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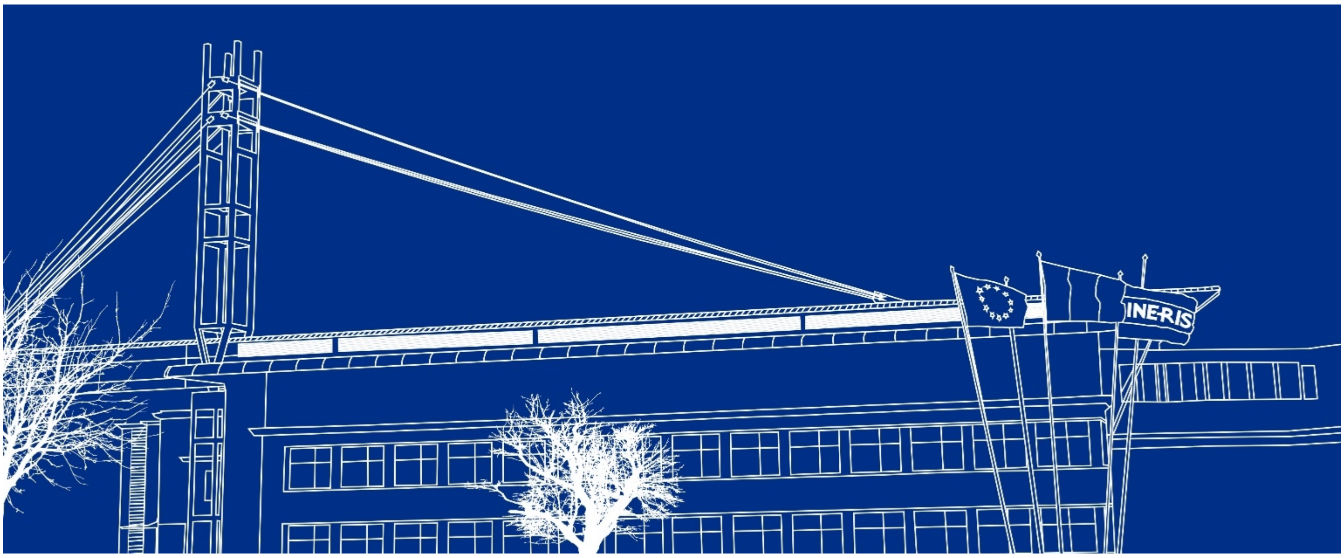

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Summary of work on extinguishing Li-ion batteries fires of electric vehicles

25 septembre 2024

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1 Introduction

The data from accidents and intervention reports indicates that extinguishing Li-ion battery fires is difficult for all applications. A 2022[1] study (Ineris report - 207085 - 2759437 - v1.0) revealed that the extinguishing systems, when equipped, often failed to effectively stop the spread of thermal runaway and generalized fire in containerized systems. In the automotive sector, extinguishing fires involving electric vehicle batteries is even more difficult due to the inaccessibility of the active battery components, which are integrated into different sub-assemblies and the vehicle chassis, hindering extinguishing agents from reaching the core of the battery pack.

This document aims to identify fixed and mobile extinguishing systems for Li-ion battery fires in electric vehicle applications and assess their effectiveness. It is based on literature research and discussions between Ineris and fire safety organizations.

2 Main characteristics of an electric vehicle fire with a Li-ion battery

2.1 Battery packs of electric vehicles

Depending on the intended application, the energy of the pack used in the electric vehicle may vary considerably, and the environment close to the pack will be very different (e.g., the presence or absence of a gasoline-powered internal combustion engine).

As shown in Figure 1, we can distinguish:

- Fully electric vehicles (BEVs), which have a purely electric motor powered by a high-energy battery (up to 100 kWh) with a voltage close to 400V;
- Plug-in hybrid vehicles (PHEV), with dual electric/thermal drive. The battery is of intermediate energy (8 to ~18 kWh) and voltage close to 400V;
- Hybrid vehicles (HEVs), which have an internal combustion engine assisted by one or more electric motors. The battery capacity is low, in the kWh range, and the voltage is generally around 200V.

To date, the battery is generally located under the passenger compartment floor in cars, on the roof or at the rear in buses, and behind the front axle in trucks.

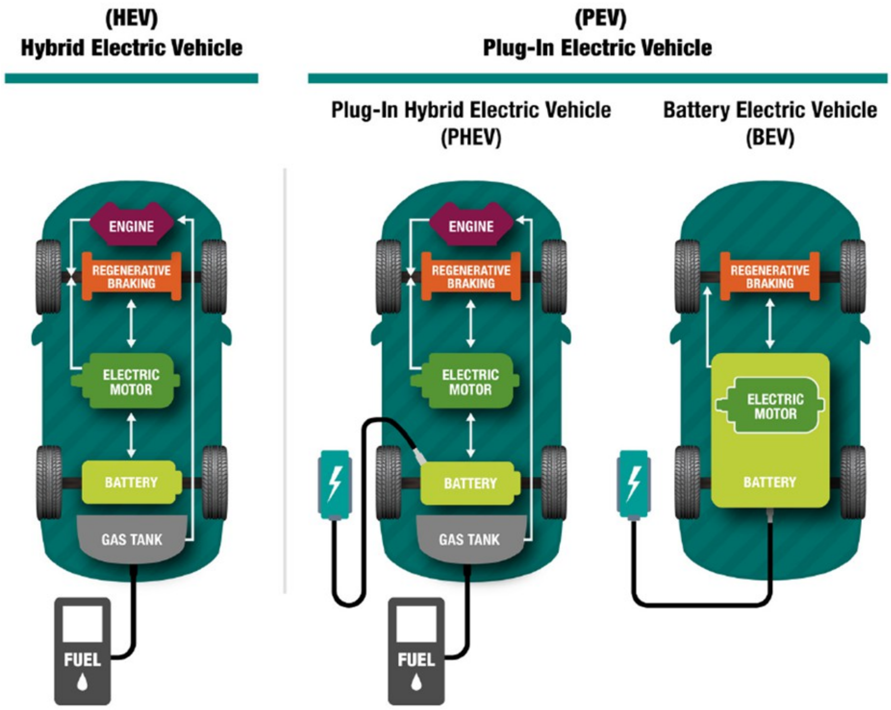


Figure 1: Schematic diagram of HEV, PHEV and BEV vehicles[2]

2.2 Inventory of electric vehicle fires

In recent years, particularly since 2017, there has been a significant increase in the market share of electric vehicles in the global automotive market, and at the same time, an increasing number of electric vehicle fires are reported each year. From 2010 to November 15, 2023, 430 electric vehicle (BEV and PHEV) traction battery fires were recorded (Figure 2)[3].

31% of fires occurred when the vehicle was parked outside, 25% when the vehicle was parked in an enclosed space (underground parking lot, garage, etc.) and 29% while driving. 18% of fires occurred when the vehicle was charging, and 2% within an hour of a charging point being disconnected. 95% of all incidents resulted in a fire, and 5% in an explosion due to gas accumulation (Vapour Cloud explosion). Of the 5% involving a gas explosion, 70% occurred in an enclosed space (underground parking lot, garage, etc.).

