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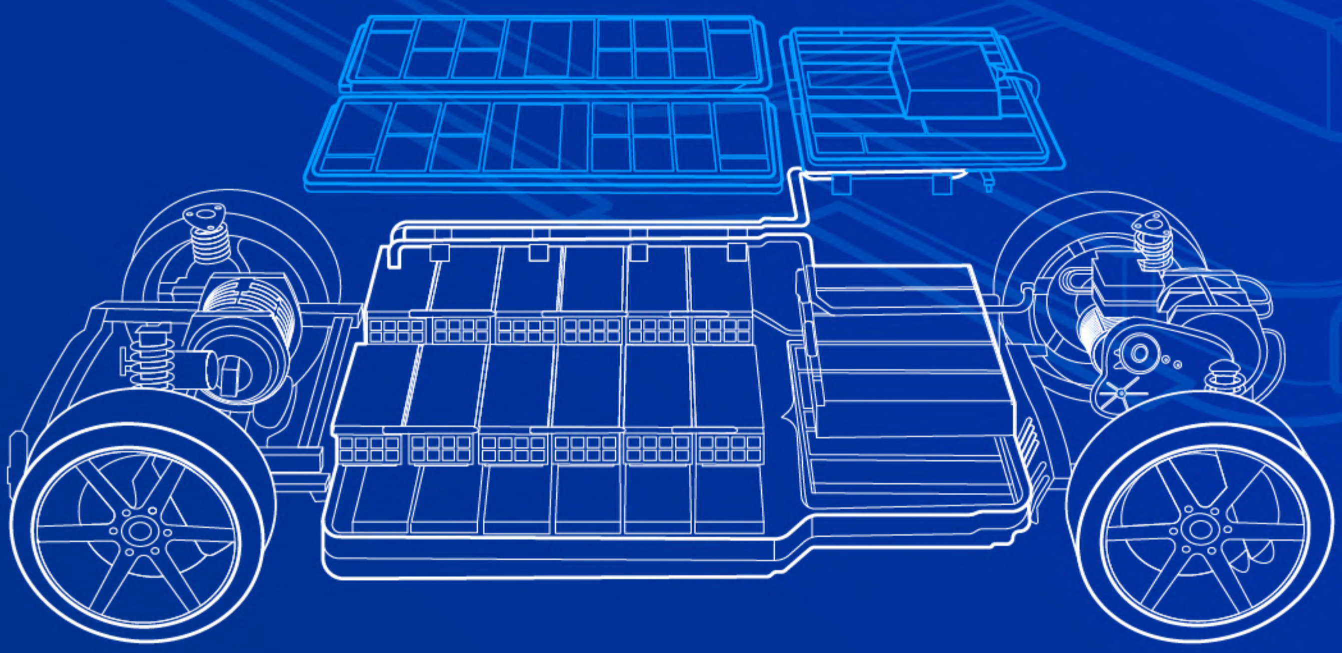
REPORT

White Paper on battery fires

Fire safety of electric vehicles and battery systems



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Cooperation F5A New Mobility Research & Consulting

In 2021, there were nearly 8 thousand car fires in Poland. None of these cases involved electric vehicles. However, the safety of zero-emission vehicles continues to be a recurring topic in public discussions, and there are numerous myths regarding fires and electromobility. This issue will become even more significant as the e-mobility market develops in Poland. According to PSPA forecasts, the total number of electric vehicles on Polish roads is expected to exceed 430 thousand by 2025. Recognizing the necessity for an evidence-based discussion on the fire safety of electric vehicles, charging stations, and charging points, we present this report. It has been compiled with the aim of gathering reliable information about this topic in a single source. The document is intended for representatives of the automotive sector, public administration, competent bodies, and electric vehicle users. The presented report is part of a broader project that aims to consolidate knowledge on the fire safety of zero-emission cars and battery systems among all stakeholders. It also seeks to develop a set of best practices and guidelines based on the latest research, reports, and international experience, which will be implemented as final solutions.

Enjoy the read.

Maciej Mazur,
Managing Director,
PSPA

Project partners

AVL	Łódź University of Technology	SPIE	Impact Clean Power Technology
Newcastle University	Renault	Office of Technical Inspection (UDT)	

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Cell-level fire protection

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1. Cell-level fire protection

Several systems and solutions are employed to ensure the safe operation of lithium-ion cells. These can be categorized as follows:

i) physical and chemical systems, and
ii) internal and external systems.

Moreover, certain systems are appropriate for specific levels within the system, such as a single battery, module, or pack for an electric vehicle[1].

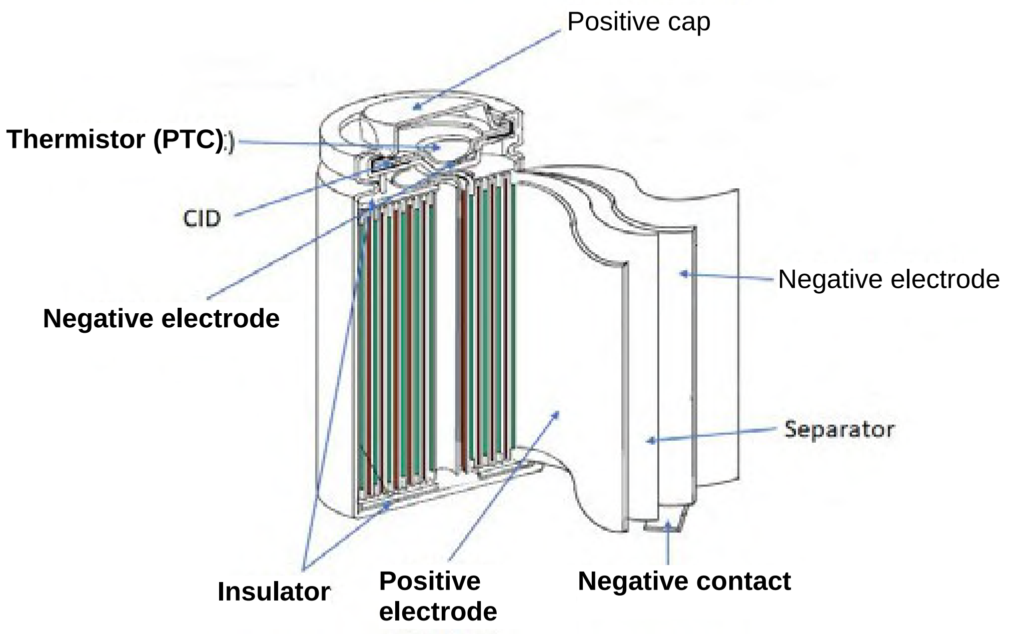

Figure 1. Cell design

[1] Xu, B. et.al. (2021) Mitigation strategies for Li-ion battery thermal runaway: A review, *Renew. Sust. Energ. Rev.*, 150, 111437, doi.org/10.1016/j.rser.2021.111437

Chemical solutions involve the addition of specific chemical substances to the electrolyte in order to modify its properties, such as flammability. These solutions are closely linked to the type of cathode used, such as NMC or LFP. On the other hand, physical systems are designed to interrupt the electrical circuit in the event of a fault. Additionally, physical solutions encompass the battery's design, including the housing type (cylindrical, prismatic, or pouch), which determines the applicable system. The above-mentioned solutions are categorized as internal battery safety systems.

External systems are concerned with the scaling of the battery, progressing from an individual battery to a module (consisting of multiple batteries) or from the module to the battery pack (composed of several modules). These systems may comprise battery management systems (BMS) and thermal management systems (TMS), which will be further discussed in subsequent chapters.

This chapter discusses the systems implemented on the level of an individual battery.

Chemical composition

The choice of lithium metal oxide chemistry in LIB (Lithium-Ion Battery) significantly influences safety due to the differing behaviors of NMC (Nickel Manganese Cobalt) and LFP (Lithium Iron Phosphate) cathodes during thermal runaway. Specifically, the exothermic collapse of the cathode structure, which marks the onset of thermal runaway, begins at around 150˚C for NMC cathodes and approximately 310˚C for LFP cathodes. Consequently, LFP cathodes were historically considered more stable and thus safer, as they rarely produce jet-like flames akin to those observed in a jet engine, unlike NMC cathodes. It's important to note that a higher onset temperature does not cause fires to start, but it does accelerate battery explosions, as demonstrated by recent incidents[2, 3].

Solid Electrolyte Interface

Another primary safety system is the Solid Electrolyte Interface (SEI), a barrier that prevents the continuous reaction of the electrolyte with graphite layers on the anode. Without it, the anode would be quickly destroyed. This barrier enables the unrestricted flow of lithium ions, enabling the charging and discharging of the battery. SEI forms during the first charging, and its thickness may vary to an extent during the service life of the battery. However, the overall tendency is for the thickness to increase over time,

[2] Shaw, V. (2021) “Two firefighters killed after Beijing battery blaze.” pv magazine.
[3] Dennien, M., (2020) Firefighter “knocked on his back” in fire blast at Griffith University, *Brisbane Times*, Brisbane, Australia

which may lead to the growth of so-called lithium dendrites, which break through the separator and cause a short-circuit resulting in a fault / TR[4].

