# 3 ELBAS – WP3: Live Fire Testing

The Danish Maritime Fund –
Project number 2021-039

**Danish Institute of Fire and Security Technology**
Jernholmen 12, 2650 Hvidovre, Denmark · Phone: +45 36 34 90 00 Fax: +45 36 34 90 01 ·
E-mail: dbi@brandogsikring.dk · Web: www.brandogsikring.dk, https://brandogsikring.dk/en/

## 3.1 Introduction

The objective of this series of large-scale experiments was to experimentally evaluate the effectiveness of different firefighting devices against electric vehicle (EV) fires. The experimental set-up was intended to simulate the vehicle deck of a passenger ferry.

EV fires are a growing concern for ferry operators. This concern is due to the unique challenges which these fires present: the danger of reaching the critical thermal runaway (CTR) event within compromised lithium-ion battery (LIB) packs, unease of access to the EVs LIB pack, potential toxic and flammable gases released from the compromised LIB pack, and risk of reignition of the LIB pack hours after extinguishment. Due to these challenges, the performance of traditional extinguishing and firefighting techniques are currently being questioned. Failure to extinguish and control these fire hazards can lead to ignition of adjacent vehicles, compounding the fire risk, or heat exposure compromising the structural members of the ship.

Additionally, EV fire behavior is exceedingly difficult to predict. The growth of an EV fire is dependent on a large variety of parameters ranging from the chemistry of the LIB cells within the pack to the ship's geometry. This uncertainty of fire growth of an EV fire is a key parameter impacting the estimated time for the fire to consume more than a single vehicle. This timeframe is an important factor for the firefighters on board and it could be a useful tool for determining the pre-deployment effectiveness of their firefighting capabilities and the available resources.

As part of the ELBAS project, a core objective was to investigate and evaluate a realistic large-scale test set-up to evaluate the effectiveness of different firefighting devices against electric vehicle (EV) fires. Several firefighting devices and technologies have been developed and tested within this project to extinguish and/or contain the fire to the vehicle of origin. Detailed descriptions of these tests are found in section 3.4. Most of these devices focus on the containment of the fire which is intended to both prevent fire spreading to neighboring vehicles/fuels and provide additional time for fire response options.

Often, the vehicle decks inside ferries are compact and the vehicles are usually stowed near each other. Furthermore, the overhead clearance on these decks can be as low as just above 2 m. Therefore, the use of large devices, navigation, and maneuvering is an additional challenge for this unique environment. Therefore, the usability of these different firefighting techniques within a confined space must also be considered when comparing or evaluating different options.

Considering the above challenges, a series of large-scale experiments were performed where an EV was ignited by means of overcharging the LIB pack. The different firefighting devices and technologies were then put to test against an EV fire. The following sections present the reader with a description of the experimental set-up, the methodology, brief background information on each device, and concluding with the analysis and the discussion on the performance of each device.

## 3.2 Experimental Set-up

The experimental set-up was designed to represent the conditions and challenges when fighting a fire on a vehicle deck in a ferry at sea. To simulate the enclosed and compact nature of the vehicle deck, the experiments were conducted inside a similar geometry with vehicles stowed tightly close to each other.

### 3.2.1 Structure

The main structure of the experimental set-up was made by combining two 40 ft ISO shipping containers inside which the vehicles were placed and overcharged until failure. Figure 3.1 below shows the main structure while it is empty for clarity. The gap in the center of the ceiling (Figure 3.1a) was reinforced and sealed with steel plate prior to conducting the experiments (Figure 3.1b). A schematic shown below in Figure 3.2 provides the dimensions of the test set-up including the frame built with the shipping containers.

*Figure 3.1: Experimental set-up (a) without the center ceiling and (b) with the center ceiling*

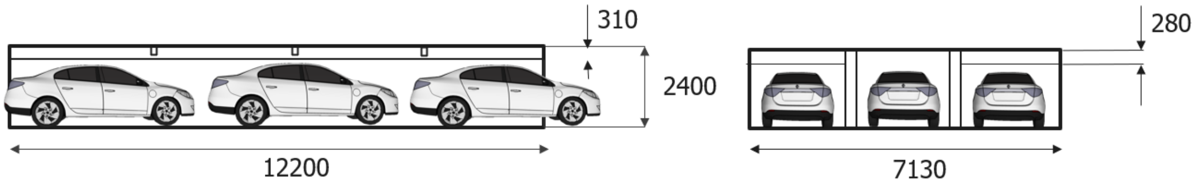


*Figure 3.2: Dimensions of the experimental set-up (dimensions in millimeters)*

The length and the height of the set-up corresponds to the length and height of a 40 ft ISO container. The length is 12.2 m, the width is 7.13 m, and the height of the set-up is 2.4 m. The ceiling of the structure was insulated with SeaRox SL 620 and Saint-Gobain Isover Ultimate is used in the center directly over the EV first ignited. The side walls were kept uninsulated during all the tests. The floor of the experimental set-up was covered with steel plates with dimensions of 2 m × 3 m and a thickness of 14mm.

### 3.2.2 Vehicle Arrangement

The tightly stowed vehicles pose challenges for the ship's crew for general maneuvering through the vehicle decks and especially for firefighters deploying tools maneuvering to the fire event. Furthermore, the proximity of neighboring vehicles increases the probability of fire spread.

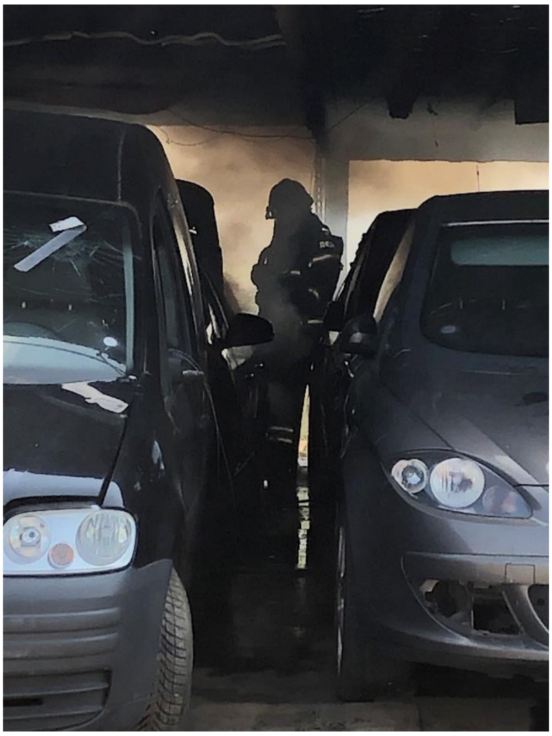

*Figure 3.3: Cramped space inside the experimental set-up*

A firefighter wearing the complete fireman's outfit including equipment will be hindered when moving around such a tightly packed space. Further, the use of firefighting equipment will be difficult and should be designed for use in these conditions. Figure 3.3, captured during the experiments, shows the limited space available for the firefighters to work on a typical tightly loaded vehicle deck.

As an important consideration for the evaluation of firefighting equipment and study of fire spread, the vehicles were placed in the test set-up such that the conditions were like a realistic vehicle deck. The gaps among cars were set to 40 cm and 20 cm (± 5 cm) from door to door and bumper to bumper respectively, as shown in Figure 3.4.

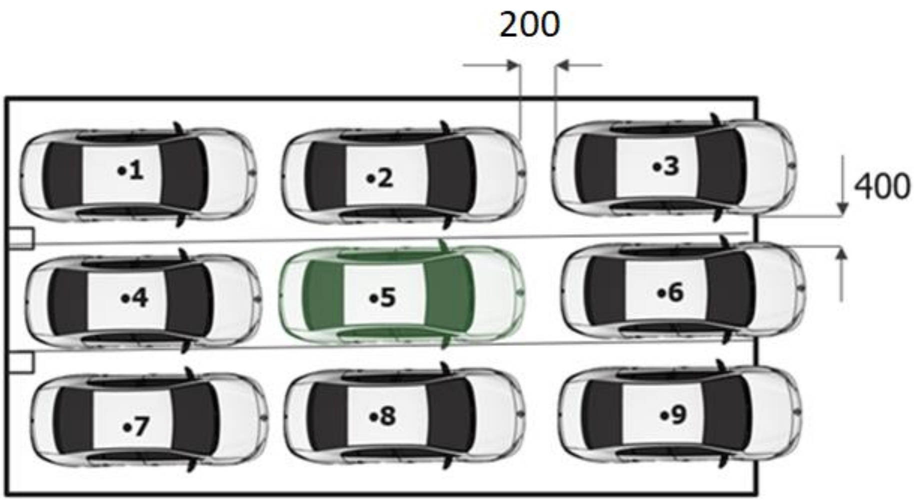


*Figure 3.4: General vehicle arrangement [green car (#5) is the EV] (dimensions in millimeters)*

The EV was placed in the center of the vehicle 'matrix' denoted by car number 5. The surrounding 8 vehicles were conventional internal combustion engine vehicles (ICEVs). It should be noted the ICEVs used were drained of all oils and other fluids and did not contain any fuel in their tanks due to environmental and safety considerations.

The surrounding ICEVs were shuffled around during the experiments depending on the condition of the cars and the EV was replaced after each experiment. Over the course of the tests, the following 3 electric car models were tested: Renault Fluence ZE (2012), Tesla Model 3 (2021) and Nissan Leaf (2011). Specifications of the cars are given in Table 3.1.

