Nederlands
Instituut
Publieke
Veiligheid

Fire experiment to examine the use of ultra high pressure extinguishing systems for fires in batteries of electric vehicles

Netherlands Academy for
Crisis Management and Fire Service
P.O. Box 7010
6801 HA Arnhem, the Netherlands
Kemperbergerweg 783, Arnhem, the Netherlands
www.nipv.nl
info@nipv.nl
+31 (0)26 355 24 00

Publication details

Authors	T. Hessels and H. Brans
Contact person	T. Hessels
Client	The Netherlands Fire Service / Haaglanden Safety Region
Contact person	W. Muysson / R. Turkenburg
Date	26 November 2024
Photos:	NIPV, unless stated otherwise

Abstract

The number of electric vehicles in the Netherlands has grown rapidly in recent years and continues to increase. When the battery pack of these vehicles is involved in a fire or something goes wrong internally, the battery pack can go into a 'thermal runaway'. Fighting a thermal runaway is complex and, in addition, current deployment techniques are not always optimal. The aim of this research is to use fire experiments to determine whether an ultra high pressure (UHP) extinguishing system can be used safely and effectively, and is suitable for practical application, by the Dutch fire service in order to fight battery fires in electric vehicles. Nine questions were formulated for this research. They were answered through a preliminary study, consisting of a working visit, a literature review, and interviews. Additionally, two almost identical experiments were conducted, in which the battery pack of an electric car was put into thermal runaway.

It was found that it is practically feasible to deploy a UHP extinguishing system safely and effectively in the Netherlands to control or extinguish an unstable or burning battery pack in an electric vehicle, provided a number of specific safety measures are taken for this purpose. These safety measures are:

> Deploying low-pressure jets (1) to suppress any jet fires from the battery pack, and (2) to shield the UHP operator to protect them from exposure to any (unexpected) jet fires.
> Determining that no flammable gases have accumulated in or around the vehicle. Busting the windows with the UHP extinguishing system, possibly supported by the use of fans, can help vent flammable gases.
> Positioning the UHP operator and other fire personnel as far away as possible from the (toxic) smoke and flames.
> Use of the long lance or extension of the UHP extinguishing system.

During the experiment, an effective deployment procedure was confirmed. This procedure consisted of identifying hot spots with a Thermal Imaging Camera, and then penetrating the battery pack and using the UHP extinguishing system to introduce water to these hot spots. Here, steam formation is an indicator that cooling is effective, and the transition from steamy to leaking water is an indicator that the deployment has been effective and can be terminated. After this, a period of visual monitoring is necessary to ensure that the situation has stabilised and there is no re-ignition. Participating fire personnel indicated that this deployment gave them a positive feeling and was relatively easy to carry out.

In conclusion, the results of the fire experiments provide sufficient confidence to have (specialised) UHP units within the Dutch fire service deploy UHP extinguishing systems in case of fires in the battery packs of electric vehicles.

Preface

BITET is a Dutch acronym that stands for BrandweerInzetTactieken EnergieTransitie (Fire Service Deployment Tactics for Energy Transition). But what is much more important is what the BITET consortium partners want to achieve. The goal of the BITET consortium is to test and validate existing deployment tactics in terms of material, equipment and tactics in connection with new developments as part of the energy transition. Where necessary, the consortium also develops new knowledge on deployment tactics; this knowledge is publicly available. For many developments in society, but particularly those that concern energy transition, it is crucial that public and private parties share knowledge to achieve optimum safety. However, the BITET initiative does not stop here. In the consortium, private parties, the fire service and the NIPV work closely together to develop new knowledge.

Battery electric vehicles are an important development as part of the energy transition. We know that unstable battery cells that go into thermal runaway pose a problem for incident response by firefighters. As NIPV, we have published several reports on this subject in which we assessed and compared deployment tactics based on a literature review and expert judgement. But BITET now takes this a step further. We conducted field trials of one of the deployment tactics used in practice to stop a thermal runaway, namely the ultra high pressure extinguishing system (UHP extinguishing system). The aim of these trials was study whether, and under what conditions, this deployment tactic can be applied in the Dutch context.

These real-life trials could only be brought about thanks to the tremendous efforts of all parties involved. We are very grateful to the supplier of the vehicles and the German VDA/VDIK 'Rescueing of people' working group for the two electric MPVs with battery packs that we were given. The Amsterdam Airport Schiphol Fire Brigade made its practice area available for the trials, the Haaglanden and Utrecht safety regions provided personnel for the actual deployment, the Amsterdam-Amstelland fire brigade provided equipment and manpower, Coldcut Systems trained the personnel, and TATA Steel and the Gezamenlijke Brandweer (Joint Fire Service) shared their ideas on the design of the trials and the practical implementation during the preparations. And RIVM (the Dutch National Institute for Public Health and the Environment) and our own researchers have done mountains of useful work when it comes to the entire script, the day itself and the measurements. The financial contributions from the Netherlands Fire Service and the Haaglanden Safety Region made it possible to actually carry out the trials.

Thanks to Floris and Tom, their boundless energy and everything they have arranged, all these parties and their people (more than 50 on the actual day of the trials) were part of an experiment that was unique for my professorship - and I dare say here: for the whole of the Netherlands. The results are compelling, can immediately be put to use and are very highly relevant for the incident response practice and for safe electrification of the mobility sector. These first successful experiments have given us an appetite for more. And since repressive challenges abound in the energy transition, we, the BITET consortium, are already developing a second set of experiments.

Nils Rosmuller
Professor of Energy and Transport Safety

Contents

Introduction

Background

The number of electric vehicles (EVs) in the Netherlands, including battery electric (BEV) and plug-in hybrid (PHEV) vehicles, has grown strongly in recent years and continues to grow steadily. The Dutch government expects this number to have grown to 1.9 million by 2030 (central government of the Netherlands, n.d.). If all other factors remain equal, this will lead to an increase in the number of fires involving electric vehicles.

The transition from conventional vehicles (powered by petrol and diesel) to electric vehicles poses new and different safety risks, mainly related to the lithium-ion battery pack in these vehicles. If this battery pack is involved in a fire or if something goes wrong internally, the battery pack can go into 'thermal runaway'. Thermal runaway is an unwanted, exothermic reaction within battery cells that releases heat and flammable and toxic gases. A characteristic of this intrinsic safety problem is that thermal runaway is self-sustaining, also because the production of heat reinforces itself.

Fighting thermal runaway in the battery pack is complex and the two deployment techniques that are currently used are not always optimal. The first technique, submerging the battery pack in an submerging container, is time-consuming and produces a large amount of contaminated water. The second deployment technique is to let the vehicle burn out, but it depends on the environment whether this is safe or desirable.

Recent research from Sweden has shown that an ultra high pressure extinguishing system (UHP extinguishing system) can be effective in stopping the propagation of thermal runaway in the battery pack in an electric vehicle that is on fire (MSB, 2023). This prompted us to conduct two fire experiments to research the suitability of this technique within the Dutch firefighting context. If the outcome is positive, the findings will serve as a basis for drafting Dutch firefighting instructions and procedures for the deployment of these extinguishing systems in electric vehicle fires in which the battery is involved.

Aim of the research

The aim of this research is to use fire experiments to determine whether the Dutch fire service can **safely and effectively** use a UHP extinguishing system to fight battery fires in electric vehicles and whether such a system is **suitable for practical application**.

- Safe: The firefighters can be adequately protected from the effects of thermal runaway and from electrocution.
- Effective: A UHP deployment technique is possible that achieves effective cooling and stops thermal propagation.
- Suitable for practical application in the Netherlands: The deployment technique is suitable for application in the field by the UHP units in the Netherlands.

Research

To achieve the aim of the research, the following research questions were drawn up and arranged under the themes of safety, effectiveness and practical applicability in the Netherlands. UHP deployment is taken to mean ‘the UHP deployment to the battery pack in case of an electric vehicle fire’.

Safety

1. How can fire personnel be prevented from being exposed to unexpected flames and jet fires during UHP deployment?
2. How can a vapour cloud explosion be prevented during UHP deployment?
3. How can fire personnel be prevented from being exposed to toxic gases during UHP deployment?
4. How can fire personnel be prevented from being exposed to electrocution risks during UHP deployment?

Effectiveness

5. What are suitable penetration points for introducing a UHP extinguishing system into the battery pack and how long should water be introduced at a penetration point?
6. When has a safe and stable situation been created and can the vehicle be safely handed over to a salvage company?

Practical applicability in the Netherlands

7. How did the firefighters feel about the UHP deployment during the experiment?
8. How do the firefighters perceive the ease or difficulty of the UHP deployment during the experiment?
9. What bottlenecks did the firefighters experience during the UHP deployment during the experiment?

Scope

It was decided to test UHP extinguishing systems because several fire brigades in the Netherlands already own these systems and use them in other types of incidents. We are aware that several other systems that pursue the same goal, i.e. injecting water directly into the battery pack, are available, but no fire brigades in the Netherlands have started to use these other systems. This means that, for these experiments, existing systems are tested for a new field of application.

1 Research method

1.1 Phase 1: Preliminary study

A preliminary study was carried out before drafting the plan for the fire experiments. The goals of this preliminary study were to identify and map the available knowledge and experience regarding the deployment of UHP extinguishing systems to fight electric vehicle fires, to connect with relevant experts in Europe, and to develop a suitable method for initiating thermal runaway. The first six research questions were examined as part of this. The findings of the preliminary study served as input for the practical design of the fire experiment.

This phase also included a working visit, a literature review, and interviews. In 2023, an NIPV researcher conducted a working visit to the car manufacturer that had offered to make two electric vehicles available for the fire experiments. Some try-outs were held there on individual battery modules to get an initial feel for applying a UHP extinguishing system to battery fires. The experts involved were also introduced to each other then.

Building on this, we talked to firefighters at home and abroad who had experience with UHP extinguishing systems in order to prepare a deployment. Next, the deployment procedure during the experiment was determined in consultation with the fire crew to be deployed. In this context, experts from Coldcut Systems, a manufacturer of a UHP extinguishing system, were also consulted. The plan for the fire experiments was drafted on the basis of the background information from the preliminary study. The preliminary study also brought about a suitable knowledge network to share and discuss the progress and results of our research with.

In addition, the Haaglanden Safety Region held two try-outs (preparatory experiments) in order to fill two knowledge gaps regarding safety that we wanted to be filled in order to ensure safety when deploying a UHP extinguishing system.

1.2 Phase 2: Fire experiment with two electric vehicles

For the fire experiment, we had two new electric vehicles with 75 kWh battery packs at our disposal. We used them to conduct two experiments. The aim was to put the battery pack of each electric vehicle into a state of thermal runaway, so that flames would occur after which the entire vehicle should catch fire. A requirement was that the battery pack should be involved in the fire. The scenario that we wanted to mimic was that the electric vehicle fire originated from thermal runaway in the battery pack. To achieve this, we initiated the thermal runaway by mechanically damaging the battery pack. The fire was then given 10 minutes to develop and spread to the entire vehicle. To mimic the situation after an electric vehicle fire is reported in the Netherlands, a fire appliance was first deployed to extinguish the vehicle fire. After this, a specialist fire service unit with access to a UHP extinguishing system was deployed. Their goal was to stop thermal propagation in the battery pack and thus stabilise the battery pack. The fire experiment tested the theoretical inputs from the preliminary study in practice and answered research questions 7, 8 and 9.

1.3 Phase 3: Analysis of the results

When the fire experiment was completed, the results were analysed and it was evaluated whether the deployment technique with the UHP extinguishing system was sufficiently suitable within the specific context of the Dutch fire service. The aspects considered were the safety, effectiveness and practical applicability of the deployment technique. The results were used to suggest possible uses of a UHP extinguishing system in case of incidents involving electric vehicles; these were discussed with the BITET consortium.

2 System description of electric vehicles and UHP extinguishing systems

This chapter gives a concise system description of electric vehicles and discusses the effects of thermal runaway. This gives some understanding of why incident responders may perceive extinguishing a battery pack in thermal runaway as problematic. The chapter ends with an explanation of how a UHP extinguishing system works, making it clear why this might be a suitable firefighting resource in this specific context.

2.1 Electric vehicle

Electrical energy that drives the electric motor of an electric vehicle is stored in the battery pack. The battery pack (300 - 1000 V) consists of several modules (< 60 V) and each module consists of individual battery cells (~4 V). The general configuration of a battery pack is shown in Figure 2.1. A vehicle that is fully electrically powered from the battery pack is also referred to as a BEV (Battery Electric Vehicle).

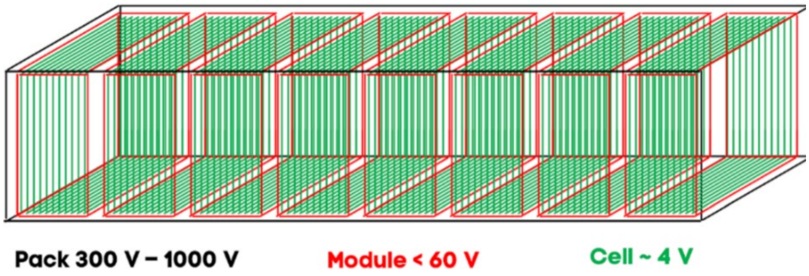


Figure 2.1 Schematic view of the battery pack of an electric vehicle

There are three main configurations depending on where the battery pack is located in the vehicle. Figure 2.2 shows these configurations, identifying them from top to bottom as: the ‘Floor’, ‘T’, and ‘rear’ configurations. In most cases, the battery pack is located at the bottom of the vehicle with the most common configurations being the 'T' and 'Floor' configurations. In the 'rear' configuration, the battery pack is located at the rear of the vehicle, as is visible in the figure at the bottom. This configuration is mainly used in small cars and hybrid vehicles with small battery packs, as their construction is less complicated, allowing for a more efficient use of space and better weight distribution.

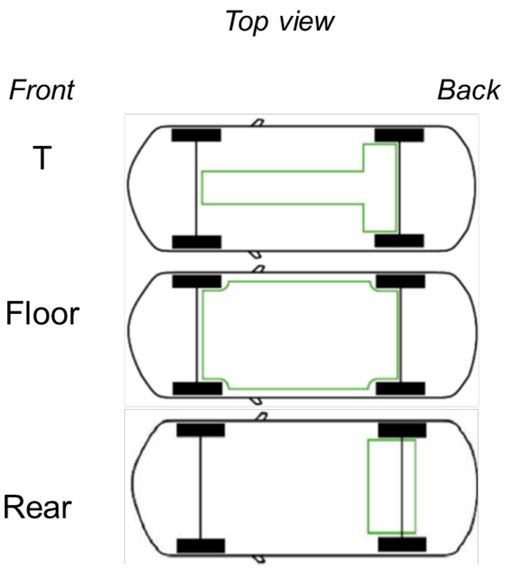


Figure 2.2 Main battery pack configurations

2.2 Thermal runaway

Thermal runaway is an unwanted, exothermic reaction in the interior of battery cells that releases heat and flammable and toxic gases. What is typical of this intrinsic safety problem is that thermal runaway is self-sustaining, partly because the production of heat reinforces itself.

In principle, **thermal runaway** is a process that takes place at a cellular level. The spread of thermal runaway from a battery cell to surrounding battery cells is referred to as **thermal propagation**. However, the term 'thermal runaway' is often also used at the module or battery pack level. For example, a battery pack can be said to be in thermal runaway if one or more battery cells inside the relevant pack have gone into thermal runaway.

Since thermal runaway in a battery cell is a self-sustaining reaction, it is, in principle, not possible to stop the thermal runaway of an individual battery cell. This report therefore states that the purpose of the UHP deployment is to **stop thermal propagation**. Once the thermal runaway of the last active battery cell in the pack has come to an end (because the chemical process has ended), and successful cooling prevents further thermal propagation, the thermal runaway in the battery pack can be said to have stopped.

The State of Charge (SoC), i.e. the extent to which a battery is charged, influences fire development during thermal runaway (NIPV, 2023). The higher the SoC, the more energy and heat are released during thermal runaway and the greater the likelihood of self-ignition of the flammable gases released, resulting in flames. In general, flame formation is strongest at an SoC of 90 % to 100 %, which is also the reason why batteries with comparable charge levels are often used in fire experiments such as in this study (K. Wilkens, personal communication, 5 and 6 June 2023). If the SoC is less than 30 %, flammable gases are still released, but the amount of energy released is limited, making self-ignition of these gases unlikely (NIPV, 2023).

2.2.1 Toxic gases

The gases released during thermal runaway are toxic (see the NIPV scenario book for composition details).

2.2.2 Flames and jet fires

The gases released during thermal runaway are flammable. Two scenarios can play out: 1) direct ignition of the flammable gases, or 2) no direct ignition, releasing a cloud of flammable gases after which delayed ignition of these gases may follow. In case of a fire, the gases will be forced out of the battery pack under high pressure through the pressure relief valves or through openings in the battery pack caused by damage, overpressure or fire. These flammable gases can result in flames and jet fires. In addition, jet fires in unexpected directions can also occur if the casing is damaged.

2.2.3 Explosion

If the flammable gases accumulate they might explode. This can happen in particular if the vehicle is parked indoors or under a carport or if the gases accumulate in the closed passenger compartment of a vehicle (Vos et al., 2024). The flammable gas cloud can ignite under certain conditions. This is known as delayed ignition.