Chemical electrolyte additives

The battery's electrolyte primarily consists of lithium salts dissolved in a non-aqueous solvent. One of the reasons why lithium-ion batteries are prone to fire incidents is the flammable nature of their electrolyte compound. To enhance the thermal stability, overvoltage protection, and reduce flammability, various chemical additives are utilized. Typically, these additives constitute approximately 5% of the electrolyte and should not compromise the overall system efficiency. Additives are commonly employed to improve the stability of the Solid-Electrolyte Interphase (SEI), incorporate redox shuttles that undergo oxidation to prevent undesirably high voltage levels, facilitate the release of gases during overvoltage to trigger the activation of other safety mechanisms, polymerize the electrolyte to impede ion transport, or form an isolation layer to prevent combustion.

While some additives may not be directly related to safety, they are introduced to suppress lithium dendrites, scavenge water, neutralize released harmful gases such as HF or PF5, and enhance SEI formation.

Physical design of the battery

The smallest functional unit of a battery is a single battery cell. When multiple battery cells are connected in series, parallel, or a combination of both, they form a module. Furthermore, an assembly of modules constitutes a battery pack. Generally, there are three main battery designs or housings: cylindrical, prismatic, and pouch[4]. It's worth noting that a fourth type, the button battery, exists, but it is predominantly used for research purposes with lithium-ion batteries. The battery's design and materials significantly impact its characteristics, such as rigidity, heat dissipation, and the feasibility of incorporating additional safety systems like gas vents or current interruptive devices.

Cylindrical batteries are metallic cylinders designed to withstand high internal pressure without deforming. The most common size for a lithium-ion cylindrical battery is 18 mm in diameter and 65 mm in length, referred to as "18650." However, newer types can have dimensions of 26x65 mm ("26650"), 21x70 mm ("21700"), or even 46x80 mm ("4680"). Electrode sheets and separators are layered, rolled, and packed into the cylindrical metal casing. This manufacturing process lends itself well to automated production methods.

[4] Christensen, PA. et.al. (2021) Risk management over the life cycle of lithium-ion batteries in electric vehicles, *Renew. Sust. Energ. Rev.*, 148, 111240, doi.org/10.1016/j.rser.2021.111240.

Prismatic cells come in various sizes depending on the intended application. They generally resemble cubes with dimensions similar to A4 or A5 paper sizes, with an overall thickness of around 16 mm. These cells feature walls made of metal or rigid plastic to ensure structural integrity. Electrode sheets and separators are layered alternately, rolled less tightly than in cylindrical cells, and placed inside the cuboid casing.

The third cell type is the pouch cell, also known as a laminated cell. It is a flexible bag usually in the size of A4 paper, with a thickness of a few millimeters. The electrodes and separator are placed together and sealed within the pouch. Due to its design, pouch cells are less rigid compared to other cell types and may experience swelling under high internal pressure. The absence of rigidity and the internal placement of electrodes make it unsuitable for using current interrupt devices.

Current interrupt devices

Current interrupt devices (CIDs) are designed to halt the current flow when the pressure or internal temperature inside the battery reaches a specific threshold in order to prevent thermal runaway (TR). However, once the CID is activated, the battery becomes unsuitable for further use[5]. It's important to note that CIDs can only be installed in cylindrical batteries due to their design limitations.

The CID functions as a valve that opens when there is a significant rise in pressure (>10 bar). Such conditions may arise from overvoltage, overcharging, or electrolyte breakdown, which leads to excessive gas production within the battery. The increased pressure disrupts the connection between the battery's electrodes and its positive terminal, effectively stopping the current flow. The interruption of current flow should help reduce gas release (lowering the pressure) as the energy supplied is required for chemical reactions. This type of CID is known as a pressure-responsive device.

Another type of CID is the thermal-responsive device, also known as a thermal fuse, which is installed at the battery's terminals. If the internal temperature exceeds a certain threshold, the thermal-responsive CID melts, thereby interrupting the current flow.

Positive temperature coefficient thermistor

A Positive Temperature Coefficient thermistor (PTC) is a thermal resistor that exhibits a change in electrical resistance corresponding to temperature variations. It serves to limit current flow in the event of an external short-circuit. When the temperature (or pressure)

[5] Li, W. et.al. (2020) Comparison of Current Interrupt Device and Vent Design for 18650 Format Lithium-ion Battery Caps. *J. Energy Storage*, 32, 101890, doi.org/10.1016/j.est.2020.101890

rises to a hazardous level (>100 °C), the PTC thermistor heats up, increasing its resistance and restricting the current flow. As the temperature decreases, the resistance of the PTC thermistor decreases as well, allowing normal current flow to be restored within the battery. Unlike the CID, the PTC is a reusable system. It is typically installed in the cap of cylindrical batteries, regardless of their size. In the case of prismatic batteries, the PTC can be placed outside the battery without impacting its functionality.

Vents

During a thermal runaway (TR) event, the battery generates a significant amount of gas, leading to a rapid increase in internal pressure. In extreme cases, if the pressure cannot be alleviated, it can cause the battery housing to burst. To address this risk, safety vents are employed to expel excess gas from the battery in a controlled and expeditious manner. The vent is typically a component of the housing deliberately designed with lower mechanical strength to rupture and create an opening under unfavorable conditions. In the case of cylindrical batteries, the vent "opens" when the pressure exceeds 27 bar, while for prismatic cells, it occurs at a lower threshold of 8-10 bar. Pouch batteries, on the other hand, do not have dedicated vents; if the maximum pressure is surpassed, they simply rupture[6]. Vents are typically incorporated into the battery cap and may consist of multiple release holes. However, it is possible for a vent to become clogged, such as when cathode nanoparticles become trapped by the gas, leading to increased pressure and potential housing rupture. To mitigate this risk, certain manufacturers have introduced an additional valve at the bottom of the battery. This valve facilitates a faster release of gas from the battery, reducing the likelihood of clogging.

Shutdown separator

The separator is a crucial component of a lithium-ion battery that plays a significant role in ensuring efficiency and safety. Certain separators have the ability to "shut down" reactions occurring between two electrodes. When the internal temperature reaches hazardous levels, the separator begins to melt or deform, forming a physical barrier that obstructs the movement of ions[7][8].

[6] Li, W. et.al. (2020) Comparison of Current Interrupt Device and Vent Design for 18650 Format Lithium-ion Battery Caps, *J. Energy Storage*, 32, 101890, doi.org/10.1016/j.est.2020.101890.

[7] Li, Z., Xiong, Y., Sun, S., Zhang, L., Li, S., Liu, X., et al. (2018). Tri-layer nonwoven membrane with shutdown property and high robustness as a high-safety lithium-ion battery separator. *J. Memb. Sci.* 565, 50–60. doi: 10.1016/j.memsci.2018.07.094

[8] Ould, ET., Kamzabek, D. and Chakraborty, D. (2019). Batteries Safety: Recent Progress and Current Challenges. *Front. Energy Res.* 7:71. doi: 10.3389/fenrg.2019.00071

Summary

The aforementioned systems greatly enhance the safety of lithium-ion battery usage and generally operate effectively when a single battery or a small number of batteries are utilized. However, they prove inadequate for modules or battery packs. The heat generated by a thermal runaway in one battery can raise the temperature of neighboring batteries, leading to thermal propagation. Considering that batteries within modules are interconnected in series, parallel, or a combination of both, the overall circuit voltage may surpass the PTC limit of just one battery, delaying the response of the entire system. In another scenario, overvoltage in a module or the entire battery pack can result in a single CID causing sparks through an electric arc. This, in turn, can ignite the released gas and flammable electrolyte inside the battery, giving rise to flames. Due to the restricted space within the battery pack, the released gases can easily obstruct the safety vents in individual batteries or the vents of the battery packs. Hence, it is of utmost importance to implement additional safety systems that operate at the module or pack level, such as a battery management system (BMS), temperature management system (TMS), or vents incorporated into the housing. Furthermore, adhering to a stringent regimen of cleanliness and quality control throughout the production of lithium-ion batteries is critical to ensure the proper functioning of all the aforementioned safety systems.

2

Battery-level fire protection

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Battery-level fire protection

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2. Battery-level fire protection

Fires in lithium-ion cells occur when the cell's temperature rises or when severe overcharging takes place, leading to the decomposition of its components known as "thermal runaway." This process is highly exothermic and self-sustaining. The cell loses its integrity, releasing a mixture of flammable gases that can ignite. In the case of electric vehicles, fires can be caused by collisions or accidents that result in mechanical damage to the battery system.

