SAFETY OF ELECTRO MOBILITY - WHITE PAPER OF THE FISITA INTELLIGENT SAFETY WORKING GROUP

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ABSTRACT

Battery electric vehicles and plug-in hybrid electric vehicles experienced significant increases in sales volume, reaching a worldwide market share of 7% of all newly registered vehicles by the middle of 2021. One of the central challenges of this paradigm shift lies in the safety aspects of electric vehicles and their components. For vehicles with combustion engines, safety aspects have been carefully investigated over decades, standards, regulations, test requirements and system limitations are widely established and acknowledged by vehicle manufacturers, suppliers, government authorities, NGOs and customers. For electric vehicles, this process has just started; yet its objective must be to establish a comparable level of safety taking in consideration the specific needs of those vehicles and their individual risk assessment.

This paper represents a pre-publication of a White Paper on the Safety of Electromobility, to be published by FISITA, the Fédération Internationale des Sociétés d´Ingénieurs des Techniques de l´Automobile. The chapters are designed by dedicated experts from all around the globe and from a variety of institutions within the engineering society under the umbrella of FISITAs Intelligent Safety Working Group ISWG. The White Paper is supposed to be published in autumn, 2023 during the FISITA World Congress in Barcelona and it summarizes the current state of the art as well as new research results for safety aspects during the product lifecycle of electric vehicles and their components. The book will be a precious handbook for all those who develop, produce, use, repair or work otherwise with vehicles with high voltage batteries and powertrains.

The structure of the White Paper follows the product lifecycle and covers the safety aspects for all phases in the following chapters:

- EV-components,
- Manufacturing,
- Use & Operation,
- Repair, Inspection, Maintenance and Service,
- Crash protection,
- Thermal events prevention or control,

- Rescue,
- Cyber Security,
- End-of-Life, Second Life of batteries and Recycling.

In separate chapters the specific Insurance aspects and the use of CAE for safety development, validation and verification are addressed. Last but not least the White Paper will give a forecast on future challenges in this area and also provide references to existing standards and best practices.

In this pre-publication the focus lies on the two chapters “Crash protection” and “Thermal events prevention or control”. Other chapters are planned to be pre-published during the time frame between today and autumn 2023.

INTRODUCTION

The Fédération Internationale des Sociétés d´Ingénieurs des Techniques de l´Automobile (FISITA) brings together the global automotive mobility sector to share ideas and advance technological development for the automotive industry. FISITA’s mission is to help create efficient, affordable, safe and sustainable automotive transportation, serving a global forum between engineers, industry, government, academia, environmental and standards organizations.

Within FISITA, the Intelligent Safety Working Group ISWG represents a global network of safety engineers, providing a platform for a precompetitive exchange of safety relevant information and experience in order to further improve traffic safety. In 2020 FISITA ISWG published a first White Paper on the safety aspects of Assisted and Automated Driving (Reference OP2020-1 F 0-01) including “Golden Guidelines” for the development and use of automated driving functions. The response to this publication was a motivator for the ISWG to start working on a second White Paper, this time focusing on the safety aspects of electric vehicles.

Battery electric vehicles and plug-in hybrid electric vehicles experienced significant increases in sales volume, reaching a worldwide market share of 7% of all newly registered vehicles by the middle of 2021. One of the central challenges of this paradigm shift are the safety aspects of electric vehicles and their components. For vehicles with combustion engines, safety aspects have been carefully investigated over decades; and so, the standards and limitations are widely acknowledged by original equipment manufacturers (OEM), suppliers, public authorities, and customers. For electric vehicles, this process has only started; yet its objective must be to establish at least the same level of safety.

The purpose of this White Paper is to document and inform the community about all of the potential impacts of Electric Vehicles (EVs) on the global stage, comprehensively covering topics ranging from manufacturing, operation, maintenance, repair, safety, cyber security, end of life and insurance.

Electric Vehicle technology eliminates some of the safety concerns of conventional vehicles powered by internal combustion engines (ICE) like gasoline leakage or fuel tank bursts as a consequence of e.g. a vehicle crash. But yet it brings its own specific safety relevant concerns e.g. due to the high voltage system with 400 V or more, its energy density or the vulnerability of the batteries.

Safety requirements for EVs should consider the differences between the two. The selection of appropriate crash load cases for conventional ICE vehicles strives for a deformation characteristic, which allows for good restraint system performance on the one hand and at the same time assures a sufficient fuel system integrity to avoid car fires. Some of the standard crash load cases are therefore defined to damage sensitive areas where there is a risk to penetrate fuel system components and the integrity of the fuel system is demanded. In the case of electric vehicles the potentially critical areas may be at different locations, the possible measures to protect electric components is different to the protection of e.g. fuel hoses and specific crash tests are required to assure a comparable level of safety for these vehicles. (Plug-In) hybrid vehicles are a mix of both worlds: the safety engineers must protect both the gasoline as well as the electric components.

Another example is the difference in the effort necessary to de-energize the two vehicle variants: for an ICE vehicle it is sufficient to reliably empty the gasoline tank and the subsequent gas hoses from flammable liquids and vapor. In practice it is much more difficult to de-energize an electric battery e.g. on the scene or in a repair shop. A clear guideline is necessary for service technicians, rescue teams, recycling mechanics or even a normal user to ensure a safe operation and handling of this system in every situation.

This White Paper shall serve as a handbook for all safety related topics in the design, manufacturing, use, service, repair, inspection, rescue, and even the re-use of vehicles with electric energy motors. We concentrate on passenger cars in this document, and it describes the state-of-the-art in this topic. To do so, we started from a full vehicle perspective, identified, or defined requirements on this level and then broke them down to subsystem or component level. In the automotive industry this approach is well known as the V-Model: define the overall objectives, create specific requirements for subsystems or components, develop those with clear and designated specifications and then go back up for the verification and validation on component, subsystem, system to full vehicle level, again.

The White Paper is focused on passenger cars in this edition. Trucks, buses, construction vehicles etc. might have different, specific requirements and options. This is also the case for some parts of Fuel Cell Electric Vehicles (FCEV): the safety aspects of e.g. fueling and the storage of Hydrogen gas is of very high importance and would demand a long and extensive discussion. This discussion was excluded from this White paper and maybe subject to a subsequent edition. The Fuel Cell converts the chemical energy of hydrogen and oxygen into electricity. From this point on an FCEV can be seen like an EV: managing and storing the high voltage power is comparable to the situation in a BEV or a PHEV. The capacity might be smaller, but the basic principle is the same.

Within the ISWG FISITA brought together a group of distinguished experts from all areas relevant to the topic. These experts serve as chapter leaders for their specific areas of expertise, formulate the story line of the chapters, call authors, review their contributions, and edit the full work product. This White Paper is perfect example of the kind of teamwork practiced in FISITA. Academia, industry, legal authorities, member societies, and others work together for the good.

The chapters of the White Paper are based on the life cycle of electric vehicles, from manufacturing all the way to their second life, end of life or recycling. One might miss a chapter on the development of vehicles. In the course of the chapter definition, the editorial team decided against such an explicit development chapter because nearly everything would have landed here: nearly every safety risk can be re-assigned to an inappropriate or missing action during the development. It was decided to allocate these aspects along their most relevant situations of occurrence. Potential risks during the recycling of electric vehicles for example are addressed in the end-of-life chapter.

The publication of the full White Paper is planned for September 2023 during the 39th FISITA World Summit in Barcelona. Two chapters of the full White Paper are published in this contribution to the 27th ESV Conference on the Enhanced Safety of Vehicles, focusing on the aspects of crash safety and the prevention of thermal events in the high voltage batteries. Other pre-publications of individual chapters are planned for the year 2023.

USED ABBREVIATIONS

EV - Electric Vehicle, general
xEV - Electric Vehicle of any type (BEV, PHEV, …)
BEV - Battery Electric Vehicle, pure electric motor
PEV - Plug-In Electric Vehicle
PHEV - Plug-In Hybrid Electric Vehicle, combination of ICE and EV
ICE - Internal Combustion Engine, conventional gasoline or Diesel engine
FCEV - Fuel Cell Electric Vehicle, Electricity produced from redox reaction of Hydrogen and Oxygen
FISITA - Fédération Internationale des Sociétés d´Ingenieurs des Techniques de l´Automobile
ISWG - (FISITA) Intelligent Safety Working Group
HV - High Voltage (e.g. 400/800V)
HVS - High Voltage System
LV - Low Voltage (e.g. 12/24/48V)

PART 1: CRASH SAFETY OF BATTERY ELECTRIC VEHICLES

INTRODUCTION

Current status of E-mobility

In 2020, electric mobility appeared to have made its final breakthrough. Global EV sales reached three million vehicles in 2020 and jumped in 2021 to more than six million vehicles. The global market has reached the level of 7% of all new registrations by the middle of 2021. Such rapid growth in market penetration left both the general public, and to some extent also vehicle safety experts, scrambling for answers regarding real world electric vehicle safety performance and specifics.

Besides reasons such as the offer and costs of vehicles available, vehicle range and charging infrastructure, a further topic discussed very critically in the media up to now has been crashworthiness, leading to pronounced uncertainty on the part of customers and also rescue organizations. Almost every single case where an electric vehicle has been involved in an accident has been reported on in great detail, including speculation about the danger of the occupants and emergency services/ rescue workers receiving electric shocks. Similarly, a significantly increased risk of fire in electric vehicles has been presumed based on some individual vehicle or battery fire events and reports.

At present, the proportion of electric vehicles on the roads is still too low to make many statistically robust observations about EVs in terms of crash safety. However, enough accidents have so far been recorded and evaluated to at least establish that there have been no major or unexpected safety abnormalities specific to EVs. For example, electric shocks as a result of an accident have not occurred yet. For design reasons, they are also fundamentally highly unlikely to occur.

In addition to a still small but growing statistical evidence, the intensive educational work on battery fires is also gradually bearing fruit among the first responders, especially firefighters. The initially strong uncertainty has given way to the realization that during a rescue operation, electric vehicles fundamentally do not need to be dealt with any differently than conventional vehicles. For example, in the event of a fire, water is the most suitable extinguishing agent, and if a vehicle needs to be opened with a cutting tool, there is typically no reason to fear an electric shock.

Confidence in the safety can also be seen in the results of crash safety rating tests. In recent years, a large number of electric vehicles, hybrid vehicles and even fuel cell vehicles have undergone several global consumer metric testings. The results are largely comparable to the tests of conventional vehicles. In fact, the Insurance Institute for Highway Safety (IIHS) in the USA has reached the following conclusion: "With more electric vehicles comes more proof of safety." To quote IIHS President David Harkey [1]: "It’s fantastic to see more proof that these vehicles are as safe as or safer than gasoline- and diesel-powered cars." “We can now say with confidence that making the U.S. fleet more environmentally friendly doesn’t require any compromises in terms of safety.”

These statements are based on an analysis of insurance data carried out by the Highway Loss Data Institute (HLDI), which confirms an analysis conducted back in 2012 that found that the risk of injury and the consequential costs of accidents involving hybrid vehicles are 25% lower than with gasoline vehicles. The analysis compared hybrid vehicles and combustion-engine-only vehicles that were built on the same platform. According to the analysis, the main reason for the apparent better occupant safety performance of the hybrid vehicles is the greater vehicle weight [2]. However, later in this chapter we discuss why this is not the sole reason those electric vehicles provide occupant safety performance that is at least comparable to that of conventional vehicles.

Generally, there is still a permanent improvement of crash behaviour ongoing from vehicle generation to vehicle generation and modern EV’s belong to the latest and advanced vehicle designs. That vehicle safety is not a concern of the drivetrain was demonstrated by different OEM’s, e.g. Mercedes-Benz at the VDI-Conference in Berlin 2022 [3].

New safety concerns

Compared with gasoline vehicles, electric vehicles have some fundamental technical differences relevant to crashworthiness:

- Battery instead of a fuel tank
- E-Motors instead of a combustion engine

- High-voltage components instead of mechanical or low voltage auxiliary systems
- High-voltage lines instead of fuel lines.

Due to these distinguishing features, the following additional safety challenges have to be considered:

- Packaging, rigidity, weight of new components due to the influence in structural safety and crash characteristics
- The need for prevention of electric shocks and short circuit by the HV system
- The risk of fire generation within electric energy storage systems
- Bursting and explosion risks of gas tanks in fuel cell electric vehicles.

Fire events involving the highly prevalent Lithium-Ion type of batteries have been attracting the attention of mass media. The resulting media reports may have caused concerns among first responders, especially among fire fighters. Thanks to emerging field event studies as well as growing education efforts on part of OEMs and research institutions, these concerns are being addressed.

Beside some others, the National Transportation Safety Board (NTSB) investigated some vehicle fire incidents of electric vehicles in the USA [4] and came to following findings due to safety risks to emergency responders from Lithium-Ion battery fires in electric vehicles:

1. Manufacturers' emergency response guides provide sufficient vehicle-specific information for disconnecting an electric vehicle's high-voltage system when the high-voltage disconnects are accessible and undamaged by crash forces.
2. Crash damage and resulting fires may prevent first responders from accessing the high-voltage disconnects in electric vehicles.
3. The instructions in most manufacturers' emergency response guides for fighting high-voltage lithium-ion battery fires lack necessary, vehicle-specific details on suppressing the fires.
4. Thermal runaway and multiple battery reignitions after initial fire suppression are safety risks in high-voltage lithium-ion battery fires.
5. The energy remaining in a damaged high-voltage lithium-ion battery, known as stranded energy, poses a risk of electric shock and creates the potential for thermal runaway that can result in battery reignition and fire.
6. High-voltage lithium-ion batteries in electric vehicles, when damaged by crash forces or internal battery failure, present special challenges to first and second responders because of insufficient information from manufacturers on procedures for mitigating the risks of stranded energy.
7. Storing an electric vehicle with a damaged high-voltage lithium-ion battery inside the recommended 50-foot-radius clear area may be infeasible at tow or storage yards.
8. Electric vehicle manufacturers should use the International Organization for Standardization standard 17840 template to present emergency response information.
9. Action by the National Highway Traffic Safety Administration, similar to that taken by the European New Car Assessment Program Euro-NCAP, to incorporate scoring relative to the availability of a manufacturer's emergency response guide and its adherence to International Organization for Standardization standard 17840 and SAE International recommended practice J2990 into the US New Car Assessment Program, would be an incentive for manufacturers of vehicles sold in the United States with high-voltage lithium-ion battery systems to comply with those standards.
10. Although existing standards address damage sustained by high-voltage lithium-ion battery systems in survivable crashes, as defined by federal crash standards, they do not address high-speed, high-severity crashes resulting in damage to high-voltage lithium-ion batteries and the associated stranded energy.

REQUIREMENTS AND LOAD CASES FOR THE HV SYSTEM IN ELECTRIC VEHICLES

Requirements and corresponding load cases for crashworthiness are defined by legislators, consumer protection organizations and the individual OEMs.

Legal Crash Tests

There are many laws and regulations regarding crashworthiness that must be fulfilled before a passenger vehicle can be approved for sale in a market. Some of them contain requirements for HV-systems. The overview below lists examples of the most design-determining laws in terms of HV safety during crash.

Table 1.
Examples of laws with HV requirements

Market	**Organisation**	**Law**
Europe / United Nations	UNECE	ECE-R 94/137/95/135*/153
USA	NHTSA	FMVSS 305
China	Guobiao	GB/T 31498-2021
Korea	MLIT	KMVSS Art.91 Cl.4
Japan	Jasic	Trias 17(2)-J111(2)

*upcoming: (GRSP) Proposal for the 02 series of amendments to UN Regulation No. 135 (Pole side impact) [5]

The laws contain chemical/thermal, mechanical and electrical requirements for the HV system which are displayed in Table 2.

Table 2.
Examples for legal HV requirements

	Markets				
requirements after crash	Europe (UNECE)	USA (NHTSA)	China (Guobiao)	Japan (Jasic)	Korea (MLIT)
chemical / thermal					
electrolyte spillage (do not exceed a certain amount)	x	x	x	x	x
no fire / explosion (no uncontrolled electric arc or short circuit)	x	x	x		x
mechanical					
REESS retention (no loss of the mechanical connection)	x	x	x	x	x
Electrical (one criteria must be met)					
voltage level (below 60VDC or 30VAC)	x	x	x	x	x
electrical isolation (more than 500Ohm/V)	x	x	x	x	x
physical barrier (IPxxB fullfillment)	x	x	x	x	x
residual energy (less than 0,2J system energy)	x		x		

*REESS – rechargeable electric energy storage system

Figure 1 shows an overview of the required load cases to validate the regulations for the beforementioned markets.

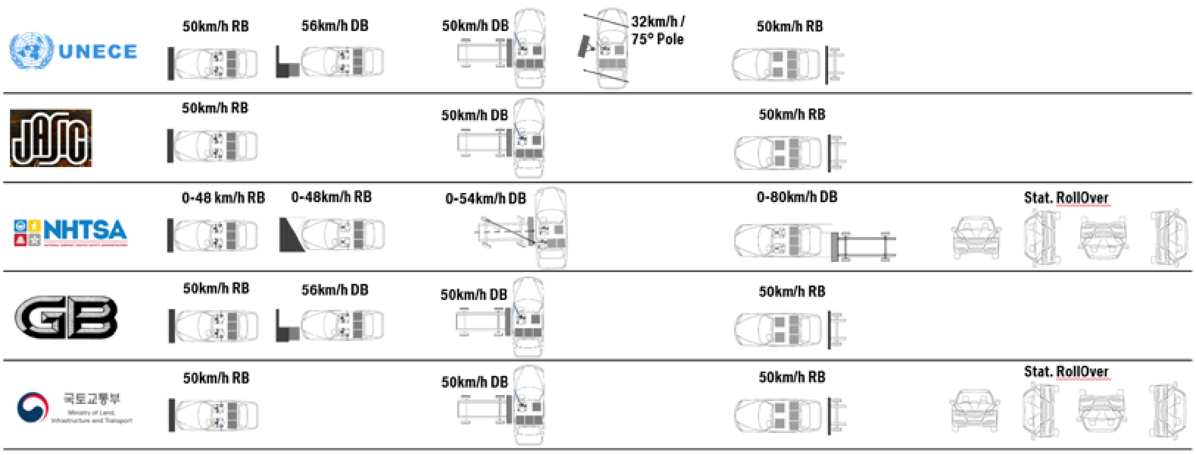


Figure 1. Examples for HV relevant legal load cases (pictograms taken from [6])

Consumer Rating Crash Tests

Most consumer rating organisations use the same or very similar HV requirements to those from the legislators, shown in Table 2. However, load cases can differ significantly in their general configuration and speed. Examples are the ‘new car assessment programs’ (NCAPs) from USA, Japan, Europe or China. The following table gives an overview about the load case configurations for some organisations.

