevant literature, and case studies of incidents involving thermal runaway of electric vehicles in closed spaces. To prevent thermal runaway, EV manufacturers use a combination of design features and safety protocols. Battery cells are designed to be more resistant to overheating and damage, and battery packs are often equipped with cooling systems to dissipate heat. In addition, EVs are equipped with sensors and software that monitor battery temperature and adjust charging and discharging rates to prevent overheating. Despite these measures, thermal runaway remains a potential risk for EVs, particularly in extreme conditions or in the event of a manufacturing defect. As a result, EV manufacturers and operators must remain vigilant and continually improve their safety measures to ensure that EVs remain a safe and reliable mode of transportation. The potential risks associated with thermal runaway in EVs are particularly acute in closed spaces, where there may be limited ventilation and a greater risk of rapid spread of smoke or fire. The research may explore methods for quantifying these risks and developing strategies to mitigate them, such as improved battery design, enhanced fire suppression systems, or better ventilation.

The findings can be used to inform policy decisions and safety regulations related to the storage and charging of electric vehicles in closed spaces. It can also provide insights for electric vehicle manufacturers, building designers, and fire safety professionals to develop effective safety measures and protocols to prevent and manage thermal runaway incidents.

## 1.2 Research problem and questions

The research problem of our topic is to assess the potential risks associated with thermal runaway of electric vehicles in closed spaces and propose mitigation measures to reduce the risk. To address this research problem, different problematic is posed, as the hazards associated with thermal runaway of electric vehicles in closed spaces, the occurrence of thermal runaway incidents in closed spaces. Furthermore, the potential consequences of thermal runaway incidents in closed spaces, and the factors that contribute to the risk of thermal runaway are discussed. Mitigation measures can be implemented to reduce the risk of thermal runaway in closed spaces, and the effectiveness of the mitigation measures that are the proposed in reducing the risk of thermal runaway. These research questions will guide the research process and help to identify the key issues related to the risk analysis of thermal runaway of electric vehicles. The answers to these questions will contribute to a better understanding of the risks associated with electric vehicles and provide valuable insights into effective safety measures and protocols to prevent and manage thermal runaway incidents.

## 1.3 Objectives and significance of the study

The objective of this work is to identify and analyse the hazards associated with thermal runaway of electric vehicles in closed spaces, to assess the likelihood and consequences of thermal runaway incidents in closed spaces and to evaluate the risk associated with thermal runaway of electric vehicles in closed spaces. In addition to propose mitigation measures to reduce the risk of thermal runaway incidents in closed spaces, and to evaluate the effectiveness of the proposed mitigation measures in reducing the risk of thermal runaway incidents in closed spaces. The significance of this thesis lies in its contribution to public safety and environmental sustainability. The increasing popularity of electric vehicles means that the risk of thermal runaway incidents in closed spaces is becoming a more pressing concern. By conducting a comprehensive risk analysis of this issue and proposing effective mitigation measures, this thesis can help to prevent or manage thermal runaway incidents, thereby reducing the risk of property damage, injuries, and fatalities. Furthermore, the proposed mitigation measures can also contribute to environmental sustainability by reducing the negative impact of thermal runaway incidents on the environment. For example, effective ventilation systems can help to reduce the amount of toxic smoke released into the air during a thermal runaway incident.

## 1.4 Scope and limitations of the study

This thesis will focus on assessing the potential hazards associated with electric vehicle (EV) batteries overheating and catching fire in enclosed areas such as parking garages, tunnels, and other confined spaces. The research would likely include a comprehensive review of literature and case studies related to thermal runaway incidents involving EV batteries, analysis of relevant regulations and standards, and the development of a risk assessment framework for identifying and evaluating potential risks and hazards. It may also explore potential mitigation strategies, including fire suppression systems, ventilation systems, and other safety measures that can help prevent or mitigate the effects of thermal runaway incidents in enclosed spaces. The research may involve simulation studies to model the behaviour of thermal runaway incidents in enclosed spaces. However, there are some limitations to this research. Firstly, it may be challenging to obtain accurate and reliable data on thermal runaway incidents involving EV batteries in closed spaces, as such incidents are relatively rare and often underreported. Secondly, the research may be limited by the availability of resources and funding for laboratory testing and simulation studies, may be limited to specific types of EV batteries or vehicle models, which may not necessarily be representative of all EVs in use today. There are several limitations that can affect the study also the limited sample size, the number of electric vehicles that can be tested in a closed space may be limited, which can impact the statistical power of the study, difficulty of reproducing real-world conditions as testing thermal runaway in a closed space may not accurately replicate the real-world conditions in which electric vehicles operate. For example, airflow, temperature, and other factors may be different in a closed space compared to on the road. Furthermore, ethical concerns as conducting experiments on thermal runaway in closed spaces may pose risks to human and animal subjects, which may limit the types of experiments that can be conducted. Thermal runaway can occur over an extended period but experiments in a closed space may only last for a short time. This may limit the ability to observe the full range of behaviours associated with thermal runaway. Limited applicability to real-world scenarios: The results of a study conducted in a controlled environment may not be applicable to real-world scenarios, where a variety of factors can impact the likelihood and severity of thermal runaway incidents.

The scope of this thesis is focused on assessing potential hazards associated with EV batteries overheating in enclosed spaces and developing strategies to mitigate these risks. However, limitations to the research may include challenges obtaining reliable data, limited resources for testing, and a narrow focus on specific types of EV batteries or vehicle models.

## 1.5 Definition of key Terms

**Cell, modules, and packs:** Cell modules are groups of individual battery cells connected in series and/or parallel configurations, typically including additional components such as protective housing and wiring. Cell packs are larger assemblies of cell modules, providing higher voltage and/or greater energy capacity.

**State of charge (SOC):** is a measure of the amount of energy remaining in a battery relative to its fully charged capacity. It is typically expressed as a percentage, with 0% representing a completely discharged battery and 100% representing a fully charged battery.

**Depth of discharge (DOD):** is a measure of the amount of energy that has been extracted from a battery relative to its fully charged capacity. It is typically expressed as a percentage, with 0% representing a fully charged battery and 100% representing a fully discharged battery.

**State of health (SOH):** is a measure of a battery's overall health or condition. It reflects the battery's ability to hold a charge and deliver the expected level of performance relative to its original capacity.

**Cycle life:** refers to the number of charge and discharge cycles that a battery can undergo before it reaches the end of its useful life. It is an important factor to consider when selecting a battery for a particular application, as it impacts the battery's longevity, performance, and overall value.

**Open Circuit Voltage (OCV or Voc):** is the voltage that a battery produces when it is not connected to a load or external circuit. It is a measure of the potential difference between the positive and negative terminals of the battery when there is no current flowing through it.

**Terminal Voltage (V):** is the voltage measured across the positive and negative terminals of a battery when it is connected to a load or external circuit. It represents the voltage that is available to drive current through the load, considering any internal resistance or losses within the battery itself.

**Nominal Voltage (V):** is the voltage assigned to a battery to broadly describe its voltage range and performance characteristics. It is typically given as an average or approximate value and may not necessarily reflect the actual voltage of the battery at any given moment.

**Cut-off Voltage (V):** is the minimum voltage at which a battery or other electrical device is designed to stop operating or be considered fully discharged. It is a safety feature intended to prevent over-discharging of the battery, which can cause irreversible damage and reduce its overall lifespan.

**Charge Voltage (V):** is the voltage applied to a battery during the charging process to restore its energy capacity. It is the voltage that is required to overcome the internal resistance of the battery and cause current to flow into it, thereby reversing the chemical reactions that occurred during discharge.

**Capacity or Nominal Capacity (Ah for a specific C-rate):** is the amount of electrical charge that a battery can store and deliver when fully charged under specified conditions. It is typically measured in ampere-hours (Ah) or milliampere-hours (mAh) and is an important characteristic of a battery that determines its overall energy storage capacity and performance.

**Energy or Nominal Energy (Wh (for a specific C-rate)):** is the total amount of energy that a battery can store and deliver when fully charged under specified conditions. It is typically measured in watt-hours (Wh) or kilowatt-hours (kWh) and is a measure of the battery's overall energy storage capacity and the amount of work it can perform.

**Specific Energy (Wh/kg):** is a measure of the amount of energy that a battery can store per unit of its weight or volume. It is typically expressed in watt-hours per kilogram (Wh/kg) or watt-hours per liter (Wh/L) and is an important characteristic of batteries in applications where weight or volume is a critical factor.

**Specific Power (W/kg):** is a measure of the rate at which a battery can deliver energy per unit of its weight or volume. It is typically expressed in watts per kilogram (W/kg) or watts per liter (W/L) and is an important characteristic of batteries in applications where high-power output is required.

**Energy Density (Wh/L):** amount of energy stored in each volume or mass of a substance or system. It is typically measured in joules per cubic meter ($J/m^3$) or joules per kilogram (J/kg). In other words, it represents how much energy can be stored in a certain amount of space or mass.

**Power Density (W/L):** amount of power that can be generated or transmitted per unit volume or mass of a system. It is typically measured in watts per cubic meter ($W/m^3$) or watts per kilogram (W/kg).

# 2. Literature Review

## 2.1 Overview of Electric Vehicle technology

Battery electric vehicles (BEVs) are becoming increasingly popular due to several reasons such as the environmental benefits, fuel cost savings, and technological advancements. As more people become aware of the advantages of BEVs, the usage of these vehicles is expected to increase in the coming years. One of the primary factors driving the increased usage of BEVs is the growing concern for the environment. With concerns about climate change, air pollution, and the depletion of natural resources, many people are choosing to switch to electric vehicles to reduce their carbon footprint. In addition, as more renewable energy sources are being used to power the electric grid, the environmental benefits of BEVs are becoming even more significant. Another factor driving the adoption of BEVs is the cost savings associated with electric vehicles. While the upfront cost of purchasing a BEV may be higher than a traditional gasoline vehicle, the long-term cost savings can be significant. BEVs require less maintenance, have lower fuel costs, and may qualify for tax incentives and rebates. The advancements in technology are making BEVs more practical and convenient for daily use. The range of BEVs has been steadily increasing, and there are now more charging stations available than ever before. Additionally, the development of fast-charging technology is making it possible to charge a BEV in a matter of minutes, making long-distance travel more feasible.

The combination of environmental concerns, cost savings, and technological advancements is driving the increased usage of BEVs. As the infrastructure for electric vehicles continues to improve, it is likely that we will see even more widespread adoption of these vehicles in the future. Nowadays, we can encounter different types of EVs, according to their engines technology. In general, they are sorted in five types:

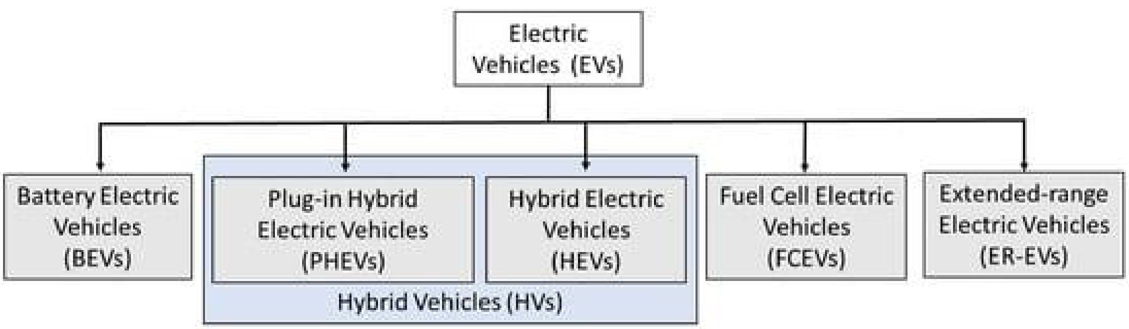


Figure 1 Electric vehicles classification according to their engine technologies and settings [1]

The market for battery electric vehicles (BEVs) is growing rapidly, driven by a combination of government incentives, consumer demand, and advances in technology. In 2021, the global BEV market was valued at approximately $183 billion and is projected to continue growing at a rapid pace over the next decade.

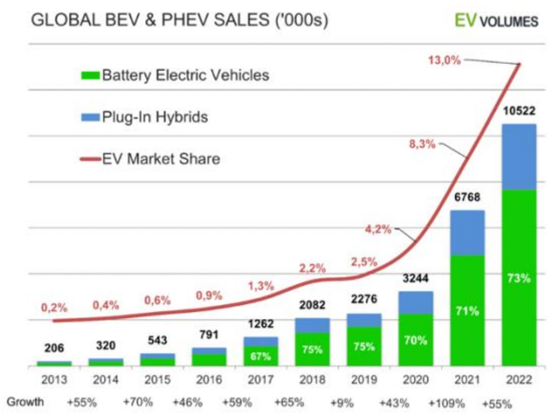


Figure 2 Global BEV & PHEV sales in '000s. [2]

Electric vehicle technology involves the use of electric motors and batteries to power vehicles, replacing the traditional internal combustion engines and fuel tanks. Electric vehicles have several advantages over traditional vehicles, including lower emissions, reduced operating costs, and improved performance. The main components of electric vehicles are the battery, electric motor, power electronics, and charging infrastructure.

Battery Systems are the most critical component of an electric vehicle. The battery pack is made up of a series of individual cells that store electrical energy. Lithium-ion batteries are the most used type of battery in electric vehicles, due to their high energy density, long life, and relatively low cost. The high-voltage battery system uses lithium-ion cells, which are also used in mobile phones and notebooks. A single battery cell is the smallest unit in the battery system. It can store energy and release it again. 24 of these cells are currently consolidated into one battery module.

The number of modules that are then put together to create a battery system is variable. This modular structure allows for maximum flexibility: if the customer requests a higher range, then more modules will be fitted to the battery system. The fundamental structure however remains the same. In the ID.3, up to twelve modules are put together via a battery connector to form a battery system.

A voltage of up to 408 volts is applied in the system, which is considerably higher than that in a domestic socket, which only supplies 230 volts.

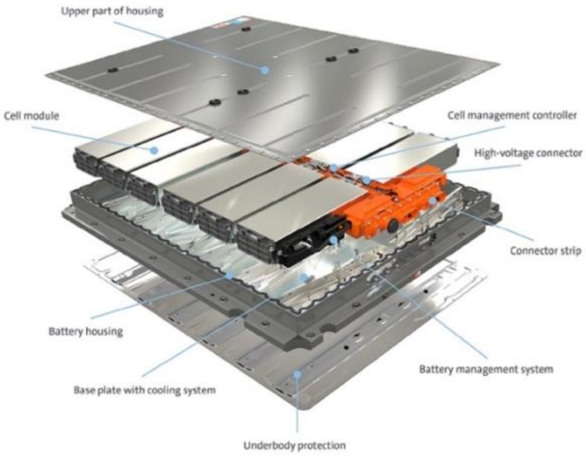


Figure 3 Key components of a battery system [3]

**Electric Motors**: Electric motors convert electrical energy into mechanical energy to power the vehicle. There are two main types of electric motors used in electric vehicles: AC induction motors and permanent magnet motors. AC induction motors are simpler and less expensive, but permanent magnet motors are more efficient.

**Power Electronics**: Power electronics control the flow of electricity between the battery pack and the electric motor. They are responsible for managing the power output of the battery and regulating the voltage and current of the motor. Power electronics also manage the regenerative braking system, which captures energy during braking and stores it in the battery.

**Charging Infrastructure**: Electric vehicles can be charged using different types of chargers, ranging from standard household outlets to high-power fast chargers. Charging infrastructure includes charging stations, cables, and adapters. The charging time and range of an electric vehicle depend on the capacity of the battery, the charging rate, and the type of charging infrastructure.

Electric vehicle technology is constantly evolving and improving, with new advancements in battery chemistry, electric motor design, and charging infrastructure expanding the capabilities and appeal of electric vehicles.

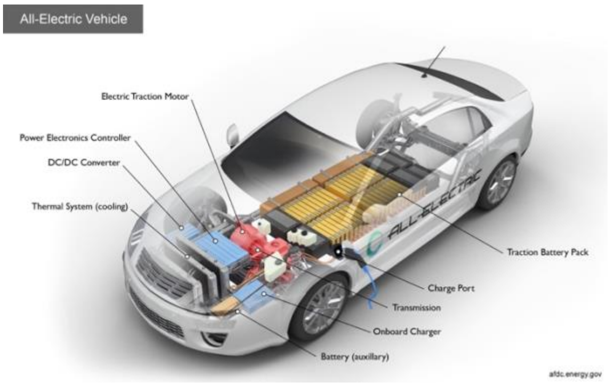

Figure 4 Key components of an All-Electric car [4]

Electric vehicles (EVs) can be charged using either alternating current (AC) or direct current (DC) charging methods.

