Horizon 2020

Project acronym:	**LASH FIRE**
Project full title:	**Legislative Assessment for Safety Hazard of Fire and Innovations in Ro-ro ship Environment**
Grant Agreement No:	**814975**
Coordinator:	**RISE Research Institutes of Sweden**

Deliverable D06.8

Development and testing of APV firefighting routines, equipment, and tactics.

June 2023

Dissemination level: **Public**

Abstract

Alternative powered vehicles (APV) pose for new challenges and risks in the maritime fire safety industry. Fixed firefighting systems remain the main tool also for these types of vehicles, but there may be cases where manual firefighting is motivated. Several visits to ro-ro ships were conducted to study current firefighting routines, equipment, and tactics for firefighting on board ro-ro vessels. It was concluded that there is still little information and previous experience about APV fires. Due to the daily intense work and limited experience with real vehicle fires on-board ro-ro vessels, firefighting routines, equipment, and tactics must be trained and prepared for. For this purpose, fire tests were conducted on electric vehicles on a land based firefighting centre. Three large scale tests were conducted:

1. Free burn test

2. First response and firefighting test

3. Manual firefighting indoor test

The main conclusion after testing is that the extinguishing techniques and equipment used were able to suppress or control the fire when applied according to the tactical recommendations. But when the fire is fully developed fully affecting the traction battery or the fuel tank, the fire will be very challenging to attack and control. So, the tactic to adopt in this case, will be defensive with the aim to avoid the escalation and propagation of the fire.

A manual firefighting operation is a risky situation that should only be performed under the following conditions:

- For life saving.
- If it is the only firefighting alternative when previous attempts were not successful.
- As backup in the spaces protected with fixed firefighting systems when the system has not been effective.
- As stable post-firefighting like cooling, inspection, or monitoring.

However, the fire development stage (early, growing phase, fully developed or decay), the natural ventilation for open, closed or weather deck, the accessibility, training, level of confidence, etc. will affect the probability of a real manual operation on board, with full PPE and deployment of fire equipment (hoses, cooling devices, foam or blankets).

As a rule of thumb, the probability for manual intervention can be as follows:

Probability of possible manual intervention

Fire development stage

Deck type	Early	Developing	Full car	Spread	Partial deck
Weather deck					
Open RoRo					
Closed RoRo					

High
Low

A thermal runaway is an undesired phenomenon that may happen when a Li-Ion battery has suffered either an electric abuse, a mechanical impact or has been directly exposed to fire/heat. It is a non-return exothermic reaction that could be very difficult to extinguish and efforts that limit the fire spread should be prioritized (if fire in the traction battery is confirmed). However, fires starting in the traction battery or gas tanks are currently very rare, and early suppression of small fires will further prevent that the fire spreads to the traction battery or trigger the pressure relief device on gas tanks.

The experience extracted after the fire testing with 3 EV is that it took some time before the traction battery is affected by the fire (around 11 min after ignition) and at that time the whole vehicle will be caught on fire (close to the peak of the heat release rate). Thermal runaway appearance as a sudden burst sound accompanied by a jet flame of short duration. Projections of gas dampers and some tires explosions were before the thermal runaway itself.

For gas-powered vehicles, burning gas or spillage of liquified gas creating jet flames should not be extinguished, to avoid creating a potential explosive atmosphere.

Several gear and equipment have been evaluated. Depending on the fire-situation suitable, and always considering the activation of the drencher as the first firefighting action to be taken, other alternatives have been identified. For instance, cooling nozzles that create a water shield and cool down the traction battery or the fuel tank is an innovative tool for a defensive tactic or post-fire situation. Other gear, equipment and tactics were also tested.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 814975

Document data

Document Title:	D06.8 – Development and testing of APV firefighting routines, equipment, and tactics.		
Work Package:	WP06 – Effective Manual Operations		
Related Task(s):	T06.12		
Dissemination level:	Public	Deliverable type: R	Report
Lead beneficiary:	15 – SAS		
Responsible author:	Jaime Bleye		
Co-authors:	Covadonga Suarez		
Date of delivery:	2023-08-21		
References:	D06.7		
Approved by	Martin Carlsson on 2023-08-14	Jonatan Gehandler on 2022-12-12	Maria Hjohlman on 2023-04-27

Involved partners

No.	Short name	Full name of Partner	Name and contact info of persons involved
15	SAS	Sociedad de Salvamento y Seguridad Marítima	Jaime Bleye, jaimebv@centrojovellanos.es Covadonga Suarez, covadongasa@centrojovellanos.es
17	MAG	Magellan-Associacao para a Representacao dos Intresses Portugueses no Exterior	Filipe Ribeiro, fbr@magellan-association.org
10	STL	Stena Rederi AB	Martin Carlsson, martin.carlsson@stena.com
8	BV	Bureau Veritas Marine & Offshore Registre International De Classification De Navires Et De Plateformes Offshore	Blandine Vicard – blandine.vicard@bureauveritas.com Eric de Carvalho – eric.de-carvalho@bureauveritas.com
1	RISE	RESEARCH INSTITUTES OFSWEDEN AB	Jonatan Gehandler, jonatan.gehandler@ri.se; Jonna Hynynen, jonna.hynynen@ri.se Maria Hjohlman, maria.hjolman@ri.se
3	FRN	RISE Fire Research AS	Davood Zeinali, davood.zeinali@risefr.no

Document history

Version	Date	Prepared by	Description
01	2022-12-07	SAS	Draft of structure
02	2022-12-11	SAS	First round of revisions after MhJ and JG comments
03	2023-01-02	SAS	Second round of revisions after MC´s comments
04	2023-02-24	SAS	Final version sent to reviewers
05	2023-03-23	SAS	Final version_2 after reviewers' comments
06	2023-04-24	SAS	Final version_3 after reviewers' comments
07	2023-06-19	SAS	Final version_4 after reviewers' comments
08	2023-08-17	SAS	Finalized version

Content

1 Executive summary 9

1.1 Problem definition....9

1.2 Method 9

1.3 Results and achievements 9

1.4 Contribution to LASH FIRE objectives 10

1.5 Exploitation and implementation....10

2 List of symbols and abbreviations....11

3 Introduction 12

4 Literature study on firefighting of APVs with consideration to ro-ro spaces 12

4.1 Alternatively powered vehicles (APV) 12

4.1.1 Gas-powered vehicles 13

4.1.2 Electric vehicles 15

4.2 Firefighting in ro-ro spaces 16

4.3 Manual firefighting of APVs 17

4.3.1 Electric vehicles 18

4.3.2 Gas-powered vehicles 19

3.3.2.2 Post treatment 19

4.4 General approach 19

5 Maritime regulation standpoint with regards to manual firefighting....21

5.1 Scope 21

5.2 Definitions 21

5.2.1 Ro-ro space, vehicle space and special category space 21

5.2.2 Closed, open and weather deck. 22

5.2.3 Fire-fighter’s outfit....22

5.2.4 Personal equipment....22

5.3 Requirements....23

5.3.1 General....23

5.3.2 Onboard organisation and crew training 23

5.3.3 Operational readiness and maintenance 23

5.3.4 Fire main....27

5.3.5 Portable fire-fighting equipment....27

5.3.6 Fire-fighter’s outfits and personal protection 27

6 Requirements definition for APV firefighting 28

6.1 Operational aspects....29

6.1.1 Fire stations and equipment 29
6.1.2 Fire teams 29
6.2 Conditions for activities 29
6.3 Presently available and potential manual equipment 30
6.4 APV aspects 31
6.5 Post mission treatment of crew and gear 32
6.6 Design and production aspects 32
6.7 Environmental aspects 32
6.8 EMSA guidance for transportation of AFV 34
7 Preparations for large scale testing of APV firefighting routines, equipment, and tactics 35
7.1 Identification of gaps of APV firefighting in the maritime industry 35
7.2 Risk Area Identification 36
7.3 Test Context 37
7.3.1 Venue of the trials 37
7.3.2 Dates 38
7.3.3 Schedule 38
7.3.4 Fire equipment selected for the large-scale testing 39
7.3.5 Resources 49
8 Testing of APV firefighting routines, equipment, and tactics 50
8.1 Free burn test 50
8.1.1 Aim of the test 50
8.1.2 Test set up 51
8.1.3 Development of the trial 51
8.1.4 Firefighting experience 55
8.1.5 Insights from temperature data 55
8.2 First response & Firefighting test 57
8.2.1 Aim of the test 57
8.2.2 Test set up 58
8.2.3 Development of the trial 59
8.2.4 Firefighting experience 61
8.2.5 Insights from temperature data 62
8.3 Manual firefighting indoor test 64
8.3.1 Aim of the test 64
8.3.2 Test set up 64
8.3.3 Development of the trial 65
8.3.4 Firefighting experience 66

8.3.5 Insights from temperature data 67
8.4 Boundary cooling nozzle test 68
9 Conclusion 71
10 References 76
11 Indexes 81
11.1 Index of tables 81
11.2 Index of figures 81
12 ANNEXES 83
12.1 ANNEX A. EV Safety instructions 83
12.2 ANNEX B. Results of the run-off water, analysed by lab (components written in Spanish) ..83

1 Executive summary

This report addresses the strategic objective of consolidating the routines, equipment and tactics for manual firefighting on board ensuring management of fires on ro-ro ships without recourse to external intervention.

The objective for this deliverable (LASH FIRE Action 6-D) is "to develop guidelines and a training module for firefighting of alternatively powered vehicles (APV) in ro-ro spaces based on the evaluation and full-scale demonstration of new equipment."

In this report, we describe the current standards for manual firefighting with specific emphasis on electric vehicles propelled with Li-ion batteries and the results of fire tests carried out during the Project.

1.1 Problem definition

Fires on board ro-ro vessels are very rare but may have catastrophic consequences. For that reason, fire prevention awareness is foremost important. According to STCW code, crewmembers (Masters, Officers and watch personnel) receive the minimum training standards in fire prevention and firefighting. Besides, fire drills are performed regularly on board. Although it is very difficult to create realistic drill scenarios and seafarers are not professional firefighters. New challenges on the maritime industry carrying APV may require updated equipment and efficient manual firefighting techniques to be tested.

1.2 Method

Earlier work in LASH FIRE is valuable information to this report, particularly from "Formal Safety Assessment" (WP04) and "Ship Integration" (WP05) working packages.

Several ship visits were conducted to analyze the current state of the art in firefighting routines, equipment, and tactics.

APV´s pose for different risks than traditional ICE and there is a huge interest in the maritime sector in finding results from testing about some interesting topics like thermal runaway, jet flames, high heat release rate or risks of reignition.

The tests were jointly organized by SASEMAR fire training Centre technicians, fire safety & risk researchers from RISE and the fire safety project manager of STENA TEKNIK at SASEMAR training facilities in Gijon (Spain) in March 2022. A group of diverse of technicians were involved in the testing from firefighting manufacturers, firefighters, marine crew, or marine institutions representatives.

The results of the tests carried out within the current Deliverable will feed D06.9 "Guidelines for firefighting gear, equipment and tactics, considering APVs"

LASH FIRE aims at ~~transferring competence~~ providing guidelines about how fires in APVs should be handled on board ro-ro spaces including evaluation of new equipment and tactics.

1.3 Results and achievements

This report aims to contribute to (the strategic objective of LASH FIRE): "provide a recognized technical basis for the revision of international IMO regulations, which greatly enhances fire prevention and ensures independent management of fires on ro-ro ships in current and future fire safety challenges." More specifically, the ~~achievement~~ final goal of this report is to develop guidelines and a training module for firefighting of APV in ro-ro spaces based on the evaluation and full-scale demonstration of new equipment.

Based on the results of test conducted, a table of recommendations highlighting pros and cons of equipment and tactics for APV firefighting has been developed. Overall conclusion after burning 3 EV with full traction battery charge (SOC) in the testing, is that APV fires represent some different risks but not more dramatic or challenging comparing to ICE.

Crew members need clear and to-the-point instructions about the use of specific APV firefighting tactics and equipment. To disseminate the results and conclusions, short movie clips showing the right use of firefighting equipment has been produced that will be distributed among shipping operators and their crew.

~~The work in the tasks that have supported this deliverable, aims to contribute to an efficient manual firefighting operation, increasing the awareness and ability to identify the risks associated with APVs.~~

1.4 Contribution to LASH FIRE objectives

This document will provide contribution to the following LASH FIRE Specific Objectives:

- Objective 1: LASH FIRE will strengthen the independent fire protection of ro-ro ships by developing and validating effective operative and design solutions addressing current and future challenges in all stages of a fire.
- Objective 4: LASH FIRE will propose new regulations and guidelines founded on common positions by drawing upon global research and experience and by facilitating international cooperation.

This report addresses the strategic objective of testing APV firefighting routines, equipment, and tactics with specific emphasis on electric vehicles propelled with Li-ion batteries.

1.5 Exploitation and implementation

The results of this deliverable, such as the ones achieved by Work Package 06 and the LASH FIRE Project as a whole, are intended to serve as recommendations for implementation by international ship operators, as well as regulatory and standardisation bodies.

This Deliverable is the product of the expertise, research and work conducted by the involved partners. It also helps inform further work in WP06, namely in D06.9, by setting the base for the definition of guidelines for manual firefighting.

Several short clip videos were recorded during the test with the aim to share the right procedures on APV firefighting routines, equipment, and tactics among the shipping industry. This is the LASHFIRE link to the video series:

The LASH FIRE project proudly presents the crew training videos series on Effective Manual AFV Firefighting! | lashfire.eu

~~The dissemination aims to kickstart a process of adoption by important players in the maritime industry, specifically in the ro-ro sector.~~ The dissemination aims to spread clear operative firefighting processes to the maritime industry, especially in the ro-ro sector.

2 List of symbols and abbreviations

APV	Alternative Powered Vehicles
BEV	Battery Electric Vehicle
BLEVE	Boiled Liquid Expanded Vapor Explosion
EV	Electric Vehicles
EEBD	Emergency Exit Breathing Device
FF	Firefighting
FSS	Fire Safety Systems Code
HF	Hydrogen Fluoride
HRR	Heat Release Rate
IACS	International Association of Classification Societies
ICEV	Internal Combustion Engine Vehicle
IMDG	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
IR	Infra-Red
Li-Ion	Lithium-ion
MIRG	Maritime Incident Response Group
MSC	Maritime Safety Committee
NFPA	National Fire Protection Association
LPG	Liquefied Petroleum Gas
OOW	Officer on the watch
PPE	Personal Protective Equipment
PRD	Pressure relief device
SCBA	Self Contained Breathing Apparatus
SOLAS	Safety Of Life At Sea
SOC	State Of Charge
SSF	RISE project Safe and Suitable Firefighting
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
TR	Thermal Runaway
UHF	Ultra High Frequency
VHF	Very High Frequency

3 Introduction

Alternative Powered Vehicles (APV) represent different types of hazards compared with vehicles with traditional fuel such as gasoline and diesel with internal combustion engines. Do our usual methods, equipment, and training work, or do we need to do something more to be safe?

Alternative Powered Vehicles (APV) are becoming a serious safety concern in the maritime industry due to the enormous growth of the APV fleets, their potential fire risks and a high uncertainty on the associated fire characteristics associated with many false and catastrophic myths.

In march 2022, WP05 and WP06 developed jointly a series of fire tests with 3 new EV that were surrounded by several scrap cars, simulating the accessibility problems that crew members might find on board the cargo space during a firefighting operation.

As a preparatory step for the planning of the fire tests, a literature study on firefighting of APVs with consideration to ro-ro spaces were conducted.

This report describes the literature study, the test set-up, equipment used and presents the results of the evaluation.

4 Literature study on firefighting of APVs with consideration to ro-ro spaces

Main author of the chapter: Jonatan Gehandler & Jonna Hynynen, RISE.

As stated in the LASH FIRE project proposal, RISE have undertaken various studies regarding new energy carriers for vehicles. Starting with experimental risk studies in 2014 that investigated tunnels and other underground spaces (Gehandler et al., 2017; Lönnermark & Ingason, 2014) and later in 2018 for ro-ro spaces with the BREND project (Vylund, Gehandler, et al., 2019; Vylund, Mindykowski, et al., 2019). In 2019 field experiments with CNG tanks exposed to local fire was performed (financed by Tunnel and Underground Safety Center (TUSC)) (Gehandler & Lönnermark, 2019) and in 2021 within BREND 2 (Gehandler et al., 2022; Temple & Anderson, 2022) field experiments with CNG and hydrogen tanks, exposed to both fire and water application that cooled the melt-fuse, were done. The BREND 2 project published guidelines for manual firefighting of APV fires in ro-ro spaces (Gehandler et al., 2022) In parallel much work at RISE has been done with regards to the potential risks of electric vehicles (EVs) and lithium-ion batteries, from literature reviews to testing in laboratory environment, some recent examples include work by: (Andersson et al., 2016; Bisschop et al., 2019, 2020, 2021; P. Sun et al., 2020; Temple & Anderson, 2022; Torbjörnsson, 2019; Willstrand et al., 2020).