*Table 3.1: Specifications of the selected EVs*

| EV model | Electrical energy rating (kWh) | Location of the battery | Number of cars tested |
|---|---|---|---|
| Renault Fluence ZE | 22 | Behind the back seat | 7 |
| Tesla Model 3 (2021) | 55 | Under the back seat | 1 |
| Nissan Leaf (2011) | 24 | Under the passenger compartment | 1 |

### 3.2.3 Measurement Equipment

#### *3.2.3.1 Temperature Measurement*

Temperatures at different locations were recorded using type K thermocouples. The thermocouples were placed inside the surrounding vehicles on the hoods of cars 1, 4 and 7, on the boots of cars 3, 6, 9, and on the doors facing the EV on cars 2 and 8. Four plate thermometers were placed outside cars 2, 4, 6, 8 facing car 5. The plate thermometers on cars 2 and 8 were placed outside the doors facing car 5. On cars 4 and 6, the plate thermometers were placed on the hood and the boot facing the EV respectively. The placement of the measurement devices including the cameras is shown in Figure 3.5.

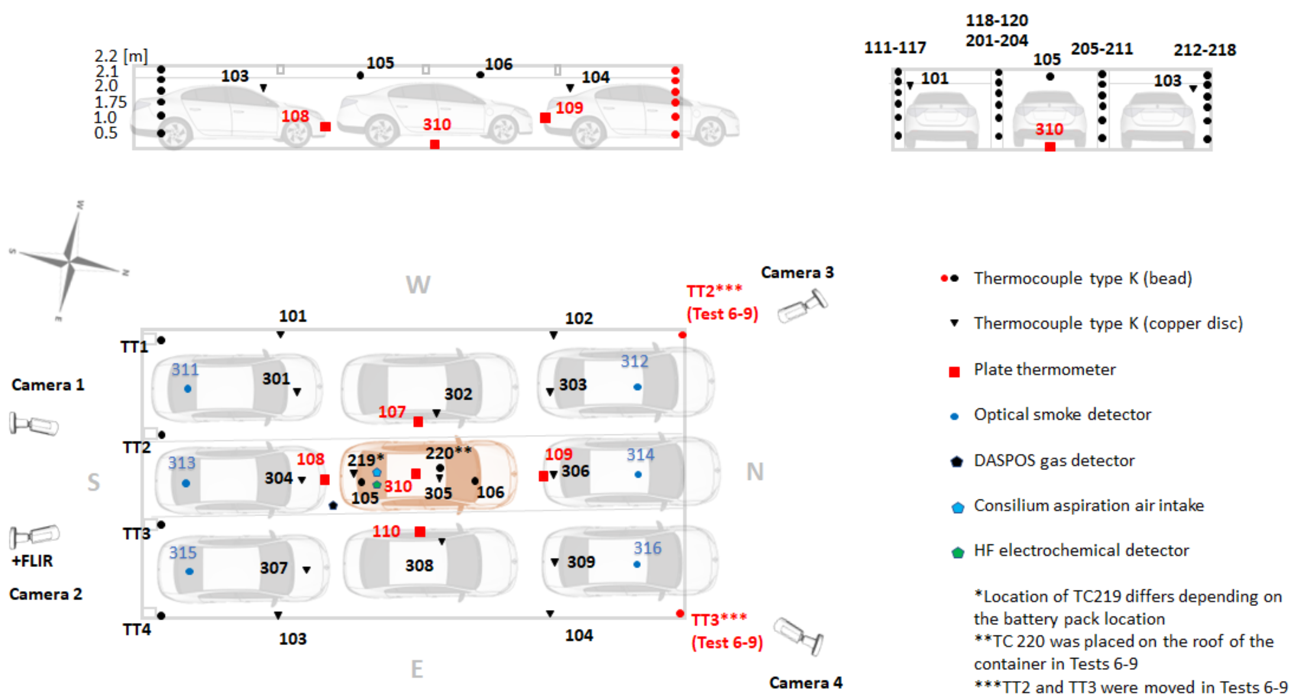


*Figure 3.5: Arrangement of the measuring devices and cameras*

The thermocouples on the EV were placed inside the passenger cabin in 2 locations: on the roof and another one placed next to the rear-view mirror (TC220) as shown in Figure 3.6. The temperature of the battery compartment was also monitored using a thermocouple attached to it (TC219). The thermocouple was attached on top of the casing of the Li-ion battery pack as shown in Figure 3.7.

*Figure 3.6: Placement of TC 220*

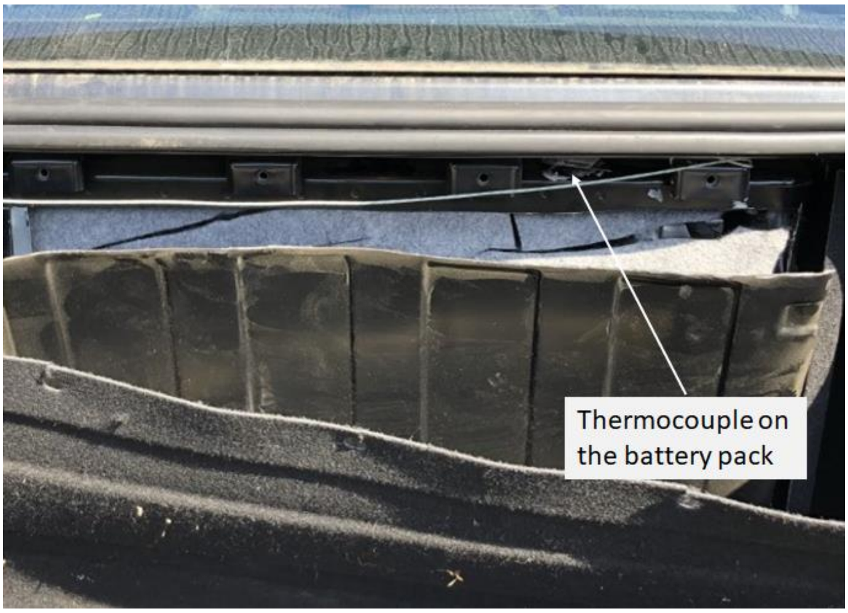


*Figure 3.7: Thermocouple placement on the battery pack*

The gas temperature above the EV was measured by two thermocouples placed directly above the hood and the boot of the EV at the ceiling level (approx. 2.4 m from the floor). Four thermocouple trees were placed on the openings of the set-up measuring temperatures at heights of 0.5 m, 1 m, 1.5 m, 1,75 m, 2 m, 2.1 m and 2.2 m from floor level as shown in Figure 3.5.

#### *3.2.3.2 Smoke/gas Detection*

Six optical smoke detectors were placed at the ceiling level directly above vehicles 1, 3, 4, 6, 7 and 9. Additionally, HF detectors were placed above the EV, near the hood of the EV in some selected experiments. The placements of these detectors are shown in Figure 3.5.

Two types of HF detection were used during the experiments. Aspiration type gas detectors produced by Consilium Safety [1] were placed on the ceiling of the set-up directly above the EV and HF detectors from DASPOS were placed behind the EV in between vehicle 4 and the EV at ground level.

## 3.3 Methodology

The test methodology is presented in the steps below. The methodology was similar for all the tests performed except for the different devices tested and their operational procedures.

1. The EV was fully charged and placed in the center of the vehicle arrangement.
2. Thermal runaway was initiated via short circuit (electrical abuse).
3. The battery temperatures were monitored to verify whether Thermal Runaway (TR) was achieved.
4. If TR was achieved just by short-circuiting, the conditions were allowed to evolve naturally.
5. If TR was not achieved (according to the battery temperature), ignition was initiated using external means such as placing gasoline burners under the EV.
6. The firefighters waited until the 10 min mark after the first optical smoke detector was triggered. The waiting time of 10 min was chosen based on information provided by the partner ferry companies. Once the alarm was activated indicating a potential fire, the crew would muster and gear up to fight the fire. This procedure takes approximately 10 min.

7. The selected firefighting device was used against the EV fire (10-min after first alarm) and additional external help was provided only when it was deemed necessary based on the conditions inside.
8. The experiment was considered fully completed when the EV fire was fully extinguished. Specifically, when the temperature of the battery dropped below 50 °C.

*Table 3.2: List of experimental set-ups and fire scenario details*

| Experiment ID | EV model | SoC | Extra battery/ energy rating | Devices used | Extinguishing media |
|---|---|---|---|---|---|
| 1 | Renault Fluence ZE | 100% | No | Bridgehill fire blanket | Fresh water |
| 2 | Renault Fluence ZE | 100% | No | E-lance - battery piercing device | Sea water |
| 3 | Renault Fluence ZE | 100% | No | BEST Rosenbauer - battery piercing device | Fresh water |
| 4 | Renault Fluence ZE | 130% | Yes/ 0.76kWh* | Jøni EV firefighter – portable water-cooling device | Sea water |
| 5 | Renault Fluence ZE | 100% | No | DAFO Water curtains | Sea water |
| 6 | Tesla Model 3 | 100% | No | Water mist system | Fresh water |
| 7 | Renault Fluence ZE | 100% | Yes/ 0.76kWh* | E-lance and water mist system | Fresh water |
| 8 | Nissan Leaf | 100% | No | Bridgehill fire blanket and water mist system | Fresh water |
| 9 | Renault Fluence ZE | 100% | Yes/ 0.76kWh* | Jøni EV firefighter and DAFO water curtains | Fresh water |

** The extra battery was at an SoC of 120% before the experiments.*

When operating each device, depending on the working mechanism of the device, additional steps were taken. These additional steps will be discussed in the following section which provides background information on different firefighting devices used during the tests.