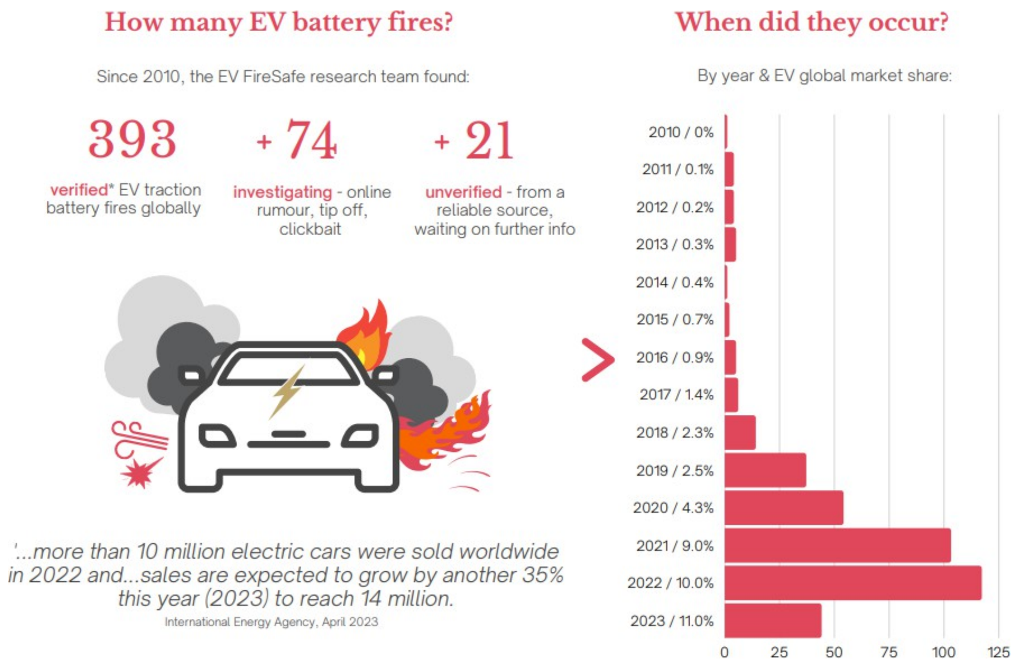


Figure 2: Extract from the infographic on electric vehicle battery fires (2010 to June 30, 2023)[4]

Several scenarios triggering thermal runaway have been identified:

- Charging the battery pack when the electric vehicle is parked (overcharging, BMS fault, unsuitable charger, etc.);
- External factors, which can cause the battery to overheat more or less immediately (heavy rain/immersion, external fire, malevolence, following a shock, collision, etc.);
- Factors internal to the battery (poor design/manufacturing) and/or unidentified.

Of course, it is important to remain cautious about using statistics, given the current penetration rate of electric vehicles in the global vehicle fleet and the cultural and technical differences in representative reporting on electric vehicle fires.

2.3 The main effects of a thermal runaway of an electric vehicle pack

Based on experience feedback and combustion tests carried out solely on electric vehicle battery packs and on complete electric vehicles by NFPA[5], Ineris[6] and the Brigade des Sapeurs-Pompiers de Paris (BSPP), the main findings are as follows:

- when the battery is involved in the fire, it only takes a few seconds for combustion to become intense. The combustion duration of an electric vehicle equipped with a Li-ion battery varies according to the energy stored. It can be as long as 1h30,
- for battery packs made up of small individual cells, projections of these cells can be observed up to several tens of meters away (case of a fire on a Tesla after a violent collision in 2020 in the USA),
- "pop" noises and/or gas emissions may be heard, and electric arcs and sparks may be observed,
- Fire tests carried out by various teams on BEV, PHEV and internal combustion vehicles show that the instantaneous peak power (Heat Release Rate-HRR) measured on electric vehicles is similar to that of internal combustion vehicles, in the order of 6 to 9 MW, depending on vehicle size and battery energy[7,8,]
- Jet fire (directional flames) or hot gas jets linked to battery pack combustion can be observed, representing a particular feature of electric vehicle fires (Figure 3). This jet fire can occur intermittently over several tens of seconds. The length of the flame varies according to the design of the pack. However, a flame length of 2 to 3 m seems to be a good order of magnitude; a length of 2.56 m has been reported in recent tests on electric vehicles[9] (Figure 3b). High temperatures (> 1000°C) are reached inside the vehicle and in the battery pack,
- Fume emissions are observed. Combustion tests on equivalent electric and internal combustion vehicles carried out at Ineris showed that similar quantities of CO_2, CO, total hydrocarbons, NO, NO_2, HCl and HCN were emitted by the 2 types of vehicles. However, the HF content was higher for electric vehicles, due to the combustion of the Li-ion battery pack. This information indicates that the toxic risk of fire fumes is present whatever the type of vehicle, electric or internal combustion. In addition to these gases, the fumes emitted by the batteries contain particles that can be very small and contain metals, which is a particular feature of electric vehicle fires. To date, little is known about the consequences of these particles,
- under certain conditions, particularly in confined spaces such as underground parking lots or garages, the accumulation of gases released by thermal runaway of the battery pack, in the absence of instantaneous ignition on degassing of the cells entering thermal runaway, is likely to generate an explosive atmosphere (ATEX) capable of triggering an explosion in the presence of an ignition source (hot surface, sparks ejected during thermal runaway, electric arcs, etc.). This is also a particular feature of electric vehicle fires and is a risk that has only recently been identified through feedback. An example of a Vapour Cloud Explosion (VCE) in an underground parking lot is shown in Figure 4a[10]. This VCE phenomenon can also occur inside the vehicle's passenger compartment, as demonstrated by an incident in Belgium in November 2023 involving a Jeep PHEV during recharging; while firefighters were extinguishing the battery's thermal runaway with water (smoke emission without ignition), an explosion occurred in the cabin, throwing the vehicle's roof off[11] (Figure 4b).

a) *b)*

Figure 3: a) Jet fire from a Tesla Model X battery pack after a collision in California in 2017 b) Length of a jet fire measured during a test on an electric vehicle

a) VCE in an underground parking lot, China, April 2019

b) VCE in a passenger compartment PHEV vehicle

Figure 4: Examples of VCE during thermal runaway of automotive batteries

3 Means of extinction and intervention against thermal runaway of Li-ion batteries in electric vehicles

Extinguishing strategies based on agents that isolate the fuel from the oxidizer, or on agents that inhibit the chain reactions that sustain combustion, are more difficult to implement, given that Li-ion battery fires are very different from fuels ones, and that some of the oxygen is available in the form of metal oxides in the active cathode materials. In addition, and above all, the cooling mechanisms conventionally targeted by aqueous extinguishing agents often come up against specific difficulties associated with the thermal runaway mechanism, which remains a source of heat production internal to the Li-ion battery, potentially lasting over time and more or less inaccessible to liquid extinguishing agents, depending on the battery's design (cf. § 3.2 of the report).

The main characteristic of an extinguishing agent in the event of a battery fire is its ability to cool the electrical energy reservoir, in order to limit the ignition of internal substances, but also to limit the spread of thermal runaway from one cell to another, from one module to another and, more generally, to limit the spread of fire to the vehicle as a whole and from vehicle to vehicle (or to other combustible elements).

Subsection 3.1 deals with the evaluation of various extinguishing agents for small-scale Li-ion battery fires (on a cell or assembly of cells); subsection 3.2 deals with the means of firefighting against thermal runaway and its propagation at pack and vehicle scales.

3.1 Small-scale: evaluation of the effectiveness of various extinguishing agents

There are many different extinguishing agents, each with its own unique characteristics.

3.1.1 Gaseous agents

Gaseous agents are divided into two main families:

- inert, "physically acting" gases. Extinguishing with these agents is achieved by reducing the oxygen content of the ambient air to stop the combustion reaction. The best-known internal gases used for extinguishing are carbon dioxide (CO_2), nitrogen (N_2) and argon (Ar), either pure or in mixtures. **Various studies[12,13,14] show the ineffectiveness of inert gases in the event of a Li-ion battery fire**, due in particular to the generation of oxygen by the battery cathode (metal oxides) during the thermal runaway process,

- halogenated hydrocarbons, known as "chemical action" or inhibitors. They act primarily through the physical mechanism of heat absorption and inhibition of the chain reaction responsible for combustion. Non-conductive agents are generally chosen to act against electrical fires to prevent short circuits or other electrical malfunctions. These inhibiting agents include the halon family (less and less usable due to their environmental impact), hydrofluorocarbons (HFCs), FM-200 (HFC 227ea), but also NOVEC 1230. **Accident analysis, studies and tests carried out[12,15,16,17] indicate that inhibiting agents cannot adequately treat Li-ion battery fires** due to their relatively low cooling power. On the other hand, halocarbon-based agents have the major disadvantage of forming toxic and corrosive by-products when exposed to high temperatures[18] such as CO, HCl, NOx and HF[14]. Another residual risk associated with their use is the formation of a secondary ATEX "after the first flames have been extinguished", through the outgassing of cells entering thermal runaway by propagation.

3.1.2 Solid agents

Solid extinguishing agents include :

- o Powder extinguishers acting by isolation, cooling, asphyxiation and chemical inhibition. Extinguishing tests carried out at the Wuhan Institute of China Classification Society on Li-ion batteries showed that **powder extinguishing agents had very little effect**[13],
- o solid aerosols whose mode of action is chemical inhibition by interrupting chemical chain reactions at the molecular level. Examples include agents based on potassium salts. In the case of batteries, chemical reactions are complex, and the analysis of certain incidents (report on the Perles et Castelet[19] accident involving a stationary system) mentions that the **potassium salt-based automatic extinguishing system fitted to the container, as dimensioned, proved ineffective**.