Figure 2.3 Explosive ignition of a vapour cloud (photo: unknown)

Explosions in case of electric vehicle fires in which the battery is involved are a realistic scenario. A recent example is an explosion of a hybrid Jeep in Ghent in November 2023. Gases caused by thermal runaway had accumulated in the vehicle. After firefighters smashed the windows, these gases reached explosive limits and the vapour cloud ignited. The time of the explosion can be seen in Figure 2.3. Data from EV Firesafe shows that, as far as is known, 22 of such explosions occurred worldwide between 2010 and June 2024 (EV Firesafe, 2024).

2.3 The problem of fighting electric vehicle fires

Responding to an incident involving a battery pack in thermal runaway is complex not only because the process is self-sustaining, but also because battery cells are in a sturdy casing. This makes it nearly impossible for cooling water to reach the cells, making cooling from the outside very difficult (Brans, 2023).

Besides the dangerous effects of thermal runaway, discussed in the previous section, there is also a high-voltage system in an electric vehicle. In an unfavourable scenario, the fire service may become part of a closed current circuit while applying a UHP system. However, this is a rare scenario and its probability is considered to be extremely low (Fire Service Academy, 2020; Hessels & Geertsema, 2023). Personal protective equipment offers some protection against this. However, since it is not possible to wear fireproof gloves and electrically insulating gloves at the same time, electrically insulating gloves designed for working with electricity cannot be used while fighting a fire.

2.4 Current deployment tactics

At present, two ways to stop thermal runaway in an electric vehicle are used in the Netherlands, i.e. using an submerging container or letting the battery pack burn out (Hessels & Geertsema, 2023).

The first method, where an submerging container is used, involves placing the vehicle in a liquid-tight container, which is filled with water until the battery pack is completely submerged. This prevents the surroundings from being exposed to the flames while the thermal runaway is left to run out in a controlled manner. This is supported by water slowly entering the battery pack through any damage spots and cracks and cooling the battery cells to some extent. However, because very little use is made of the cooling capacity of the water in this situation, this procedure is quite inefficient in this respect. This is because the battery cells are surrounded by the vehicle chassis and the casing, making it very difficult or impossible for water to reach the battery cells. Water can only properly penetrate the battery pack and reach the cells if the battery pack is damaged or has openings. This submerging process also takes a lot of time: the vehicle must remain in the submerging container for several days. The deployment of this method is also costly because several thousands of litres of contaminated water from the submerging container must be disposed of.

A second method is to let the vehicle burn out: all the energy from the battery pack is then consumed by the fire. The advantages of this method are that no contaminated extinguishing water is left behind and, in principle, firefighters cannot be exposed to the expected or unexpected effects of thermal runaway. Moreover, in principle, the battery will largely or completely burn out, minimising the probability of re-ignition. However, this method can only be used if sufficient space is available and there are no harmful effects that would cause a nuisance to the surrounding area. Obviously, letting a car burn out is not an appropriate solution in a built-up environment, such as a city centre.

2.5 Ultra high pressure cutting and extinguishing system

NIPV has previously investigated possible alternatives for the submerging method, including a UHP extinguishing system (Hessels & Geertsema, 2023). In the Netherlands, a situation in which this type of system is used for offensive exterior attacks if a building is on fire (NIFV, 2012). Several Dutch fire brigade regions use the Coldcut Cobra, and the comparable CoolFire system (different brands of ultra high pressure cutting and extinguishing systems) (UHD-Blussing.nl, 2024).

A UHP extinguishing system enables the seats of fires to be approached from the outside. This is because such a system makes it possible to make a hole on the outside of a wall or a wall partition, through which water can then be injected. UHP extinguishing systems have been used for more than 20 years. They are spin-offs from the offshore industry where they were used to fight fires on ships. Their development was based on a desire to improve safety for firefighters.

The operation and original deployment method of a UHP extinguishing system is as follows. Water is pumped to ultra high pressure; i.e. 300 bar in the case of the Cobra. The abrasive is then added. This is a pellet/powdery substance that has a grinding effect. Additives can be added to the extinguishing water as required. The flow rate of the water is 60 litres per minute and the exit velocity of the water can become as high as 200 m/s, causing it to atomise. This enables a large surface area to be reached so that the confined space can be cooled faster (J. Hellsten and A. Trewe, personal communication, 17 and 18 July 2023). The phase transition from water to steam enables a lot of energy (heat) to be extracted from the seat of the fire. This is due to the physical principle of high latent heat associated with the phase transition from water to steam.

Tests conducted with a UHP extinguishing system on a confined space generally show that the smoke coming out of the fire room is initially thick and black (J. Hellsten and A. Trewe, personal communication, 17 and 18 July 2023). Once water mist is applied through the hole created, the smoke or vapour becomes predominantly white and looks more like steam from the evaporated water. Tests in shipping containers showed a sharp decrease in temperature during this process, which indicates that the cooling is effective and fast.

In the fire experiments carried out for the present research, the way in which the extinguishing system was deployed differed from its initial purpose. Instead of atomising water over a confined space, this system was now used to inject water into a battery pack. This is one of the reasons why it is important to test whether the system is effective for this new application.

3 Existing knowledge and experience

3.1 MSB and Coldcut Systems

The Swedish Civil Contingencies Agency (MSB), in collaboration with Coldcut Systems from Sweden, has recently conducted a study that led to the conclusion that a UHP extinguishing system is effective for stopping the propagation of thermal runaway in the battery pack when an electric vehicle is on fire (MSB, 2023). The lessons learnt from this research and Coldcut Systems' advice are discussed in this section.

3.1.1 Jet fires

During its fire trials with a full battery pack (67 kWh), a smaller pack (26 kWh), and a module (6.54 kWh), MSB observed the fire development and then extinguished the fires. During the observations it was studied where most jet fires were released. Based on the experiment and other experience of Coldcut Systems, it was found that flames and jet fires can be released from the pressure relief valves and from any points of damage to the battery pack casing. It is quite common for battery pack casings to have pressure relief openings (also referred to as pressure relief valves) to vent gases in the event of thermal runaway and thus prevent excessive pressure build-up. However, it should be emphasized that pressure relief valves and visible points of damage only give an indication of where jet fires may be released, but that it is not certain that they will be released there (Coldcut Systems, 2024).

Unexpected flames (which includes jet fires) can make it difficult for firefighters to work safely. During the experiment, MSB assessed that the probability of jet fires occurring was greater than the risks of explosion or electrocution (P. Malmquist, personal communication, 2 November 2023). Jet fires can prevent firefighters from reaching the right position to be able to effectively deploy the UHP extinguishing system. There is also the risk of firefighters being unexpectedly exposed to such jet fires. That is why constantly monitoring where the flames are during the deployment and adjusting the location of the UHP extinguishing system accordingly is crucial. This means that firefighters should take position on the side with the fewest flames (Coldcut Systems, 2024). In addition, someone with a low-pressure jet should be deployed to protect the UHP extinguishing system operators from the jet fires (Coldcut Systems, 2024).

3.1.2 Explosion

The risk that explosions pose for firefighters can be reduced. If the car is still closed, a safe situation must be created first. This requires the gases to be expelled from the vehicle (MSB, 2024). A fan can be used for this purpose (Coldcut Systems, 2024).

3.1.3 Toxic gases

The MSB study shows that firefighters' firefighting clothing, including breathing apparatus, provides sufficient protection against exposure to toxic gases (MSB, 2024). However, cleaning the firefighting clothing after contact with the gases from a thermal runaway is necessary (RIVM, 2021).

3.1.4 Electrocution

The fire service might become part of a closed current circuit while applying a UHP system. MSB thinks that the probability of this occurring is extremely low.

3.1.5 Penetration point and deployment location

Based on their experiment and other practical experiences, Coldcut Systems (2024) and MSB (2024) recommend that the penetration point for deploying the UHP extinguishing system should be as close as possible to the largest hot spot. A thermal imaging camera (TIC) can be used to identify this hot spot. A prerequisite is that there is a safe deployment position for the person operating the UHP system, i.e. that he or she will not be exposed to flames. Once the deployment is successful, the TIC is used to find a possible next hot spot for the UHP extinguishing system to be deployed. This procedure should be repeated until there are no more hot spots.

It is possible that the best penetration point cannot be used and another penetration point should be found. MSB's experiment showed that water can flow from another (secondary) location to the primary location (MSB, 2024), provided the battery pack is not compartmentalised. If a battery pack is compartmentalised (i.e. consists of several separate modules with separations between them), it is not possible to have water flow freely. Water introduced into the compartment of the secondary location cannot reach the compartment of the primary location. This means that if water is introduced into another compartment, the water will not reach the compartment that is in a state of thermal runaway. In such a case, the UHP extinguishing system should always be deployed to a new location within the primary fire compartment in question (Coldcut Systems, 2024).

If the vehicle is in an inclined position, for example on a hill, it may be useful to deploy from the highest point (Coldcut Systems, 2024). In that case, water will flow from the highest point to the lowest point in the battery, filling it with water as much as possible. Deployment at a lower point involves the risk of the upper part not being sufficiently cooled.

As regards the angle of attack, i.e. the angle at which the lance of the UHP extinguishing system is pointed at the battery pack, Coldcut Systems came to the following findings:

- Penetrating the battery pack casing is relatively easy with a 90-degree angle of attack (straight from above). In practice, this is the easiest angle of attack.
- If the angle of attack is approximately 45 degrees (+/- 15 degrees), it takes slightly longer to penetrate the casing, because the distance from the point of penetration to the bottom of the battery pack is longer. However, the advantage of this is that a larger part of the battery pack is reached by the direct water jet.
- If penetrating the side of the battery pack is the only option, this is also a possibility. Although the direct jet of water may reach fewer modules then, the water introduced will still quickly lead to a cooling effect.

3.1.6 Introducing water

After making the hole in the battery pack, the water must be introduced for such a long time that propagation can be stopped. Coldcut Systems (2024) and MSB (2024) experienced that this can take several minutes (a general indication is five to ten minutes).

A good indicator of when the introduction of the water actually leads to cooling of the battery cells is when the water in the battery pack is converted to steam by the heat of the thermal runaway (Coldcut Systems, 2024). This steam can be recognised visually. If no steam is formed any more and water runs out of the top of the battery pack, this is an indication that much of the heat has been removed and propagation has stopped. Introducing the water can then be stopped. A TIC can then be used to search for any hot spots left and the UHP extinguishing system can then be deployed to those hot spots. MSB recommends a temperature of 50 degrees Celsius or more as an indicator of a hot spot (MSB, 2024). If the water is not converted to steam after one minute, the battery pack may be compartmentalised as referred to above or the location identified for the hot spot may be incorrect. Deploy at a different location then.

Furthermore, when deploying the UHP extinguishing system, undamaged cells may be hit by the water containing the abrasive. These cells can then go into thermal runaway due to the damage caused by the abrasive; this cannot be avoided. However, because water is introduced directly, propagation of this thermal runaway is prevented almost immediately (MSB, 2024).

3.1.7 Safe situation

The goal of deploying the UHP extinguishing system is to restore a safe and stable situation, i.e. a vehicle whose battery pack is no longer in thermal runaway. According to MSB and Coldcut Systems, a temperature of 50 degrees Celsius or less across the entire battery pack (which means that there are no hot spots) is a good indicator that the thermal runaway and its propagation have stopped. Coldcut Systems (2024) recommends continuously monitoring the vehicle with a thermal imaging camera for 15 minutes after this. MSB (2024) stated that it is not yet clear how long this period should be.

In connection with possible re-ignition, it is advised that the vehicle be placed in a safe place after deployment so that any re-ignition will not lead to fire spread or risk to people (MSB, 2024). This is because it is possible that there is still 'stranded energy' in any parts of the battery pack that have not burnt out (MSB, 2024). This stranded energy can cause re-ignition at a later time.

3.2 Czech Republic

Tests of the deployment of a UHP extinguishing system to stabilise batteries in electric vehicle fires were started in the Czech Republic five years ago (J. Hellsten and A. Trewe, personal communication, 17 and 18 July 2023). Several tests have been conducted there in collaboration with a car manufacturer in recent years, A UHP extinguishing system was deployed to an actual incident with an electric vehicle fire in an underground car park in Prague in the Czech Republic (EV Firesafe, 2023). Standard action guidelines for the deployment of a UHP extinguishing system to electric vehicle fires are being developed in the Czech Republic.

3.3 Knowledge gaps related to the Dutch context

The knowledge and experience gained abroad provide a good basis for further exploring the possibility of deploying a UHP extinguishing system in the Netherlands. We have identified the following knowledge gaps that we aim to fill by means of the fire experiment at Schiphol Airport:

- The research findings that were published do not provide a sufficient base for developing operational action guidelines for Dutch UHP units. A different system than that advised by Coldcut Systems may be desirable, partly because, in the Netherlands, deployment of UHP extinguishing systems tends to be left to specialist units. To determine what system is desirable, we are studying whether the deployment procedure advised by Coldcut Systems and MSB also proves effective and suitable for application in the field when carried out by a Dutch UHP unit.
- The lack of visual data in order to gain a convincing and clear picture of the UHP deployment.

In addition, the preliminary study by the Haaglanden Safety Region (see section 1.1) identified the following two knowledge gaps:

- There are no guidelines for action if gas has accumulated in a closed passenger compartment.
- A substantiation of the statement that the probability of electrocution risk is considered to be low; this can be substantiated by means of current conductivity tests or by other means.

4 Preparation and design of the Schiphol fire experiment

4.1 Thermal runaway initiation method

Prior to the experiments, a preliminary study was carried out into the different methods that can be used to initiate thermal runaway in an electric vehicle. This preliminary study can be found in Annex 1; its results are summarised in Table 4.1.

Table 4.1 Results of preliminary study into initiating thermal runaway

	Heating plate ***thermal***	**Gas burner** ***thermal***	**Penetration by a nail or a screw** ***mechanical***
Advantages	> Possibility to install thermocouples and voltmeters for monitoring. > Possibility to apply two plates. > Typical thermal runaway scenario > Predictable (location and time) > Controllable (temperature and safe distance)	> Simple > Financially advantageous > Direct ignition of flammable gases, reducing explosion risk. > Safe distance (limited)	> Multiple attempts possible > Immediate or fast results > Location of thermal runaway predictable to a certain extent
Disadvantages	> Specific expertise is needed; this takes time and costs money > Risk of explosion	> Rare scenario > Worst-case scenario > Thermal runaway as a consequence of a vehicle fire *instead of* a vehicle fire as a consequence of thermal runaway. > Limited mobility of the gas burner	> Damage is done to the battery pack. > Gases and jet fires can come out of the holes. > The battery pack is hard to reach. > Preparing the penetration setup takes time.
Final assessment	**The method is safe and effective.**	**The method is neither safe nor effective.**	**The method is safe and effective.**

Based on this preliminary study, it was concluded that a heating plate in the battery pack is a suitable and safe method to induce thermal runaway for several reasons, including the fact that it can be started in a controlled manner, it mimics a realistic scenario and has few disadvantages. This option was discussed with the vehicle supplier, but it turned out that it was not possible to factory-fit heating plates. That is why the mechanical method was chosen, since it was also found to be safe and effective. The mechanical method involves putting a battery pack into thermal runaway by causing mechanical damage at the battery cell level.

We wanted to ensure the safety of the person who was to cause the mechanical damage by providing a construction that would allow them to maintain a safe distance. For this purpose, the Haaglanden Safety Region developed a system that consists of a drill stand to which a pillar drill is attached. A rope is attached to the pillar drill. Unwinding the rope lowers the pillar drill. This enables the rope to be pulled from outside the vehicle, introducing the drill into the battery pack. The system as installed in the vehicles is shown in Figure 4.1. In principle, if this method is successful and an electric vehicle fire starts, the drill is lost.

The setup consists of the following elements:

- drill stand
- chuck
- drill
- long drill bit
- rope
- small materials to construct and attach the setup.

Schematic drawings of the battery pack provided by the vehicle supplier were used to identify the point where the drill should penetrate the battery pack. The floors of the cars were removed at the point to be drilled beforehand in order to improve the probability that thermal runaway could be initiated successfully.

Figure 4.1 Drill setup

4.2 Current conductivity tests

Try-outs by the Haaglanden Safety Region
The Haaglanden Safety Region carried out two preliminary sub-experiments in order to test two aspects that could not be examined during the Schiphol fire experiment. The first sub-experiment involved current conductivity tests to rule out any risk of electrocution. The second sub-experiment was held to test the possibility of using a UHP extinguishing system in order to remotely bust the windows, enabling any flammable gases to be expelled if the passenger compartment was closed. A brief report with the results of these preliminary sub-experiments can be found in this section and in section 4.3.