## 3.4 Tested Devices and Technologies

Different firefighting devices and technologies are available in the current market but each with different approaches. Some devices directly address the battery fire and cool the battery temperature below the TR onset but with less focus on cooling the area surrounding the battery pack. Another way of approaching an EV fire is to ensure that the fire remains always under control without the fire spreading to the surroundings. Containment of the flames is the primary focus of these methods while the direct cooling methods focus on cooling the battery pack. Both methods can be effectively used to fight an EV fire. However, due to the narrow focus on each method, there are disadvantages as well, when depending only on one type of method.

The devices selected for the ELBAS tests were chosen based on the review of currently available systems performed under the second work package, section 2.2.3, of this project.

### 3.4.1 Car Fire Blanket

#### *3.4.1.1 Background*

Fire blankets are an effective solution for ICEV fires. These blankets, made of high temperature resistant materials, are designed to contain the smoke and flames within the covered car. This method of fire protection does not extinguish the vehicle fire but instead contains the fire which can continue potentially until burnout.

The Bridgehill Car Fire Blanket [2], shown in Figure 3.8 is a fire blanket intended for use against EV fires. The general dimensions of the blanket are 6 m × 8 m and weighs approximately 26kg [2]. The standard model single use blanket was used in this experiment.

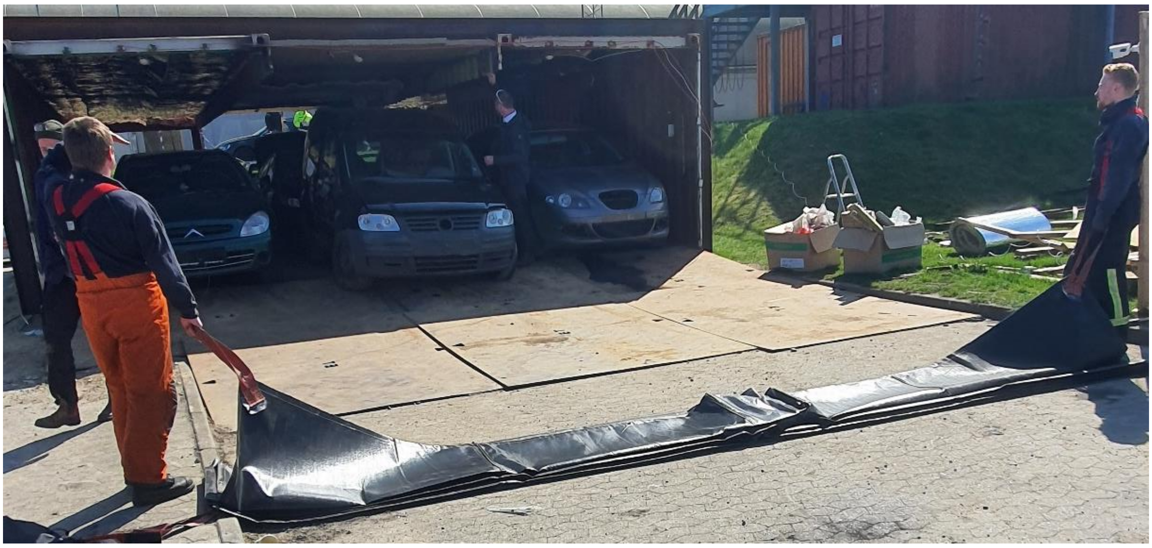

*Figure 3.8: Standard Bridgehill Car Fire Blanket unrolled on the ground ready for use*

Using the blanket is relatively straight forward, but two fire fighters are required to pull the blanket from each side and over the car on fire. When using on tightly stowed vehicle deck on a ferry, the two firefighters must go around and over the adjacent vehicles to reach the car on fire (see Figure 3.3). Due to the size of the blanket and the provided handles on the corners, with some initial training the fire fighters testing the blanket demonstrated it is possible and relatively easy to use. This method also gave some additional protection to the firefighters deploying the blanket as they were shielded from the ignited car to some degree by the neighboring cars.

*Figure 3.9: Bridgehill Car Fire Blanket being used during experiment 1*

The fire blanket's main purpose is to limit the flame spread to adjacent vehicles or to the structural elements and provide enough time for the vessel to reach land and get external landside assistance. The performance of the Car Fire Blanket was tested in experiment 1 and is discussed in section 3.4.1.2. The fire blanket was used as a standalone technology without the assistance of secondary firefighting technologies, such as water mist.

#### *3.4.1.2 Results and Discussion*

After the fire blanket has been placed over the ignited car, it limits the oxygen available to the fire from the surrounding environment. This method of fire response would smother most fires, but the combustion process of EV LIB packs is somewhat different. Once the LIB pack has passed the point of TR and becomes involved in the fire, a byproduct of the decomposition of the electrodes within the LIB cells is oxygen. This stage of self-production of oxygen tends to accelerate fire development. Placing the fire blanket over the involved EV will cause heat feedback cycle on the compromised LIB pack which in turn will likely result in complete burnout of the vehicle. The temperature of the battery compartment recorded during the test is shown in Figure 3.10. It should be noted that the battery had to be ignited using EXXOL D60 after no ignition was achieved via short circuiting the fully charged battery pack.

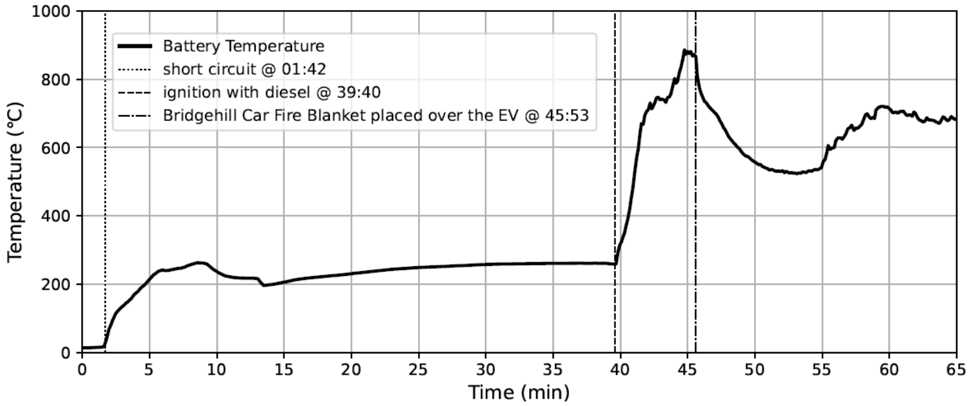


*Figure 3.10: Battery compartment temperature during experiment 1*

As seen in Figure 3.10, the temperature of the battery compartment was 886 °C just before the blanket was placed over the car. A sudden drop of temperature was observed after the car on fire was fully covered by the blanket. The minimum temperature was recorded at 523 °C afterwards but, the battery temperature started to slowly rise before it reached a steady temperature of around 680 °C. After the blanket was placed, the temperatures in the battery compartment never dropped below 500 °C during the logged time. Nevertheless, the initial sudden drop of battery temperature could be due to the limited oxygen during that phase but, the battery was already in the TR range which caused the temperatures to rise.

Containment of flames is a key performance indicator of a fire blanket, but this requires that the blanket is used before flames have spread to adjacent environment. During the experiments, it was observed that flames and smoke could penetrate through the blanket or go under the edges of the blanket as shown in Figure 3.11.

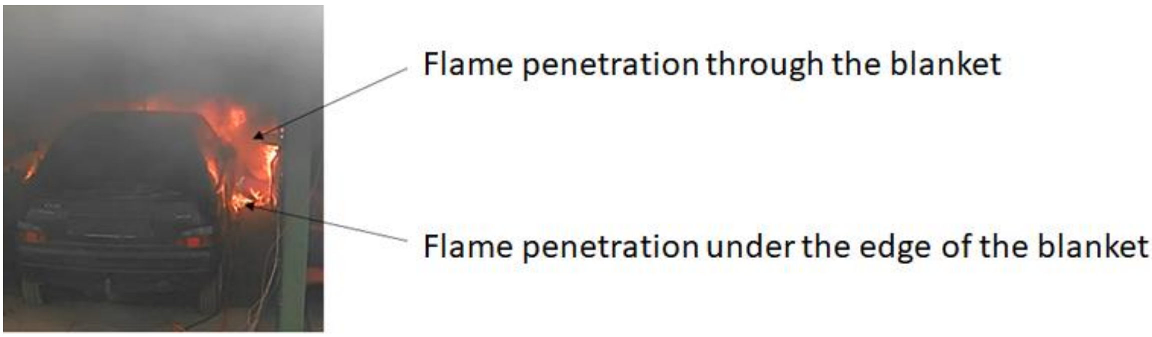


*Figure 3.11: Flame penetration through the fire blanket*

Flames were observed in the vicinity of car 7 even before the blanket was deployed. This highlights the importance of response time using a similar blanket where the main advantage is containment of the fire to a single vehicle. However, the temperature readings from TC 105 and TC 106 show that the conditions around the EV changed as soon as the EV was covered by the blanket and continued to be that way. The temperatures around the EV (at the ceiling level) dropped from around 600 °C to below 100 °C soon after the blanket was used. This indicates that the blanket was able to contain the EV fire and it is highly unlikely that another vehicle would catch fire in temperatures below 100 °C.