**AC charging** is the most common method of charging EVs and is similar to how you charge your phone or laptop. AC charging uses a charging cable that is plugged into the vehicle and an AC charging station or a regular electrical outlet. The charging station or outlet provides AC power to the vehicle's on-board charger, which converts the AC power to DC power to charge the battery. AC charging typically takes several hours to fully charge an EV, depending on the battery size and the charging speed.

**DC charging**, also known as fast charging, uses a DC charging station that provides high-voltage DC power directly to the vehicle's battery. DC charging can charge an EV much faster than AC charging, typically taking 30 minutes or less to charge to 80% capacity. However, DC charging is more expensive and requires more sophisticated charging equipment than AC charging.

Most EVs can accept both AC and DC charging. AC charging is usually used for overnight charging at home or work, while DC charging is used for longer trips and when fast charging is required. It's worth noting that different EV models have different charging capabilities, so it's important to check the manufacturer's specifications to determine the charging options available for a particular EV.

Table 1 Charging classification [5]

| Mode | Standard | Rated Voltage | Rated Current | Maximum Power |
|---|---|---|---|---|
| AC Charging | GB/T-20234.2-2015 | 250 V | 10 A<br>16 A<br>32 A | 27.7 kW |
| | | 440 V | 16 A<br>32 A<br>63 A | |
| DC Charging | GB/T-20234.3-2015 | 750–1000 V | 80 A<br>125 A<br>200 A<br>250 A | 250 kW |

The IEC-62196 standard is an international standard created by the International Electrotechnical Commission (IEC) in 2001 for charging electrical vehicles in Europe and China. The IEC-62196 establishes the general characteristics of the charging process, as well as the way in which the energy is supplied. This norm derives from the IEC-61851 and it provides a first classification of the charging type according to its nominal power and, thus, of the charging time. Users are provided with four modes to charge the vehicles.

Table 2 Charge ratings of the IEC-62196 [5]

| Charge Method | Phase | Maximum Current | Voltage (max) | Maximum Power | Specific Connector |
|---|---|---|---|---|---|
| Mode 1 | AC Single | 16 A | 230–240 V | 3.8 kW | No |
| | AC Three | | 480 V | 7.6 kW | |
| Mode 2 | AC Single | 32 A | 230–240 V | 7.6 kW | No |
| | AC Three | | 480 V | 15.3 kW | |
| Mode 3 | AC Single | 32–250 A | 230–240 V | 60 kW | Yes |
| | AC Three | | 480 V | 120 kW | |
| Mode 4 | DC | 250–400 A | 600–1000 V | 400 kW | Yes |

Plugs, socket-outlets, vehicle connectors and vehicle inlets according to this series of standards are used in EV supply equipment according to IEC 61851 series or IEC 62752 and in electric vehicles according to ISO 17409 or ISO 18246.

Most plugs, socket-outlets, vehicle connectors and vehicle inlets according to this series of standards provide additional contacts that support specific functions that are relevant for charging of electric vehicles, power is not supplied unless a vehicle is connected, and the vehicle is immobilized while still connected. Several parts of this series of standards have been published as European standards (EN 62196 series) which in turn have been published as British standards (BS EN 62196 series). Similar requirements are contained in SAE J1772 which is widely applied in the US.

## 2.2 Regulations for EV´s Safety

Electric vehicles (EVs) have gained popularity due to their low environmental impact and efficient performance. However, the widespread adoption of EVs has raised concerns regarding safety, particularly regarding battery technology. To address these concerns, various regulations and standards have been developed to ensure the safety of EVs.

**Regulations and standards related to EV safety:**
Several organizations have developed regulations and standards related to EV safety, including the National Highway Traffic Safety Administration (NHTSA), the International Electrotechnical Commission (IEC), and the Society of Automotive Engineers (SAE). These regulations and standards cover various aspects of EV safety, including battery safety, crash safety, and electrical safety.

**Battery safety regulations and standards:**
Battery safety is a critical aspect of EV safety, and several regulations and standards have been developed to ensure the safe operation of EV batteries. For example, the NHTSA has developed safety standards for lithium-ion batteries used in EVs, which cover various aspects of battery safety, including electrical safety, mechanical safety, and thermal safety. The IEC has also developed safety standards for EV batteries, which cover topics such as cell safety, module safety, and pack safety.

**Crash safety regulations and standards:**
Crash safety is another critical aspect of EV safety, and regulations and standards have been developed to ensure the safe operation of EVs in the event of a crash. For example, the NHTSA has developed crash safety standards for EVs, which cover various aspects of vehicle safety, including occupant protection, structural integrity, and electrical safety.

**Electrical safety regulations and standards:**
Electrical safety is also an important aspect of EV safety, and regulations and standards have been developed to ensure the safe operation of EV electrical systems. For example, the SAE has developed standards for EV charging systems, which cover topics such as electrical safety, electromagnetic compatibility, and communication protocols.


Figure 5 Regulations and certification for electric vehicles [6]

The widespread adoption of EVs has raised concerns regarding safety, particularly about battery technology. To address these concerns, various regulations and standards have been developed to ensure the safety of EVs. These regulations and standards cover various aspects of EV safety, including battery safety, crash safety, and electrical safety. By adhering to these regulations and standards, EV manufacturers can ensure the safe operation of their vehicles, reducing the potential for accidents and injuries.

With the continuous development of LIBs, the corresponding LIB test standards are constantly improved. The various organizations and institutions that make these standards have actively participated in guaranteeing the safety of the battery industry, including the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), the Society of Automotive Engineers (SAE), the UL certification body, the China Administration for Standardization (SAC), and the Ministry of Industry and Information Technology of China (MIIT).

A large number of standards have been developed to regulate the safety testing of LIBs.  All LIBs must pass a series of safety test standards, and each nationality or region should conduct safety tests according to their domestic standards. These safety tests evaluate the LIBs by simulating extreme situations that may occur during usage. All the standards have a criterion or hazard rating for judging whether the test sample is qualified or unqualified.

# 3. Batteries For EV´s

Electric car batteries are rechargeable batteries used to power electric vehicles. They are typically lithium-ion batteries, which offer a high energy density and can provide long-range driving capabilities. Electric car batteries typically consist of hundreds or thousands of individual cells that are interconnected to form a battery pack. The performance and range of an electric vehicle depend heavily on the quality and capacity of its battery. The capacity of an electric car battery is measured in kilowatt-hours (kWh), and the higher the capacity, the longer the range the vehicle can travel on a single charge. The lifespan of an electric car battery depends on various factors, such as the quality of the battery, the charging habits of the driver, and the climate in which the vehicle is operated. Generally, electric car batteries can last anywhere from 5 to 20 years or more, depending on these factors. As electric vehicles become more popular, there is increasing research and development around electric car batteries to improve their performance, reduce their cost, and increase their lifespan. There are several important characteristics that are considered when choosing batteries for electric vehicles. These include energy density, power density, cycle life and charging time. The cost of batteries is an important factor in the overall cost of an electric vehicle. The cost of batteries has been decreasing over time as technology improves and production scales up. Safety is an important consideration for batteries, as they can pose a fire risk if they are damaged or overcharged. Battery designs that are less prone to catching fire or exploding are preferred for electric vehicle applications. And lastly, the environmental impact of batteries is an important consideration, as their production and disposal can have significant environmental impacts. Batteries with lower environmental impacts, such as those made from recycled materials, are preferred for electric vehicle applications.

Table 3 Characteristics of battery types used in EV´s [7]

| Characteristic | Lead Acid | NiMH | ZEBRA | Li-ion |
|---|---|---|---|---|
| Nominal cell voltage | 2 v | 1.2 v | 2.58 v | 2.5 v/ 3.3 v/ 3.6-3.7 v |
| Specific energy | 30-45 Wh/kg | 30-80 Wh/kg | 90-100 Wh/kg | 90-220 Wh/kg |
| Energy density | 60-75 Wh/L | 140-300 Wh/L | 160 Wh/L | 280-400 Wh/L |
| Specific power | 180 Wh/kg | 250-1000 Wh/kg | 150 Wh/kg | 600-3400 Wh/kg |
| Cycle life | 500-800 | 500-1000 | 1000 | 1000-8000 |
| Self-discharge | 2-4% /month | 20-30% /month | 0% /month | 2-5% /month |
| Temperature range | -20-60 | -20-60 | 270-350 | -20-60 |
| Relative costs | Low | Moderate | Low | High |

There are three basic types of battery cells used in electric vehicles: cylindrical cells, prismatic cells, and pouch cells. There are also coin cells, which are used in research and development for testing purposes, but never actually used in electric vehicles.
The number of cells in an EV varies widely based on the cell format. On average, EVs with cylindrical cells have between 5,000 and 9,000 cells. This is in stark contrast with pouch cells, which only have a few hundred cells, and an even lower number in prismatic cells.

**Cylindrical cells** are the least expensive format to manufacture because they are already self-contained in a casing that offers good mechanical resistance. The technology is not only cost-efficient, but it is also mature, making it a format easy to manufacture. Because of their shape, cylindrical cells have limitations in terms of power. For this reason, EVs with smaller batteries such as hybrid vehicles use pouch or prismatic cells to deliver more power during accelerations.

Cylindrical cells need to be manufactured in a smaller format than other types of cells to make sure they dissipate heat well, helping prolong the battery life. That’s why the most common cylindrical cell formats are the 18650 and 21700. Larger formats such as the 4680 are viable because their new internal design allows more efficient heat transfer to the thermal adhesives used in structural batteries. [29]

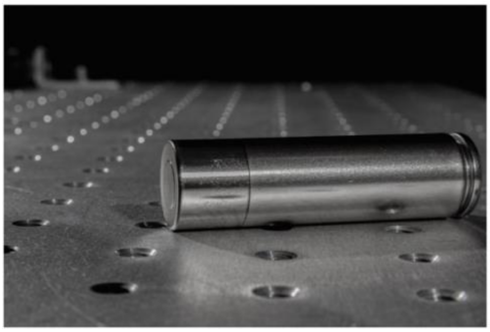

Figure 6 Cylindrical cell [8]

**Prismatic cells** can be 20 to 100 times larger than cylindrical cells. They can typically deliver more power and store more energy for the same volume because less material is used for the casing. The casing’s shape and thickness also allow better heat management than cylindrical cells. Prismatic cells are popular among Chinese manufacturers because their preferred cell chemistry (the lithium iron phosphate battery) currently mostly exists in the prismatic format.

Lately, prismatic cells have been gaining in popularity elsewhere in the world. While cylindrical cells used to be the most popular format, prismatic cells might take over a large share of the market in the upcoming years.

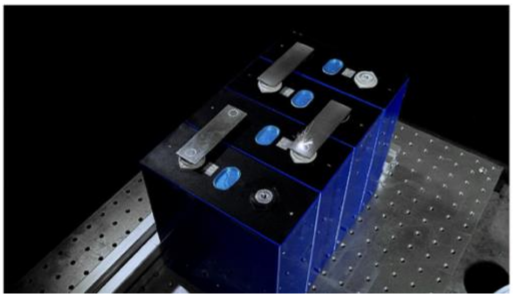

Figure 7 Prismatic cell [8]

**Pouch cells** are made to deliver more power than other cell types. They are also very efficient when it comes to space usage. Their soft plastic casing, however, means they have the lowest mechanical resistance of all cell types. For this reason, an additional structure needs to be added during pouch cell assembly to protect them from mechanical damage.

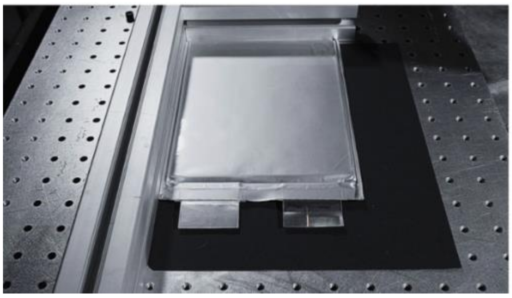

Figure 8 Pouch cell [8]

In practice, the components can be manufactured as thin foils that can be packaged into different configurations such as the cylindrical, pouch and prismatic geometries, Figure 9. Pouch cells are typically packaged in a soft aluminium plastic film. Prismatic cells are rectangular in shape but have a hard shell. At least one battery manufacturer combines prismatic cells into packs without modules, a cell-to-pack (CTP) battery system, that is claimed to reduce complexity, weight, space, and cost.

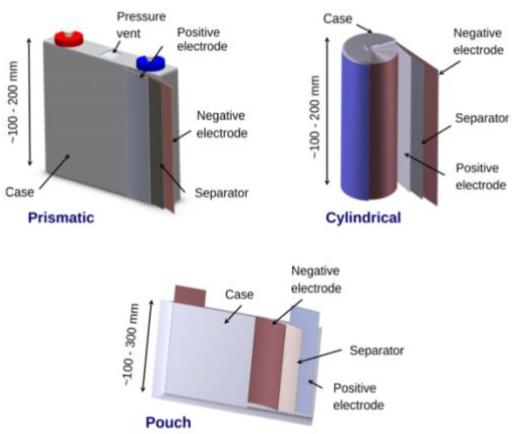


Figure 9 Battery cell configuration [9]

## 3.1 Battery Chemistry and Operation

Batteries used in electric vehicles are typically rechargeable lithium-ion batteries, which have a high energy density, long cycle life, and low self-discharge rate. These batteries use lithium ions to store and release energy, which allows them to power electric motors in vehicles. The specific type of lithium-ion battery used in electric vehicles can vary depending on the vehicle's design and performance requirements.

Some popular types of lithium-ion batteries used in electric vehicles include different types, Nickel Cobalt Aluminium (NCA) Batteries, these batteries offer high energy density, making them suitable for high-performance electric vehicles. Tesla uses NCA batteries in its Model S and Model X vehicles. Nickel Manganese Cobalt (NMC) Batteries, these batteries offer a balance between energy density and safety, making them a popular choice for a variety of electric vehicles. Nissan and BMW use NMC batteries in some of their electric vehicles. Lithium Iron Phosphate (LFP) Batteries: These batteries have a lower energy density than NCA and NMC batteries, but they are more stable and have a longer lifespan. LFP batteries are commonly used in electric buses and other heavy-duty vehicles.

Overall, lithium-ion batteries are the most common type of battery used in electric vehicles due to their high energy density, long cycle life, and low self-discharge rate. However, researchers are also exploring new types of batteries, such as solid-state batteries, which could offer even higher energy density and safety.

Table 4 Examples of different Li-ion batteries used in EVs. [10]

| **Developer** | **Chemistry** | **Vehicle** | **Year** |
|---|---|---|---|
| A123 | Doped Lithium nanophosphate | Volt-EV Vue-PHEV<br>Think | 2010<br>2009<br>2009 |
| PanasonicJCI-Saft | Lithium nickel cobaltAluminum oxide | Toyota- PHEV<br>S400-HEV<br>Vue-PHEV | 2010<br>2009<br>2009 |
| Hitachi | Lithium cobalt oxide | GM-HEV | 2010 |
| Available Cells | Lithium manganese Oxide | Tesla-EV | 2008 |
| Altair Nanotechnologies | Lithium titanate spinel | Phoenix Electric | 2008 |

A lithium-ion battery operates by using a chemical reaction to produce electrical energy. The mode of operation of a lithium-ion battery can be broken down into several steps:

**Charging:** The battery is charged by applying a voltage to it, which causes lithium ions to move from the positive electrode (cathode) to the negative electrode (anode), where they are stored. This process is known as intercalation.

**Discharging:** When the battery is connected to a load, such as an electric motor, the stored lithium ions move back to the cathode through an electrolyte solution, creating an electrical current that can be used to power the load.

**Recharging:** Once the battery is discharged, it can be recharged by reversing the direction of the current, causing the lithium ions to move back to the anode.

**Maintenance:** Lithium-ion batteries require maintenance to ensure optimal performance and longevity. This includes monitoring the battery's state of charge, temperature, and voltage, as well as ensuring that the battery is not exposed to extreme temperatures or overcharged.

The mode of operation of a lithium-ion battery relies on the movement of lithium ions between the electrodes, driven by an external voltage or current source. This process enables the battery to store and discharge electrical energy, making it a popular choice for a wide range of applications, including electric vehicles, consumer electronics, and renewable energy systems.