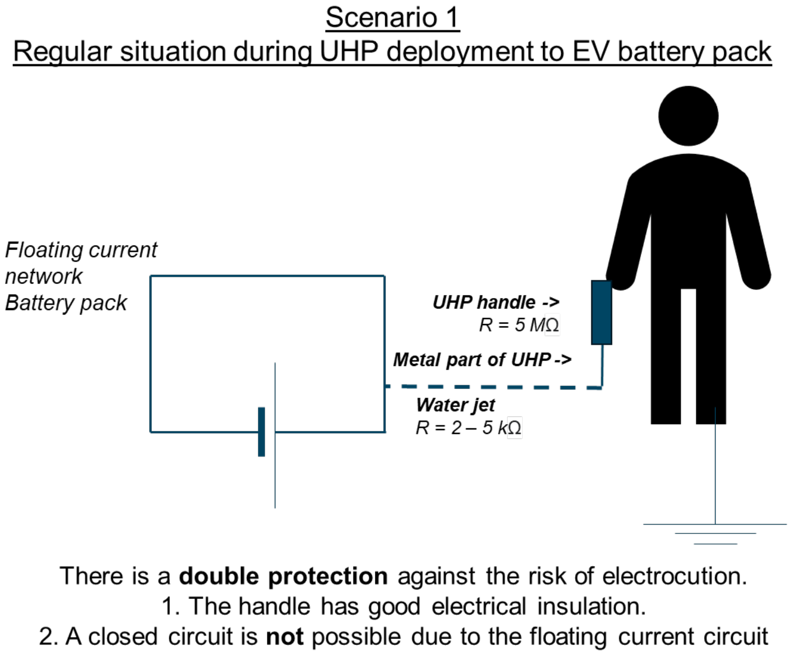
There is a risk of electrocution if both the plus and minus poles of a battery are touched. The probability of this happening in regular fire service action involving an electric vehicle is almost zero (Fire Academy, 2020). When the Fire Service Academy made risk assessments in 2020, the deployment of UHP extinguishing systems to batteries of an electric vehicle was not considered. According to section 3.1.4, experts from abroad who used UHP extinguishing systems to cut into a battery pack consider the risk of electrocution to be small. To verify this and further understand the risk of electrocution, current conductivity tests were carried out.

These tests were conducted using a 1000 V voltage source, an oscilloscope, a car wreck and a Coolfire extinguishing system (a type of UHP extinguishing system). The oscilloscope was used to measure resistances of various current circuits. The results can be found in Table 4.2. The left-hand column of this table lists the components of the current circuit and the middle column lists the resistance values measured. The conclusion that can be drawn from the measurement is in the right-hand column. To interpret and visualise what this means, three scenarios have been developed. They are discussed below.

Table 4.2 Current conductivity test results

Current circuit	Resistance (R) measured	Conclusion based on the resistance measured
Steel Coolfire parts connected to the **vehicle chassis** with a live voltage.	5 – 7 Ohm	There can be a live voltage on the steel parts of the Coolfire.
Handle of the Coolfire connected to the **vehicle chassis** with a live voltage	5,000,000 ohms	Handles are well insulated.
Nozzle via the water jet to a voltage source. *Scenario during UHP deployment with the voltage source acting as a battery pack.*	20,000 – 50,000 ohms	In theory, a potential current can flow. However, the risk of the UHP operator being electrocuted is very unlikely because of the floating network of the electric vehicle.

4.2.1 Scenario 1: Regular situation during UHP deployment to the battery pack of an electric vehicle

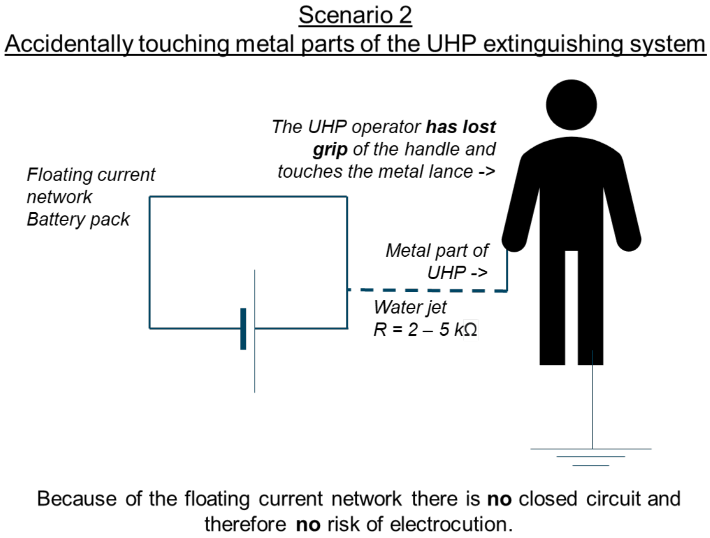

Scenario 1
Regular situation during UHP deployment to EV battery pack

There is a **double protection** against the risk of electrocution.
1. The handle has good electrical insulation.
2. A closed circuit is **not** possible due to the floating current circuit

Figure 4.2 Regular situation during UHP deployment (R = resistance)

In essence, under regular conditions during a UHP deployment there is double protection against the risk of electrocution (see Figure 4.2). Firstly, tests by the Haaglanden Safety Region showed that the handles have proper electrical insulation, so that they will not conduct any electric current. Secondly, there is a floating current network that prevents a closed current circuit from being formed (Victron Energy, 2023). The situation where the first protection 'fails', i.e. where the UHP operator touches metal parts of the UHP extinguishing system (for example in response to the operator losing grip), is visualised in scenario 2.

4.2.2 Scenario 2: The UHP operator accidentally touches the metal parts of the UHP extinguishing system


Scenario 2
Accidentally touching metal parts of the UHP extinguishing system

Because of the floating current network there is **no** closed circuit and therefore **no** risk of electrocution.

Figure 4.3 Accidentally touching the metal parts of the UHP extinguishing system

The tests showed that there can be a live voltage on the steel parts of the UHP extinguishing system when they are in direct contact with a voltage source. This is also possible in case of contact via the water jet. In that case, the water jet will form a resistance (the test showed 20,000 to 50,000 ohms), which will considerably reduce the potential electric current. However, this resistance is not high enough to rule out all possibilities of a potentially dangerous current.

Although a water jet can also lead to a live voltage on the metal parts of the UHP extinguishing system, there is still no direct risk of electrocution in that case (Figure 4.3). This is explained by the fact that the battery pack is a floating network that is not connected to the earth or to any parts outside the electric vehicle (Victron Energy, 2023). This prevents a closed current circuit from being formed.

4.2.3 Scenario 3: Theoretical situation in which a closed current circuit could occur

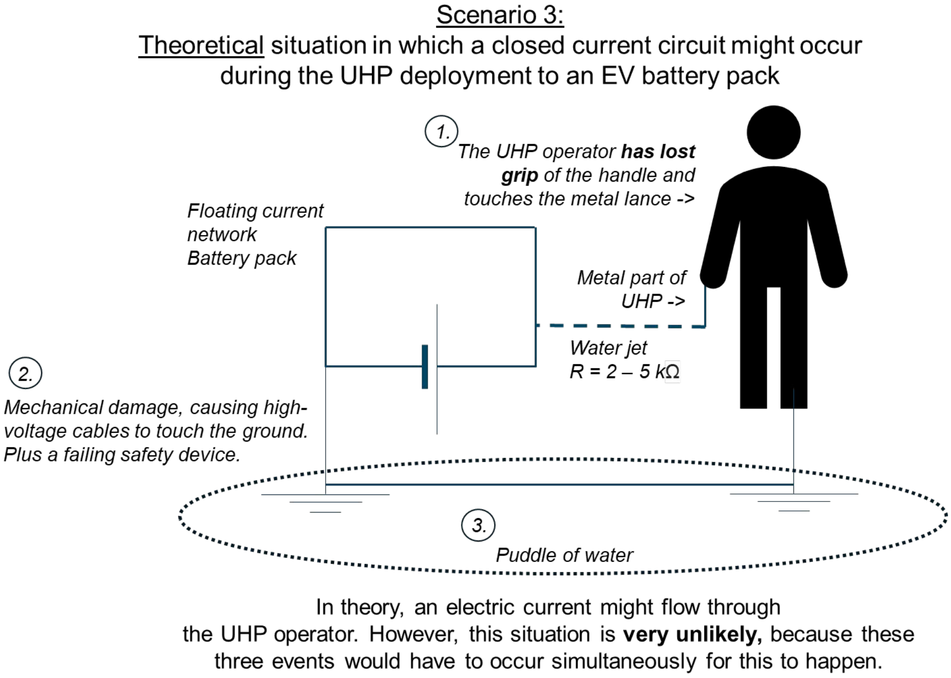


Figure 4.4 Theoretical failure situation

Figure 4.4 shows the situation where it is theoretically possible that an electric current will flow through the UHP operator. It should be noted that this current will be limited because of the resistance of the water jet. This would only happen if the UHP operator accidentally touched the metal parts of the UHP extinguishing system while also being in contact with another point of the battery pack, e.g. through a puddle of water on the ground. In this example, that other point is a high-voltage cable that forms a circuit with the UHP operator through mutual contact with a puddle of water. It should be noted that this is only possible if safety devices that should have made the high-voltage cable dead, failed in the process.

4.2.4 Conclusion of current conductivity tests

In summary, the conclusion is that, under ordinary conditions (scenario 1), as well as when metal parts are accidentally touched (scenario 2), there is hardly ever a risk of electrocution. It is possible to imagine a theoretical failure situation where there is a closed current circuit (scenario 3), but the probability of this occurring is minute.

4.3 Blasting the windows

As discussed in section 3.3, no advice for action is known that relates to the scenario of a closed passenger compartment where there may be a risk of explosion due to flammable gases that could accumulate. The Haaglanden Safety Region has a suggestion for this, which is to use a high pressure water jet to bust the windows of the vehicle from an ample distance. If water that contains abrasive is used, the UHP extinguishing system can do this. This will cause the windows to crack, enabling the flammable gases to exit the vehicle. The high impulse of the jet water will also drastically accelerate the venting of the gases. It is important that an ample distance is kept here; see Figure 4.5.

Figure 4.5 Deployment of UHP extinguishing system to bust the windows (photo: Haaglanden Safety Region)

The Safety Region conducted a sub-experiment with an end-of-life vehicle and found that it is possible to use a water jet to bust the windows from a distance of seven metres. It was also established that it is possible to bust the windows on both sides of the car by deploying a water jet to one side of the car. To do this, the jet is directed through the vehicle from the same position. Of course, no one should be in the area covered by the water jet of the UHP extinguishing system. The removal of gases from the vehicle can be accelerated by means of a fan.

4.4 Test vehicles used in the Schiphol fire experiment

Two almost identical electric vehicles were used for the two experiments. Both vehicles were fully electric multi purpose vehicles (MPV) with a 75kWh Li-ion battery pack of the NMC (nickel manganese cobalt oxides) subtype. The battery pack consisted of a casing containing loose modules. There were no partitions or compartments in the battery pack. A picture and a schematic drawing of the type of vehicle is shown in 4.6. This is also the 'rescue information sheet' of the test vehicles. This shows a drawing of the battery pack with high-voltage cables in orange. The first test vehicle had an empty cargo bay. The second test vehicle had two leather upholstered seats and fabric floor covering in the cargo bay.

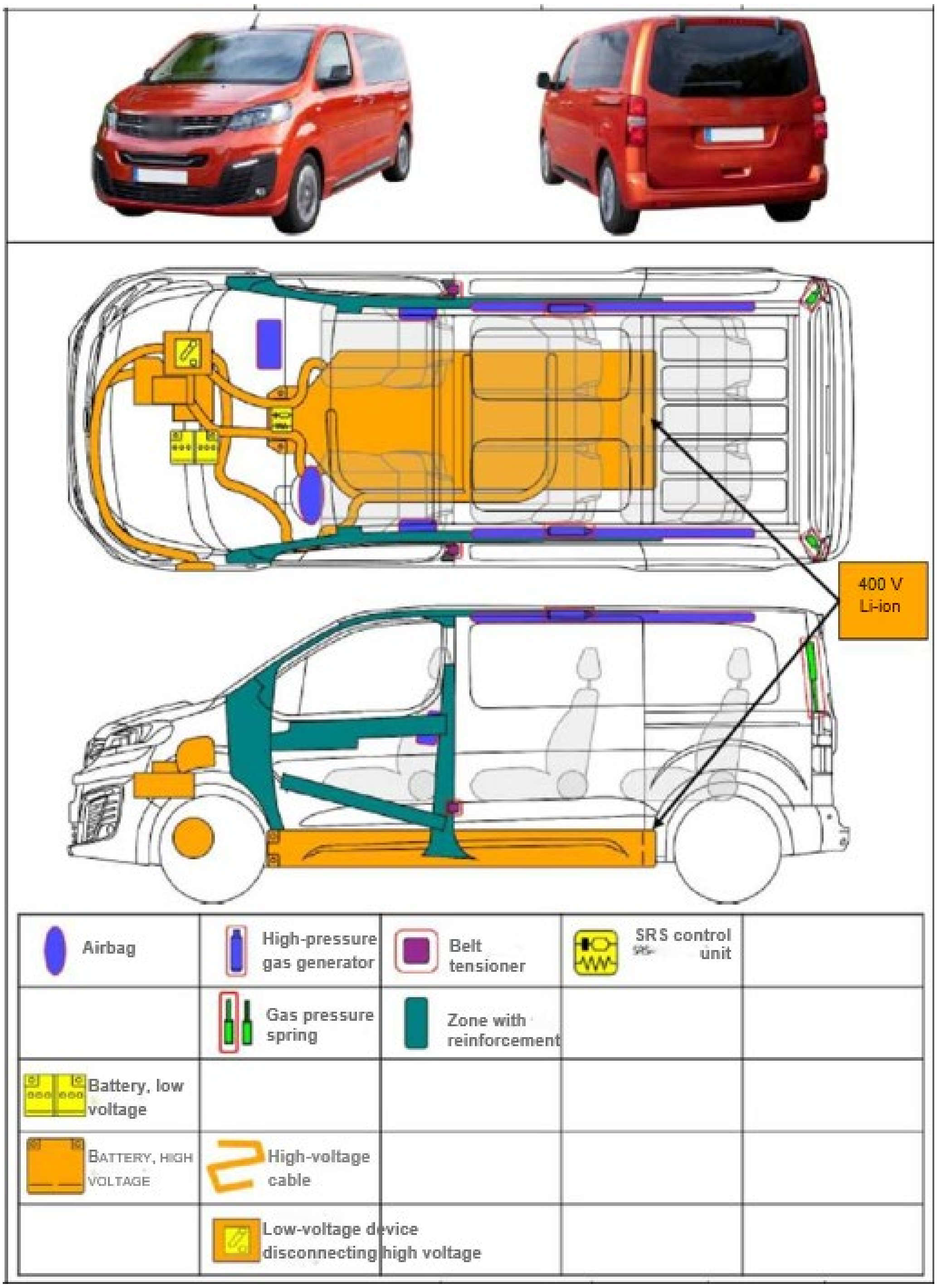


Figure 4.6 Rescue information sheet of the test vehicle[1]

4.4.1 Preparations to the vehicle for the experiment

Prior to the experiment, the vehicles were fully charged (100 % SoC) after which they were driven from the charging location to the location of the experiment (approximately one kilometre). This enabled the highest possible SoC to be guaranteed. To enhance the safety of the fire personnel to be deployed during the incident, the following additional actions were carried out on the vehicle:

---

[1] The drawing shows a vehicle configuration with two rows of seats in the back of the vehicle. Our first test vehicle had no rear seats and our second test vehicle had one row of seats there.

- The tyres were deflated to prevent them from exploding unexpectedly.
- Gas springs were removed to prevent them from exploding unexpectedly.
- The driver and passenger door windows, as well as the sliding doors on the sides of the vehicle, were opened. This prevented any accumulation of flammable gases, thus minimising the explosion risk.

4.5 Participating fire crews

4.5.1 Basic firefighting unit

The basic firefighting unit to be deployed, a fire appliance (FA) with a six-person crew, was briefed to follow the usual procedure for fighting vehicle fires. The FA crew had studied the information in the Electronic Learning Environment of the Dutch Fire Service (ELO Brandweer) once more for this. The FA was made available by the Amsterdam-Amstelland Safety Region and was manned by firefighters from the Amsterdam-Amstelland, Haaglanden and Utrecht safety regions.

Intermezzo: deployment procedure when fighting vehicle fires:
In accordance with the e-module on vehicle fires, the procedure for fighting vehicle fires basically consists of the following steps:

- Approach the vehicle at a 45-degree angle.
- Wear a breathing apparatus and do not walk in the smoke.
- Use two jets of low pressure to extinguish the vehicle fire.

4.5.2 UHP units

The UHP units that participated in the experiment came from the fire stations located in:

- Nieuwegein-Zuid / Vreeswijk (Utrecht Safety Region); this unit was deployed in the morning. The unit had a Coldcut Cobra UHP extinguishing system.
- Rijswijk (Haaglanden Safety Region); this unit was deployed in the afternoon. The unit had a Coolfire UHP extinguishing system.

Both units had practical experience with and were trained in deploying a UHP extinguishing system. The participating units received additional training from Cold Cut Academy, the training arm of Coldcut Systems. During this session, they were trained on how to deploy the UHP extinguishing system to the burning battery pack of an electric vehicle. Consequently, these fire units largely worked according to Coldcut Systems' advice.

The reasons why it was decided to work with two different UHP units, rather than deploying the same team twice, were:

- Fire brigades in the Netherlands use two different high-pressure cutting and extinguishing systems.
- Two test vehicles were available. Deploying two separate teams promoted equivalence between the two tests because it was ruled out that any lessons learnt from the first session were applied to the second session.

4.6 Location

The experiments took place in the fire practice area (Brandweer Oefenplaats - BROEF) of the Amsterdam Airport Schiphol Fire Brigade which is sufficiently far away from any buildings. The vehicle was placed on a sloping stretch of asphalt with a dam behind it to collect any contaminated extinguishing water. This extinguishing water was immediately extracted by a processing company. The vehicle was placed on metal road plates to prevent the asphalt from being damaged.