### 3.4.2 Extinguishing Lance

#### *3.4.2.1 Background*

This device, in contrast to a fire blanket, is focused on providing direct cooling to the battery. This type of extinguishment method can be considered aggressive since the device has to be used directly on the top of the battery itself regardless of the surrounding conditions. The device, as shown in Figure 3.12, weighs approximately 7kg to 8kg depending on whether the extension tube is attached or not [3].

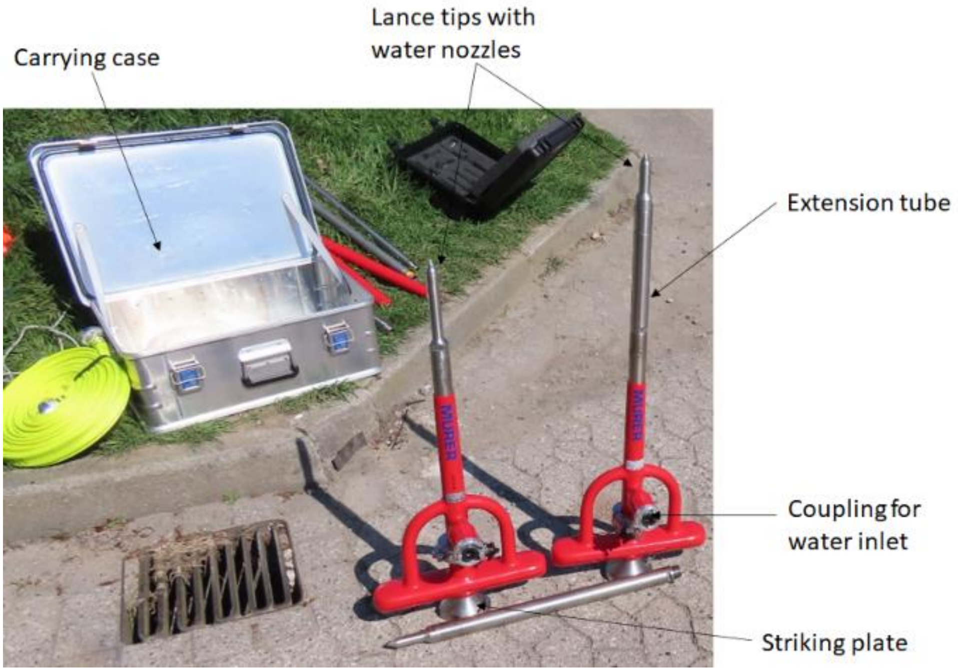


*Figure 3.12: E - Extinguishing Lance by Murer-Feuerschutz GmbH with the extension tube and carry case*

The working principle of this device is, once the LIB pack location is determined, the lance tip is placed above the LIB pack and then hammered into the LIB pack using the striking plate. The lance will need to be held by one firefighter while another strikes on the striking plate with a sledgehammer, refer to Figure 3.13. Once the pack is penetrated, the water supply can be activated which provides direct cooling on the battery modules itself. This method of cooling is intended to apply a cooling spray of water droplets directly onto the compromised LIB and absorb heat energy. This increases the efficiency of the used water and significantly reduces the amount of water required to bring the battery temperature down to a desired level.

*Figure 3.13: Holding the E-lance in place prior to striking*

#### *3.4.2.2 Results and Discussion*

Since the lance must reach the battery pack, prior knowledge of the location of the battery in the car is required. It is not likely that this information will be easily available to the firefighting crew on board. During the experiments, the trained professional firefighters knew beforehand where to strike and where the battery pack was located. Furthermore, Renault Fluence ZE model was designed in favor of providing easy access to the battery modules through the opened boot. Depending on the design of the vehicle, it can be a more tedious task to reach the battery pack with this device. Once the lance had pierced through the battery, it stayed in place even with the water supply on. Figure 3.14 shows the lance standing in place still attached to the battery pack after the experiment was finished.

*Figure 3.14: E - Lance on the battery after the experiment*

Using this device in a confined space with a low ceiling height slightly hampers the swing of the sledgehammer. This leads to an increased number of strikes before the lance penetrates the battery pack. This was observed during the experiments when the sledgehammer contacted parts of the ceiling during full swings. During the E-Lance testing day, flaming combustion was not achieved on the battery pack and therefore, the conditions inside the structure were not as severe as in a fully engulfed flaming EV fire. The temperature variation with time before the device was used and after is shown in Figure 3.15.

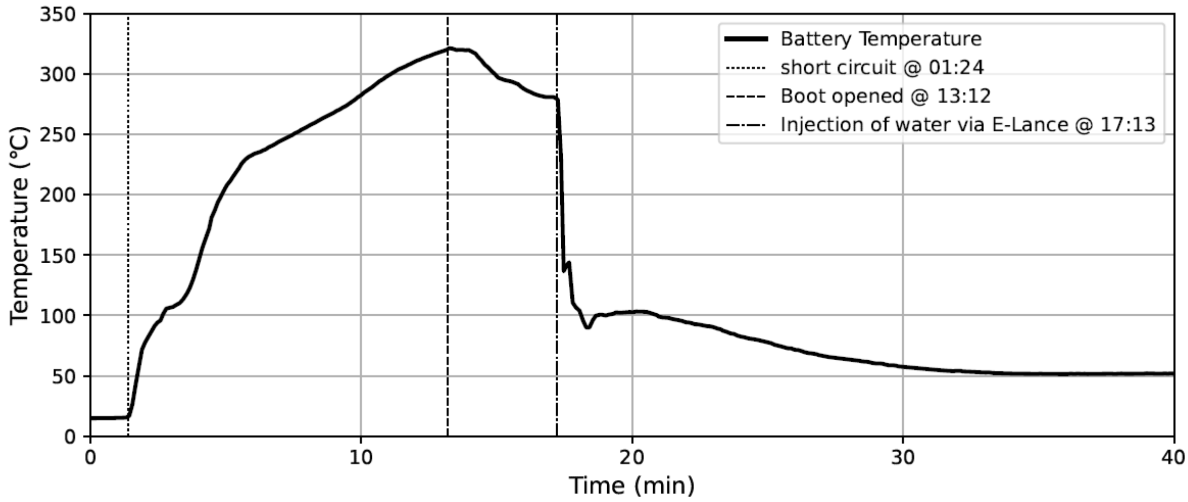


*Figure 3.15: Battery compartment temperature during experiment 2*

An increase in the temperature to 321 °C after the 13 min. mark can be observed initially after the short circuit onset. A slight but noticeable drop in temperature was observed when the boot was opened by the firefighters to deploy the lance. However, the temperature started to stabilize at around 280 °C just before the water supply was turned on. After this point a rapid drop in temperature was observed and this trend continued around the 32 min. mark where the battery compartment temperature remains constant around 50 °C.

An important factor that can be observed from Figure 3.15 is the time taken from reaching the battery pack and to turning on the water supply. This time could be considered approximately as the time gap between the dashed line and the dash-dotted lines. During the experiments, it took 4 min from reaching the vehicle until water had been applied on the battery. It should be noted that prior knowledge of the battery available to the firefighters had a direct effect on this time gap.

Direct cooling of the battery is advantageous and extremely efficient when controlling the battery fire. The battery pack was cooled down with a considerably lower water consumption compared to other water based extinguishing systems used in this series of experiments. However, this device is not capable of putting out the flames inside the passenger cabin. The device is most appropriate when only the battery fire is the concern. It is therefore required that the flames outside the battery have been put out prior to using this device. This makes it much easier for the firefighters to attack the battery without the effects from external flames and smoke. The intended use of the device is primarily to cool down the battery after the fire has been extinguished and during the experiment it could successfully bring the LIB temperature below TR onset temperature. It is worth noting that this device was used further after some of the other experimental tests as a precautionary method to ensure the battery TR reactions had stopped completely.

### 3.4.3 Battery Extinguishing System

#### *3.4.3.1 Background*

A similar device to the E-lance, focusing on direct cooling of the battery, has been developed by the company Rosenbauer. The device can be considered as an automated battery piercing device which can be controlled further away from the battery fire after the piercing device has been placed in the desired location. Using the device requires two main steps: placing the piercing device and activating the piercing mechanism afterwards. Operation of the device requires two firefighters: one to place the piercing device and another one at the control unit to activate the device as shown in Figure 3.16.

*Figure 3.16: BEST by Rosenbauer [4]*

The piercing unit weighs approximately 26 kg which must be pushed under the vehicle directly under the battery pack before it is activated. The water flow rate through the device is 30 l/min (8 gallons/min) at a pressure of 7 bar (100 psi). The ride height of the vehicle and the location of the battery pack must be compatible with this device for proper usage. Otherwise, additional steps such as lifting the vehicle using a jack or deflating the tires to bring the vehicle down should be taken. Due to these uncertainties, the flexibility of the device is of a major concern. Despite these drawbacks, one major advantage of the device is the fact that it can minimize the time spent near the battery fire. Once the piercing device has been placed, the firefighter can retreat away from the fire and the expected buildup of toxic gases and heat. Furthermore, the direct application of water on the battery will efficiently cool the battery down to safe temperatures with low water consumption.