In most cases, fires occur due to a short-circuit, which takes place when the anode comes into contact with the cathode. Factors that may contribute to battery ignition also include high temperature and cell overheating as a result of, for instance, the fire of spilt fuel or overheating due to incorrect charging or overcharging. This causes a sudden temperature rise and melting of the separator between the electrode, as a result of which the battery heats up further. The loss of control over the increasing temperature of the system causes thermal runaway, starting a chain reaction, which is particularly dangerous in batteries consisting of multiple cells because it initiates reactions in further cells, which are often undamaged. When the temperature increases, the cathode releases oxygen, which reacts with the organic electrolyte, eventually causing the battery to ignite or explode.

Non-mechanical causes of li-ion battery fires can also include design errors, not limited to buses or cars. One notable incident involved the market recall of 2.5 million Galaxy Note 7 devices due to a design flaw. The battery manufacturer failed to provide sufficient space between the electrodes, resulting in an explosion during smartphone charging when the electrodes expanded slightly, causing a short circuit. Another reason may be the overcharging of the battery due to, for instance, the use of a poor-quality charger. Most manufacturers use mechanisms that prevent this, which is why the poor quality of the battery, and the charger is more dangerous to users of smartphones than to users of vehicles. Another risk may be an external source of high temperature.

Preventive measures can reduce the risk of battery ignition. Proper operation of traction batteries, which avoids overcharging and overheating, significantly eliminates the risk of spontaneous fires. This is achieved through the implementation of a battery management system (BMS). The BMS includes first and second protection systems that automatically cut off power supply in the event of any risks. Additionally, manufacturers are responsible for using non-flammable materials in battery packs and ensuring proper cell separation to prevent fire propagation. The mechanical structure of the packs should also minimize the spread of heat as a risk factor. In summary, when battery systems are used correctly and in accordance with the manufacturer's recommendations, fires caused by li-ion cells are extremely rare.

Regulation No 100 of the Economic Commission for Europe of the United Nations (UNECE)

Regulation No 100 of the Economic Commission for Europe of the United Nations (UNECE) – Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train [2015/505] – defines the conditions and safety tests required for traction batteries to obtain type approval and be permitted for use.

The third revision of the UN Regulation was formally approved and became effective on 9 June 2021. The implemented revisions are in line with the general guidelines of the “Global Technical Regulation” GTR No. 20: “Electric Vehicle Safety”.

The most important changes concerning energy storage facilities (REESS) Part 2 of the Regulation

1) List of tests to be performed:

- → vibration tests
- → thermal shock
- → mechanical shock (“impact”)
- → mechanical integrity (“crushing”)
- → fire resistance
- → short-circuit protection
- → overcharge protection
- → over-discharge protection
- → over-temperature protection

2) List of new tests to be performed:

- → overcurrent protection (REESS for vehicles of categories M1 and N1)
- → low-temperature protection (may be demonstrated via documentation)
- → management of gases emitted from REESS (the requirement is considered to be met if a battery other than an open-type traction battery successfully passes all other tests)

3) The driver must receive a warning of a fault of the REESS monitoring system (monitoring from the level of the vehicle)

4) The driver must receive a warning of battery overheating

5) The driver must receive a warning 5 minutes before the danger (fire, explosion) unless such a heat increase is not dangerous to the people in the vehicle. The manufacturer of the battery has to prove that it has taken adequate action to mitigate the risk to vehicle users. It is recommended to follow, for instance, ISO 26262 (Functional safety).[9][10]

[9] Regulation No 100 of the Economic Commission for Europe of the United Nations (UNECE) – Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train [2015/505] (OJ L 87, 31/3/2015, p. 1, ELI: http://data.europa.eu/eli/reg/2015/100/oj)
[10] *Kamil Przewoski, IDIADA Poland,* https://www.linkedin.com/pulse/r10003-baterie-i-samochody-elektryczne-coraz-bardziej-kamil

3

Vehicle-level fire protection

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3. Vehicle-level fire protection

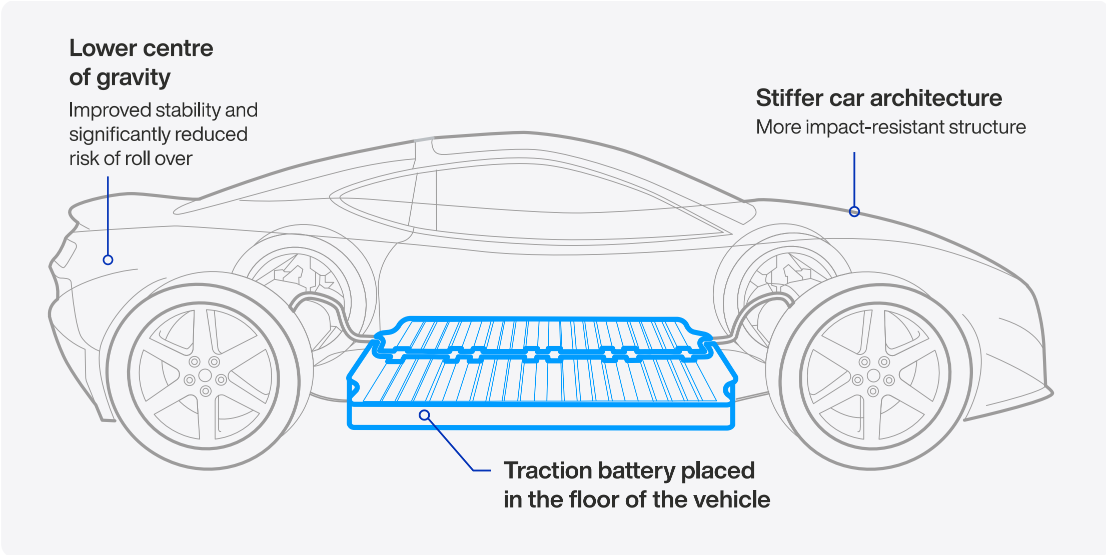
Electric vehicles must meet the same requirements as vehicles with internal combustion engines to be approved for traffic and sale. One of the requirements is Regulation No 100 of the Economic Commission for Europe of the United Nations (UN/ECE).

Most important changes introduced in 2021 in Regulation No 100 concerning vehicles / Part I of the Regulation

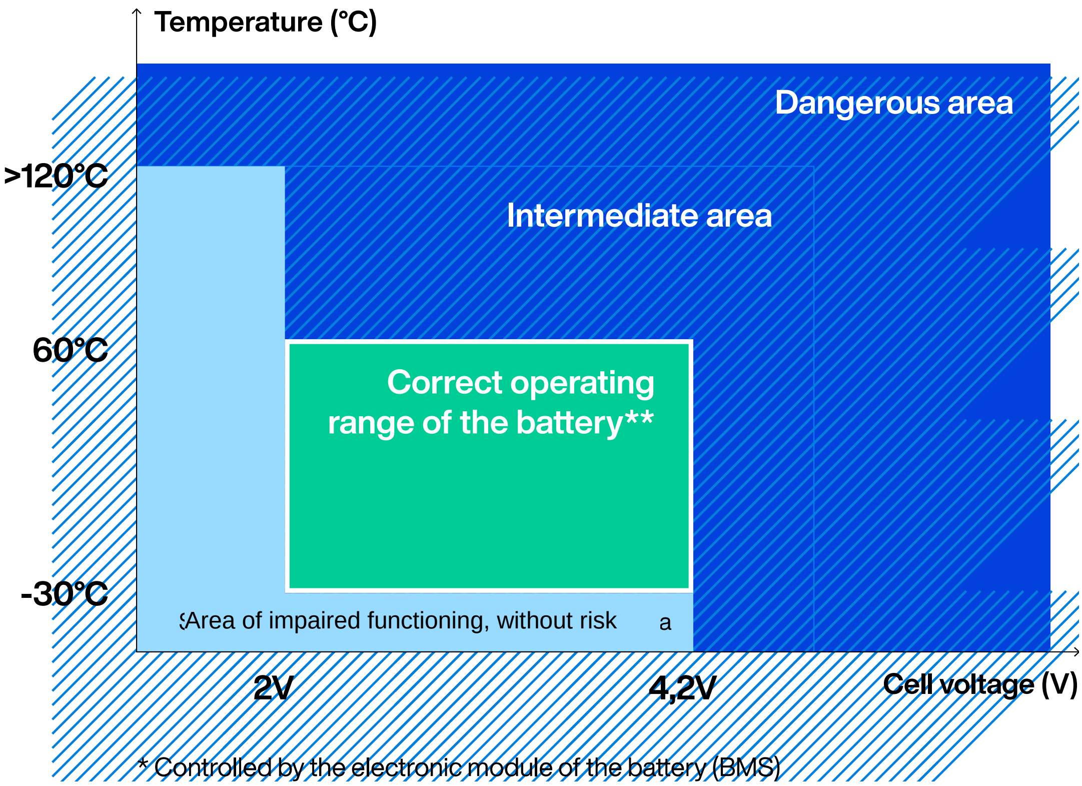
- It was explicitly confirmed that R100 also applied to low-voltage vehicles with batteries / Energy storage (REESS)
- New requirements were added concerning the protection of HV connections in the vehicles
- A new requirement was added concerning the resistance of safety barriers located less than 2.5 m away from each other
- The requirement concerning maximum DC voltage for the test of insulation resistance was removed
- It is necessary to install an insulation monitoring system – also in vehicles with fuel cells (hydrogen cars)
- It is necessary to protect the electrical system of the vehicle against water jets – a special testing procedure has been developed for this requirement
- Additional requirements were added concerning fault alerts –the vehicle level and energy storage