3.1.3 Liquid agents

There are many different liquid extinguishing agents, each with its own unique characteristics. The main ones can be classified as follows:

- o water (used as a baton jet, by flooding action or diffused in automated systems (sprinklers, deluge systems, water mist)),
- o water-based agents and additives,
- o emulsifying agents: saponifying aqueous solution (foam),
- o aqueous vermiculite dispersion (AVD).

3.1.3.1 Aqueous or biphasic agents

Numerous small-scale extinguishing tests using aqueous agents have been carried out on Li-ion cells and assemblies of a few cells. **At this scale, the results of these studies showed that water and aqueous agents (water and additives) were the most effective** for cooling the cell, limiting the propagation of a thermal runaway within a group of a few cells, and that this effectiveness increased with the volume applied[20]. Water has the best cooling capacity and significantly reduces cell temperature.

Water mist extinction tests at cell/cell assembly scale have been carried out by several research teams[21,22, 23, 24, 25.] The tests carried out as part of these studies showed that the effectiveness of water mist applied to a Li-ion cell fire depended in particular on droplet size, spray duration, fog particle dynamics and its ability to reach the combustion surface through the smoke generated by the battery.

For example, some studies[21,26] show that water mist is effective against fire in Li-ion cell assemblies, reducing the spread of thermal runaway from cell to cell under certain conditions, whereas other studies[27,28] show that pure water mist is relatively ineffective, with a heat dissipation rate of only 3.54% of the heat released during thermal runaway of an 18650 cell. It is therefore difficult for pure water mist to slow down the rapid rise in cell temperature during thermal runaway. Thus, the addition of additives to water mist has been extensively studied, and a clear improvement in extinguishing efficiency has been demonstrated after the addition of additives[27,29]. The cooling effect of water mist containing additives is influenced by both surface tension and foaming capacity. The additive with lower surface tension and foaming capacity improves the heat transfer of the water mist.

Tests with and without the application of water mist have shown that the maximum instantaneous HF concentration recorded when water mist is applied to the flames is around two times higher than during tests without extinguishing[25]. This is because the water mist provides more [H] radicals, resulting in higher HF formation. In subsequent tests, the HF was rapidly dissolved in the water mist, resulting in a rapid decrease in HF concentration[30]. It should also be noted that some road tunnels are equipped with water mist extinguishing systems (e.g. the double-decker A86 tunnel southwest of Paris) which the effectiveness had been tested in large-scale trials on conventional vehicles in Switzerland.

3.1.3.2 Foaming agents

Fire extinguishing tests on 18650-size Li-ion cells carried out by the fire department of China's Ministry of Public Security showed that the use of AFFF (Floating Film Forming Agent) foam agents did not completely extinguish the fire, and reignition was observed. Foam contributes to cooling, but compared with water, it is more difficult for foam to penetrate the space inside battery packs and cool the interior of the batteries[14].

3.1.3.3 Aqueous vermiculite dispersion (AVD)

Vermiculite is dispersed in water after grinding, forming a stable dispersion of vermiculite in water. Its extinguishing mechanism mainly involves cooling and insulating by forming a film on the surface of batteries. Tests to extinguish thermal runaway of 21,700 Li-ion cells showed that aqueous vermiculite dispersion (AVD) effectively reduced the battery surface temperature and prevented the fire from re-igniting and spreading. However, in these tests, the agent is applied directly to the cells. Other tests show that AVD takes longer to extinguish a battery pack fire than other aqueous extinguishing agents, as it is difficult for the high-viscosity AVD extinguishing agent to penetrate the space between the cells/modules[14].

3.1.4 Conclusion on the effectiveness of various small-scale extinguishing agents

Small-scale studies show that:

- the cooling effect of currently available gaseous extinguishing agents is poor, with a high risk of thermal runaway propagation or battery reignition. In confined spaces, gaseous extinguishing agents can increase toxicity and reduce oxygen concentration in the space, representing risks to be taken into account by firefighters in the event of a fire,
- the solid extinguishing agent has an insufficient cooling effect and low penetration capacity between the cells. As a result, the extinguishing effect is limited and the battery will continue to burn or reignite,
- Among liquid extinguishing agents, water-based agents have the greatest cooling capacity and are the most effective against a Li-ion cell fire. Appropriate additives can significantly improve the cooling capacity of pure water and reduce water consumption. Emulsifying (foam) and vermiculite-based (AVD) agents are less effective due to their difficulty in penetrating the spaces between cells/modules and cooling the batteries. It should be noted that all liquid agents can have a certain impact on the battery due to their conductive properties, and in particular, can lead to short-circuiting, as well as on the environment through run-off of polluted extinguishing water if not contained.

These results are illustrated in Figure 5, which shows the results of extinguishing tests on a Li-ion cell. Water, followed by foam, is the most effective agent for cooling the cell alone. The effectiveness of water mist is lower and depends, in particular, on the uniformity of the water mist, the size of the droplets, and the impulse at which the droplets reach the combustion surface. Gaseous (CO_2) and solid (powder) agents are the least effective.

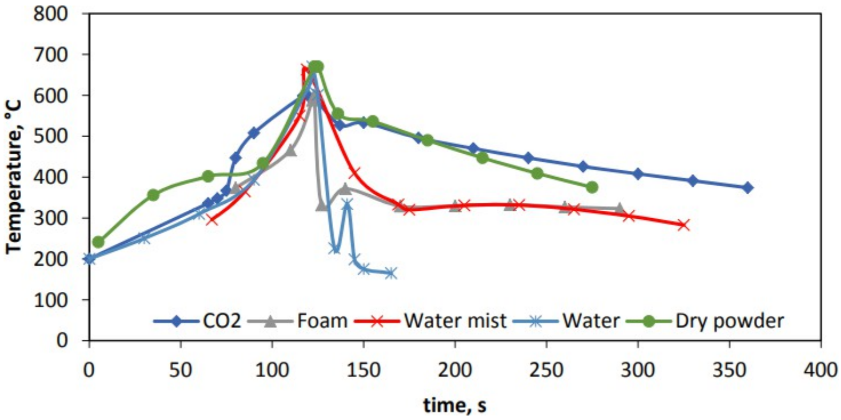


Figure 5: Temperature evolution during extinction tests on a Li-ion cell[31]

As far as the normative context is concerned, only one Dutch standard (NTA 8133) was published in 2021[32]. This is the first publication for fires involving medium-capacity Li-ion batteries up to 600 Wh (batteries used in smartphones, laptops, power tools, drones, electric bikes, etc.). This standard describes the test procedure to be applied to assess the effectiveness of an extinguishing agent. Thermal runaway of the battery is initiated by overcharging, and the extinguishing agent is applied as soon as the first flames appear. The fire must be extinguished within 3 minutes, with no re-ignition observed for 20 minutes after extinguishing, and a portion of the cells must be operational[33]. A standard for Li-ion battery extinguishing is currently being prepared at European level (CEN), based in particular on Dutch work, with a view to extending it to larger scales. This will require further experimental work.

The studies presented in section 3.1 were carried out on a small scale (cells and cell assemblies). It is necessary to assess the effectiveness of extinguishing agents on a larger scale (pack and vehicles), which is the subject of the following sub-section 3.2.

3.2 System scale (pack and vehicle): main means of firefighting against thermal runaway and its propagation

3.2.1 Fire blanket

A fire blanket is a fire-fighting device commonly used to smother small fires; in particular, it stops the production of smoke and cuts off heat radiation. This technology has recently been extended to cover vehicle fires. These blankets are generally made from specific materials, with dimensions of around 6 m x 9 m, to cover most vehicles completely. The blankets feature integrated handles that enable firefighters to physically apply the containment blanket directly to the burning vehicle. Once the fire blanket is placed over the burning vehicle, it limits the oxygen available from the environment and limits heat transfer. Its effectiveness has been demonstrated on incipient fires in conventionally powered vehicles.

In tests carried out by Austrian fire departments on electric vehicles[34], the use of the blanket led to a significant reduction in heat release. However, as the oxygen supply to the fire is partly provided by the battery itself, it is not possible to smother the flames - as would be possible with conventional fuel. The battery's thermal runaway phenomenon continues under the blanket. After around 3 minutes, the attempt with the fire blanket had to be abandoned, as among other things, the fire blanket had already been damaged.