#### *3.4.3.2 Results and Discussion*

The reach of the BEST piercing lance was insufficient to fully pierce the battery pack of Renault Fluence ZE. Therefore, the tires of the EV were deflated which allowed the battery pack to be pierced with the BEST. The BEST was also placed prior to the EV being ignited but only activated 10 min after the first smoke detector was triggered.

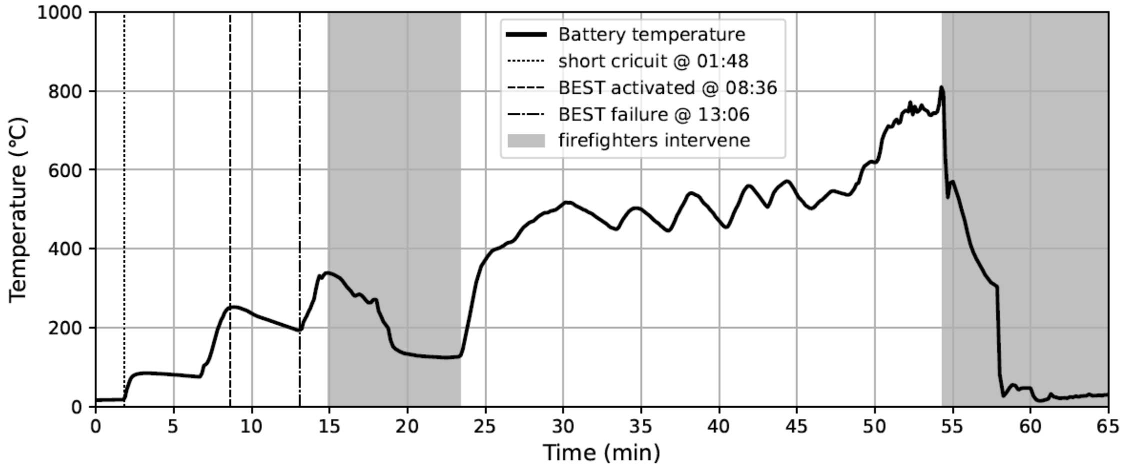


*Figure 3.17: Battery compartment temperature during experiment 3*

A noticeable drop in battery temperature was observed after BEST was activated (battery temperature at 251 °C) and water was applied on the battery. However, after 4.5-min, the battery temperature started to rise even while the device was in operation. The battery temperature eventually rose beyond what it was when the device was activated. At this point, the device was assumed to fail in cooling down the battery and the firefighters intervened and attacked the fire. Therefore, even after activation of the BEST the compromised LIB pack continued to produce heat and propagate TR within the LIB. Finally, after 54 min the fire was completely extinguished, and the battery temperature was brought below the TR onset temperature.

The failure of the device could be related to the battery compartment being opened during short circuiting process. This configuration did not allow the water to be kept within the battery compartment. Upon, further investigation after the experiments, it was observed that the device successfully pierced through the battery compartment [Figure 3.18a] but, due to the opened compartment [Figure 3.18b], the attempt was unsuccessful at completely stopping TR. The device relies on the injected water remaining in the battery pack absorbing heat from the battery, failing to do so leads to propagation of TR within the LIB pack.

*Figure 3.18: Post fire LIB pack of (a) pierced battery compartment and (b) the opened battery compartment after the experiment*

The battery extinguishing system technology (BEST) by Rosenbauer is suitable for battery packs which are located on the underside of the vehicle. Locating the exact battery pack which is on fire is vital to the effectiveness of the device. In vehicles where the batteries are split up and spread around the structure of the vehicle could be an additional challenge during the extinguishing process. In situations where more than a single battery pack has reached TR conditions, the device is not capable of providing effective cooling. If the BEST is effectively used on the battery pack on fire with due time, the device can cool the battery pack down with a lower water consumption like the E - Lance.

### 3.4.4 Portable Mist Curtain with Undercarriage Cooling

#### *3.4.4.1 Background*

In contrast to the previous two firefighting devices presented, EV Firefighter by the company Jøni Aabybro ApS does not focus on cooling the battery down. Instead, the purpose of the device is to cool down the surroundings via water sprays, containing the fire to the original vehicle. The device can be considered as an array of water mist nozzles mounted on rails which can be pushed on the sides and under the EV as shown in Figure 3.19.

The rails come with wheels mounted on the bottom for easier handling. Additionally, the device must be first connected to the water supply before placing it. Afterwards, two firefighters should place rails on each side of the burning vehicle and the smaller array under the burning EV. The intention is to create a water barrier around the EV through which the flames cannot penetrate and spread. Such a device, if used as intended, might keep the fire from growing and spreading until the ship reaches the shore. However, the device must be placed prior to the flames spreading to the surrounding environment.

*Figure 3.19: EV firefighter by Jøni Aabybro during experiment 4*

#### *3.4.4.2 Results and Discussion*

During experiment 4, the EV battery was overcharged to 130% and the boot of the EV was left opened prior to short circuit to induce a stronger TR reaction. Shortly after a short circuit approximately at the 2 min mark, the battery compartment caught fire and the fire grew rapidly. Flame spread around the burning vehicle and to adjacent vehicles was observed within 5min after ignition before the devices were pushed inside.

Figure 3.20a shows the evolution of the battery temperature. Figure 3.20b shows the temperatures recorded on the external surface of the doors facing the EV. Specifically, the doors on car 2 and car 8.

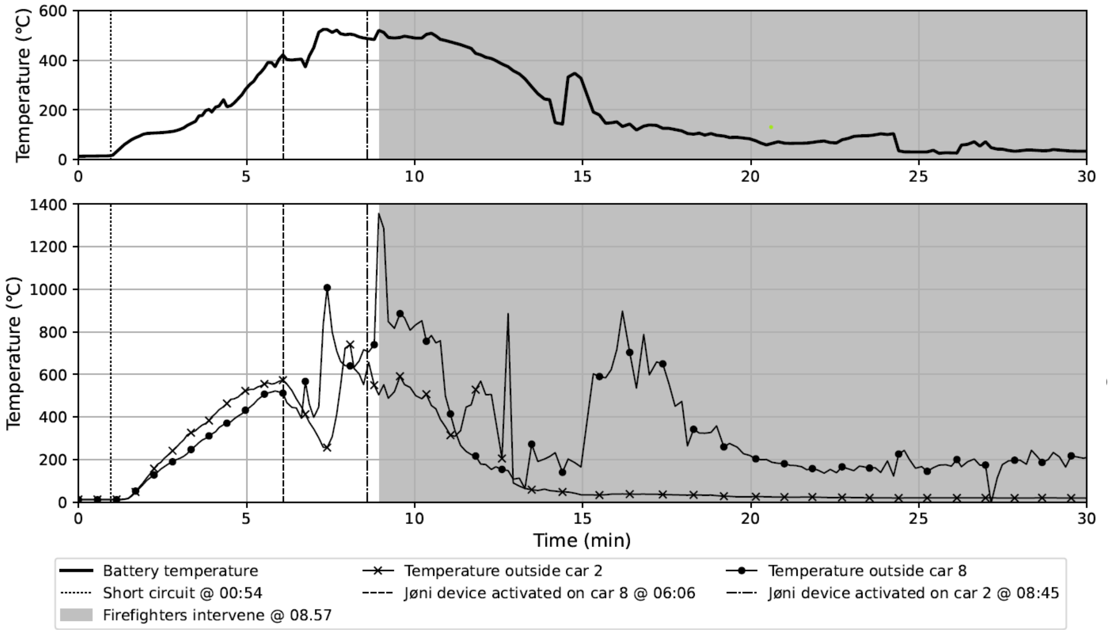


*Figure 3.20: Temperature reading during experiment 4. (a) Battery compartment temperature and (b) temperatures of the exposed sides of adjacent cars*

Due to the nature of this device, it is highly unlikely that this device will cool the battery down on its own. This is due to the battery being located inside the structure of the vehicle in an enclosed space. This does not allow the water droplets to reach the battery pack, which is evident from the battery temperature evolution shown in Figure 3.20a. The battery temperature was not affected after the EV firefighter was activated. A substantial decrease in the battery compartment temperature can be observed only after firefighters decided to attack the fire directly.

Temperatures higher than 500 °C were already reached when the EV firefighter rails were pushed in on the sides of the car. Visual observations confirmed that flames had spread over to the cars on all sides by this time. The EV firefighter uses a technique focused on minimizing flame spread, it was at a disadvantage due to this reason. Furthermore, the rails only had water mist nozzles facing towards the EV but not away from the EV. Therefore, any flames on the blind side of the nozzles were not affected by the water spray. Even though within 3 min the EV was surrounded by the water mist arrays, the fire kept growing fast. Due to that it was decided to send in firefighters to attack the fire using the conventional firefighting hoses for safety reasons.

The usability of the device in a tight space could be challenging due to its large size. Maneuvering the rails through a vehicle deck filled with vehicles could take a longer time. However, choosing a favorable entrance to the vehicle deck could assist the firefighters to reach the fire in quick time.

#### *3.4.4.3 Second Test with Extinguishing Lance*

This device was put to test for a second time, this time in combination with the E - Extinguishing Lance by MURER-Freuerschutz GmbH. It was observed that cooling was necessary on both sides of the rails to fully cool down the surroundings in the vicinity of the EV. The nozzle layout on the rails was modified with nozzles facing both into and away from the EV.