4.1 Alternatively powered vehicles (APV)

For this report, APVs are divided into gas-powered vehicles and EVs. Here 'gas' refer to that the fuel is in gas phase at ambient temperature (i.e. not the American meaning were 'gas' is synonymous with the, at ambient temperature, liquid fuel petrol). The gas cylinder of a car is normally situated in the rear part of the vehicle either below or in the boot. Those of trucks are often placed in the same location as diesel tanks are traditionally placed, although they can also be found below the trailer or behind the cab. On buses, gas cylinders are often placed on the roof.

The traction battery in EVs is most often placed in the "safe zone" of passenger cars, which normally refers to the area in the centre of the chassis, between the wheelbase (Bisschop et al., 2019). For buses, a large variety of battery placements can be found and for trucks the batteries are commonly placed in the area where the diesel tanks are traditionally placed (Bisschop et al., 2019).

4.1.1 Gas-powered vehicles

Gaseous fuels are stored in three different ways; compressed, pressure-condensed or as a cooled-condensed, i.e. a cryogenic gas.

4.1.1.1 Compressed gases

Methane and hydrogen are two of the most common gases that most often are stored as compressed gas. Compressed gases (e.g., CNG and hydrogen gas) are often handled under high pressure; the maximum pressure used in pressure vessels varies between 200 and 700 bar. The high pressures used are necessary for the cylinder to hold enough fuel to provide a vehicle with a sufficient driving range for everyday usage.

The use of CNG is governed by the UNECE R.110 regulation. The UNECE R.134 and GTR13 regulations contain the requirements on hydrogen gas vehicles (including fuel cell vehicles) and their components. The high pressure in the gas tank may lead to a pressure vessel explosion if the cylinder rupture in the event of fire. For this purpose, the tanks are equipped with a thermally activated melt fuse that would release the gas. This melt fuse is called thermal pressure relief device (TPRD).

Theoretically, the energy released by a 130 L CNG cylinder, at a pressure of 200 bar, exploding (8.7 MJ) is equivalent to 1.85 kg of 2,4,6-trinitrotoluene (TNT) detonating. Such explosion would break windows in a 30 m radius (area in which the pressure would exceed 50 mbar) and within a 12 m radius it would be lethal (pressure exceeds 140 mbar) (Perrette & Wiedemann, 2014).

In BREND 1 (Vylund, Gehandler, et al., 2019), a CNG pressure vessel explosion in ro-ro space was simulated using Ansys Autodyne (simulations software). Results from these simulations indicated that the greatest consequences of a gas tank explosion in ro-ro spaces were obtained if a gas tank explodes near a corner or a wall. If the explosion would instead occur near an opening, for example in the stern, the risks would be reduced considerably. The pressure wave itself is lethal near the explosion centre and other hazards related to gas tank explosions are splinters and/or projectiles.

Sun and Li (K. Sun & Li, 2021) found that the main hazard from hydrogen fuel cell electric vehicles (powered by compressed hydrogen) to firefighters result from splinters and the hydrogen fireball heat radiation that follows from a pressure vessel explosion. As an example, a pressure vessel explosion of an 88 L cylinder filled to 318 bars, resulted in a fire ball with a maximum diameter of 24 m and tank fragments flying over forty meters.

4.1.1.2 Pressure-condensed gases

LPG and dimethyl ether (DME) are normally handled in pressure-condensed form. For pressure-condensed gases, the gas condenses when it is compressed, and is found in both liquid and gaseous phase in the cylinder. The pressure in the vessel varies with the ambient temperature but is approximately 5 bar at 20 °C, increasing rapidly with increasing temperature. LPG and DME are regulated by the UNECE R.067 regulation. LPG and DME can cause suffocation and will flow along the ground and accumulate in topographical low points.

If the cylinder would fracture above the liquid surface of the condensed gas, the leaking gas vapours would form a vapour cloud. However, this leak will decrease in intensity as the pressure in the container falls, as vaporisation requires heat transfer into the container. If the container is damaged in such a way that the fracture occurs below the surface of the liquid, cold liquid will flow out under pressure and, initially, instantly vaporise when it encounters the ground or other hot surfaces but will then gradually cool the ground towards the boiling point of the gas (25°C) and a liquid pool will develop.

During exposure to fire, the condensed gas is heated, increasing the vaporisation rate and thus the pressure inside the container, which leads to the pressure-relief device (PRD) opening. If the PRD does not manage to reduce the pressure increase, it can result in a rupture and a BLEVE can occur (NOTE: for a BLEVE to occur, LPG must be heated above 53 °C and DME above 127 °C at the time of cylinder rupture). A BLEVE results in a shock wave from the rapid conversion to gas phase and a large burning vapour cloud that exposes the surrounding area to a very high heat flux for a period of several seconds. These events can be very rapid, and in some cases a BLEVE has occurred in less than 5 minutes of fire exposure. In 2014, an LPG-powered vehicle in Germany, experiencing flashover and exploded. This event injured 10 firefighters, where 5 were injured seriously, who were attempting to extinguish the vehicle. The firefighters suffered, among other injuries, severe burns (MSB, 2016).

4.1.1.3 Cryogenic gases

Methane and hydrogen can be stored as a liquid (cryogenic) gas, whereby the gas is cooled so that the gas condenses into a liquid. Most common so far is LNG, which has a boiling point of -162ºC. In the future, liquid hydrogen LH2, may become widely used. LH2 has a very low boiling point at -253 °C. Cryogenic storage systems have significantly larger capacity than compressed gas storages since the gas is condensed, which greatly increase the driving range.

Cryogenic containers are well insulated (in a similar manner to a thermos) to minimize heat transfer into the container. The small amount of heat that is transferred into the vessel despite the insulation, causes a very small portion of the gas to vaporise. This vaporisation of gas will increase the pressure inside the container. If the pressure increase is not removed during normal use, some of the gas must be vented through the PRD to avoid the pressure becoming too high (vent-off gas). The release pressure for the PRD is often in the range of 5-15 bar.

If the container is damaged such that leakage occurs without fire, two possible situations can unfold:

1. Container is fractured above the liquid surface of the condensed gas.

This will result in that the leaking gas vapours will form a vapour cloud. However, this leak will decrease in intensity as the pressure in the container falls since vaporisation requires heat transfer into the container.

2. Container is fractured below the surface of the liquid.

This will result in that cold liquid will flow out under pressure. Initially the liquid will instantly vaporise when it encounters the ground or other surfaces (which are, relatively speaking, much hotter, due to the gas being stored at 162°C). Subsequently, particularly with larger quantities of gas, the liquid will cool the ground quite quickly, resulting in a liquid pool. This liquid pool will then vaporise more slowly to form a vapour cloud that may linger for longer time. A cryogenic gas leak can, due to its very low temperature, cause frost injuries and damage to people and objects.

During exposure to fire, the cooled gas inside the container is heated, increasing the vaporisation rate and thus the pressure inside the container; this in turn, leads to that the pressure-relief valve release. Under unfortunate circumstances, if the insulation is lost or damaged, heating can be too fast so that the pressure-relief valve has no time to respond to the increase in pressure and, consequently, lead to an explosion that may results in a BLEVE (NOTE: for a BLEVE to occur, LNG must be heated above -93

°C and LH_2 above -245 °C). This results in a large, burning vapour cloud that exposes the surrounding area to a very high heat flux for a period of several seconds.

Liquid fuel spills, also produce a vapour cloud, these vapour clouds are often 'washed away' using a water spray. However, the same approach cannot be used for emissions of condensed gas clouds, as the heat of the water will increase the vaporisation rate. In such scenario the water must be prevented from coming into contact with the liquefied gas pool. If possible, some form of tarpaulin or sheet should be used to cover the spillage, or a 'very dry' Compressed Air Foam System (CAFS) could be applied to decrease the vaporisation rate.

Condensed methane gas emissions spread along the ground, rapidly filling topographical low points. After a short time, the methane gas will begin to mix with the air and further disperse. Such vapour cloud is clearly visible, as the cold gas causes moisture in the air to condense and form mist. Regardless of whether the gas emitted is condensed or compressed, a combustible mixture of gas and air is rapidly formed. The vapour cloud could be ignited and burn as the flame front spreads and, if it is in an enclosed space when it is ignited, a vapour cloud explosion may occur. However, liquid spills of cryogenic gases onboard ro-ro ships are very unlikely since the vehicles will be parked and the condensed gas is sealed in the cryogenic tank. Smaller boil-off emissions of vent-off gas should not be an issue in large ro-ro spaces.

4.1.2 Electric vehicles

There are different types of vehicles that drive partially or fully on electric power. Depending on the definition, an electric vehicle can be hybrid, plug-in hybrid, fuel cell electric or battery electric (Bisschop et al., 2019). Focus of this report will be on the battery electric vehicle (BEV). This section of the report is largely based on RISE report 2019:50 Fire Safety of Lithium-Ion Batteries in Road Vehicles (Bisschop et al., 2019).

4.1.2.1 Lithium-ion batteries

Today's BEVs are powered by lithium-ion batteries (LIBs). LIBs have high cycle life, high energy density, and high efficiency which makes them suitable for automotive applications. To achieve sufficient driving ranges, these batteries need to be significant in size. For example, in a Tesla Model S 85, the battery makes up 30% of the total weight of the vehicle (Bisschop et al., 2019).

The battery pack in a vehicle is commonly placed in the floor i.e "safe-zone" of the vehicle, examples of configurations can be found in work by Bisschop et al.(Bisschop et al., 2019). The pack consist of several battery modules which hold the battery cells. In some systems, several battery packs are coupled to create a larger system. In doing so, applications such as passenger cars, heavy vehicles and electric ships can increase their capacities (Bisschop et al., 2019).

4.1.2.2 Battery cell configuration

The battery cell can come in a variety of formats (cylindrical, pouch and prismatic) and chemistries. Conventional configuration of the components used for LIB cells include a negative electrode, a positive electrode, an electrolyte, separators, and current collectors. Each component plays a role in the battery properties regarding energy density, battery lifetime, safety, and cost.

The material of the negative electrode (anode) is generally graphite or Li_2TiO_3 (LTO). The material of the positive electrode (cathode) is used to classify LIB in groups. For BEVs, $LiFePO_4$ (LFP) and $LiNi_xMn_yCo_zO_2$ (NMC) are the two most frequently used cathode materials. The stoichiometries, shown here as x-y-z, of metals can also vary. For example, $LiNi_xCo_yMn_zO_2$ come in a variety of compositions such as 1-1-1, 5-3-2, 8-1-1 etc. and will influence the properties of the cathode material and battery cell. Furthermore, cathode materials can also be blended to enhance their performance. Such materials are referred to as hybrid or blended cathode materials.

The electrolyte used are traditionally based on organic carbonate-based solvents, which are mixed with lithium salts, for example LiPF6. Even if the mass fraction of electrolyte is low (~ 10% of the cell mass), the electrolyte may correspond to a significant source of energy upon combustion of the battery cell (Ping et al., 2015). The electrolyte together with the separator material account for approximately 80% of the heat release in a LIB fire (Ping et al., 2015; Ribière et al., 2012).

The separator serves as a barrier between the cathode and anode which provide protection against internal short circuits. Separator material are often polymers based and uses polyethylene, polypropylene or composites of these. Additionally, during cycling of the cell the separator functions as an electrolyte reservoir enabling the transport of lithium-ions.

4.1.2.3 Battery failure

Battery failure, so called thermal runaway, can be caused by mechanical-, electric- or thermal abuse (Feng et al., 2018). The initiation of thermal runaway is often attributed to the failure of the separator material, causing an internal short circuit (Zhang et al., 2021). When the separator material is damaged, chemical reactions are initiated between the cathode, anode, and electrolyte. These reactions are exothermic chemical reaction meaning that they release energy, in form of heat. This results in an increase of battery cell temperature and consequently increased pressure inside the battery cell. This pressure increase may lead to cell rupture which will release a mixture of toxic and flammable gases which eventually can lead to a fire.

The different pack configurations, cell formats, cell chemistries, state of charge, cell capacity etc. will all affect the safety and the performance of the cell, which makes it hard to draw generalized conclusion regarding the safety and performance of LIBs.

4.1.2.4 Lithium-ion batteries and fire hazards

In BREND 1 (Vylund, Gehandler, et al., 2019), the identified hazards for LIBs found were that they are difficult to extinguish and that damaged batteries can re-ignite several hours, or even days after the damaging event, due to stranded energy in the battery cells.

Toxic and flammable gases produced from a battery, even though the vehicle is not on fire, was also identified as a hazard. However, the toxicity of the combustion products from a vehicle on fire were not judged to be significantly more severe if there is a battery involved than when it is not. Comparison of full-scale fire test and the released combustion gases from internal combustion engine vehicles and EVs can be found in work by example: (Lam et al., 2016; Sturk et al., 2015; Willstrand et al., 2020).

Furthermore, a traction battery fire can be difficult to extinguish. The battery is often difficult to access, and it can therefore be complicated to cool the battery cells. Recommended practise during and after a BEV fire can be found in chapter 4.

4.2 Firefighting in ro-ro spaces

Japan has, following severe fires on ro-ro ships, submitted a document to IMO working group SSE 5, concerning effective fire risk control measures (SSE 5-7). The following key issues for fire safety were identified:

- Early detection and alerting of the outbreak of a fire.
- Improvement of initial fire-extinguishing procedures with portable fire extinguishers.
- Effective execution of fire-extinguishing using hydrants.
- Smoke extraction

- High mobility of firefighters, i.e. crew; and
- Dedicated drills on ro-ro spaces or special category spaces simulating actual firefighting.

In comparison with traditional procedures Japan favour a manual intervention using smoke extraction to enable fire-fighters to move in a less smoky environment (unless a fixed firefighting system is used that quench the fire by oxygen depletion). Japan further highlights the importance of a firefighting strategy that includes (SSE 5-7):

- The assumption of the fire location
- Which actions should be taken and in which order
- Which equipment should be used by whom

In the projects BREND 1 and BREND 2, firefighting in ro-ro spaces was investigated. BREND is an acronym for the research project Fire in Alternative Fuel Vehicles in ro-ro spaces which was funded by the Swedish Transport Administration (Trafikverket) (Gehandler et al., 2022; Temple & Anderson, 2022; Vylund, Gehandler, et al., 2019; Vylund, Mindykowski, et al., 2019).

In BREND 1, a literature study was carried out and compiled research regarding hazards related to fires in APVs in ro-ro spaces. This work also included land based firefighting tactics related to APV fires. If the fuel storage on an APV is affected, land-based firefighters often use a defensive tactic. A defensive tactic means securing the area around the vehicle and preventing fire propagation from a distance. In BREND 1, this tactic was evaluated in the context of a ro-ro space. The use of water-based equipment, for example hose or water curtain, that could be used from a distance and to limit that the fire spread to adjacent vehicles, was investigated, both in field tests and in laboratory fire tests (Vylund, Mindykowski, et al., 2019).

Different ships and different spaces will entail different possibilities for fighting fires. For instance, a fixed firefighting system (FFFS), crew size and training will all play a role. In a RISE project called Safe and suitable firefighting (SSF) (Burgén et al., 2022), requirements for safe and suitable protective equipment were investigated. Conclusions advised the use of fire suits according to EN 469, Level 2 for manual firefighting.

A general fire response strategy was defined in BREND 2 (Gehandler et al., 2022) as follows:

1. First intervention by runner, without protective clothing.
2. Activation of FFFS alternatively manual operation for spaces without FFFS, for example on weather deck.
3. Check and assess the situation. The fire team is sent into the space to investigate the fire from a distance and if needed to do a manual intervention.
4. Post extinguishment. Fire team performs post-extinguishing at close range to the seat of fire.

The recommendations formed in the project is based on that vehicle fires regardless of the fuel can be fought in a similar way, in particular at the initial stage. The fuel storage of APVs is stored more safely than conventional fuels and thus are less susceptible to initiate fires and contribute to fires. Thus, initial firefighting by the runner or nearby crew, should be done with the available means, e.g. hose or hand-held fire extinguishers. An early effort could extinguish the fire or at least slow down the fire development and subsequent events that may occur with regards to APVs.

4.3 Manual firefighting of APVs

This section is divided into manual firefighting of electric vehicles and gas-powered vehicles.

4.3.1 Electric vehicles

4.3.1.1 During fire

The NFPA emergency field guide (National Transportation Safety Board, 2020) states that in the initial response, the electric vehicle should be immobilized by switching off the ignition and disabling the 12-volt battery. Care should be taken when approaching the vehicle. The NFPA emergency field guide also states that emergency responders should look out for damaged high-voltage cables (orange in colour), and that high-voltage cables should not be cut.