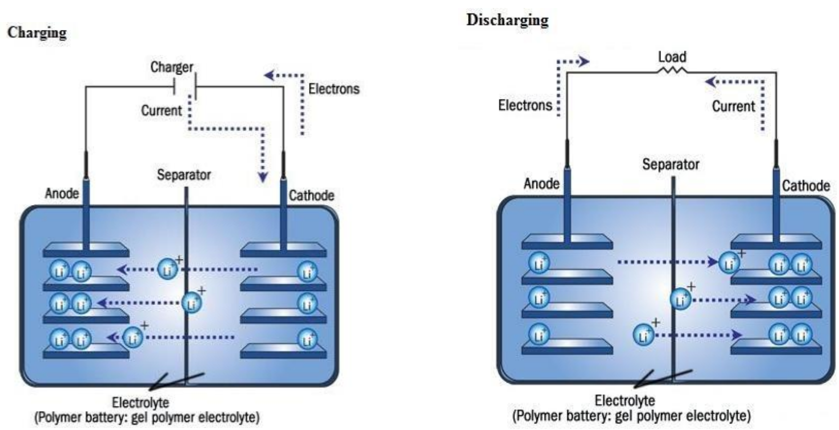


Figure 10 Charge and discharge mechanism in Li-ion battery [11]

A lithium-ion (Li-ion) cell is made up of several components that work together to store and release energy. Here are the main components of a typical Li-ion cell:

**Anode:** The anode of a Li-ion cell is typically made of graphite or other carbon-based materials. During charging, lithium ions are intercalated (inserted) into the anode structure, and during discharging, the lithium ions are released from the anode and move to the cathode.

**Cathode:** The cathode of a Li-ion cell is typically made of metal oxides such as lithium cobalt oxide ($LiCoO_2$), lithium manganese oxide ($LiMn_2O_4$), or lithium iron phosphate ($LiFePO_4$). During charging, lithium ions move from the cathode to the anode, and during discharging, they move from the anode back to the cathode.

**Electrolyte:** The electrolyte of a Li-ion cell is typically a lithium salt (such as $LiPF_6$) dissolved in an organic solvent. The electrolyte allows the lithium ions to move between the anode and cathode during charging and discharging.

**Separator:** The separator of a Li-ion cell is a thin, porous material that physically separates the anode and cathode and prevents them from coming into contact. The separator also allows the lithium ions to pass through while preventing the electrodes from touching.

**Current collectors:** The current collectors of a Li-ion cell are usually made of metal foils (such as aluminium or copper) and are connected to the electrodes. They are used to collect and conduct the electrical current produced during charging and discharging.

**Protection circuit:** A protection circuit is often included in Li-ion cells to prevent overcharging or over-discharging, which can damage the cell and reduce its lifespan. The protection circuit typically consists of a control circuit, a fuse, and a thermistor to monitor the cell's temperature.

These components work together to store and release energy in a safe and efficient manner, making Li-ion cells an ideal choice for a wide range of electronic devices and applications.

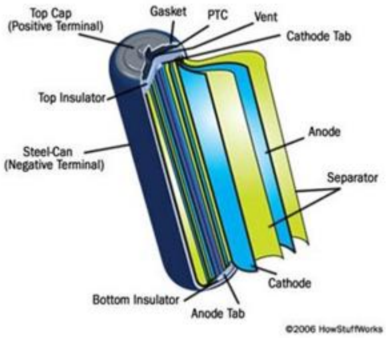


Figure 11 Composition of a cylindrical Li-ion battery [12]

A lithium salt as electrolyte refers to a lithium compound that is dissolved in a solvent to create an electrolyte solution that is used in a lithium-ion battery. The lithium salt serves as the source of lithium ions, which are necessary for the battery's electrochemical reactions. When the battery is charged, lithium ions move from the positive electrode (cathode) to the negative electrode (anode) through the electrolyte solution.

When the battery is discharged, the lithium ions move in the opposite direction, from the anode to the cathode, generating an electrical current that can be used to power a device or electric motor. Different types of lithium salts can be used in the electrolyte solution, each with its own properties and advantages and disadvantages. The choice of lithium salt depends on the specific application and performance requirements of the battery.

Table 5 Well-known lithium salts for use in electrolytes & their major disadvantages [13]

| Salt | Disadvantages |
|---|---|
| $LiAsF_6$ | Toxic |
| $LiClO_4$ | Thermal runaway leading to explosion |
| $LiBF_4$ | Interferes with anode passivation |
| $LiSO_3CF_3$ | Low conductivity |
| $LiN(SO_2CF_3)_2$ | Corrodes aluminum cathode current collector |
| $LIC(SO_2CF_3)_3$ | Corrodes aluminum cathode current collector |
| $LiPF_6$ | Thermally decomposes to HF and $PF_3O$, deteriorates both anode and cathode |

# 4. Thermal runaway in EV´s an Overview

Thermal runaway is a phenomenon in which a battery's temperature increases uncontrollably, causing it to become increasingly hot and potentially leading to a fire or explosion. Thermal runaway can occur in any battery-powered device, including electric vehicles (EVs). The risk of thermal runaway in EVs is primarily associated with the lithium-ion batteries used to power them. Lithium-ion batteries are highly energy-dense and can store a large amount of electrical energy in a relatively small space. However, they are also sensitive to changes in temperature and can become unstable if they are subjected to extreme conditions, such as overcharging or overheating.

To mitigate the risk of thermal runaway, EV manufacturers use a variety of safety features in their battery packs. These features include thermal management systems that monitor the battery's temperature and prevent it from becoming too hot, as well as redundant safety mechanisms that can isolate individual cells or modules if they become damaged or overheated.

In addition to these safety features, EV manufacturers also conduct rigorous testing to ensure that their battery packs can withstand a wide range of environmental conditions and usage scenarios. This testing includes extreme temperature testing, overcharge testing, and puncture testing, among other things.

The consequences of thermal runaway in an EV battery can be severe, including fire or explosion. When a battery undergoes thermal runaway, it can release flammable gases and generate high levels of heat that can damage the vehicle and pose a risk to passengers and bystanders.

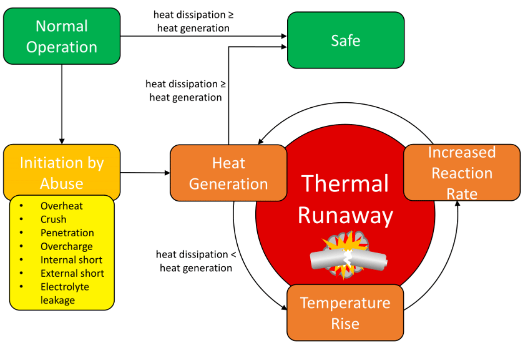


Figure 12 Thermal runaway process within a single cell [14]

To explain further as to why we see such a rapid heating rate we need to understand a little more about the decomposition reactions. When a Li-ion cell, or a small spot within the cell, reaches a certain critical temperature range, the materials inside the cell start to break down, to decompose. These decomposition reactions are exothermic in nature which is why we have a self-heating behaviour.

Further, the decomposition rates, which are directly proportional to the exothermic self-heating rates, follow Arrhenius form which means that the decomposition rate (and subsequently the self-heating rate) goes up exponentially as temperature goes up. Put simply, as the temperature increases, so does decomposition rate, and likewise, so does the self-heating rate. The result is a self-feeding heating rate within the cell that increases until the cell loses stability, ruptures, and all remaining thermal and electrochemical energy is released into the surroundings.

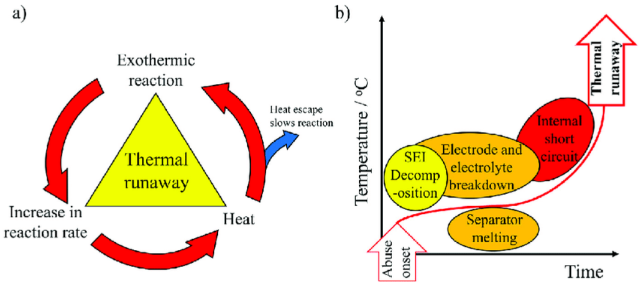

Figure 13 (a) Thermal runaway positive feedback loop; (b) Qualitative interpretation of the chain reactions during thermal runaway. [15]

While the risk of thermal runaway in EVs is real, it is also relatively low due to the safety features and testing that manufacturers employ. It is important for EV owners to be aware of the risks and to follow the manufacturer's guidelines for safe use and charging of their vehicle's battery. Although thermal runaway is a serious issue, it doesn’t mean your EV will spontaneously combust. The warning signs for thermal runaway are normally obvious before the situation becomes life-threatening, giving motorists time to move to a safe distance. And like all discussions of safety, the risk is relative.

## 4.1 Previous studies on Thermal runaway

There have been several studies conducted on thermal runaway in batteries, including those used in electric vehicles. Here are a few examples:

"Thermal Runaway Mechanisms in Lithium-Ion Batteries" by Venkat Viswanathan et al. (2012) - This paper discusses the various mechanisms that can lead to thermal runaway in lithium-ion batteries, including overcharging, internal short circuits, and external heat sources. The authors also propose several strategies for mitigating the risk of thermal runaway.

"Thermal Runaway Propagation in Lithium-Ion Battery Packs with Multiple Cells" by Jian Liu et al. (2013) - This study uses numerical simulations to investigate the propagation of thermal runaway in battery packs with multiple cells. The authors identify several factors that can affect the propagation of thermal runaway, including the spacing between cells and the thermal properties of the surrounding materials.

"Investigation of Thermal Runaway in Lithium-Ion Batteries Using Accelerating Rate Calorimetry" by Chao-Yang Wang et al. (2014) - This paper describes an experimental study using accelerating rate calorimetry (ARC) to investigate the thermal runaway behaviour of lithium-ion batteries. The authors examine the effects of various parameters on thermal runaway, including cell size, state of charge, and temperature.

"A Review of Thermal Runaway in Lithium-Ion Batteries" by Chris Yuan et al. (2015) - This review article provides an overview of the current state of research on thermal runaway in lithium-ion batteries. The authors discuss the various causes and mechanisms of thermal runaway, as well as the methods used to detect and prevent it. One of the most high-profile cases of thermal runaway was the 2013 Tesla Model S fire in Seattle, which prompted investigations and analysis from the National Highway Traffic Safety Administration (NHTSA) and the National Transportation Safety Board (NTSB). Following this incident, Tesla implemented several changes to their battery pack design to improve safety, including better thermal management systems and reinforced battery casings. Other researchers have also studied thermal runaway in electric vehicle batteries to understand the underlying mechanisms and develop strategies for preventing and mitigating it.

## 4.2 Risk assessment and Management of TR in closed spaces

Thermal runaway is a serious risk in closed spaces, as the build-up of pressure and heat can cause an explosion or fire, leading to significant damage to property and injuries or fatalities to personnel. Therefore, it is essential to assess and manage the risk of thermal runaway in closed spaces to prevent such incidents. The objectives of this chapter are to identify potential sources of thermal runaway in closed spaces, evaluate the likelihood and consequences of thermal runaway events, develop preventive and emergency procedures to manage the risk of thermal runaway in closed spaces, and to monitor and maintain safety measures to prevent thermal runaway incidents. Potential sources of thermal runaway are chemical reactions that produce heat, such as oxidation or polymerization. Closed spaces, such as storage tanks, vessels, or reactors, where heat dissipation is limited, are particularly susceptible to thermal runaway. Therefore, it is important to identify the chemicals and processes involved in the operation and determine their potential to generate heat.


Figure 14 How TR in one cell can lead to destruction of the entire battery [16]

Behind the recent headlines of electric vehicle (EV) fires, engineers are working to get in front of the thermal runaway conditions that lead to battery failure by developing technologies that provide early warning of an impending catastrophe. Some detection platforms are currently in production.

EV battery fires are complicated and challenging. In a study of 101 EV fires that occurred before 2019, half could not be attributed to any cause at all, let alone something obvious like damage to the battery pack or overcharging. Equally concerning, some 50% of the fires resulted from spontaneous combustion, and 16% of the vehicles were in neither charging nor driving mode. Often, damaged cells with stranded energy can reignite long after any initial fire. In at least one vehicle incident, a collision-damaged vehicle's battery pack caught fire four times within a five-day interval following the initial crash.

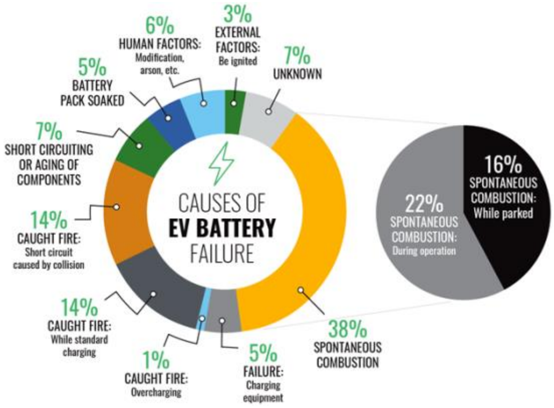


Figure 15 Causes of EV Battery failure [17]

The likelihood of thermal runaway events depends on the conditions under which they could occur, such as temperature, pressure, and oxygen concentration. These conditions may be influenced by various factors, including equipment design, environmental factors, and human error.

The consequences of thermal runaway events can be severe and may include explosions, fires, or toxic releases, leading to significant damage to property and injuries or fatalities to personnel. Preventive measures are essential to reduce the likelihood of thermal runaway events. These measures may include controlling the temperature, pressure, and oxygen concentration, using appropriate containers and equipment, and training personnel on safe handling procedures. In addition, emergency procedures should be developed to respond to thermal runaway events, including evacuation plans, emergency shutdown procedures, and measures to contain the release of energy and chemicals.

Regular monitoring and maintenance of safety measures are critical to ensure that they are functioning as intended. This may include monitoring temperature and pressure, inspecting equipment, and conducting regular training and drills to ensure that personnel are familiar with emergency procedures.

Thermal runaway is a serious risk in closed spaces, and it is essential to assess and manage this risk to prevent incidents. The risk assessment and management process should involve identifying potential sources of thermal runaway, evaluating the likelihood and consequences of thermal runaway events, developing preventive and emergency procedures, and monitoring and maintaining safety measures. By following these steps, the risk of thermal runaway in closed spaces can be effectively managed, reducing the potential for damage to property and injuries or fatalities to personnel.

## 4.3 Causes and Mechanisms of Thermal Runaway

Thermal runaway is a complex phenomenon that occurs when the heat generated by a chemical reaction exceeds the ability of the system to dissipate the heat, causing a self-sustaining reaction that can lead to an uncontrollable release of energy. Thermal runaway can have devastating consequences, including fires, explosions, and toxic releases. Therefore, it is crucial to understand the causes and mechanisms of thermal runaway to prevent such incidents.

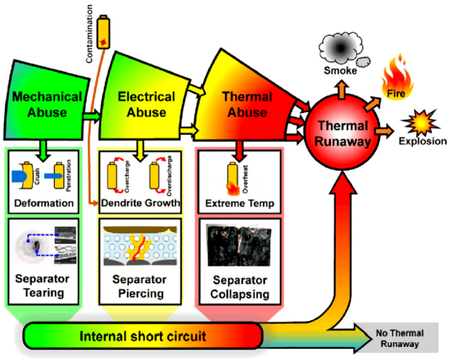

Figure 16 Abuse conditions leading to thermal runaway [18]

Chemical reactions that produce heat, such as oxidation or polymerization, can lead to thermal runaway. These reactions can be exothermic or endothermic and can be influenced by various factors, including temperature, pressure, and the presence of catalysts or inhibitors. Therefore, it is essential to identify the chemicals and processes involved in the operation and determine their potential to generate heat. Several factors can contribute to the occurrence of thermal runaway, including environmental factors, equipment design, and human error. For example, the temperature and pressure of the system can influence the onset of thermal runaway, and inadequate cooling or heat transfer can exacerbate the situation. Similarly, equipment design that does not consider the potential for heat build-up can increase the risk of thermal runaway. Human error, such as improper handling of chemicals or failure to follow safety procedures, can also contribute to thermal runaway. The mechanisms of thermal runaway are complex and can vary depending on the specific chemical reactions involved.