4.6.1 Layout

Figure 4.7 shows the general layout of the location.

Figure 4.7 Site layout

The blue areas show the location of the UHP unit and the FA. The yellow area was where the researchers worked. Breathing apparatus had to be worn in the orange area. No access was allowed to the red area during the experiments due to toxic gases and smoke. The curved green line shows the location of the extinguishing water dam, and the orange arrow indicates the prevailing wind direction that day.

4.6.2 Meteorological conditions

According to the measuring point of the Royal Netherlands Meteorological Institute (KNMI) at Schiphol, the following meteorological conditions prevailed during the experiments. What is particularly relevant is the wind direction, since this influenced the positioning of the danger and safety areas referred to above.

10:00
26.5 degrees Celsius; relative humidity of 51 %; hourly average wind speed of 6 m/s with maximum gusts of 10 m/s; wind direction 230 degrees, i.e. almost southwest.

14:00
27.1 degrees Celsius; relative humidity 49 %, hourly average wind speed of 6 m/s with maximum gusts of 10 m/s; wind direction 260 degrees, i.e. almost west.

From a firefighting point of view, conditions were hot and because of that, the firefighters that were deployed rotated sufficiently frequently to avoid overheating.

4.7 Safety and ethics

As part of this research, a fire service unit was asked to apply an existing type of tool to a new situation. Although the members of the fire service unit were professionally trained to handle hazardous situations, this experiment required them to perform actions in a new situation close to the source of risk (the burning vehicle). Typical of electric vehicle fires is that there is a certain degree of unpredictability in how the fire develops. This may lead to potentially hazardous situations, making it appropriate for us to justify the choice of a fire experiment with research participants (the fire personnel). We wrote an ethical justification for this, since, in experimental science, an ethical statement is recommended when conducting research with people not covered by the Dutch Medical Research Involving Human Subjects Act (Wet medisch-wetenschappelijk onderzoek met mensen - WMO) (Radboud University, 2023).

Radboud University (2023) drew up seven ethical principles that such an experimental research proposal should comply with. We based our ethical consideration on these principles. These seven principles are listed below and their corresponding substantiation can be found in Annex 2: Ethical considerations.

1. Scientific relevance: The research is scientifically relevant.
2. Proportionality: The expected benefits are proportional to the expected efforts.
3. Soundness of methods: The researcher uses appropriate research methods for the research problem at hand.
4. Risks and safety: Research participants should be as safe as possible and exposed to as little risk as possible.
5. Implementation: The research and the experiments should be carried out by qualified personnel.
6. Data management: Relevant data management procedures should be taken into account. They relate to various aspects, including data storage, data collection and access to the research data.
7. Autonomy: The autonomy of research participants must be respected.

In addition to this ethical justification, some participating parties conducted risk assessments (Dutch RI&Es):

- Coldcut Systems conducted a risk assessment of the deployment of a Cobra Coldcutter to a burning battery pack of an electric vehicle.
- The Haaglanden Safety Region conducted a risk assessment of the deployment of a Coolfire to a burning battery pack of an electric vehicle.
- The Amsterdam Airport Schiphol Fire Brigade conducted a risk assessment of conducting the trial at the location in question.

The Omgevingsdienst Noordzeekanaalgebied environmental authority granted a permit to conduct the trial at this location. There were also several contacts with MSB on the tests

MSB conducted to assess the deployment of a UHP extinguishing system to a burning battery pack. The information obtained by MSB was incorporated into the test design.

And last but not least, there was an submerging container at the site of the experiment as a safety feature, so that the electric vehicle could be placed in the submerging container if the experiment failed. A safety officer was also present during the experiment.

4.8 Timetable for the experiments

A timetable outlining the course of the experiments was drafted as a guideline for the two experiments in advance. This is shown in Table 4.3. In this schedule, the basic firefighting unit was tasked with extinguishing the vehicle's bodywork and the UHP unit should then deploy the UHP extinguishing system to stabilise the battery pack. The safety officer monitored both experiments to make sure that everyone acted safely.

Time t_1 = timer start or $t_1 = 0$ means that the timer started running. This time was established when the researcher who was tasked with visually observing the experiment and managing the timer observed flames coming from the battery pack and/or vehicle. After this time, it was decided to assume a response time of 10 minutes for the basic firefighting unit, or FA, as this is a realistic response time for a fire appliance to arrive at the scene after an incident is reported in the Netherlands.

After the commanding officer called the UHP unit at time t_2 = UHP unit alert, a 5-minute response time for this unit followed. This is a shorter response time than can be expected for an actual incident. This was decided with an eye to the smooth progress of the experiment and to prevent the battery from burning out too far. This improved the probability that the fire load of the battery was still sufficient and avoided the UHP extinguishing system being deployed to a burnt-out battery.

When the UHP deployment was found to have been effective, it was stated that the fire was under control. The UHP deployment was considered to have been effective if no more smoke, flames and steam came from the battery pack and water was seen to be leaking out of the battery pack. This was established visually and using a TIC by the commanding officer and/or UHP operator of the UHP unit.

The end of the experiment was announced after no smoke, flames or detectable increase in temperature of the battery pack were detected by means of the TIC for 45 minutes. If the temperature increased during these 45 minutes, a UHP extinguishing system would be deployed again. After this, the 45 minutes would start again. If the temperature repeatedly increased or continued to increase, it might be decided to immerse the vehicle.

Table 4.3 Time sequence of the experiments

Time	Action/Event
Start of experiment *determined by the test leader*	Start thermal runaway by starting the drill
	Development of thermal runaway
t_1 = timer start *determined and started by researcher*	Flames observed from the battery pack.
t_1 + 9 minutes	Alerting the basic firefighting unit
t_1 + 10 minutes	Basic firefighting unit on the scene; deployment to the vehicle fire
time interval between t_1 + 10 min. and t_2	**Deployment of fire appliance (FA)**
t_2 = calling the UHP unit *determined by FA commanding officer*	FA commanding officer called the UHP unit to the scene
t_2 + 4 minutes	UHP unit alerted
t_2 + 5 minutes	UHP unit on site
time interval between *t_2 + 5min. and t_3*	**Deployment of UHP unit**
t_3 = fire under control *determined by the commanding officer for the fire appliance*	Fire under control: the battery pack is stable
t_3 + 45 minutes	End of the experiment, provided the temperature of the battery pack did not increase in these 45 minutes.

The participants were debriefed after the experiments; this was coordinated by NIPV researchers. During the debriefing session, the participating units verbally shared their experience(s) of the experiment in question as a group.

4.9 Descriptions for (visual) observations during the experiment

In this experiment, the observations to assess the state of the battery pack and the effectiveness of the UHP extinguishing system are mainly visual observations, supported by a TIC. We have drafted four descriptions to determine the state of the battery pack in relation to the UHP deployment; they are shown in Table 4.4. Because we aim to assess practical applicability and therefore want to mimic a real-life situation as much as possible with our experiment, no resources that are not standard equipment on a fire appliance were used to determine the state of the battery pack. An exception to this is the inspection of the battery pack after the end of the fire service deployment.

Table 4.4 Descriptions of (visual) observations of battery pack

Definition	Explanation
Thermal runaway is in effect. *Observation: visual, auditory and thermal imaging camera.*	Smoke and/or flames continue to emerge from the battery pack after the bodywork of the electric vehicle has been extinguished. This is visually established by the FA commanding officer. In support of this, hissing and popping sounds of bursting battery cells can be heard or a TIC can detect hot spots on the battery pack.
The battery pack is being cooled. *Observation: visual*	Steam comes from the battery pack. This is visually established by the UHP unit's commanding officer.
The UHP deployment is effective. *Observation: visual and thermal imaging camera*	Smoke and flames due to thermal runaway, as well as steam from the battery pack have all stopped *plus* water is observed to leak out of the battery pack. The commanding officer and/or UHP operator establish(es) this visually and by means of a TIC. Also, hot spots can no longer be detected with the TIC.
The UHP deployment is successful and can be terminated. *Observation: visual and thermal imaging camera*	No visible smoke and flames have been observed for an uninterrupted period of at least 45 minutes. In addition, no hot spots are observed on the battery pack within and after these 45 minutes. The UHP commanding officer establishes this visually and by means of a TIC.

5 Measurement data for the Schiphol fire experiments

This chapter describes the observations made during the two fire experiments. Section 5.1 describes the observations for the morning experiment and section 5.2 gives the results for the afternoon session.

5.1 Fire experiment 1 – morning

This section describes the observations made during the morning fire experiment and presents the experiences of the participating fire crews. A timeline with visual data and explanations of the first fire experiment can be found in Annex 3: Timeline for the morning session. The researchers' visual observations are recorded here.

5.1.1 Initiation of thermal runaway

During the first experiment, flames were observed briefly (for a few seconds) immediately after the battery pack was pierced. In response to this, the timer was started in accordance with the timetable in section 4.8. However, no more smoke or flame development was visible during that period. After nine minutes, the researchers decided not to send a basic firefighting unit to the scene, since the desired scenario of a fully developed electric vehicle fire had not been achieved. It was decided to drill another hole at that point in time to initiate thermal runaway. However, during this attempt, a thermal runaway as yet developed ‘all by itself’. When flames were clearly visible from the battery pack 14 minutes after the initial timer start time (t_1 =0), it was decided to start the timer again, to re-establish the 'timer start' time.

5.1.2 Deployment of UHP unit

The UHP extinguishing system was initially deployed to the location with the major hot spot after locating the hot spots with a thermal imaging camera (Figure 5.1). After this, the system was deployed several times to the locations where there were other hot spots. As expected, steam was also observed here, confirming that cooling was taking place (5.2). The UHP extinguishing system was deployed to the different hot spots for a couple of minutes each time in order to contain thermal propagation. Water could flow through the battery pack relatively easily.

During this experiment, no flames from the battery pack were observed during the UHP deployment. As instructed in the training course, the commanding officer decided to deploy one low-pressure jet as backup to be able to immediately extinguish any unexpected flames from the battery pack.

Figure 5.1 Locating and monitoring hot spot and preparing for penetration

Figure 5.2 Steam formation during deployment of UHP extinguishing system

5.1.3 End of UHP deployment

It had been determined in advance that the experiment would only be terminated if no visible smoke and/or flames had emerged from the battery pack for 45 minutes. However, due to repeated deployment of the UHP extinguishing system, smoke kept coming out of the battery during the first experiment. The TIC showed only a slight increase in temperature (the exact temperature was not recorded by the TIC) around the opening of the battery pack from where this smoke was coming. The size of this hot spot did not increase for fifteen minutes, as the TIC showed. A 4-gas detector was used. This detected CO. The LEL (lower explosive level) detector did not show any value. This indicated that there was no hydrogen gas (a flammable gas released during thermal runaway). Considering the above, some project members, a high-voltage specialist and Coldcut Systems' instructors consulted with each other. It followed from this consultation that the most plausible explanation for the smoke at that time was that wires or insulation were burning in a location that could not be reached by the water.

Only two options then remained: submerging or removing the battery and setting it aside. The submerging option was discussed first. One of the reasons why this option was not chosen was that there was no thermal runaway. Submerging would rule out all further possibilities of studying the pack and it serves a different goal: stopping the propagation of the thermal runaway. The project leader then decided to remove the vehicle from the location of the experiment, have a high-voltage specialist remove the battery and set it aside somewhere safe.

5.1.4 Inspection of the battery pack after the end of the experiment

As described above, the battery pack was set aside because smoke kept developing and the cause of this could not be explained. The battery pack was then visually monitored for about four hours. The smoke had disappeared after this time. We could not determine the cause of this smoke with absolute certainty, but it is possible that the smoke is the result of an exothermic reaction between electrolyte released from the battery cells and extinguishing water. In the period between the research and disposal to recycling (Thursday 27 June to Tuesday 2 July), the battery pack did not re-ignite.

It was discussed in section 3.1.5 that it is possible that the UHP extinguishing system damages battery cells, causing them to go into thermal runaway. An example of such damage in the battery of the experiment is shown in Figure 5.3, where the slanting entry of the extinguishing agent with abrasive can be seen. It is not known whether this damage caused these cells to go into thermal runaway. Figure 5.4 has red circles indicating the locations of the holes cut by the UHP extinguishing system.

Figure 5.3 Damage or holes after deployment of the UHP extinguishing system

Figure 5.4 Holes cut by deployment of the UHP extinguishing system

Furthermore, the top of the battery pack came loose from the bottom during the experiment. This is because the heat caused the adhesive between the top and bottom to come loose in some places. The overpressure created by gases from the thermal runaway detached the top from the bottom in some places. This created several openings of about four centimetres halfway up the height of the battery pack (see Figure 5.5).

Figure 5.5 Opening of battery pack by overpressure

There were two modules at the front of the vehicle that showed only limited damage from the fire. A 100V voltage was measured on these modules.

5.1.5 Scores and debriefing of the fire service unit

The fire crews that participated in the first experiment individually assigned scores on a scale of 1 to 10 to their feelings about the deployment and the perceived ease or difficulty of the deployment. As regards their feeling, a score of 10 was extremely positive and a score of 1 was extremely negative. As regards the perceived ease or difficulty, 10 was extremely easy and 1 was extremely difficult. The scores of the FA unit are shown in Table 5.1 and those of the Cobra unit in Table 5.2. The fire appliance belonged to the Amsterdam-Amstelland Safety Region and was manned by fire personnel from the Amsterdam-Amstelland, Haaglanden and Utrecht Safety Regions. The Cobra unit consisted of fire personnel from the Utrecht Safety Region.

Table 5.1 FA scores for the morning experiment

Task during deployment	Unit	score for feeling (1 negative – 10 positive)	score for the level of difficulty (1 difficult - 10 easy)
Commanding officer	FA (VRU)	8	9
Number 1	FA (VRH)	8	10
Number 2	FA (VRH)	8	8
Numbers 3 or 4	FA (VRH)	9	9
Numbers 3 or 4	FA (VRAA)	9	9
Average score	FA	**8.4**	**9**

When giving scores, individual participants from the first FA indicated the following:

- Number 2: “Cobra team blocked the jet crew's view.”
- Number 1: “The car was empty, this made things easier.”
- Numbers 3 or 4: “Positively surprised by Cobra, extinguishing a battery pack is difficult for a fire appliance. Cobra gives more time."

Table 5.2 Scores of Cobra unit (UHP) for the morning experiment

Task during deployment	Unit	score for feeling (1 negative – 10 positive)	score for the level of difficulty (1 difficult - 10 easy)
UHP operator	Cobra (VRU)	8	10
Commanding officer	Cobra (VRU)	8	8
Thermal imaging camera operator	Cobra (VRU)	9	9
Observer	Cobra (VRU)	10	10

Fan operator	Cobra (VRU)	8	9
Average score	Cobra (VRU)	**8.6**	**9.2**

When giving their scores, the individual participants of the Cobra unit made the following comments.

- Observer: “It [the battery fire] is out.”

The Cobra unit also stated that the fan was not optimally positioned in the first experiment, as a result of which the smoke was not blown away properly.

A joint debriefing session was held with the FA and Cobra units after the experiment. The report of this debriefing session can be found in the text box below. The debriefing session was conducted by an NIPV trainer-consultant with ample firefighting experience. The information from the debriefing session is analysed in the next chapter.

Report of joint debriefing session for the fire units of the first experiment - morning

What outcome was expected?
The approach had been discussed; the plan was to look for a hot spot and deploy there. The prevailing feeling was ‘we're going to put out this sucker’. The prior instructions to the Cobra team had inspired confidence.

What actually happened?
The plan to look for a hot spot and deploy there was actually implemented. The hot spot was in the middle of the battery pack.
There were discussions between the two commanding officers on matters concerning the deployment of the Cobra. The TIC told us how to deploy the Cobra. Targeted instructions were very important.

What went well?
- Good preparation.
- Clear orders from the commanding officer.
- Monitoring during the incident. During the Cobra deployment, you're focused on one thing. That's why it is good thing that what is happening around you is being monitored.
- It is nice for the Cobra unit that the other unit has the fire under control, giving them a little more time.
- Steam becomes visible after one or two minutes, and then you realise it works.

What could be improved?
- According to the Cobra team, there should have been a greater distance between the Cobra operator and the man behind the operator, giving more freedom of movement to operate the Cobra.
- To prevent plastics from burning afterwards, the space between the floor and the battery could have been filled with water. This would actually have been done if this had not been a practice experiment.
- Increasing the little ‘Cobra hole’, creating more play.
- The commanding officer confirming that there are no more risks.

Could it have been found out earlier that the plastics were burning instead of the battery pack?

> When the Cobra is deployed, the temperature is lowered and smoke/vapour are generated. This was not the case for the plastics.

Anything to add?
Cobra team: Follow your instincts.

5.2 Fire experiment 2 – afternoon

This section describes the main observations made during the afternoon fire experiment and presents the experiences of the participating fire crews. A timeline with visual data and explanations of the fire experiment can be found in Annex 4: Timeline for the afternoon session. The researchers' visual observations are recorded here.

5.2.1 Initiation of thermal runaway

Jet fires from the battery pack were observed immediately after the drill was introduced in the second experiment. The entire vehicle was on fire within 10 minutes.