Additionally, whooshing/popping/bubbling sounds from the battery may indicate a thermal runaway process in the battery. However, fires seldomly start in the traction battery. To induce a thermal runaway in the battery would commonly require a prolonged fire scenario. A fast response to the initial fire is of great importance to limit the fire spreading to the battery.

As mentioned previously, if the battery is experiencing thermal runaway, large amounts of water would be needed to cool the energy storage and hinder thermal propagation between battery cells (Long et al., 2013). The battery pack is usually situated in or under the car, making it difficult to access the battery cells from the outside. The aim should therefore not be to extinguish the battery fire but to limit fire spreading between adjacent vehicles. If available, water curtains could be used to limit the fire spread (Gehandler et al., 2022; Vylund, Mindykowski, et al., 2019).

Long et al. studied the effect of water application on battery fires regarding electrical hazards. No electrical hazards were found when extinguishing electric vehicles with water (Long et al., 2013). The NFPA emergency field guide also states that the battery should not be penetrated i.e., using for example extinguishing spears (National Transportation Safety Board, 2020).

Rescue personnel should wear personal protective equipment (PPE) and breathing apparatus (BA) for all types of vehicle fires.

4.3.1.2 Post treatment

According to SAE J2990 the high-voltage system should be disabled (disconnected) after an incident if it has not already been disconnected. Disabling the high-voltage system does not remove the energy in the battery but it disconnects the high-voltage system from the source (the battery). There are three methods to disconnect the high-voltage system, (1) automatic shutdown; (2) switching ignition to off and (3) cut or disconnect battery cables to the 12-volt system.

SAE J2990 state that the manual disconnect (manual off switches) should not be the primary method for the first responders since it can be hard to locate and often requires special PPE to be done safely.

Additionally, SAE J2990 recommends two inspection stages (post incident vehicle inspection) after an electric vehicle have been involved in an incident, one at the incident scene and one at the storage site afterwards. Steps include visual inspection, use of thermal cameras, listening for noise from the battery as well as investigations of the mechanical integrity and potential leaks (National Transportation Safety Board, 2020).

If the traction battery has been involved in the fire, there is a risk of re-ignition due to stranded energy. The vehicle should therefore be monitored (visually or with the help of an infrared/thermal camera) and later, when back to shore, taken to a quarantine area. Instructions on towing procedure can be found in the emergency response guides/rescue sheet for the vehicle (SAE J2990 Hybrid and EV First and Second Responder Recommended Practice, ISO 17840 Road Vehicles—Information for First and Second Responders). Generally, the recommendation is to tow damaged electric vehicles on a flatbed to avoid generating energy from the turning wheels.

4.3.2 Gas-powered vehicles

4.3.2.1 During fire

In the event of fire exposure of gas cylinders, it is important to watch out for jet flames from PRDs or TPRDs. There is one reported event in Sweden of a firefighter that got hit by a jet flame, but without being injured or needing any medical treatment (Strömgren Mattias, 2019). This is supported by field tests where the radiation from jet flames have been measured. At a few meters distance the radiation is very low compared to other firefighting situations, e.g. radiation from the hot smoke gas layer inside a compartment.

The approach towards the vehicle that is on fire, should be performed preferably at the front corners of the vehicle at an ~ 45° angle, to limit the exposure of jet flames, as well as other vehicle related hazards from for example exploding airbags, dampers, tires, etc (K. Sun & Li, 2021)

One positive aspect with vehicle fires onboard ro-ro ships is that the vehicles are parked with the engine shut off, gear in parking mode and handbrake pulled. In normal traffic accident fires this is one of the first things that rescue personnel will have to do manually (K. Sun & Li, 2021). This means that the magnetic valve on the gas tanks is already shut limiting the gas-related hazards to the gas storage tanks.

Since jet-flames are short-lived and have a low incident heat radiation, they are better left un-extinguished. This also lowers the risk of accumulating gas vapor and the worse event of a vapour cloud explosion.

3.3.2.2 Post treatment

After a fire, gas containers made of composite may leak. However, if that is not the case, Tamura et al. (Tamura et al., 2018) has shown that composite cylinders regain strength when they have cooled down. Additionally, tests performed by RISE on three steel containers, support that this is the case also for steel containers. At the same time the pressure inside the cylinder is lowered when the gas cools down, which result in a margin of safety against a rupture. However, when the fire has been extinguished the gas cylinders should be left to cool down before the vehicle is approached.

4.4 General approach

To RISE knowledge, in the context of ro-ro fires, the available research support that vehicle fires should be extinguished, or at least controlled. The energy storage should be cooled to limit the risk of an escalating fire and possible flash fire, TR, jet fires or explosions. Onboard ro-ro ships, an escalating fire can have a catastrophic outcome for the ship and the persons onboard.

Most vehicle fires do not start in the energy storage, APVs and conventional vehicles can most often be fought by the same means. Hazards related to any vehicle fire are heat, smoke, and toxic gases. Additional hazards are related projectiles as a result of small explosions from for example dampers, tyres or airbags.

The risk of tank rupture needs to be considered. This is valid for conventional vehicles (risk of flash fire or pool fires), as well as for gas vehicles and particular for gas cylinders that have been exposed to direct flames for 10-20 min or more. If the fuel storage on an APV is affected, land-based firefighters often use a defensive tactic, which means that the area around the vehicle is secured, and that fire propagation is controlled from a distance.

Water is an effective extinguishing medium and is readily available in a great surplus on all ships. In BREND 1 different manual water-based systems were tested and it was shown that they in general are effective in blocking radiation and thus preventing fire spread (Vylund, Mindykowski, et al., 2019).

In 2017, The Swedish Civil Contingencies Agency (MSB) published guidelines to Swedish firefighters on how to deal with fires in modern vehicles (Myndigheten för samhällskydd och beredskap, 2017). These guidelines, in combination with the result form BREND 1 (Vylund, Gehandler, et al., 2019) and BREND 2 (Gehandler et al., 2022) result in the following general approach for fighting fires on-board of ro-ro vessels:

- After risk assessment, choose a suitable tactic, method and technology for rescue and extinguishment.
- Identify the fire development
    - where did it start?
    - Consider the risk of projectiles form exploding shock absorbers, gas springs / cylinders, or other pyrotechnical components.
    - Try to figure out what type of vehicle that is on fire.
        - For gas-powered vehicles consider possible jet flames.
        - Is the battery on fire (are there any jet flames beneath the EV?)
- Decision on protective measures:
    - Consider using a fan to blow away the fire gases and to create a better work environment.
    - Extinguish open flames (not jet flames) with suitable means such as powder or water.
    - Try to protect the energy storage by cooling it.
    - Limit fire spread.
    - Avoid using a collected water jet against burning magnesium alloys, especially magnesium rims.
- Post-extinguishment:
    - Disconnect 12/24 V battery, if not already done.
    - Consider possible re-ignition, in particular for EVs.
    - For smoke divers, remove protective clothing and take a shower. Breathing apparatuses should be removed as the last item. Contaminated clothing should be taken care of, e.g. according to the "Skellefteå Model" (Magnusson & Hultman, 2014).

5 Maritime regulation standpoint with regards to manual firefighting

Main author of the chapter: Blandine Vicard and Eric de Carvalho, BV

5.1 Scope

This section aims at giving an overview of the requirements applicable in ro-ro spaces regarding "effective and efficient manual firefighting". It is based on the currently applicable regulations. Therefore, some of the requirements detailed below may not be applicable on old ships.

IMO Documents	SOLAS Convention, as amended
	MSC.1/Circ.1615, Interim Guidelines for minimizing the incidence and consequences of fires in ro-ro spaces and special category spaces of new and existing ro-ro passenger ships
	MSC.1/Circ. 1432, as amended by IMO MSC.1/Circ.1516 "revised guidelines for the maintenance and inspection of fire protection systems and appliances"
	STCW convention, as amended
	FSS Code, as amended
IACS & Class Rules	IACS Blue book dated January 2019
	BV Rules for Steel Ships (NR467), as amended in July 2019
	DNVGL Rules for the Classification of Ships, January 2017
	LR Rules and Regulations for the Classification of Ships, July 2016
Flag Administration Rules	MMF (French Flag Administration) Division 221 "Passenger ships engaged in international voyages and cargo ships of more than 500 gross tonnage", 28/12/17 edition
	US Coast Guard Code of Federal Regulations (CFR) 46, 2019 online edition
	MCA (UK Flag Administration) Guidance on SOLAS Ch.II-2

Table 1. List of documents used for the review of regulations for manual firefighting.

5.2 Definitions

This section provides the definitions of key terms used in regulations relevant to manual firefighting.

5.2.1 Ro-ro space, vehicle space and special category space

As per SOLAS II-2/3 [1]:

- *"Vehicle spaces are cargo spaces intended for carriage of motor vehicles with fuel in their tanks for their own propulsion."*
- "Ro-ro spaces are spaces not normally subdivided in any way *and normally extending to either a substantial length or the entire length of the ship in which motor vehicles with fuel in their tanks for their own propulsion and/or goods (packaged or in bulk, in or on rail or road cars, vehicles (including road or rail tankers), trailers, containers, pallets, demountable tanks or in or*

on similar stowage units or other receptacles) can be loaded and unloaded normally in a horizontal direction."[1]

- "Special category spaces are those enclosed vehicle spaces above and below *the bulkhead deck, into and from which vehicles can be driven and to which passengers have access. Special category spaces may be accommodated on more than one deck provided that the total overall clear height for vehicles does not exceed 10 m."*

Special category spaces are ro-ro spaces to which passengers have access, possibly during the voyage. Special category spaces are the most frequent type of closed ro-ro spaces on ro-ro passenger ships.

It is to be noted that open ro-ro spaces are not considered as special category spaces.

5.2.2 Closed, open and weather deck.

As per SOLAS II-2/3 [1]:

- A "*weather deck is a deck which is completely exposed to the weather from above and from at least two sides.*"

IACS UI SC 86 [3] additionally details that: "For the purposes of Reg. II-2/19 a ro-ro space fully open above and with full openings in both ends may be treated as a weather deck."

For practical purposes, drencher fire-extinguishing system cannot be fitted on weather decks due to the absence of deckhead. This criterion is often used for a practical definition of weather decks.

- An open vehicle or ro-ro space is "*either open at both ends or [has] an opening at one end and [is] provided with adequate natural ventilation effective over [its] entire length through permanent openings distributed in the side plating or deckhead or from above, having a total area of at least 10% of the total area of the space sides.*"
- A closed vehicle or ro-ro space is any vehicle or ro-ro space which is neither open nor a weather deck.

As a reference criterion, it can be considered that a vehicle space that needs mechanical ventilation is a closed vehicle space.

5.2.3 Fire-fighter's outfit

As per FSS Code Ch 3, a fire fighter's outfit consists of a set of personal equipment and a self-contained air-breathing apparatus. As a note, a 30 m lifeline is also required with each air breathing apparatus [FSS Code Ch 3 §2.1.3].

5.2.4 Personal equipment

A set of personal equipment means [FSS Code Ch 3 §2.1.1]:

- Water-resistant and heat-protective clothing;
- Non-conducting (rubber) boots;
- Rigid helmet;
- Electric safety lamp with 3 hours autonomy; and

[1] In other words, ro-ro spaces are vehicle spaces into which vehicles can be driven. It is to be noted however that, for the purpose of the application of SOLAS II-2/19 [1], the following interpretation can be found in MSC.1/Circ.1120 [2] and IACS UI SC 85 [3]: "Ro-ro spaces include special category spaces and vehicle spaces".

- Axe (handle with high-voltage insulation).

5.3 Requirements

5.3.1 General

International regulations effectively foresee manual fire-fighting insofar as they give provisions for:

- Drills and procedures;
- Manual fire-fighting equipment;
- Fire-fighter personal protection equipment; and
- Keeping the relevant equipment in working order.

5.3.2 Onboard organisation and crew training

SOLAS includes general requirements requiring that emergency situations including fire scenarios are foreseen so as to ensure efficient manual fire-fighting: crew members are to be trained to react to fire situations, assigned with a relevant duty in case of a fire and be well aware of that duty. Associated drills and training are to be carried out regularly and all relevant manuals for the use of the fire-fighting or emergency response equipment are to be available on board. In addition, regular fire drills are required on passenger ships [SOLAS II-2/15].

In addition to SOLAS [1], STCW Convention specifies that all crew members shall receive appropriate approved basic training or instruction in fire prevention and fire-fighting. Table A-VI/1-2 provides the specification of minimum standard of competence in fire prevention and fire-fighting, i.e. competence, knowledge, understanding and proficiency, methods for demonstrating competence, and criteria for evaluating competence [STCW VI/A-VI/1 Table A-VI/1-2].

For crew members designated to control fire-fighting operations, they shall have successfully completed advanced training in techniques for fighting fire, in accordance with the STCW Code. In particular, Ch VI Section A-VI/3 and Table A-VI/3 provide the mandatory minimum standard of competence in advanced firefighting [STCW VI/A-VI/3 and Table A-VI/3].

5.3.3 Operational readiness and maintenance

SOLAS [1] includes general requirements stating that:

- All fire safety systems are to be kept in proper working order. Especially portable fire-extinguishers are to be immediately replaced when they have been discharged [SOLAS II-2/14.2.1.2].
- Fire-fighting systems and appliances, including fire-fighter's outfits and portable fire extinguishers, are to be regularly maintained and inspected [SOLAS II-2/14.2.2].

IMO recommends the maintenance and inspection plan shown in Table below for manual fire-fighting equipment, to be completed by inspection and maintenance according to each manufacturer's instructions. These inspections are to be carried out by the crew on a regular basis [IMO MSC.1/Circ.1432, as amended by IMO MSC.1/Circ.1516].

As a complement, Class Societies carry out third part surveys on a yearly, 3-yearly and 5-yearly basis.

Table 2. Minimum inspection and maintenance plan for manual fire-fighting equipment according to IMO MSC.1/Circ.1432

Equipment	Inspection and maintenance period					
	One Week	One Month	Three Months	One Year	Five Years	Ten Years
Breathing apparatus	Examine all breathing apparatus and EEBD (Emergency Escape Breathing Device) cylinder gauges to confirm they are in the correct pressure range.			- Check breathing apparatus air recharging systems, if fitted, for air quality; - Check all breathing apparatus face masks and air demand valves are in serviceable condition; and - Check EEBDs according to maker's instructions.	Perform hydrostatic testing of all steel self-contained breathing apparatus cylinders. Aluminium and composite cylinders should be tested to the satisfaction of the Administration.	
Fire main, fire pumps, hydrants, hoses and nozzles		- Verify all fire hydrants, hose and nozzles are in place, properly arranged, and are in serviceable condition; - Operate all fire pumps to confirm that they continue to supply adequate pressure; and - Emergency fire pump fuel supply adequate, and heating system in satisfactory condition, if applicable.	Verify international shore connection(s) is in serviceable condition.	- Visually inspect all accessible components for proper condition; - Flow test all fire pumps for proper pressure and capacity. Test emergency fire pump with isolation valves closed; - Test all hydrant valves for proper operation; - Pressure test a sample of fire hoses at the maximum fire main pressure, so that all fire hoses are tested within five years; - Verify all fire pump relief valves, if provided, are properly set; - Examine all filters/strainers to verify they are free of debris and contamination; and - Nozzle size/type correct, maintained and working.		
Firefighter's outfits		Verify lockers providing storage for fire-fighting equipment contain their full inventory and equipment is in serviceable condition.				

Equipment	Inspection and maintenance period					
	One Week	One Month	Three Months	One Year	Five Years	Ten Years
Portable foam applicators		Verify all portable foam applicators are in place, properly arranged, and are in proper condition.		- Verify all portable foam applicators are set to the correct proportioning ratio for the foam concentrate supplied and the equipment is in proper order; - Verify all portable containers or portable tanks containing foam concentrate remain factory sealed, and the manufacturer's recommended service life interval has not been exceeded; - Portable containers or portable tanks containing foam concentrate, excluding protein based concentrates, less than 10 years old, that remain factory sealed can normally be accepted without the periodical foam control tests required in MSC.1/Circ.1312 [7] being carried out; - Protein based foam concentrate portable containers and portable tanks should be thoroughly checked and, if more than five years old, the foam concentrate should be subjected to the periodical foam control tests required in MSC.1/Circ.1312 [7], or renewed; and - The foam concentrates of any non-sealed portable containers and portable tanks, and portable containers and portable tanks where production data is not documented, should be subjected to the periodical foam control tests required in MSC.1/Circ.1312 [7].		