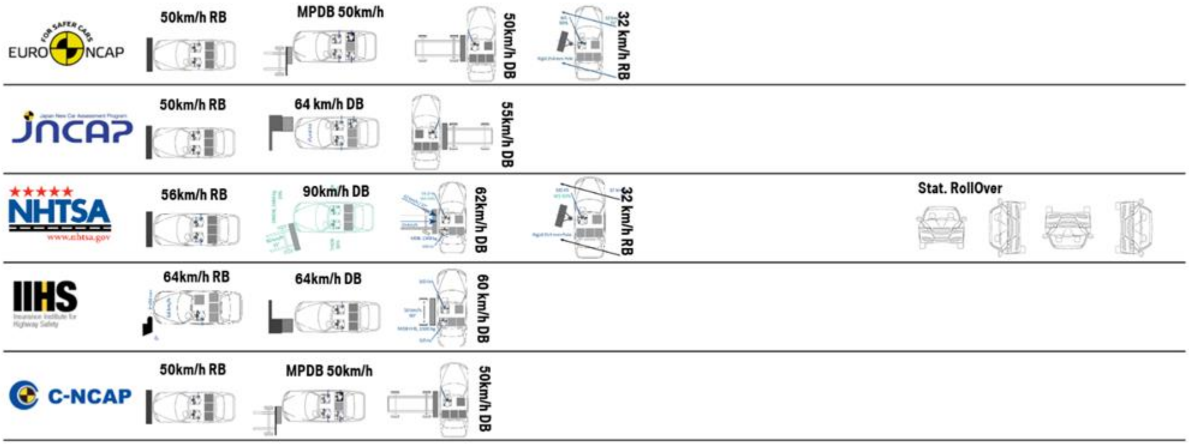


Figure 2. Examples for HV relevant consumer rating load cases (pictograms taken from [6])

Duty of Care Crash Scenarios

The existence of legal and consumer rating crash tests does not abolish the duty of OEMs to carefully observe their products in the field and to define further requirements and load cases if necessary. A Field data analysis can provide the probabilities for an impact with respect to the opponent size, mass, speed, direction, and impact position. Crash scenarios with a certain field relevance must then be assessed in terms of their risk for the occupants which can depend on the vehicle concept. A crash scenario that only implies a low risk within an ICE vehicle might be critical in a BEV and vice versa.

An example for an OEM duty of care crash scenario is the frontal pole impact. For BEVs, many OEMs consider side pole impacts on the entire length of the HV battery.

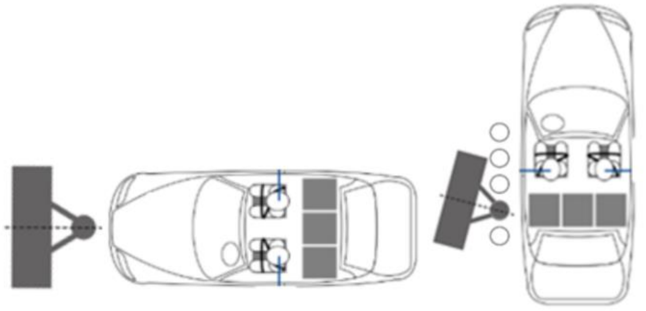


Figure 3. ***Front and side pole impacts (pictograms taken from [6])***

Abuse Tests

A mayor abuse scenario with a high risk for the REESS are bottom impacts when the vehicle runs over, falls on or hits obstacles like stones, lost components from other vehicles or curbs. Figure 4 shows a schematic illustration of how to validate the energy storage device with the aid of various geometric structures that impact the underbody of the vehicle.

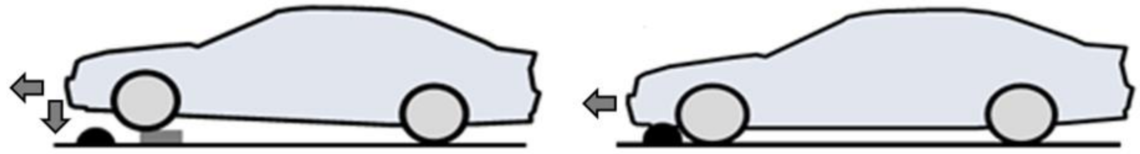


Figure 4: Examples for HV relevant consumer rating load cases

CRASH STRATEGY FOR ELECTRIC VEHICLES

The crash strategy of an electric vehicle has to balance three conflicting objectives:

1. Risks from the HV system shall be minimized. There are 4 major risks that have to be considered:
    - a mechanical load on the battery cell might cause electrolyte spillage or a thermal event in the REESS,
    - a short circuit in the HV system might cause a thermal event,
    - uninsulated live components could be touched by passengers or first responders,
    - a short circuit between HV and LV system could lead to a loss of all critical functions e.q. post-crash functions.

   Those four risks lead to two important design objectives for electric vehicles:
    I. Battery cells must be kept free of mechanicals loads that cause thermal events or electrolyte spillage.,
    II. Components of the HV system must be kept free of mechanical loads that cause insulation faults before they are disconnected from electrical energy supplies (e.g. REESS) and sufficiently discharged.
2. Availability of vehicle shall be maximized. Crashes with low severity should not lead to a breakdown of the vehicle but allow for further usage.
3. Space and material usage for the protection of HV components shall be minimized. Mechanical protections of HV components are heavy and stand in conflict with the objective to design light and efficient vehicles.

Those objectives can be translated to three safety design principles for electric vehicles that help to solve the conflict of goals:

1. Battery cells should be placed in the core zone of the vehicle where lowest mechanical loads appear.
2. All parts of the HV system should be placed as close as possible to the core zone of the vehicle.
3. Components of the HV system that are not placed in the core zone of the vehicle should be disconnected from electrical energy supplies and discharged as soon as possible after detecting a crash with medium or high severity.

The following picture illustrates the relationships of vehicle zones, protection areas, crash severity and HV shutdown within the crash strategy for electric vehicles. The states and terms mentioned here will be described in more detail below.

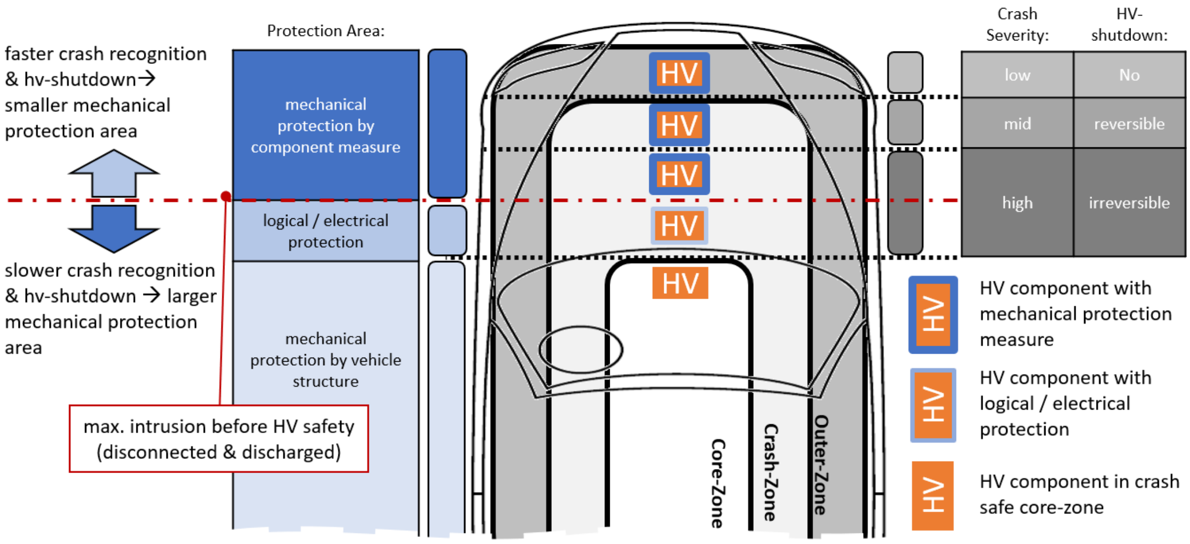


Figure 5. Crash Strategy for electric vehicles (example frontal crash)

Low Severity Crash:
In a low severity crash without damages to the HV-system, there is no need for a HV-shutdown. In this case, e.g. a low speed bumper damage, the customer is able to drive his car to a save place or even keep using it without further restriction. Deformation only appears in the outer zone of the vehicle. If placed in that zone, HV components need a mechanical protection to avoid electrical risks and to ensure functional availability after crash. Vehicle manufactures try to avoid HV components in that zone.

Medium Severity Crash:
In a medium severity crash with a possible damage of the HV-system, a reversible HV-shutdown is executed. A medium severity crash can also go along with an airbag ignition but must not. In a medium severity crash scenario, e.g. a rear-end collision in stop and go traffic, the customer is able to start the HV-system again, if the automatic HV safety check during restart is ok. The customer has the possibility to drive his car to a save place or to continue his journey and drive to a car workshop. Deformation reaches to the outer part of the crash zone. HV components in that zone need a mechanical protection because they are exposed to load before they are cut of and discharged as well as to ensure further availability after crash.

High Severity Crash:
In a high severity crash with a probable destruction of the HV-system, an irreversible and yet faster HV-shutdown should be commanded. It separates the HV-system from the battery and discharges all remaining energies as fast as possible. A high severity crash normally goes along with an airbag ignition. The vehicle cannot be restarted again. Deformation reaches up to the inner part of the crash zone. HV components in that area might not need a mechanical protection when they are disconnected and discharged before they are exposed to critical mechanical loads (see red line in Figure 5). Depending on the overall damage of the vehicle, the HV-System might be repaired at a workshop.

The OEM implements this strategy by designing an appropriate vehicle structure with concerted geometric locations for the HV components, designing mechanical component protections and by implementing logical as well as electrical safety measures. The following three subchapters explain the mechanical, electrical and logical safety mechanisms in more detail.

Structural / Mechanical safety mechanisms

Architectural implications: Currently, hybrid vehicles are generally based on vehicle platforms for combustion powered vehicles that are then, if necessary, selectively reinforced to account for the additional vehicle weight. Especially beneath the passenger compartment, those load path are not able to ensure broad non-deformation zones for the battery cells while dealing with the significantly higher vehicle weights. Within classical vehicle architectures, battery packs will therefor contain additional load path (lengthwise, crosswise or even both). This reduces the available space for cells which have to be placed between the load path as smaller modules.

Even in the case of many electric vehicles to date, an all-electric drivetrain is still implemented in conventional vehicle structures. One example of such a convertible concept is shown in Figure 6.
With a special tubular frame it is possible to support both the electric motor of the front wheel drive and also the

other HV components while acting as a protective structure for them in the event of a collision. In terms of the bodyshell structure, it is possible to use, among other things, the mounting points of the conventional drive unit including transmission, which is no longer needed in an electric vehicle.

This design means the crash kinematics of a conventional drive unit incl. backward displacement and support in the vehicle tunnel during a frontal impact can be simulated to a very large extent. The load paths present in the basic vehicle can thus also be used effectively in the electrical variant [3].

As the electric drive motor is significantly smaller, there is nevertheless a greater clearance in front of the motor. In the event of a frontal impact, this results in a more harmonious characteristic, an acceleration level that rises in a controlled manner, and 25% more deformation overall.

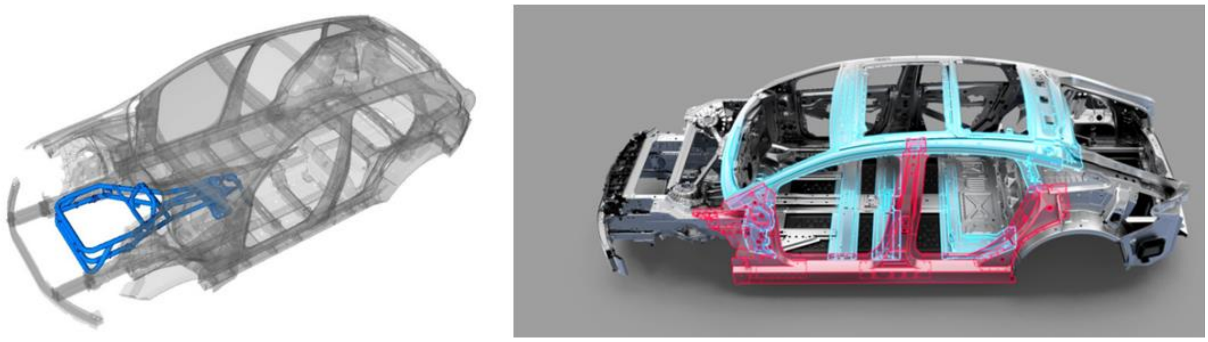


Figure 6. Comparison of Convertible (EQC) vs Purpose Platform (EQS)

In the event of a side impact, the side pole impact represents the main challenge for the accident safety of electric vehicles, as the nature of the battery layout in the underbody makes a direct impact to the battery almost unavoidable. Serious damage to the battery can lead to uncontrolled chemical or electrical reactions in the battery. In the car shown in Figure 6 this challenge is solved by a crash structure integrated in the battery housing that absorbs the impact energy while protecting the interior of the battery from damage.

The crash characteristics of a side pole impact are diametrical to those of a frontal impact. Due to the rigid battery that is firmly fixed to the underbody, the deformation path is reduced almost by half when compared with a conventional vehicle. By contrast, when it comes to the vehicle acceleration, there is a higher acceleration peak in an early crash phase. However, this higher acceleration does not negatively affect the loads on the occupants. The overall outcome is in fact positive since the additional clearance between the occupants and the door permits undisturbed deployment of the sidebags.

The battery itself contains additional energy absorbers that go beyond load conditions in the lab and are intended to provide an additional reserve in the event of potentially greater accident severities in real accidents.

In the future, newer models of electric vehicles will be based on separate electric platforms (Figure 6). Known as the "purpose concept", this has the advantage that the bodyshell structure can be consistently designed for the integration of an all-electric powertrain. In particular, this new architecture takes into account a flat floor concept designed to accommodate an underbody battery in an optimum manner. A center tunnel for housing a transmission and a propeller shaft can be omitted from electric vehicles completely. Two-wheel and all-wheel drive is implemented by the integration of one or two electric motors directly in the front axle/front and rear axles. The large, flat underbody battery can thus be connected to the vehicle structure in a stable and highly integrated manner. This results in significant advantages in terms of durability, rigidity and crashworthiness. The vehicle center of gravity is significantly lower, thus reducing, for example, the risk of rollover in the event of an accident.

In the event of a side impact, and in particular in the event of a side pole impact, intrusions are reduced further as a result of the stable unit of the battery and the underbody. The mounting frame integrated in the battery housing for fastening the battery can be designed as an energy-absorbing crash structure. This allows more installation space to be made available to accommodate battery cells in the battery housing. Due to the highly stable nature of the battery housing, intrusions into the housing during a pole impact can be kept to a minimum.

General Package concept for HV vehicles: Over 50 years of real-life accident research by different OEMs and institutes involving thousands of investigated accidents has led to what is known as a protection zone concept specially developed for electric vehicles. In this concept, the vehicle is divided into three areas:

- Outer zone: Vehicle damage with low accident severity featuring what is known as minor damage, which does not lead to crash recognition and therefore does not lead to an automatic shut-off of the HV system. In this case, the HV system must retain full functional availability in the event of damage.

- Crash zone: The HV system is switched off once the accident severity is sufficient to trigger the occupant protection system. Depending on the accident severity and degree of damage, a distinction could be made between a reversible shut-off (reactivation of the HV system by the customer is possible) and an irreversible shut-off (reactivation of the HV system is no longer possible).

- Core zone: Vehicle areas in which damage is less likely. In crash tests, only very little or no deformation usually occurs here. This area is ideal for accommodating the HV battery and particularly sensitive components.

Inherent stability of HV components: If in individual cases, HV components are accommodated in the outer deformation areas where reliable HV deactivation is not yet ensured, the safety of these components is increased by ensuring that the housings fulfill a minimum requirement for mechanical stability. For this purpose, a damage pattern and load level are derived from the crash simulations and crash tests. For the corresponding HV component parts, the presence of contact protection must be ensured as a minimum. The requirements for the intrinsic mechanical safety of the HV batteries are particularly stringent. Here, alongside the standard crash tests, further load cases are also used to cover real-life accidents to an even greater extent. The need for particular, mechanical protection of HV-components in the crash zone can be reduced by fast cut of times of the battery pack and fast discharge times of the capacitors in the HV-components.

High-voltage line protection: All HV components are connected with each other via high-voltage lines. High-voltage lines are flexible lines that in some cases can be routed inside structural areas. Although this usually involves two separate lines, they can be provided with a shield in particularly sensitive areas in addition to the insulation in order prevent a loss of insulation if crushed. Besides their inherent stability, the degree of protection provided to other HV component parts can also be increased further through the use of deflecting surfaces or protective panels.

Electric Safety mechanisms

Insulation: The high-voltage on-board electrical system (HV system) is fully insulated from the vehicle structure. That means that all HV lines are electrically insulated with a shielding. Hence, there is no possibility that anyone can touch the high voltage live parts. In addition, the orange color of the sheathing indicates that there are HV live parts inside.

Figure 7. HV-lines with orange warning colour

All live parts of HV components are also protected from contact by an appropriate housing. These housings are equipped with a corresponding warning message so that it can be recognized as an HV component.

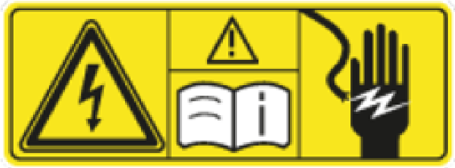


Figure 8: Warning message on HV components

Electric separation: The galvanic isolation of the HV storage from the rest of the HV system after the HV active state has ended (e.g. driving) ensures that no more electrical energy can flow from the HV storage system to the HV system. The energy already stored in the intermediate circuit capacities is reduced by a suitable discharge function and there is therefore no longer an electrical hazard in this area. The AC and DC charging lines are also only active in charging mode via HV switches. After charging, they are opened and discharged again. As a result, there is no more energy in the charging lines.

IT-Network: All HV components are connected to each other with both a positive and a negative line. In contrast to conventional 12 V on-board electrical systems, there is therefore no connection to the vehicle body. This type of network is called IT network (Isole Terra, French). Even in the event of damage to the positive or negative line, there is no risk of electric shock or short circuit, as there is not a closed circuit in this case either. So the IT network is error-tolerant against direct contact. There is no electric shock possible by touching the positive or negative side and the car body simultaneously.

Potential equalization: Due to the network type (IT network) used, it is possible to set up potential compensation across all HV lines and HV components via the vehicle body. All housings of HV live components and all the shieldings of the HV lines are connected to each other via a very low resistance across the vehicle body. If both the positive and negative sides of the HV system are damaged, the energy flows off via this low-resistance short circuit. The human body has a much higher transition resistance than the potential equalizer. This ensures that there is no electrical shock hazard for a person when the vehicle is touched in this state.

Logic Safety mechanisms

Monitoring: The entire HV system, especially the battery, monitors itself constantly. Fault currents are detected and displayed at an early stage through continuous temperature monitoring, insulation and short-circuit measurement. For example in the event of serious faults, such as very high short-circuit currents, the system can also protect itself and open the circuit irreversibly via a pyrofuse. All HV components are connected via what is known as an interlock circuit, which monitors whether all the component parts of the HV system are connected correctly. Depending on the fault identified in the HV system, it is either displayed, the component part concerned is prevented from starting again, or the HV system is even switched off.