It has been shown that the use of a fire blanket, once the battery is already involved in the fire, does not provide significant added value. The application of the blanket must be carried out without the presence of air pockets between the blanket and the vehicle, which is very difficult in the case of a battery fire due to the dynamics of the fire (strong flames close to the ground) and the generation of oxygen by the battery.

It's not easy to set up these blankets; there has to be enough space around the vehicle, and workers have to get close to the burning vehicle or pack, and may be put at risk (Figure 6) - this operation requires workers to be trained and aware of the risks, and to wear appropriate personal protective equipment (in particular fire resistance clothes and self-contained breathing apparatus SCBA).

It is important to note that re-ignition can occur when the fire blanket is removed from the vehicle. A recent test[9] showed that a large amount of white smoke was emitted when the fire blanket was removed, and that re-ignition occurred 57 s after its removal.

Figure 6: Installing a fire blanket on an electric vehicle[34]

So, in the case of an electric car fire, a fire blanket used alone will control the spread of the fire in the early stages but will have little effect in stopping the thermal runaway of the battery pack. This device can be used in conjunction with an active cooling system, such as a water wall placed under the vehicle[35], although the effectiveness of these 2 means combined remains to be proven.
A fire blanket can also be used to protect other vehicles nearby or as a preventive measure on a damaged electric vehicle.

3.2.2 Water hose

Firefighters have developed strategies for alternative energy vehicles. The Service départemental et d'intervention de secours de la Vienne (SDIS86) has published a guide[36] listing these strategies based on real-life trials.

The guide describes the general principle of intervention in the event of fire on an electric vehicle. This principle consists of :

- securing the action of the emergency services: protect yourself (50 m behind a screen if possible - a wall, for example), offensive attack using 2 attack pairs, progress in the ¾ front axis (front wing) of the vehicle on fire (Figure 7), extinguishing with self-contained breathing apparatus (SCBA), 50 m safety perimeter,
- the first attack pair cools the battery to prevent thermal runaway and/or ignition or attempts to extinguish it if it is in thermal runaway, while the second attack pair is responsible for extinguishing the vehicle to stop any heat radiation in the vicinity of the battery. This offensive method is a massive, targeted and simultaneous attack, requiring the use of 2 fire hoses simultaneously. In open spaces, the attack from a distance (50 m) and the progression within lance range are carried out with two 2 variable flow fire hoses using a 250 L/min baton jet, then from 10 m away from the fireplace using a 250 L/min diffused jet.

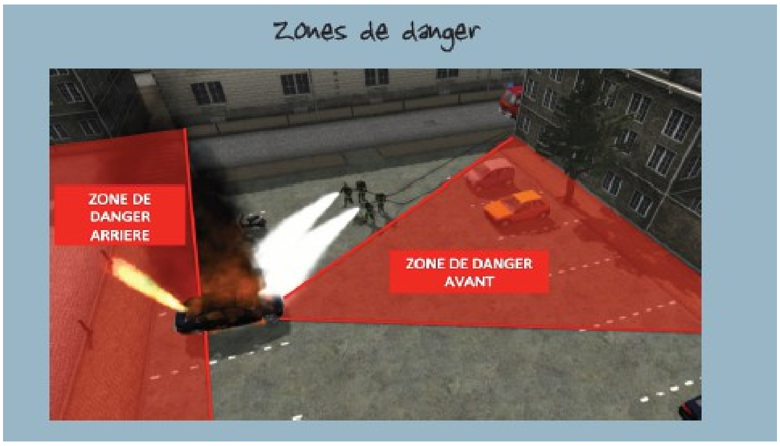


Figure 7: Hazard aeras when working on electric vehicles and representation of the attack in the ¾ axis in front of the vehicle.

The guide specifies that the notion of what is at stake must remain present, as in any emergency response. A defensive attitude (no extinguishing, safety perimeter, protection of the environment) may be preferred when an offensive attack is no longer justified (e.g. an isolated vehicle fully engulfed in flames with no nearby target).

Extinguishing tests carried out by the BSPP, NFPA and feedback from firefighters responding to electric vehicle fires show that :

- extinguishing time and the total volume of water required to extinguish the fire are significantly higher than for an internal combustion engine vehicle and depend on the size and location of the battery[37]. Up to 30 m^3 of water may be needed to extinguish the fire,
- the difficulty of effectively cooling the "core" battery pack (internal components). The design of the pack and its integration into the vehicle can make it difficult to apply water directly to the burning battery, thus significantly reducing extinguishing efficiency, increasing extinguishing time and the amount of water required,
- only batteries on certain vehicles are designed to allow internal flooding of the pack, making extinguishing much easier (see § 3.2.5).

For most electric vehicles, the external application of water therefore only affects visible flames, the external surface of the battery and all surrounding materials. The large quantity of water and high flow rate required for cooling and extinguishing leads to the generation of large quantities of polluted extinguishing water. Nevertheless, the use of a large quantity of extinguishing agent will result in greater dilution of pollutants. Further study of this issue is required.

Other water hose technologies are currently being studied, in particular two-phase hoses, which operate at a lower flow rate (100 L/min) and are based on a process that uses compressed air to break up water droplets. Tests on thermal vehicles have shown that the quantity of water needed to extinguish a fire with this type of hose is significantly less than that used with a conventional hose. Two-phase hoses are also more effective at reducing radiated heat flux and capturing suspended particles. Extinction tests with this type of lance on electric vehicles are needed to assess their performance in the event of a fire involving the thermal runaway of a battery pack.

Given the difficulties involved in accessing and extinguishing an electric vehicle's battery pack, experience shows that there is a high risk of the fire reigniting because of thermal runaway of the cells of the pack that have not reacted. Accident analysis shows that reignition of the battery pack can occur several times after extinguishing (e.g. an electric vehicle fire in Florida in the USA in 2018[38]).

Delayed reignition, i.e. several hours (22h in the case of an NFPA test[39]), days (6 days in a California case[40]) or weeks (3 weeks after a collision[41]) after the battery has been switched off, has also been observed.

The high degree of sealing and insulation of batteries means considerable complications for the firefighters, both in terms of cooling the battery cells and measuring the temperature. A thermal imaging camera is recommended to assess a re-increase in pack temperature and possible re-ignition. However, good insulation of the battery pack may distort the temperature picture.

3.2.3 Immersion systems

The extinguishing difficulties posed by electric vehicles and the high risk of reignition have led some emergency services to opt for the use of immersion systems when the battery is in the process of thermal runaway, or after visible flames have disappeared but with high risk of reignition (high battery temperature monitored by thermal camera). This solution makes it possible to immerse all or part of the vehicle.

There are a number of different immersion systems, the main ones of which are listed below:

- immersion tank: this is a liquid-tight container in which the vehicle can be placed so that it is completely submerged. The liquid may be water, with or without additives. The container must be brought to the scene of the fire, for example on the loading platform of a tow truck, or using a vehicle fitted with a hook chassis. There are several variants of immersion containers, an example with a winch for hoisting the car into the container can be seen in Figure 8. This method provides external cooling, and water can penetrate the battery pack if it is not or no longer sealed, accelerating cooling. The battery can also become electrically discharged if it remains immersed in water for several days or weeks. However, this method has a number of disadvantages: operational difficulties associated with handling the vehicle with a battery in an unstable state, the possibility of the fire flaring up again when the vehicle is removed (or several days later) due to persistent micro-short circuits, the need for a large volume of water compared with the weight of the battery, the possibility of flammable gases (notably hydrogen) and oxygen (water electrolysis) being formed, and the management of polluted water after the vehicle has been removed. The German emergency services recommend using this method as a last resort in exceptional cases[42],
- removable immersion bath: this is a watertight barrier built quickly in the field around the vehicle involved. Four barriers or several panels can be placed around the vehicle, secured together and filled with water or foam to submerge the vehicle's battery pack (Figure 9). This method can control or even extinguish an electric vehicle fire and/or prevent it from spreading to neighbouring vehicles. Tests combining the use of a conventional fire hose and an immersion bath were recently carried out on an electric vehicle fire[43]. These tests confirmed that the fire hose alone could not extinguish the battery pack fire, but only the vehicle fire. Under the conditions of these tests, filling the immersion bath with water ensured effective cooling of the battery pack, with no reignition once the tank had been emptied. Water consumption was lower than when using a hose alone. The use of foam as a replacement for water showed a lower cooling efficiency, which is consistent with tests carried out on a small scale (see § 3.1.3.2). The effectiveness of this method, combining the use of a fire hose and a water immersion bath, needs to be assessed with other types of electric vehicle. The duration of the pack's immersion in the bath also needs to be determined, and merits further testing/studies.