Equipment	Inspection and maintenance period					
	One Week	One Month	Three Months	One Year	Five Years	Ten Years
Wheeled (mobile) fire extinguishers		Verify all extinguishers are in place, properly arranged, and are in proper condition.		- Perform periodical inspections in accordance with the manufacturer's instructions; - Visually inspect all accessible components for proper condition; - Check the hydrostatic test date of each cylinder; and - For dry powder extinguishers, invert extinguisher to ensure powder is agitated.	Visually examine at least one extinguisher of each type manufactured in the same year and kept on board.	All extinguishers together with propellant cartridges should be hydrostatically tested by specially trained persons in accordance with recognized standards or the manufacturer's instructions.

5.3.4 Fire main

The first resource for manual fire-fighting is the fire main, providing ready water supply throughout the whole ship with hydrants regularly distributed. Very extensive requirements for the fire main can be found in SOLAS:

- Materials – in order to avoid failures in case of fire [SOLAS II-2/10.2.1.1].
- Sizing of the pumps and piping in order to ensure effective availability of water at a required pressure at each hydrant [SOLAS II-2/10.2.1.2, 10.2.1.3 and 10.2.1.6].
- Number and position of hydrants in order to ensure that any point in the ship can be reached by two fire hoses emanating from two different hydrants [SOLAS II-2/10.2.1.5].
- Number and capacity of fire pumps together with location/segregation requirements in order to ensure minimum redundancy. This is associated with specific requirements to be able to isolate the section of the fire main located in the engine room in case of fire there, and switch on another fire pump [SOLAS II-2/10.2.2, FSS Code Ch 12].
- Requirement for an international shore connection so as to allow external water supply (from the shore or from fire-fighting ships) [SOLAS II-2/10.2.1.7].
- Technical specifications for fire hoses and nozzles [SOLAS II-2/10.2.3].

5.3.5 Portable fire-fighting equipment

A number of portable equipment are required on board in order to allow manual fire-fighting in a vehicle or ro-ro space:

- Portable fire extinguishers are to be stored every 20 m within any vehicle or ro-ro open or closed space and at each access to the space [SOLAS II-2/20.6.2.1].
- 3 water-fog applicators are required in each ro-ro or vehicle open or closed space [SOLAS II-2/20.6.2.1].
- 1 portable foam applicator per ro-ro or vehicle open or closed space is also required, with at least 2 applicators to be available on board [SOLAS II-2/20.6.2.2].

FSS Code provides more details about type approval and engineering specifications of fire extinguishers and portable foam applicators [FSS Code Ch 4].

5.3.6 Fire-fighter’s outfits and personal protection

Fire-fighter’s outfits are required on board any ship, regardless of whether they carry vehicles. The basic principle is to have [SOLAS II-2/10.2.1 and 10.2.2]:

- 2 fire-fighter’s outfits – since fire-fighting teams are expected to include at least two fire-fighters;
- On passenger ships, additional fire-fighter’s outfits, the required number of which depends on the length of the ship occupied by passenger and service spaces. For practical purposes, on standard passenger ships, the required number of additional fire-fighter’s outfit can be approximated as 2 x L /80, L being the length of the ship in meters. Each of these additional fire-fighter’s outfits is to be complemented by an additional set of personal equipment and
- In addition, on passenger ships carrying more than 36 passengers, 2 fire-fighter’s outfits per main vertical zone.

The FSS Code provides more details about type approval and the pieces of personal protective equipment included in fire-fighter’s outfits [FSS Code Ch 3].

It can be noted that:

- Two two-way portable radiotelephone apparatus for each fire party are required (the number of fire parties is not imposed by the regulations; it is up to the ship operator to define it) [SOLAS II-2/10.4]; and
- A lifeline is required together with each air-breathing apparatus [FSS Code Ch 3 §2.1.3].

In general, attention is paid to avoiding creating sparks with fire-fighter's equipment: radiotelephones, as well as safety lamps intended to be used in hazardous areas, are required to be explosion proof or intrinsically safe [SOLAS II62/10.4 & FSS Code Ch 3 §2.1.1].

In general fire-fighter's outfits are to be stored in clearly marked and readily accessible lockers. When there are more than 2 fire-fighter's outfits onboard, they are required to be stored in widely separated locations. In passenger ships, it is made clear that fire-fighter's outfits are to be stored at least by pairs – considering that any fire party will include at least two fire-fighter's that will have to get ready at the same time [SOLAS II-2/10.3].

One key element for fire-fighter's protection and autonomy is the air breathing apparatus. Standard air breathing apparatuses are required to contain 1200 L of compressed air, associated with 30 minutes functioning [FSS Code Ch 3 §2.1.2].

In addition, spare charges are required onboard for each air breathing apparatus, with a view to extend the available intervention duration:

- On cargo ships and passenger ships carrying not more than 36 passengers: 2 spare charges per breathing apparatus or 1 spare charge per breathing apparatus and a means for recharging the air cylinders; and
- On passenger ships carrying more than 36 passengers: 2 spare charges per breathing apparatus and a means for recharging the air cylinders (compressor or self-contained high pressure air storage).

6 Requirements definition for APV firefighting

Main author of the chapter: Martin Carlsson, STL.

Primary ~~requirement~~ reason for a manual firefighting activity in a high-risk location is to save lives, either directly on the scene or indirectly via critical activities that prevents or delays fire spread, thereby safeguarding the ship and its crew and passengers.

This may be the influence by the culture of the vessel, their level of confidence and awareness, training and many other aspects.

It is also important to consider that crew members are not professional firefighters and real on-board fires are fortunately vary rare and most of seafarers will never face a real fire in their career.

In such context the performance and proper use of fixed fire suppression system is of extreme importance, minimizing the crew exposure for demanding situations, but focusing to lifesaving only or status checks.

For reasons mentioned above it is essential to create rich and educative drill scenarios, since this is such significant part of the maintenance and development of firefighting skills of the crew. It is of high importance to perform training sessions in a fully parked car deck, as often as possible. There are certain fire conditions that cannot be reproduced on board, so in order to achieve a more realistic fire scenario, they must be conducted at a shore-based training facility.

6.1 Operational aspects

6.1.1 Fire stations and equipment

Normally two main fire stations and few further spare stations are arranged on a vessel. Common location for Fire Station 1 is outside, on a high-level weather deck, and for Fire Station 2 in the vicinity of the engine control room.

Spare fire stations may be located in any suitable location in the vessel.

Communication within the fire team is secured using UHF band radio, one channels per internal fire team. Communication with the bridge team is maintained by Fire Fighting team leader on UHF, but on a dedicated channel. This means that the Fire Fighting team leader needs physically two radio units active at all times. Present challenges with communication are radio coverage and function.

Protective clothing and equipment are essential for the safety and confidence of the crew. Reference is made to Safe and Suitable firefighting-project (Burgén et al., 2022) that establish a marine specification for fire suits, and to MSB report on performance of fire suit to HF gases (Wingfors et al., 2021).

6.1.2 Fire teams

Normally one or two fire teams are organised onboard. If two teams are organised, most commonly one team is based on deck crew, whom will be first out on a cargo space or accommodation fire, while the other team is based on engine crew, whom will be first out on engine room and machinery spaces fire. If only one team is organised, it is based on a mix of crew. There are also other crew members identified as reserve if additional resources are need.

Time from activation to ready for action on site will vary between night and daytime but may be 10 minutes and 15 minutes respectively.

What can be expected from a fire team is related to many things, as will be described in the following sections. One part is the physical capacity of its members depending on age, gender, and physical fitness. In shore-based fire brigades physical exercise is high on daily agenda and part of the work, which is not so much the case on a vessel, even if some incentives may be in place to encourage personal fitness.

Sometimes, specially trained shore-based fire-fighting teams (MIRG teams) are provided for support to vessels, either on arrival to port or embarked to the vessel still under way. Such system could be of great importance to relief the crew in extensive fire scenarios.

6.2 Conditions for activities

Primary purpose with any manual activity in a high-risk location is to save lives, either directly on the scene or indirectly via critical activities that prevents, or delays fire spread, thereby safeguarding the ship and its crew and passengers.

The way people and teams act is very dependent on the influence of culture. This may be the influence of the culture of the vessel, between officers and crew or between peers, it may be of the culture of the company or of a country of origin, as well as relation to other present cultures onboard. It should be made very clear what is expected from everyone, and also validated through drills and daily work that expectations will be met.

Important factor to consider is also the difference between an onboard fire group and a land based professional fire brigade. Onboard team rarely, if ever, encounter a real fire, while fire brigades' ashore handle fires frequently. This must be taken into consideration when discussing capabilities, methods and expectations. Ship fire teams skills are built by training and drills only and occasionally on real situations.

In such context the performance and proper use of fixed fire suppression system is of extreme importance, minimizing the crew exposure for demanding situations, but focusing to, more or less, lifesaving only or status checks.

For reasons mentioned above it is essential to create rich and educative drill scenarios, since this is such significant part of the maintenance and development of firefighting skills of the crew. It is of high importance to perform training sessions in a fully loaded environment, as often as possible.

For many reasons drencher system should be activated in an early stage of a fire. This means that a manual firefighting operation can be performed with the drencher system activated. Fire team must be coordinated with OOW or Captain to stop or activate the drencher depending on fire situation and development.. Depending on the situation, either the drencher is shut off or it is kept flooding, with the crew being soaked by potentially freezing cold sea water as a result. In the latter case, such situation reduces the ability of the crew. On the other hand, drencher system will continue to suppress the fire and wash out the smoke and gases. The risk with stopping drencher must be balanced with the value of manual intervention.

For Vehicle Carriers the fixed fire-fighting system, normally CO2-low pressure system, is activated after other means of extinguishment has been considered and attempted. No manual firefighting can continue or start after the CO2-system has been activated. The cargo space must be evacuated and all openings to be closed and remain closed.

Cargo stowage, especially at fully loaded conditions, is in many cases a challenge. Distance between units may be very small (as short as 15 cm) and also the cargo may move, due to vehicle suspension system flexibility, which may lead to injuries of the crew or getting stuck. The stowage situation will influence both the safe movement of crew, especially with fire-fighting gear, and handling of fire-fighting equipment as well as unobstructed pressurizing of hoses.

In Vehicle Carriers the stowage is done with minimal distance in between the vehicles so that it is practically impossible for a fire team to access a fire within a “block” which could consist of hundreds of vehicles. All cargo is secured at sea by web lashings or chain lashings which makes access even more difficult.

Access to the fire origin is also hindered where shielded under tarpaulin covers, inside rigid cargo units or inside cabins of vehicles. Such conditions may hinder accurate observations and decisions.

Further, fire origin may be located in a high or low position, making the observations and access challenging.

6.3 Presently available and potential manual equipment

Presently available and potential manual equipment is listed and described as follows:

- **Firemans IR camera** (harsh condition and heat resistant) is handy for detailed investigation related to overheating and temperature trends. Remote observations possible.
- **Gas detector** is in some cases stipulated for vehicle carriers to be available onboard and may be brought to the scene in order to better understand the situation or to check if the atmosphere is safe.
- **Fire extinguisher** of different types

- **Fire blankets** may be an option in certain cases, however there are challenges and limitations. To apply a fire blanket properly on a car fire, the fire team need to act in close proximity to the fire. Also, the fire blanket need to be placed accurately to reach the maximum expected performance.
- **Passive water-cooling device** (boundary or direct)
- **Water mist nozzle** suitable for ingress and water mist application of closed spaces such as truck cabins, cargo containers, covered trailers, without opening up for oxygen supply.
- **Classic hose with water**, to be used for classic cooling at a distance
- **Foam equipment** for liquid fires

6.4 APV aspects

Ro-ro vessel crews are familiar to the risks, early signs and countermeasures related to the liquid flammable fuel vehicles. At present, similar skills need to be established for new types of drive lines i.e. APVs.

At present operations of Ro-Ro and Ropax it is not always possible to know what type of driveline to expect in a certain vehicle. Depending on the set of actions we see coming per type of driveline, this may or may not be needed in future. On Vehicle carriers in the transportation of factory new cars, or checked pre-owned cars, there are other possibilities to label APV's and also to include typical APV-information on the cargo loading plan, depending however on the operator's standards and routines.

Ventilation management is important in order to safeguard crew members actively in a cargo space. The crew must be familiar to the ventilation system in order to achieve the desired safe airflow which should be practiced during the drills. The best situation would be if a fire scenario-based ventilation modes are predefined, activated by a single command.

All modern vehicle fires exhibit high hazardous gas emissions, where Li-Ion batteries contributes in particular to HF. Due to the challenges to succeed with final extinguishment of a battery fire smoke/gas emission must be anticipated during an extended time period compared to a case where a fossil fuelled car fire is extinguished before all fire energy is released.

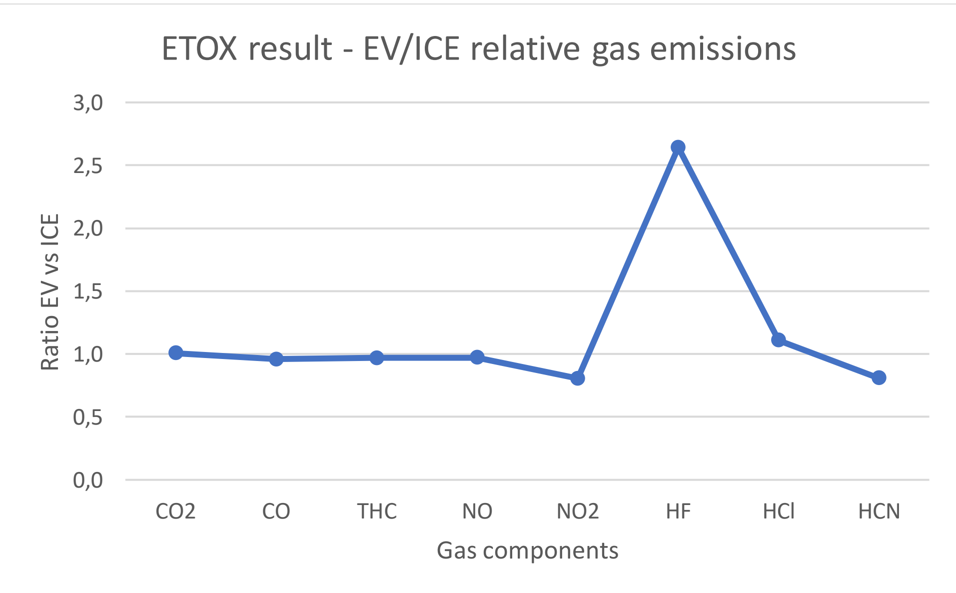


Figure 1. Comparison of amounts of released gas components from fully burned cars of EV and ICE type. Extracted from (Willstrand et al., 2020).

Fire team skin and breathing protection with proper use of breathing apparatus and fire suit with hand and foot gear is hereby essential. Recent studies have proven that proper use of adequate equipment protects well.

Due to the hazardous gases and risk of exposure of the crew to severe situations, the use of portable devices for cooling and boundary cooling, may be suitable. Such devices should be possible to put in place by manual action, within as large as possible safety distance from the hazard.

Different safety precautions may be needed when approaching gas vehicles, electric vehicles or fossil fuel vehicles due to the variation in ignition, fire growth and fire spread characteristics. However, to reduce the complexity for crew, the objective should be to establish one single methodology valid for all types of vehicles.

Compressed gas vehicles (CGV) pose a certain risk if the gas tank is heated which could lead to a jet-flame or in worst case an explosion if the safety valve fails or if the valve is cooled down unintentionally. If there is a fire near a gas tank a safe distance must be established which probably means that the cargo space must be evacuated.

Special methods may be required for discharging of damaged APVs ashore, which should be known to the crew and shore-based functions. Such methods should be mentioned in the Emergency Card.

At present, the number of transported APVs is low, but steadily growing and, in the near future, may make the majority of the vehicles onboard. This fact shall be considered during the development of firefighting methods.

6.5 Post mission treatment of crew and gear

Post mission treatment of the crew, gear and PPE need to be established. The first step is the treatment of smoke diving teams at exit from the space of a fire event. The objective of the treatment is to relief the crew from exposure and isolate potentially contaminated equipment without further exposure to the support team and contamination of adjacent spaces. The following step is to ensure that the exposed smoke divers exit the hazardous area and are subject to an adequate treatment such as shower, fresh drinking water and fresh air.

Inspiration can be found from chemical incident operations.

6.6 Design and production aspects

Size and layout of fire stations need to allow for efficient mustering and gearing of crew as well as safe demobilization. This should include treatment of the team members and equipment from exposure of hazardous substances. Such post mission treatment locations must also be organized in immediate vicinity of the scene of event, in order to avoid contamination of clean spaces.

Predefined/programmed cargo-space ventilation operation modes that, depending on the site of a fire, gives best conditions for approach, may be established.

Main and alternative access points and paths to site of fire should be predefined to speed up the decision-making process in a fire event.

6.7 Environmental aspects

Fires in vehicles will emit smoke and toxic gases that could pose immediate threat to human or other life or could spread to and accumulate on surfaces with risk of subsequent secondary exposure.