HV Crash-shutdown: As soon as a certain accident severity is detected in an impact, the HV system is switched off automatically. When this happens, the high-voltage battery relays are opened to prevent further power supply to the HV system. In order to reduce the residual voltage in the high-voltage intermediate circuit to a level of < 60 V DC as quickly as possible (< 5 seconds), HV components with high energy content, e.g. the electric motor or the power electronics, can be actively short-circuited at the same time. This is done by switching on a resistor, through which the current can quickly flow away and be turned into thermal energy. The use of multi-stage occupant protection systems makes it possible to distinguish between reversible or irreversible HV shut-off. If, in the event of less severe accidents, the vehicle still needs to be operational, a reversible shut-off means that the HV system can be switched back on. A reversible shut-off is a precaution triggered by simple shut-down signalling. An insulation test takes place prior to switching the HV system back on. If the insulation test does not detect an insulation fault, the switching back on of the HV system is permitted. In severe accidents, after which there is no way the journey can be continued, the HV system is irreversibly switched off through the ignition of one or several pyrofuses. In addition to the HV crash shutdown via the airbag control unit during normal driving, measures are integrated to trigger a HV shutdown of the high-voltage system in the event of a crash during vehicle standstill (e.g. HV charging, remote software update, use of digital media while standstill).

Manual shut-off points for emergency services: In addition to the automatic crash shut-off, it is possible to switch off the vehicles manually using what are known as rescue shut-off points. For this purpose, redundant options are available via a 12 V switch and an additional 12 V cable loop that can be simply cut. The installation locations are documented in the rescue data sheets. These options are also used during towing away after an accident if the vehicle is only slightly damaged and it cannot determined without doubt if an automatic crash shut-off has occurred.

HVS Intrinsic safety: The above-mentioned safety mechanisms in the event of a crash are supplemented by safety functions that ensure the intrinsic safety of the HV system. These are of course also active in the event of a crash if crash shutdown detection is defective. These functions , e.g. HV short-circuit monitoring or isolation monitoring, which switches off the HV system in case off fault.

OCCUPANT AND PEDESTRIAN SAFETY

The combination of limited energy density of EV batteries and the demand for increasing driving range leads to large battery installations often dimensionally overlapping with the occupant compartment: the EV batteries can be commonly found in the occupant compartment floor, under the seats, in the floor tunnel, etc., as shown in Figure 9. This overlap, as well as the need to minimize battery intrusion in crash events, typically leads to reduced intrusions into the occupant seating areas if compared to non-EV vehicles, especially in load cases where intrusion is the primary cause of occupant loading, like the side pole impact.

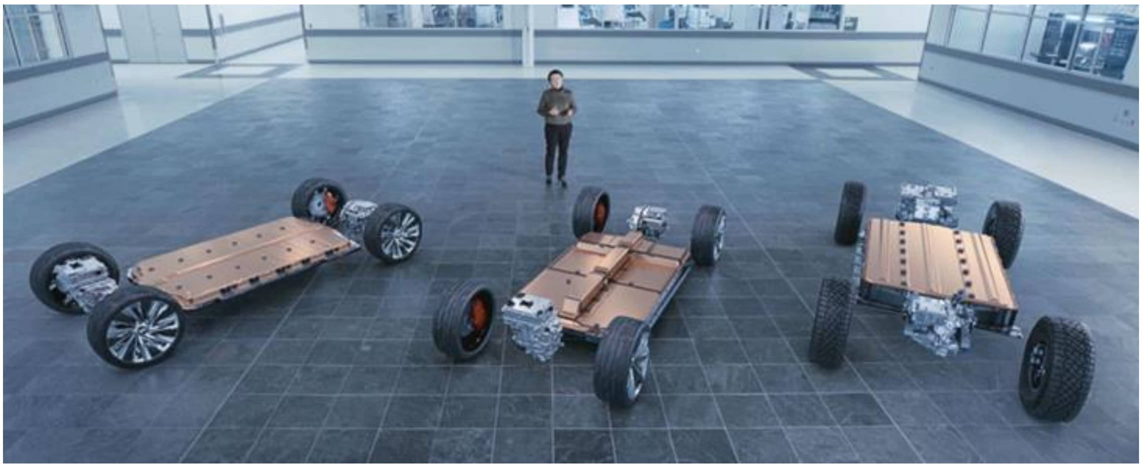


Figure 9: In passenger vehicles, EV battery installations often overlap with occupant compartment footprint

Large EV batteries also often increase mass of EVs when compared to their non-EV peers [7]. Higher vehicle mass has implications for occupant protection. Heavier vehicles tend to have an advantage in car-to-car impacts, providing lower severity crash pulse to its occupants and more severe pulse to the occupants of the lighter vehicle [7]. It remains to be seen if larger penetration of EVs in the global fleet will lead to a more asymmetric distribution of masses in vehicle-to-vehicle crashes.

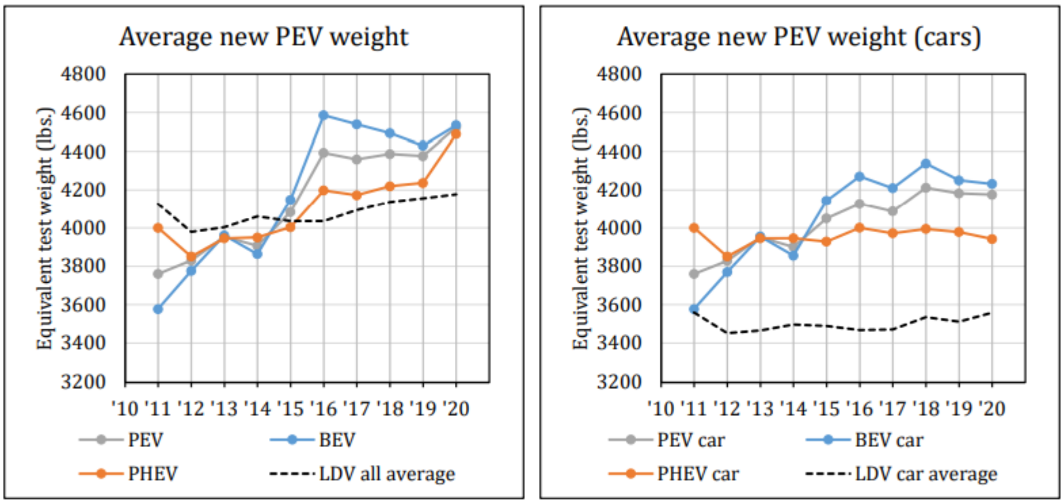


Figure 10: Average new PEV equivalent test weight compared with all LDV. All size classes – left, cars only – right [7]

In conventional vehicles, the internal combustion engine, transmission, drive-shaft and other components can limit the available crush space in severe crashes. The front compartments of EVs typically contain smaller components which may allow designing the vehicle structure for more occupant friendly acceleration pulse in full frontal impacts into a flat rigid barrier. The benefits of such improved pulse characteristics in real world car-to-car collisions needs to be researched and better understood.

The recent rise of EVs coincides with the rise of many new active safety features as well as advanced occupant sensing and occupant restraint technologies. These technologies reduce the risk of a crash event happening as well as the risk and severity of injuries in crash and other events. Even though these technologies are not specific to EVs, they will significantly contribute to overall EV safety performance improvements.

EV propulsion architecture also affects the under-hood compartment layout. Maintaining clearance between the hood and hard components under the hood is important for providing sufficient energy absorption distance for the head of the impacted pedestrian. For example, a sports car with conventional propulsion could face a challenge in this respect because of stacking a large engine under a typically low hood with crank shaft box, engine block, cylinder head and intake manifold taking a lot of space vertically. EVs can bring more flexibility in arranging the under-hood components. On the other hand, some EVs have a luggage compartment under the hood, creating a possibility of hard objects stored there, potentially requiring additional design considerations relevant to pedestrian safety.

Another component of pedestrian safety is related to the low noise emission of the EVs at low speeds when compared to typical ICE vehicles, making them less likely to be noticed by pedestrians and bicyclists. A number of regulatory requirements have emerged around the globe in the past two decades requiring EVs to produce acoustic alerts or warning sounds. Various aspects of this EV feature are still being researched, like optimal sound patterns, intensity and direction, environmental noise pollution, etc.

VERIFICATION/VALIDATION

Even in the age of computer simulations, testing remains indispensable to ensure the high level of occupant safety and partner protection. It became increasingly clear that the development tools for vehicle safety need to be elevated to a new level. Therefore, an increase in the number of load cases that need to be physically crash tested to represent the future road accidents may be expected.

For future car concepts a flexible and efficient crash track concept is needed that not only offers the possibilities of conventional crash tests, but also the prerequisites for new test arrangements such as, for example:

- Crash tests with electric vehicles and other alternative powertrains
- Process optimisation of the entire testing and measuring operation for improving the quality and shortening the preparation and analysis times
- HV battery testing at component and vehicle level

Crash Testing aspects

Electric and hybrid vehicles are assessed and tested as any other transport vehicle of the same category to fulfil with the safety standards. Nevertheless, they have a potential danger in specific cases such as severe crashes due to the risk of electric shock, electrolyte spillage or thermal runaway from the HV battery.

Overall, a huge number of crash test configurations are possible. Testing vehicles equipped with charged lithium-ion batteries or with filled hydrogen introduce very specific requirements for occupational and fire safety and the correspondent testing procedures. In more detail, the laboratory requirements expected for the electric and hybrid crash test performance must include:

- Conventional fire extinguisher at every crash location
- CO2 extinguishing systems at every crash location
- Fireproof blanket to cover the vehicle or HV battery in case of temperature increase or fire
- Smoke extraction flaps
- Gate and door concept for fire and explosion protection
- Depressurization openings for explosion protection
- Jet nozzles at exposed crash points for extreme air mixtures
  to inhibit the formation of explosive mixtures of gasoline, hydrogen, etc.
- Remote-controlled reconnaissance/measurement robots for safe detection of hazards
- Telescopic loader for removing damaged cars
- Water basins for damaged vehicles containing Li-ion batteries
- High-voltage garages for safe, supervised storage of HV crash vehicles after crash testing
- Wireless temperature monitoring systems
- Implications to workshops and laboratory layout (sled setup for ECE R100, battery tear down)
- Hydrogen detectors
- Pressure measurements

- Workshops adaptations – Emergency door to outdoors, extraction system, smoke and fire detection, temperature control
- Crash area adaptation – Emergency door to outdoors, extraction system specially designed for a very fast extraction, smoke and fire detection, temperature control
- Quarantine areas – enclosed areas with flooding system, smoke and fire detection and extinguishing, temperature control
- HV battery storage

According to legal and consumer standards, people safety is guaranteed. The crashworthiness evaluation of EV does not only require preparation of EV measurements, it is also recommended to adapt the layout of the testing facilities but also the deployment of enhanced safety standards during the whole process. Live voltage implies a high risk to all workers involved in the crash test and, therefore, specific safety protocols have to be implemented to guarantee the treatment of vehicle samples to minimize risks in the test preparation, its execution and the post-crash activities.

Main risks of EV are:

- Electric shock
- Fire or smoke

In addition to all the safety procedures described below, the main safety recommendation is the staff training. EV training should be developed by experts and according to the tasks of each worker. Safety training and protocols should be given to all workers without exception.

All EV process should be done considering the two main risks associated to High Voltage and Chemical processes of the lithium-ion batteries. On one hand, Electric shock; all the vehicles should be instrumented with HV harness measurement. Moreover, workers should wear appropriate PPEs and follow internal procedures.

On the other hand, fire or smoke risk; HV batteries temperature should be controlled using appropriate equipment. It is very important to monitor temperature after a crash test to avoid damages in case of thermal propagation. It is also strongly recommended to wear clothes capable to protect against a sudden flame, at least, during crash test and first minutes after crash test. Safety procedures for each test phase are described below.

Test vehicle preparation

Loading / unloading: Vehicle loading/unloading should be done taking into account that most of the HV batteries are located at the vehicle floor, between the wheels. So that, it is very important that, if you use a forklift, to use appropriate separators with the forklift shovels to avoid applying pressure to the HV battery cover. Also, it is recommended to transport the vehicle with the HV system safely disconnected. It is also important to take into account that when disabling HV system, vehicle wheels could be blocked. It is strongly recommended to use trucks with lateral dock.
After unloading the vehicle, it would be important to mark the vehicle as Electric or Hybrid or Hydrogen.

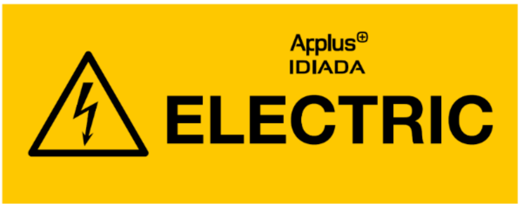


Figure 11: Label used to identify electric vehicles when unloaded into the crash facilities

Vehicle battery charging: Vehicle charging should be done according to the vehicle development stage. When vehicle is a prototype, there could be some safety requirements not 100% operational so the charging should be done under supervision. Also, charging facilities should has some detection and extinguishing mechanisms to avoid fire spread to other facilities.

Vehicle disconnection: Before any preparation, vehicle should be disconnected in such a way that it is impossible to energize powertrain cables. There are two types of disconnection: Mechanical device that separates HV Battery from HV Battery output cables and electric switch that controls High Voltage Battery relays through Low Voltage lines. It is very important to put up poster signalling the vehicle status: connected or disconnected. The vehicle should remain disconnected until the test execution to guarantee workers safety.

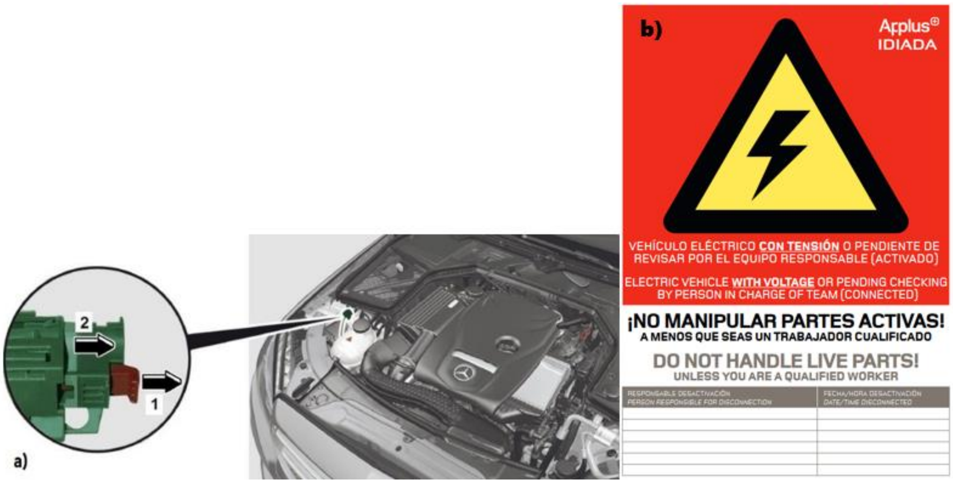


Figure 12: (a) Switch to connect and disconnect the high voltage system of the vehicle [12]. (b) Example poster to be attached on the exterior part of the vehicle indicating the presence of high voltage system activated.

Safety measurements after instrumentation: Previously, legal and consumer standards were explained. Those standard requirements are to measure HV at powertrain lines. For this reason, special instrumentation of HV is necessary. Special cabling should be used to powertrain lines and it is the responsibility of the test facilities staff to verify their correct operation. Also, sensors for data acquisition should be tested and verified.

Activation previous to crash test: Crash test performance: A display is mounted in the outer part of the vehicle to know if the voltage of the HV battery is higher than the 60V allowed. Moreover, an extra switch has to be installed in the vehicle and a temperature monitoring system has to be installed to identify any fire risk.

Safety protocol: The safety protocol is a special procedure for electric vehicles to guarantee workers safety during and after the crash. This protocol is life, meaning that all the time is improving with new experiencies.

Before the crash test, a meeting is organized to order all the actions to the people that should be during the safety protocol. During this meeting, it is formed a team of 8 people divided in 4 sub-team:

- Measurement team: 1 measurement leader and 2 measurement assistants. The team mission is to measure voltage values after the crash and verify the vehicle safety.
- Evacuation team: 1 emergency leader and 1 driver. The team mission is to lead the emergency protocol and vehicle extraction outdoors in case the measurement team advise of any problem.
- Car adjustment team: 1 adjustment leader. The team mission is to make adjustments with HV activated in the vehicle.
- Firefighters: 2 professional firefighters subcontracted. The team is supervising the test, analyzing if there is any hazard and, in case of emergency, to lead the fire extinguishing.

During the meeting, all the actions to be performed during standard safety protocol are named and ordered to the workers. It is very important to know which actions should do every worker and the precise order of the actions.

Besides the specified actions, all the workers received EV training related to the protocol, so that, they already know the PPEs and specific tools they should use during the protocol. To summarize it:

- PPEs
  - Fireproof and chemical protection clothes
  - Dielectric gloves
  - Mechanical cover for dielectric gloves
  - Firefighter helmet
  - Isolated shoes
- Protection tools:
  - Dielectric harness
  - Dielectric carpet
- Measurement tools:

  - Thermal camera
  - Voltmeter
  - Megaohmeter
  - Known resistance box

Once all the workers involved in the process are ready, the display is connected to verify its correct operation. Also, temperature monitoring system is turned on to verify the temperature of the HV battery. Finally, the HV system is activated and voltage values and isolation resistance of the vehicle is verified. Once all safety devices are tested, the crash test can be performed.

After the crash, first people to be near to the vehicle are measurement team. Their actions are:

- Verify there is no smoke or fire
- Spread dielectric carpets at the measurement area
- Make voltage and resistance measurements
- Push emergency button to open battery relays (if vehicle has not disconnected after the crash)

Once the measurements are performed, the measurement leader allows to hook the vehicle with the extraction cable. The extraction cable is attached to a forklift outside of the lab. In case of emergency, the forklift can pull the vehicle out of the lab using guiding pulleys. The forklift is driven by evacuation driver.

During 15 minutes after the crash, a quarantine period is stablished. During that 15 minutes, only people using appropriate clothes and tools can be near the vehicle. From crash test until the vehicle is outside of the building, wireless measurement of battery temperature is controlled and monitored through control room staff, specially during the first 15 minutes.

Evacuation team is double checking vehicle temperature using a thermal camera. The team leader is connected with a telephone with the driver and with control room and it is in charge of the vehicle evacuation in case of fire or smoke anomaly.

Emergency protocol: The emergency protocol is the result of some possible problems that can appear and some experiences with EV crash test.

Before mention the different emergencies that can appear, it is very important to know clearly the rescue priority:

1st: PEOPLE

2nd: FACILITIES

3rd: EQUIPMENT

It is also very important to analyze the risks to anticipate the emergency protocol to be performed. The main risks are:

- Electrocution
- Battery temperature increase
- Smoke
- Fire
- Explosion
- Chemical burn because of battery liquids

Emergency protocol cases:

1) No absence of voltage (electrocution)
   After the crash test, it could be possible to detect more than 60 V. If this occurs, there is a risk of electrocution. To avoid any risk, all the people should wear dielectric gloves.
   Once the measurements are performed, it is necessary to push the emergency switch installed at the vehicle. This switch can open the battery relays forcing the voltage drop to 0V.
2) Battery temperature increase (No fire or smoke)
   If the temperature of the battery increase, emergency protocol is activated.
   First, evacuation team with help of firefighters should pull the vehicle outside of the facility. Then, the temperature increase should be evaluated:

$\Delta T \leq 5^{\circ}C/minute$ and T< 60 ºC → Measurement team should try to remove the data acquisition equipment and dummies with help of firefighters

$\Delta T > 5^{\circ}C/minute$ or T > 60 ºC → All the staff not equipped with SBA (self-contained breathing apparatus) should evacuate the crash area and move to Emergency Point. Only firefighters can be near the vehicle.