Figure 8: immersion tank

Figure 9: Examples of removable immersion baths

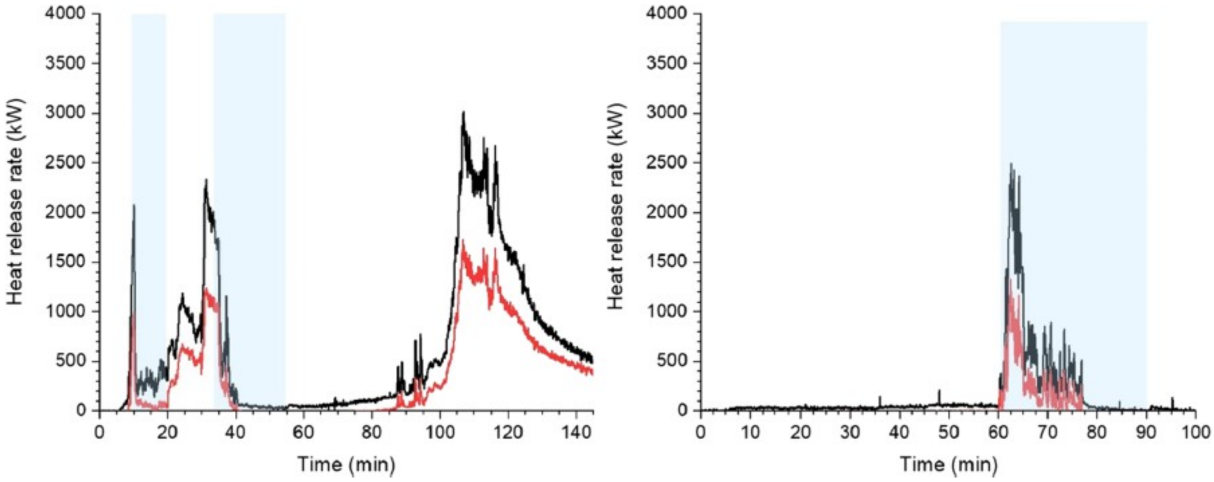
The effectiveness of these immersion methods depends largely on the ability of the water to penetrate the battery pack; if the pack's casing is altered during the fire, this water entry is possible and can provide effective cooling. In the opposite case (burnt vehicle but unpacked, unstable and leakproof battery pack), cooling capacity will be much lower, as water will not be able to penetrate the pack. Further studies on the effectiveness of this immersion method are needed.

On the other hand, the water in these containers or immersion baths is polluted, and the emergency services must take steps to dispose of the contaminated water properly. Here too, studies on the quality of drowning water would be useful in order to refine water treatment methods.

3.2.4 Fixed water sprinkler and water mist systems

Droplets from a sprinkler system penetrate the fire plume and cool surfaces. As the water vapor evaporates, it displaces the oxygen in the air, thus limiting the power of the fire.

Sprinkler tests were carried out by RISE on combustion and electric vehicles, as well as on a protected pack (to represent the chassis). The fire was initiated using a gas burner directed towards the battery pack. As shown in Figure 10a, the 1st activation of the sprinkler system during the fire test on the all-electric vehicle (EV) resulted in a drastic reduction in firepower (Heat release Rate - HRR). The study indicates that this decrease can be attributed to the breaking of the rear window, allowing water to reach the vehicle's interior and cooling the top of the battery, which was confirmed by the significant drop in battery surface temperature. After 10 minutes of application, the sprinkler system was then switched off for 15 minutes, allowing the fire to develop. When the sprinkler system was triggered for the 2nd time and left on for 20 min, a thermal runaway of the battery was observed. Figure 10b shows the evolution of the HRR during the fire test with sprinklers on the battery pack alone. As the battery pack was protected from the direct impact of the sprinkler water (to represent the protection of the chassis), no cooling effect of the water on the battery was observed.



a) *b)*

Figure 10: Evolution of fire power (Heat Release Rate - total HRR represented by the black curve and convective HRR represented by the red curve) during fire and extinguishing tests by sprinkler on a) electric vehicle and b) protected battery pack. The blue areas correspond to the sprinkler activation period[44]

Further fire extinguishing tests on electric vehicle packs were carried out by RISE. This study showed that external water sprinkler extinguishing (3 nozzles, 7.2 L/min flow rate and 30 s application) had a cooling effect and limited impact on the propagation of thermal runaway, except for extinguishing flames outside the battery pack to prevent the fire from spreading to the environment[45]. Integrated into an electric vehicle, batteries are difficult to access, and most of them are sealed to prevent them from being penetrated by water and dust and to provide protection against external shocks. External application of water, therefore, only affects visible flames, the external surface of the battery and all surrounding materials. **By contrast, the application of water directly inside the pack has led to greater cooling and reduced cell-to-cell propagation using a limited amount of water.**
These results are illustrated in Figure 11, which shows a drastic reduction in battery temperature by the application of a sprinkler inside the pack, compared with an external sprinkler, which does not allow a reduction in pack temperature. The external application of the extinguishing agent to the battery, therefore, offered no apparent advantages; it gave similar results to a test without extinguishing in terms of propagation speed, surface temperature and gas temperature inside the module.

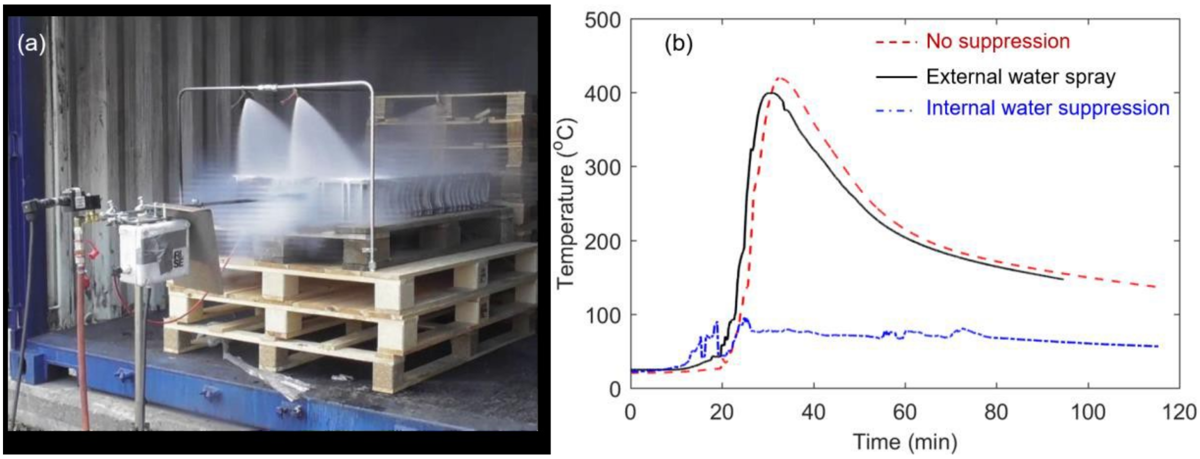


Figure 11: Photo of sprinkler system and comparative effects of water sprinklers inside and outside the battery [pack45]

The RISE test campaign continued with water mist extinguishing tests outside and inside the pack. Water mist comprises a range of droplet sizes below 1000 µm, well below those of a sprinkler system. Finer droplets have a greater surface-to-volume ratio, resulting in greater thermal energy absorption from hot air for the same volume of water. In the tests, the droplet size was 50 µm in diameter, the flow rate 1.7 L/min and the application time 3 to 4 min. The water mist system was slightly more successful in hindering cell-to-cell spread than the water sprinkler system. This could be explained by the difference in agent release times (30 s for water sprinklers and up to several minutes for water mist). This may have affected the amount of water sprayed inside the battery casing. Another potential cause may be linked to the content of the agent and the difference in droplet size between a mist and a sprinkler.