Source: *Kamil Przewoski, IDIADA Poland,* https://www.linkedin.com/pulse/r10003-baterie-i-samochody-elektryczne-coraz-bardziej-kamil

Fire safety of lithium-ion batteries
Reinforced EV design



Electric vehicles are equipped with a traction battery that undergoes rigorous safety tests to assess its resilience against mechanical damage, electrical damage, thermal damage, and internal faults within the cells. The main objective of these tests is to verify that the design of the traction battery, installed in both electric and hybrid vehicles, effectively mitigates the risk of spontaneous combustion throughout its operational lifespan.



In the case of electric vehicles and hybrid vehicles, there are two main types of fire hazards:

→ spreading of fire from outside the vehicle
→ arson

3.1. Case Study according to the Renault Group

In 2010, the Renault Group decided to engage in close collaboration with the road accident rescue services regarding the rescue of people. The evolving structure of vehicles on our roads has been undergoing rapid changes, necessitating significant adaptations in the operational procedures of emergency services. In parallel with the introduction of the first electric vehicles, the Renault Group began to intensify its partnership with fire department units.

Specific requirements concerning electric vehicles and hybrid vehicles

Electrified vehicles pose an additional consideration for emergency rescue teams in the development of field procedures. The protection of the vehicle's electrical system becomes crucial in these cases. Unlike vehicles with internal combustion engines, where the standard procedure involves protecting the battery used for car equipment (12/14 V), electric and hybrid vehicles require additional measures. This is because the impact speeds in such vehicles often exceed those specified by Euro NCAP protocols. In electric and hybrid vehicles, it is essential to safeguard the high-voltage (400 V) battery and its power cables. These protective measures should not hinder the rescue of passengers and must ensure 100% safety. Manual safety features for high-voltage batteries are located in various parts of the vehicle, depending on the manufacturer, such as the trunk, engine block, or under the seat. Therefore, it is crucial for the fire department to have access to the decision aid card.

To ensure the safety of passengers trapped inside their vehicles, Renault and Dacia, as part of their cooperation with emergency services, have ensured that no electrical cables pass through areas that need to be cut for extrication purposes.

Similar to electricity meters in homes, electric vehicles manufactured by the Renault Group also have a main disconnect switch. This switch allows for the direct disconnection of power cables. For example, in the Renault ZOE, the switch is conveniently located in the leg space on the passenger side in the front, making it easily accessible.

A faulty electric vehicle or hybrid vehicle cannot pose an additional threat to emergency services, which is why:

→ high-voltage cables are run outside the safe extrication areas
→ the service plug of the high-voltage battery is placed directly on the battery
→ access to the service plug for the rescue crews does not require moving the pelvis of the passenger(s)
→ new solutions are introduced – in the case of Renault: fireman access and QR code that significantly shorten the time of intervention

Fireman Access

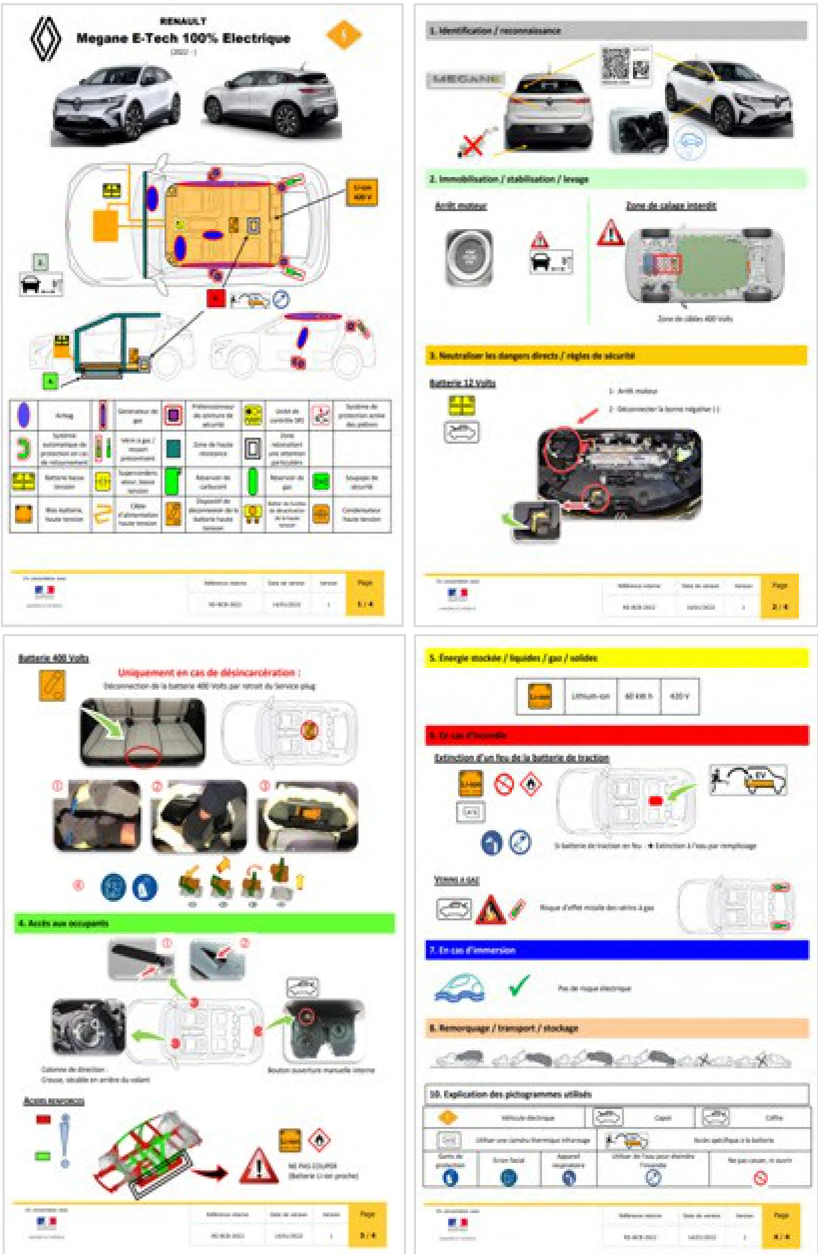
The electronic module (BMS) routinely monitors the temperature and voltage of individual cells and responds accordingly to prevent the self-ignition of the battery. If one battery in an electric or hybrid Renault vehicle is already on fire, it may be extinguished if its cells are quickly cooled down with water. Traction batteries are fully sealed – their design prevents water from getting inside. In cooperation with firemen, Renault has developed a technical feature referred to as Fireman Access to enable feeding water to the inside of the traction battery to extinguish the vehicle in a time similar to the time required to extinguish a car with an internal combustion engine.

Figure 1.
Traction battery Electric Renault Megane E-Tech with the Fireman Access system and the service plug

The Fireman Access system, a result of over ten years of collaboration between the Renault Group and the fire department, is an innovative special access system designed for rescue teams. Its purpose is to enable them to swiftly deliver water to a burning battery and extinguish the flames within a timeframe of 5 minutes and not – as is the case with electric vehicles without this system – within one to three hours.
Furthermore, in addition to this groundbreaking solution, the car features a conveniently accessible disconnect located under the back seat. This disconnect allows rescue services to swiftly disconnect the battery from the high-voltage circuit in the vehicle.