3) Smoke
   Evacuation driver should pull out the vehicle and move to the Emergency Point. All the staff not equipped with SBA (self-contained breathing apparatus) should evacuate the crash area and move to Emergency Point. Only firefighters can be near the vehicle.
4) Fire
   Evacuation driver should pull out the vehicle and move to the Emergency Point. All the staff not equipped with SBA (self-contained breathing apparatus) should evacuate the crash area and move to Emergency Point. Only firefighters can be near the vehicle.
5) Explosion
   Evacuation driver should pull out the vehicle and move to the Emergency Point. All the staff not equipped with SBA (self-contained breathing apparatus) should evacuate the crash area and move to Emergency Point. Only firefighters can be near the vehicle.
6) Chemical burn because of battery liquids
   In case of a chemical burn because of battery liquids, it is very important to wash the skin or the eyes with Hexafluorine solution. Most of the lithium-ion batteries leakage could be hydrofluoric acid. Only Hexafluorine solution could wash the burn, never use water.

In addition, the possibility of an emergency is very slim, however, crash lab should be prepared for an emergency because the damages of a possible emergency are very high for the facilities and people safety is first.

Figure 13: Equipment and tools needed to deploy the safety protocol within a crash test execution

Post-crash activities: Once the crash test has been performed, extreme care needs to be taken to ensure that there is no high voltage exposed before anybody working with the vehicle. European regulations (R94, R95, Euro NCAP) and American regulations (FMVSS 208, 214 and 301 new, 305), specify some voltage measurements that should be taken and some calculations that must be made after the crash test. However, as EV's can become dangerous when crashing due to electroshock hazard and chemical fire hazard, the addition of extra requirements from the ones defined in official safety standard procedures will help to reduce as much as possible any incident, personal damage risk and its consequences. The post-crash activities and the sample treatment are widely described in Chapter 8 named "Firefighting, Rescue and Post-Crash Vehicle Handling".

Nevertheless, a short introduction to the required workflow for sample treatment and storage can be found hereunder and summarized in Figure 14.

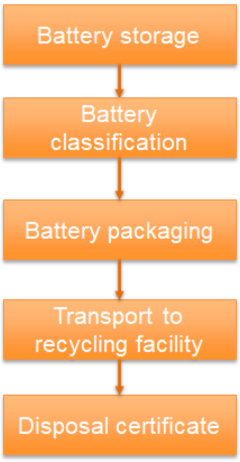


Figure 14: Workflow for high voltage battery treatment after a crash test

Sample treatment: Every EV sample will be treated with extreme care after the test execution to ensure safety of the testing facilities and the workers involved in the vehicle towing and management. Therefore, the crashed samples will be marked with the corresponding label identifying the HV components, the type of test performed and the risk level of the sample.

After participating in a crash test, the EV will stay overnight in the quarantine area where a monitoring system will follow-up any temperature increases of the HV battery, and the fire detectors will inform the firefighters in case of any incidence to intervene and minimize consequences.

Storage: If the HV battery does not show a clear damage after the overnight process it can be stored in isolated containers specially designed to control the temperature of the samples and reduce the risk of fire propagation to other vehicle samples and laboratory facilities. Once the HV battery is not needed for testing purposes it must be correctly packaged and sent to recycling facilities for its dismantling. The recycling facility will provide a disposal certificate ensuring the end-of-life of the HV battery and guaranteeing that post-crash activities are finished.

PART 2: STRATEGIES TO MITIGATE PROPAGATION IN BATTERY ELECTRIC VEHICLES

DESCRIPTION OF THE PHENOMENON

The fire triangle shown in Figure 15 represents a simple model for understanding the necessary conditions to start a combustion reaction (→ fire).

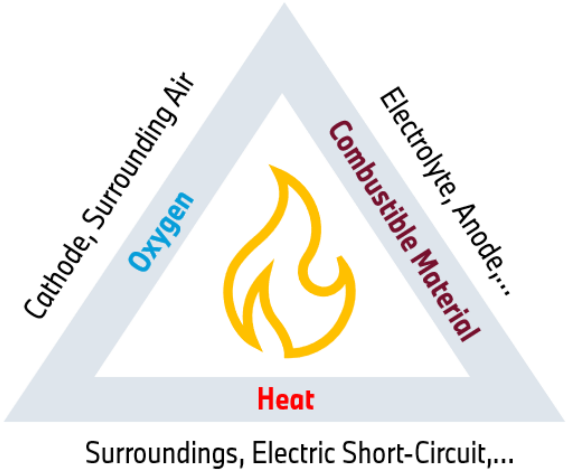


Figure 15: Fire Triangle: The three key elements necessary to start a combustion reaction.

For most fires, the presence of three elements is necessary: A flammable material, an oxidizing agent (most commonly: oxygen), and an initial heat source to trigger the combustion reaction. Modern battery cells consist of flammable materials such as the electrolyte or the anode and bring their own oxygen stored within the cathode material. Conclusively, battery cells typically meet two of three conditions for a fire and already an erroneously high heat input can lead to a strong exothermal reaction, which is commonly called “Cell Thermal Runaway” (TR). Typical errors which can lead to Cell Thermal Runaways are cell-internal short circuits, improper treatment of the battery cell, or heat input from the cell’s environment and are presented in detail in the next section. An important key figure to describe a Cell Thermal Runaway is the total amount of heat Q_{tot} released. Figure 16 shows Q_{tot} for state-of-the-art Lithium-Ion battery cells depending on their respective capacity C_{cell}, measured using autoclave calorimetry.

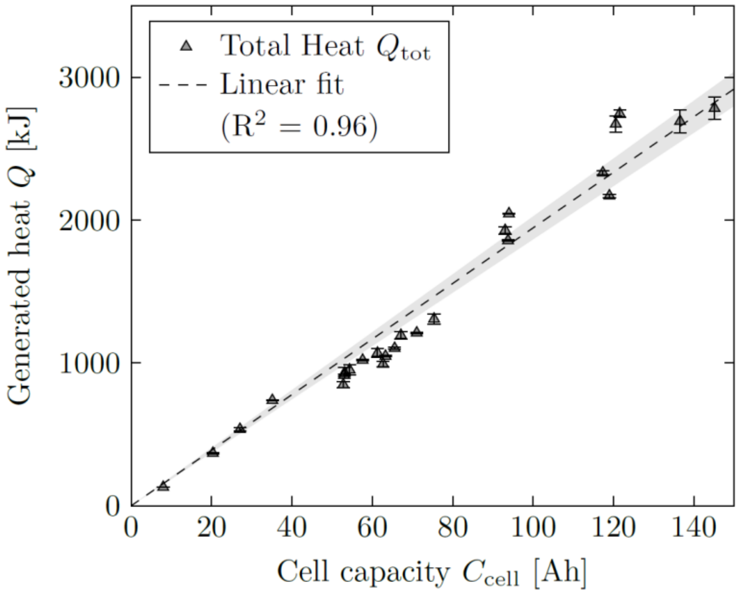


Figure 16: Total amount of heat released during a cell thermal runaway dependent on cell capacity [13].

For the battery cells investigated and depending on cell capacity, the total released energy during a Cell Thermal Runaway can easily exceed 1000 kJ. Furthermore, the data shows a strong dependence of Q_{tot} on cell capacity: a higher energy content typically leads to a higher heat release during a Cell Thermal Runaway. For cell chemistries enabling high energy densities, TRs typically only last a few seconds. Heat release rates can therefore be expected in the range of hundreds of kilowatts. Obviously, on battery pack level, an error on this scale has the potential to trigger a Thermal Runaway of a neighboring cell which is typically placed millimeters away. A chain reaction in such a worst case scenario is called "Thermal Propagation" and can potentially lead to a fire spreading to the vehicle and imposing a danger to the passengers.

RULES, REGULATIONS AND MOTIVATION TO MITIGATE PROPAGATION

There are different motivations for manufacturers of battery packs or electric vehicles to develop concepts to mitigate propagation. On the one hand, an OEM obviously wants to sell safe vehicles that do not cause situations endangering life and health of the users. On the other hand, regulations and norms concerning battery packs for electric vehicles exist in different countries, which must be obeyed to be able to sell the product in the respective market~~.~~

The UNECE (United Nations Economic Commission for Europe), under the "1998 Agreement", releases regulations to create harmonized conditions for the approval & homologation of vehicles. In 2018, Global Technical Regulation (GTR) Nr. 20 phase 1 was published. It includes requirements relating to thermal propagation. Applying a "documentation approach", the OEM must establish a description of the system and its safety concept using a risk analysis. Furthermore, an outline of the validation procedures and results, demonstrating that the customer is not exposed to a dangerous situation, is required. So far, a pure documentation thereof is sufficient and no clearly defined homologation test for a robustness concerning thermal propagation is included. Several countries work on national laws to adopt the UNECE regulations into compulsory regulations, however not always in the same manner.

A very relevant regulation which also includes homologation testing concerning thermal propagation is the Chinese GB 38031-2020. China is the world's biggest electric vehicle (EV) market and wants to play a pioneering role in EV safety regulations. The current GB standard includes, among other things, a thermal propagation homologation test of the battery pack in which a battery cell is brought into thermal runaway by nail penetration or overheating (or an alternative method which the OEM can choose, with some conditions). The thermal event must be detected and for at least 5min after sending out an alarm signal, no explosion shall occur, and no fire must leave the battery system. If the homologation test is performed on the vehicle level, additionally no fire or smoke shall enter the passenger cabin of the electric vehicle for at least 5min.

The GB standard is currently under revision and a new version is being drafted that will possibly replace the current standard in 2025. It may include an increase in requirements concerning thermal propagation with a significant prolongation of the 5min time interval (from detection until fire or smoke inside the passenger compartment would be allowed). If this is implemented, the propagation from cell to cell must be further reduced or even stopped completely to fulfill the homologation requirements.

Besides laws and regulations, the OEM must obey to be able to sell the vehicles in the respective market, also other motivations come into place. On top of all legal requirements and regulatory demands, a product manufacturer has the duty of care. A product shall be failure tolerant and not cause unnecessary harm. But also, economic aspects must be considered. As electric vehicles are a relatively new technology (besides some electric car prototypes at the very early beginning of automotive history), people very closely monitor the abilities and safety performance of this new type of vehicles. A burning electric car will have a many times higher impact in press and customer awareness than a burning internal combustion engine (ICE) vehicle, despite the statistical evidence that electric vehicles do not show any higher probability of car fires compared to ICE vehicles [14] [15]. Additionally, the situations in which EVs and ICE vehicles catch fire are very different. In the rare cases of ICE vehicle fires, the thermal event most often starts during operation due to overheating of the combustion engine and the exhaust system igniting other parts of the vehicle. In the few cases of electric vehicle burns, car fires have been ignited during or after charging the battery pack [16]. The charging situation has a higher potential for escalation because of the proximity to critical areas like garages or houses. For these many reasons, the safety of the electric vehicle including its thermal propagation robustness should always be high priority for every product manufacturer.

STRATEGIES TO HANDLE PROPAGATION

To strongly limit or even to avoid the risk of fire incidents of electric vehicles, a comprehensive safety concept on all levels of the high voltage storage system is essential. Measures only on one level alone will not be sufficient in most cases. The different possible layers of a propagation safety concept are illustrated in Figure 17.

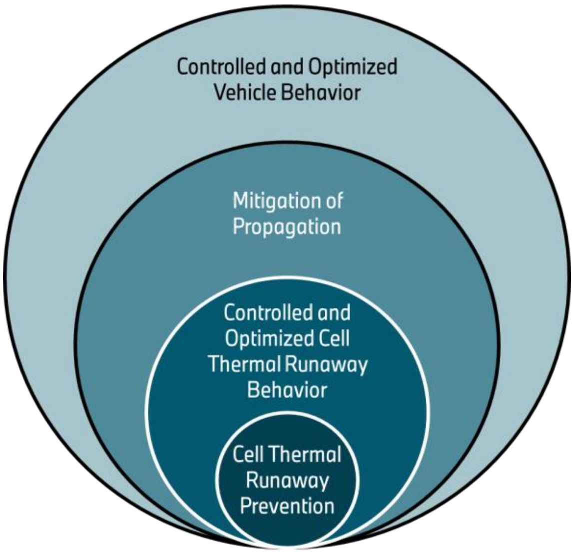


Figure 17: From cell to vehicle level - Four layers to mitigate propagation.

The innermost layers consist of the safety concept on battery cell level. Due to a robust cell design and a mature production process with advanced process and quality measures, safety critical events with a possible cell thermal runaway can be made extremely unlikely or even avoided ***("Cell Thermal Runaway Prevention")***. If, nevertheless, a battery cell will undergo a Thermal Runaway, the cell design should allow a controlled and predictable behavior that, for example, does not lead to side-openings or even an explosion-like rupture of the cell housing ***("Controlled & Optimized Cell Thermal Runaway Behavior")***. Within the next layer of the safety concept, the battery storage should be able to cope with the controlled thermal runaway of a battery cell and hinder or at least mitigate an uncontrolled chain reaction of consecutive thermal events of neighbor cells (***"Mitigation of Propagation"***). The latter safety layer is for example also reflected in the current Chinese GB norm, which requests no fire outside the battery for at least 5min after detection of a safety critical event. The final layer "***Controlled & Optimized Vehicle Behavior***" includes safety measures on vehicle level to further protect customers and to allow passengers to leave the vehicle safely.

All the described layers of the overall safety concept add up to achieve a high level of safety for the electric vehicle passengers. In the following, possible measures on each level are illustrated in more detail.

SAFETY LEVEL 1: CELL THERMAL RUNAWAY PREVENTION

In the following chapter, an insight is given on possible root causes for cell thermal events and how to avoid or mitigate them.

Cell Thermal Runaway

The thermal runaway of a lithium-ion cell can be described as an uncontrollable, strongly exothermal process through the combustion of the cell-internal materials, in particular electrodes, separator, and electrolyte. To start the combustion reaction, the activation energy of the reactions must be reached. One possibility for the initial heat-up necessary to activate the self-heating of the cell, might be a cell internal short-circuit. Depending on the temperature level the cell material reaches due to such a failure, different exothermal reactions can be triggered. Even at relatively low values above the operating temperatures of typical lithium-ion cells (~70-80°C), the decomposition of the solid electrolyte interface (SEI), marks the entry point to the exothermal heat release and self-heating of the battery cell. The associated heat release is still very low, and the SEI decomposition has a bigger impact on cell lifetime than causing a safety critical event. At temperatures above that point, the electrolyte starts to decompose and even higher up in temperature the decomposition reactions of the anode set in. Those reactions already contribute more significantly to a further self-heating of the cell. Nevertheless, depending on the thermal boundary conditions of the lithium-ion cell, those reactions might not yet lead to the strong uncontrollable exothermal heat release called thermal runaway. If heat is dissipated in a significant way to surrounding cell material or neighbor cells, the temperature threshold for the very critical cathode reactions might not be reached (typically 150°C-200°C for NCM chemistry) and the cell might survive without catching fire. If, however, the cathode reactions are triggered, very significant exothermal reactions, as for example the combustion of the electrolyte with the released oxygen from the cathode material, can lead to an uncontrollable thermal event with very high self-heating rates (→ "Cell thermal runaway"). In Figure 18 three different scenarios are depicted with a different initial heat up of the lithium-ion cell.

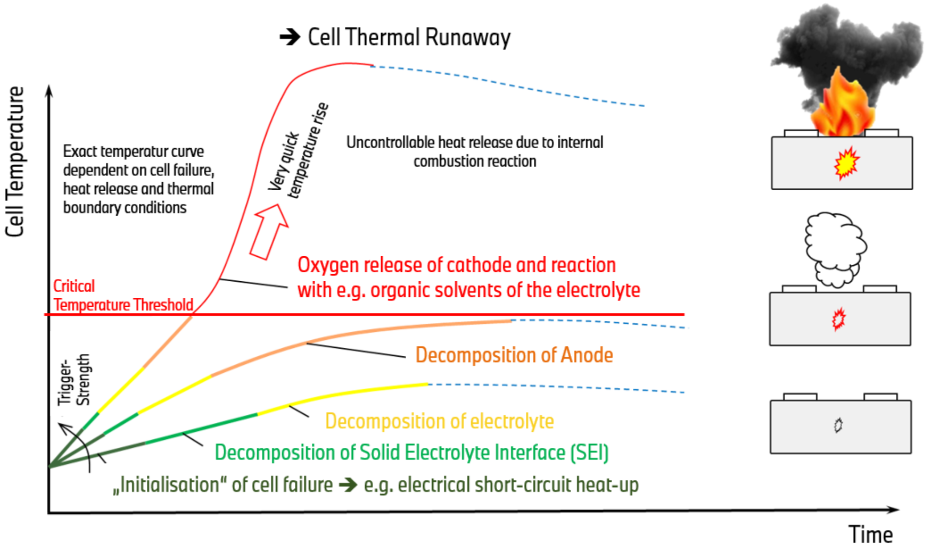


Figure 18: Cell-Temperature over time for different initial failure severity and thus short-circuit-based heat-up of the battery cell. If a critical failure is observed with significant short-circuit power, the different heat release reactions within the cell can be activated. If the temperature threshold necessary to trigger the cathode reactions is reached, an uncontrollable thermal event with quick temperature rise can be observed (figure kindly provided by S. Scharner, BMW)

In Figure 19 the measured temperature-dependent self-heating of a lithium-ion cell under adiabatic conditions is shown. The data has been acquired via ARC (Adiabatic Accelerating Rate Calorimetry). These measurements illustrate at which temperature point exothermal reactions of cells start and at which rate they lead to a self-heating of the cell. With increasing temperature, the self-heating rate increases as additional exothermal reactions are added. The exothermal reactions start with very low rates 0.05°C/min at 70-80°C (→ SEI decomposition) and go up to very high rates (→ "Onset of thermal runaway") at temperatures above 170-180°C as soon as the cathode related exothermal reactions kick in.

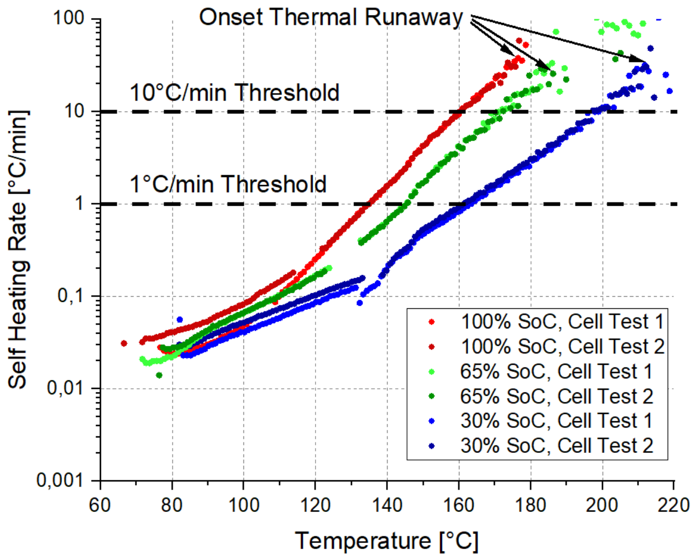


Figure 19: Temperature-dependent self-heating rates in [°C/min] for a Ni-rich NMC cell at three different states of charge (100%, 65% and 30%). The self-heating rate thresholds for 1°C/min and 10°C/min are indicated as well as the temperature regime of thermal runaway. (Data kindly provided by S. Dandl, BMW).