It should be noted, however, that in this study, none of the tests prevented the spread of heat throughout the entire module, but the internal fire extinguishing systems had a positive effect, as some cells were spared. This trend was also observed when examining average propagation rates. The average propagation rate corresponds to the time required for thermal runaway to propagate in the order of successive failures, i.e. from the first to the third, from the third to the sixth and finally from the sixth to the last cell. These rates were reduced by installing an internal fire extinguishing system (Figure 12).

During the water sprinkler tests, large quantities of water were sprayed out of the battery pack, probably due to the short activation time and limited space inside the battery pack. As tests have shown, a lower flow rate and longer release time are preferable since the water mist system had a greater cooling effect than the sprinkler system throughout the traction battery.

Test	Nr. TR cells, module 1 (–)	Mean propagation rate for cells (cells/min.) 1st–3rd	3rd–6th	6th–last	Mean temp 1st–last + 60 min (°C) Mod. 2 front (TC7/8)	Mod. 2 back (TC9/10)	Air (TC14/15)
ref 1	12	8.57	1.07	0.61	248	97	88
mist 1	11	**2.36**	0.92	**0.26**	100	**70**	53
mist 2	**8**	2.61	0.48	**0.26**	**98**	**70**	**44**
ref 2	11	10.34	1.36	0.56	223	109	116
spray ext	11	11.11	0.91	0.50	241	164	78
spray 1	9	5.66	**0.45**	0.37	141	88	82
spray 2	9	3.85	0.97	0.31	143[a]	97	82

The lowest values presented, and thus the most positive effect for the different evaluation criteria, are highlighted in bold values

[a]Estimated value since TC8 failed after the 6th consecutive thermal runaway in Module 1

Figure 12: Number of cells with thermal runaway reaction in fire tests with sprinkler and mist extinguishing, comparison of propagation rates and temperatures reached as a function of extinguishing agents[46]

These tests, therefore, showed that total internal flooding of the battery pack, preferably at a low rate and with long release times, is the most effective way of preventing propagation from cell to cell and module to module.

Confined fire tests involving several combustion-powered vehicles in enclosed parking lots were conducted in the late 1980s[47]. The aim of these tests was to study the effect of a thermal vehicle fire in an enclosed parking lot equipped with sprinkler and ventilation systems. The tests showed that the sprinkler system was effective in controlling a developing fire and limiting its spread. Dangerous levels of smoke were reached for long periods with or without sprinklers.

Internal combustion engine (ICE) vehicle fire tests carried out between 2007 and 2009 in the UK in representative indoor parking lot infrastructures[48] demonstrated the potential benefit of sprinklers in limiting (or delaying) the spread of fire from one car to another and in reducing structural damage. The report also mentions the limitations of these systems, particularly their limited impact on the intensity of the fire in the first vehicle (the fire continued to develop even after the sprinklers were triggered, and the power achieved remained relatively high under the test conditions applied). All these tests were carried out on conventional vehicles.

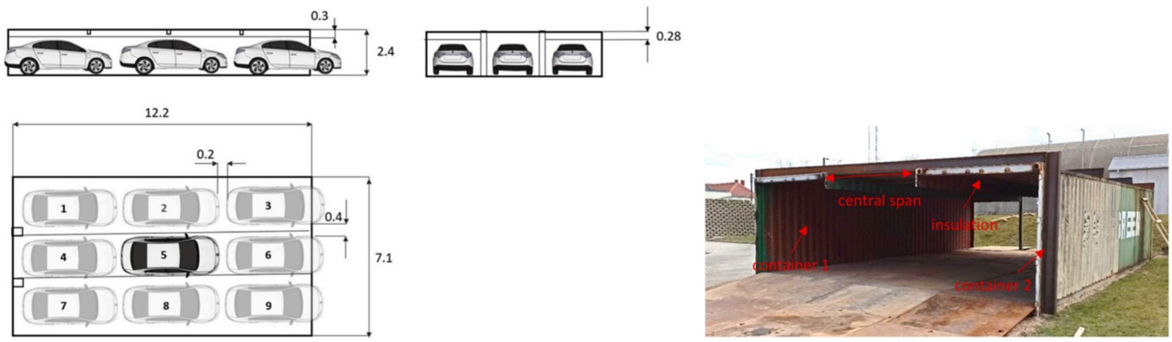
In cases where the battery does not initiate the fire, or where the fire has not spread to the battery - early extinguishing being recommended - sprinklers or water mist can be used to cool the vehicle and limit the risk of thermal runaway of the battery pack, limiting the spread of the fire and the impact on structures before the arrival of the emergency services, thus facilitating their intervention. Recent cases of electric vehicle fires in underground parking lots have shown that the sprinkler system brought the fire under control, preventing it from spreading to the vehicle's battery pack and other vehicles[49].

If the fire is initiated by the vehicle's battery, or if the vehicle fire has spread to the battery pack, the effectiveness of sprinkler/water mist devices will depend on the ability of the water droplets to reach the battery pack. Tests involving the initiation of a thermal runaway on a battery pack of an electric vehicle surrounded by several ICE cars at a distance of less than 40 cm in a covered (but not completely enclosed) environment have recently been carried out[50] (Figure 13). Various extinguishing methods were tested. In one test, a low-pressure water mist system (8 barG / 400 L/min water flow) was used (Figure 14).

During the test, this system cooled the battery casing, even though the water droplets did not reach the pack directly. As soon as the water mist was activated, a drop in temperature was observed in the battery, in the smoke layer above the electric vehicle and in the surrounding cars. The study mentions that the drop in battery temperature is most likely due to the poor condition of the electric vehicle, which allowed the droplets to reach the battery (positioned in the trunk - Renault Fluence). The water mist system proved capable of managing the environment and reducing the temperature at high speed over a wide area within 2 minutes of activation. However, depending on the car's design (battery location), a similar effect on battery cooling may not be achieved in all cases.

Another recent study[9] evaluated the effect of water mist (100 bar-20 L/min) on an electric vehicle fire incorporating a battery pack under the passenger compartment. The average cooling rate of the water mist was -3.1°C. The water mist helped to reduce the temperature and heat release rate, but neither extinguished the fire in the passenger compartment nor stopped the thermal runaway of the battery pack under the test conditions applied (low flow rate in particular).

Funk's study[50] concludes that if water droplets reach the battery, and if activation and layout are appropriate, water mist systems appear to be capable of containing electric vehicle fires (without necessarily extinguishing them) and of reducing spread to adjacent structures and vehicles.



a) *b)*

Figure 13: Test configuration for fire propagation from an electric vehicle to ICE vehicles parked nearby, and testing of different extinguishing methods a) vehicle layout in m, with vehicle 5 being the electric vehicle whose battery pack has been short-circuited
b) covered area for vehicles[50]

Figure 14: Fixed low-pressure water mist system[50]

This study also evaluated the effectiveness of 2 types of portable water curtain devices: one from the JØNI brand (Figure 15a) available in different sizes and suitable for placement under or between vehicles, and the other from the ALBERO brand (Figure 15b) of simpler, lighter design with upward-facing nozzles. The JØNI water curtain did not prevent the fire from growing and spreading, due to the time required to activate the device and the inability of the droplets to reach the pack. The ALBERO device was able to cool adjacent vehicles. However, in the event of thermal runaway of the battery, the study showed that the effect of these portable water curtains can be considered minimal or negligible on battery temperature.

a) *b)*

Figure 15: Mobile water curtains a) JØNI b) ALBERO

It should also be noted that the application of water to a Li-ion battery fire changes the composition of the gases; an increase in the concentration of CO, H_2, hydrocarbons and HF and a decrease in the concentration of CO_2 are observed during tests with extinguishing; this can lead to a change in the risk profile and, in particular, the appearance of an explosion risk in the presence of ignition sources, such as sparks from batteries or hot surfaces. Indeed, large quantities of gas can continue to be released after the flames have been extinguished. To fully understand this risk, and to ensure that the fire extinguishing system is well designed and effective, it is recommended to carry out tests on each battery installation before installing an internal fire extinguishing system.

These studies show the importance of direct access to the battery pack when it needs to be switched off or cooled. However, such access is difficult when the pack is integrated into the vehicle. The next paragraph will discuss this.