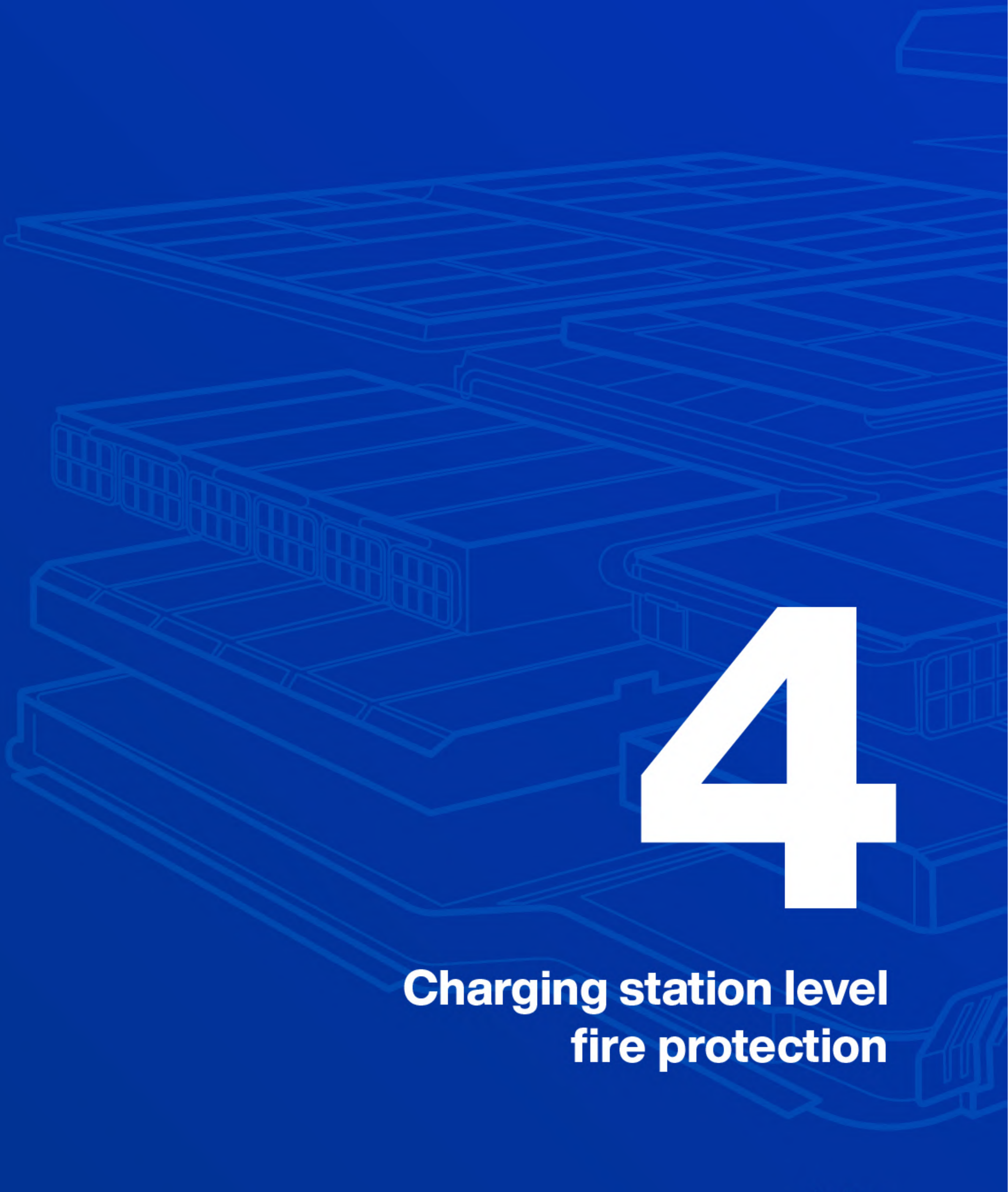
QR code and rescue card

The second innovation is the QR code. It is a label used for scanning that is placed on the windscreen and rear window of the vehicles. It enables the rescue teams to quickly access all required technical information about the vehicle that is necessary for rescue actions. The information is collected in a so-called intervention card. After reaching a damaged vehicle, the rescue teams can scan the QR code and instantly determine if it is a hybrid vehicle, a plug-in hybrid vehicle or an electric vehicle and conduct rescue operations accordingly. In particular, this includes information concerning the design details such as the location of the traction battery and airbags, areas that enable quick and easy extrication, etc. This helps to accelerate rescue operations and shorten the time required to take the passengers out of the broken vehicles by as much as 15 minutes.



Rescue cards can be downloaded using the Euro Rescue and Rescuecode applications.

The provision of intervention cards initiated by the Renault Group has led to a series of positive changes in the area of road safety because the cards are currently required by the Euro NCAP organization when they assign their stars.



4

Charging station level fire protection

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Charging station level fire protection

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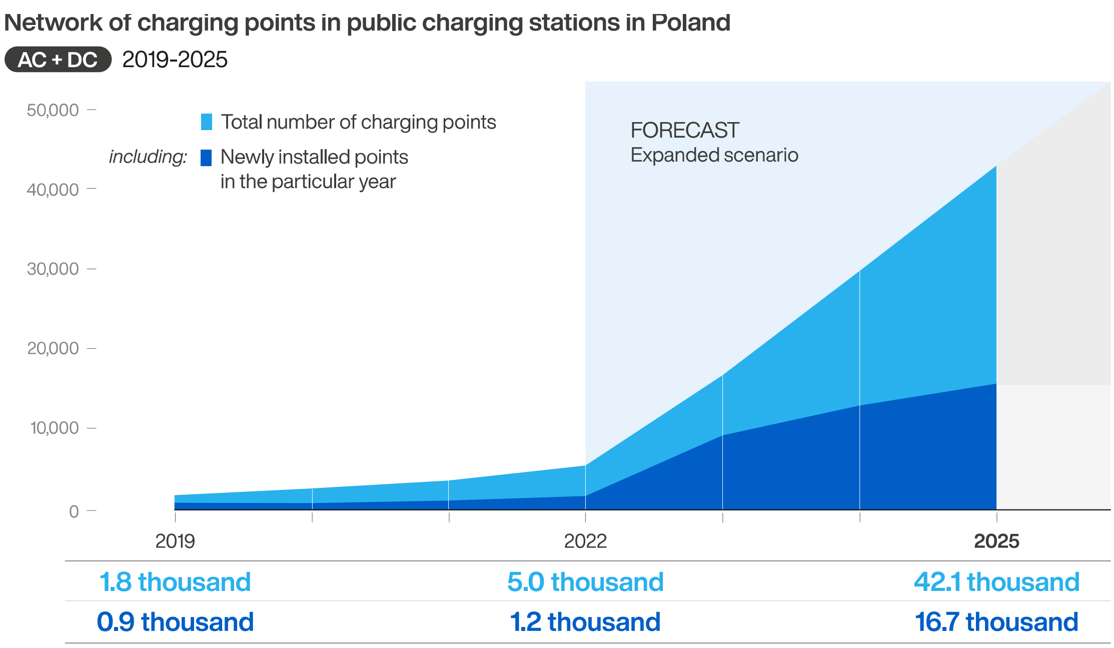
4. Charging station level fire protection

Public charging infrastructure in Poland
Development forecast



Source: Polish EV Outlook 2022, PSPA

Charging stations must meet the technical and operating requirements defined, in particular, in the Polish Standards that enable their safe use, including fire safety and safe functioning of power grids. Compliance with these requirements guarantees the safety of the stations to the users and the surrounding area.

During the preparation of the user manual for the charging station, the manufacturer should already include instructions on how to respond in the event of a fire at the charging station. Additionally, the manufacturer needs to determine the fire protection requirements for the charging station. The Office of Technical Inspection verifies the inclusion of these requirements in the user manual by inspecting the documentation submitted along with the request for the technical inspection of the charging station.

The key fire safety requirements for charging stations are as follows:

→ prohibition on using faulty equipment or using equipment contrary to its intended use,
→ prohibition on using the stations in conditions other than those prescribed by the manufacturer of the equipment,
→ prohibition to storing flammable materials and lighting fires near the equipment.

Regardless of the above, when requesting a technical inspection of the charging station, the operator must also provide a **report on conformity to fire safety requirements issued by a fire risk surveyor.**

The list of licensed fire risk surveyors can be found in the public information bulletin of the National Headquarters of the State Fire Service [x1], and it is updated on an ongoing basis.

The report should specifically pertain to a particular charging station, including its identification, rated parameters, and fire protection requirements at the installation site. Another aspect relevant to the safe operation of the charging station is the technical inspection conducted by a technical office inspector at the installation site. During this inspection, the inspector directly or indirectly verifies the following areas that affect the fire safety of the charging station:

→ Visual inspection of the equipment, including the presence of features protecting the charging station from collision risks, checking sockets, cable plugs, and glands for tightness and moisture protection, and verifying the operator's contact information in case of station faults or fires,

→ Safety measurements, including measurements related to electric shock protection, insulation resistance, continuity of protective conductors, functioning of residual-current devices, and insulation monitoring devices (IMD) (if applicable),

→ Functional tests, including the activation of the emergency stop switch (if applicable).

The successful completion of the technical inspection of the charging station by the technical office inspector is certified with a suitable certificate enabling the operation of the charging station. This confirms that the particular charging station can be operated safely.