5.2.2 Deployment of UHP unit

The same procedure was followed during the second deployment. Hot spots were located with the TIC and then penetrated with the UHP extinguishing system (Figure 5.6). Flames coming from the battery pack were repeatedly observed during this procedure (Figure 5.7). Because of this, a jet was continuously deployed to extinguish these flames and a second jet was deployed as a backup for the first jet in order to be able to extinguish the flames from a different angle. The extinguishing of these flames is shown in 5.8. The optimum location for the UHP deployment, as close to the hot spot as possible, was difficult to reach because of the flames from the battery pack. A low-pressure jet was therefore deployed to create a safe workplace for the staff of the UHP unit. The UHP extinguishing system was deployed to several different hot spots until no more hot spots were observed.

Figure 5.6 Locating hot spots using a thermal imaging camera

Figure 5.7 Jet fire from battery pack (under the front passenger door)

Figure 5.8 Deployment of low-pressure jet to extinguish jet fires during UHP deployment

5.2.3 End of UHP deployment

The waiting time of 45 minutes after it was confirmed that the fire was under control was applied in this experiment as well. No reignition was observed during that time. In accordance with the timetable, the vehicle from this second experiment could be safely parked away from other objects.

5.2.4 Inspection of the battery pack after the end of the experiment

This experiment also involved removing the battery pack from under the vehicle after the experiment in order to study it and for easy disposal to a recycling company. After removing the battery pack from the vehicle it was set aside in a dry submerging container for closer inspection. This battery is shown in Figure 5.9.

Figure 5.9 Battery of the second fire trial

The top and bottom of the casing of the battery pack of this experiment also came loose and some damage occurred. The damage to the battery pack was greater in the second experiment than in the first. This can be explained by the fact that more jet fires and flames came out of the battery pack in the second experiment. The casing of this battery also had several openings of between 2 and 4 cm. An example is shown in Figure 5.10.

Figure 5.10 Opening on the side of the battery pack of approx. 4 cm

The battery pack did not reignite between Thursday 27 June and Tuesday 2 July, that is from the time of the research until disposal to recycling.

5.2.5 Scores and debriefing of the fire service units

The fire crews that participated in the second experiment also individually assigned scores on a scale of 1 to 10 to their feelings about the deployment and the perceived ease or difficulty of the deployment. As regards their feeling, a score of 10 was extremely positive and a score of 1 was extremely negative. As regards the perceived ease or difficulty, 10 was extremely easy and 1 was extremely difficult. The scores of the FA unit are shown in Table 5.3 and those of the Coolfire unit in Table 5.4.

Table 5.3 FA unit scores for the afternoon experiment

Task during deployment	Unit	score for feeling (1 negative – 10 positive)	score for the level of difficulty (1 difficult - 10 easy)
Commanding officer	FA (VRU)	8	9
Number 1	FA (VRH)	8	10
Number 2	FA (VRH)	8	8
Numbers 3 or 4	FA (VRH)	9	9
Numbers 3 or 4	FA (VRAA)	9	9
Average score	FA	**8.4**	**9**

The FA unit that attended to the morning experiment also attended to the afternoon one. They gave the same scores for both sessions and orally indicated that their feelings had not changed, although the fire was physically more intense and, strictly speaking, more complex because of that higher intensity.

Table 5.4 Coolfire unit scores for the afternoon experiment

Task during deployment	Unit	score for feeling (1 negative – 10 positive)	score for the level of difficulty (1 difficult - 10 easy)
Second man	Coolfire (VRH)	9	8
Commanding officer	Coolfire (VRH)	8	7
Driver	Coolfire (VRH)	9	8
UHP operator	Coolfire (VRH)	10	8
Average score	**Coolfire (VRH)**	**9**	**7.8**

A joint debriefing session was held with the FA and Coolfire units after the experiment. The report of this is debriefing session can be found in the text box below. The debriefing session was conducted by the same NIPV trainer-consultant who also conducted the briefing session for the morning experiment. The information from the debriefing session is analysed in the next chapter.

Report of joint debriefing session for the fire units of the second experiment - afternoon

What outcome was expected?
It was agreed to check how things were going after four minutes.

What actually happened?

- The fire was more intense, this possibility was anticipated in advance.
- Tackled full on immediately, the plan was executed as discussed.
- In retrospect, a faster result was expected when fighting a fire involving an open vehicle with two low-pressure jets.

- As planned, after four minutes it was checked how things were going. The Coolfire had to be deployed more often than previously hoped.
- The fire was tackled with two low-pressure jets from two positions, namely from front left and front right. The extinguishing action was from the front towards the back; we 'manoeuvred' while extinguishing.
- The fire kept coming back.
- We hadn't expected magnesium to burn. It was decided to let this burn, so it did not impact the extinguishing action any further.
- Compared to the first experiment, the fire came out at the bottom more. The heat release lasted longer because more cells were burning at the same time. This could also be heard.
- The fire was activated faster than the first, despite it being an identical pack. The interior of the car had better insulation qualities; this may have caused more cells to burn at the same time and may have led to a higher heat release rate.
- Communication was complicated by the noise.

Weren't you taken aback by deployment in high-voltage circumstances?
No, also thanks to Coldcut Systems' instructions. They said that there was no dangerous voltage due to the individual cells.

What went well?
- Piercing the battery
- Own safety: safe approach and safe positioning
- Procedures
- Quickly cooling full on with two jets → rapid striking power
- The ‘plank shot in’[2] improved working comfort, we did not get tired.
- Responding to what you see.
- The use of the fan went better during the second deployment as it was closer.

What could be improved?
- This experiment also went well because it was 'a practice experiment’. If a similar incident happens on a street then:
  - Better evaluation of the actions is required.
  - More time must be taken for proper reconnaissance to properly carry out the plan.
  - The surrounding area should be monitored better.
  - The specialist unit should be supported → first unit assists the Coolfire unit.
  - Now the smoke went in one direction, but this may be different in practice [more difficult if the smoke spreads in several directions].
- Spread the cooling power better → adjust positions.
- It was a setback that the fan stopped at one point, smoke concentrations then immediately increased. From now on, use more fans and put the right fans in the right places. The windows could have been busted to increase ventilation. A centre punch on a stick by means of which a pane of glass can be broken could perhaps be used for this purpose.
- Longer lance. For own safety.
- Find out where the steam is coming from.
- Focus on the result.

Was the outcome as planned (as expected)?
The result was achieved. The plan changed because we had to respond to:
- The burning magnesium.
- The fire flaring up again.
- The higher heat release rate compared to the morning experiment.

---

[2] The Coolfire unit had decided to attach a wooden plank to support the nozzle of the UHP extinguishing system.

6 Analysis of results and answers to the research questions

This chapter first gives a further analysis of the results of the research and the fire experiment and then answers the research questions. All answers can then be used to assess the safety, effectiveness and practical applicability in the Netherlands.

6.1 Safety

When deploying a UHP extinguishing system, a vehicle must be approached within a very short distance. Action inside the vehicle may even be necessary although the battery may still be in a state of thermal runaway and although there are additional risks due to fire or explosion. The three effects that are known – fire, explosion and toxic gases – are discussed below. The risk of exposure and the measures that can be taken to minimise this risk are also discussed. The risk of electrocution is discussed after this discussion of these three effects.

6.1.1 Fire

Flames complicate the fire service deployment. They may prevent firefighters from getting to the desired spot necessary to safely deploy the UHP extinguishing system, and furthermore, firefighters may be unexpectedly exposed to these flames.

Therefore, to minimise the risk of exposure to unexpected jet fires or flames for fire personnel during deployment of the UHP extinguishing system, at least one and possibly two low-pressure jets were deployed. The first low-pressure jet was deployed as a safety measure to *offer direct protection* for the UHP operators against unexpected flames in their direction, enabling them to retreat safely. In that case, the second low-pressure jet would be deployed to *fight* possible flames and as such, to also shield the operators.

Answer to research question 1

How can fire personnel be prevented from being exposed to unexpected flames and jet fires during UHP deployment?

The risk can be reduced by correct positioning (as far away from the flames and smoke as possible) of the UHP unit and by using a low-pressure jet to immediately extinguish any flames from the battery pack. In addition, a 'free' low-pressure jet should always be available as a safety measure and back-up.

6.1.2 Explosion

No explosions occurred during the field experiments. As indicated, windows and doors in the vehicle were opened to minimise the risk of explosion. In addition, the deployment of a fan also helped reduce the risk of explosion during deployment of the UHP extinguishing system.

Fire personnel should be aware that immediately after the transition from a situation with a closed passenger compartment to an open passenger compartment, for example immediately after the windows are blasted, air can flow into the compartment. A gas mixture can then accumulate to within the explosive limits, possibly resulting in an explosion. It is therefore important to allow sufficient time after flammable gases have been vented from a closed space. Until then, an ample distance must be kept from the vehicle and as few people as possible should be near the vehicle.

Answer to research question 2

How can a vapour cloud explosion be prevented during UHP deployment?

A vapour cloud explosion can be prevented by ensuring that flammable gases have been vented from the vehicle before deployment. A fan can help with this. In addition, the fan can ensure a safe working environment during deployment of the UHP extinguishing system by immediately blowing away any gases that are released. In the case of a closed passenger compartment, the windows will have to be blasted out with a water jet from a distance to create ventilation.

6.1.3 Toxic gases

The preliminary study had shown that, in principle, personal protective equipment and breathing apparatus provided sufficient protection against the toxic gases. However, as with other fires, it is important that any contact with smoke be minimised. Working upwind as much as possible helps in this respect. However, whether this is possible depends on the position of the vehicle, and the locations of the battery pack and the hot spots. The UHP extinguishing system can also be fitted with an extension to create a greater distance to the vehicle.

Because of the polluting smoke, the firefighting clothing should be removed after the deployment, in accordance with the clean work procedure, and presented for cleaning. That is why during the two experiments, the personnel that had been deployed were decontaminated afterwards by means of dry decontamination and the firefighter suits were cleaned in accordance with the clean work procedure of the safety region in question.

Answer to research question 3

How can fire personnel be prevented from being exposed to toxic gases during UHP deployment?

If fire personnel wear personal protective equipment and breathing apparatus, they are sufficiently protected from toxic gases near an electric vehicle fire. A fan can reduce the risk of contamination of the firefighting clothing to a certain extent, as can an extension fitted to the UHP extinguishing system.

6.1.4 Risk of electrocution

Section 4.2 discusses current conductivity tests and explains them in detail by visualising three scenarios. The conclusion of this section is the answer to research question 4. During the fire experiment, there were no signs that the UHP operator or other fire personnel were exposed to electric shock.

Answer to research question 4
How can fire personnel be prevented from being exposed to electrocution risks during UHP deployment?

There is no risk of electrocution for the UHP user if the UHP system is operated correctly. Even if metal parts of the UHP system are accidentally touched this risk is very unlikely.

6.2 Effectiveness

To assess the effectiveness of the UHP deployment, it is important that an appropriate deployment procedure is followed. A UHP deployment is effective if it cools the battery cells and stops thermal propagation.

6.2.1 Penetration point, deployment location and introduction of water

To stop propagation of the thermal runaway, the cells must be cooled in a way that prevents surrounding cells from going into thermal runaway due to the heat formed. This requires the water to be introduced into the battery pack so that the water sufficiently cools the heated battery cells, enabling propagation of the thermal runaway to be stopped.

Here, safety always takes precedence over the preferred deployment location (based on hot spots). Therefore, if it is not possible to deploy a UHP extinguishing system to the largest hot spot, even if a protective jet is used, another location in the battery pack must be chosen for the deployment. The experiments have shown that, in principle, introducing water to each hot spot for 5 minutes is sufficient. The water that is introduced is actively cooling the hot spot if the water is visibly converted into steam. There has been sufficient cooling if no more steam comes out of the battery pack. It should be noted that compartmentalisation may prevent water from reaching all cells in thermal runaway, as a consequence of which the UHP extinguishing system may have to be deployed again.

Answer to research question 5
What are suitable penetration points for introducing a UHP extinguishing system into the battery pack and how long should water be introduced at a penetration point?

Ideally, the UHP extinguishing system penetrates the battery pack at the location of the largest hot spot, provided there is a suitable deployment position for the UHP operator (i.e.: where the operator is not exposed to flames). If this is not possible, an alternative location should be found. After deployment to the largest hot spot, the system can be deployed to the remaining hot spots. In most cases, approx. 5 minutes per hot spot will be sufficient then.

6.2.2 Safe situation

Coldcut Systems' recommendations were followed in both experiments. According to the units that were deployed, this method was basically adequate. The timetable established that the deployment would be considered successful if no smoke and flame development was visible for 45 minutes and no increase in temperature was measured on the TIC.

This was the case during the second experiment. No more smoke, flames and elevated temperatures were measured during those 45 minutes, leading us to conclude that the UHP deployment was sufficiently able to stop propagation of the thermal runaway and create a stable situation. During the first experiment however, light smoke was still visible 45 minutes after each UHP deployment and, after careful consultation with all experts present, we decided to remove the battery pack from the vehicle and open it up. An inspection of the battery pack enabled us to list the following reasons to assume that the smoke did not come from a thermal runaway reaction, but probably came from smouldering wiring or insulation material.
> The TIC detected only a slight increase in temperature.
> The 4-gas detector detected CO, but the LEL (lower explosive limit) detector did not show any value.
> The visual characteristics of the smoke were much less intense than usual in a thermal runaway.

It may be argued that, during the first experiment, the procedure effectively stopped the thermal propagation, but that a smoke-producing reaction remained active in the battery pack. So, in essence, the goal of achieving a stable situation was achieved. Moreover, the incident did not spread further and no new thermal runaway was observed at a later time either.

However, given the constantly recurring smoke in the first experiment, the deployment of the UHP extinguishing system might have been qualified as unsuccessful if this deployment had taken place 'in the streets'. To ensure a safe situation, the vehicle would have been transported to a location where it could burn out or be immersed in an submerging container.

Answer to research question 6
When has a safe and stable situation been created and can the vehicle be safely handed over to a salvage company?

The cooling effect of the water is effective if the water is visibly converted into steam. There has been sufficient cooling if no more steam comes out of the battery pack and no more smoke or flames are observed. The UHP deployment is effective then. The situation is stable as soon as there has not been any visible smoke or flame development for 45 minutes. In principle, the vehicle can then be handed over to a salvage company.

6.3 Practical applicability in the Netherlands

To assess the practical applicability of the UHP extinguishing system in electric vehicle fires, it is important to evaluate how the participating fire personnel experienced the fire service deployment during the experiment. We consider practical applicability to be good if fire personnel are sufficiently positive about the fire service deployment, have not perceived it as too difficult and the perceived bottlenecks can be solved or are acceptable. Both criteria should score 7 or higher for this.

6.3.1 Feeling and perception

The participating firefighters individually assigned scores to their experience of the fire service deployment during the experiment. Since the FA and UHP units had different tasks, average scores were calculated for the individual units. A score of 10 indicates an extremely positive feeling; 1 indicates an extremely negative feeling.

The FA unit gave the same scores for the morning and the afternoon sessions. The average score they gave was 8.4, with individual scores ranging between 8 and 9. The average score that the Cobra unit gave for the morning experiment was 8.6, with individual scores ranging between 8 and 10. The Coolfire unit gave a score of 9 for the afternoon experiment, with individual scores ranging between 8 and 10. It can thus be concluded that all the fire personnel felt positive about the fire service deployment.

Answer to research question 7

How do the firefighters feel about the UHP deployment during the experiment?

Both the FA crew and the UHP unit felt positive about the deployment to the electric vehicle.

6.3.2 Difficulty

The participating firefighters also individually scored their experience of the difficulty of deployment during the experiment. Since the FA and UHP units had different tasks, average scores were calculated for the individual units. A score of 10 indicates that the deployment was extremely easy, and 1 indicates that it was extremely difficult.

The FA crew gave the same scores for the morning and the afternoon sessions. They gave an average score of 9, with individual scores ranging between 8 and 10. The average score that the Cobra unit (morning) gave for the morning experiment was 9.2, with individual scores ranging between 8 and 10. The Coolfire unit (afternoon) gave a score of 7.8 for the afternoon experiment, with individual scores ranging between 7 and 8. The different levels of difficulty perceived by the UHP units in the morning and in the afternoon might be explained by the presence of passenger seats in the test vehicle in the afternoon, as these made it somewhat more difficult to properly position the lance of the UHP extinguishing system.

It can be concluded that the participating FA personnel and the UHP units experienced the firefighting deployment as relatively easy. However, two aspects that make it difficult to generalise this experience to real-life situations should be noted here. Firstly, the side doors of the vehicle had been opened in advance of the experiment to minimise the risk of explosion. This will be different in a real-life situation. It speaks for itself that a UHP deployment is easier if the doors are open. A spreader might be needed to open closed doors. And if the doors are closed, a hot spot will be difficult or impossible to locate from outside. Secondly, prior to the experiments, the UHP units received extensive training on how to deploy a UHP extinguishing system to fires in electric vehicle batteries. As a consequence, when they started the experiment, they were prepared better than would have been the case in a regular real-life situation.

Answer to research question 8

How do the firefighters perceive the ease or difficulty of the UHP deployment during the experiment?

Both the FA crew and the UHP unit found the deployment relatively easy. It should be noted that the UHP deployment may be found to be more difficult in a real-life situation, partly because doors and windows will not always be open.