Extinguishing water from EVs will include toxic component that may be harmful for the environment. This will be investigated in E-TOX2 where toxic substances in extinguishing water from conventional cars, electric vehicles and standalone batteries will be quantified as well as its environmental impact Also the effect of drencher water gas wash-out will be investigated.

6.8 EMSA guidance for transportation of AFV

Proposals for developments and restrictions are listed by EMSA AFV Guideline in Table 3 below.

Parameter	**General car**	**ICE**	**HEV**	**EV**	**LNG**	**LPG**	**CNG**	**Hydrogen**
Energy carrier	Plastic material, rubber,textile etc	Petrol, Diesel	NiCd battery & Petrol	Li-Ion battery	Liquified CH_4	Liquified Butane & Propane	Compressed CH_4	Liquified H_2
Tank pressure	N/A	Ambient	N/A	N/A	12 bar	12 bar	200 bar	200 bar
Gas form density relative air	N/A	N/A	N/A	Heavier	Lighter	Heavier	Lighter	Lighter
Odour/visibility	N/A	Liquid	Liquid	??/White	No/No			
Toxicity (pre-fire)	N/A	N/A	N/A	Yes	Asphyxiant		Asphyxiant	Asphyxiant
Stowage advice	N/A	N/A	N/A		Preferably open decks	Preferably open decks	Preferrably open decks, avoid corners	Preferrably open decks, avoid corners
Pre-ignition signs of malfunction	Smoke, heat	Fuel leak	Fuel leak	Heavy smoke & heat 50-80 deg from battery. Popping sounds from battery cells	Noise from pressure release valve. Smell of venting gases.	Noise from pressure release valve. Smell of venting gases.	Noise from pressure release valve. Smell of venting gases.	Noise from pressure release valve.
Ignition	Electric heat/ spark	Electric heat/ spark	Electric heat/ spark	Battery heat, external heat/spark	External heat/spark	External heat/spark	External heat/spark	External heat/spark
Fire characteristics	Plastic, Carbon fibre Al/Mg-alloys, misc Violent fire	Pool fire	Pool fire	Unpredictable leaks due to bursting cells. Explosion if delayed ignition.	Jet fire from boil off valve. BLEVE Fire ball Explosion if delayed ignition	Jet fire from boil off valve. BLEVE Fire ball Explosion if delayed ignition	Jet fire from PRV Explosion if delayed ignition Explosion of tank if heated and no pressure release	Jet fire from PRV Explosion if delayed ignition Explosion of tank if heated and no pressure release
Modes of fire spread	Heat	Fuel pool	Fuel pool	Short lived jet flames 1-5 m Scatter of hot objects, mainly for cylindrical cells	Jet flame 1-3 m Tank explosion	Jet flame 1-3 m Tank explosion	Jet flame 10 -25 m Tank explosion	Jet flame 10 -25 m Tank explosion
Main hazards	Haz gases Exploding tyres, airbags, gas springs	Fuel pool	Fuel pool	Thermal run-away gas release, explosion/ignition risk. Unpredictable battery contribution 50% extra HF gas from fire compared to	Gas boil off Tank explosion	Gas boil off Tank explosion	Extensive jet flame Tank explosion	Extensive jet flame Tank explosion
Suppression	Water/Powder/ Foam	Water/Foam	Water/Foam	Water, under vehicle	Water on tank	Water on tank	Water on tank	Water on tank
Containment	Drencher Hose	Drencher/Foam	Drencher/Foam	Drencher/extra water	Drencher	Drencher	Drencher	Drencher
Post fire	Cool until temp is low	Cool until temp is low	Cool until temp is low	Must be monitored, risk of spontaneous re-ignition	Cool until temp is low. Maintain safe distance XX m to tank	Cool until temp is low. Maintain safe distance XX m to tank	Cool until temp is low. Maintain safe distance XX m to tank	Cool until temp is low. Maintain safe distance XX m to tank

Table 3. Idea of a APV drive line type characteristics overview.

EMSA offers a step by step event sequence decision support, considering different development of events and objects involved in the incident. The target should be to define one general approach to avoid complexity, where specific statements shall be specified for eventual special consideration of an event. Fire incident steps to consider:

1. Indication
2. Detection
3. Confirmation
4. First response
5. Fixed system activation
6. Fire team mustering
7. Fire team approach to scene
8. Manual life saving
9. Manual fire suppression
10. Manual fire containment
11. Situation development follow-up

12. Escalation
13. Fire team post-mission treatment
14. Post fire activities

For each step, recommended considerations and actions to be listed for different incident object, if different from the generally applicable approach:

a) ICE vehicle
b) EV vehicle
c) LNG vehicle
d) CNG vehicle
e) Hydrogen vehicles
f) Minor e-vehicle

Above list may also be expanded to traditional hazard objects:

- DG
- Reefers
- RV with aux energy source
- ICE heavy vehicle

Hands-on guidelines for specific pieces of equipment.

Information on the space-of-incident and adjacent spaces to speed up decision process and make sure no mistakes are made due to the lack or wrong data.

Land based online emergency response decision support centres for crew.

Support app on phone for decision makers of fire teams.

Guidelines for post-mission treatment of crew and gear

7 Preparations for large scale testing of APV firefighting routines, equipment, and tactics

Main author of the chapter: Jaime Bleye, SAS

Large scale fire tests require a lot of preparation and it also implies a co-creative approach and an open mind. Workshops and preparation meetings are essential, as several iterations (especially for preparation) are usually needed. Trials are evolving processes.

Time should be devoted to adjusting the design. Key decisions must be taken in agreement with different stakeholders that need to be identified. The success of a trial then clearly depends on its design: a robust design will lead you to find appropriate answers to your needs. This trial guidance methodology provides step-by-step guidelines, a list of roles and responsibilities, tools, and methods to perform a trial through a clear, structured, and co-creative approach.

7.1 Identification of gaps of APV firefighting in the maritime industry

LASH FIRE aims at transferring competence about how fires in APV should be handled on board ro-ro spaces including evaluation of new equipment and tactics.

Several ship visits were conducted to analyze the current state of the art in firefighting routines, equipment, and tactics of APV (in chronological order):

- STENA FLAVIA covering the route between Nynäshamn (Sweden) to Ventspils (Latvia). February 2020
- NAPOLES-BALEARIA covering the route between Malaga to Almeria (Spain). March 2020
- BAHAMA MAMA covering the route between Melilla to Motril (Spain). July 2021
- STENA LIVIA on an ethnography fire drill. October 2021
- ABEL MATUTES covering the route between Barcelona to Palma. May 2022

After several interviews with crew members and related stakeholders, main identified concern is that APV represent other hazards than traditional ICEV and a new challenge for the maritime industry; gas tanks may explode or provoke a BLEVE and Li-Ion batteries fire produce very toxic gases like HF.

According to SOLAS Chapter II-2, Firefighting equipment used on board vessels shall consists of protective clothing, boots, gloves, rigid helmet, safety lamp, fire axe and a SCBA. Firefighting equipment might be not properly updated to deal with alternative fuel vehicles fires.

Real hands-on firefighting techniques cannot be carried out and trained on board and should be tested in a proper facility, however APV firefighting is not part of current STCW curriculum.

7.2 Risk Area Identification

RISK AREA IDENTIFICATION	
EXPLANATION	MITIGATION MEASURE
Technology-orientation: Once a solution is pre-selected, trials participants tend to develop the trial according to the functionalities of the solution	Don´t design the trial scenario following the logic of technical solutions
Realism of trials: Tendency to come up with complex scenarios to make sure that all requirements were met (address all gaps and trial all solutions)	Scenarios should cover all gaps and should be as realistic as possible.
Co-participation & communication: It is often observed that a participatory approach was used internally but not externally	Have an inclusive approach with all the stakeholders involved in a trial, including those who only join in the execution phase
Involvement of solution providers: The experiences collected in trials highlighted an active involvement of solution providers during the actual execution	Ensure that tests are appropriate to minimize an active involvement of solution providers during trials
Reference data: Assessing innovative solutions can be done in many ways	The mitigation measure is to start each trial with a proper presentation of an agreement on the trial guidance methodology
Trial, not exercise: Due to the nature of the trial guidance methodology, the innovative solutions are trialed under as much realistic as possible circumstances	It is key to design the scenarios in a way that the use of the solutions is enforced
Responsibility diffusion: The trial guidance methodology is a highly scalable approach.	To overcome a potential diffusion of responsibilities, it is important to not overload the

RISK AREA IDENTIFICATION	
EXPLANATION	MITIGATION MEASURE
Trials can be simple by investigating one solution in a modest scenario, but trials can also be used to assess several solutions at the same time in a complex scenario	number of roles, to clearly define and differentiate the responsibilities as well as to regularly communicate the state of the trial development structured along the roles and the responsibilities
Timing and time pressure: In collaborative projects in general, every project member has the tendency to get things done fast. This causes conflicts of interest with the allocation of time to different decisions.	It is important to be patient and realistic with scheduling and setting deadlines during the trial's development
Language: There are many reasons why the trial guidance methodology it is suggested to use English as the trial language.	Try to use a common language of the involved practitioners as much as possible. The more familiar the practitioners get with the new solutions, the more relevant the trial result might be.
Expect the unexpected: No matter how precise and detailed you are doing the preparation; unexpected events may happen	Having pan B with regards to organizers and participants and always have more than one person appointed for a specific role/responsibility

7.3 Test Context

7.3.1 Venue of the trials

Jovellanos Maritime Safety Training Centre https://www.centrojovellanos.es/ Located at Gijón (North coast of Spain) belongs to the Spanish Maritime Search and Rescue Agency (SASEMAR) Salvamento Marítimo (salvamentomaritimo.es)

Created in 1993, Jovellanos Centre aims to implement, develop, and design high quality and comprehensive maritime safety training.

Figure 2. Jovellanos Safety Training Centre. Gijon Maritime Rescue Coordinator Centre. Aerial picture

7.3.2 Dates

The tests were conducted in 29th and 30th of March, 2022.

7.3.3 Schedule

TIME SCHEDULE	
Day 1	
0800 to 1000	Set up meeting
1000 to 1030	Coffee/snack break (cafeteria)
1030 to 1130	Fire ground arrangement for test 4.1
1130 to 1300	Test 4.1: Free burn test
1300 to 1330	Lunch
1330 to 1430	Conclusions
1430 to 1500	Dry tests
Day 2	

0800 to 0900	Set up meeting
0900 to 1000	Fire ground arrangement for tests 4.2 & 4.3
1000 to 1030	Coffee/snack break (fireground)
1030 to 1200	Test 4.2: First response test & firefighting
1200 to 1230	Conclusions and preparation
1230 to 1330	Test 4.3: Manual firefighting test (indoor)
1330 to 1430	Lunch
1430 to 1500	Conclusions

7.3.4 Fire equipment selected for the large-scale testing

Fire Equipment selected to be evaluated during the fire tests are presented below.

- 4 Fire hoses 70 mm. 4 layers of protection. 20 meters length.

Figure 3. 70 mm hoses

- 8 Fire Hoses 45 mm. 4 layers of protection. 20 meters length.

Figure 4. 45 mm hoses

- 8 Fire Hoses 25 mm. 4 layers of protection. 20 meters length.

Figure 5. Different sizes hoses on fireground. Firefighters are holding 25mm type.

- Water curtains 70 & 45 mm to create a vertical spray pattern. Important NOTE: This type of boundary nozzles creates a vertical spray that is perpendicular to the hose line, making unusable to be place between vehicles in a fully parked ro-ro cargo space. The boundary cooling devices substitute efficiently the cooling effect. Therefore, water curtains were dismissed for testing.

Figure 6. Water curtains. Finally, not used for testing.

- Bifurcations. Hoses connections Barcelona type

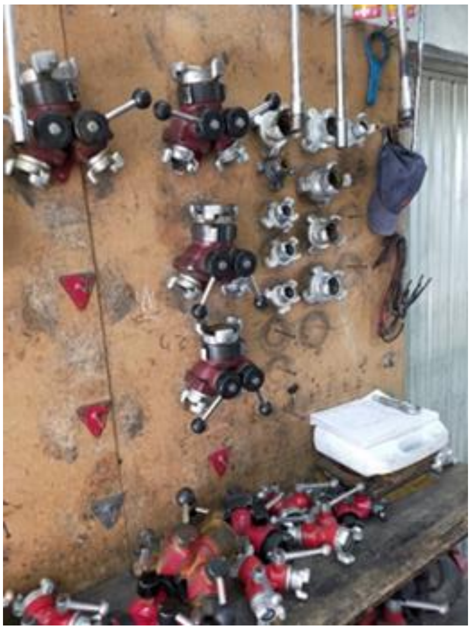


Figure 7. Bifurcations. Y pieces and hose connectors.

- 4 Fire nozzles. Different flow rates at 7 bar from (115,230,360, 475 lpm) EN 15182-2 standard

Figure 8. Water nozzles

- Special nozzle for cooling down the batteries pack in case of thermal runaway of an electric car traction battery. The prototype has been initially manufactured by Lloyds Register as part of the Projekt webseite ALBERO (alberoprojekt.de), second prototype was developed by LASHFIRE (extra information in Chapter 8.4)

Figure 9. Boundary cooling devices. Version 2.0. Note the hooks attached to a long rod to push the device into position

- 4 Portable 9 kg dry powder (sodium bicarbonate) hand-held portable extinguisher. (Efficacy: 43A-233B-C)

Figure 10. Dry Chemical powder extinguisher.

- 4 portable 6 liters foam hand-held portable extinguisher (fluorin free type) (Efficacy: 27A-233B)

Figure 11. Portable fire extinguisher

- 4 Portable 5 kg CO2 hand-held portable extinguisher (Efficacy 89B)

Figure 12. 2 and 5 kg portable CO2 fire extinguishers.

- Water mist lance (92 cm length, 45 hose connection) for piercing into containers or vehicles

Figure 13. Water mist lance

- 8 UHF portable radios.

Figure 14. Portable radio apparatus.

- 2 Large Car fire blankets. 6 meters x 8 meters

Figure 15. Large fire blanket

- 1 Infra-red camera for monitoring the temperature at regular intervals

Figure 16. Infra-red camera

- Firefighting gear CE EN469 level 2

Figure 17. Firefighters with full PPE

- Flash hoods (to be wear under the BA mask)

Figure 18. Flash-hood or balaclava

- Fire boots (with reinforce steel tip)

Figure 19. Fire boots

- Overall or undergarment

Figure 20. Overalls or undergarment.

- Firefighting helmets. EN 443:2008

Figure 21. Fire helmet.

- Safety torch (EX type)

Figure 22. Safety torch

- Breathing Apparatus. 6 litres cylinder capacity. 300 bar working presure.

Figure 23. Full BA set with air cylinder, backplate, face mask and demand valve.

7.3.5 Resources

Besides the fire equipment, other resources required at the fire ground was:

- Fire hydrants. Working pressure 7 bar
- 11 Scrap cars. (8 for outdoors, 3 for indoors)
- 3 BEV Opel Mokka (2 for Outdoors, 1 for indoors) Battery 50Kwh 216 cells in 18 modules
- Indoor facilities for inner fires. Approx. Dimensions 20mx7mx7m
- 1 forklift
- LPG from pipeline. Pressure gauge 3.5 bar. LPG storage tank total capacity 30m3
- 2 Lighters for fire ignition

A large group of experts were attending the tests. Participants had different background from fire technicians, marine crew, fire manufacturers and researchers:

- 5 Personnel (One coordinator, 3 fire technicians and 2 for supporting and logistics) from Jovellanos Maritime Safety Training Centre, SAS
- 1 Project manager Fire Safety, STENA TEKNIK
- 2 Crew members ,STENA LINE
- 2 Safety superintendents, STENA LINE
- 1 Researchers, RISE Research Institutes of Sweden
- 3 Researchers, RISE Fire Research Norway
- 2 Researchers, DBI The Danish Institute of Fire and Security Technology
- 1 Crew member, DFDS AS
- 1 Project consultant, Magellan-Associacao para a Representacao dos Intresses Portugueses no Exterior
- 1 Project manager, Center of Maritime Technologies gGmbH
- 1 Professor, University of Oviedo
- 1 Foam Technician, Perimeter Solutions

- 1 Sales representative, Bridgehill AS
- 1 Sales representative , TSF Sales & Services GmbH
- 1 photographer from a video production company

8 Testing of APV firefighting routines, equipment, and tactics

Main author: Jaime Bleye, SAS, Martin Carlsson, STL & Jonatan Gehandler, RISE.

In total three series of fire tests were performed on 3 BEVs, see section 8.1 (free burn test), 8.2 (outdoor first response & manual firefighting tests), and 8.3 (Indoor manual firefighting tests) below. In addition, a boundary cooling device (see section 8.4) was tested.