Information prepared by the Fire Protection Association (FPA), a UK organization, indicating the recommendations for the use of fire protection and safety features depending on the location of the charging station and the related risk level:

Recommendations for the use of fire protection and safety features at the charging station

Location	Fire protection and safety features	Risk level
Basement	→ automatic fire suppression system → ventilation → access for the fire department → drainage of firefighting water	
Public space (e.g., a car park in the city)	→ mechanical protection against collision (kerbs, bollards, barriers) → safe fastening of the charging cable at the charging station → CCTV surveillance	
Indoor space (ground floor or first floor)	→ fire detection sensor → automatic firefighting system → ventilation → fire extinguishers → fire barrier	
Top floor of the building (e.g., car park on the roof)	→ fire extinguishers → firefighting water drainage	
Dedicated detached building	→ fire detection sensor → fire extinguishers → lightweight structure, including the roof → safe distance to other buildings	
Safe space (e.g., RSA at a motorway)	→ mechanical protection against collision (kerbs, bollards, barriers) → safe fastening of the charging cable at the charging station → fire extinguisher	

Source: RC59: Recommendations for fire safety when charging electric vehicles. Fire Protection Association (FPA). 2021

5

Potential sources of fire

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Potential sources of fire

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5. Potential sources of fire

Frequency of vehicle fires
Number of vehicles per 100,000 vehicles

Source: New York Times citing AutoInsuranceEZ

The scenarios of electric vehicle fires are still being updated. However, they can be initially categorized into one or more of the following cases:

- → EV ignites when parked (spontaneous ignition). This may be due to extreme weather conditions (low/high temperatures, high humidity, damage due to saltwater) or an internal fault of one of the cells.
- → EV ignites during charging. This fault may be due to a battery failure caused by overcharging and/or faulty or unprotected charging stations and/or cables.
- → EV ignites due to a collision or another type of mechanical damage.
- → EV batteries often heat up and re-ignite after the fire is extinguished.[11]

[11] Sun P., Huang X., Bisschop R., Niu H., (2020), A Review of Battery Fires in Electric Vehicles, Fire Technology, https://doi.org/10.1007/s10694-019-00944-3

Battery fire tests

Regrettably, research on large-scale testing of EV batteries remains inconclusive and has been conducted to a very limited extent. The available literature cautions against the incorrect interpretation of data regarding battery fires on a small scale and using it to assess the hazards associated with real-scale electric vehicle fires. Therefore, the expected magnitude of EV battery fires is still uncertain. To illustrate, let's consider the battery in a Tesla Model S, which weighs 2250 kg, five times more than the tested battery cell (45 g for the 18650 cell). The heat release rate for a fire involving the entire battery is increased three times, not five times. Consequently, the heat release rate of a battery fire can range from several kilowatts for a single battery cell to several hundred kilowatts for an individual EV battery, and even several megawatts for a full-scale fire involving an electric vehicle.

In fire engineering studies, the heat release rate (HRR) is the most important parameter in the assessment of the fire hazard connected with EVs used to assess the designs of car park fire safety systems. The heat release rate HRR [kW] is the standard indicator of the design size of the fire, and it can be adopted as:

$$HRR = \dot{m}\Delta H_e = A_f \dot{m}'' \eta \Delta H_c \quad (1)$$

where $\dot{m}$ is the combustion rate [kg/s] determined by the rate of loss of specimen mass during a combustion test [20]; ΔH_e is the heat of combustion [MJ/kg]; A_f is the area of the fuel or fire source [m^2] being the basis for EV; $\dot{m}''$ is the mass burning rate [kg/m^2s]; ŋ is the burning intensity, which depends on the availability of oxygen, and ΔH_c is the heat of combustion of EV batteries, which changes depending on the battery type.

The energy of an EV fire can also be assessed using the average heat flux (q'') of the battery and its area. For the calculations of the expected design heat release rate of the fire, the battery charging level can be assumed to be 100%, which is the worst-case fire scenario.[14] For the example of an electric vehicle supplied with lithium-titanium batteries (LTO), the average heat flux (q'') is approximately 2.3 MW/m^2 in the fully charged phase.[15] Considering the area of the battery $A_{EV} \approx 3\ m^2$, the average HRR of a fire of such an EV can be estimated as 7 MW (1).

$$HRR = A_{EV}\, q'' = 3\ m^2 \times 2.3\ MW/m^2 \approx 7\ MW \quad (2)$$

[12] Sun P., Huang X., Bisschop R., Niu H., (2020), A Review of Battery Fires in Electric Vehicles, Fire Technology, https://doi.org/10.1007/s10694-019-00944-3
[13] Liu X, Wu Z, Stoliarov SI et al (2016) Heat release during thermally induced failure of a lithium-ion battery: impact of cathode composition. Fire Saf J 85:10–22. https:// doi.org/10.1016/j.firesaf.2016.08.001
[14] US Department of Transportation (2014) Interim guidance for electric and hybrid electric vehicles equipped with high-voltage batteries. DOT HS 811 575.
[15] Wang Q (2018) Study on fire and fire spread characteristics of lithium-ion batteries. In: 2018 China national symposium on combustion.

The scale of the battery fire (HRR) calculated using the methods described above can also be used to determine the required amount of water or other firefighting media needed to extinguish the fire.

The absence of comprehensive fire tests for electric vehicles (EVs) restricts our engineering understanding of the actual fire risk associated with their usage. However, the referenced calculations suggest that the commonly accepted design heat release rate (HRR) for fire protection systems in car parks should be around 7 MW, which is comparable to conventional vehicle fires. Nevertheless, it is important to acknowledge that the heat release rate is likely to escalate much more rapidly in this scenario.

6

Car fires indoor

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6. Car fires indoor

6.1. Regulatory requirements for indoor spaces (indoor car parks)

The increasing urbanization and rapid growth of the automotive industry over the past few decades have necessitated the development of appropriate infrastructure. This infrastructure includes not only road systems, petrol stations, and workshops but also, importantly, an adequate number of parking spaces. The goal of maximizing the utilization of residential, commercial, hotel, or office development areas has led to the construction of enclosed and often underground indoor car parks. According to the Construction Law, all civil structures, including their individual components, must be designed and constructed in compliance with relevant codes, such as building codes, and in accordance with good technical practices[16]. These requirements encompass various aspects, including fire protection measures for car parks. The primary objective when designing such facilities is to ensure the safety of users during evacuation, facilitate effective operations for rescue and firefighting teams, and protect the building structure.[17]

The latest amendments to the regulation on technical requirements for buildings and their location regarding the fire protection of car parks were introduced in 2018. The most important rules for car park design have been discussed below, with a particular focus on issues connected with smoke ventilation[18].

[16] Construction Law of 7 July 1994 (Journal of Laws of 2013, item 1409, as amended)
[17] Regulation of the Minister of Infrastructure of 12 April 2002 on the technical requirements for buildings and their location (Journal of Laws No. 75, item 690, as amended)

Car parks located below the second underground storey, if they do not have a direct entrance or exit, must be fitted with automatic water-based firefighting systems (§ 277(3) of the Regulation on technical requirements for buildings and their location [18]).

The requirement to utilize automatic smoke control devices applies to car parks that have a fire zone size exceeding 1500 m2 or smaller car parks without a direct entrance or exit (as stated in Section 277(4) of the Regulation on technical requirements for buildings and their location). In an enclosed car park, the smoke ventilation system must effectively extract smoke to prevent its accumulation or the rise of temperatures that could impede safe evacuation within the required evacuation time for individuals in protected passages and evacuation routes. Additionally, the system should maintain a constant supply of outside air to compensate for the air discharged along with the smoke (as specified in Section 270(1)).
According to Section 237(6)(2), the distance to the nearest emergency exit, which should not exceed 40 m in an enclosed car park, may be extended by 50% if automatic smoke control systems activated by the smoke detection system are employed. However, this provision does not apply when a jet-fan smoke ventilation system is utilized (as outlined in Sections 278(2) and (3)).

6.2. Rules for designing fire ventilation systems in indoor car parks according to European standards

The most widely used standard in Poland, followed by designers and experts, is the British Standard BS 7346-7:2013. This standard provides recommendations and guidelines for the operation of smoke and heat removal systems in fully enclosed car parks, partially enclosed car parks, and even car parks accommodating vehicles powered by LPG. According to this British Standard, the designed system aims to achieve one of three objectives. These objectives include: removing smoke during and after a fire (using ducted and ductless systems), facilitating smoke-free access to the fire source for rescue teams (primarily through ductless systems), and/or safeguarding evacuation routes within the car park area (using ductless systems or smoke and heat control systems, also known as SHEVS). It is important to note that the discussed standard does not mandate the installation of sprinkler systems for car parks. However, the impact of sprinklers is taken into account when determining the design fire parameters. If the car park is equipped with a water-based firefighting system, the recommended total heat release rate for the design fire is 4 MW (6 MW for two-storey car parks). In cases where no firefighting system is installed, it is necessary to consider the risk of ignition from another vehicle, and the total heat release rate should be 8 MW. Currently, there are no specific requirements for the design heat release rate of electric vehicle fires.