EV Firefighter rails were used before the fire had spread to the adjacent vehicles. Furthermore, the array of water mist nozzles was doubled this time, with additional nozzles facing away from the EV. The effect of timely activating device and the additional nozzles were evident and flame spread was kept under control during this run. This highlights the importance of reaction time of the fire crew when depending on such a device. However, due to the unpredictable nature of EV fires, even the quickest credible reaction could be ineffective in some instances as observed during experiment 4.

### 3.4.5 Portable Water Mist Curtains

#### *3.4.5.1 Background*

An underdevelopment side water curtains made by Dafo Comtec AB were tested against an EV fire during experiment 5. The device has a similar principle to the EV Firefighter developed by Jøni Aabybro ApS but, the compact and linear design increases ease of handling this device in an enclosure with limited space, however this also comes with a reduced water output. The device is a single rail with an array of water mist nozzles attached to the rail. The device should be pushed using the provided steel bar on each side of the EV while being connected to the water supply as shown on Figure 3.21a. For each side, a firefighter is required to push the device in. The device lies on the ground once placed near the EV with the water mist nozzles facing the ceiling as shown in Figure 3.21b.


*Figure 3.21: Albero/dafo water curtains (a) during firefighting operations and (b) before the experiment set-up*

Once the device has been placed, the water supply can be activated to release the water spray from the nozzles. This water curtain is to act as a barrier for flame spread and keeps the fire contained within the originally ignited vehicle. The device is not capable of providing cooling directly on the battery pack due to its design.

#### *3.4.5.2 Results and Discussion*

During experiment 5, even though the battery pack was fully charged and short circuited, TR was not achieved. However, the EV was ignited using a diesel pool fire placed under the EV. Even during the fire, battery compartment temperatures suggest that TRA was not achieved. The battery temperatures and the temperature recorded inside the passenger cabin are shown in Figure 3.22a. The temperatures of the sides of the adjacent cars are shown in Figure 3.22b.

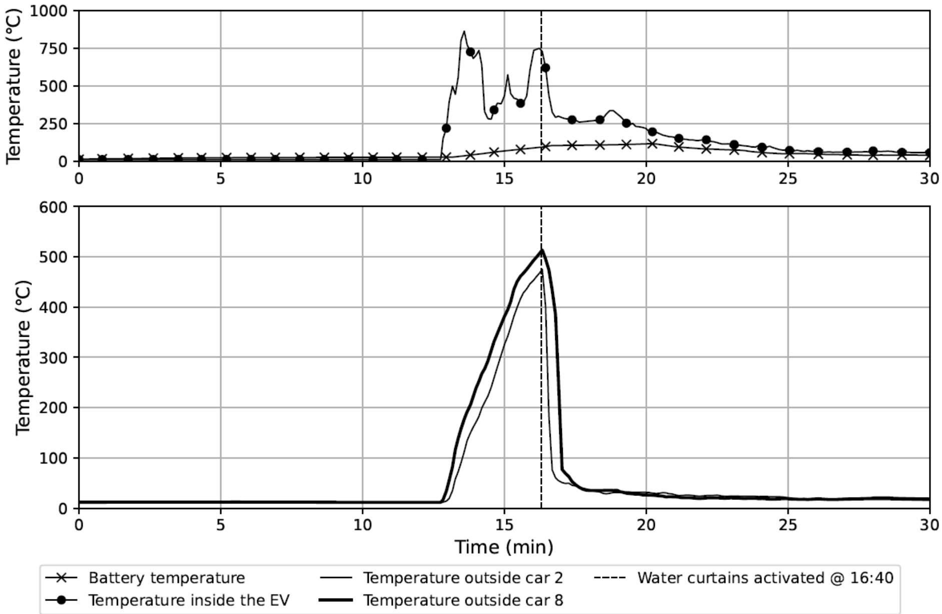


*Figure 3.22: Recorded temperatures during experiment 5 of (a) the EV passenger cabin and (b) the exposed sides of adjacent cars*

In review of the temperatures recorded around the water curtains on each side, a steep drop was observed as soon as the water supply was activated. Within a few minutes, the devices were able to reduce the temperature of the surroundings and inside the EV to a large extent. However, the effect on the temperature inside the EV was due to the windows being opened. In a real-life scenario, this cannot be assumed to be the case unless the firefighters decide to break the windows. Had the battery pack reached TR, the effect from this device can be assumed as minimal or negligible on the battery temperature.

Quick reaction is the key to the efficiency of this device, as it was for EV firefighter by Jøni Aabybro ApS. During experiment 5, flame spread was observed on both sides (on car 2 and car 8) just before the devices were placed as shown in Figure 3.23. However, due to the upward spray from the rails, cooling water was able to reach both sides of the EV which was not the case for the EV Firefighter before additional nozzles were added in on the rails in the modified version. In that regard, the simple design of these side water curtains provides cooling to both sides of the rails in an efficient manner.

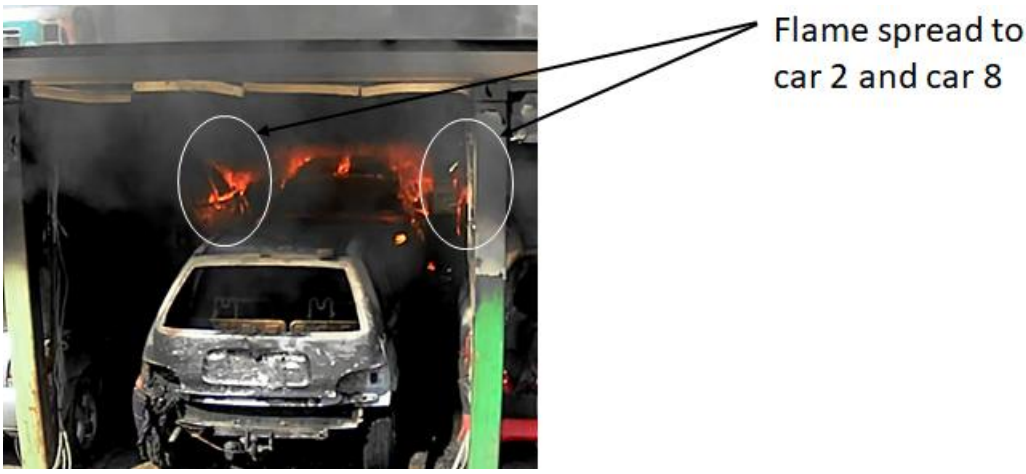


*Figure 3.23: Flame spread to car 2 and car 8 during experiment 5*

The water consumption of this device was lower compared to the EV firefighter by Jøni Aabybro ApS mostly due to the differences in the nozzle layouts of the two devices. Still, the least water consumption can be expected from the device which provides direct cooling on the battery pack.

## 3.4.6 Low-Pressure Water Mist System

### *3.4.6.1 Background*

Water mist systems usually require high operating pressures to be able to generate a fine enough water droplet distribution within the spray. Sprinklers on the other hand generate a spray with larger droplets with low operating pressure. Due to the finer droplets providing better heat absorption characteristics, water mists are often more efficient compared to sprinklers in terms of water consumption. However, water mist systems are equipped with components with a high-pressure rating making the whole system more expensive compared to a sprinkler system. Low-pressure water mist systems attempt to eliminate the downside of both conventional water mist and sprinklers and provide a water spray with better heat transfer characteristics with cost efficient components. In Figure 3.24, the nozzle head is shown alongside its dimensions.

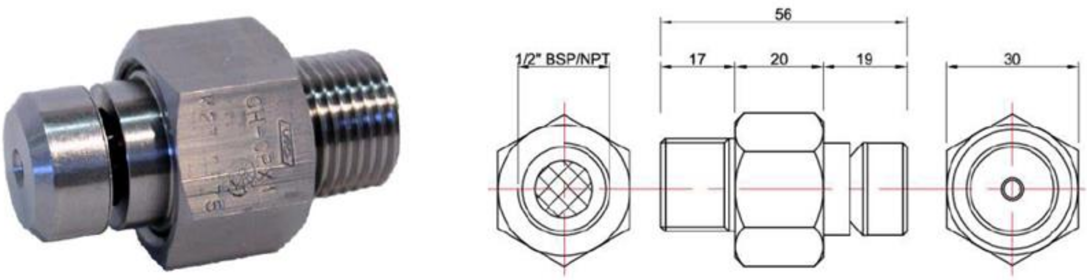


*Figure 3.24: VID Fire-Kill low pressure water mist nozzle (left) and the dimensions (right)*

The operating pressure range for the system is from 6 bar to 16 bar which is lower than the pressure requirement for a conventional water mist system. The coverage by the spray cone from a single nozzle varies from 12.25 $m^2$ (3.5 $m^2$ × 3.5 $m^2$) to 16 $m^2$ (4 $m^2$ × 4 $m^2$) and can be installed on ceiling heights up to 2.5 m and

5m [5]. As per the product data sheet [5], 90% of the water droplets from the nozzle will have diameters less than 300 µm. The housing of the nozzle is made of brass (ANSI 304) with a Ni-Sn coating.

#### *3.4.6.2 Results and Discussion*

The low-pressure water mist nozzles were evenly distributed in the experimental set-up with six nozzles fixed on the ceiling directly above car 1, 2, 3, 7, 8 and 9. The water mist system was activated 7.5 min after the first detector signal was received. The EV was ignited using a diesel pool fire placed under the battery pack after ignition was not achieved via short circuit. The temperature evolution of the battery compartment [Figure 3.25a], the smoke layer temperature directly above the EV [Figure 3.25b], and the temperatures of the exposed sides of the surrounding vehicles (car 2, 4, 6 and 8) [Figure 3.25c] are shown below.