6.3.3 Points for consideration with UHP deployment

The following paragraphs discuss the bottlenecks experienced by the fire units during their deployment.

Use of the fan

After the first experiment, the fire crew indicated that the fan was not in an optimum position and the smoke was not blown away properly.

The battery of the fan ran out and the fan stopped working during the second experiment. This reduced the view of the battery pack. The fan was not optimally positioned during the second experiment either. Lessons to be learnt from this are (1) make sure the equipment is good, and, more importantly, (2) put the fan in the correct position. Ideally the operators should be positioned 'with the wind in their backs’. Make sure that the position of the fan is changed where necessary, if circumstances show, for example, that the effect of the fan is insufficient during deployment.

Work area and monitoring

The working space during the first experiment was perceived to be too small and UHP operators and their assistants felt that they were too close to one another. The lesson to be learnt from this is that good coordination between UHP operator and their assistants is necessary in order to allow the operator sufficient space to work.

The monitoring of the surrounding area was indicated as a bottleneck after the second experiment. Too little attention was paid to this during the deployment. This underlines the importance of the commanding officer keeping track of things and, where necessary, addressing people who enter the unsafe work area.

Heat release rate and burning time

The aim of the fire service was to safely and effectively get both the vehicle fire and the battery fire under control. The units deployed during the second experiment indicated that the deployment took longer than hoped. They said that the UHP extinguishing system had to be deployed more often than they had expected beforehand. The heat release rate of the vehicle also surprised the units deployed during the second experiment. A complicating factor identified by the UHP unit was the flames coming out of the battery pack. This required the deployment plan to be adjusted, for example by applying more cooling power. Eventually, the FA crew helped bring cooling power to the right location.

Two lessons can be learnt from this. Firstly, both the FA crew and a UHP unit should be reminded in advance of the fact that such flames can keep emerging from the battery pack, and that active cooling is needed to prevent this. The second lesson is that it is sometimes necessary to repeatedly deploy the UHP system to stop propagation of the thermal runaway.

Communication

The UHP unit that participated in the second experiment perceived the communication (both the personal verbal communication and by walkie-talkie) between crew members as a bottleneck. It was, in particular, the operator of the UHP extinguishing system who experienced this bottleneck. The deployment of one and sometimes two low-pressure jets negatively affected view and hearing. This led to visual and acoustic signals being observed less well, for instance whether and when the UHP extinguishing system had pierced the top of the battery pack.

Here, communication is closely related to safety. Deployment of the low-pressure jets was necessary to create a safe working environment, but it also made it more difficult for the UHP operator to do their work. The decision whether or not to deploy the low-pressure jets can only be made during an incident: when are flames suppressed, and when might suppressing the flames be stopped temporarily to enable the UHP operator to look and listen for signals? It is important that clear agreements are made about this in advance between the UHP unit and the FA crew. This requires clear signals and signs, which can be interpreted even if sight and hearing are limited, so that the UHP operator can communicate with the nozzle operator.

Another communication issue that was mentioned was explicitly stating the stages of the incident. It was also stated that, during the first experiment, the fact that there no longer were any risks could have been confirmed better. The lesson that can be learnt from this is that the ‘end of incident’ point should be communicated clearly during the final phase of an incident.

Lance
A final bottleneck mentioned by the operators of the UHP extinguishing system of the second experiment was the choice of lance. Because the short lance had been chosen, they had to stand close to the vehicle. This experience has taught that a longer lance should be used if possible. This enables a greater distance to be kept. This improves safety and gives the UHP operator a better view of what is going on in the vehicle.

Answer to research question 9
What bottlenecks did the firefighters experience during the UHP deployment during the experiment?

Points for consideration mentioned by the fire personnel were the limited work area, the proper deployment of fans, communication, and no long lance being available on the UHP extinguishing system.

6.4 Discussion

In terms of safety, this analysis shows that mitigating safety measures have been found and proven to be suitable for practical application in the Dutch firefighting practice for all three effects of a thermal runaway, i.e. exposure to (unexpected) jet fires, explosion and toxic gases. Targeted low-pressure jets can be used to reduce exposure to (unexpected) jet fires. To prevent an explosion, any gases that may have accumulated can be vented and, in the case of a closed passenger compartment, the UHP extinguishing system can be used to bust the windows. The existing personal protective equipment and breathing apparatus offer sufficient protection from toxic gases. There is no risk of electrocution for the UHP operator if the UHP system is operated correctly; even if metal parts of the UHP system are accidentally touched this risk is very unlikely.

The experiment also showed that the deployment procedure used was effective. This procedure consists of using a TIC to identify hot spots in the battery pack, after which the battery pack is penetrated at the location of the hot spot, using the UHP extinguishing system. A prerequisite for this is that the UHP operator is able to reach the penetration point from a safe deployment location. After this, water should be introduced for up to five minutes. Visible steam is an indication that cooling is active. After some time, no more steam will be visible when introducing water at this hot spot; only water leaking away will be visible then. This should be repeated until all hot spots have been deployed to. The battery pack should be monitored for smoke, flames and temperature increase for some time after this to ensure that a stable situation has been established.

An active monitoring period of 45 minutes was used for both experiments; no re-ignition was observed after those 45 minutes. Some smoke kept coming out of the battery in the first experiment, but it was established that this smoke did not come from a battery cell in thermal runaway. The smoke may have been caused by smouldering insulation materials or cables. It can be inferred from this event that the injected water cannot reach all locations or openings in the battery pack. Therefore, in the field, the situation may arise where repeated UHP deployment is considered not to have been successful, and the vehicle is immersed after all.

The responses from the fire crews and the debriefing showed that they felt positive about their deployment and that they perceived it as relatively easy. Furthermore, in principle, a solution to the bottlenecks reported that is suitable for implementation in real-life situations is possible.

All things considered, it can be concluded that, if combined with additional safety measures, the UHP extinguishing system can be safely applied to the battery pack of electric vehicles and that an effective deployment procedure for this exists which is suitable for application and implementation in real-life situations by (specialist) UHP units in the Netherlands.

7 Conclusion

This report discusses the preliminary study, results and analysis of two experiments on the deployment of a UHP extinguishing system to a battery pack of an electric car in thermal runaway. The conclusion is that it is practically feasible to deploy a UHP extinguishing system safely and effectively in the Netherlands to control or extinguish an unstable or burning battery pack of an electric vehicle, provided a number of specific safety measures are taken for this purpose. These safety measures are:

> Deploying low-pressure jets (1) to suppress any jet fires from the battery pack, and (2) to shield the UHP operator to protect them from exposure to any such (unexpected) jet fires.
> Determining that no flammable gases have accumulated in or around the vehicle. Busting the windows with the UHP extinguishing system, possibly supported by the use of fans, can help vent combustible gases.
> Positioning the UHP operator and other fire personnel as far away as possible from the (toxic) smoke and flames.
> Use of the long lance or extension of the UHP extinguishing system.

During the experiment, an effective deployment procedure was confirmed. This procedure consisted of identifying hot spots with a Thermal Imaging Camera, and then penetrating the battery pack and using the UHP extinguishing system to introduce water to these hot spots. Here, steam is an indicator that cooling is effective, and the transition from steamy to leaking water is an indicator that the deployment has been effective and can be terminated. After this, a period of visual monitoring is necessary to ensure that the situation has stabilised and there is no re-ignition. Participating fire personnel indicated that this deployment gave them a positive feeling and was relatively easy to carry out.

In conclusion, the results of the fire experiments provide sufficient confidence to have (specialised) UHP units within the Dutch fire service deploy UHP extinguishing systems in case of fires in the battery packs of electric vehicles. Chapter 8 lists our recommendations for this, based on the results of this research.

8 Recommendations for UHP deployment action guidelines

8.1 Introduction

This study has shown that deployment of the UHP system is safe and effective, provided additional safety measures are taken. This chapter translates the results of the experiment and the experiences of Coldcut Systems (2024) and MSB (2024) into recommendations for operational action guidelines for Dutch UHP units. These recommendations are based on the assumption that the vehicle fire, i.e. the fire in the bodywork of the car, has been extinguished. The steps required for this are part of regular firefighting operations.

This chapter is based on the usual phases of incident response: identification, reconnaissance, stabilising, fighting and aftercare. The issues relevant to deciding whether or not to deploy a UHP system and how to deploy the system are addressed. Finally, it is discussed which situations are appropriate situations for deploying the UHP system and in which situations alternative techniques would be more suitable.

If numbers are used in the sections below, you are advised to perform these steps in the sequence indicated by the numbers. If there is a > sign, no specific sequence needs to be followed.

8.2 Identification

Once the vehicle has been identified as an electrically powered vehicle, it is important to look at indicators that indicate whether the battery is involved in the fire. This is because the battery is not involved in all cases: the battery is involved in only approximately 20 % of incidents in the Netherlands (Hessels, 2024).

Indicators to identify involvement of the battery in a fire are:

> Smoke: grey-white smoke or vapour from the battery pack. Often intermittently, as cells become involved in a thermal runaway in turns.

> Flames: flames or flash fire from openings around the battery pack.

> Sound: thermal runaway produces a thudding, hissing and/or crackling sound due to the overpressure in the cells in the battery pack or due to these cells exploding.

> Heat: the battery pack is hot (as can be detected using a TIC). Keep in mind that the thermal image may be disturbed by the smoke cloud and the fact that battery cells are carefully protected by a casing.

8.3 Reconnaissance

The reconnaissance serves to establish whether the battery pack is involved in the fire.

1. Use the rescue information sheet to establish the location of the battery pack.[3]
2. Wear breathing apparatus during reconnaissance.
3. During the reconnaissance, pay attention to the identification indicators listed in the Identification section above. If so, a state of thermal runaway has been reached.
4. Visually determine if gas has accumulated in the vehicle, for example if all doors and windows are still closed. If so, first create a safe working situation (see Stabilising).
   - Also pay attention to any gas that may have accumulated in the surroundings of the vehicle, for example under a carport.
5. Determine from which side of the vehicle the gases and jet fires or the majority of the gases and jet fires emerge. Approach the vehicle and the hot spot from the other side. Stay upwind as much as possible.
6. If gas cannot accumulate, use a TIC to detect any hot spots at the point where the battery is located. An example of a typical location that should be examined is the floor of the interior.

Once it has been established that the battery pack is involved:

1. Use the thermal imaging camera to identify the largest hot spot. This will be the '*penetration point'* which the nozzle of the UHP system will be deployed to.
2. Next, establish the nearest suitable *deployment position* for the UHP operator. A suitable deployment position is a position from where the UHP operator can start the deployment without being exposed to flames or jet fires from the battery pack.
3. If the nearest deployment position is not free of flames, find another suitable deployment position.
4. If there is no suitable deployment position for the preferred penetration point, find an alternative hot spot (penetration point) that can be reached without exposing the UHP operator to flames.

Consideration: contamination of surface water

Contamination of surface water should be a criterion when considering whether or not to deploy a UHP extinguishing system. During the experiments, RIVM sampled the extinguishing water to take stock of the degree of contamination of the extinguishing water. Based on RIVM's preliminary results, it can be said that the deployment of the UHP extinguishing system leads to a significant increase in contamination of the extinguishing water. A selection of the RIVM results is shown in table 8.1

Table 8.1 Values measured by RIVM

	Average of 5 samples before UHP deployment (mg/l)	Average of 2 samples after UHP deployment (mg/l)
Li	10.1	286
Mn	1.7	97
Ni	13.3	920
Co	2.3	152

The lithium concentrations in table 8.1 exceed the indicative safe environmental risk threshold for acute effects in surface water of 210 µg/l as derived by RIVM (RIVM, 2023). This risk threshold

---

[3] Keep in mind that there may also be batteries in non-standard locations, for example if an additional battery pack was retrofitted.

includes safety margins; concentrations in extinguishing water cannot be directly compared to this risk threshold. However, if large quantities of extinguishing water with high concentrations of lithium end up in a pond or ditch with little outflow, this may affect aquatic organisms. This is especially true if lithium concentrations are higher than those concentrations that have shown acute effects in laboratory tests. The lowest relevant effect concentration from the literature is 2.1 mg/l.

Research has shown that lithium in particular dissolves well in water. Therefore, lithium will disperse rapidly with the extinguishing water. The compounds containing manganese, nickel and cobalt released in the fire dissolve significantly less well. These compounds leave heavy particles on the ground near where the UHP system was deployed. For this reason, acute effects of these compounds on the aquatic environment are considered to be less relevant.

Consequently, RIVM and NIPV advise against using a UHP extinguishing system in the following situations:

- if the UHP extinguishing water can flow away into small pools of water (of a surface area of less than +/- 30m x 30m) with little outflow. An example of this is when the UHP extinguishing water can flow directly into the pool via the soft shoulder and the pool consists of stagnant water.
- if the UHP extinguishing water can flow away into drinking water catchment areas.

The final RIVM report is expected in mid 2025 or early 2025.

8.4 Stabilising (the work situation for the UHP operator)

The stabilisation phase consists of applying safety measures to create a safe and stable working situation prior to deploying the UHP extinguishing system.

The following actions can be taken for this:

- Make one low-pressure jet available ready for use to protect the UHP personnel.
- If flames emerge from the battery pack, make a second low-pressure jet available, ready to suppress the flames.
- Place a fan such that the operator of the UHP system has the wind from the fan in their back during deployment. This is shown schematically in figure 8.1.

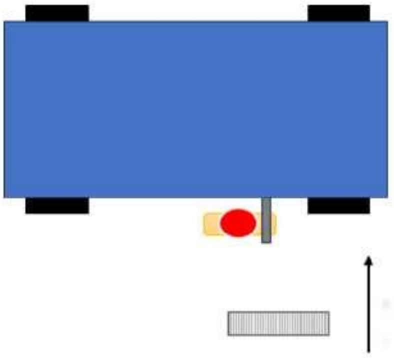


Figure 8.1 Fan deployment

8.4.1 Closed vehicle compartment

If the vehicle compartment is closed, so if all windows and doors are still closed, there is a risk of explosion due to flammable gases that have accumulated in the vehicle. Opening doors from a short distance is not safe in this situation. This also applies to situations where the gases accumulate near the vehicle, for example under a carport or in a garage.

In those situations, the UHP extinguishing system can be used from an upwind position to bust the windows on both sides of the vehicle. A safe distance should be maintained after this until the gases have largely disappeared from the vehicle.[4] Here, the mist from the UHP extinguishing system also helps create ventilation inside the vehicle. It can be decided to use a fan as well. Install it before the windows are removed so that it can be switched on immediately once the windows have been broken.

8.5 Fighting

Once a safe situation has been created, the UHP extinguishing system can be deployed to stop the thermal runaway in the battery pack from propagating. As also recommended by Coldcut Systems (2024) and MSB (2024), the following procedure is advised:

1. If the UHP unit has an extension for the extinguishing system, the extension should be used.
2. Place the UHP extinguishing system in the penetration point identified during the 'reconnaissance' stage.
3. A good indicator of cooling activity is if the extinguishing water evaporates into visible steam. If no steam is seen after about one minute, find another deployment location.
4. UHP extinguishing can take several minutes. If only water and no steam is seen to come out of the battery pack, the propagation of the thermal runaway has stopped.
5. Then use a TIC to find any remaining hot spots.
6. Deploy the UHP extinguishing system to any remaining hot spots.
7. Repeat this process until no more hot spots are found using the TIC. A criterion that can be applied is that no spots with a temperature of more than 50 degrees Celsius can be detected on the battery pack using the TIC.
8. Use a TIC to monitor the vehicle for any increases in temperature for 30 minutes. Check this several times a minute.

30 minutes
At present, insufficient data is available to determine how long the vehicle should be monitored for re-ignition as a minimum. Therefore, in conjunction with fire service personnel, a time of 30 minutes has been chosen as the time to be applied in practice.

When deploying a UHP extinguishing system, be aware of the following:

> Batteries may be compartmentalised or foamed in. If so, water cannot flow through the entire battery pack, which may mean that not all hot spots can be extinguished. It may therefore be necessary to deploy to the different compartments several times.
> Damage to the battery pack can make it necessary to deploy more frequently or can make deployment impossible.
> If the vehicle is on an incline, the water will run to the lowest point. In that case, where possible, deploy the UHP extinguishing system to the higher side of the vehicle.
>

---

[4] If extreme amounts of smoke develop, the unit to be deployed should wait with this until the situation is sufficiently safe.

Has thermal runaway or propagation of thermal runaway stopped or has it not stopped?
The deployment of the UHP extinguishing system is successful if no more smoke comes out of the battery pack after one or multiple deployment(s) and the TIC no longer detects any increases in temperature. The situation is stable then.

If smoke still comes out of the battery pack after repeated deployments, there **may** still be a thermal runaway. Consider not deploying a UHP system for some time (10 to 15 minutes) then. If the hot spot does not get any bigger, the temperature does not increase and the smoke does not look ‘puffy’, insulation material may be burning. If this smoke does not disappear after deploying the UHP extinguishing system, the smoke might be coming from a place that cannot be reached by the water. Using the UHP extinguishing system does not offer any added value then. The situation is stable then: thermal runaway is not taking place any more.

If the temperature does rise during those 10 to 15 minutes, the situation is still unstable. Then consider deploying the UHP extinguishing system again, or place the vehicle in an submerging container or let it burn out in a controlled manner.