However, some common mechanisms include autocatalysis, heat feedback, and gas generation. Autocatalysis occurs when the reaction products promote further reactions, leading to a self-sustaining reaction. Heat feedback occurs when the heat generated by the reaction causes the temperature to increase, leading to more heat generation and a positive feedback loop. Gas generation occurs when the reaction produces gases that increase the pressure in the system, leading to further heat generation.

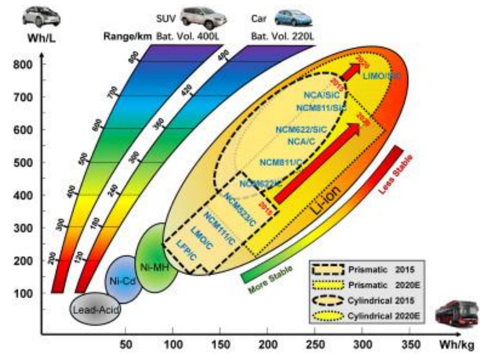

Figure 17 Thermal runaway mechanism of Li-ion battery for electric vehicles [19]

Thermal runaway is a complex phenomenon that can have devastating consequences. Understanding the causes and mechanisms of thermal runaway is essential to prevent such incidents. Chemical reactions that produce heat, environmental factors, equipment design, and human error can all contribute to thermal runaway. The mechanisms of thermal runaway are complex and can vary depending on the specific chemical reactions involved. Therefore, it is essential to identify potential sources of thermal runaway, evaluate the likelihood and consequences of thermal runaway events, and develop preventive and emergency procedures to manage the risk of thermal runaway.

Although thermal runaway is clearly life-threatening, to date there is yet to be global regulation in place. Whereas China has implemented the GB/T 31485 standard, the UN has only proposed legislation. This leaves automotive manufacturers with the choice of whether they want to design their battery packs with systems designed to deal with thermal runaway incidents. It's up to their own risk assessment programmes to determine how likely thermal runaway is to occur. Putting any protection in is likely to hinder the range capacity of the vehicle though – naturally, more protective materials equal less space for cells in a finite space.

Battery safety is a prominent concern for the deployment of electric vehicles (EVs). The battery powering an EV contains highly energetic active materials and flammable organic electrolytes. Usually, an EV battery catches fire due to its thermal runaway, either immediately at the time of the accident or can take a while to gain enough heat to ignite the battery chemicals.

There are numerous battery abuse testing standards and regulations available globally. Electrical runaway occurs when there is an uncontrolled increase in current flow in the electrical system. This can happen due to a short circuit, which can result in overheating, fire, or explosion. Electrical runaway can be caused by faulty components, damage to the electrical system, or incorrect installation or use of charging equipment. Thermal runaway occurs when the battery in an electric vehicle overheats and begins to generate heat at an increasing rate. This can happen due to overcharging, exposure to high temperatures, damage to the battery, or other factors. If left unchecked, thermal runaway can cause the battery to catch fire or explode, which can be dangerous for passengers and bystanders.

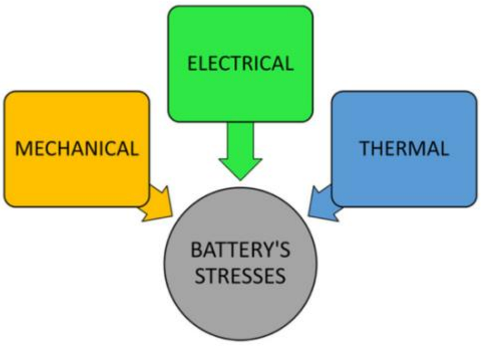


Figure 18 Stresses occurring in lithium-ion batteries. [22]

In various research, the reactions to the safety incidents that occur in the energy sources after overloading have been analysed in detail, and based on this, the following classification, the external stresses on the energy sources have been determined as follows:

- Mechanical: impact, deformation, penetration, free fall, mechanical shock, vibrations, and immersion.
- Electrical: overload, overloading, forced download, and high C-rate.
- Thermal: heating, overheating, and thermal runaway.

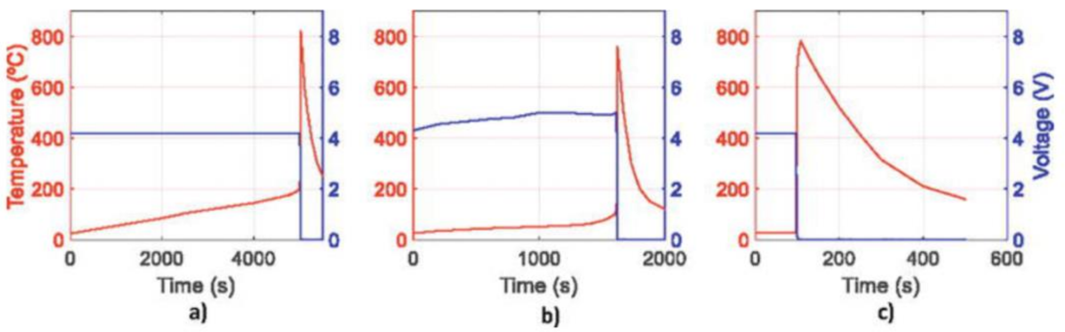


Figure 19 Temperature and voltage evolution of the cell under different type of abuse (a)overheating (b)overcharge (c)nail penetration data obtained from [23]

To prevent accidents related to lithium-ion thermal runaway caused by mechanical impact in electric vehicles, manufacturers and designers take several measures to ensure the safety of the batteries. Here are some of the ways they address this issue:

- Battery design and placement: The battery pack is designed to be located in a protected area of the vehicle to reduce the risk of mechanical impact. The battery pack is usually located in the centre or the bottom of the vehicle, where it is surrounded by a robust structure that can absorb shock.

- Battery enclosure: The battery pack is enclosed in a durable case that can withstand mechanical impacts. The enclosure is designed to prevent the battery from being punctured, crushed, or otherwise damaged.

- Battery management system (BMS): The BMS continuously monitors the battery's temperature, voltage, and other parameters. If the BMS detects any abnormalities, it can automatically shut down the battery to prevent thermal runaway.

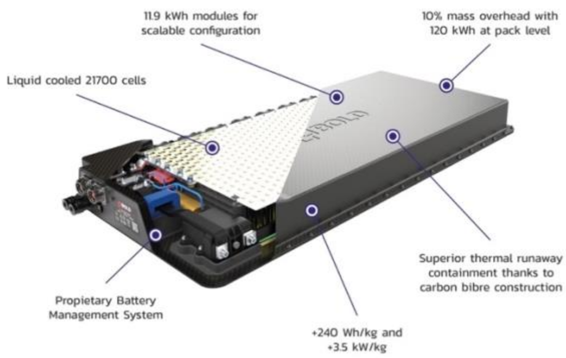


Figure 20 Thermal design of composite battery enclosures [24]

Crash sensors: Electric vehicles are equipped with sensors that detect a crash and can automatically shut down the battery to prevent thermal runaway.
Fire suppression system: Electric vehicles are equipped with a fire suppression system that can extinguish a battery fire. The system uses a mixture of water and firefighting foam to suppress the fire and prevent it from spreading.

Regular inspections and maintenance: Electric vehicles require regular inspections and maintenance to ensure that the battery pack is in good condition. The battery pack should be inspected for any signs of damage, and any issues should be addressed promptly.

Electric vehicle manufacturers take several measures to prevent thermal runaway caused by mechanical impact. These measures ensure the safety of the battery pack and minimize the risk of accidents.

## 4.4 Solutions to avoid Thermal Runaway

Thermal runaway in electric vehicles can occur when the battery pack gets too hot, causing the temperature to rise rapidly and uncontrollably, potentially leading to a dangerous situation such as a fire or explosion. Some studies shown different ways to avoid thermal runaway in electric vehicles:

Battery thermal management system (BTMS) regulates the temperature within the battery pack in high and low-temperature environments to avoid overheating and improve the electrochemical performance of the battery, respectively [19]. The use a well-designed battery management system (BMS) which is an essential component of an electric vehicle, and it can help prevent thermal runaway by monitoring the temperature of the battery pack and controlling the charging and discharging rates to ensure that the battery stays within a safe operating range. Finally, to avoid high temperatures, one of the most common causes of thermal runaway is exposure to high temperatures. To avoid this, electric vehicles should be designed with efficient cooling systems that can dissipate heat from the battery pack.

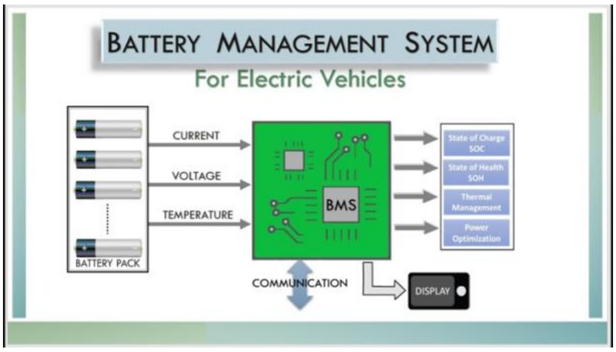

Figure 21 BMS for EV's [20]

High-quality components such as battery cells, wiring, and connectors can help prevent thermal runaway by reducing the risk of faults or malfunctions that can cause overheating, regular monitoring of the battery pack can help identify any potential issues before they become a problem. This can be done using sensors that monitor the temperature and voltage of the battery cells.

Overcharging the battery can cause it to overheat and potentially lead to thermal runaway. To avoid this, electric vehicles should be equipped with a charging system that stops charging when the battery is fully charged. And finally adequate ventilation is essential for dissipating heat from the battery pack. Electric vehicles should be designed with proper ventilation systems that allow air to circulate around the battery pack to prevent overheating. By following these guidelines, electric vehicle manufacturers can help prevent thermal runaway and ensure the safe and reliable operation of their vehicles.

There are two methods that can be used to stop a battery thermal event – active and passive thermal management systems.

Active thermal management makes use of cooling systems to keep battery packs at an optimal temperature. An active thermal management system extracts heat from the cells using air or cooling plates with conventional automotive coolants or even refrigerants to bring temperatures back down when the cells start to heat up during charge or discharge. It is like the way a radiator is used to maintain temperatures inside an internal combustion engine.

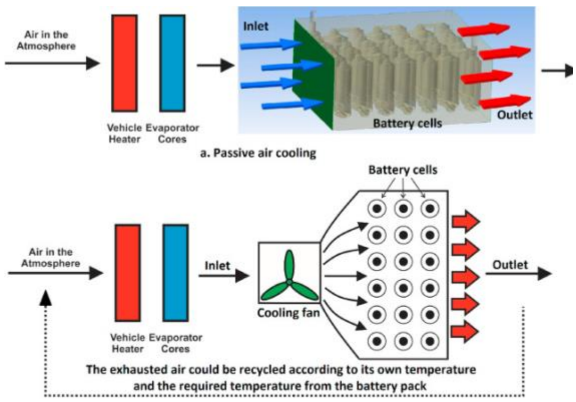

Figure 22 Active air cooling [21]

Passive thermal management systems are used to focus on the later stages of preventing thermal runaway. Passive systems, like insulation or a heat shield, block excessive heat from passing from an individual cell to the rest of a battery pack and continuing the chain reaction instead of keeping an affected cell cool. The concept of passive thermal management systems is like the use of compartmentalization for fire protection in buildings. Containing a fire to an area prevents it from spreading to other parts of the structure.

Morgan Advanced Materials has been significantly researching and developing a range of thermal management protection materials and methods over many years. These can provide more time for occupants to exit a vehicle, while the dissipation of heat lessens the chance of thermal runaway spreading uncontrollably. It is not a ‘one-size-fits-all’ approach though. Every battery design is different, and so the protection method must be unique.

There are three levels of protection that engineers can design into their systems to significantly reduce the impact of thermal runaway in electric vehicles. Namely, these are cell-to-cell, module-to-module, and battery pack level.

**Cell-to-Cell**

Cell-to-cell protection involves designing a material to go between individual cells. It is the highest level of protection, but also the most challenging due to space constraints. If an individual cell experiences thermal runaway, the absorption of heat and deflection of flame from the protective materials minimise the thermal affects to adjacent cells. One of the most effective methods of protection at cell level is by using phase change materials (PCMs), such as Morgan's thermal insulation EST (Energy Storage Technology) Superwool Block, a solution that can be used for certain cell formats.

PCMs absorb the heat of ruptured cells, as when the temperature of the cells gets too high, they turn the insulation material from either solid to liquid, or liquid to gas. During the phase change, the heat can be dissipated throughout the body of the material. If the phase change is from solid to gas, this offers additional protection as the gas from the insulation material pushes the cell's gases out through vents of the module, helping to lower the temperature quicker.

It is important to consider the cell's shape when specifying cell protection, as different cells have different insulation needs. Cells are split into three main types, cylindrical, prismatic and pouch. With cylindrical batteries, the insulation material can be solid shapes, but with pouch cells, they expand and contract, so you cannot use a rigid insulation to protect them. Prismatic cells can use either solid or flexible insulation materials.

**Module-to-Module**

There are several materials designed to go between modules depending on the module size and design. Thermal runaway within the module can occur but can be contained to stop spread to adjacent modules. With module-to-module protection, protection can come in a paper format. Notably, module-to-module protection offers significant weight savings compared to cell-to-cell protection. Lighter batteries in turn increase the range and allows the battery to be more easily accommodated in the vehicle's design.

**Pack Level Protection**

Pack level protection is the simplest and most affordable type of protection. This is aimed towards improving safety to the vehicle's occupants by giving them additional time to exit the vehicle but provides little protection for the battery pack itself. [18]

# 5. Methodology

The equivalent (ECM) is a battery model often used in the battery management system (BMS) to monitor and control lithium-ion batteries (LIBs). The accuracy and complexity of the ECM, hence, are very important. State of charge (SOC) and temperature are known to affect the parameters of the ECM and have been integrated into the model effectively. However, the effect of the state of health (SOH) on these parameters has not been widely investigated. Without a good understanding of the effect of SOH on ECM parameters, parameter identification would have to be done manually through calibration, which is inefficient. In this work, experiments were performed to investigate the effect of SOH on Thevenin ECM parameters, in addition to the effect of SOC and temperature. The results indicated that with decreasing SOH, the ohmic resistance and the polarization resistance increase while the polarization capacitance decreases. An empirical model was also proposed to represent the effect of SOH, SOC, and temperature on the ECM parameters. The model was then validated experimentally, yielding good results, and found to improve the accuracy of the Thevenin model significantly. With low complexity and high accuracy, this model can be easily integrated into real-world BMS applications. [17]

Battery modelling based on differential equations can provide a deep understanding of the physical and chemical process inside the battery and is useful when designing a cell; however, high computational time makes these models impractical for applications that require several model iterations. Therefore, to reach a reasonable economy in computations, battery losses are represented as equivalent electrical circuit components. Equivalent circuit-based modelling is the preferred method of modelling since it does not require an in-depth understanding of electrochemistry of the cell but is still capable of providing useful insight into battery dynamics.
The mathematical modelling of a battery is significant because of the following reasons:

- Development of efficient BMS.
- Key in the improvement of charging/discharging techniques and the enhancement of battery capacity.
- Need to capture the influence of power consumption on the battery.
- To prevent serious damage to batteries from overcharging or over-discharging.
- Faster and safer way to study battery behaviour under different operating conditions.
- Identifying the operating limits that achieve best lifetime for specific applications.

## 5.1 Types of abuse in TR

There have been several reported accidents related to lithium-ion thermal runaway caused by mechanical impact in electric vehicles, including the Tesla Model S fire in Seattle: In 2013, a Tesla Model S caught fire after hitting a metal object on the road. The impact caused the battery pack to be punctured, which resulted in a thermal runaway. Tesla Model S fire in Norway: In 2016, a Tesla Model S caught fire after colliding with a concrete barrier. The impact caused the battery pack to be punctured, which resulted in a thermal runaway. Chevy Volt fire in Wisconsin: In 2011, a Chevy Volt caught fire three weeks after being involved in a crash.

The fire was caused by a thermal runaway in the battery pack, which was triggered by a coolant leak. BMW i8 fire in Germany: In 2016, a BMW i8 caught fire after colliding with a tree. The impact caused the battery pack to be punctured, which resulted in a thermal runaway. BYD e6 fire in China: In 2012, a BYD e6 electric taxi caught fire after colliding with a sports utility vehicle. The impact caused the battery pack to be punctured, which resulted in a thermal runaway.