3.2.5 Internal battery pack extinguishing methods

As far as the strategy for extinguishing electric vehicles fitted with Li-ion batteries is concerned, water flooding is recommended. Two cases are possible:

- the battery pack has a dedicated system (thermo-fusible hatch or similar), also known as "fireman access" (e.g. Renault Zoé). To take the example of the first generations of Zoé, this was located under the rear passenger seat, and its material melted with heat, making the "core" of the battery accessible to direct a fire hose to flood the pack. This makes extinguishing the fire quicker and easier and requires less extinguishing agent. Tests have proven the effectiveness of this device in rapidly extinguishing a vehicle battery pack fire,
- the battery pack has no "fireman access" (most vehicles), making extinguishing more difficult and time-consuming, and requiring large quantities of water. If a hole or gap is created in the battery pack during combustion, this is a possible water entry point to facilitate extinguishing. The greater the mechanical protection (pack conditioning) of the battery and the better the seal, the more difficult it will be to extinguish.

These difficulties of access to most battery packs have prompted some manufacturers to develop perforating lances, which allow the battery pack to be pierced and a jet of water to be introduced inside the battery pack. These lances have the advantage of consuming less water. Various types of perforating lances are available on the market:

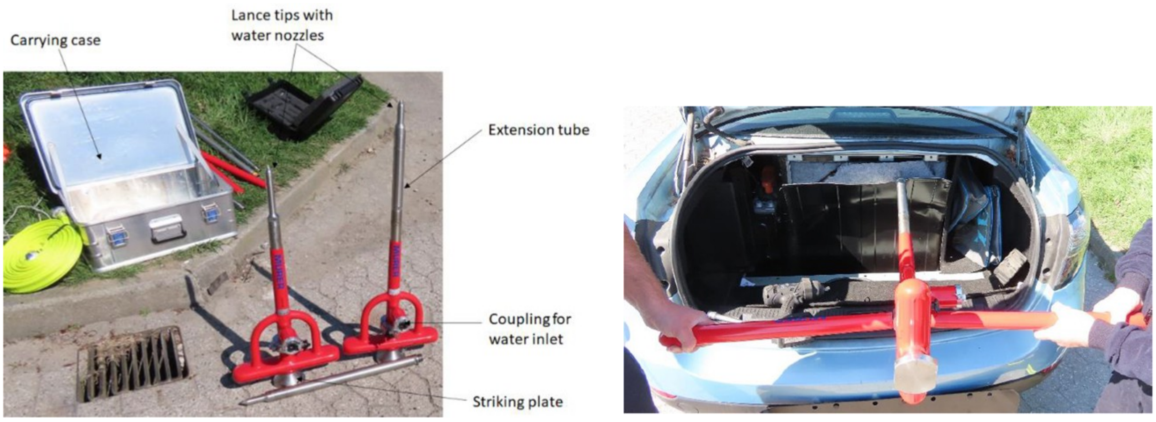
- Cobra Cold Cutter or Cobra Ultra High Pressure Lance (UHPL) based on a high-pressure (300 bar) cutting and extinguishing system. This equipment uses a water-entrained abrasive to drill, then a water mist is introduced into the hole at a flow rate of 58 L/min (Figure 16a). All this is applied in a single continuous action. Extinguishing tests with this type of lance were carried out in Austria during battery fires. The Coldcutter was effective in penetrating the casing of the battery pack, but had a destructive effect once the casing had been penetrated: the introduction of high-pressure water caused part of the battery pack to explode, with some cells being projected more than 1 m from the pack[51],

- Murer Feuerschutz "e-fire" lance. Water is pumped through a spearhead-shaped lance. According to the manufacturer of the extinguishing lance, the aim in the event of a battery fire is to strike the lance through the battery casing (Figure 16b), then flood the battery. It uses water at a flow rate of 25 L/min. The extinguishing lance is electrically insulated and suitable for voltages below 1000 V. A German institute has carried out experiments with the e-fire extinguishing lance on vehicles and batteries. Although in many cases the lance can extinguish and cool the battery, practical tests have shown that penetrating battery cells with the lance can also aggravate the situation. Battery cells that have not yet been damaged by fire or thermal runaway risk being damaged precisely by the penetration of the lance and ending up in thermal runaway. High temperatures can also destroy the lance and melt the material. This device requires a hammer to penetrate the battery with the perforating lance; firefighters are thus directly exposed to smoke and heat[51].

  The use of these types of lances (Cobra Cold Cutter and "e-fire") represents a particularly risky intervention for firefighters in the immediate vicinity of the battery. There is increased electrical risk (arcing, electric shock, etc.), dangerous jet fire on penetration, and the risk of thermal runaway of cells that have not yet reacted. **For these reasons, the French and German fire departments do not recommend the use of this type of lance[42,52].**

Some lance technologies enable remote operation, for example Rosenbauer's BEST battery extinguishing system technology. This system consists of a wheeled extinguishing unit positioned under the electric vehicle (Figure 16c), connected by hoses about 8 m long to a control unit containing a compressed-air cylinder. The device is positioned under the vehicle, then compressed air is fed to a pneumatic nail which penetrates the chassis to the battery, and water is injected at 30 L/min at a pressure of around 7 bar. A test with this device on a Renault Fluence-type vehicle, carried out as part of the ELBAS[53] project, did not prove very effective. The report explains that the water could not accumulate in the pack due to the opening of its casing during thermal runaway. Further tests need to be carried out on other types of vehicles/packs to assess the effectiveness of this system. A number of implementation difficulties may also be raised: proximity of the operator to position the device under the vehicle (risk to be assessed according to the stage of development of the fire), accessibility of the battery if it is close to the ground, adjustment of the penetration depth, which varies according to the vehicle/pack, increased risk of thermal runaway due to perforation of cells not involved, training of operators, etc.

a)



b)

c)

Figure 16: Perforating lances a) Cobra Cold Cutter[53], b) e-fire lance (Murer Feuerschutz)[53], c) BEST technology from Rosenbauer[50,53]

Finally, some fully electric buses (BYD's K9M series) have an automatic suppression system. In case of a thermal event (detected by thermal sensors placed in the battery areas), nozzles will spray fire-fighting agent into the battery area. This extinguishing system can also be discharged manually by the driver. The on-board extinguishing system can be seen in Figure 17 (top of photo). The extinguishing agent used could not be identified.

Figure 17: Rear of BYD bus with on-board extinguishing system at the top[54]

3.2.6 Special case: intervention strategy for emergency services in confined spaces

In confined spaces (garages, parking lots, tunnels, etc.), dangerous phenomena (particularly thermal and toxic) can be accentuated or accelerated, making interventions complex and dangerous. Smoke accumulation is one of the major challenges in confined spaces. Smoke density can be higher in confined spaces than outside. As a result, relatively high atmospheric concentrations of HF can be formed in such configurations. An example of where this risk may be relevant is fires in underground parking lots involving several electric cars[55].

The deployment of personnel also considers the risks associated with infrastructure fires. Rapid intervention is essential to prevent thermal runaway of the battery, limit propagation and damage to the infrastructure and ensure the safety of firefighters. The fire department intervention guide[31] specifies that the fire must be attacked very quickly using a maximum flow hose (500 L/min), reinforced as soon as possible by a second hose of the same type. Attacking the fire to cut off the heat radiation causing the battery to rise in temperature will first be carried out within range of the hose, then once the fire is fully under control, in contact with the vehicle, excluding, if possible, the positioning of firefighters in the hazard areas (front and rear of the vehicle). Wherever possible, the first attack should be protected by vehicles, architectural elements or even airlock doors.

The risk of flammable gas accumulation and explosion must be particularly considered in enclosed spaces.

The intervention guide also mentions that the use of thermal imaging cameras, operational ventilation and, where possible, fixed fire-fighting equipment (smoke extraction, sprinklers, etc.) must be integrated to complement the emergency resources already involved.

Innovative techniques, such as deploying robots in covered parking lots, could also be considered. Several studies have already been launched, such as the possibility of delivering water directly to the vehicle's battery in case of fire[56]. To date, these are exploratory studies.

4 Conclusion

This document aims to review the state of the art in fixed and mobile extinguishing systems for Li-ion battery-equipped electric vehicles and determine their degree of effectiveness. The study was based on bibliographical research, feedback, and exchanges with fire safety organizations.

Table 1 provides an overview of the main extinguishing agents and their degree of effectiveness. Aqueous liquid extinguishing agents (water or water and additives) have the highest cooling effect and are the most effective against a Li-ion cell fire. This assessment is based on small-scale tests (on one cell or cell assembly).