As it can be seen from Figure 19, the self-heating rate curve is dependent on the state of charge (SoC) of the lithium-ion cell. With increasing SoC and thus state of delithiation of the cathode, the cell materials get more unstable and produce the same exothermal self-heating already at lower temperature points (see 1°C/min and 10°C/min thresholds). The thermal runaway onset regime also shifts from about 210°C at 30% SoC to about 175°C at 100% SoC. In conclusion, lithium-ion cells are more thermally stable at lower state of charge.

Similar trends can be seen for different ageing conditions of a battery cell. Over the ageing process of cells and depending on the operational conditions and use case (e.g., percentage of fast-charging cycles and fast-charging power and temperature), lithium plating might occur on the anode. The presence of metallic lithium in the battery cell makes it again more temperature sensitive and will shift the onset of exothermal reactions and thus the self-heating curves towards lower temperatures. In Figure 20, the measured self-heating profiles for different ageing conditions are depicted.

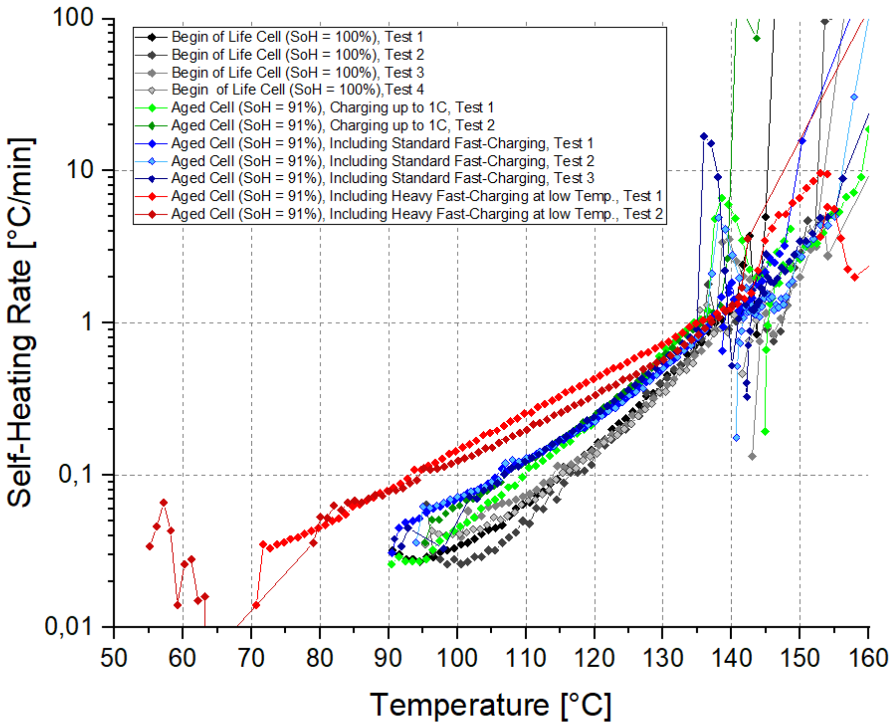


Figure 20: Temperature-dependent self-heating rates in [°C/min] for a NMC cell at four different ageing conditions: begin of life, SoH = 91% & low current charging, SoH = 91% & normal + fast-charging, SoH = 91% & normal + heavy fast-charging at low temperatures. (Data kindly provided by S. Dandl, BMW).

Aged cells show higher self-heating rates and an earlier onset of exothermal reactions in comparison to cells at begin of life. Furthermore, with an increased share of fast-charging cycles and with increasing severity of the charging profile (→ reduced charging time & decreased charging temperatures), the exothermal reactions start already at lower temperatures and show an overall increased self-heating rate.

Cell Internal Root Causes

As described in the sub-chapter above, the precondition required to trigger a thermal runaway of a battery cell is the initial heat input (→ “activation energy”) starting the exothermal self-heating of the cell. This initial heat-input might be delivered by different root causes within the cell or from the outside. In the following, a deeper insight to the cell internal root causes is given.

In the table below an exemplary overview over possible cell internal failures and their root causes is given. This table is only a small insight into a comprehensive cell design & process FMEA (“failure mode and effects analysis”). Nevertheless, it becomes clear that cell internal failures, that have the potential to generate enough heat to trigger a thermal runaway, are mainly cell internal short circuits.

Table 3: Exemplary cell internal failures that could potentially lead to a cell thermal runaway. Possible failure root-cause are indicated as well as their potential origins.

Failure	**Root Cause**	**Origin**
Cell internal short-circuit via particles	Metal particles (Al, Cu, Steel), non-metallic particles	Welding processes, Particle contamination from the outside, …
Cell internal short-circuit via dendrites	Lithium-dendrites/-plating, Cu-dendrites	Inhomogeneous local charging resistance, electrode misalignment, Cu-particles, inhomogeneous electrolyte wetting,
Cell internal short-circuit via misalignment or deformation	Anode-Cathode electrode(-foil) contact, electrical contact with current collector and cell housing	Bad manufacturing tolerances, cell design errors considering electrode swelling and vibrations
Cell internal short-circuit via damage to isolation layers	Damaged separator, damaged isolation between electrode stack and cell can	Isolation failure in base material, damage of isolation layer during manufacturing

As can be seen, the reasons for cell internal short circuits are various. In the following, a closer look is directed towards the first two failure types – cell internal short-circuits via particles and dendrites.

Particle Short-Circuits: Particles in lithium-ion cells can have many and diverse origins. Besides particles that are introduced to the cell from the outside during the cell manufacturing process or due to the contamination of sub-components, particles can also be generated during the cell manufacturing process. As the cathode and anode current collector and foils are made of Aluminum (Al) and Copper (Cu), all welding processes will produce Al and Cu metal particles when connecting the different electrode layers of same polarity together and joining them to current-collectors and terminals. A possible cap-plate-to-can sealing weld of the housing will generate aluminum or steel- particles depending on the choice of cell housing material. The amount, size distribution and location of the particles will depend on the exact welding process (LASER, resistance, ultra-sonic, …), welding geometry and particle shielding, welding power and size of the connected subcomponents. Also, particles inside the cell might move during the electrolyte filling process if their size and the cell internal space allows that.

If, for example, conductive Al or Cu particles will get to rest at critical locations within the cell and are large enough to penetrate through isolation layers like the polymer separator film (typical thickness in the range of 10-20µm), an internal short circuit can develop. Such internal short circuits (ISC) might have different local heating power $P_{\mathrm{ISC}} \propto ({U_{\mathrm{Cell}}}^2 \,/\, R_{\mathrm{ISC}})$ depending on the momentary cell voltage U_{Cell} and the internal short circuit resistance R_{ISC} (particle resistance plus contact resistances towards electrodes). The larger the particle, the more electrode and separator layers can be penetrated and with each electrode layer contacted, R_{ISC} is further reduced and the short-circuit heating power increased. In Figure 21(a) an electrode plus separator layer is depicted that was locally punctured by a larger particle. If the generated local heating power P_{ISC} is large enough to reach temperatures above the melting temperatures of the polymer separator, the separator between anode and cathode will locally melt and retract further, leading to even a better contact and a stronger short-circuit between the electrodes of opposite polarity (see Figure 21(b))

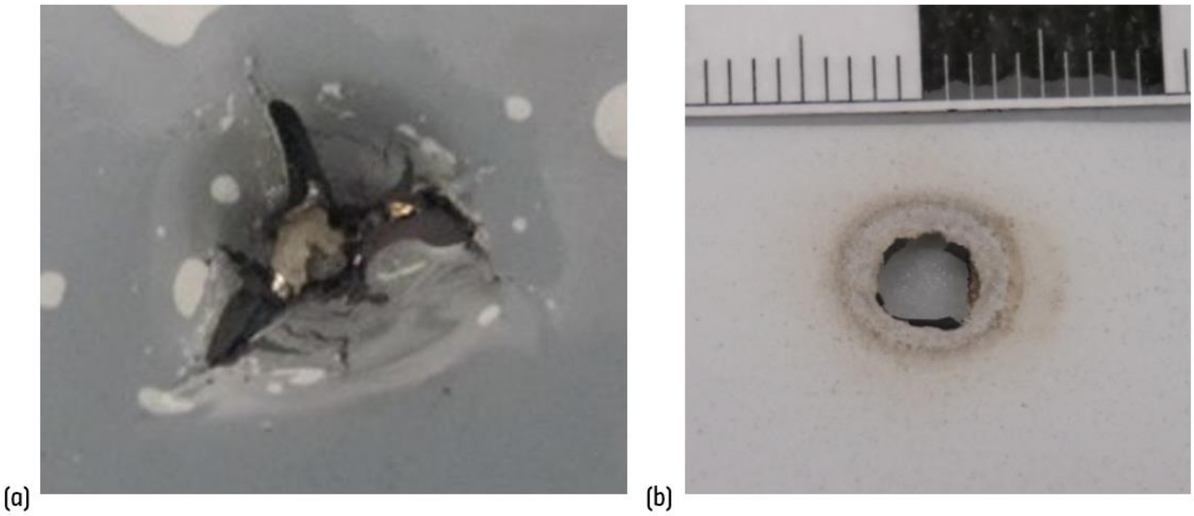


Figure 21: (a) Electrode and separator layer mechanically perforated by a cell internal particle. (b) If the local heat up exceeds the melting temperature of the polymer-based separator layer, the isolator film melts around the particle short circuit and enlarges the contact area between anode & cathode.

In case of small particles and high contact resistances or also a weak current carrying capability of the particle, the local particle short-circuit might just lead to an increased self-discharge of the cell without thermal runaway. That latter case corresponds more to a quality issue than to a safety critical state. If, however, short-circuit currents are strong enough and the local heat deposit by the short circuit current is sufficient to trigger the critical exothermal reactions of the cell materials, the cell will go into thermal runaway. Such a scenario can be seen in Figure 22, which shows the measurement data of a partial nail penetration into a lithium-ion cell simulating the case of a very large particle defect penetrating multiple electrode layers (see also exemplary CT image in Figure 22(b)).

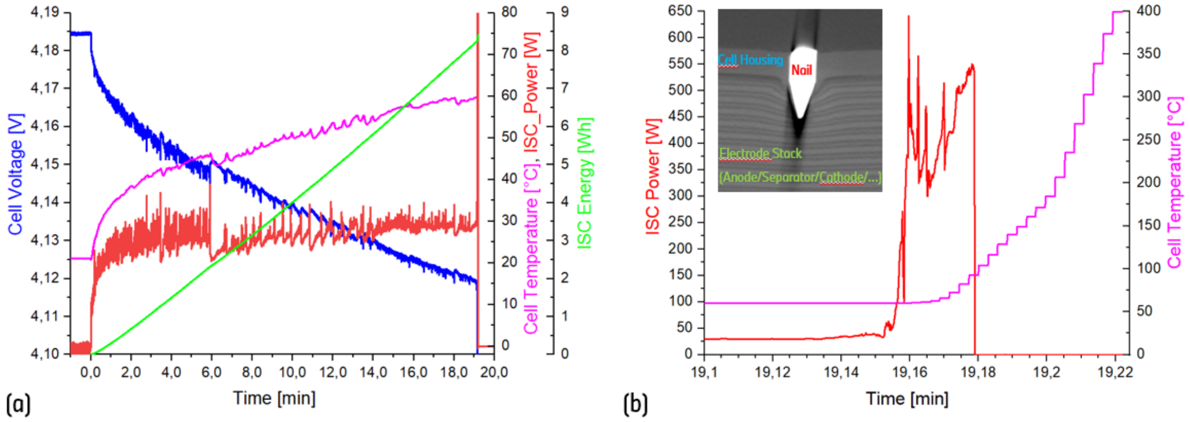


Figure 22: (a) Measurement of a partial nail penetration test with a lithium-ion battery simulating a local internal particle short-circuit. The cell discharges over the short-circuit with about 25-30W and heats up. (b) After about 19min and a local heat deposit of about 8.5Wh (ISC Energy), the severity of the short circuit increases suddenly and increases its power to more than 500W locally, leading to the thermal event of the battery cell with a very strong increase of the cell temperature.

Upon activation of the local short-circuit (→ partial nail penetration), the cell voltage breaks down and the cell is discharged over the particle/nail. The measured local short circuit power P_{ISC} is in the range of 25-30W, which leads to relatively strong local heat-up of the cell material surrounding the particle short-circuit. To the outside the cell steadily increases its temperature towards 60°C, however, inside of the cell close to the short-circuit zone, material temperatures well above that point can be expected. After about 19min and a local short circuit heat depot of 8.5Wh (ISC energy in Figure 22(a)), the separator reaches locally its melting temperature, retracts, and causes a sudden increase of the internal short circuit power to values above 500W and a breakdown of the cell voltage.

These very significant heating power values directly lead to a local activation of the very critical cathode reactions and subsequently to the thermal runaway of the battery cell with a drastic increase of the cell temperatures.

Dendritic Short-Circuits: Another potentially critical root cause for cell internal short-circuits which can lead to thermal events are dendritic short-circuits. The two most relevant dendrites that can develop in lithium-ion cells are Cu-dendrites and Lithium-dendrites. Cu-dendrites can for example develop if Cu-particles get to rest on the positive cathode at positive potentials outside their electrochemical stability window. In that case, they are oxidized into Cu2+ ions which are positively charged and consequently move through the separator to the negatively charged anode. There they are reduced again to metallic copper which starts to grow and build spikey dendritic metal structures that perforate the separator. Eventually these Cu-dendrites reach the cathode and can create an internal short-circuit between the electrodes.

Also, lithium can form potentially critical dendrites inside the cell. There are various root causes that can lead to Li-dendrite growth, two examples are shown in Figure 23. They all have in common that the lithium, which is initially stored within the cathode, is not homogeneously or to quickly transferred into the anode upon charging and the anodes locally exceeds its capability to fully intercalate the lithium-ions. Metallic lithium then develops on the anode surface in the form of plating or dendrites.

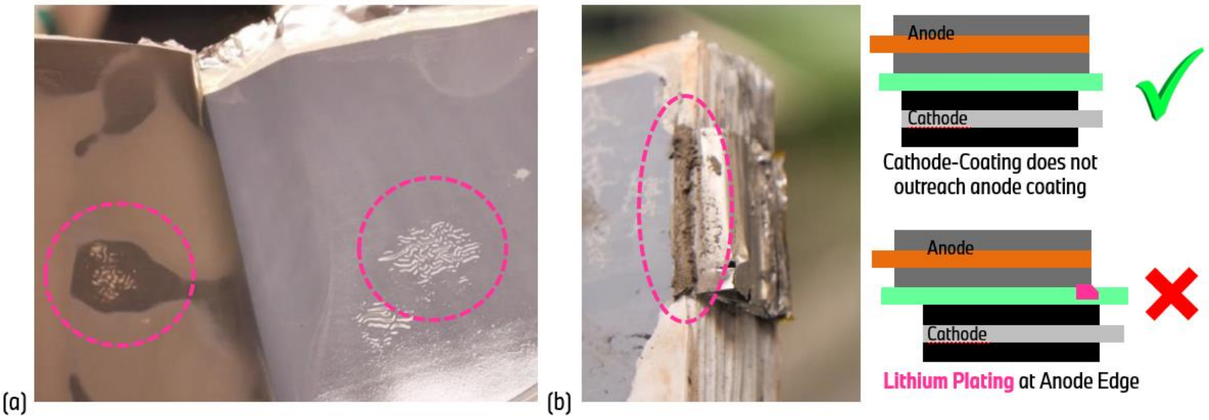


Figure 23: Different cases of lithium plating / dendrite growth. (a) Small lithium plating pattern caused by separator wrinkles. (b) Strong lithium plating due to misalignment of cathode and anode coating.

In Figure 23(a) an opened cell is depicted with local separator wrinkles between anode and cathode. The wrinkles in the separator have led to an alternating distance between anode and cathode and thus to a locally varying charge resistance leading to a reduced charge uptake of the anode at larger distance from the cathode. The anode material in between the separator folds had to take more lithium which then was plated locally onto the anode. As a result, the pattern of the separator wrinkles was transferred into a lithium plating pattern on the anode. This weak lithium plating does most probably not correspond to a large safety risk. In Figure 23(b) however, a more drastic form of lithium dendrite growth can be seen at the edge of an electrode stack due to a manufacturing error. In the latter case, the cathode coating did geometrically outreach the anode coating and therefore did not have a opposite reservoir at the electrode edge to take the lithium upon charging. The lithium from the cathode is then transferred to the outermost edge of the anode which has no sufficient active material to intercalate the lithium. Consequently, a large amount of metallic lithium builds-up locally with the potential to short-circuit the battery cell. Those larger areas of massive lithium dendrite growth can impose a significant safety risk, as they have a much better current carrying capability than the one of individual lithium dendrites and the reactivity of the cell material is locally increased due to the presence of metallic lithium (compare also Figure 20).

Cell External Root Causes

Besides the cell-internal root causes for a thermal event discussed in the previous sub-chapter, also cell external failures are possible that have the potential to lead to a thermal event of a battery cell. Table 4 depicts some exemplary cell-external failures which might lead to a cell thermal runaway, also indicating possible root causes and their origin.

Table 4: Table with exemplary cell external failures that could potentially lead to a cell thermal runaway. Possible failure root-cause are indicated as well as their potential origins.

Failure	**Root Cause**	**Origin**
Overtemperature via heat introduction from the outside	Breakdown of or inhomogeneity in cooling/heating system of battery pack, hot-spot upon operation caused by bad contact/welding resistance, short-circuit in HV storage system, fuel-fire from outside, …	Leakage in or breakdown of cooling system, blocking of individual cooling channels, bad busbar welding parameters, HVS-internal short-circuit between cells, external fires, e.g., fuel fires after an accident with ICE vehicles, …
Cell external Short-Circuit	Short-circuit in HV battery pack, battery pack external short-circuit, ...	Particle contaminations, deformation of components, …
Cell internal short-circuit due to mechanical cell deformation	Deformation of battery cell leading to damage to cell internal isolation layers or bringing subcomponents of opposite polarity in contact	Deformation or intrusion of the battery pack, e.g., through an accident.
Overcharge	Failure in battery management system, No or wrong voltage signal available, …	Problems with chipset or software, detachment of voltage sense cables, …
Deep discharge with subsequent continued cell operation	Failure in battery management system, No or wrong voltage signal available, …	Problems with chipset or software, detachment of voltage sense cables, …
Violation of current limits	Failure in battery management system	

As can be seen from non-comprehensive exemplary Table 4, the cell external reasons for a cell thermal event can be various and a more detailed description would exceed the scope of this document.