The EV chosen for experiment 6 was different from the previous experiments. A Tesla Model 3 (2021) with a new battery was used for the experiments. The car was not in good condition, a set of passenger seats was placed inside, and the roof was covered with a steel plate to avoid water droplets reaching the passenger compartment from above.

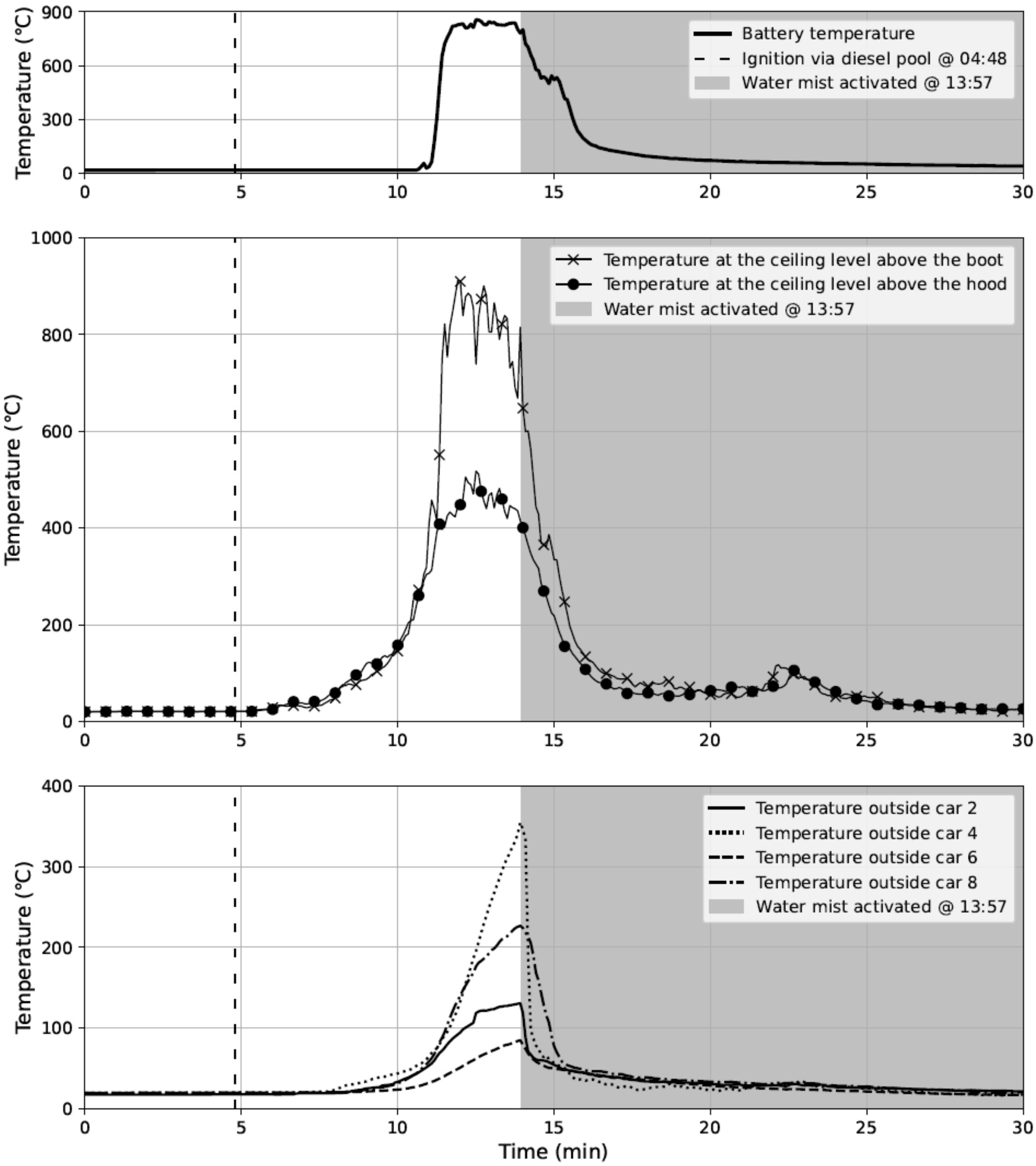


*Figure 3.25: Temperature of the battery compartment (a), smoke layer temperatures above the EV (b) and temperatures of the exposed sides of the surrounding cars (c)*

Unlike all previously mentioned techniques, a water mist system will not necessarily target the battery or the EV, but it will produce a spray once activated from its fixed position. If the nozzles are installed with good coverage, the effects of water mist can be felt on the burning car itself and the surroundings including nearby structural elements. As soon as the water mist system was activated, a drop in temperature on the battery, smoke layer above the EV and the surrounding cars were observed. The temperature drop in the battery was most likely due to the bad condition of the EV allowing droplets to reach the battery pack which would otherwise be better shielded from the water mist. The cooling effect on the surroundings can be clearly seen on the snapshots taken from the thermal imaging camera as shown in Figure 3.26.

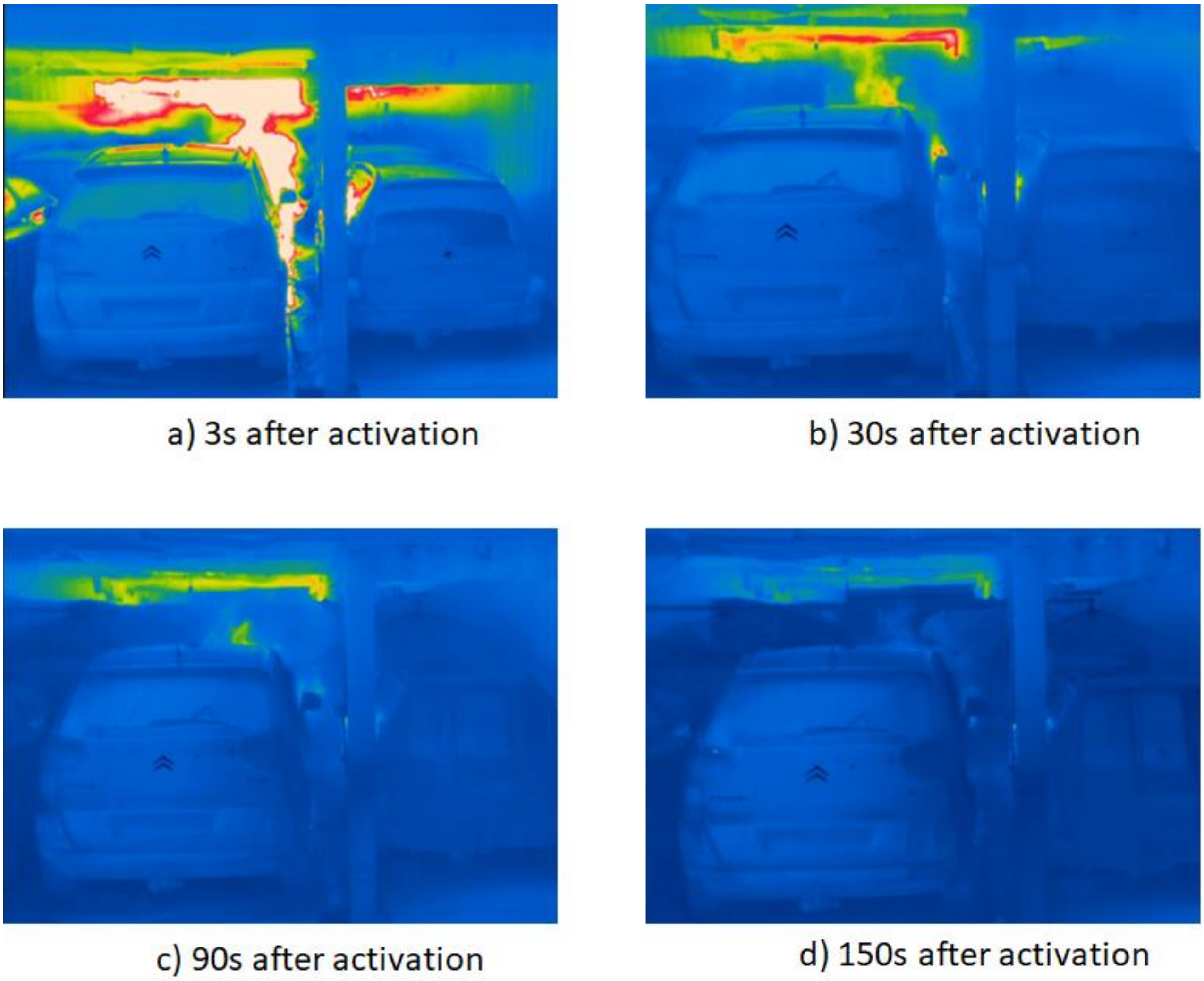


*Figure 3.26: Thermal images of the surrounding after sprinkler activation; a) 2 sec after activation, b) 30 sec after activation, c) 90 sec after activation, d) 150 sec after activation*

Figure 3.26 shows how the conditions in the vicinity of the EV fire had evolved during experiment 6. Initially hotspots were observed emerging from the EV and on the window railings on the adjacent cars on the left and right to the EV suggesting flame spread at that point. However, within 90 sec all the hotspots disappeared and within 150 sec the conditions inside the set-up (in terms of temperature) had changed to an environment with mild temperatures on the cars and the surroundings. This shows the larger coverage of water mists systems compared to the previously discussed firefighting systems. However, the battery temperature after 150 sec of water mist system activation is around 140 °C and further decreases with time.