8.1 Free burn test

8.1.1 Aim of the test

The purpose of the free burn test was to see how the fire develops and to study thermal runaway (TR) on the EV. Traction battery surface temperature was monitored, and the different timing of events were documented.

The critical hazards from lithium-ion batteries are that they are difficult to extinguish and if damaged can start a fire several hours/days after the damaging event. The toxic gases that can be produced from a battery even though the vehicle is not on fire is also identified as a critical hazard while the toxicity of the combustion products from a vehicle on fire are not judged to be significantly more severe if there is a battery involved than when it is not. This is particularly problematic in poorly ventilated spaces such as in closed ro-ro spaces where the gases can accumulate.

A battery fire in an electric vehicle is difficult to extinguish, under some circumstances is no possible. The battery is often difficult to access, and it can be complicated to cool the battery with water. Normally there are no risks of electric shock when extinguishing water is applied, but the fire may continue for an extended period. There is also a risk that a battery will re-ignite after extinguishing.

Fire development in vehicles varies greatly depending on where the fire started, on materials and on vehicle fuel storage. However, a "normal" passenger car fire can generally be considered to have a burning time of ½ to 1 hour with a maximum fire effect (around 4-5 MW) after about 10-15 minutes. The literature research shows that time for fire spread to the nearest vehicle in a parking garage with conventional vehicles differs quite considerably, 5 to 40 minutes, while fire spread to the next closest and third closest vehicles goes faster.

If a fuel storage in an APV is affected, a defensive tactic is usually selected on land. Defensive tactic can be obtained by securing the area around the vehicle and prevent fire propagation from a distance.

The distance between parked vehicles may be as little as 0.15 m. This makes it more difficult to manually fight the fire. The close stowage of cargo coupled with the large open area means fires can spread quickly and become very large if the fire does not become controlled by deluge system, limited ventilation, or manual response.

8.1.2 Test set up

One scrap-car was parked next to the BEV, approximately 0.5 m distance between the vehicles.

The fire was started by means of a gas burner (LPG) located underneath the EV.

Several thermocouples were installed in different locations of the BEV to monitor the temperature peaks

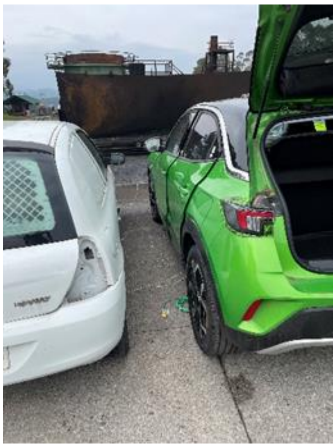


Figure 24. Free burn test set up.

8.1.3 Development of the trial

Time	Fire development	Photo	Comment
0:00	Ignition of burner		LPG burner was put on minimum flow and ignited such that flames did not engulf the sides of the vehicle.
1:20	Ignition of BEV underneath the vehicle		

Time	Fire development	Photo	Comment
3:10	Fire grows quickly to involve the exterior burnable parts below the vehicle.		Thick black smoke.
4:40	The rear left damper (shock absorber) explodes.	  	A bang is heard, and a jet flame extends below the adjacent vehicle for a brief period. This triggers the car alarm which can be heard for nearly 30 seconds.
5:20	Adjacent vehicle catches fire in the wheelhouse.		Burning plastic underneath the vehicle

Time	Fire development	Photo	Comment
5:25	The rear left tire gets ruptured. Seconds later, sudden outburst of flames is observed at the back for a moment.	  	As the tire gets emptied, a jet flame extends toward the open side of the car, while the chassis drops closer to the ground once the tire becomes flat. This triggers the car alarm again. Soon after, two fire balls suddenly appear at the back, possibly due to a thermal runaway event in the rear battery modules.
7:30	Fully developed fire		
7:50			Burner is turned off.
8:50			Fire in scrap car is limited by two firefighters using a single hose.

Time	Fire development	Photo	Comment
11:00	The front right-side tire of the adjacent car gets ruptured.		The sound of the tire getting emptied can be heard for more than 20 seconds.
11:20	A sudden burst sound accompanied by a jet flame is observed very briefly (< 1 s) on the rear left side of the main car.	 	The jet flame extends from the side of the main car. The origin is not clear.
11:40	The front left-side tire of the main car gets ruptured when two firefighters start using a single hose to limit the fire on the adjacent car.		The chassis of the main car drops closer to the ground once the front left-side tire becomes flat.
12:00			Fire in scrap car is limited.

Time	Fire development	Photo	Comment
24:00	Decay phase		
30:00	Fire is extinguished		The fire is extinguished with fognail and 45 mm hose.

8.1.4 Firefighting experience

During the test, the scrap car was being cooled twice. The firefighters tested to use fog nails and water curtain to stop the spread of fire to the car on the side. The effect of using some form of fog curtain has a significant effect in preventing the spread of fire. The fog nail became like a curtain by putting it into the ground which resulted in effective cooling.

Explosions from tires, dampers and airbags were heard during the fire test that most likely had nothing to do with the battery. Projections of gas dampers are a real risk for crew members who are not equipped with PPE.

Run-off water may present a stability issue on board if drainage is not working properly. That is the reason because suppers should be monitored during the event of firefighting operation on board. The risk of electrification does not seem to be an important risk in the event of EV fires.

Contamination of the water might be an environmental issue and the ship should inform to the local Port Authorities. The runoff water has been analyzed by specialized laboratories in Spain and the results show a content of organic contaminants and metals (µg/l). See ANNEX B.

The total amount of water used in 7.1 test was 11m3 by means of one 45 mm hose line 360lpm at 7 bar. This total volume was not totally used as a firefighting mean of the EV as the adjacent car had been cooled down several times. We estimate that the amount of water needed to suppress a car caught on fire will be between (3500-6000 liters) which means 10-15 minutes of intervention with a single 45mm hose considering that the water used is effective and is reaching the car effectively.

8.1.5 Insights from temperature data

For temperature measurement, 8 thermocouples were installed at four zones on the battery packs of the BEV. The location of the measurement zones is shown in Figure 5, where zone 1 is by the driver's seat and other zones are by the passengers' seats. For each zone, one measurement is made at the top of the battery packs and one at the bottom of the battery packs. In addition, the temperatures at the burner, the engine, the passenger compartment, and the trunk compartment, were also measured.

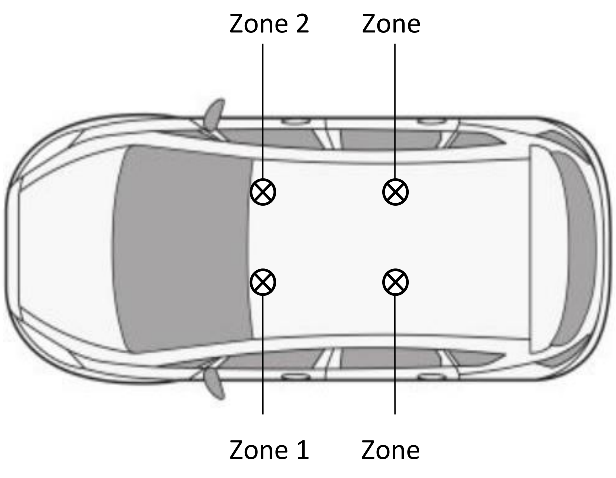


Figure 25. Location of temperature measurement.

The temperature development in each zone during the test is shown in Figure 26 and temperatures at the burner, passenger, trunk, and engine compartment are shown in Figure 27. The temperature in the measuring zones is generally lower than 600 °C, except that at the top of zone 1, while the temperature in the compartments can reach 1000 °C. In most zones, a sharp temperature increase is found between 1.5 min and 5 min, which corresponds to the fast-growing period of the fire. The temperature variation after 80 min is small and therefore the analysis is focused on the first 80 min.

The temperature at the top of the measuring zone is generally higher than that at the bottom. The fire grows quickly after ignition and at 3:10, the fire reaches the exterior burnable parts below the vehicle. The temperature development in Figure 26 and 27 suggests that the fire can be controlled immediately after applying fire suppression, but the successful extinguishing comes about 10 min afterwards, indicated by a sharp drop of temperatures at about 40 min.

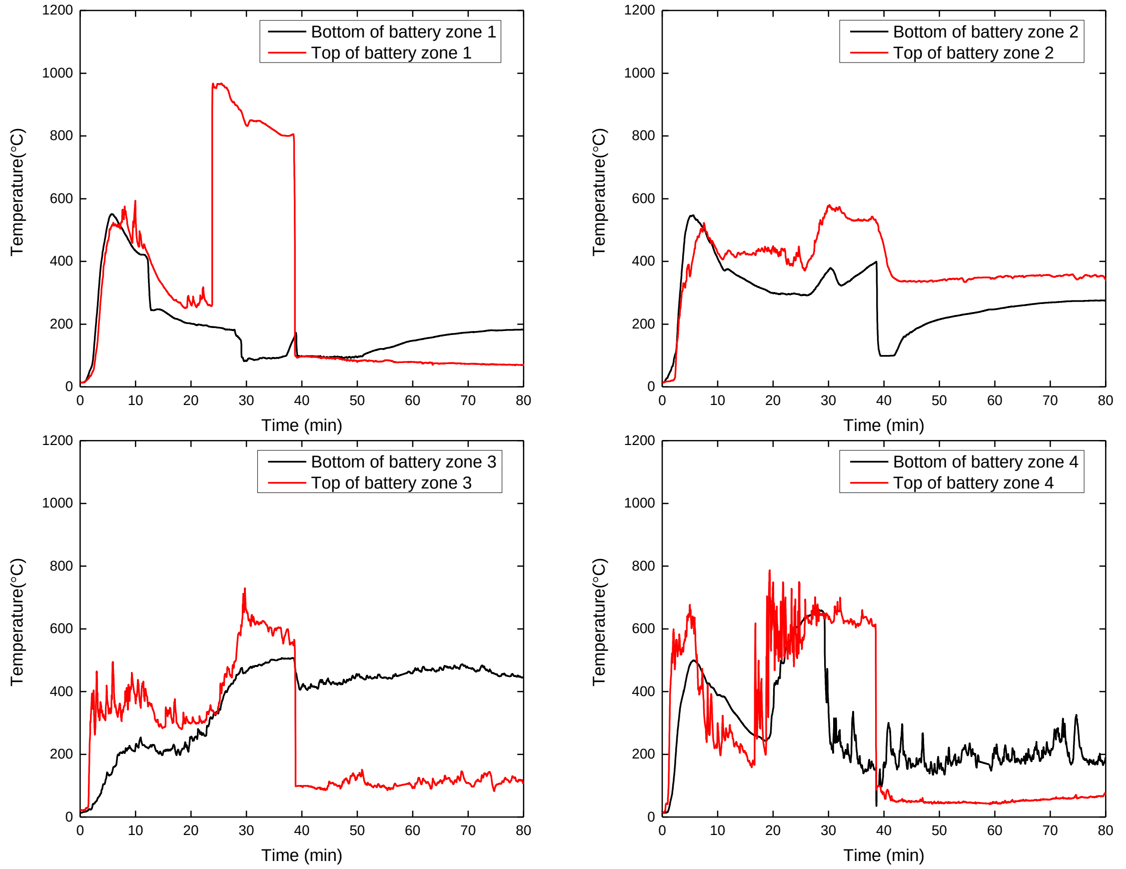


Figure 26 Temperature at the bottom and top in each zone in the free burn test.

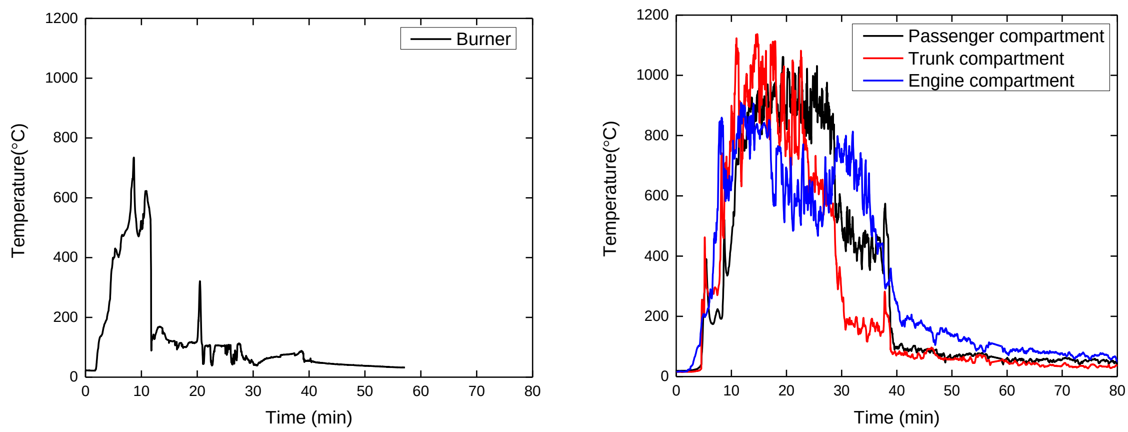


Figure 27. Temperature at burner, passenger, trunk, and engine compartment in the free burn test.

8.2 First response & Firefighting test

8.2.1 Aim of the test

A first response to firefighting is a concept directly link to the early detection and reflects that the fire is detected at its early stage, a quick and safe firefighting action may be provided. It is important to notice that with regards APV if the id affected and the TR has been triggered or the PRV has been activated, a first response action must not be initiated (only protected crew members may approach)

A first response is typically carried out when the fire is in the initial stage with the equipment that the crew member may have at hand (fire extinguisher)

A first responder will be a member of the fire patrol or a designated first responder (skilled personnel with access to restricted cargo spaces). Reference on Deliverable 06.7

The aim of the test is to analyze the efficacy of the different hand-held firefighting equipment for a first response, the right technique and timing to do so.

IMPORTANT NOTE: By definition, a first response should be carried out on working clothes. However, for safety reasons and due to the fact that some trials of the test 8.2 we carried out beyond the initial stage of the fire, the technicians were equipped with fire protection (fire suits and BA sets) that are out of the scope of first response.

Five tests were performed:

- Two hand-held CO2 extinguishers
- Two hand-held ABC-powder extinguishers
- Two hand-held foam extinguishers
- One fire blanket
- Limitation / extinguishing with the help of water mist nozzle and water

8.2.2 Test set up

A full ro-ro deck is a place that might be full of parked cars. Each car is about 4 meters long by 2 meters wide with a separation of 0.5 m and the cars are separated from to back by a gap of 0.1m

Accessibility to the site of the fire it seems like the main issue for a manual firefighting intervention on board a ro-ro vessel. The identification of the vehicle caught on fire and the approach to a distance where the hand fire extinguisher (between 2 – 6 meters) is effective is one important barrier, but not the only one: Projections of different units, gas dampers bursts and tire explosions represent real risks for first responders with no extra protection.

For testing the distance between cars was about 50 cm. One EV on fire (black one) and 8 ICE (scrap cars) parked surrounding the EV.

To facilitate the visibility and the performance of the test, 8.2 was carried out in an open-air environment (not enclosed). This aspect cannot represent a closed ro-ro deck with a fully developed fire.

Water pressure was 7 bar at hydrant.

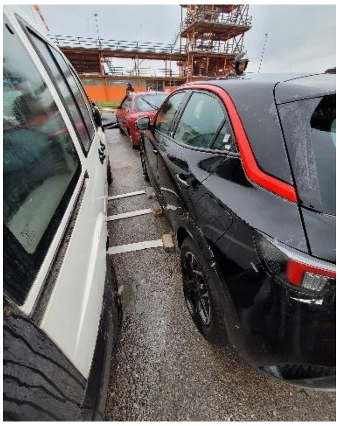
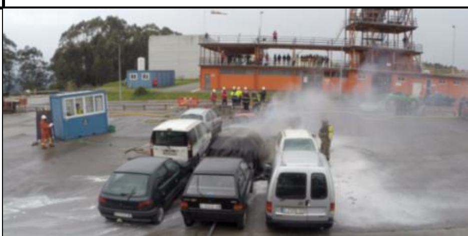


Figure 28. First response and manual firefighting test set up.

8.2.3 Development of the trial

Time	Fire development	Photo	Comment
0:00	Ignition of burner		LPG burner was put on minimum flow and ignited such that flames did not engulf the sides of the vehicle.
2:20	Growth phase		The fire before the first extinguishing attempt. Burner was turned off.
3:00	Fire is limited.		Fire was limited by two CO_2 hand-held fire extinguisher
3:40	Fire is extinguished.		Fire was extinguished by two hand-held powder extinguishers.
4:45	Fire was re-started		Burner is turned on.