[18] BS 7346-7:2013 Components for smoke and heat control systems – Part 7: Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered car parks

The alternative standard, Belgian NBN S 21-208-2, is not commonly used in Poland due to its stringent requirements for car park smoke ventilation systems, which exceed the general level of fire safety mandated by Polish regulations. However, there are compelling reasons to consider adopting this standard as the dominant one, especially with the increasing number of electric vehicles that require improved access for emergency firefighting services compared to conventional cars. The standard is applicable to car parks larger than 1000 m2. According to this standard, in the event of a fire, the fire ventilation system should allow users of the car park to safely evacuate while maintaining smoke-free access to the fire location from the outside, within a maximum distance of 15 m from that point. If a ducted smoke ventilation system is utilized, the standard imposes several conditions depending on whether the car park has a sprinkler system. The minimum required height for a car park employing ducted smoke ventilation with water-based firefighting systems is 2.8 m, while for car parks without such systems, it is 3.8 m. Additionally, the smoke-free layer should be maintained at least 0.3 m below the lowest part of the upper floor slab, with a height of 2.5 m in the first case and 3.5 m in the latter. These stringent requirements aim to ensure that the temperature beneath the upper floor slab does not exceed 200°C, allowing unrestricted movement for both evacuees and rescue teams. The standard also necessitates dividing the car park into smoke zones with a maximum length of 60 m and an area of 2600 m2 (2000 m2 for natural ventilation). In car parks that do not meet the requirements for ducted ventilation, the standard mandates the use of jet-fan ventilation[19]. This is a very reasonable rule, also analyzed and confirmed many times in Poland[22]. However, due to vague regulations, this rule is often not followed in practice.

The primary objective of implementing fire protection measures is to achieve a level of building safety that aligns with the local regulations. In Poland, the requirement to determine the expected evacuation time for people and the fire conditions and parameters on evacuation routes in planned buildings arises from § 270(1) of the aforementioned Regulation 18. Critical parameters regarding the safety of individuals and the conditions for evacuation on evacuation routes, as specified in the regulation concerning the technical requirements for metro stations (currently considered a mandatory requirement for all civil structures in this context), include smoke accumulation not exceeding a height of 1.8 m on the floor, visibility of building edges and luminescent evacuation signs limited to a maximum of 10 m, air temperature not exceeding 600°C at a height of 1.8 m or lower, and 200°C in the layer under the ceiling at a height greater than 2.5 m from the floor.

[19] NBN S 21-208-2 Protection incendie dans les batiments. Conception des systems d'evacuation des fumees et de la chaleur (EFC) des parkings interieurs
[20] Brzezinska D., Powstanie i rozwój inżynierii bezpieczeństwa pożarowego w Polsce [Formation and development of fire safety engineering in Poland], BiTP, 2(2016), 141–149
[21] Regulation of the Minister of Infrastructure of 17 June 2011 on technical requirements to be met by metro structures and their location (Journal of Laws No. 144, item 859)

A key aspect is the inclusion of an appropriate number and layout of emergency exits in the car park area, which affects the calculated travel time based on the distance from the farthest point in the car park to the emergency exit and the average speed of people's movement. The required safe evacuation time, which is the time from the onset of the fire until the planned number of people can evacuate to a safe location, includes not only the time needed for people to move but also the time for fire detection, alarm activation, and the pre-movement time (the time from receiving the fire alarm warning until the first and last person begins to evacuate). Designs should ensure early fire warning, and fire detection and alarm systems should provide timely warnings to allow for a complete evacuation before conditions become hazardous. The time between the start of the fire and its detection depends on the chosen fire detection system, and the proper selection and placement of fire detectors can significantly reduce this time.

7

Fire protection of car parks in the context of charging stations and parking electric vehicles

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7. Fire protection of car parks in the context of charging stations and parking electric vehicles

In terms of regulatory requirements in Poland and the USA, there are no additional provisions mandating the use of firefighting systems (such as fixed water-based systems or ventilation) at electric vehicle charging station installations.

The necessity of providing firefighting systems in car parks, including fixed water-based systems like sprinklers and mist systems, depends on the specific building codes applicable in each country. Requirements vary, with the most stringent regulations typically applied to fully enclosed and underground car parks.

From the perspective of insurance companies and their recommendations, in turn, the risk connected with electric vehicle charging stations/points and the parking of hybrid and electric vehicles is real and depends primarily on the type/location of the car park (underground, fully enclosed).

Insurance companies recommend implementing organizational and technical measures to mitigate fire risk and enhance safety:

- selecting the optimum place of installation for the charging stations (preferred locations include unenclosed car parks, roof spaces, etc., with fully enclosed and underground car parks being the least recommended),
- installing water/mist sprinkler systems (fixed water-based firefighting systems),
- using additional fire barriers,
- installing smoke/fire detection systems.

It is worth emphasizing that as designers, project owners, users, and insurers become increasingly aware of the fire development and firefighting operations involving hybrid/electric vehicles, there is a growing need to employ and recommend firefighting systems that enhance fire safety in car parks. Examples of such systems include smoke detection systems, smoke ventilation systems, and fixed water-based firefighting systems (sprinklers and mist systems).

Fires involving electric vehicles and equipment with Li-ion batteries pose a challenge for the fire protection industry. Manufacturers and research institutes in various countries, such as RISE Research Institutes of Sweden and DBI – The Danish Institute of Fire and Security Technology, are currently working on addressing this challenge through testing and research.

Based on current knowledge and preliminary test results and simulations, a recommended solution appears to be a combination of early smoke/fire detection and modern firefighting systems utilizing high-pressure water mist.

However, due to the dynamic nature of the fire protection market and the extensive testing and research conducted by manufacturers and research institutes, it is advisable to regularly review and adhere to legislation and recommendations to employ technical solutions that enhance fire safety.

7.1. Legislative situation in Poland

The obligation to use fixed water-based firefighting systems and smoke ventilation systems for car parks is only mandatory in the situations defined in the Regulation of the Minister of Infrastructure of 12 April 2002 on the technical requirements for buildings and their location. It should be noted that the regulation concerns all car parks, without any distinction as to whether they are intended for vehicles with internal combustion engines / electric vehicles.

The secondary legislation for the Electromobility and Alternative Fuel Act of 11 January 2018 includes the following:

- → Regulation of the Minister of Energy of 26 June 2019 on the technical requirements for charging stations and charging points forming a part of charging infrastructure for public road transport
- → Regulation of the Minister of Development of 16 September 2020 amending the regulation on the technical requirements for buildings and their location
- → Regulation of the Minister of Infrastructure of 12 April 2002 on the technical requirements for buildings and their location.

The above-mentioned documents do not include any additional requirements for the use of fire protection systems (detection, ventilation, fixed firefighting systems) at places of installation of vehicle charging stations and points. However, the Regulation of the Minister of Energy of 26 June 2019 on the technical requirements for charging stations and charging points forming a part of charging infrastructure for public road transport requires the approval of the documentation by a fire risk surveyor, as an appendix to the documentation submitted with the request for an inspection by the Office of Technical Inspection (UDT).

The obligatory use of fixed water-based firefighting systems / smoke ventilation systems / smoke detection systems in car parks is defined in the Regulation of the Minister of Infrastructure of 12 April 2002 on the technical requirements for buildings and their location. The Electromobility and Alternative Fuel Act of 11 January 2018 and the related secondary legislation did not introduce any additional requirements for the use of fixed water-based firefighting systems / smoke ventilation systems / smoke detection systems in car parks used for the installation of electric vehicle charging points.

7.2. Legislative situation in the USA

According to RISE report 2020:30: there are no requirements for the use of fire protection systems (fixed water-based firefighting systems, smoke ventilation systems, smoke detection systems) at places of installation of vehicle charging points and stations. However, regarding fully enclosed car parks, NFPA 88A requires the installation of fixed water-based firefighting systems (sprinkler systems) according to NFPA 13.

7.3. Position of VdS according to Leaflet VdS 3856en

In its position, VdS finds that car parks for EVs or, generally, vehicles with Li-Ion batteries are classified according to VdS CEA 4001, i.e., as an OH2 hazard. The system should be able to suppress the fire (not extinguish it). Thus, for car parks with charging stations/points, the parameters of the sprinkler system are the same as for the protection of car parks according to VdS CEA 4001. Also, regarding the remaining requirements (layout, electrical protection), the document refers to other VdS guidelines.

7.4. Case study – concept of protection using a high-pressure AQUASYS system implemented by SPIE Building Solutions for a housing cooperative in Warsaw

SPIE Building Solutions prepared a concept for a housing cooperative that designed an oversized system for automatic extinguishing using a high-pressure water mist (AQUASYS system) for 30 parking spaces intended for the parking and charging of electric/hybrid vehicles. The system, as a technical solution intended to increase fire safety and protect the property of the users, will be started automatically (Firefighting Control system detectors) or manually (START buttons). This proposed technical solution aims to leverage the benefits of early fire detection facilitated by multi-sensor detectors, combined with a modern extinguishing system employing high-pressure water mist.