The water mist system proved to be capable of handling the surrounding environment and reducing temperature at a rapid speed in a large area in less than 2 min after activation. However, depending on the design of the car (location of the battery), a similar effect on the battery cooling might not be achieved in all the cases. Nevertheless, if the water droplets reach the battery pack and with proper activation and layout, water mist systems appear to be capable of dealing with EV fires (i.e., containing the fire) successfully.

## 3.5 Additional Findings

### 3.5.1 Fire Characteristics

Over the series of experiments, a similar methodology was used to induce thermal runaway (TR) and the conditions were then allowed to develop without any intervention. However, the time taken to reach TR and the overall development of the fire was different for each experiment. During experiment 2, flaming combustion was not achieved whereas with the same methodology, much larger fires were induced in the other experiments. The unpredictable nature of EV fires was evident during the experiments.

Flame spread to adjacent vehicles is dependent on the fire development. Due to the unpredictable nature of an EV fire, the time taken for the flames to consume adjacent vehicles is also unpredictable. However, it was observed that the rubber railing of the windows was the first ignited item on an adjacent car when the car is next to the EV as shown in Figure 3.23.

### 3.5.2 Gas Measurements and Detection

The HF measurements recorded from the two detection systems showed that location of the detections system affects the alarm time. The firefighters also carried wearable gas detectors [6] with them which could also trigger an alarm when the concentrations of a gas species are higher than the threshold. However, during the experiments these devices did not trigger any alarm on the danger from the gas species even though both detection systems installed indicated high levels of HF in the vicinity of the EV.

The selective gas detectors from Consilium [1] could detect hydrocarbons, CO, and HF at the same time. The measured concentrations of HF, hydrocarbons (HC) and CO are shown in Figure 3.27.

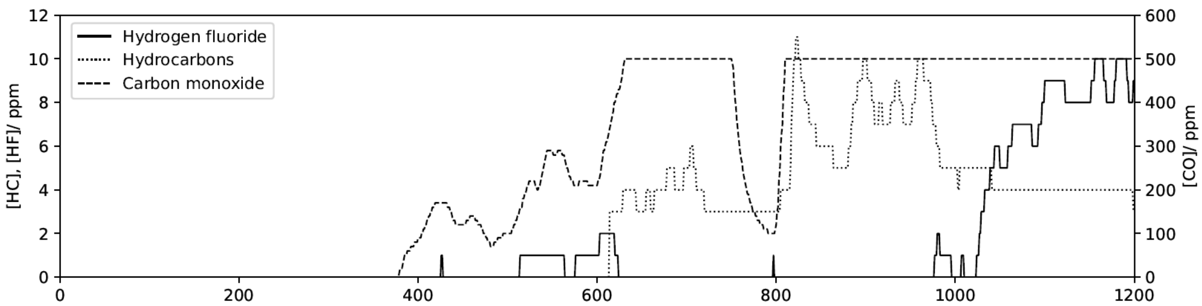


*Figure 3.27: Live measurements of HC, HF and CO concentrations from experiment 6*

During experiment 6, short circuiting did not lead to ignition of the battery pack. Therefore, a gasoline burner was placed under the battery pack to initiate ignition. When comparing the detected concentrations of each species, CO and unburnt HC was detected by the detectors 15 min – 10 min earlier than HF. The use of a pool fire could be a probable reason for this gap between the detection times among the species. HF is only emitted when the battery pack has reached TR whereas, unburnt HC and CO could be emitted via different burning items such as the passenger car seats and other plastic material present. However, the rapid increase of detected HF concentrations clearly suggests that EV fires could be detected via HF detection. It is not 100% clear from these experiments which method of detection could be the better option due to the use of the gasoline pool fire beneath the battery pack. It should be noted that the concentrations measured by these detectors are capped at 10 ppm (for HF and HC) and 500 ppm (for CO), therefore, the actual concentrations could be higher and beyond the limits of the device.

The earliest detection times of the smoke detectors from experiments 1, 2, and 3 are given below in Table 3.3. The arrangement of the optical smoke detectors is shown in Figure 3.5.

*Table 3.3: The earliest detection times recorded during the experiments*

| Experiment ID | Detection time (s)* | Detector ID [Figure 3.5] |
|---|---|---|
| 1 | 111 | SD 311 |
| 2 | 107 | SD 313 |
| 3 | 119 | SD 313 |

**Time measured after initiating short circuit*

The detection times are less than 2 min for all three experiments which shows that even with conventional optical smoke detection, low detection times could be achieved. However, due to the extra time requirements related with firefighters gearing up, the conditions could escalate towards extremes by the time the firefighters are ready to fight the fire.

### 3.5.3 Weather Effects

Wind effects were visible in the temperatures measured from the thermocouple trees. The smoke movement within the set-up was affected by the presence of wind. Recorded temperature from the thermocouple trees confirmed these effects. Higher temperatures were recorded on the downwind side of the set-up implying the hot smoke had been pushed in that direction.

The location of the first activated detector reflects the phenomenon described above and it was evident that the earlier detection times were recorded on the downwind side on the set-up. Similar observations were made during the CFD simulations detailed in section 0 (WP2: Technological Aspects – Fire Scenarios and Technologies).

### 3.5.4 Structural Response

Plate thermocouples attached to the structure on the inside surface showed varied temperatures on each experiment. The temperatures on the structure reached as high as 500°C during experiment 4. During the same experiment, the ceiling of the structure began to sag even with the protection of the insulation provided against the flames.

### 3.5.5 Use of Sea Water as Extinguishing Medium Sea vs Fresh Water

Sea water is the primary medium used in fixed firefighting systems onboard ships, given its plentiful availability and unlimited supply.

As noted earlier, toxic and flammable gases can be generated when using sea water as a firefighting medium. Electrolysis of salt water, caused by water impregnating a compromised LIB pack, can form hydrogen gas and chlorine gas. The rate of generation of these gases is found to be higher than when using fresh water.

From all the tests conducted during ELBAS, there is nothing to suggest that use of sea water makes the onboard firefighting work more dangerous as related to the risk for electrocution, despite the crew standing on a metal deck and using sea water for extinguishing.

## 3.6 Conclusions

Large-scale fires tests performed using a similar set-up with a similar methodology for triggering thermal runaway (TR) within the battery pack resulted in different fires. This showed the unpredictable nature of an EV fire and the wide range of the total spectrum of how the conditions might escalate during such a fire. These variations should be considered in designing safety systems for EV fires and when modelling EV fire scenarios.

Flame spread was one of the focus areas provided the tight stowage arrangements usually seen on vehicle decks on board ro-ro vessels. Flame spread among vehicles depends on parameters such as the flame length and radiation from the flames which can be unpredictable during an EV fire as mentioned earlier. Flame spread was also observed at different times into the fire ranging from a few minutes to flame spread not occurring 10 min after detection of the fire via the smoke detectors. The assumed 10 min of time taken for the shipboard firefighters to gear up and reach the fire becomes crucial as the shipboard firefighters might have to deal with a fire involving multiple vehicles by the time, they reach the fire.

Both direct and indirect cooling methods were tested within the experimental set-up. The usability of larger devices proved to be challenging due to the limited space around the stowed vehicles. The smoke layer descends to eye levels, which also poses additional challenges on locating the fire seat and maneuvering and handling the devices. These challenges were observed when hammering in the extinguishing lance into the battery pack and maneuvering larger devices.

Providing direct cooling on the battery pack was the most efficient way of cooling the battery pack down below TR with a lower water consumption. Providing cooling around the EV, contained the fire to the EV without flame spread to adjacent vehicles. However, the time of activation is key to ensure both methods achieve their goals. The water consumption was considerably lower for direct cooling methods compared to indirect methods. The amount of water used on a ro-ro ferry could be limited due to stability issues with the vessel. Therefore, the use of water efficient direct cooling on the battery pack and containing the fire with a non-water-based techniques (e.g., fire blankets) could limit the water consumption without reaching stability issues. Both direct and indirect cooling methods have their pros and cons but combining both methods proved to be a more efficient approach during the experiments.

Conventional smoke detectors installed on the ceiling were able to respond with alarms shortly after the smoke could was visible. Selective detection systems for HF also generated alarms but, based on the location of the detection system the times varied. The HF detectors placed inside the battery compartment gave the earliest detection as expected. But the aspiration system installed above the EV on the ceiling triggered after a longer time. Nevertheless, the readings from HF sensors showed the possibility of detection using selective HF detectors for an EV fire. Placement of smoke/ gas detectors should be done considering the ventilation and wind effects within the decks. Lower detection times can be achieved by proper placement of such detectors.

The ceiling of the experimental set-up (stainless steel) was protected with thermal insulation and during experiment 4, the ceiling was observed to be sagging some time into the fire which was then cooled down by the firefighters using water. The conditions just above the fire reached severe enough that, even with thermal insulation, the structure was affected during the fire. The uninsulated side walls of the set-up also reached up to 600 °C of temperature during experiment 4 but direct cooling via water cooled the walls down with quick time.

## 3.7 References


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