Figure 23 Model S catches fire near Seattle [25]

Lithium-ion batteries in electric vehicles can also experience thermal runaway caused by electrical impacts. Here are a few examples of accidents related to li-ion thermal runaway caused by electrical impact in electric vehicles, Hyundai Kona EV fire: In 2020, Hyundai Kona EVs were recalled due to several fires caused by a short circuit in the battery cells. The fires were caused by a manufacturing defect in the batteries that could cause an electrical short circuit. Fisker Karma fire: In 2012, a Fisker Karma hybrid electric vehicle caught fire and was destroyed while parked in a garage in Texas. The fire was caused by a short circuit in the lithium-ion battery.

Chevrolet Bolt EV fires: In 2021, General Motors recalled all Chevrolet Bolt EVs due to several fires caused by battery pack thermal runaway. The fires were caused by two manufacturing defects that could cause a short circuit in the battery cells. Tesla Model S fire in Austria: In 2014, a Tesla Model S caught fire while parked in a garage in Austria. The fire was caused by a short circuit in the lithium-ion battery.

Thermal impact, such as exposure to high temperatures, can also cause lithium-ion batteries in electric vehicles to experience thermal runaway. Here are a few examples of accidents related to li-ion thermal runaway caused by thermal impact in electric vehicles, Tesla Model S fire in California: In 2018, a Tesla Model S caught fire while traveling on a California highway. The cause of the fire was attributed to the vehicle's battery being exposed to high temperatures from the road debris, causing thermal runaway.

Chevrolet Volt fire in Arizona: In 2011, a Chevrolet Volt caught fire and destroyed a garage and a portion of a house in Arizona. The cause of the fire was attributed to the vehicle's lithium-ion battery overheating and causing thermal runaway. Nissan Leaf fire in Portugal: In 2012, a Nissan Leaf caught fire while parked in Portugal. The cause of the fire was attributed to the vehicle's lithium-ion battery overheating and causing thermal runaway. BMW i3 fire in Germany: In 2019, a BMW i3 caught fire and exploded in a parking garage in Germany. The cause of the fire was attributed to the vehicle's lithium-ion battery overheating and causing thermal runaway.

Table 6 List of EV fire accidents in 2018 [26]

| Date | Location | Vehicle | Incident | Comments |
|---|---|---|---|---|
| Jan 2018 | Chongqing, China | Tesla, BEV | Fire in the parked vehicle | Spontaneous ignition |
| Mar 2018 | Bangkok, Thailand | Porsche Panamera, PHEV | Fire while being charged | Car's charging cable plugged to socket in the living room without built-in safety systems, and fire spread to the house |
| Mar 2018 | Catalonia, Spain | BMW i3 REx, PHEV | Fire in the parked vehicle | Spontaneous ignition |
| Mar 2018 | California, USA | Tesla Model X, BEV | Post-crash fire | Fire extinguished on the scene but reignited twice at tow yard 5 days later |
| May 2018 | Anhui, China | Other, BEV | Fire while being charged | |
| May 2018 | Unknown | Yiema, BEV | Fire while being charged | |
| May 2018 | Florida, USA | Tesla Model S, BEV | Post-crash fire | Fire initially extinguished quickly but reignited during loading on tow truck and once again at the tow yard |
| May 2018 | Ticino, Switzerland | Tesla, BEV | Post-crash fire | Vehicle hit a barrier, turned over and burst into flames |

These incidents highlight the importance of proper battery management and temperature control in electric vehicles to prevent thermal runaway caused by exposure to high temperatures. Manufacturers are continuously developing and improving battery management systems to monitor and regulate the temperature of lithium-ion batteries in electric vehicles, which can help reduce the risk of thermal runaway and fires.

Although a regular battery system has a low probability of self-ignition, it is vulnerable to external thermal, mechanical, and electrical impacts that may materialize during extreme operating conditions or incidents. Comparatively, electrical impacts and extreme operating conditions are rare for most portable electronic devices, such as the laptop and smartphone, but they are considered as the normal operating conditions. In contrast, the operation condition is more severe for an EV battery considering the frequent acceleration and deceleration in complex road and traffic conditions.

Moreover, the battery capacity (or fuel load) of EV is thousands of times greater than that of portable electronic devices, which means a more severe fire hazard in the case of thermal runaway and ignition. On the other hand, the safety measures that are included in the EV and battery pack design are more advanced, reducing the likeliness of (spontaneous) failure, therefore it is inappropriate to assess the battery fire risk in EVs, based on the impression of battery fire risk in portable electronic devices as the battery is not only the fuel to power the EV but also the major fuel to feed the EV fire, similar to gasoline or diesel being the major fuel to feed ICEV fires.

Previous reviews emphasized the safety characteristics of battery material and chemistry and summarized recent scientific understandings of battery fire dynamics, the overall fire risk and hazards of EV are still poorly understood as fire tests on large-scale EV battery packs and full-scale EVs are expensive and rarely published. Nowadays as the expansion of the EV market, EV ownership is constantly increasing, so the energy density of LIBs continues to increase [21], despite unsolved fire-safety issues. As a result, the probability of EVs fire accidents will increase.

## 5.2 Phases of Thermal Runaway

Any TR phenomenon is associated with prior phases which, although they do not trigger TR, do affect the cell temperature, increasing the probability of the occurrence of those reactions that do cause TR. Each of the reactions between the internal cell components is initiated when the temperature reaches a certain value, while its duration is based on the rate at which the cell temperature increases [29]. Therefore, depending on the cause of the TR, these reactions may occur consecutively or simultaneously. For example, an LIB may be subject to mechanical abuse that causes an ISC, generating a large amount of heat in a very short space of time. In this case, the diverse reactions between the internal components will take place almost simultaneously.

However, if the battery is exposed to external heating which slowly increases its temperature, then each reaction will take place when its starting temperature is reached. In this section, in order represent the temperature at which the chemical reactions are triggered, an external heating abuse of 2°C/min has been considered. The evolution of the cell temperature, its voltage and the gases released. These three variables are a good representation of the consequences of each of the TR stages. Furthermore, Figure 5b shows the temperature increase rate (dT/dt) in relation to the cell temperature. This is a widely used graph to represent the TR in LIBs, given that it permits the visual analysis of the exothermic behaviour and the moment at which the temperature that initiates the TR is reached.

Furthermore, both graphs show the three most significant temperatures that permit the characterisation of a TR incident. These temperatures are identified as T1, T2 and T3, and correspond to the onset temperature of exothermic reactions (T1), the TR onset temperature (T2) and the maximum temperature (T3). T1, T2 and T3 provide extremely valuable information on the safety characteristics of a TR. The greater the values of T1 and T2, the safer the cell, given that they indicate the safety margin available until the start of the exothermic reactions that degrade the LIB and the temperature of no return.

On the other hand, the lower the value of T3, the safer the cell, given that a lower value for this temperature indicates less energy released during the TR phenomenon which conditions, among other things, its potential propagation to the adjacent cells.

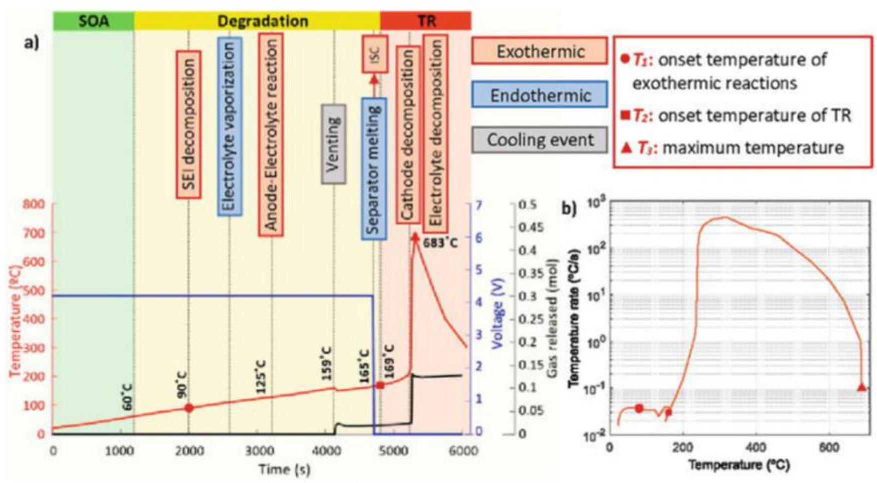

Figure 24 Phases of TR. (a)evolution of temperature, voltage, and gases release during an overheating test; and (b)temperature rate vs. Temperature [27]

**SEI layer decomposition**

Once the cell temperature is outside the SOA, the decomposition of the SEI is the first exothermic reaction to take place. Therefore, the start of this reaction relates to temperature T1, as can be seen in Figure 5a. Depending on the composition of the SEI layer, T1 can be between 85 and 120°C [30]. However, it has also been confirmed in some cells that the decomposition of the SEI can start at lower temperatures, ranging from 60 to 80°C [31]. Heat is released during the decomposition of the SEI, which increases the cell temperature.

Moreover, flammable gases are produced such as ethylene (C2H4) and also some oxygen, due to the fact that the metastable components of the SEI such as (CH2OCO2Li)2 are not thermally stable in the presence of lithium ions and may react exothermically. In short, the decomposition of the SEI layer degrades the LIB and generates heat and gases, but does not in itself trigger the onset of TR. However, it does help to accelerate the temperature rise, which could lead to the start of new exothermic reactions. Furthermore, the loss of the protection of the SEI layer exposes the anode and means that it could react with the electrolyte.

**Electrolyte vaporisation**

The continued increase in the cell temperature leads to the vaporisation of the organic components of the electrolyte. The organic solvents making up the electrolyte, such as dimethyl carbonate (DMC), ethyl methyl carbonate (EMC) and diethyl carbonate (DEC), have boiling points of 91, 107 and 126°C, respectively [12]. On evaporation, these carbonates are converted into gases, which contribute to increase the cell pressure. Given that the volume remains constant, this causes the temperature to increase. In other words, despite the fact that the change of state from the liquid to vapour phase is endothermic, the energy absorbed is negligible in comparison to the increase in temperature caused by the pressure increase. In this phase, the temperature increases above the flashpoints of the gases produced by the electrolyte. However, these gases do not combust, given that there is insufficient oxygen inside the cell to cause a fire. Due to the utilisation of highly volatile and flammable organic-solvents-based electrolytes, new electrolyte systems are being developed to achieve safer electrolytes, such as ionic liquids, polymer-based electrolytes and solid-state electrolytes. Ionic liquid electrolytes are characterised by low volatility and/or flame retardants properties. Polymer-based and solid-state electrolytes have the advantage of being free of liquid and organic solvents, avoiding the risk of cell leakage. Thus, this phase can be avoided or delayed with the use of other electrolyte system.

**Lithium intercalated in the anode and electrolyte reaction**

The decomposition of the SEI exposes the lithium intercalated in the anode which, at temperatures above 120°C, rapidly reacts with the organic solvent of the electrolyte [38]. This reaction leads to the formation of lithium carbonate and flammable hydrocarbons (ethylene, ethane, and propylene). During the temperature rise, a second SEI layer may be formed, which again decomposes as a result of the above-mentioned reactions, with an exothermic peak at a temperature of 230°C.

**Cell venting**

The formation of gases in the cell interior causes the internal pressure to increase. Normally, the cells are fitted with devices that relieve the pressure when high values are reached, as this would involve a risk of explosion. When the safety vent is activated, the gases produced are released into the surroundings and the internal pressure is reduced. If the cell does not have a built-in safety vent, then the venting may occur through the rupture of the casing at its weakest point, as is the case with the pouch cells.

This process lowers the cell temperature due to the Joule-Thomson effect. This drop in temperature is due to the release of the hot gases, which reduces the pressure while maintaining the volume constant and therefore the temperature drops. This event takes place before the TR and, despite the drop in temperature, account should be taken of the fact that it involves a release of inflammable gases which, in contact with the oxygen in the air, could combust, causing an increase in the ambient temperature. This could accelerate the heating of the adjacent cells, favouring the propagation of TR. Finally, it is important to emphasise the fact that the amount of gases released during venting is significantly lower than those released in the TR itself.

**Separator melting and ISC**

The separator consists of a porous membrane intended for two principal purposes: to allow ions to pass through and to electrically isolate the electrodes. Therefore, the separator material has high ionic conductivity and low electrical conductivity. At present, polyethylene (PE) and polypropylene (PP) are the most widely used materials for the separator. PE melts at 130°C, while PP does so at 165°C. Once melted, the separator membrane can no longer perform its function, triggering an ISC. As can be seen in Figure 5a, at the time when the separator melts, causing the subsequent ISC, the cell voltage abruptly drops to zero. The separator melting process is endothermic and absorbs energy during the change of state. However, the energy absorbed is negligible in comparison with that produced by the ISC.

**Rupture of the cathode material and reaction with electrolyte**

At high temperatures (175–250°C), the active material of the cathode (generally an oxide) decomposes exothermically, releasing oxygen. Both the oxygen released, and the actual cathode material react with the electrolyte at this temperature. This chemical reaction is highly exothermic, causing the sharpest temperature increase in the TR process [29]. This reaction and the reaction between the intercalated lithium in the anode and electrolyte and the ISC caused by the collapse of the separator are the main triggers of the TR phenomenon in LIBs [6]. Therefore, the value of T2 will be influenced by the weakest among the cathode, anode, and separator.

**Electrolyte decomposition**

Both the anode and the cathode materials react with the electrolyte during TR. When the cell temperature exceeds 200°C, the electrolyte decomposes exothermically [27]. However, account should be taken of the fact that certain organic solvents in the electrolyte evaporate at temperatures below 100°C, thus, at 200°C, part of the electrolyte has already evaporated. The electrolyte decomposition produces flammable and toxic gases such as HF from the decomposition of LiPF6 salt [32]. The generation of CO2, C2H4 and HF, among other gases, has been documented in the decomposition of electrolytes comprising LiPF6 and organic carbonates [29].

**Reactions at higher temperatures**

Other exothermic reactions that take place at very high temperatures have also been documented. At 220°C, the lithium intercalated in the negative electrode starts to react exothermically with the fluorine-based binder, usually polyvinylidene fluoride (PVDF) [29]. At temperatures above 300°C, metallic lithium can form from the decomposition of the stable components of the SEI layer (LiF and Li2CO3), and the graphite portion of the anode can exothermically decompose [30].

However, these take place following initiation of TR, and they have less influence in comparison with the aforementioned reactions [5].

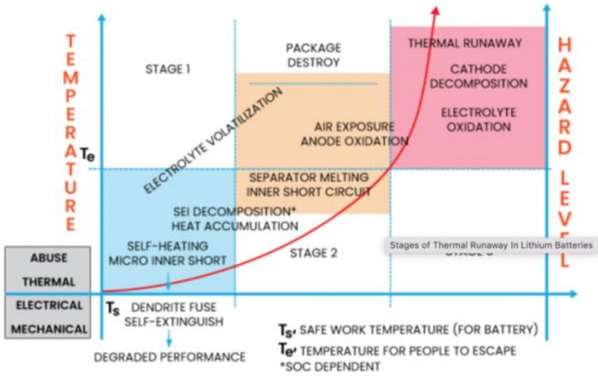


Figure 25 Stages of TR [28]

The chemistry of the batteries determines the characteristics of their TR, given that the reactions involved depend to a large extent on the materials used in the internal components. Depending on the type of chemistry, it is possible to find cells with a higher or lower degree of thermal stability, and therefore, they are more or less prone to TR. As discussed above, there are currently a number of different types of LIB chemistries on the market, which differ with regard to their electrochemical performance, lifespan, and safety.

In general, the name is determined by the active material used in the cathode. However, even when the same material is used for the cathode, the cells made by different manufacturers may behave differently with regard to the TR phenomenon, depending on the materials used in the rest of the internal components.

The active material of the cathode is either a lithium compound (LCO, LMO, NMC, NCA, LFP…) or a combination of these. The thermal stability of this material is crucial to determine the safety of the cell. Thermal stability refers to the temperature at which the cathode material decomposes and releases the oxygen contained in its structure. When this oxygen is released, it reacts with the electrolyte, generating heat and even igniting.

Cells with an LFP cathode are the safest, given that the strong phosphate bonds prevent the release of oxygen. By contrast, transition-metal oxides have weaker bonds, causing oxygen to be released at lower temperatures.