8.6 Aftercare

If a stable situation has been reached, i.e. if no temperatures of more than 50 degrees Celsius have been measured for 30 minutes using a TIC, the incident can be handed over to a third party, e.g. a salvage company.

Given the risk that the battery pack might re-ignite, it is recommended that the vehicle be placed at a safe distance from other objects or vehicles to prevent the fire spreading. Based on a model calculation, as a rule of thumb, a safe distance for this is five metres (Brans & Reinders, 2024). It can also be decided to place the vehicle in a *dry* submerging container, which can be filled with water if the batteries re-ignite.

The units deployed should start their 'clean work' procedure and present their personal protective equipment for cleaning in accordance with regional agreements.

Soil contamination
Analyses of extinguishing water by RIVM have shown that it is possible that the use of UHP extinguishing systems introduces significant amounts of harmful substances into the environment. After the vehicle has been towed away, there can still be hazardous concentrations of hydroxides and harmful metals (cobalt and nickel compounds) on the ground.

Currently, there are uncertainties about the amounts of lithium, cobalt and nickel released from the use of a UHP extinguishing system and its environmental impacts. In the future, it may be necessary to develop additional techniques and procedures to reduce contamination or mitigate impacts to acceptable levels.

8.7 UHP deployment in relation to other methods

This report considers the UHP extinguishing system. However, this is not the only deployment tactic that can be used in fires involving the battery pack of an electric vehicle: there are many different extinguishing agents and/or methods to choose from (Hessels &

Geertsema, 2023). This makes UHP 'one of the tools in the toolbox'. This section compares the UHP extinguishing system with the two most common methods in the Netherlands: the deployment of the submerging container and letting the vehicle burn out.

In essence, the submerging container serves the same purpose as a UHP extinguishing system: stopping the propagation of thermal runaway and stabilising the battery pack. The submerging container does this *indirectly* by letting water penetrate for a long time without forcing it through any cracks and possible damage that might be present. The deployment of an submerging container requires several thousands of litres of water. A UHP extinguishing system stops the propagation of thermal runaway by introducing water *directly* into the battery pack. This requires significantly less water than an submerging container. However, the advantage of the submerging container is that it can also serve as a storage facility and that a car can be transported in an submerging container without any water in it. In situations where it is doubtful whether there is or will be thermal runaway, the vehicle can be transported and stored in an submerging container without any water in it. If thermal runaway still occurs at a later point in time, the salvage company can still fill the container with water.

Inherent in the other deployment tactic, i.e. letting the vehicle burn out, is that all, or a major share, of the energy from the battery pack will basically burn out. This makes this method different from UHP deployment and the submerging container where propagation is stopped and some energy remains in parts of the battery pack that have not burnt out. This energy can be referred to as 'stranded energy' (MSB, 2024). This stranded energy can cause re-ignition at a later time. This probability is greatly reduced if the vehicle is allowed to burn out. However, letting the vehicle burn out means that the incident lasts for a long time and has impacts on the surrounding area for a long time. This also involves more harmful substances being emitted and enables more deposition into the immediate downwind surroundings. Therefore, letting a vehicle burn out is only possible if the surrounding area lends itself to this option.

With the introduction of UHP extinguishing systems, there are now two methods in the Netherlands to stop propagation of thermal runaway in a battery pack: submerging and UHP extinguishing, plus the option of letting the vehicle burn out. Each method has its own characteristics and specific preconditions. The speed with which a method can be deployed may also play a role: the response time of the UHP extinguishing system compared to the response time of an submerging container. We are therefore of the opinion that there is no preferred method to be deployed; the best option depends on the actual situation.

The above considerations involved in deciding what method to use are presented in figure 8.2 on the next page.

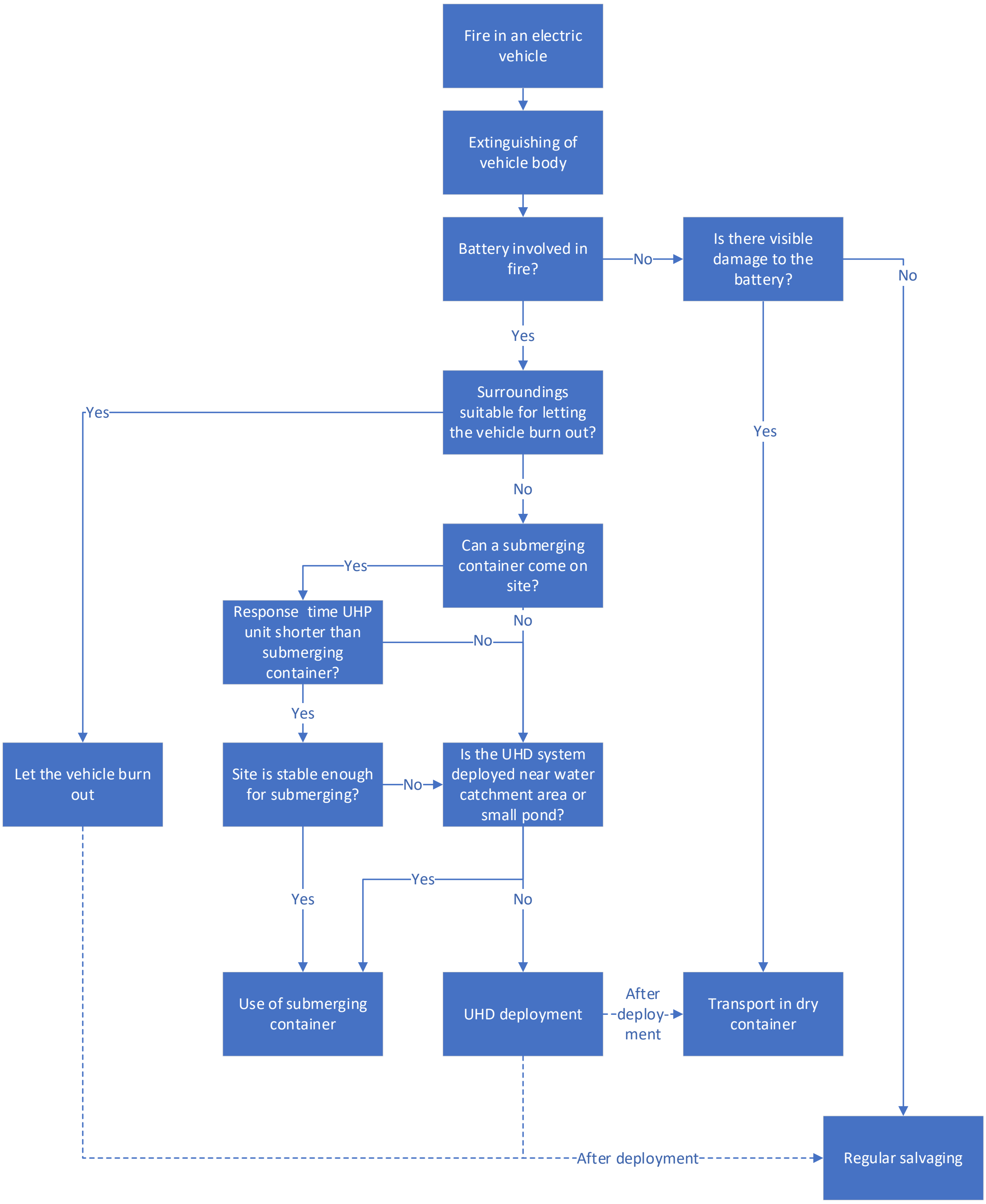


Figure 8.2 Flowchart for deciding what method to use in case of an electric vehicle fire[5]

---

[5] The flowchart does not provide guidance for the situation where a vehicle cannot burn out in a controlled manner, there is no submerging container available on site, and the site is near a water catchment area. In this specific situation, the commander on duty should make an individual assessment.

List of references

Dutch Fire Service Academy. (2020). *Onderbouwing van risico op elektrocutie/elektrische schok bij incidenten met e-voertuigen*.

Brans, H. (2023). *NIPV-samenvatting van het ELBAS rapport Incidentbestrijding elektrische voertuigen op schepen*. https://nipv.nl/wp-content/uploads/2023/06/20230613-NIPV-Incidentbestrijding-elektrische-voertuigen-op-schepen.pdf

Brans, H., & Reinders, J. (2024). *Model voor het berekenen van de warmtestraling van elektrische voertuigbranden*.

Christensen, P. A., Milojevic, Z., Wise, M. S., Ahmeid, M., Attidekou, P. S., Mrozik, W., Dickmann, N. A., Restuccia, F., Lambert, S. M., & Das, P. K. (2021). Thermal and mechanical abuse of electric vehicle pouch cell modules. *Applied Thermal Engineering*, *189*, 116623. https://doi.org/10.1016/J.APPLTHERMALENG.2021.116623

Coldcut Systems. (2023). *Cobra Use Case | Electric Vehicle*. https://www.coldcutsystems.com/news/cobra-use-case-electric-vehicle/

Coldcut Systems. (2024). *Cobra & BEV (Li-Ion) Fires* (p. 55).

EV Firesafe. (2023, May 7). *EV fire incident management - case study from Prague*. https://www.evfiresafe.com/post/ev-fire-incident-management-case-study-from-prague

EV Firesafe. (2024). *Electric Vehicle Battery Fires 2010 - 30th June 2024*.

Feng, X., Ouyang, M., Liu, X., Lu, L., Xia, Y., & He, X. (2018). Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. In *Energy Storage Materials* (Vol. 10, pp. 246–267). Elsevier B.V. https://doi.org/10.1016/j.ensm.2017.05.013

Hessels, T. (2024). *Incidenten met alternatief aangedreven voertuigen jaarrapportage 2023*.

Hessels, T., & Geertsema, T. (2023). *Onderzoek dompelcontainers*.

Joppe, K. (2024). *Thermal runaway op een veilige effectieve wijze. Stageverslag NIPV en Hogeschool van Amsterdam*.

Kang, S., Kwon, M., Yoon Choi, J., & Choi, S. (2023). Full-scale fire testing of battery electric vehicles. *Applied Energy*, *332*, 120497. https://doi.org/10.1016/J.APENERGY.2022.120497

Kleiman, A. B., Koch, N. S., Flecknoe-Brown, K., Wijesekere, T., Husted, B., Valiente, B., Meehan, S., & Moller, C. (2021). *The ELBAS Project - Electric Vehicle Fires at Sea: New technologies and methods for suppression, containment, and extinguishing of battery car fires onboard ships*.

MSB. (2023). *Demonstration av släck metod för litiumjonbatterier Metodtillämpning på olika aggregations nivåer-modul, sub-batteri, elbilspack och fordonsnivå*.

MSB. (2024). *Räddningsinsats där litiumjonbatterier förekommer*.

NIFV. (2012). *Praktijkexperimenten technieken offensieve buiteninzet*.

NIPV. (2023). *Brand in opslag van Li-ion accu's - Scenarioboeken*. https://scenarioboeken.nipv.nl/brand-in-opslag-van-li-ion-accus/

Radboud University. (2023). *Protocol Research Ethics Committee Faculty of Science Radboud University*.

RIVM. (2021). *Risico's van rook door branden van Li-ion-batterijen*. 1–104. https://doi.org/10.21945/RIVM-2021-0019

RIVM. (2023). *Indicatieve milieurisicogrenzen voor lithium in oppervlaktewater*. https://www.rivm.nl/bibliotheek/rapporten/2023-0186.pdf

UHD-Blussing.nl. (2024). *Locaties UHD Blussystemen*. https://uhd-blussing.nl/locaties/

Victron Energy. (2023). *Aarding, aarde en elektrische veiligheid*. https://www.victronenergy.com/media/pg/The_Wiring_Unlimited_book/nl/ground,-earth-and-electrical-safety.html

Vos, J., Brans, H., & Reinders, J. (2024). *Literatuuronderzoek naar de brandeffecten van Lithium-ion batterijbranden*.

Zhang, G., Wei, X., Tang, X., Zhu, J., Chen, S., & Dai, H. (2021). Internal short circuit mechanisms, experimental approaches and detection methods of lithium-ion batteries for electric vehicles: A review. *Renewable and Sustainable Energy Reviews*, *141*, 110790. https://doi.org/10.1016/J.RSER.2021.110790

Annex 1: Thermal runaway method

The causes of thermal runaway can be divided into three categories: electrical, thermal and mechanical. Thermal and mechanical methods that can be used to cause thermal runaway can be found in scientific literature. These methods can be applied to different levels, i.e. cell, module, battery pack and the entire electric vehicle (Joppe, 2024).

Thermal

> Heating plate (internal)
> Gas burner (external).

Mechanical

> Penetration by a nail or screw.

Our preliminary study showed that a heating plate and penetration by means of a nail or screw were suitable methods for the experiment (Joppe, 2024). The heating plate is safe, effective, controllable and predictable. This is also a good method because it mimics a typical scenario. In principle, the mechanical method is also safe and effective, but it is less predictable and less easy to control. However, the mechanical method takes less time to implement. These results are summarised in table 4.1. The following two sections go into the heating plate and the mechanical method in more detail.

A1.1 Heating plate

Heating the battery pack from the inside by means of a heating plate is a thermal method that can be used to bring the battery pack into thermal runaway. A heating plate contains a heating element in the form of a resistance wire. A current flows through this wire. The wire is heated and transfers its heat to the heating plate, increasing the temperature of the plate (Kang et al., 2023). A thermocouple can be placed on the heating plate to monitor the temperature of the plate. The temperature readings can be used to increase the current and thus increase the temperature. This enables the temperature of the heating plate to be controlled. In the case of the battery pack, the heating plate will be mounted on one or more battery cells, as was done in previous experiments (Coldcut Systems, 2023; Kang et al., 2023). One of these experiments involved a BEV with a battery pack of about 64 kWh (SOC 100 %). Figure A1.1 (left) shows the battery pack of this BEV with its ten modules (M1 to M10). Here, the heating plate is mounted on a battery cell of the module in the centre of the battery pack (M9, pink rectangle). This is a 575 W heating plate of 90 x 65 mm, stuck to the surface of the battery cell with heat-resistant tape.

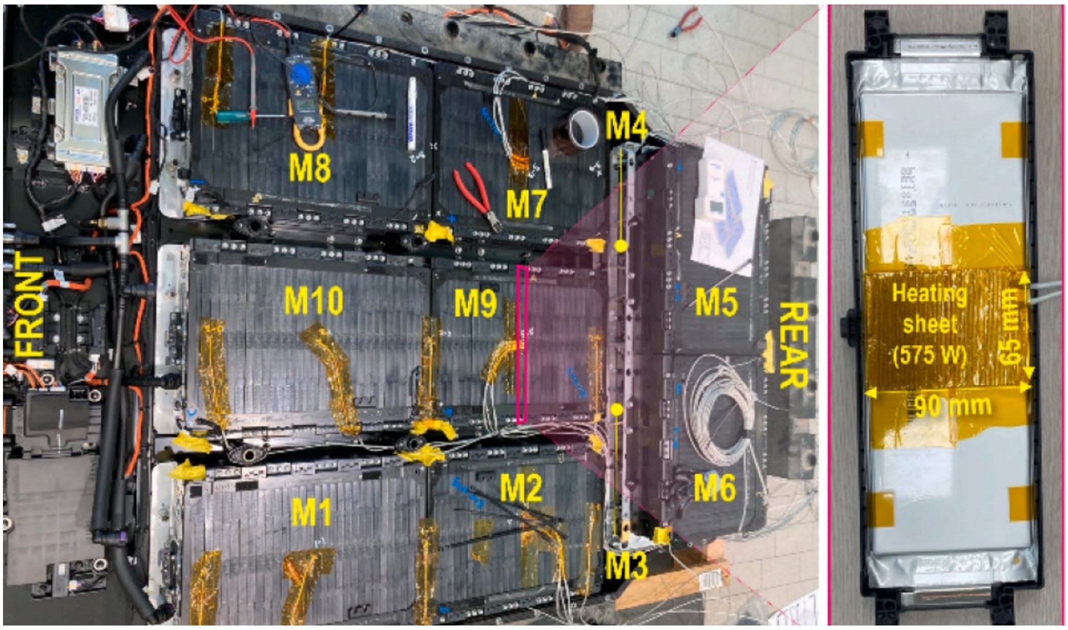


Figure A1.1 Test setup of battery pack with a mounted heating plate (Kang et al. 2023)

This method requires a modification to the battery pack and this requires specific expertise. Heat from the mounted heating plate will cause the temperature to increase in one or more battery cells. This will disrupt the electrochemical process. Once the temperature has gone up to about 135 °C, a short circuit can occur between the cathode and anode because the separator has melted (Feng et al., 2018). This heating plate method mimics a typical scenario for the occurrence of thermal runaway (Kang et al., 2023), since, in fact, thermal runaway is most commonly caused by a short circuit in a battery cell due to the failure of the separator (Zhang et al., 2021).

Another advantage of this method is that two heating plates can be mounted on different modules allowing thermal runaway to be initiated at multiple locations. And the method is predictable in terms of location and time:

- Location: Prior to the experiment, the heating plate is mounted on one or more battery cells in a module in the battery pack. Thermal runaway is very likely to first occur in these battery cells. This means that this method allows the location of the thermal runaway to be predicted.
- Time: The experiment with the BEV showed that thermal runaway had occurred after 21 minutes and 20 seconds (Kang et al. 2023). This means that, during the experiment with an UHP extinguishing system, thermal runaway might occur in one of the battery cells after about 20 minutes. Once thermal runaway is detected, the fire may develop rapidly, since the experiment with the BEV showed that there was a fire after about 25 minutes and the entire vehicle was on fire after 40 minutes.