Cell Design and Manufacturing Process Measures to Avoid Critical Failures

In the following sub-chapter, a more detailed overview is given on potential cell thermal runaway prevention due to process and design measures on cell level. To not exceed the scope of this document, the focus will be on cell internal failures & measures.

Process & Quality Measures – Pushing the failure occurrence to the minimum…

Concerning critical defects or contaminations inside the cell, from process and quality side, there are only two options: avoid the generation or insertion and sort out sub-assemblies and complete cells that possess these contaminations despite all precautions. To avoid the insertion of contaminations, a minimum cleanliness level of subcomponents is required and should be monitored as well as cleanliness of the manufacturing facility. After that, the process control can assure that, for instance, welding processes are well regulated and do not generate larger amounts of particles of significant size. Furthermore, geometric shields, magnetic traps and air-flow systems can hinder the production process particles from entering the cell assembly. In case of electrode misalignments, camera surveillance can help to sort out affected electrode assemblies. If despite all these measures, for instance, critical welding particles enter the cell, there are different means to detect those, at least if they have a critical size. During cell manufacturing, high-potential isolation-failure tests are carried out at different steps. For example, after the stacking or winding of the electrode assembly, the dry electrodes are pressed together, and a high voltage difference (typically above 1kV) is applied to the electrodes of opposite polarity. If larger particles penetrate (partially) the separator, a failure current is measured, and the assembly can be sorted out. Also, camera surveillance can sort out cells with larger contaminations as well as inline X-ray imagining. Finally, at the end of production, the cells undergo an ageing step during which the self-discharge is monitored. An increased capacity loss might be an indication for a discharge over a cell-internal defect. Also, obtained cell capacities and internal resistance values outside the specified tolerance band can be indications for cell internal defects. A reduced cell weight might be an indication for a reduced electrolyte volume or a missing electrode layer. A deviating cell thickness can give an indication for both additionally integrated defects or an insufficient cell degassing and missing layers in the electrode assembly. It should be noted that the effectiveness of the measures described in this section depends on boundary conditions, such as cell type, chemistry, and the specific manufacturing process.

Design Measures – Avoid failures to occur or mitigate their severity…

Despite the best process and quality control that limit the defect cell rate to a minimum, one must expect a share of produced cells to have an internal defect. By clever cell design measures, however, failures from such defects can be avoided or their consequences at least mitigated.

Starting with the example of a conductive metal particle inside the cell, there are different locations where the particle can come to a rest and potentially cause an internal short-circuit. Three exemplary positions are depicted in Figure 24, one between anode coating and bare cathode current-collector foil (A), one between anode and cathode coating (B) and finally a particle connecting the outermost anode layer and the can of the lithium-ion cell.

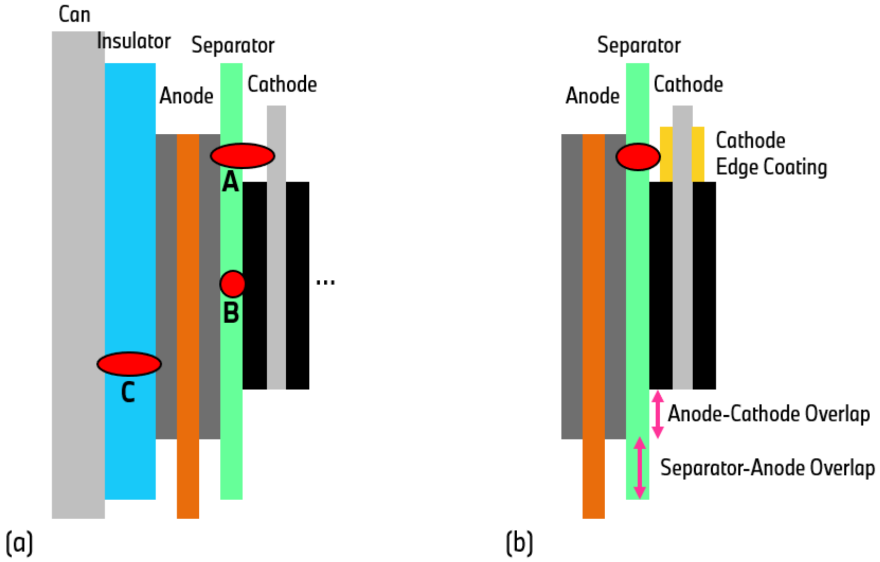


Figure 24: (a) Different exemplary particle positions A, B & C in a lithium-ion battery cell. (b) electrode assembly with cathode edge coating to protect against particles at location A. Indication of anode-cathode overlap and separator-anode overlap.

Of utmost importance are the insulating layers inside the battery cell. The choice of the separator concerning base material (PE, PP, PET, Polyamide, …), potential ceramic coating (thickness, single-side vs. double-side) and thickness resulting in a different mechanical and thermal robustness behavior, strongly impacts the likeliness of a particle pressing through it and creating a short-circuit. The size of the separator-anode overlap and anode-cathode overlap (see Figure 24(b)) strongly influences the possibility of a particle at the edge of the electrode assembly to create a short-circuit. By means of a potential cathode edge coating (from ceramic, polyamide, …) the criticality of a particle at position A can be mitigated (see Figure 24(b)). Particles at that location have the potential to create very low ohmic short-circuits as they connect the bare Al-foil with the anode without the significant ohmic resistance of the cathode coating. Particles at location C short-circuit the outermost anode with the housing of the lithium-ion battery. Depending on the cell format and choice of housing material, internal short-circuits of different criticality can occur. For a pouch-cell, the housing cannot support any severe short-circuit current as it is mostly insulating with only a very thin Al-layer within the composite film used as vapor and electrolyte barrier. For prismatic and cylindrical cells, the polarity of the housing (Aluminum → positive, Steel → negative) strongly influences the particles criticality as well as the ohmic resistance of the connection between housing and terminal. In many cases, a thicker and mechanically more stable insulator layer between can and electrode assembly can create an additional robustness-increase for these short-circuits not to develop.

Obviously, the choice of the cells active material also has an imminent impact on the severity of a potential particle short-circuit. Cathode materials with lower nickel content or lithium-iron phosphate have, for instance, a better thermal robustness. Latter cathode materials, due to their higher temperature stability, can impede a certain internal short-circuit to directly trigger an uncontrollable exothermal heat release in the form of a cell thermal runaway. More information on the choice of the cell active material from a safety perspective can be found in the next chapter.

In some cases, also cell design measures can help to protect the battery cell against failures from the outside. In case of an external short-circuit, a cell internal fuse, realized for example as section of limited cross-section within the Aluminum current-collector, can help to protect the cell from critical short-circuit currents. Another example is the so-called “overcharge safety device” or “current interruption device”. In case of an overcharge of the battery cell, the electrolyte is decomposed and larger amounts of gas are released that lead to a cell-internal pressure build-up. The increased pressure is used to tear off or fuse the cell internal electric connection between cell terminal and electrode assembly. By this a further critical overcharge of the battery cell is supposed to be stopped.

Early Detection of Potentially Critical Cell Failures in the Field

No manufacturing process can be 100% perfect. Despite the above-described measures to develop a robust cell design and to avoid failures during production by means of process measures and quality surveillance, one must expect a certain failure rate during cell production. A “Gigafactory” with a production volume of 20 GWh producing for example 21700 cells with ~20Wh, has an output of 1 billion cells per year (enough for 250.000 cars with an 80kWh battery pack each). To have less than one defect car in a year’s production, the defect cell rate of the Gigafactory would have to be below the extreme value of 0,001ppm. On top of all product and process quality optimizations, redundant safety measures should be installed to further reduce the risk even in case of single failures.

As described in the previous chapters, not every failure automatically initiates an immediate cell thermal runaway. Many defects will never lead to any safety issue, like for example a metal particle in the cell that is not big enough to penetrate through an isolation layer. Others will only cause weak damages that correspond more to quality defects than a safety relevant failure such as a metal particle creating a weak increased self-discharge without enough heat development to trigger the critical exothermal reactions causing a thermal runaway. Going even further, defects are possible with the potential to create for instance a safety relevant internal short-circuit bringing the cell into a thermal event after minutes to hours or even weeks of operation. If such a defect is slowly developing, there is a chance to detect it and even to react in the form of countermeasures to avoid the thermal event from happening. If we stay in the picture of the cell internal short-circuit created by a particle (simulated by a nail) in Figure 23(a) it took about 19min until the thermal event started. During that period, a sudden initial voltage-drop and voltage reduction due to internal discharge was detectable as well as an increase in cell temperature and a loss of charge (~8.5Wh). Via an advanced battery management system and appropriate safety functions, those signals can be used to detect the critical internal short-circuit caused by the particle already before the event. But it has to be clear that, depending on the failure characteristics and the sensor limitations, not each and every such endeavor can be successful. In case of multiple cells connected in parallel within the battery pack, voltage breakdown due to the internal short-circuit might be reduced and the lost charge visible in the balancing step at the end of a charging process will show less current as it will be small compared to the overall energy of the p-string and not as significant in comparison to balancing inequalities due to cell ageing effects. A temperature sensor on the other hand, might only be helpful to detect the unexpected temperature increase if it is close to the suspect cell.

Despite all these challenges, there is a good chance to sort out a number of critical failures and to initiate reaction mechanisms like a reduction of the maximum SoC (→ cells with lower SoC are more thermally robust, see Figure 21), a reduction of the maximum charge- and discharge-power and/or an immediate driver warning requesting the customer to drive to the next garage for a check-up.

SAFETY LEVEL 2: CONTROLLED AND OPTIMIZED CELL THERMAL RUNAWAY BEHAVIOR

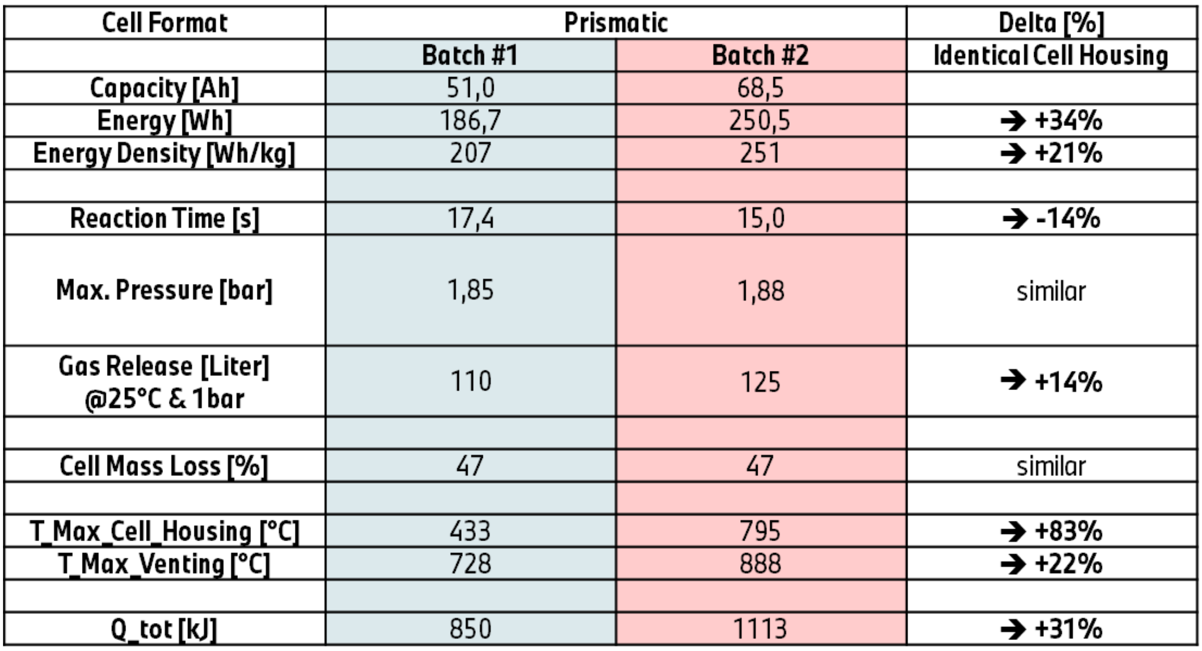
If, despite all above-described measures, a thermal runaway of a lithium-ion battery occurs, one leaves the first shell of the safety concept. The next layer targets to assure a controlled and optimized thermal runaway behavior, the high-voltage (HV) storage system can support and handle. This includes, among other things, a defined heat release, as well as a controlled gas & mass ejection via a burst membrane to increase the integrity of the cell housing and reduce the risk of ruptures or explosions.

Heat Release upon Thermal Runaway

The heat release upon thermal runaway is, together with the thermal robustness of the battery cell, one of the key-parameters to manage the risk of thermal propagation.

Table 5 shows results of autoclave calorimeter measurements of lithium-ion cells. These measurements allow the determination of the heat release as well as the mass- & gas-ejection characteristics of the battery cell upon thermal runaway.

Table 5: Measurement results of lithium-ion cells in an autoclave calorimeter for the characterization of heat release and mass- & gas-ejection. Comparison of the results for two types of cells with different capacity & energy density in the same cell housing.



Cell Format	Prismatic		Delta [%]
	Batch #1	Batch #2	Identical Cell Housing
Capacity [Ah]	51,0	68,5	
Energy [Wh]	186,7	250,5	➔ +34%
Energy Density [Wh/kg]	207	251	➔ +21%
Reaction Time [s]	17,4	15,0	➔ -14%
Max. Pressure [bar]	1,85	1,88	similar
Gas Release [Liter] @25°C & 1bar	110	125	➔ +14%
Cell Mass Loss [%]	47	47	similar
T_Max_Cell_Housing [°C]	433	795	➔ +83%
T_Max_Venting [°C]	728	888	➔ +22%
Q_tot [kJ]	850	1113	➔ +31%

The results are shown for two batches of cells with different capacities but identical cell housings to illustrate the impact of a change in energy density on the thermal runaway behavior. The increase of total heat release Q_{tot} matches well with the increase of the total energy content of the cell from batch #1 to batch #2. At the same time, the increased cell energy density reduces the reaction time of the thermal event and increases the maximum temperature of the cell housing. In other words, the severity of a thermal event increases with energy content and energy density of the battery cell.

The gas release and the resulting pressure peak in the confined space of the autoclave show, however, a smaller impact of the capacity increase from batch #1 to batch #2. Latter could have its origin in the reduced electrolyte/active material ratio for larger capacity cells.

The active mass loss of 47%, defined as the share of mass of the active cell material (→ electrolyte wetted electrode assembly) that was ejected during the thermal event, is similar for both cell batches. By influencing the mass loss ratio via the cell design, the ejection of heat from the cell depending on the overall propagation safety concept can be influenced.

Besides a change in absolute cell size and energy density, another way to strongly impact the thermal runaway behavior and the exothermal heat release, lies in the choice of cell chemistry. In Figure 25, measurements of the specific heat power of different cathode chemistry are illustrated.

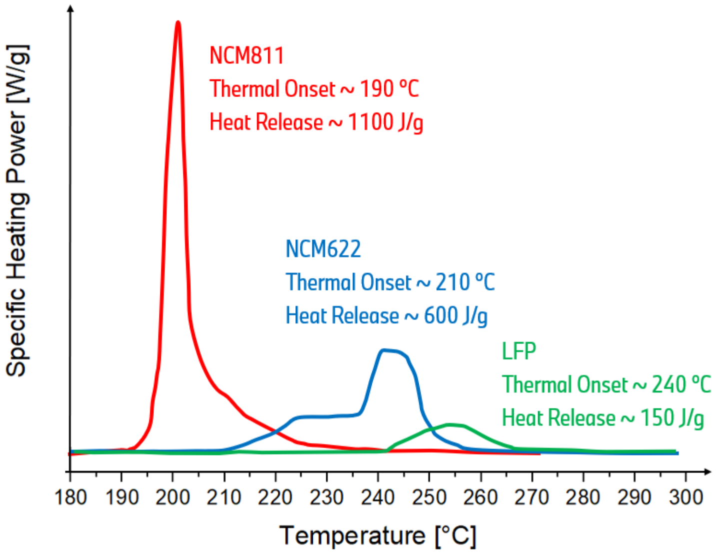


Figure 25: Exemplary differential scanning calorimetry measurements for different cathode chemistries. Specific heat power [W/g], onset of exothermal reactions and heat release [J/g].

In a first step, comparing the different NCM ($Li_xNi_{1-y-z}Co_yMn_zO_2$) variants, it appears that the safety criticality increases with Nickel ratio of the cathode active material. NCM811 (ratio of 8:1:1 of nickel, cobalt, and manganese) shows with 1088 J/g the largest specific heat release ΔH which corresponds to the area underneath the measured specific heat power curve. Also, the exothermal onset is the earliest at about 190 °C. The depicted NCM622 cathode shows with 572 J/g a much-reduced heat release and a higher onset temperature of about 210 °C. With an increase in the nickel content of the cathode, an increase in energy density and cost reductions may be achieved. However, the cells' thermal robustness will suffer, and more heat will be released during a thermal runaway.

Besides the NCM cathodes, also LFP (lithium iron phosphate) is shown in Figure 25. The LFP cathode shows with a specific heat release of 149 J/g and a high exothermal onset temperature of about 230°C the best safety performance, allows however only much reduced energy densities in comparison to NCM cells. The good safety behavior of LFP cells can also be seen in the autoclave calorimeter test results given in Table 6.

Table 6: Measurement results of lithium-ion cells in an autoclave calorimeter for the characterization of heat release and mass- & gas-ejection. Comparison between cells with NCM and LFP cathode chemistry.

Cell Format	**Prismatic**		**Delta [%]**
Cathode Chemistry	**Ni-Rich NCM**	**LFP**	
Capacity [Ah]	136,6	112,6	
Energy [Wh]	500	333	
Energy Density [Wh/kg]	247	167	**➔ -32%**
Reaction Time [s]	12,2	126,5	**➔ +937%**
Max. Pressure [bar]	5,7	0,58	**➔ -90%**
Gas-Release [Liter] @25°C & 1bar	289	50	
Gas-Release per Capacity [Liter/Ah] @25°C & 1bar	2,11	0,44	**➔ -79%**
Cell Mass Loss [%]	61	21	**➔ -66%**
T_Max_Cell_Housing [°C]	992	508	**➔ -49%**
Q_tot [kJ]	3211	1515	
Q_tot/Energy [kJ/Wh]	6,42	4,55	**➔ -29%**

The tests have been performed for two prismatic cells with capacities in roughly the same order of magnitude yet different cathode chemistries (Ni-rich NCM vs. LFP). The exothermal heat release per stored electric energy is reduced by about 30% for the LFP cell. Furthermore, cell housing temperatures are cut by about 50% upon thermal runaway. The cell reaction times are increased by one order of magnitude, which explains in combination with the smaller mass and gas release also the significantly lower resulting maximum pressure (→ -90%) in the closed autoclave chamber upon thermal runaway. In conclusion, the LFP cell shows a much-improved safety performance. However, the achieved gravimetric energy density is reduced by more than 30%.