Operating principle of the high-pressure water mist system

- → The extinguishing agent is water, which is converted into water mist under high pressure in dedicated nozzles. The water mist created in this way, with adequately sized droplets (smaller than 1000 microns) is supplied at a high rate to the area under fire.
- → Thanks to the large specific surface area of the droplets and the increased absorption of thermal radiation, the water mist quickly cools down the combustion area and the gases in the surroundings.
- → This limits the fire from spreading. Also, the safe extinguishing agent, i.e., water mist, improves the conditions for the evacuation of people and facilitates firefighting operations by the fire department.

Properties of water mist

- → High vaporization rate enables the absorption of an enormous amount of heat from the fire source – approx. 2.3 MJ per liter of water,
- → The mist locally displaces oxygen from the burning area through instant vaporization (water increases its volume 1672 times during the liquid-vapour phase transition),
- → By cooling down the burning area and absorbing enormous amounts of heat, the risk of fire spreading and re-ignition (flashover) is minimized.

8

Selected methods for fighting electric vehicle fires

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Selected methods for fighting electric vehicle fires

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8. Selected methods for fighting electric vehicle fires

Tests carried out by the Federal Aviation Administration (FAA) in the USA demonstrated that water-based firefighting agents proved to be the most effective. Their effectiveness stemmed from their ability to extinguish the burning electrolyte while simultaneously cooling the cell. Hence, the substantial importance of a significant amount of water as the cooling medium was established.

8.1. Stingray One and Testbed System

Stingray One is a system designed to prevent a vehicle from completely burning down in the event of a traction battery malfunction. AVL offers two systems, Stingray One and the Testbed System, which facilitate controlled testing conditions and can effectively prevent the spread of fire resulting from a battery fire.

Both systems achieve this objective by employing a common approach, which involves extinguishing the burning battery from within by inserting a needle and dispensing water or another extinguishing agent onto the battery. This approach reduces the quantity of extinguishing substance required, minimizes the duration of the fire, and prevents the fire from spreading to other vehicle components.

The battery is punctured using a dedicated needle operated by a mechanism utilizing compressed air. The needle, with one end inserted inside the battery, allows for the introduction of the cooling medium. Test results indicate that the specific location of the puncture does not significantly impact effectiveness; the crucial factor is ensuring that the needle penetrates the battery.

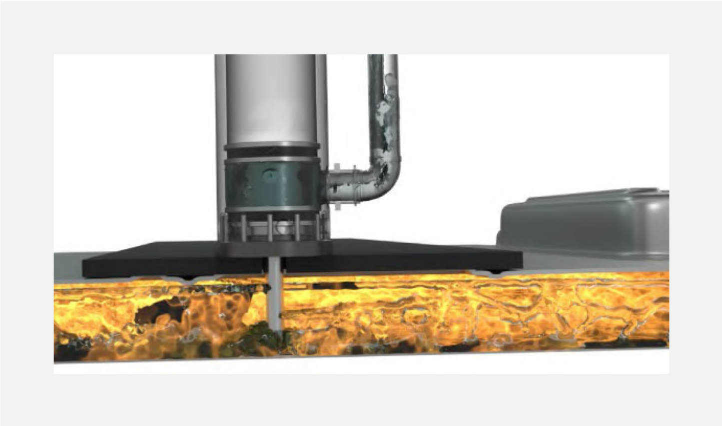

Figure 1. Visualisation of the needle penetrating the battery

To verify the effectiveness of the equipment, AVL conducted numerous tests using various battery types. Tests specifically focused on the battery alone, excluding the vehicle, were carried out utilizing the Testbed System. This allowed for the evaluation of the system's efficiency under safe and controlled conditions. Notable examples demonstrating the effectiveness of the solutions include a test conducted using the battery from the VW ID.3. Prior to the test, the battery was charged to a minimum of 97%. The ignition was initiated by simultaneously short-circuiting three cells. Approximately 30 seconds after the appearance of the first flames, the extinguishing process commenced. Within approximately 1 minute and 20 seconds from the start of the process, the fire was brought under control. To prevent re-ignition, the battery was cooled down to a temperature of around 30°C, with water being used for the extinguishing process. The total water consumption did not exceed 1000 liters. The battery was equipped with 42 temperature sensors, three pressure sensors, and one sensor to monitor coolant flow to ensure continuous monitoring of changes. Additionally, battery voltage was measured throughout the test.

Stingray One

Stingray One is a firefighting system specifically designed for field use by firefighters. The system is compact and lightweight, weighing approximately 20 kg, allowing for easy deployment in actual emergency conditions. With its dedicated mounting system, Stingray One can be swiftly installed in less than one minute. It is simply placed on the vehicle's floor, above the battery, and pressed against the car's roof. In the case of a convertible car, Stingray One is equipped with specialized lashing eyes to secure it with a chain or belt.

The concept revolves around installing the system inside a burning vehicle and initiating the extinguishing process remotely using a control unit from a safe distance. The key advantage of this system is its reusability. If there is uncertainty about whether the fire has been completely suppressed after extinguishing the battery, and the possibility of re-ignition remains, the system can be left inside the vehicle without the supply of extinguishing medium. If the battery re-ignites, the water supply can be activated, and the extinguishing process can be remotely restarted.

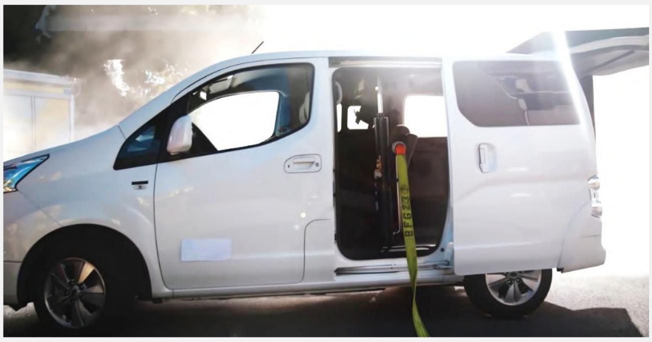

Figure 2. Sample use of the Stingray One device

In reference to the drawing below, Stingray One consists of the following main parts:

- → Support (1)
- → Handle (2)
- → Storz C coupling (3)
- → Device for filling the compressed air reservoir (4)
- → Valve to release the extinguishing system (5)
- → Connection to release button (6)
- → Air reservoir (7)

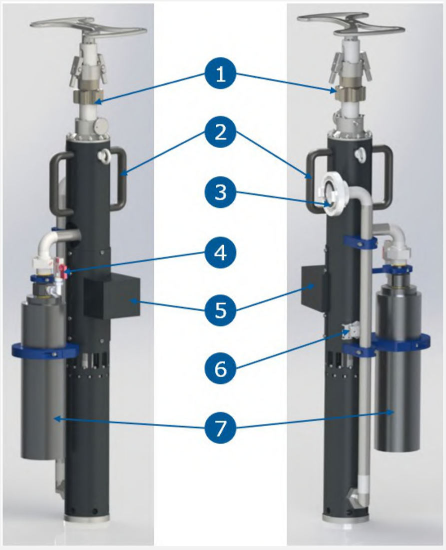

Figure 3. Stingray One

Components of the remote control unit are described below:

→ Connection to lance (approx. 10m long cable) (8)
→ Release button (9)
→ Main switch (10)
→ Connection for charging (11)

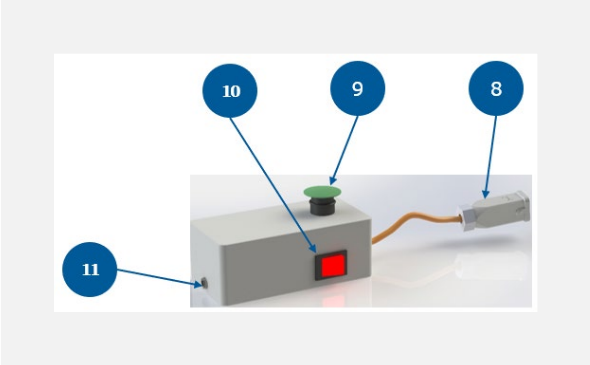

Figure 4. Remote control unit

Testbed System

This is a fully automatic system that can start the extinguishing on its own. The combination with the fire detection system expands the capabilities of the system.
The Testbed System consists of 2 main components:

→ Trolley – on the trolley, there is a PLC cabinet to control the system, a pump to change the water pressure and additional compressed air supply.
→ Penetration Unit – the penetration unit is mounted in a vehicle or on a battery to test a prototype vehicle in a safe and controlled way.

Figure 5. Trolley

Figure 6. Penetration unit

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