Being able to predict the time and location of the occurrence of thermal runaway is a good thing. Another advantage is that the temperature of the heating plate can be controlled from a safe distance. However, a disadvantage and also a risk of this method is that the flammable gases do not ignite immediately and accumulate in the vehicle, leading to a risk of explosion.

A1.2 Mechanical method

Thermal runaway can be caused mechanically by fully penetrating one or more battery cells with a sharp steel rod (nail). Scientific literature also identifies this method as 'nail penetration'. To cause thermal runaway, the nail must penetrate the casing of both the battery pack and the modules and that of the battery cell. The location of the battery pack and, as a consequence, the need to penetrate the chassis and the bodywork must be taken into account. When penetrated by the nail, the separator in the battery cell creates a connection between the cathode and the electrode (Zhang et al. 2021). A current can flow through the nail, creating a current circuit at the penetration location. This leads to an ISC (Internal Short Circuit). The short circuit leads to heat being generated, causing other reactions to occur as well. The temperature in the battery cell will rise sharply, eventually leading to thermal runaway. This process is shown in Figure A1.2.

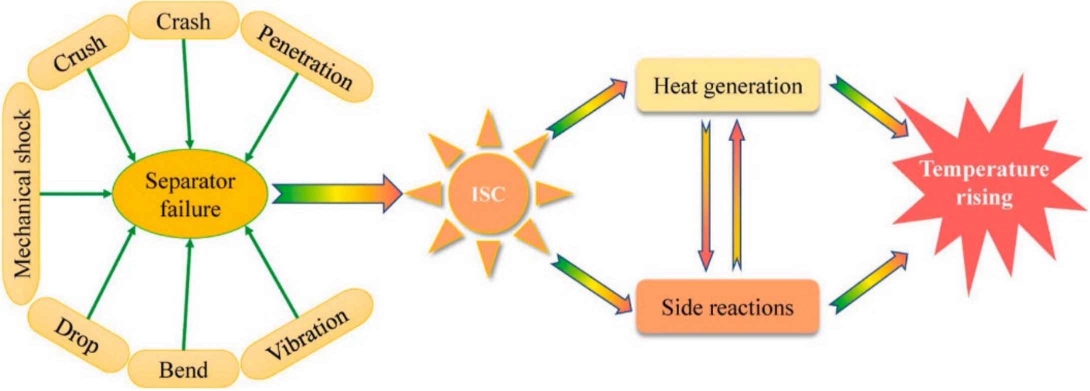


Figure A1.2 Process after mechanically influencing the battery cell (Zhang et al. 2021)

Apart from a nail, a screw can also be used to pierce a battery cell. This can be done by means of a drill (P. Malmquist, personal communication, 2 November 2023). A long attachment of at least 2 metres can be used for this purpose, enabling the screw to be screwed into the battery pack from a safe distance. The length of the attachment also depends on the location of the battery pack, the bodywork and chassis of the vehicle, and the thickness of the battery pack casing and the module. The length of the screw must be such that the screw is completely inside the battery cell, as the pressure will increase which may cause the screw to collapse (P. Malmquist, personal communication, 2 November 2023). This means that the length of the screw also depends on the thickness of the battery cell. In addition, the screw must be able to withstand high temperatures, as the temperature during a thermal runaway is at least 200 °C and potentially rises to around 1000 °C (Feng et al. 2017).

Nail penetration was applied to a single module of an electric vehicle (Nissan Leaf) during a previous experiment (Christensen et al., 2021). The module contained eight NMC battery cells with a total capacity of 1.64 kWh. White smoke and jet fires were observed coming from the module after a few milliseconds to seconds. This means that, after fully penetrating a battery cell, a thermal runaway was immediately visually observed.

The nail and screw methods are basically the same; the only difference is that, if the screw method is applied, the hole is always sealed (by the screw itself). However, a hole created by a nail can also be sealed by simply leaving the nail in place. The disadvantage of a mechanical method is that it damages the battery pack. Another disadvantage is that a hole is created from which flammable and toxic gases, and jet fires can escape. Another inconveniencing factor is that the battery pack is difficult to reach because it will usually be at the bottom of the vehicle, surrounded by the bodywork and the chassis. The preparations to enable penetration will take some time and money. An external company with technical expertise can be called in for this.

An advantage of a mechanical method is that multiple attempts are possible if, for example, no battery cell is hit initially. If a battery cell is hit, a thermal runaway is likely to be immediately observed visually. Another advantage of this method is that the location of the occurrence of a thermal runaway is somewhat predictable, and that the results can be observed immediately or almost immediately.

Annex 2: Ethical considerations

This annex follows our substantiation for the following ethical principles, which we established before conducting the experiment.

1. Scientific relevance: The research is scientifically relevant.
2. Proportionality: The expected benefits are proportional to the expected efforts.
3. Soundness of methods: The researcher uses appropriate research methods for the research problem at hand.
4. Risks and safety: Research participants should be as safe as possible and exposed to as little risk as possible.
5. Implementation: The research and the experiments should be carried out by qualified personnel.
6. Data management: Relevant data management procedures should be taken into account. They relate to various aspects, including data storage, data collection and access to the research data.
7. Autonomy: The autonomy of research participants must be respected.

A2.1 Scientific relevance

Section 2.3 explains that the problem of fighting electric vehicle fires is caused by thermal runaway and the fact that, if external cooling is applied, it is very difficult for the cooling water to reach the battery cells.

Recent studies in Sweden by MSB (Swedish Civil Contingencies Agency) and ELBAS have shown that internal cooling (cooling directly on the cells after penetrating the battery pack casing) is the more efficient method to lower the temperature inside the battery pack and ultimately stop the propagation of the thermal runaway (Kleiman et al, 2021; MSB, 2023). This is an indication that developing a new firefighting method that uses direct cooling may be preferable. The battery can then be stabilised on site, which can be more efficient and time-saving. However, at present, there are no firefighting instructions and procedures for the use of UHP extinguishing systems in case of electric vehicle fires.

The new procedure may be particularly interesting for large and heavy electric vehicles and for vehicles in hard-to-reach locations. There are no action guidelines for these situations yet. These are the reasons why we believe that research into new firefighting techniques for electric vehicle fires is scientifically relevant.

A2.2 Proportionality

The goal of this research is to study the effectiveness and applicability of a UHP extinguishing system for an electric vehicle fire involving the battery pack. Recent research in Sweden by MSB has shown that the method is effective with a loose battery pack. To also be able to make a statement about its efficiency in a real-life situation, it is necessary to also test the UHP extinguishing system on a complete electric vehicle, with a fire crew

In this context, it should be considered how many electric vehicle fires we want to carry out. Our experimental goal is primarily to test the applicability and effectiveness of the UHP extinguishing system. This outcome will then be used to determine whether we want to invest in follow-up research to develop guidelines and instructions for the operation of the UHP extinguishing system for having firefighters fight electric vehicle fires. Although there are several different models of electric vehicles, the causes of problems when fighting an electric vehicle fire are identical since these causes are intrinsic to the basic vehicle design and the characteristics of the lithium-ion batteries. This is why we think that the results of a test on one type of electric vehicle will be sufficiently indicative for the goal envisaged. We have opted to test two electric vehicles so that we can identify any practical learning points and start-up problems during the first test and apply what we learn from them to improve the second test. We think that, by following this phased approach, where we initially conduct two fire tests, there is a good balance between the efforts and the results expected.

A2.3 Methodological soundness

A preliminary study was carried out before drafting the plan for the experiments. The goal of the preliminary study was to build on the knowledge and experience of others and engage with stakeholders. For this purpose, a literature review was carried out and a working visit and interviews were conducted. This enabled us to obtain as complete a picture as possible of the available knowledge and experience regarding bringing an electric vehicle into thermal runaway and the application of the UHP extinguishing system to battery packs. This also gave us a suitable knowledge network to share and discuss the progress and results of our research with.

The background information from the preliminary study formed the experiment-specific technical basis of the experimental plan. In order to determine the fire service deployment during the experiment, we studied research protocols of previous relevant experiments, including fire gas cooling experiments. Building on this, we conducted interviews with firefighters who had experience with the Coldcut Cobra. Next, the deployment procedure was determined in consultation with the fire crew to be deployed. Experts from Coldcut Systems were consulted to train the fire crew.

We think that the combination of (1) a preliminary study into the experiment-specific technical aspects of putting a battery pack into thermal runaway, (2) building a knowledge network and (3) determining the fire service deployment in consultation with experienced fire service personnel is a methodologically sound approach to the research issue at hand.

A2.4 Risks and safety

If a battery is mechanically damaged, a jet fire may immediately emerge from the affected battery cell(s). This is evidenced by visual data and by attending previous experiments. Based on this, being able to initiate the thermal runaway remotely is the preferred option. However, the nature of the experiment makes it impossible to completely rule out all exposure to risks to the fire crew, since they will come quite close to the vehicle on fire. We will therefore take mitigating measures to minimise the effects of potential safety risks during the fire service deployment. In addition, an exercise leader and safety officer will be present to supervise the entire experiment.

Our previous research (NIPV, 2023) showed three effects of thermal runaway, i.e. a (1) battery fire with jet fires, (2) a vapour cloud explosion and (3) a toxic cloud. Since cells being flung away is something that is hardly ever observed in vehicle fires, the current protocols do not include any measures in this respect. The table below shows how we plan to limit the exposure to hazards from each of these effects for the fire crew. MSB has been contacted to discuss the risk of electrocution. According to MSB, there is a very slim risk, but, to make this absolutely certain, this will be tested during out try-out experiment described in section 1.1 (J. Hellsten and A. Trewe, personal communication, 17 and 18 July 2023).

Danger	**Measure**
(Spontaneous) jet fires from affected battery cells	Behind the person who operates the UHP extinguishing system, there is always someone with a ready-to-use low-pressure jet to immediately spray water onto any jet fires. As the pressure-relief valves discharge straight upwards, there is no need to approach the vehicle from a specific direction.
Vapour cloud explosion	The experiment will be conducted with the windows open, preventing pressure to build up in the vehicle chassis. Moreover, no action will be taken near the vehicle until ignition has occurred.
Toxic cloud	The fire crew always wear personal protective equipment and breathing apparatus. If they visibly stood in the toxic cloud, their firefighter suits will be decontaminated.
Electrocution	Prior to the fire experiment, electrical conductivity tests are performed to clarify the electrocution risk.

An submerging container is present to stabilise the incident if, during the fire service deployment it is found that the UHP extinguishing system is not or insufficiently effective. If the experiment escalates for any reason, a second fire crew is immediately on site to assist.

A2.5 Implementation

NIPV was established as the public knowledge institute for crisis management and fire services in the Netherlands by an act of law. This experiment was prepared and set up by NIPV researchers with sound knowledge and experience of battery safety and incident response. Their independence is guaranteed by NIPV management.

The fire crew to be deployed consists of fully qualified firefighters who have received additional training on how to use a UHP extinguishing system. In addition, certified instructors from Coldcut Systems will be present to provide additional instruction and share experiences about the experiment conducted in collaboration with MSB in Sweden.

A2.6 Data management

Not applicable.

A2.7 Autonomy

To respect the fire team's autonomy, the approach described below is applied to the experiment.

The fire crew will be composed of members who have themselves stated that they are willing to participate. To enable them to make this decision, they will be given the opportunity to read the research proposal and project dossier beforehand and ask questions to the researchers. Before the day of the tests, they can discuss their envisaged deployment with Cobra's instructor.

During the fire service deployment, the commanding officer has final command of the fire crew. The test protocol provides guidance for firefighting, but it does not set out any strict frameworks for this. The fire crew has the freedom to decide as it sees fit within the targets set.

The exercise leader is in charge of the experiment and can abort the test at any time. The commanding officer can always decide to withdraw and interrupt the test. If the commanding officer decides to withdraw or wants to briefly interrupt the test, he will consult with the exercise leader. After this consultation, it can be decided whether to resume or abort the test. The commanding officer in person indicates whether he is prepared and willing to resume the experiment in this situation. The exercise leader then gives permission to resume the test. If it is decided to abort the test, the submerging container will be deployed in order to stabilise the vehicle.

Annex 3: Timeline for the morning session

Time	Action/Event	Photo	Other
9:47	Start signal given	N/A	
09:50	Drilling of first hole; a white plume of smoke immediately appears and quickly subsides.		

09:52 Smoke can be seen again.

09:53 As the smoke started to subside, a new plume formed, which also subsided.

09:58 Since no smoke has been visible for some time, it is decided to drill a second hole.

10:03 The second hole is drilled. This attempt to drill a hole is not successful

10:04 A third attempt to drill a hole is started.

10:04 A black cloud of smoke forms (before drilling) and fire is visible. The fire slightly subsided and then flared up again. The 10-minute timer is started.

10:07 The fire has really taken on (the vehicle fire is growing) and the vehicle is burning quite vehemently.

10:08 A short blowing sound has come from the battery pack.

10:13	The first unit is called.	
10:14	The first unit has arrived at the scene and is preparing for deployment.	

10:16 The vehicle is extinguished with two low-pressure jets from both sides from a distance of approx five metres.

10:17 The fire has subsided.

10:18 The remaining seats of fires are now fought with low-pressure jets at close range.

10:20 The UHP unit is informed.

10:22 The bonnet is opened and the fire in the bonnet is extinguished by the first FA.

10:24 The battery pack is continuously being cooled with two jets.

10:25	Flames can be seen on the underside of the car in phases.	
10:25	The UHP unit has arrived to the scene. The commanding officer of the FA and the commanding officer of the UHP unit immediately consult with each other	

10:28 The fan is placed on the right-hand side and switched on.

10:32 The UHP extinguishing system is deployed on the right-hand side.

10:36 UHP deployment is discontinued and the fan is switched off.

10:37 The TIC is used to take measurements around the vehicle.

10:40 The UHP extinguishing system is deployed again, on the left side of the vehicle

10:43 The UHP deployment is discontinued.

10:57 Monitoring reveals a hot spot. It is decided to redeploy the UHP.

11:01 The UHP is deployed again.

11:05	The UHP deployment is discontinued.	
11:11	Smoke is observed around the battery pack again. It is decided to redeploy the UHP extinguishing system	*No visual data is available of this point*
11:30	After briefly deploying the UHP extinguishing system again, deployment is discontinued.	*No visual data of this point is available*
11:45	White smoke from the battery pack is observed again. This smoke exhibits a constant, steady course.	*No visual data of this point is available*

Annex 4: Timeline for the afternoon session

Time	Action/Event	Photo	Comments
14:10	Start signal given. The first hole is drilled.	 2024-06-27 14:10:29	

14:13	Black smoke quickly formed and flames were quickly visible, the car is on fire.	
14:14	“	

14:16	The car is fully on fire, except for the engine compartment. A short circuit has occurred in the vehicle, causing the headlights to flash.		
14:17	A jet fire has emerged from the battery pack.		On the right, under the floor of the car.

14:19	The windscreen has exploded.		Flying shards of glass can be seen visible in the camera footage.
14:21	A bang was audible and at the same time sparks were visible from the battery pack.		The white ball of fire in the centre of the car is the result of the bang, resembling a minor explosion.

14:22	The first unit has arrived.	
14:23	Two low-pressure jets are applied from a distance of approx. 5 metres from the left front and the right front to extinguish the fire. Bursting sounds are heard, probably from cells. The smoke is gradually turning white.	

14:23 + 10 sec.	
14:23 + 20 sec.	

14:25	Extinguishing is briefly paused, after which it is continued with a low-pressure jet.	
14:27	The UHP unit is called.	*Not recorded in the visual data.*
14:29	The fire has flared up again. Low-pressure extinguishing continues, mainly targeted to the underside of the vehicle. Clearly visible recurrent gas fires keep occurring as a result of batteries in the battery pack blowing off.	

14:32	The UHP unit has arrived and is preparing for deployment.	
14:37	A fan is installed. So far, flames from below have complicated the deployment of the UHP unit. These flames come from the battery pack.	

14:42	The UHP unit is deployed.		The times registered by the note-taker's time and the video timer differ.
14:49	The UHP deployment is discontinued.		

14:50 The UHP unit is redeployed to another hot spot.

14:51 The UHP deployment is discontinued.

14:53	The UHP unit is redeployed to another hot spot.		Note: the time for this camera angle is not in sync with the note-taker's timeline in the left column of this table.
14:55	The UHP deployment is discontinued.		Note: the time for this camera angle is not in sync with the note-taker's timeline in the left column of this table.

14:56	The engine compartment is damped down.		This concerns the firefighter with the jet on the right side of the photo, to the left of the fire appliance.
14:57	Flames have again flared up at the bottom.		

14:58	Two low-pressure jets are deployed from below to fight the flames at the bottom.	
15:00	The flames are out and a low-pressure jet is used for damping down.	

15:03	Flames continue to flare up at the bottom; they are fought with a low-pressure jet.		Flames are visible in the centre of the picture.
15:07	The UHP extinguishing system is deployed to a hot spot at the front of the battery pack.		

15:10	The UHP deployment is discontinued.	
15:13	The fire is damped down with a low-pressure jet.	

15:21 Light smoke develops after some time. The fire is fully put out.