Finally, another exemplary approach to potentially safe battery cells, is the use of solid-state lithium cells. There are plenty of possible variants of this technology, however most of them have in common that the liquid electrolyte is fully (or at least to a large extend) replaced by a solid electrolyte. This promises improved safety behavior as the organic solvents of the electrolyte contribute strongly to the exothermal reactions of conventional lithium-ion cells. However, also new challenges must be tackled, like for example the safety behavior of metallic lithium anodes.

All in all, it becomes clear that the cell material choice strongly impacts the safety of a battery cell. However, tradeoffs with other cell characteristics as energy density, lifetime and several other parameters must be considered, as well. The safety measures will be different depending on the selection of the cell material. There is no such thing as a one-fits-all safety recommendation.

Integrity of Cell Housing

Another key factor for the overall safety behavior of a lithium ion cell is the thermal and mechanical stability of the cell housing during a thermal runaway (→ cell housing integrity). On the one hand, the hydraulic diameter of the cell overpressure burst membrane has to be sufficiently large and possess an adequate opening pressure. On the other hand, the stability of the housing should be large enough to reduce the risk of a side-opening of the battery cell or even a rupture or explosion of the cell housing. A rupture or larger side-opening of the cell could cause a significant share of the venting material to be directed towards the neighbor cells and might lead to cell propagation. Furthermore, an explosion like behavior will result in a very large pressure peak within the HV battery storage system risking an undesired opening of the battery pack housing. In Figure 26, different examples for unwanted cell housing side-openings are depicted.

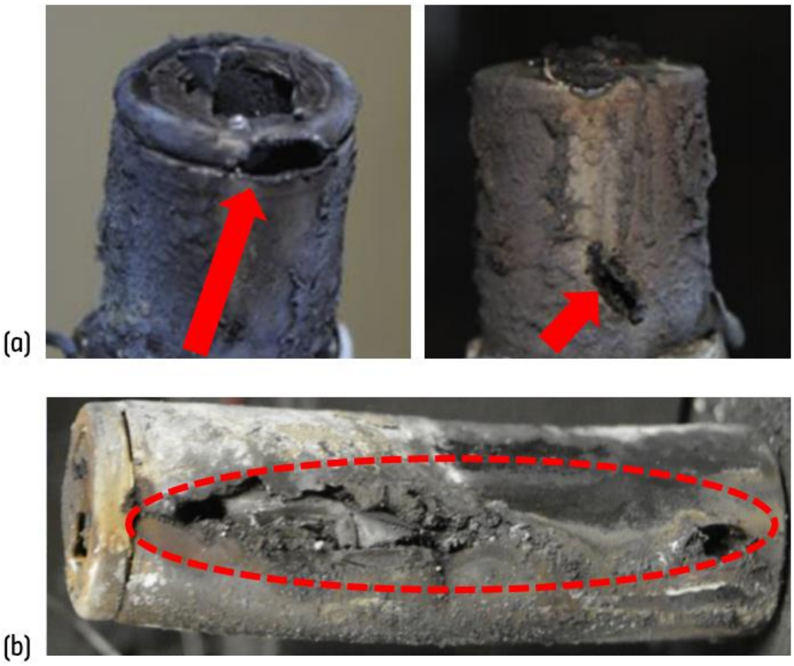


Figure 26: Experiment results to produce unwanted side-openings of 21700 battery cells. (a) Smaller openings due to thermal hot-spots on the cell housing and the internal pressure build-up during thermal runaway. (b) Side rupture of a 21700 cell with an opening over the whole length of the battery cell including strong deformation of the cell housing. Significant exhaust release over the side-opening can be expected. Pictures taken from [17]

For a robust design of the cell housing, the mechanical stress on the housing as well as its ultimate yield strength at the elevated temperature that can be expected during a thermal event need to be considered. In the case of a cylindrical cell, the tangential stress on the housing leading to a possible side-rupture, iscalled Hoop stress. It can be described by the equations in Figure 27.

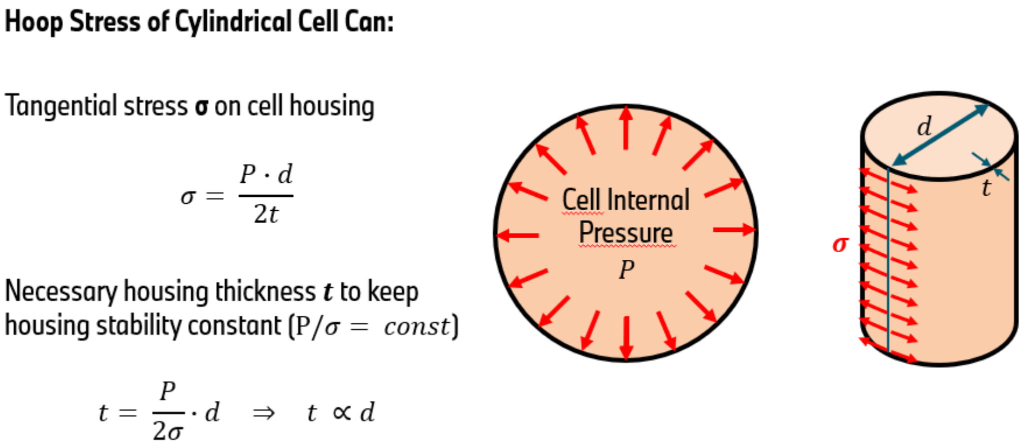


Figure 27: The Hoop stress correlation for a cylindrical cell housing gives the connection between can wall thickness and cell diameter.

In the case of a typical 21700 Ni-plated steel cell housing with a can thickness in the order of 300µm and a vent activation pressure of 28bar, the maximum hoop stress experienced by the cell housing is:

$$\sigma = \frac{P\cdot d}{2t} = \frac{28bar\cdot 21mm}{2\cdot 300\mu m} = 98MPa \quad \textit{Equation 1}$$

The ultimate yield strength of low carbon steel lies in the order of 400MPa at room temperature but decreases significantly with higher temperature. The exact steel alloy, the cell energy density (influencing the maximum housing temperature), the vent activation pressure and the can thickness should be selected in such way that the stress of 98MPa (including a safety buffer) will not be exceeded during the thermal event. For comparison, the ultimate yield strength of 1000 series Aluminum is with about 100MPa only about a quarter of the one of steel. In order to keep the same safety factor between maximum hoop stress and yield strength, an 21700 Aluminum housing would require a four times thicker housing.

SAFETY LEVEL 3: MITIGATION OF PROPAGATION

The entry point to “Safety Level 3: Mitigation of Propagation” is the thermal runaway of a battery cell within the battery pack. To better understand propagation, first, the mechanisms which can lead to the undesirable chain reaction are described. Afterwards, possible measures to mitigate propagation and to ensure passenger safety are presented.

From Cell Thermal Runaway to Propagation – Overview over the Main Mechanisms

Thermal Propagation is defined as the chain reaction which is triggered after a one Cell Thermal Runaway leads to a Thermal Runaway of another cell.

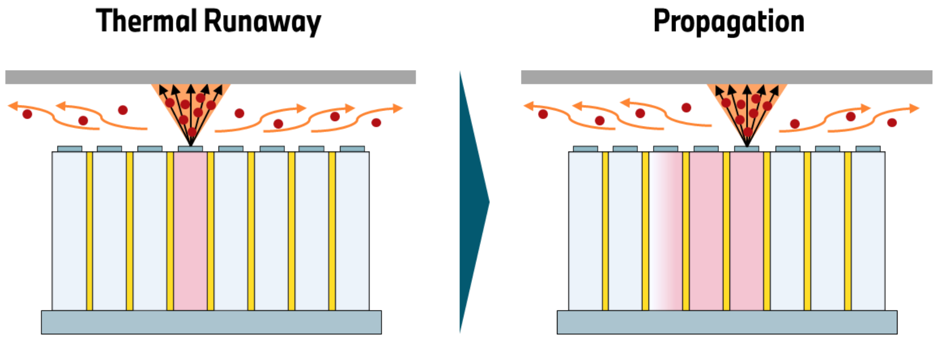


Figure 28: Definition of Thermal Propagation: A Cell Thermal Runaway leads to the Thermal Runaway of another cell.

During and after a cell thermal runaway, differently categorized disturbances are introduced into the battery pack with each having the potential to ultimately lead to Thermal Propagation: Beside the cell internal short circuit within the respective parallel circuit itself, heat diffusion to adjacent battery cells, the emission of hot venting gases, and the emission of electrically conductive particles play a major role.

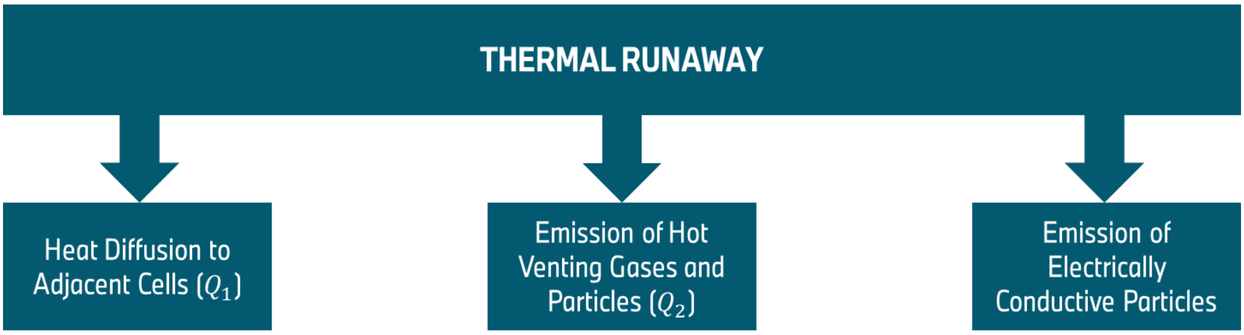


Figure 29: Mechanisms associated with a cell thermal runaway which can lead to Thermal Propagation.

Heat diffusion to adjacent cells (Q1): During and after a cell thermal runaway, the defective battery cell is a source of heat within the battery pack. Exemplarily, Figure 30 shows the temperature profile of a prismatic Li-Ion-Battery Cells during and after a Thermal Runaway in the autoclave test setup.

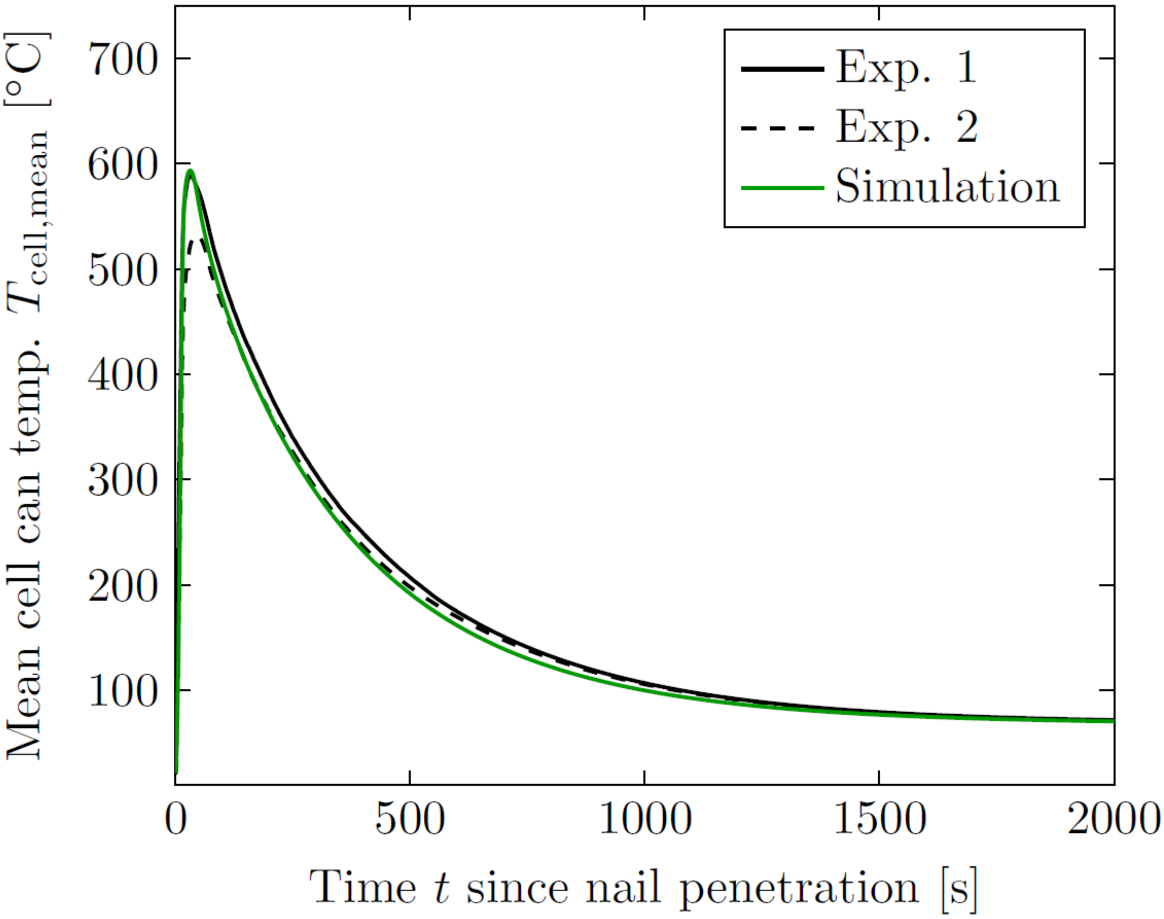


Figure 30: Can Temperature profile of a state-of-the-art 63,5Ah Lithium-Ion Battery Cell during and after a TR [18].

Depending on chemistry and format, battery cells in a Thermal Runaway can reach surface temperatures well above 500°C. Since commonly used insulation materials typically degrade at temperatures around 200°C, a Thermal Runaway holds the potential to lead to secondary short circuits due to degraded insulations.

Furthermore, the heat release also leads to rising temperatures in adjacent cells. As described in Cell Internal Root Causes, this rise in temperature leads to increased self-heating-rates of the cell, which further heat up the adjacent cell. If the cell temperature exceeds its critical value T_{crit}, the thermal runaway and conclusively Thermal Propagation is inevitable. To better understand this interaction, Equation 2 allows to calculate the heat input Q_{crit} necessary to trigger a Thermal Runaway:

$$\boldsymbol{Q_{crit} = V \cdot \left(\rho c_p\right)_{eff} \cdot (T_{crit} - T_{op})} \quad \textbf{\textit{Equation 2}}$$

In the above equation, V describes the outer cell volume, $\left(\rho c_p\right)_{\text{eff}}$ is defined as the cell's effective heat capacity and T_{op} is the operating temperature. Table 7 summarizes the assumed values for both prismatic and cylindrical cells.

Table 7: Estimation of possible heat intake before reaching the critical temperature $\boldsymbol{T_{crit}}$***.***

	Prismatic	**Cylindrical**
Size	180 x 32 x 72,5 mm³	D46 x 95 mm
Volume V	417600 mm³	157881 mm³
$\left(\rho c_p\right)_{\text{eff}}$	2400 kJ/m³ K	
T_{crit}	150°C	
T_{op}	50°C	
Q_{crit}	100 kJ	38 kJ

As a result of the conducted calculations, a net heat intake in the order of 100 and 38kJ can lead to Thermal Propagation for prismatic and cylindrical cells, respectively. However, the emitted heat during a Thermal Runaway can be orders of magnitude higher. The design should aim for a possibly direct heat flow to mitigate Thermal Propagation. It should be noted that the calculation in Table 7 only serves as a rough estimation. The exact values naturally depend on various parameters, like the cell's self-heating-rate, and the temperature distribution within the cell. Furthermore, if a battery cell is heated locally above its critical temperature, significantly lower heat inputs can be sufficient to trigger a Cell Thermal Runaway (see Safety Level 1)

Emission of hot venting gases and particles: During a cell thermal runaway, the defective cell emits a hot gas- and particle stream with temperatures up to 1200°C. The rapid rise in both temperature and pressure imposes a high mechanical load on the battery cell and therefore carries the risk of an uncontrolled opening of its housing. Furthermore, the venting mass flow transfers heat to other battery cells through convection and the accumulation of hot particles. This mechanism further increases the net heat input in neighboring cells and can ultimately lead to propagation through the mechanics which are mentioned above. Other consequences include the ignition of surrounding components and cell-external short circuits through degradation of electrical isolations which themselves trigger propagation.

Emission of electrically conductive particles: Battery cells contain highly electrically conductive materials like copper and aluminum, which can be emitted during a Thermal Runaway. The high flow velocities cause a distribution of the conductive particles along their respective flow trajectories, with the risk of bridging air and creeping distances. Conclusively, the emission of electrically conductive particles can cause secondary short-circuits which impose an additional electrical load on other cells within the battery pack and potentially trigger Thermal Propagation. It should be noted, that due to the cell-external heat input, not only low-resistance short circuits and their corresponding high currents, but also long moderate short-circuit currents can potentially trigger propagation.

Measures to Mitigate Thermal Propagation

For the safety of vehicle occupants, to minimize damage, and to comply with all legal requirements, propagation mitigation is essential. In this chapter, measures to handle the hot venting gases, the thermal load on adjacent battery cells as well as measures to avoid secondary short circuits and functional reactions are presented. These categories represent four pillars to mitigate Thermal Propagation.

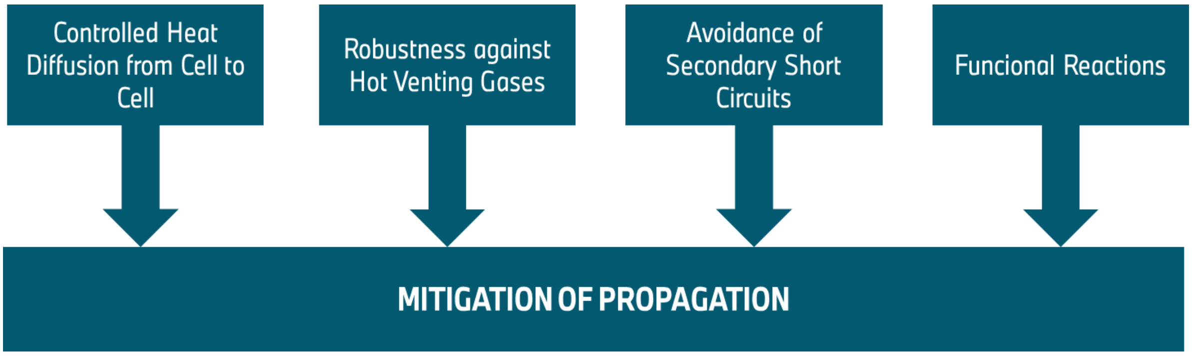


Figure 31: Four Pillars of Measures to Mitigate Propagation

Measures to control heat diffusion to neighboring cells: During and after a cell thermal runaway, the exothermal reactions within the cell lead to a rapid rise in temperature. Heat transfer to the neighboring cells, especially through heat conduction, can lead to critical temperatures in the neighboring cells which can ultimately trigger propagation. From this perspective, it seems obvious to thermically insulate each battery cell as good as possible. However, a sufficient insulation is difficult to obtain since battery packs require a good thermal connection to a cooler which conclusively thermally interconnects neighboring cells. Furthermore, a thicker insulation increases the package space and thus reduces the capacity of the full battery pack. Therefore, a rise in temperature of the neighboring cells cannot be fully prevented. As described in Cell Internal Root Causes, a rise in temperature above T_{ISH} also leads to an increased self-heating (ISH) rate of adjacent cells. If this additional heat input by a neighboring cell itself cannot be fully dissipated to its surrounding, temperature further increases up to the point where the critical temperature T_{crit} is reached. This rises a dilemma: On the one hand, a cell should be thermally insulated as good as possible to strongly limit heat diffusion to its neighboring cells. On the other hand, a good thermal connection between battery cells must be obtained to dissipate heat away from the cell. To further explain these mechanisms, heat diffusion during and after a Cell Thermal Runaway within a battery module of five Lithium-Ion prismatic cells was simulated for two scenarios utilizing the approach presented in [18]: a good ($R_{\text{th}} = 4 \cdot 10^{-6}\,\frac{\mathrm{W}}{\mathrm{m^2K}}$, scenario 1) and a bad thermal connection ($R_{\text{th}} = 0.023\,\frac{\mathrm{W}}{\mathrm{m^2K}}$, scenario 2) between neighboring cells. Scenario 1 represents an ideal heat exchange between the cells. On the contrary, scenario 2 represents a good insulation of the cells; heat dissipation mainly takes place via the bottom-plate-cooler. Figure 32 and Figure 33 show the respective simulation setup and the calculated results, respectively.