## 5.3 Risk Analysis of Thermal Runaway in Closed Areas

EVs are currently powered by Lithium-ion batteries. They are also used as energy storage systems in battery buffered high power charge points. Failures within cells can quickly lead to fire and explosion of adjacent cells, uncontrolled thermal runaway follows. Increasing reports of EV battery have led to vehicle and property destruction, injuries, and major EV recalls in the US, Europe, and Asia, e.g. Hyundai's recall of its Kona EV's earlier this year. When discussing battery fires, it is useful to appreciate how EV batteries are constructed and their failure mechanisms.

**1) Li-ion battery construction**

An EV battery consists of multiple smaller cells that are constructed with an anode and cathode separated by a porous electronically insulating separator. During discharge, lithium leaves the anode as lithium-ion (Li+) and an electron (e-). The Li+ flows through the ion conducting electrolyte and separator to the cathode. As the separator is electronically insulated, the electron must flow via an external circuit where useful work is done. During re-charge, the Li+ ions and electrons on the anode recombine on the cathode to form lithium on the cathode electrode.

Contaminants in raw materials, damages during construction and the high number of cell components within a battery result in challenges in the defect detection during manufacturing. These defects are seldom identified during quality control, testing or operation.

**2) Li-ion battery failure modes**

Li-ion batteries can degrade over time or fail rapidly. Degradation can be caused by high or low temperature, high current/loading, high or low voltage/state of charge per cell, number of cycles, chemical or mechanical stress. The degradation mechanism includes growth or decomposition of the solid electrolyte interphase layer, lithium plating or dendrite formation piercing through the separator, and general failure of the battery component parts. This leads to the loss of lithium inventory, active anode material or active cathode material and results in a capacity loss or power fade.

While degradation is usually a time related occurrence, accidents to EV can result in a rapid deterioration, due to failure of the battery monitoring management system (control system).

Accidents related to lithium-ion battery failures can be caused by:

- Mechanical abuse – deformation or separator tearing (e.g. crash, shock, crush or penetration).

- Electrical abuse – internal short circuit, lithium dendrite growth leading to the piercing of the separator (e.g. internal short circuit, over discharge, over charge). Thermal abuse – high temperature leading to a collapse of the separator (e.g. overheating).

All the above can result in an internal battery short circuit leading to thermal runaway. This failure may occur in a single cell, but as these are closely packed within the EV, thermal runaway can quickly lead to flames, explosion, oxygen release, high temperature and a myriad of noxious gasses (hydrogen fluoride (HF), phosphorus pentafluoride (PF5), hydrogen cyanide (HCN) and carbon monoxide (CO)) being released. Studies into the failure mechanisms of many battery types included the gaseous emissions and toxicity.

**3) Identifying failures in Li-ion batteries**

Li-ion battery failures are time dependent, however failure can occur rapidly after damage or abuse. Consider the following failure detection options:

Electrolyte vapour detection:  The event in which the cell case vents due to a rise in internal pressure of the cell is termed off gas. (NFPA 855/UL 9540A). This unique event is useful to determine incipient faults within the battery construction. At the early stages of failure, lower explosion limit sensors or voltage, temperature and current measurement variations are not easily detected, as the characterises have not changed much. However, the electrochemical reaction inside the battery creates a noticeable amount of gas at this early stage. Some commercially available detectors use gas sensors to monitor and detect off gassing events a few seconds after failure occurs and long before battery measurements are effective. Early detection coupled with a correctly designed shutdown system is an effective safety barrier. Note, this method cannot predict the state of the battery.

• Measure terminal voltage variations using battery management system. This is a widely used monitoring method with redundancy and comparative measurements assumed to be providing integrity, but due to the complexity of programmable systems and a lack of segregation between control an protective safety systems this assumption may not result in the required integrity and is difficult to validate. This method is not very fast at identifying early stages of thermal runaway.

• Monitor the battery temperature using embedded fibre Bragg grating optical temperature sensors or electrochemical impedance spectroscopy measurements. This method provides an accurate temperature measurement but adds cost and complexity to battery packaging.

• Measure current variations (short circuits). The BMS can be configured to measure current flow. Any abnormal rate of current flow or load-requested level can trigger an alarm indicating a potential short circuit. Usually, irreversible failure has occurred at this stage.

• Measure mechanical deformation or delamination of electrode coatings. Other than visual or x-rays, no commercially viable passive method is employed.

**4) Li-ion battery fire management**

Internal short circuits consequences can be discussed in 3 levels as summarised in the table:

Table 7 Battery failure characteristics

| Level | Cell voltage | Cell temperature | Identification and consequences |
|---|---|---|---|
| Level 1 | At cell voltage, but slow decrease | Slow increase, self-discharge, no/low obvious heat | Off gas detection Electrical approach, BMS identification. Self-extinguish behaviour. |
| Level 2 | Fast decrease | Rapid increase, Joule heating | Electrical-thermal coupled approach. Consequences depends on heat dissipation. |
| Level 3 | No voltage | Thermal runaway. Joule + chemical reactions | Too late. Unstoppable consequence. |

The temperature increases rapidly over time up to about 100°C, increases slowly further up to about 200°C after which the separator and electrolyte separating the anode and cathode fails leading to a significant rapid increase in temperature to well above 500°C. Figure represents an example of different cathode materials.

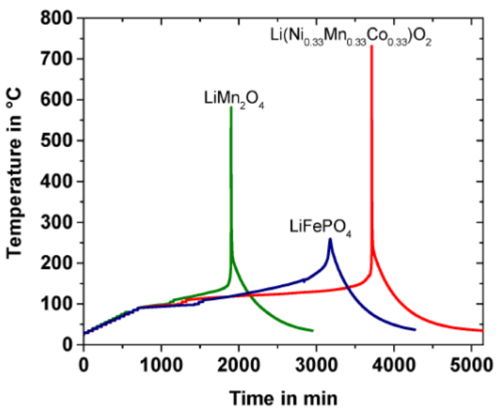

Figure 26 Typical temperature versus time of different cathode material failure

## 5.4 Hazards of Thermal Runaway

Once the thermal runaway process begins, it is very unlikely that the condition will stop on its own. If the temperature increases and isn’t effectively dispelled, the inevitable result will be the battery overheating. The heat will cause significant damage to the battery and its compartment. In some cases, the battery may leak toxic chemicals or gas. Beyond battery damage, thermal runaway poses severe risks to the product’s users and surroundings, including sudden system failure and dangerous events such as fire or explosions. While traditional combustion vehicles can also experience these hazardous situations, fires with EVs can be more extreme. As a newer technology, issues with EVs also tend to attract more media attention and can harm a company’s reputation.

Lithium-ion batteries are known for their exceptional performance and higher charge and discharge currents. However, as a rechargeable battery, their ability to produce heat has led to incidents such as fire and explosion.
Thermal runaway in lithium-ion batteries can cause a range of issues from minor to severe. Hazards may include:

- Melting batteries
- Irreversible damage to the battery cell
- Gassing of the battery
- Extremely hot fires
- Explosion

In general, a LIB is mainly composed of electrodes, electrolytes, and a separator. The electrodes can further be divided into the cathode and the anode. The thermal hazard of the LIB usually results from the destructive reactions of battery components such as the decomposition of electrode/electrolyte, the reaction between electrodes, the reaction between electrode and electrolyte. With the proceeding of chain reactions inside battery during thermal runaway such as the decomposition of SEI layer, the decomposition of electrode and electrolyte, the reactions between electrode and electrolyte, and the combustion of electrolyte substantial heat will be generated which leads to the sharp increase of battery temperature. A battery pack possesses the hazard of thermal failure propagation, that is, the thermal failure of one or several batteries will propagate to the neighbouring ones, resulting in catastrophic consequences. The thermal hazard will be heightened during the propagation; hence it is essential to pay attention to the issue of failure propagation within a battery pack.

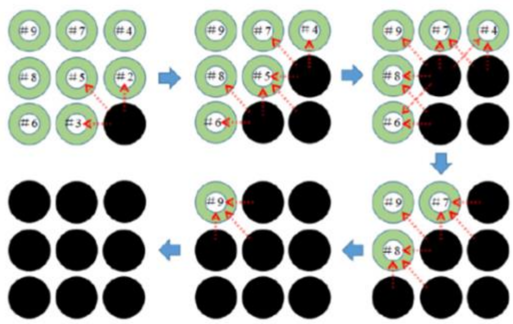

Figure 27 Schematic of thermal failure propagation [31]

Generally, the thermal hazards of LIBs can be caused by several abusive factors: physical, electrical and thermal factors, manufacturing defect and battery aging. The physical factor can trigger electrical abuse, and the electrical abuse releases heat which will further induce thermal abuse; namely, thermal hazard and even thermal runaway. During the process of battery thermal hazard, a series of destructive reactions among battery components such as the decomposition of electrodes/electrolytes, the reaction between electrodes, the reaction between electrode and electrolyte, etc. are induced, substantial heat is released and quantities of combustible gases are generated.

Due to the high energy density of the LIB and the inherent hazards of battery components described above, it is common for the LIB to experience thermal hazards especially under abusive conditions. For a single battery, the thermal hazards are generally exhibited as high-temperature, ejection, combustion, explosion, and toxic gases during thermal runaway. As for a battery pack, thermal failure propagation within the pack can also be observed.

Battery packs are generally consisted of single batteries, in which the quantity of batteries depends on the application ranging from several to thousands. For example, one charge-pack usually contains 2–4 batteries (18,650), while there are more than 7000 batteries for the pack in a Tesla Model S. Consequently, battery pack possesses the thermal hazards of a single battery as described.

Whereas, different to a single battery, a battery pack possesses the hazard of thermal failure propagation, that is, the thermal failure of one or several batteries will propagate to the neighbouring ones, resulting in catastrophic consequences.

The thermal hazard will be heightened during the propagation; hence it is essential to pay attention to the issue of failure propagation within a battery pack. Besides battery components, the thermal hazards of a single battery and a battery pack are also reviewed. For the former, the thermal hazards that are generally exhibited are high-temperature, ejection, combustion, explosion and toxic gases during thermal runaway. While for a battery pack, thermal failure propagation provides a thermal hazard in addition to thermal runaway. Thermal failure propagation will aggravate the thermal hazard further, resulting in a serious incident. In addition, the influence of low-pressure environment and cathode chemistry on the thermal hazard of LIBs is discussed here. However, it still lacks sufficient examinations on the thermal behaviour of LIBs under low pressure, the hazard difference between normal condition and low-pressure condition is worth nothing in future research.

To conclude, EV fires are extremely rare but as the number of EVs on the streets has grown worldwide, so has the occurrence of fires. The environmental conditions of the batteries in an EV are harsh and the batteries are exposed to vibrations and large temperature variations as well as severe mechanical shocks and possible deformations in the event of a crash. The off-nominal conditions, poor quality of the cells and batteries, or use beyond their specifications, may cause the battery to go into thermal runaway, which can lead to the release of extensive heat, fire, smoke, and toxic gases.

A major concern with the large battery systems used in EVs is that the thermal runaway of one cell can lead to a catastrophic fire in the whole battery system and re-ignitions even after visual flames have been extinguished. In addition to the fire hazard, the high-voltage nature of the EV batteries gives rise to new risks compared to traditional internal combustion engine cars.

A meticulously designed and functioning BMS as well as effective methods to prevent the propagation of thermal runaway from one cell to another as well as to other components in the battery pack are needed to tackle the hazards caused by EV fires. Fire and emergency response departments must also prepare for the increased number of EVs on the roads and train their personnel to respond safely and effectively to any EV crash or fire incident. New extinguishing media and methods for EV fires may need to be developed as those used to extinguish internal combustion engine vehicles may not be effective with EVs.

The Fire Protection Research Foundation in the United States has recommended using standard vehicle firefighting equipment and tactics as well as copious amounts of water to extinguish EV fires. However, the amounts of water required to put out some of the EV fires are extremely large and might not be available in all areas where EVs are used. In Europe, some fire departments have started submerging burning EVs in large water-filled containers to avoid the reignitions commonly encountered in EV battery fires. However, this practice is against the recommendations of some of the EV manufacturers.

## 5.5 Methods for early detection of TR

For the majority of applications employing lithium-ion batteries, such as the energy storage component of micro-grids and the battery pack of electric vehicles, are actually using modules composed of a large number of lithium-ion battery cells connected in series and in parallel, all stacked in a specific container. If one or a few lithium-ion battery cells in the container experienced thermal runaway, due to the extremely constrained container space and the heat transfer among battery cells through convection and conduction, some local heated spots will be created, which further leads to the propagation of thermal runaway failures to all the neighbouring cells. Due to the domino effect, all of the lithium-ion battery cells in the container can ultimately run into thermal runaway failures. Based on the mechanism of thermal runaway, it is applicable and convenient to take the voltage/current, the temperature, and the released gas as the characteristic fault signals to monitor and detect the presence of thermal runaway events in lithium-ion batteries. This section will discuss and summarize three types of thermal runaway monitoring and detection schemes as follows:

- Real-time detection of the lithium-ion battery cell/module terminal voltage and its surface temperature.
- Real-time monitoring and estimation of the internal temperature and the strain of lithium-ion batteries.
- Real-time monitoring and analysing the characteristic vent gas component of lithium-ion batteries during thermal runaway.

The battery management system (BMS) is the most widely used method for monitoring and detecting thermal runaway events in lithium-ion battery applications. It mainly relies on the built-in voltage sensors and temperature sensors as measurement tools. With a sufficient number of sensors installed, this system can measure the terminal voltage and the surface temperature of each lithium-ion battery cell in real time. Once an abnormal signal is detected, the BMS can trigger an alarm immediately. Regarding to the methods used for monitoring and detecting the surface temperature of a lithium-ion battery pack, the temperature sensor is usually a thermistor or a thermocouple. However, both types of temperature sensors have similar problems such as the low detection accuracy and the vulnerability to environment change. In order to improve the detection accuracy of surface temperature and improve the reliability for monitoring and detecting a thermal runaway process with the surface temperature, fiber Bragg grating optical sensors and K-type thermocouples are employed to detect the surface temperature at the top, middle, and bottom part of the lithium-ion battery at both the normal and abnormal state with various discharge rates (0.53 C, 2.67 C, and 8.25 C). Locations of fiber Bragg grating optical sensors and K-type thermocouples are illustrated in fig. (a). It is found that the fiber Bragg grating optical sensor has a better temperature resolution and a higher temperature sensitivity when compared to a K-type thermocouple. The result indicates that the fiber Bragg grating optical sensor can be used to detect the surface temperature of lithium-ion batteries in real-time, thus improving the performance and robustness for monitoring and detecting the thermal runaway process of lithium-ion batteries with BMS.

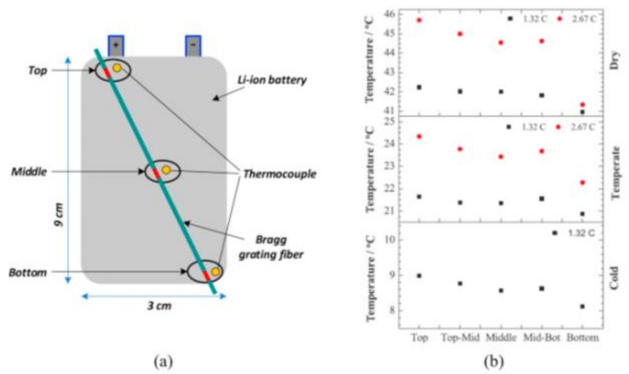


Figure 28 Thermal runaway monitoring and detecting method based on surface temperature measurement: (a) the location of fiber Bragg grating optical sensor and K-type thermocouple; and (b) the absolute surface temperature of each position [29].

Thereafter, based on the fiber Bragg grating optical sensor, the same team proposed a fiber optical sensor network for measuring the surface temperature of lithium-ion batteries. Through experimentation, the surface temperature of a lithium-ion battery in a smartphone was detected in real-time, at various discharge rates in a dry environment [27]. It is found that the surface temperature of a lithium-ion battery in a smartphone during the thermal runaway process induced by a large discharge rate is nearly twice as much as the temperature at normal conditions. In addition, the fiber Bragg grating optical sensor is used to detect the absolute surface temperature that is discharged at 5.77 C, and its surface temperature is as high as 65 °C. There is also an obvious tendency of temperature decrease from the top to the bottom of the battery cell, with the temperature of each position shown in Fig 28 (b). The highest temperature detected is at the top of the battery cell (close to the electrodes), followed by the top-middle position. The temperature at the mid-bottom is slightly higher than that of the middle, and the temperature detected at the bottom of the lithium-ion battery is the lowest among all of the above positions.