Time	Fire development	Photo	Comment
6:45	Growth phase		The fire before extinguishment with hand-held fire extinguishers. Burner was turned off.
7:20	Fire is limited.		Fire was temporarily limited by two hand-held powder extinguishers. Flames appeared under the hood shortly afterwards.
7:50	Fire is limited or extinguished.		Fire was temporarily limited or extinguished by two hand-held foam extinguishers. The fire fighters aimed at the hood where it was still burning.
9:30	Burner is turned on, fire re-ignites by itself.		The fire slowly picks up. Probably the slow growth is attributed to the powder and foam.
15:30	Fire spread to nearest vehicle on the downwind side.		
20:00			The fire before the blanket is being applied. Burner is turned off.
21:00	Fire is extinguished.		BEV fire is extinguished by fire blanket.

Time	Fire development	Photo	Comment
26:00			Fire blanket is pulled off.
27:00	Fire is reignited.		Burner is turned on.
46:00	Fully developed fire in the BEV		
47:00			Fog nail used as “water curtain” is tested on the upwind side of the BEV. Hose is being applied from the other side unto the scrap car.
70:00	Decay phase in BEV		Fire is extinguished.

8.2.4 Firefighting experience

The hand-held fire extinguishers were effective in limiting the fire and slow down the fire development. Based on these tests it is difficult to advised to use a certain type before another, in any case efficacy rate from our experience ranked in increasing order was CO_2, dry chemical powder and foam. In a real situation, take the nearest of them. It can be good to keep in mind that it is an advantage to come from the same direction and empty the extinguishers one after the other. It can be difficult to see if you come from opposite directions in such a cramped space.

After a total of 20 minutes after the fire started in test 7.2, the fire had been growing for 10 minutes since last being limited by hand-held fire extinguishers. The temperature was then 550 degrees above the battery. A fire blanket was then pulled over the car and the temperature dropped from 550 to 300 degrees in 7 minutes showing great efficacy.

At 47 min, the fog nail was placed as a curtain and a water curtain "plume" was created on the upwind side of the car to stop the spread of fire. This gave a good effect. The fog nail continued to be used during the extinguishing both inside and outside the cars, with a good effect.

8.2.5 Insights from temperature data

Just as discussed in section 7.1.5 for the free burn test, the temperature development in each zone during this second test is shown in Figure 29 and temperatures at the burner, passenger, trunk, and engine compartment are shown in Figure 30. Since the fire extinguisher is applied near zone 2, the temperature in zone 2 is chosen as a reference to study the suppression effect. The temperature at the bottom of zone 1 and zone 2 is generally higher than that at the top, while in zone 3 and zone 4, the temperature at the top is generally higher.

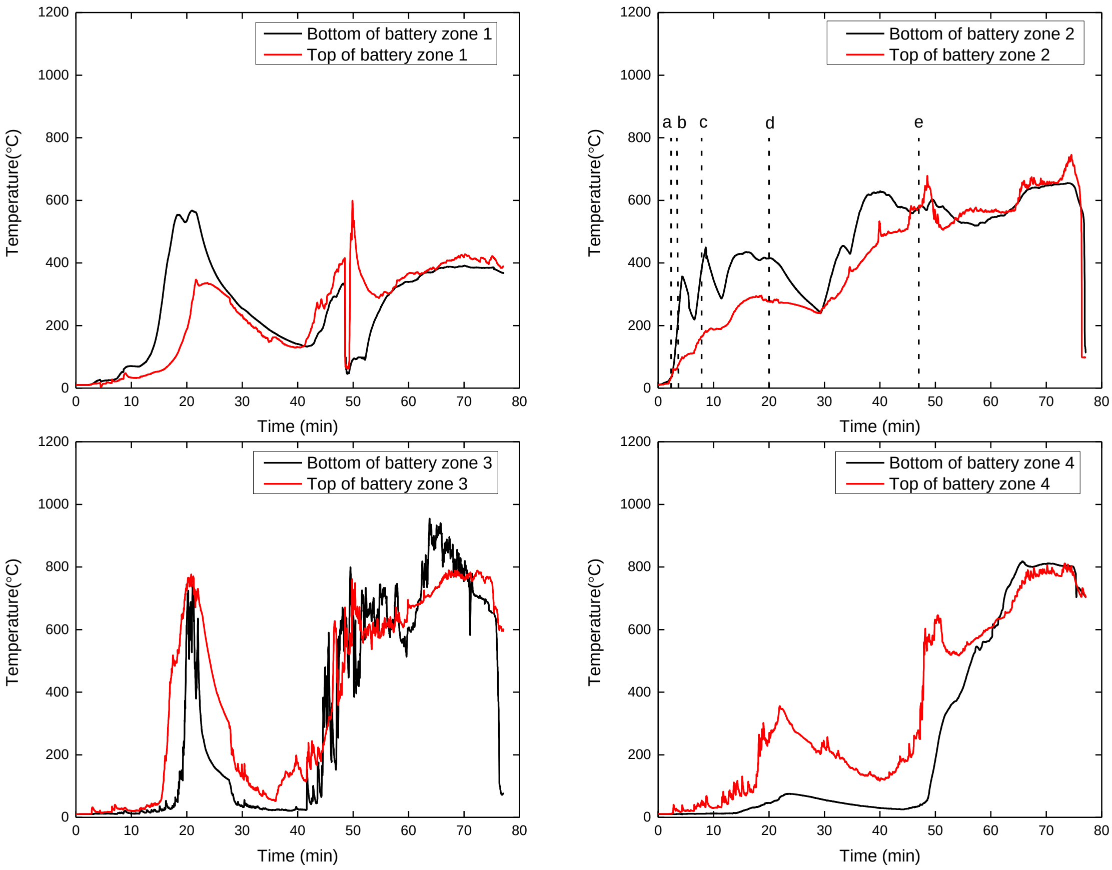


Figure 29. Temperature at the bottom and top in each zone in the outdoor test. Dash lines in zone2 indicate the time of applying fire extinguishing equipment, with CO2 (a), powder (b), foam (c), blanket (d) and fog nail (e).

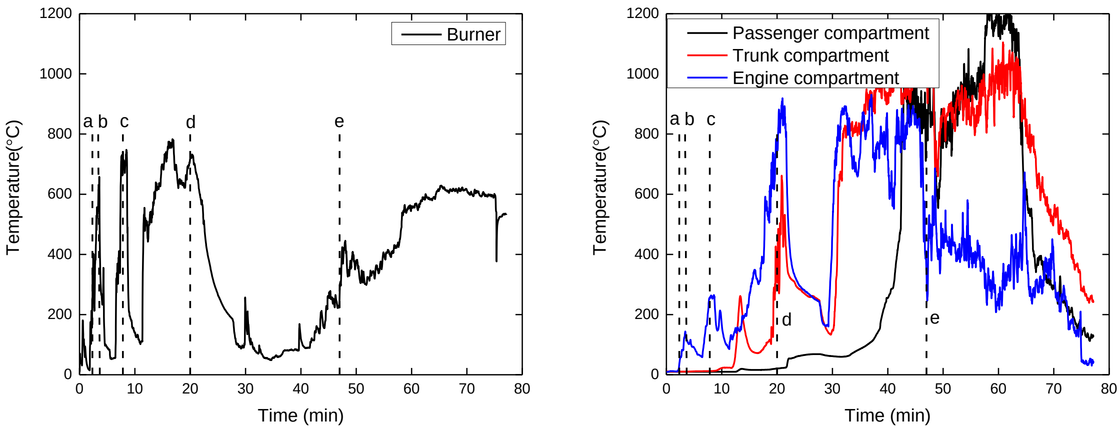


Figure 30. Temperature at burner, passenger, trunk, and engine compartment in the outdoor test. Dash lines indicate the time of applying fire extinguishing equipment.

At 2:20 (time 'a' tagged in Figure 29 and 30), the burner is turned off to prepare for fire extinguishing attempt using two CO2 handheld fire extinguishers. At 3:00, fire is limited by the fire extinguisher. The temperature still grows at the measuring positions, but at a low level close to the ambient.

At 3:40 (time 'b' tagged in Figure 29 and 30), the fire is extinguished by two handed powder extinguishers. The temperature at the bottom of zone 2 drops shortly afterwards, as well as the temperature at the burner and the engine compartment. The temperature at other measuring positions still grows at a low level, since the fire is largely limited at zone 2. The fire is then re-ignited at 4:45 by turning on the burner and the fire is at the growth phase.

At 7:50 (time 'c' tagged in Figure 29 and 30), the fire is temporarily limited/extinguished by two handheld foam extinguishers. The fire fighters aimed at the hood where it is still burning. The temperature at the bottom of zone 2 drops shortly afterwards, while temperature at the top of zone 2 becomes stable. The temperature at other measuring positions is low, which indicates that the fire is still mainly limited at zone 2. The fire is re-ignited at 9:30 by turning on the burner. The fire grows slowly, probably due to the powder and foam around. At 15:30, the fire spreads to the nearest vehicle on the downwind side.

At 20 min (time 'd' tagged in Figure 29 and 30), the burner is turned off to prepare for the use of fire blanket and the fire is extinguished at 21 min by the blanket. The temperature at zone 3 experiences a sharp drop from 750 °C to less than 400 °C at the top and less than 200 °C at the bottom within 5 min. Temperature at other zones also decreases but is less intense. It is the first time since the test that the fire spreads to the whole zones of the BEV. From the temperature drop, it seems that the fire blanket performs best in suppressing fire at the left side of the BEV (zone 1 and zone 3), as well as in the engine and trunk compartment. Fire is re-ignited at 27 min and at 46 min it becomes fully developed.

At 47 min (time 'e' tagged in Figure 29 and 30), water mist nozzle used as "water curtain" is tested on the upwind side of the BEV, with the hose being applied from the other side unto the scrap car. The direction of applying fire extinguishing equipment is different from previous tests. The temperature at all zones decreases shortly afterwards, but still at a high level, except the temperature at the bottom of zone 4, which keeps rising until 800 °C. After about 5 min, the temperature rises again and keeps at high level, which is about 400 °C at zone 1, 650 °C at zone 2 and 800 °C at zone 3 and zone 4. The fire in BEV is in decay phase from 70 min and is eventually extinguished.

Figure 31. Scenario in the outdoor test with fog nail.

In summary, the hand-held fire extinguishers were effective in limiting the fire and slowing down the fire development. Based on the test, it cannot be advised to use a certain type of hand-held fire extinguisher before another. In a real situation, one may take the nearest one. It can be good to keep in mind that it is an advantage to come from the same direction and empty the extinguishers one after the other. It can be difficult to see if you come from opposite directions in such a cramped space.

After being limited by hand-held fire extinguishers, the fire was allowed to grow once again. The temperature after 10 min was then higher than 550 °C above the battery. Fire blanket was then pulled over the car and the temperature dropped from higher than 550 °C to lower than 300 °C in 7 minutes.

At 47 min, the water mist nozzle was placed as a curtain and a water curtain "plume" was created on the upwind side of the car to stop the spread of fire. This had a positive effect. Accordingly, the fog nail was continued to be used during the extinguishing both inside and outside the cars, with a good effect.

8.3 Manual firefighting indoor test

8.3.1 Aim of the test

LASHFIRE Project aims to enhance fire prevention and effective fire management on board ro-ro vessels. Manual firefighting (Firefighting actions to be carried out by the fire squad in accordance with the on-board Muster List) is one of the last steps in the firefighting chain of events (Ignition-Detection-Confirmation-First Response-Decision-Activation of fixed systems-Manual Firefighting-Containment-Evacuation). Reference to *FIRE SAFE II- WP2 Final Report, December 2018*

Manual firefighting (with full PPE and BA) should be performed under the following circumstances:

- If it is the only firefighting alternative when previous attempts were not successful
- For life saving
- If needed in addition for fixed FF systems
- As stable post-FF like cooling down, inspection or monitoring.

The aim of the test was to study the level of protection of the PPE (fire suit EN 469 level 2 together with gloves, boots, flash hood, long sleeved undergarment and Breathing apparatus), the suitable equipment (focusing on fire hoses) and the right procedure during extinguishment and post extinguishment actions.

8.3.2 Test set up

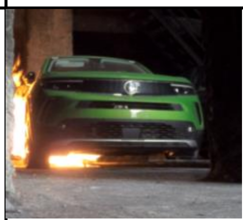
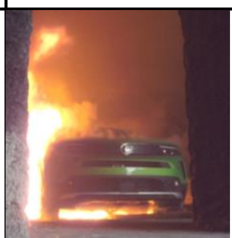
The indoor space aimed to simulate a ro-ro open space in dimensions (with openings less than 10% of the total area of the space sides).

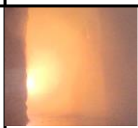
Water pressure was 7 bar. To make accessibility difficult to the fire team, the distance between cars was about 50 cm. One EV on fire and 8 ICE (scrap cars).

The horizontal distance between the fire hydrant and the car caught on fire was slightly shorter (around 10 meters) than expected in real life.

Fig 32. Indoor test set up. BEV located at the corner.

8.3.3 Development of the trial

Time	Fire development	Photo	Comment
0:00	Ignition of burner		LPG burner was placed in the centre and put on minimum flow and ignited. Flames extended towards the right hand side of the BEV.
1:00	Ignition of BEV at the right rear-wheel		
3:00	Fire grows quickly to involve the right hand side and underneath of the BEV.		
4:00	TR?		A hissing sound is heard for an extended period of time, indicating a jet flame. Difficult to see the jet on video, there was only videorecording from the front of the vehicle.

Time	Fire development	Photo	Comment
9:00	Fully developed fire		Picture right before intervention with 25 mm hose. Burner is turned off.
10:00			Manual intervention with 25 mm hose.
13:00		 	Manual intervention with 25 mm hose and fog nail. Fog nail is used to extinguish inside the hood and kupé. Very poor visability.
19:00	Fire is extinguished	 	

8.3.4 Firefighting experience

The purpose of this test was manual firefighting with water. The cars were placed with the BEV at the far left with a pillar in front and a scrap car on the right side of the BEV. A second scrap car was placed in front of the first scrap car to the right.

Two tests were performed:

- Fire fighting with joint fighter and 25mm hose.
- Fire fighting with joint fighter and 25mm hose and water mist nozzle with 45mm hose.

Two smoke divers performed the firefighting operation with two smoke divers as a backup group.

The operation started 10 min after ignition when the temperature in the battery reached about 700 degrees, probably TR, based on test 7.1.

The first operation was with 25mm hose and a joint firefighter. The smoke divers entered towards the left front corner of the BEV. The electric car then burned heavily from the rear part left side, from inside the passenger compartment and from the car's right side. The right rear wheel of the scrap car had also been ignited. The smoke divers perceived that the extinguishing work with 25mm hose and joint fighter worked well, but was not sufficient for extinguishment, the course of the fire slowed down somewhat. The smoke divers then backed out.

The second operation was with a fogfighter on a 25mm hose as well as a water mist nozzle on a 45mm hose. First, the water mist nozzle was placed under the car from the front towards the right side of the car while the extinguishing was in progress with a fogfighter on the left side of the BEV and on the right side of the scrap car. The water mist nozzle was then moved into the passenger compartment, the extinguishing work was continued with the fogfighter. The smoke divers were able to see through the hood that there was a large fire in the engine room. This limited the possibility of continuing the extinguishing work in between the cars. The water mist nozzle was thus moved and pushed through the hood. The smoke divers then left the water mist nozzle in the position under the hood and moved around together with the fogfighter between and around the cars so that it became possible to extinguish the BEV and the scrap car from behind. After this move, the car was extinguished.

The smoke divers could not experience that there were any special bangs or other contributions to the fire from the traction batteries.

8.3.5 Insights from temperature data

Once again as discussed in section 7.1.5 for the free burn test, the temperature development in each zone during this third test is shown in Figure 13 and temperatures at the burner, passenger, trunk and engine compartment are shown in Figure 14 the temperature at the bottom and at the top of zone 3 shows similar trend and reaches about 700 °C during the test, while in other zones difference is found between the top and the bottom and the maximum temperature is lower than 600 °C. The maximum temperature in the compartment is about 600 °C. The BEV is ignited at the right rear wheel at 1 min. At 3 min, the fire quickly grows to involve the right-hand side and underneath of the BEV. At 4 min, a hissing sound is heard for an extended period of time, indicating a jet flame. The temperature in the passenger compartment and engine compartment shows a sharp increase from ambient to 350 °C and 550 °C in less than 1 min. Note that this increase is also observed in the free burn test in Figure 6, indicating a good repeatability of the test. At 9 min, the fire is fully developed, and the burner is turned off to prepare for using the hose.