Table 2 shows the main means of firefighting methods against thermal runaway and its propagation on a larger scale (vehicle and pack). Intervention strategy is defined according to fire scenarios and the environment.

In an open environment, if the battery of a burning electric vehicle is not yet affected by the fire, the strategy will be to simultaneously extinguish the vehicle and cool the battery pack to prevent thermal runaway, using water hoses. In the case of thermal runaway of the battery, the most effective method is to flood the pack internally with water. This is possible on certain types of vehicles fitted with a thermo-fusible or similar hatch which melts when heated. The fire hose is directed at this hatch, ensuring rapid and effective extinguishing. For vehicles not fitted with such a device, extinguishing is difficult, requires large quantities of water and the risk of re-ignition is high. Immersion systems (containers for the complete vehicle or immersion baths for the battery pack) can be effective where water can penetrate the battery pack. However, various implementation difficulties have been noted, as well as generating a potentially large quantity of polluted water. The difficulty of gaining access to the inside of the battery pack has prompted some manufacturers to develop perforating lances, which is based on piercing the battery and introducing water into it. The ability to inject water directly into the battery pack means lower water consumption and greater cooling efficiency. However, manual perforating lances are very risky for emergency responders (electrical risks, risk of thermal runaway of cells not impacted during perforation and dangerous jet fire in the vicinity of firefighters). A remote piercing device has been developed, but its effectiveness has yet to be proven, and difficulties in implementation have been noted.
Vehicle fire blankets have not proved very effective in cases where the vehicle battery is in thermal runaway. They could, however, be used for preventive purposes, to limit the spread of the fire to an adjacent vehicle, or after the fire has been extinguished, to prevent the fire from re-igniting and contain smoke emissions. However, these fire blankets have not yet been fully validated in terms of their effectiveness compared with existing practices.

In a confined environment, the use of a fixed sprinkler or water mist system enables a rapid response: although such a system does not necessarily target the electric vehicle's battery pack, early activation of the system is the key to ensuring cooling of the vehicle, limiting the spread of the fire to adjacent vehicles and limiting the impact on structures, thus enabling control of the fire while awaiting emergency intervention. The effectiveness of sprinkler/water mist systems on an electric vehicle fire will depend on the ability of the water droplets to reach the battery pack. In all cases, the likelihood of the fire developing and spreading to adjacent structures and vehicles can be reduced. When water is introduced directly into the pack, the cooling effect is enhanced when the flow rate is low and the release time longer, making water mist a priori somewhat more effective than sprinkling. It should also be noted that thermal and toxic risks are increased in confined spaces, and that the application of water to a Li-ion battery fire alters the composition of the gases, potentially leading to the appearance of an explosion hazard and a momentarily higher concentration of HF before it is reduced by dissolution in the water.

Finally, further studies and/or trials are needed to assess the effectiveness of certain extinguishing methods already in use or under development.

Extinguishing agents			
Type	**Main extinguishing agents**	**Degree of efficiency**	**Comments**
Gas	Inert gas (CO_2, N_2, Ar,...)	Ineffective	• Oxygen generation from the battery cathode during the thermal runaway process
	Hydrocarbons halogenated (halons, HFCs, NOVEC 1230...)	Poor	• Low cooling capacity • Formation of toxic and corrosive by-products when exposed to high T°
Solid	Powder extinguisher	Ineffective	• Insufficient cooling capacity
	Solid aerosols (e.g. based on potassium salts)	Ineffective	• Mode of action by chemical inhibition not effective; chemical reactions of batteries during thermal runaway complex • Insufficient cooling capacity
Liquid	Aqueous (water / water + additives)	Efficient	• High cooling capacity • Adding additives can reduce water consumption and improve cooling capacity compared with pure water
	Foaming agent	Poor	• Lower cooling capacity than water • Difficulty penetrating the inter-cell/module spaces of the pack
	Aqueous vermiculite dispersion (AVD)	Poor	• Lower cooling capacity than water • Difficulty penetrating the inter-cell/module spaces of the pack

Table 1: A summary of the main extinguishing agents and their degree of effectiveness on Li-ion cell or cell assembly fires.

Means of firefighting methods against thermal runaway and its propagation on pack and vehicle scale			
Type	**Main resources identified**	**Degree of efficiency**	**Comments**
Blanket	Fire blanket	Poor if battery in thermal runaway (needs further testing)	• In cases where the battery is involved in the fire, it has been shown that the cover does not add significant value • Not easy to set up: need for sufficient space around the vehicle and proximity of firefighters • Can be used in combination with another active cooling system (e.g. wall of water under the vehicle), but effectiveness to be proven • Fire blankets could be used for preventive purposes, to limit the spread of the fire to an adjacent vehicle, and after extinguishing, to prevent the fire from re-igniting and contain gas emissions. However, these fire blankets have not yet been fully validated in terms of effectiveness against existing practices
Water hose	Variable flow hose	Effective if penetration in the battery pack	For most electric vehicles : • High water volume requirements (up to 30 m^3) and long extinguishing times • Difficulty in effectively cooling the "core" battery pack • Risk of reignition after extinction (immediate or delayed) • Generation of large quantities of polluted water For electric vehicles equipped with thermo-fusible hatches or equivalent : • Quick, easy extinguishing (water introduced directly into the battery pack)
	Two-phase hose	To demonstrate	• Positive results for extinguishing combustion-powered vehicles (significantly less water required than with a conventional hose, better heat flow abatement and capture of suspended particles). Effectiveness yet to be demonstrated on electric vehicle fires
Immersion systems	Container	Effective if penetration in the battery pack	• Operational difficulties associated with handling the vehicle with a battery in an unstable state • Immersion time to be assessed • Possibility of fire reignition when leaving the vehicle (or several days later) due to persistent micro-short circuits, • Large volume of water required compared to battery weight • Potential formation of flammable gases (especially hydrogen) and oxygen (water electrolysis) • Managing polluted water after vehicle removal • The German emergency services recommend using this method as a last resort in exceptional cases

	Removable immersion bath	Effective if penetration in the battery pack	• Proximity of workers when using the removable bath around the vehicle - requires extinguishing the vehicle before installation (combined use of fire hose and immersion bath). • Potential formation of flammable gases (especially hydrogen) by electrolysis of water • Immersion time to be assessed - possibility of fire reignition after bath removal • Managing polluted water after vehicle removal
Piercing lance	Manually operated (Cobra Cold Cutter / e-fire from Murer Feuerschutz)	Could be effective **but very risky for firefighters**	• Introduction of water into the battery pack for internal cooling • Use of limited quantities of water • Proximity of the operators to pierce the battery • Electrical risk (arcing, electrification, etc.) • Risk of thermal runaway of cells that have not reacted during perforation (risk of dangerous jet fire).
	Remote operation (Rosenbaueur BEST device)	To demonstrate	• Conclusive tests according to the manufacturer on batteries up to 120 kWh. Test inconclusive in the ELBAS project on one type of vehicle (water could not accumulate in the pack due to the opening of its casing during thermal runaway) • Difficulties in implementation: accessibility of the battery if it is close to the ground, variable penetration depth settings depending on the vehicle/pack, increased risk of thermal runaway due to perforation of uninvolved cells, etc.
Fixed systems	Sprinkler	Effective for bringing the fire under control (not necessarily for extinguishing it) / dependent on water's ability to reach the battery pack	• If the fire is not initiated by the battery: water sprinkler systems are recommended to cool the vehicle, prevent the fire spreading to the battery and neighbouring vehicles, and limit the impact on structures • Case where the battery is in thermal runaway: external application of water affects only visible flames, the external surface of the battery / application of water directly inside the pack has led to greater cooling and reduced cell-to-cell spread using a limited amount of water
	Water mist	Effective if applied internally to the pack	• Variable efficiency depending on droplet size, spray duration, mist particle dynamics and its ability to reach the combustion surface through the smoke generated by the battery • Enhanced extinguishing efficiency with additives • When injected into the pack: greater cooling effect than with sprinklers because of lower flow rate and longer water release with water mist
Mobile devices	Portable water curtains	Poor if battery in thermal runaway	• Can cool adjacent vehicles but not very effective on a battery fire (1 study carried out - probably requires further testing)

Table 2: A summary of the main firefighting methods against thermal runaway and its propagation

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