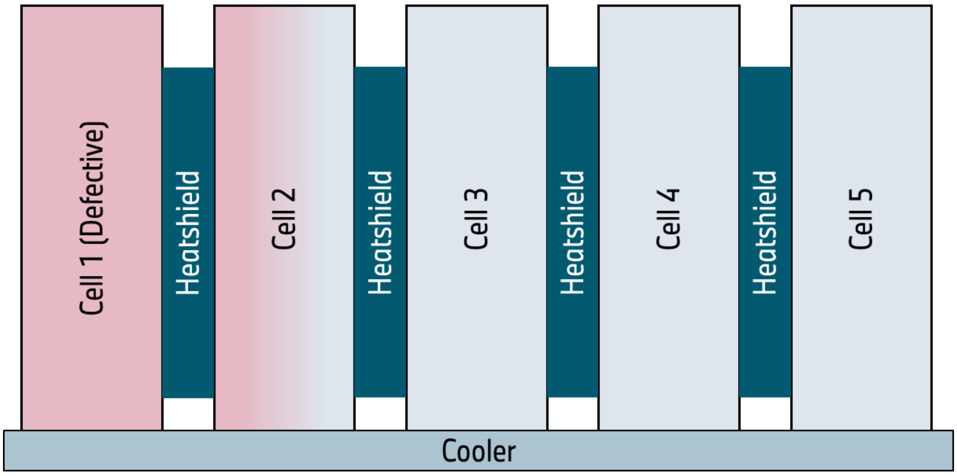


Figure 32: Model setup proposed by Hölle et al. for simulating propagation behavior within a battery pack [18].

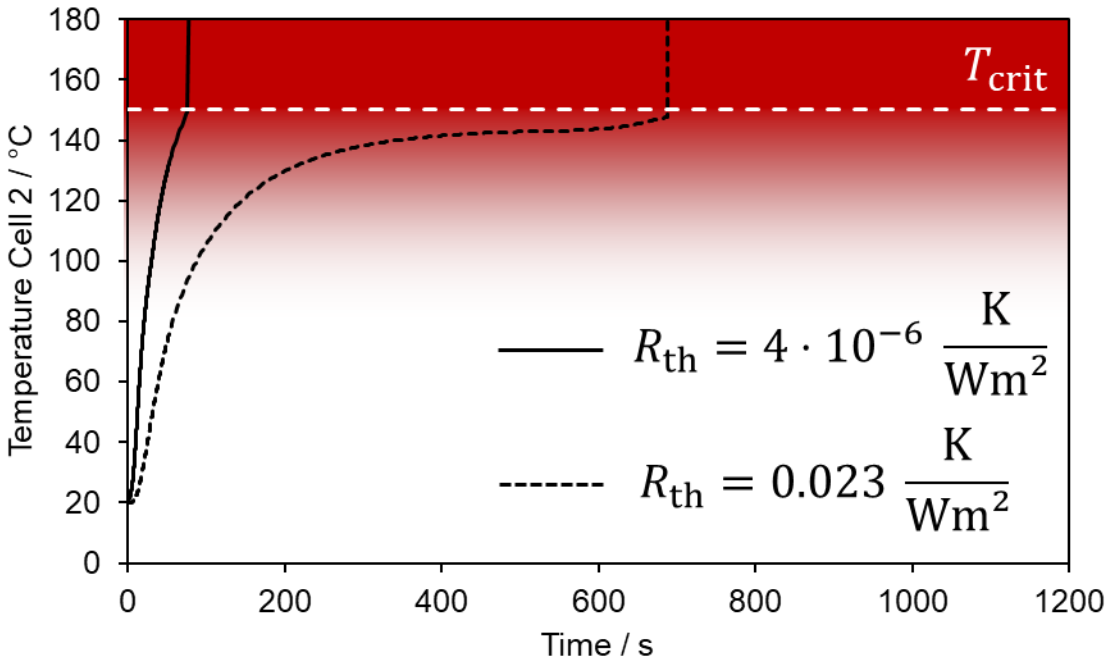
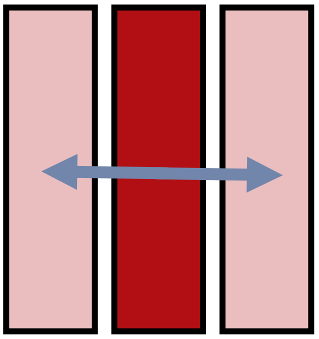
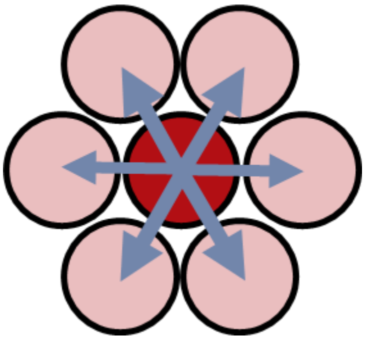


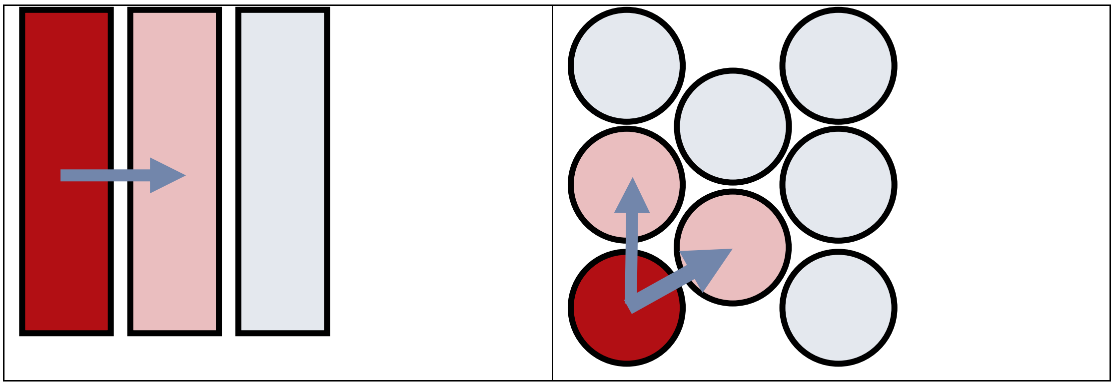
Figure 33: Difference between good and bad insulation. The red region indicates the temperature associated with an increased self-heating rate

Figure 33 shows the temperature of cell 2 adjacent to the TR cell over time. For scenario 1, after only 77 seconds, the average temperature of cell 2 overshoots its critical temperature, leading to another Thermal Runaway thus propagation. However, a good thermal insulation (scenario 2) cannot prevent propagation either. The slow heat input (mainly through the cooling plate) leads to a continuous heat-up of the adjacent cell 2. Once the temperature reaches the area of increased self-heating, the net heat-intake increases over several minutes, eventually heating cell 2 above T_{crit} and leading to a Thermal Runaway thus propagation. Battery manufactures therefore face an optimization problem which must take the following aspects into account:

- Number of nearest neighbor-cells: In this context, a nearest neighbor is defined as a battery cell which is directly thermally connected to the defective cell. To limit the temperature rise of adjacent cells to its minimum, it is crucial to distribute Q_1 as homogenously as possible and thus provide as many nearest neighbors as possible. The number of nearest neighbors strongly depends on the cell format.

Table 8:Cell format and resulting max. numbers of nearest neighbor Cells

Prismatic Cells.	**Cylindrical Cells.**
Max. Number of Neighbor Cells: 2	Max. Number of Neighbor Cells: 6
	
Min Number of Nearest Neighbors Cells: 1	Min Number of Neighbor Cells: 2



- Thermal connection of neighboring cells. The thermal resistance R_{th} between two cells can be expressed by $R_{th} = \frac{t}{\lambda A}$ where t defines the distance between two neighboring cells, λ is defined as the effective thermal conductivity and A describes the area available for heat transfer. Since today's main goal of battery development is to reach high energy densities, the distance t between two neighboring cells is typically chosen to be as small as possible. Furthermore, the area A mainly depends on cell format and cell arrangement and is also typically constrained by packaging requirements. Therefore, the thermal resistance between cells is typically manipulated through λ by choosing different materials. Since prismatic cells are typically interconnected by their larger side area, heat exchange must be inhibited: In mass produced batteries for automotive use, this inhibition is achieved by heatshields with a comparably low thermal conductivity. For cylindrical cells, however, due to their curved surface and comparably small useable area, it can be preferable to interconnect the cells through higher-conductive materials like aluminum. It should be noted that the thermal behavior also depends on the cells' surrounding like the thermal connection to a cooling plate.
- Thermal coupling of other heat capacities: Heat capacities can smoothen temperature peaks. It can be therefore beneficial to thermally connect the battery cells to surrounding heat capacities or to introduce extra heat capacities into the system.

Measures to Increase Robustness against Hot Venting Gases: As mentioned before, a Cell Thermal Runaway leads to a rapid emission of venting gases with temperatures up to 1200°C.To mitigate propagation, the energy storage needs to implement measures to discharge these venting gases in a well-controlled manner. Energy storages are therefore typically equipped with dedicated degassing units. Degassing units are designed to represent predetermined breaking points in the housing of the energy storage which open a flow cross-section after the pressure within the battery overshoots a certain threshold. After activation, the pressure within the energy storage drops immediately and an uncontrolled opening of the housing can be prevented. Nevertheless, the battery housing must be designed to withstand a certain over-pressure. Once the degassing unit has opened, the hot venting gases and abrasive particles flow from the defective cell to the newly created opening. Highly turbulent flows of high velocity and therefore high heat transfer coefficients are to be expected. Battery packs therefore often use sheet-silicate-materials, also known as Mica shields, to protect the housing from a direct impact of hot and abrasive venting gases to prevent penetration. To prevent ignition of secondary fires, only non-flammable materials should be used within the expected flow path. If flammable materials cannot be fully avoided, it might be possible to use the inerting behavior of the venting gases. Furthermore, heat-proof materials like Mica can be used to protect critical components which cannot be localized outside the venting flow.

Measures to avoid short circuits**:** During a Thermal Runaway, the battery cell not only emits hot venting gases but also electrically conductive particles, for example, copper and aluminum. To avoid secondary short circuits, potential-carrying components, like battery cells, busbars, and high-voltage connections should not be exposed to the venting flow. If package design permits, it can therefore be beneficial to provide dedicated venting channels connecting the cell vents to the degassing unit of the battery pack. Ideally, these venting channels do not lead the gas- and particle flow past potential-carrying surfaces. However, due to packaging-restrictions a full separation of functions is not always suitable. If exposure of potential-carrying components to the venting flow is not fully avoidable, short-circuits can be efficiently prevented by using temperature-resistant isolations. Due to the high temperatures during Cell Thermal Runaway modern battery therefore use isolations made of Mica or polyurethan-based foams which keep their isolating properties even at high temperatures.

Functional Measures: To effectively warn and therefore protect car occupants, a cell thermal runaway must be detected. Common concepts involve the detection of a rapid rise in pressure and temperature as well as abnormal behavior of electrical cell parameters like voltage or current. Eventually, engine power can be either restricted or deactivated to prevent additional heat input from ohmic heating. Furthermore, it can be beneficial to activate cooling to dissipate heat from the Cell Thermal Runaway. To illustrate the effect of "emergency cooling", a propagation simulation was conducted with and without the cooler being a heat sink. The temperature of the cooling fluid was set to 60°C. Figure 34 shows the resulting temperatures of the battery cell next to a Thermal Runaway.

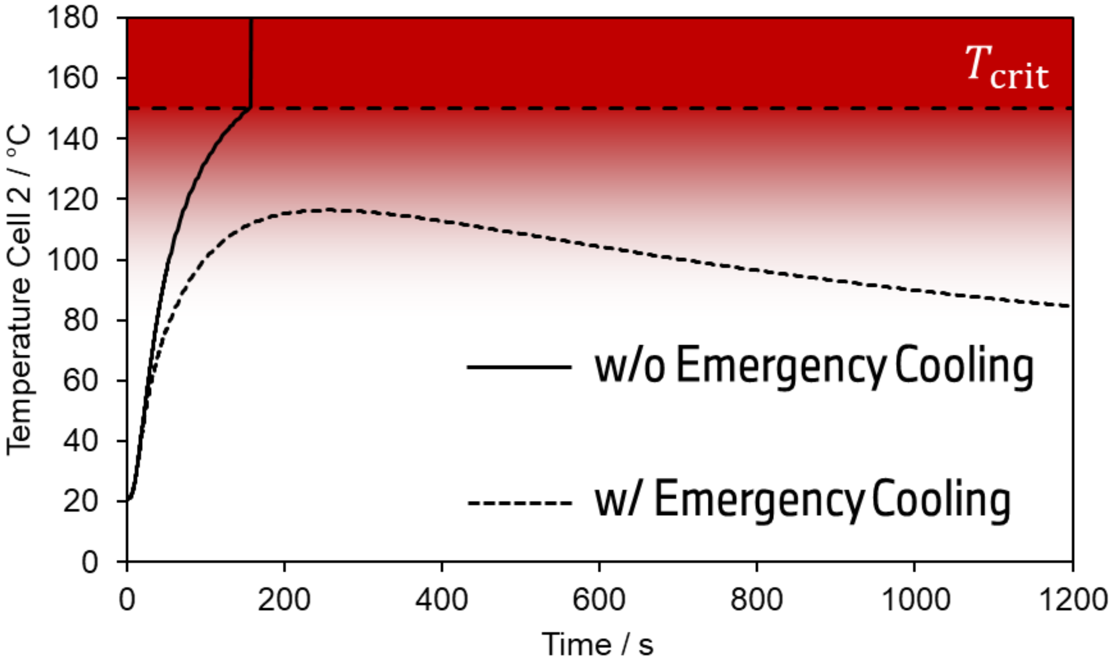


Figure 34: Temperature of the neighboring cell over time with and without "emergency-cooling".

The simulation results indicate a strong influence of the emergency cooling on the temperature of the adjacent cell. Under the chosen boundary conditions, the activation of emergency cooling increases the robustness to a level, where propagation through heat transfer can be fully prevented.

SAFETY LEVEL 4: CONTROLLED AND OPTIMIZED VEHICLE BEHAVIOR

For as long as the risk for thermal propagation cannot be fully eliminated, risk mitigation measures on vehicle level should be installed to further improve overall safety. Those measures aim at enlarging the time span between the warning of passengers, pedestrians or fire fighters and the point where the vehicle gets into a safety critical state.

Warning concept

Directly after detecting a cell thermal runaway, car occupants should be informed and urged to leave the vehicle as fast as possible. Engine power can be taken away to ensure that the warning is not dismissed by the passengers. The surrounding of the vehicle can be informed by activation of warning lights or horn. The automatic emergency call can be started with a specific note for the rescue coordination center indicating a critical status of the vehicle battery.

Protection of passenger compartment

The passenger compartment should be kept free of cell gases and smoke as well as extensive heat input for as long as possible. To achieve this, degassing units of the battery pack should be placed in a way that allows an unhindered flow away from the cabin and the exit area of the passengers. A direct flow towards the ground is preferred. Furthermore, flammable components should not be placed close to hot venting gases to prevent secondary fires. Guide plates or profiles can be used if the degassing units cannot be placed at the bottom of the battery pack where they risk of being hit and damaged by obstacles while driving. The cabin should be by and large leak tight and temperature tolerant, especially in proximity to the gas flow. Active measures to obtain safer conditions in the cabin are a shut off of the ventilation and closing of windows upon the warning signal from the battery.

CONCLUSION

Electric Vehicle technology eliminates some of the safety concerns of conventional vehicles powered by internal combustion engines (ICE) like gasoline leakage or fuel tank bursts as a consequence of e.g. a severe vehicle crash. Yet it brings its own specific safety relevant concerns for example due to the high voltage system with 400 V or more, its energy density or a potential vulnerability of the batteries.

Safety requirements for EVs should consider the differences between the two. The selection of appropriate crash load cases for conventional ICE vehicles strives for a deformation characteristic, which allows for good restraint system performance on the one hand and a sufficient fuel system integrity to reduce the risk of car fires on the other. Some of the standard crash load cases are therefore defined to damage sensitive areas where there is a risk to penetrate fuel system components and the integrity of the fuel system is demanded. In the case of electric vehicles, the potentially critical areas may be at different locations, the possible measures to protect electric components is different to the protection of e.g. fuel pipes and specific crash tests are required to assure a comparable level of safety for these vehicles. (Plug-In) hybrid vehicles are a mix of both worlds: the safety engineers task is to protect both the gasoline as well as the electric components.

Another example is the difference in the effort necessary to de-energize the two vehicle variants: for an ICE vehicle it is sufficient to reliably empty the gasoline tank and the subsequent gas hoses from flammable liquids and vapor. In practice it is much more difficult to de-energize an electric battery on the road or in a repair shop. A clear guideline is necessary for service technicians, rescue teams, recycling mechanics or even a normal user to ensure a safe enough operation and handling of this system in every situation. Crash laboratories often handle early prototypes or other pre-production vehicles with high voltage components or systems. Also here, safety is an important aspect for everyone working in this area and specific processes and tools are used to keep a high level of safety.

With the continuous strive for higher energy densities, thermal proliferation after a malfunction cannot be fully prevented, in every case. To reach a sufficient level of passenger safety, engineers face the challenge to handle this safety threat and to at least delay the ignition of other battery cells within the pack, which is commonly referred to as thermal propagation. This Whitepaper offers a variety of measures from cell level over pack level to vehicle level to avoid or at least further mitigate such propagation.

DISCLAIMER

The exemplary solutions, described in this paper in most cases are not meant to be demanding obligations. The main intention of this publication is to demonstrate ways to improve the safety of electric vehicles. When solutions are presented, they are meant to be examples of good practice, recommendations or good engineering judgements. It well may be that the desired improvement can be achieved by alternative measures or processes. This publication shall provide possible options to achieve a higher degree of safety and the authors fully accept that alternatives exist, that might fulfil the same target.

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