Table 8 Advantages and disadvantages of different methods for monitoring and detecting TR. [30]

| Method | Advantages | Disadvantages |
|---|---|---|
| Terminal voltage and surface temperature monitoring method | ✓ Monitor the voltage and surface temperature in real-time;<br>✓ Capable of locating faulty battery;<br>✓ Predict the state of health, state of charge, etc. of the battery in real-time. | ◆ Low accuracy of thermal runaway prediction;<br>◆ Complex topology of voltage sensors and high cost. |
| Embedded optical fiber sensors method | ✓ Monitor the internal core temperature of the battery directly;<br>✓ High accuracy of thermal runaway prediction. | ◆ Higher cost of embedded optical fibers;<br>◆ Higher requirements for battery packaging. |
| Electrochemical impedance spectroscopy analysis method | ✓ Predict the internal core temperature of the battery without complex hardware;<br>✓ High accuracy of thermal runaway prediction; | ◆ Fail to monitor large-scale batteries quickly and effectively;<br>◆ Complex calibration process as different lithium-ion battery systems have different parameters of |

In order to prevent serious consequences introduced by thermal runaway events of lithium-ion batteries, it is not only necessary to detect the thermal runaway by monitoring the status of lithium-ion batteries in real time, but it also requires taking some protective measures to mitigate the thermal runaway process once it occurs. Generally, it can start from two aspects to attenuate the thermal runaway process: improving the inherent safety of lithium-ion batteries at the cell level and the cooling capability at the system (module or pack) level. The cell-level safety elevation can be achieved by using safer materials and improved preparation processes for the battery itself.

At the system level, protection measures include better cooling designs for effective heat dissipation and the isolation of heat propagation towards all of the neighboring cells.

## 5.6 Role of Battery Management System

The Battery Management System (BMS) plays a critical role in managing thermal runaway in lithium-ion batteries in electric vehicles. The BMS is responsible for monitoring the battery's state of charge, state of health, and temperature, as well as balancing the voltage across the individual cells in the battery pack. When the battery temperature exceeds safe limits, the BMS can take several actions to prevent thermal runaway:

Thermal management: The BMS can activate the battery's cooling system to reduce the battery's temperature and prevent it from exceeding safe limits.
Cell balancing: The BMS can balance the voltage across individual cells in the battery pack to prevent overcharging or over-discharging, which can lead to thermal runaway.

Shutdown: If the temperature of the battery pack exceeds safe limits, the BMS can shut down the battery to prevent further heating and damage.
Fault detection and isolation: The BMS can detect faults in the battery pack, such as short circuits or overcurrent, and isolate them to prevent thermal runaway. In summary, the BMS plays a crucial role in managing the temperature of lithium-ion batteries in electric vehicles and preventing thermal runaway. The BMS continuously monitors the battery's state and takes appropriate actions to maintain safe operating conditions, which helps to improve the safety and reliability of electric vehicles.

**Types of BMS**
The BMS designs come with features and functions that vary from application to application. In the case of small portable equipment batteries that have energy that is less than 60 Wh, a hard blow or resettable fuse, a MOSFET switch for overvoltage and one for Undervoltage, an integrated circuit chip/microchip that monitors the voltage of every single cell and the current of the battery as well as temperatures in strategic locations, forms the main components of the BMS. In most commercial battery designs with the energy of less than 30 Wh and more than one cell in a series configuration, cell balancing during charge and discharge is included. This function not only extends the life of the battery but also increases the safety of the battery in its application. An important feature that has been added to battery designs is the need for communication between the battery and the equipment it is used in

as well as the charger that is used for charging. Since various combinations of cathode and anode chemistries in lithium-ion cells have different end-of-charge voltages, it is imperative that the charger recognizes the electrode chemistry and provides charge. This communication can be performed in various ways, one being the use of the Electrically Erasable Programmable Read-Only Memory (EEPROM), where the action to provide power to the load or to take charge from the charger is initiated after confirmation of the compatibility of the battery with the load or charger. Other logic circuit designs have also been used for the same purpose. This helps in preventing the use of low-quality or non-dedicated chargers that could result in an unsafe condition due to the lack of understanding of the lithium-ion battery chemistry.

As the battery design gets larger, containing energy greater than 60 Wh, the design of the BMS can get more complex. In some designs, the charging protocol is integrated into the BMS design along with the safety-relevant functions. Another significant feature is the addition of temperature sensors and sense circuits to confirm that the battery is at a temperature that is conducive to safe charging. Most BMS also communicate the health of the battery to the charger before the charging is initiated. In some cases, this feature of monitoring the health of the battery before charge initiation can be found in the charger design. In critical applications such as with the power source for the International Space Station, the BMS also has the function of load-leveling which calls for the removal of non-critical loads to have enough power to run the critical ones.

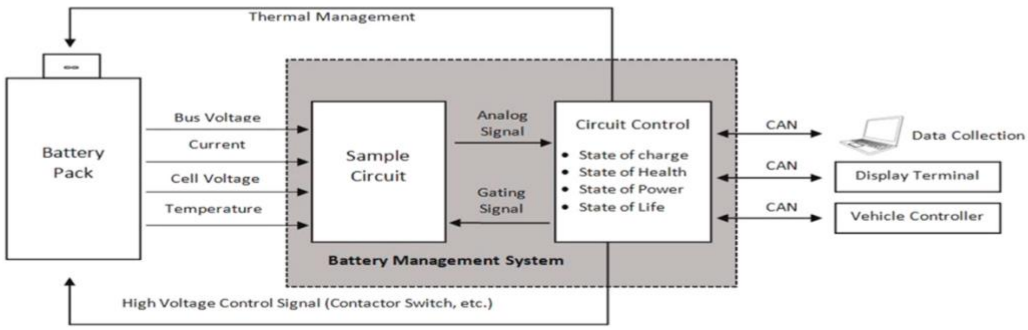


Figure 29 A general diagram of a BMS [31]

**Functionality & required features of the BMS.**

A minimum set of features are essential in designing a BMS. The BMS should have the capability to carry out cell level voltage monitoring, a series string level current sensing, and the ability to monitor an appropriate number of thermal sensors designed into the battery pack. The BMS not only monitors but should also control any off-nominal conditions of current, voltage, and temperature and provide suitable methods to keep them in control. This may require removing power to the application or stopping the battery charge to maintain the battery in a safe state. Apart from this, BMS functions should include cell balancing capability when the battery has more than one cell and it is in a series configuration. Most BMSs can provide the state of charge (SOC) and state of health (SOH) of the battery. The SOC determination is very critical as it provides information on capacity left which indirectly provides the time that a load can be supported for and it can also provide information on how long a subsequent charge would take. The SOH is an indication of the condition of a battery in use compared to its condition when it was new or fresh. The SOH is critical in determining the battery's capability in delivering the required loads. This will also provide information on whether maintenance cycles are required for the long-duration battery. The BMS provides the optimum charging algorithm based on the SOC and SOH of the battery. This will allow the charging to be adjusted to allow for low charge rates for low SOC batteries to prevent large inrush currents and cause high temperatures in the cells and battery. The BMS should have access to charging cells or modules individually or bypassing failed or problematic cells or modules inside a battery pack. The BMS should also have the capability to record the data at the relevant frequency to determine any excursions beyond the specified tolerances for voltage, current, and temperature as this will be very important whenever an investigation is to be carried out after a failure.

Some BMS designs maintain a record of the cell specifications as given by the manufacturer that includes the model number and capacity, the lot number, date of manufacturing, and similar battery details. This provides a method for traceability in the event of cell or battery failures. The BMS should be capable of having its software updated as required. A compatible and strong communication interface between the BMS and the system with which it is being charged or discharged will help to provide updates to the software for factors such as diagnostics, safety control settings, etc.

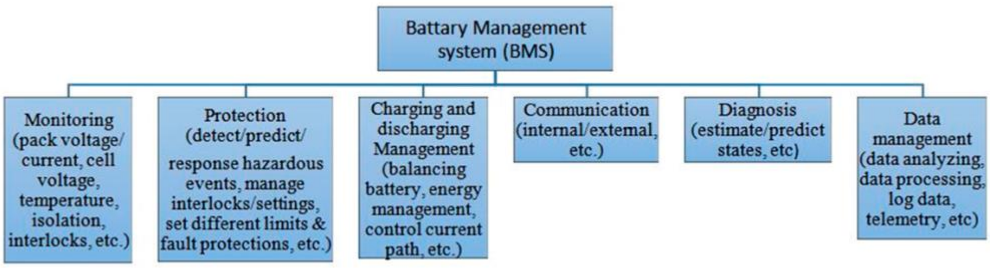


Figure 30 BMS functionalities [32]

All BMS should be designed with a 'smart' circuit board that allows for individual cell/cell bank voltage, series string current, and temperature monitoring in the battery. This requires the inclusion of voltage, current and thermal sensors in the battery and BMS as a unit. The BMS should be capable of providing overvoltage and under-voltage as well as overtemperature cut-off thus preventing the battery from going into an unsafe condition. And lastly, the BMS should have cell balancing capability.

Table 9 Comparison between commercially available BMS [33]

| Features | Orion BMS | Lithiumate Pro | MK 3*8 | Mini BMS |
|---|---|---|---|---|
| Overcharge/discharge, thermal & overcurrent protection | Capable | Capable | Capable | Capable |
| Cell & Pack Health Monitoring | Capable | Capable | In capable | In capable |
| Cell balancing | Capable | Capable | Capable | Capable |
| Field Programmable | Capable | Capable | Capable | In capable |
| SOC monitoring | Capable | Capable | Optional | Separate |
| Charge/discharge current limits | Capable | Capable | In capable | In capable |

Only a high-level voltage BMS has internal communication, low-level centralized ones simply measure cell voltage by resistance divide. A distributed or modular BMS must utilize a low-level internal cell controller for modular architecture or implement controller-to-controller communication for a distributed architecture. However, such communication is difficult, especially in high voltage systems, due to the voltage shift between cells. What this means is that the ground signal in one cell may be hundreds of volts higher than that of the next cell. This issue can be addressed using software protocols or using hardware communication for volt-shifting systems. There are two methods of hardware communication—using an optical-isolator or wireless communication. Another factor hampering internal communication is the restriction of the maximum number of cells that can be used in a specific BMS architectural layout. For instance, for modular hardware, the maximum number of nodes is 255. Another restriction affecting high voltage systems is the seeking time (for reading voltage/current) of all cells, which limits bus speeds and causes loss of some hardware options.

**Optimal Energy Utilization**

Battery management systems keep the battery safe, reliable, and increase the senility without entering a damaging state. Different monitoring techniques are used to maintain the state of the battery, voltage, current, and ambient temperature. The BMS communicates with the onboard charger to monitor and control the charging of the battery pack. It also helps maximize the range of the vehicle by optimally using the amount of energy stored in it. It is a crucial component in electric vehicles to ensure that batteries do not get overcharged or over discharged, thus avoiding damage to the battery and harm to occupants. The battery is a fundamental component of the electric vehicle, which represents a step forward toward sustainable mobility. The battery management system is a critical component of electric and hybrid electric vehicles.

## 5.7 Issues and Challenges of BMS

**SOC Estimation Issues**

SOC estimation is very critical, however, estimating SOC accurately is very challenging due to the high nonlinearity characteristics of EVs. Coulomb counting is one of the easiest approaches, but it has many issues such as initial SOC errors, current measurement and integration errors, uncertainty about battery capacity, timing oscillator errors, etc. Similarly, the open circuit voltage (OCV) approach cannot be used in real time as the battery needs to rest before the OCV can be measured, due to the relaxing effect, etc. Similarly, errors in the parameter estimation, voltage and current measurement errors, effects of aging and temperature are other issues with the OCV approach. Similarly, the electrochemical impedance spectroscopy (EIS) approach requires a longer time and is costly. Therefore, the existing approaches have many challenges and SOC estimation under realistic conditions has not been broadly done. The most difficult job is to estimate SOC by using a low cost BMS which should have small memory storage, but fast speed.

**Real-Time SOH Estimation Issues**

Real time SOH estimation is an open challenge as current approaches do not estimate battery health precisely. Existing model-based approaches have many limitations and do not predict the health status accurately. Similarly, data driven approaches have issues such as different training and machine learning methods. Therefore, the available options are to replace the battery prematurely impacting financial burden to owner and too much waste in the environment or wait for a complete failure which enhances the safety issues.

**Optimal Charging Problem**

Battery charging techniques are less efficient, less safe, and take lot of time as compared to refuelling combustion engine cars. Constant trickle current is the common method for charging, but it uses low current which takes long charging time. By increasing charging current the time to charge a battery can be decreased, but it may increase the battery OCV above than safety threshold and generate heat. Traditional battery charging approaches have many limitations as shown in Table 10. [32]

Table 10 Comparison of charging methods [32]

| Approach | Issues |
|---|---|
| Constant current (CC) | Low capacity utilization |
| Constant current (CC) | Battery lattice may collapse |
| Constant current-constant voltage (CC-CV) | Balancing issues for charging speed, energy loss & temperature variations |
| Multi stage constant current (MCC) | Balancing issues for charging speed, capacity utilization & battery lifetime |

**Fast Characterization**

SOC and SOH are two important offline characteristics required in a BMS, but it is very time consuming and real time estimations have many issues. For real time SOC estimations by simple OCV-SOC models reduces accuracy, accumulates different errors from other estimated parameters, etc. These OCV models also cover the estimated SOC range depending on the battery usage pattern and do not cover the entire SOC range which can only be achieved by a complete charge/discharge profile. Similarly, SOH characterization is almost impossible in real-time.

**Existing Battery Models Issues**

Generally, physical methods (equivalent models, electrochemical models, etc.), data driven methods, and hybrid methods are used to characterize batteries in a BMS. However, these models have many issues as presented in Table 4. For physical approaches, exact conditions are required for the conduction of different tests which is not possible in different environments. Data driven methods have higher computational complexity and performance depends on the test data and training approaches. Although many new intelligent techniques/algorithms have been developed for efficient BMS, these approaches also have many challenges.

**Data Abundance, Variety, and Integrity Issues**

Data abundance and data variety are the main challenges in executing intelligent algorithms in battery models as the accuracy of these approaches depends on these factors. However, it takes a lot of time to collect a large amount of diverse data which also increases the computational complexity and leads to over-fitting issues due to the training time extension. Similarly, data integrity is another issue as the existing data base has a permanent charge/discharge pattern and temperature conditions used in a laboratory environment. Moreover, battery test benches used in laboratories suffer from equipment precision, noise impact, and electromagnetic interference issues, etc. Therefore, BMS evaluation under various changing conditions is needed in real world environments.

When it comes to assessing mechanical abuse in the Battery Management System (BMS) of electric vehicles (EVs), there are specific considerations and suggestions to ensure the system's reliability and safety. Some Key points:

**Sensor Integration:**

Integrate additional sensors within the BMS to monitor mechanical parameters relevant to abuse, such as acceleration, vibration, and shock. These sensors can provide real-time data on the vehicle's mechanical behaviour and help detect any abnormal or abusive events.

**Fault Detection and Diagnostics:**
Develop algorithms and software within the BMS to detect faults or anomalies associated with mechanical abuse. Implement robust diagnostic capabilities that can identify issues like excessive vibrations, impacts, or structural deformation.

**Data Logging and Analysis:**
Incorporate data logging capabilities within the BMS to capture relevant information during abusive events. Analyse the logged data to identify patterns or trends that may indicate mechanical abuse and assess its impact on the battery system.

**Threshold Monitoring:**
Set predefined thresholds for mechanical parameters, such as acceleration or vibration levels, within the BMS. Continuously monitor these parameters and trigger warnings or protective actions when the thresholds are exceeded, indicating potential abuse.

**Communication and Reporting:**
Establish a communication protocol between the BMS and other vehicle systems to report mechanical abuse events. Enable the BMS to communicate with the vehicle's onboard diagnostics system, alerting the driver or service technician about detected abuse.

**System Protection and Response:**
Develop strategies within the BMS to protect the battery system when mechanical abuse is detected. Implement response mechanisms such as reducing power output, activating emergency shutdown procedures, or notifying the driver to mitigate potential damage.

**Robust Design and Testing:**
Ensure the BMS is designed to withstand mechanical abuse itself, including vibrations, impacts, and environmental conditions. Conduct rigorous testing and validation of the BMS under various abusive scenarios to verify its reliability and durability.

**Continuous Improvement:**
Regularly update and improve the BMS based on the insights gained from monitoring and analysing mechanical abuse data. Incorporate feedback from real-world abuse incidents to enhance the BMS's ability to detect and respond effectively.

# 6. Conclusion

## 6.1 Summary of the study's key findings

As lithium-ion batteries find increasing popularity, safety concerns characterized by the thermal runaway event have become a life-threatening issue in many applications and have become a major challenge for industry. Many feasible solutions for detecting a thermal runaway process are based on monitoring certain characteristic fault signals, including the terminal voltage, the surface/inner temperature, and the vented gas. For the terminal voltage and surface temperature monitoring method, improving the precision of voltage sensors and temperature sensors in the BMS can enhance the thermal runaway detection accuracy. In addition, both the hardware and software solutions can be designed to optimize the sensor array topology with a minimum number of sensors and an intelligent measurement/control strategy.

The causes of thermal runaway of lithium-ion batteries are mainly divided into mechanical abuse, electrical abuse, and thermal abuse. In the process of thermal runaway caused by these 3 abuse conditions, a series of uncontrollable exothermic reactions are the key to causing thermal runaway, including the decomposition of SEI, the reaction between the anode and the electrolyte, the reaction between the cathode and the electrolyte, the decomposition of the electrolyte, etc. In addition, the thermodynamic parameters such as the initial temperature, heat release rate, and heat release amount of each side reaction are summarized, which lays a theoretical foundation for the production design of lithium-ion batteries and the development of thermal runaway prediction methods.

Similarly, for the internal state prediction method, it is necessary to improve the detection resolution and the high temperature resistance of sensors embedded in the battery, as well as the sealing of the lithium-ion battery packaging, to ensure the electrolyte will not leak. Finally, the internal state prediction method can be coupled with BMS to establish a more accurate risk assessment model for thermal runaway of lithium-ion batteries. Monitoring the thermal runaway process with gas sensors has been shown as a more effective method than with voltage sensors or temperature sensors. However, depending on the working principle of a specific sensor, such as the electrochemical or semiconductor gas sensor, etc., there are still many sensor-related problems including the low detection accuracy, the complex gas cross-interference, and the gas sensor poisoning.

Therefore, the development of new types of portable gas sensors, such as the MEMS micro-optical gas sensor, can be beneficial in generating an accurate early-warning signal for applications involving lithium-ion batteries that can run into a thermal runaway problem.

The purpose of monitoring and detecting the status of lithium-ion batteries is to warn the potential risk of a thermal runaway event in lithium-ion battery systems. Apart from these monitoring schemes, more attempts can be also made to improve the inherent safety of the lithium-ion battery itself, such as using safer materials and improving the quality of the preparation process. In addition, many protection measures can be also designed at the battery system level by adopting more effective heat dissipation and heat isolation methodologies to restrain the occurrence and the spread of thermal runaway events.

From the material point of view, to further improve battery safeties, the cathode material with a higher heat resistance and the anode material capable of suppressing the accumulation of lithium dendrites are vital goals for the next-generation electrode materials. Most of the recent research work on the non-flammable electrolyte are focused on the flame-retardant additive, which would help decrease the conductivity of the electrolyte and inhibit the formation of the SEI layer on the anode surface, but it comes with a cost of decreasing the coulombic efficiency of lithium-ion batteries.

Therefore, the main goal for developing the future non-flammable electrolyte would be ensuring the high flame retardancy of the electrolyte and improving the stability of the electrolyte and anode interface, and enhancing the battery coulombic efficiency.

Furthermore, in terms of improving the heat dissipation and thermal isolation technologies, it is necessary to improve the performance and reliability of the cooling design with an effective mechanical structure. Ultimately, with the proper implementation of the measures, only minor temperature deviations will be present among all of the battery cells in a lithium-ion battery system.

## 6.2 Contributions to the field of EV safety

High safety is a critical feature for the promotion of electric vehicles, and the thermal runaway risk of lithium-ion batteries determines the safety of electric vehicles. In this thesis, the thermal runaway mechanism of lithium-ion batteries is expounded, and a variety of thermal runaway predictions and early warning methods for lithium-ion batteries are summarized and analysed. It is common understanding that a severe single cell TR failure in a battery system, while rather improbable, cannot be completely eliminated. Nevertheless, there is a clear need for reliable batteries and components. As a consequence, such scenarios should be addressed when evaluating battery safety. One approach for assessing related risks further is a thermal propagation test.

There was general agreement about the need for a harmonised definition of thermal runaway. Possible criteria for such definition include temperature increase rate, occurrence of venting, fraction of converted energy of overall cell's chemical energy content. A more detailed understanding of the mechanisms of thermal runaway might make also feasible to have several sub-definitions for discriminating between different types of thermal runaway.

Thermal propagation testing and standardisation needs as there is no single, clearly defined single cell TR failure scenario, it seems most useful to develop a thermal propagation test of general robustness versus a single cell thermal runaway test. No reliable and practical method exists to create on demand internal shorts in Li-ion cells (single cell failure) that produce a response that mimics field failures. Heating is the initiation method suggested in most standards, but at the same time there is a potentially strong influence of the utilised initiation method on the outcome of the TP thermal propagation test. Therefore, the selection of a suitable initiation method is crucial. Besides the scenario starting for a single cell failure, other scenarios include multiple cell failure (due to BMS failure, mechanical crash), and the TR propagation from such scenario may be more difficult than from a single cell, however, propagation protection and testing may be important. There is agreement that further pre-normative research is required to develop fit for-purpose testing methods and standards. In this context there is also the need to address the question on which level (cell, module, pack, complete product) a test can and should be performed to provide representative results for assessing safety in the actual application.

Testing parameters, comparability, and reproducibility of testing There has been identified a wide variability in the pass/fail criteria requirements in various standards, which does not favour comparability of testing. Another important consideration concerns the significance of the outcome of a thermal propagation test: whether propagation occurs depends mainly on the difference between heat introduced in and heat removed from a neighbouring cell. From a statistical point of view, this is a difficult situation as a relatively small change in heat flow (in or out) can change the test outcome. Consequently, it must be evaluated carefully how often a test needs to be repeated to receive a reliable test result and thereby a relevant confirmation of a certain level of safety. Even though many standardisation efforts have been on-going in the recent past, current standards still typically allow for different initiation methods and test details (location of initiation cell) are not always defined. Further work is required to define standardised abuse testing methods regarding thermal propagation.

Gas and toxicity consideration More information on physico-chemical properties and behaviour of vented gas during thermal runaway and propagation are necessary. Such information is not only relevant for understanding the energy transfer during thermal propagation, but also to assess risks that first responders or firefighters would encounter in severe battery safety events. Other areas for further research are the impact of oxygen availability inside the battery enclosure and the effect of ignition of exhaust gases on thermal propagation. It remains unclear if an external spark source should be applied during thermal propagation testing as spark sources are additional risk scenarios and impose additional technical hurdles but may be representative of a realistic scenario.

Impact of aged systems It is a common challenge for product developers, that even shorter battery development cycles are required to be competitive in a fast-changing market. At the same time the long-term reliability of offered products must be ensured. In battery abuse tests, big differences in test outcomes have been observed-while not consistently-between EOL and BOL cells. Therefore, thermal propagation testing seems also advisable on aged systems also in view of potential second use scenarios. On the other hand, such tests are difficult to realise within the rather short development cycles and lead to extra costs.

Simulation and modelling Progress in modelling has made simulation of abuse testing more representative of real tests and thereby more relevant. Modelling efforts can support thermal propagation testing (for selection of an initiation cell).

Early detection tools There is a need for more accurate and faster early detection tools, which could allow control of certain safety events at an even earlier stage (before thermal runaway occurs). Further research efforts in this direction seem justified and promising.

Mitigation approaches There is a general belief that some cathode materials are 'safer' than others; however, an overall safety assessment is required. Solid state batteries (SSB) may change the game with respect to safety: as there is no longer any liquid flammable electrolyte. However, rapid reactions are favoured between sulphur and lithium and other hazards will become apparent, such as fusion of cells, hindered thermal energy dissipation, etc. so the risk of TP might not be fully eliminated Many other developments also might help reducing the consequences or eliminating the actual occurrence of TR in conventional LIBs in terms of electrode/electrolyte composition, separator characteristics, use of thermally resistant materials, etc.

The mitigation of risks related to thermal propagation requires a holistic view of cell, module, pack, and application. Defining measures on one level-independent of the other levels-may lead to high cost and/or limited increase in safety. Nevertheless, for the near and medium term avoiding thermal propagation will be a key challenge for making Li-ion battery systems safer and the development of suitable tests is of high importance.

# 7. References


[1] Sanguesa, Julio A., Vicente Torres-Sanz, Piedad Garrido, Francisco J. Martinez, and Johann M. Marquez-Barja. “A Review on Electric Vehicles: Technologies and Challenges.” *Smart Cities* 4, no. 1 (March 2021): 372–404. https://doi.org/10.3390/smartcities4010022.

[2] “EV-Volumes - The Electric Vehicle World Sales Database.” Accessed April 10, 2023. https://www.ev-volumes.com/.

[3] “Alternative Fuels Data Center: How Do All-Electric Cars Work?” Accessed April 10, 2023. https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work.

[4] “Key Components for a New Era – the Battery System.” Accessed April 10, 2023. https://www.volkswagenag.com/en/news/2019/12/key-components-for-a-new-era--the-battery-system.html.

[5] ResearchGate. “Fig. 2. (a) Thermal Runaway Positive Feedback Loop; (b) Qualitative...” Accessed April 10, 2023. https://www.researchgate.net/figure/a-Thermal-runaway-positive-feedback-loop-b-Qualitative-interpretation-of-the-chain_fig2_340469570.

[6] “H.B. Fuller.” Accessed April 10, 2023. http://www.hbfuller.com/en/eimea.

[7] “To Fight EV Fires, Focus Is on Early Detection of Battery Cell Thermal Runaway.” Accessed April 10, 2023. https://www.avnet.com/wps/portal/us/resources/article/to-fight-ev-fires-focus-is-on-early-detection-of-battery-cell-thermal-runaway/.

[8] ResearchGate. “Figure 2. Abuse Conditions Leading to Thermal Runaway [7].” Accessed April 10, 2023. https://www.researchgate.net/figure/Abuse-conditions-leading-to-thermal-runaway-7_fig2_348887693.

[9] “Thermal Runaway Mechanism of Lithium Ion Battery for Electric Vehicles: A Review - ScienceDirect.” Accessed April 10, 2023. https://www-sciencedirect-com.ezproxy.biblio.polito.it/science/article/pii/S2405829716303464.

[10] “Battery Thermal Management System - an Overview | ScienceDirect Topics.” Accessed April 10, 2023. https://www-sciencedirect-com.ezproxy.biblio.polito.it/topics/chemistry/battery-thermal-management-system.

[11] Tran, Manh-Kien, Manoj Mathew, Stefan Janhunen, Satyam Panchal, Kaamran Raahemifar, Roydon Fraser, and Michael Fowler. “A Comprehensive Equivalent Circuit Model for Lithium-Ion Batteries, Incorporating the Effects of State of Health, State of Charge, and Temperature on Model Parameters.” *Journal of Energy Storage* 43 (November 1, 2021): 103252. https://doi.org/10.1016/j.est.2021.103252.

[12] “Fighting Thermal Runaway in Electric Vehicle Batteries.” Accessed April 10, 2023. https://www.powersystemsdesign.com/articles/fighting-thermal-runaway-in-electric-vehicle-batteries/22/13991.

[13] “Battery Thermal Management System - an Overview | ScienceDirect Topics.” Accessed April 15, 2023. https://www-sciencedirect-com.ezproxy.biblio.polito.it/topics/chemistry/battery-thermal-management-system.

[14] “Electric Vehicle Battery Cells Explained | Laserax.” Accessed April 10, 2023. https://www.laserax.com/blog/ev-battery-cell-types. (figure 4-5-6)

[15] Szabo, Ioan, Liviu I. Scurtu, Horia Raboca, and Florin Mariasiu. “Topographical Optimization of a Battery Module Case That Equips an Electric Vehicle.” *Batteries* 9, no. 2 (February 2023): 77. https://doi.org/10.3390/batteries9020077. (figure 7)

[16] “Troubleshooting Thermal Design of Composite Battery Enclosures,” May 18, 2022. https://www.compositesworld.com/articles/troubleshooting-thermal-design-of-composite-battery-enclosures. (figure 8)

[17] “Fire & Thermal Runaway Propagation Challenges in EVs & Mitigation Methods - .” Accessed April 10, 2023. https://etn.news/e-mobility-blogs/fire-thermal-runaway-propagation-challenges-in-evs-mitigation-methods.

[18] Essl, C., A. W. Golubkov, and A. Fuchs. “Comparing Different Thermal Runaway Triggers for Two Automotive Lithium-Ion Battery Cell Types.” *Journal of The Electrochemical Society* 167, no. 13 (October 2020): 130542. https://doi.org/10.1149/1945-7111/abbe5a. (30)

[19] Lalinde, Iñaki, Alberto Berrueta, Juan José Valera, Joseba Arza, Pablo Sanchis, Alfredo Ursúa, Iñaki Lalinde, et al. *Perspective Chapter: Thermal Runaway in Lithium-Ion Batteries*. IntechOpen, 2022. https://doi.org/10.5772/intechopen.106539.

[20] “Stages of The Thermal Runaway Process in Lithium Batteries.” Accessed April 11, 2023. https://sinovoltaics.com/energy-storage/batteries/stages-of-the-thermal-runaway-process-in-lithium-batteries/.

[21] “Advances in Prevention of Thermal Runaway in Lithium-Ion Batteries - McKerracher - 2021 - Advanced Energy and Sustainability Research - Wiley Online Library.” Accessed April 15, 2023. https://onlinelibrary.wiley.com/doi/full/10.1002/aesr.202000059.

[22] Uzair, Muhammad, Ghulam Abbas, and Saleh Hosain. “Characteristics of Battery Management Systems of Electric Vehicles with Consideration of the Active and

Passive Cell Balancing Process.” World Electric Vehicle Journal 12, no. 3 (September 2021): 120. https://doi.org/10.3390/wevj12030120.

[23] B. M. Kopf, F. R. Kalhammer, D.H. Swan, V.P. Roan, and M.P. Walsh, "Status and prospects for zero emissions vehicle technology," 2007. (3)

[24] Doron Aurbach et al. "Design of electrolyte solutions for Li and Li-ion batteries: a review," Electrochimica Acta, vol. 50, pp. 247-254, 2004, Polymer Batteries and Fuel Cells: Selection of Papers from First International Conference.

[25]. Liao, Zhenghai, Shen Zhang, Kang Li, Guoqiang Zhang, and Thomas G. Habetler. “A Survey of Methods for Monitoring and Detecting Thermal Runaway of Lithium-Ion Batteries.” Journal of Power Sources 436 (October 1, 2019): 226879. https://doi.org/10.1016/j.jpowsour.2019.226879.

[26] ResearchGate. “Fig. 1. Thermal Runaway Process within a Single Cell.” Accessed April 10, 2023. https://www.researchgate.net/figure/Thermal-runaway-process-within-a-single-cell_fig1_341562984.

[27] Omariba, Z.B.; Lijun, Z.; Dongbai, S. Review on Health Management System for Lithium-Ion Batteries of Electric Vehicles. Electronics 2018, 7, 72.

[28] “New Registrations of Electric Vehicles in Europe.” Accessed April 15, 2023. https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles.

[29] Laserax. “Electric Vehicle Battery Cells Explained.” Laserax, May 6, 2022. https://www.laserax.com/blog/ev-battery-cell-types.

[30] Xiong, R.; Jiayi, C.; Quonking, Y.; Hongwen, H.; Sun, F. Critical Review on the Battery State of Charge Estimation Methods for Electric Vehicles. IEEE Access 2018, 6, 1832–1843.

[31] Ouyang, Dongxu, Mingyi Chen, Que Huang, Jingwen Weng, Zhi Wang, and Jian Wang. “A Review on the Thermal Hazards of the Lithium-Ion Battery and the Corresponding Countermeasures.” Applied Sciences 9 (June 18, 2019): 2483. https://doi.org/10.3390/app9122483.

[32] Keerthi, Sravan Kumar. “Battery Management System in Electric Vehicles.” Accessed May 6, 2023. https://www.cyient.com/blog/battery-management-system-in-electric-vehicles.