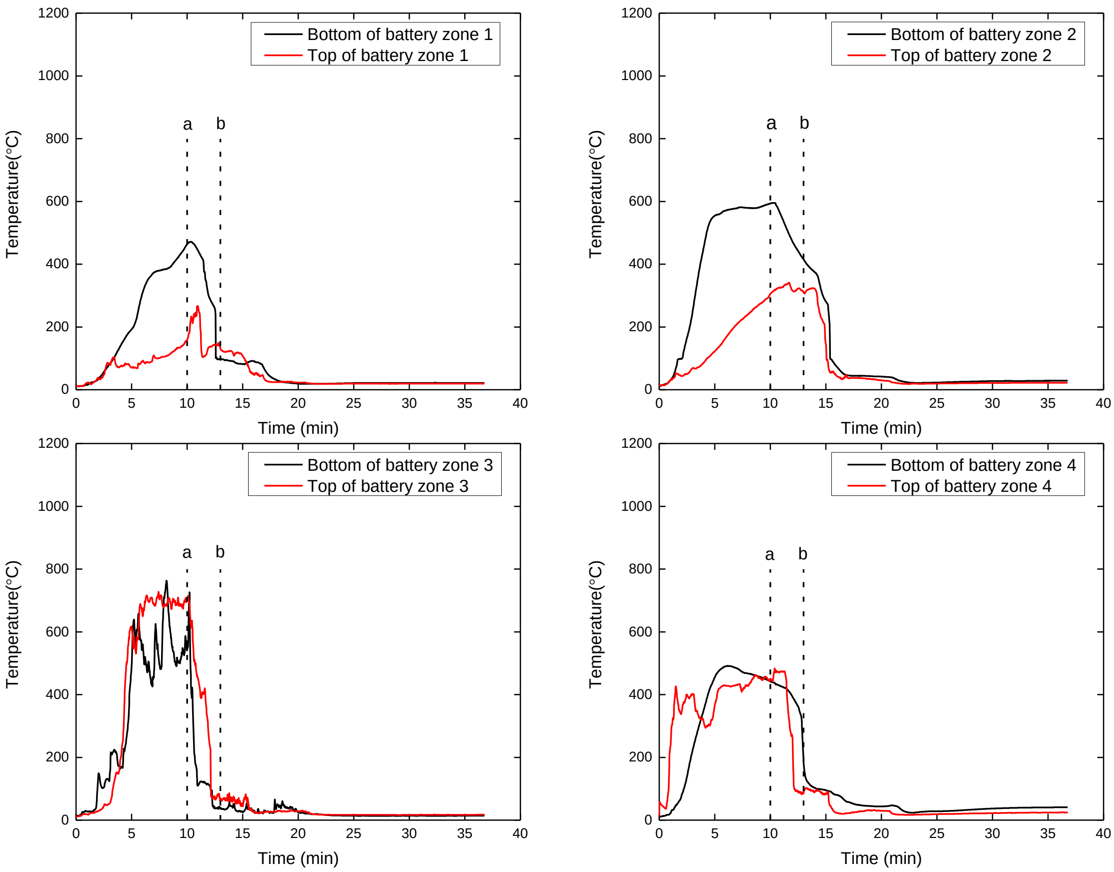


Figure 33. Temperature at the bottom and top in each zone in the indoor test. Dash lines indicate the time of applying hose at 10 min (a) and fog nail at 13 min (b).

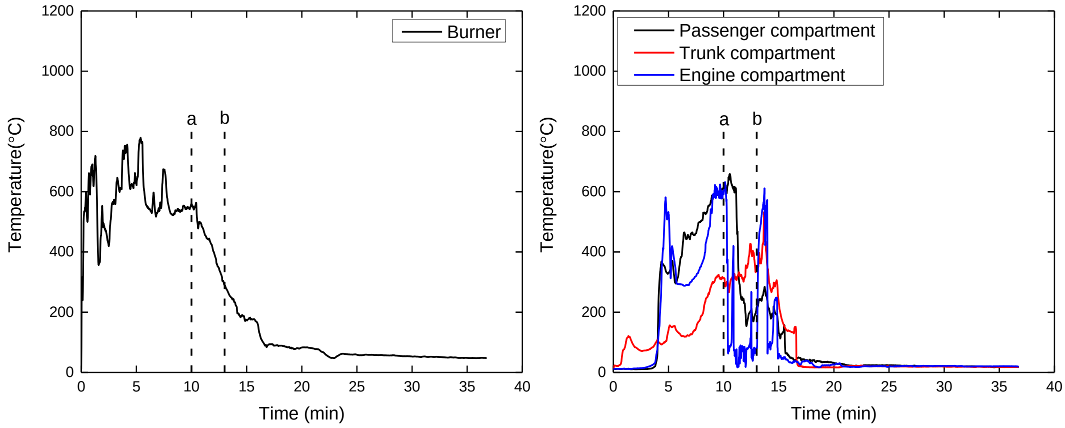


Figure 34. Temperature at burner, passenger, trunk, and engine compartment in the indoor test. Dash lines indicate the time of applying fire extinguishing equipment.

At 10 min (time 'a' tagged in Figures 33 and 34), the fire is manually intervened with the hose. A drop in temperature is observed in all the 4 zones, with the largest drop found in zone 3. The temperature in zone 3 drops from about 700 °C to 100 °C in 2 min, while the temperature in other zones is still at high level. During the intervention, the smoke divers entered towards the left front corner of the BEV (zone 1). It was found that the electric car burned heavily from the rear part left side, from inside the passenger compartment and from the car's right side. The right rear wheel of the scrap car had also been ignited. The smoke divers perceived that the extinguishing work with 25mm hose and joint fighter worked well but was not sufficient for extinguishment.

At 13 min (time 'b' tagged in Figures 33 and 34), the fire is manually intervened with the hose and the fog nail. The fog nail is used to extinguish inside the hood and cabin. At this time, the temperature in zone 1 and zone 3 is already low. In zone 4, the temperature immediately drops from 400 °C to 100 °C. In zone 2, the temperature drops from about 400 °C to 90 °C in 2 min. During the intervention, the fog nail was placed under the car from the front towards the right side of the car while the extinguishing was in progress with a fogfighter on the left side of the BEV and on the right side of the scrap car. The fog nail was then moved into the passenger compartment, the extinguishing work was continued with the fogfighter. The smoke divers were able to see through the hood that there was a large fire in the engine room, which was also reflected by the high temperature in the engine compartment. This limited the possibility of continuing the extinguishing work in between the cars. The fog nail was thus moved and pushed through the hood. The smoke divers then left the fog nail in the position under the hood and moved around together with the fogfighter between and around the cars so that it became possible to extinguish the BEV and the scrap car from behind. The fire is successfully extinguished at 19 min, with the temperature in all 4 zones dropping to the ambient.

During the test, the smoke divers could not experience that there were any special bangs or other contributions to the fire from the traction batteries.

8.4 Boundary cooling nozzle test

Three scrap cars were placed next to each other, with a standard separation of 50cm from side to side. The car placed in the middle was ignited using diesel that was poured into the car. Some windows were smashed before the test. The boundary cooling nozzle were placed on each side of the central scrap car.

Fig 35. Car´s set up for the boundary cooling test.

The purpose of the device is to provide water cooling in addition to, or as intermediate option between the drencher system and the manually operated fire hose. The boundary cooling nozzle has a good shielding effect creating a vertical barrier between cars and also and spray pattern pointing to the traction battery or the gas tank (located in the lower part of the vehicle). The first prototype has been developed under the umbrella of the ALBERO PROJECT Project website ALBERO (alberoprojekt.de) and then several tests were carried out by LASHFIRE. After testing LASHFIRE has developed different and updated versions of the prototype, reaching 4.0 version

The main specifications are:

- Flexible coupling type to fit with many different standards on ships.
- It provides self-rightening/stabilizing when put under pressure.
- Symmetric spray pattern
- Max pressure 15 bar, normal operation pressure 8-10 bar
- Lowest pressure to fulfill spray pattern 5 bar
- With hose connected to be possible to pull device along deck using a pulling-line in a minimum 300 m wide corridor between cars
- Shape of device to prevent being stuck under cars or tires when moving between cars lanes
- Minimum width of device but wide enough to provide stability while pulling and in operation
- Swivel solution to minimize impact of hose turning when put under pressure.
- Lightweight
- Carrying handle in centre of device
- Interface to deck surface being such that device can pass over lashing pots/elephant feet, fish bone 6x6 square bar patterns, welds, gaps at hatch covers etcetera without getting stuck or topping over.
- Horizontal spray pattern to fit sideways between tires with wheelbase of 3000 mm and also cooling partly tires themselves.
- Width of horizontal spray pattern should be such that both underside of cars and deck below to be sprayed.
- Assume clear height of cars of 150-250 mm.

- Width of vertical spray to be such that both cars located at distance of max 1 m will be sprayed.
- Vertical spray pattern to reach full length and height+0,5m of a standard car.
- Possibility to use device as a water shield for any close-range manual operation.

Figure 36: boundary cooling device tested at SAS ´facilities. (version 1.0)

Figure 37: Updated boundary cooling device at SAS ´facilities. (version 4.0). October 2023

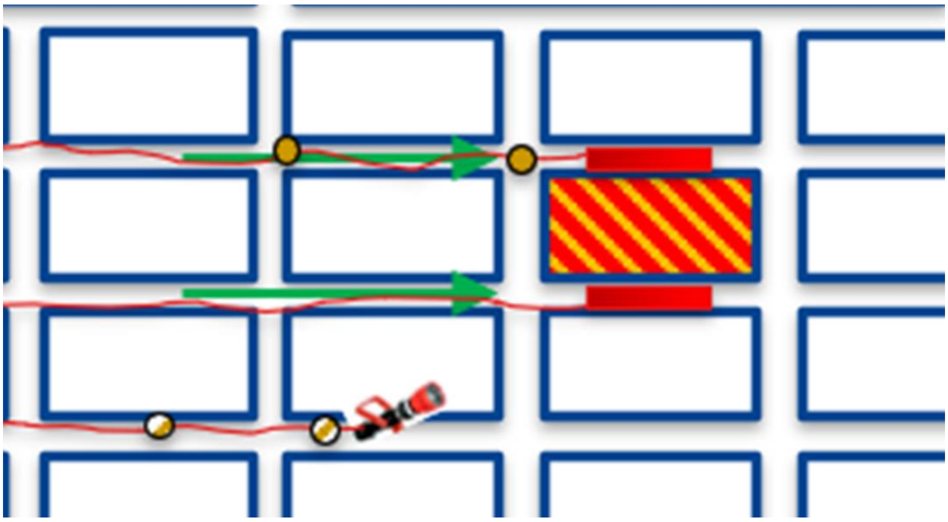


Figure 38. Cooling device. Usability and accessibility

Figure 39. Cooling device version 4.0 Spray pattern

9 Conclusion

Main author of the chapter: Jaime Bleye, SAS

Manual firefighting in a high-risk location like a ro-ro space is intended to save lives, either directly on the scene or indirectly via critical activities that prevents, or delays fire spread, thereby safeguarding the ship and its crew and passengers. For many reasons drencher system should be activated in an early stage of a fire. This means that manual firefighting will occur after or during drencher operation

It is very difficult to visually differentiate a classic fossil fuel car from an APV. From the firefighting perspective, the overall procedure will be the same since APV firefighting does not differ significantly from traditional ICE and the risks of projections, intense heat release, production of toxic gases and lack of visibility would be basically the same.

Lithium-ion batteries expose a risk of self-generated temperature increase with may lead to emission of flammable gases, jet flames and fire. Such event is known as thermal runaway.

If one cell becomes hot, it can start a chain reaction in adjacent cells in which yet more heat is generated. A flammable gas cloud may then be generated that may be ignited or if contained in a confined space, cause an explosion.

On an emerging situation in an electric vehicle, it is important to consider the risk of an thermal runaway. Crew should only approach the vehicle if it is safe to do so. If risk of fire, explosion or violent ignition, all crew and passengers are to evacuate the space immediately.

There are a few signs that indicates an electric vehicle may be experiencing a thermal runaway. These include:

- Popping sounds from battery cells caused by a thermal runaway.
- A sudden increase in battery temperature.
- A burning smell coming from the battery pack.
- A vapour cloud coming from the battery pack. It is important to note that a vapour cloud may not necessarily behave in the same way that smoke from a developed fire would. The vapour cloud could in the absence of ventilation build up and present a significant explosion risk.

In the presence of extensive smoke without flames, thermal runaway shall be assumed, and the appropriate section of the vehicle deck drencher system should be activated. The drencher system will stop the spread of any potential fire but won’t stop the thermal runaway in the battery of the vehicle.

It should be borne in mind by Masters and Crew that the vast majority of fires in electric vehicles do not involve the Lithium-Ion battery. Such general fires should be handled in the traditional way with first response if safe and applicable, thereafter application of fixed suppression system and manual firefighting as appropriate. It takes time for a car fire to spread to the Li-Ion battery if it did not start there.

All crewmembers must have successfully completed advanced training in firefighting techniques. The STCW Code Ch VI Section A-VI/3 and Table A-VI/3 provide the mandatory minimum standard of competence in advanced firefighting. However, current STCW do not mention the specific risks associated with APVs or how a firefighting operation should be organized in case a manual firefighting would be necessary. WP06 has created a proposal of a minimum standard of competence with regards to APV manual firefighting as described in Table 4 below:

Table 4: Proposal for development of the STCW minimum standard of competence with regards APV manual firefighting.

Competence	Knowledge, understanding and proficiency	Methods for demonstrating competence	Criteria for evaluating competence
Identify the hazards associated with carriage and charging of electric cars	Ability to identify electric battery vehicles and stablish cargo separation procedures. Knowledge of possible consequences of overcharging, fast	Assessment of evidence obtained from approved training and/or instruction	Quantitative Risk assessment to estimate the likelihood of fire or thermal runaway when electric cars are loading on board.

	charging, charging damaged battery. Knowledge of the procedures to charge on board electric cars, risks associated and possible mitigation actions		
Organize and control methods and equipment for APV firefighting operations on board ro-ro spaces	Basic knowledge on suppression systems needed in case of AFV firefighting operations on board ro-ro spaces. Ability to perform firefighting technics and tactics regarding AFV fires	Assessment of evidence obtained from approved training by practical demonstration, shipboard training drill or instruction	Correct installation of cooling devices for the attenuation of radiant heat with the aim of producing a blockage effect Correct selection of the right manual firefighting tactic (defensive or offensive) depending on how the fire can be reached considering fire size and potential dangers

During the tests performed in Spain at Jovellanos Maritime Safety Training Centre, three series of tests were conducted, including free burn test, outdoor first response & manual firefighting test and manual firefighting indoor test.

The free burn test was to study the fire development and thermal runaway (TR)

The first response and manual firefighting test was to study the efficacy of different firefighting equipment for a first response, the right technique, and the timing to do so.

The purpose of the manual firefighting indoor test was to study the level of protection, evaluation of extinguishing equipment (focusing on fire hoses) and the right procedure during extinguishment and post-extinguishment actions. The PPE used was a fire suit that comply with EN 469 level 2, together with gloves, boots, flash hood, long-sleeved undergarment and breathing apparatus.

Several pieces of equipment were tested during the testing. The overall result featuring advantages/disadvantages of each equipment is presented in Table 5.

Table 5: Pros and cons about the pieces of equipment tested.

Equipment	Plus	Minus
CO2 4Kg portable extinguisher	Suppression of the fire is possible in the very early stage of the fire. It is clean and does not compromise the visibility of the area	Limited cooling effect on the battery Very limited effectiveness when the fire is fully developed
Dry powder 9Kg portable extinguisher	Limits the fire growth and fire development, extinguishing at early stages of the fire. Most common fire equipment at hand	Battery pack is well hidden, so effectiveness is limited. Powder cloud may hinder firefighting operations due to poor visibility
Foam 6liters portable extinguisher	Quite effective, as the liquid state helps to reach hot hidden zones when media is applied. Good cooling effect	Not very common to find in ro-ro cargo spaces. Fluorine products will cause environmental issues.
Fire blanket 6x8m	Good efficiency for general car fire, in particular for engine/passenger/hood compartment fires. Large size, typically 6x8 m, allows safe approach with adjacent vehicles as heat/flame barrier, as long as these are not on fire also. Contains energy bursts in case of reignition. Reduces amount of smoke in space and no additional steam generation. Stabilizing psychological effect due to fire/car not visible. Short crew heat/smoke exposure time. Good option, if water system supply is not operative	A fully parked scenario with great cargo variation can jeopardize the effective blanket deployment. As firefighters need to be close to the car to apply blanket, it is not possible to do it with a fully developed fire, without previous suppression by water. Captures smoke underneath at time of application and may temporary direct it towards crew members. Require manual activities on all sides of fire scene, challenging tactical ventilation. Requires 2 crewmembers for application plus, in a developed fire state, 2 protective hose operators if water shield is needed for application and return. Limitation with roof racks and high vans to deploy the blanket smoothly
Water mist lance	Good shield/blockage effectiveness	Unlikely but dangerous possibility of penetration of the battery pack No open/close valve on the nozzle

Equipment	Plus	Minus
	Can penetrate surfaces and be left inside enclosures for efficient extinguishing/cooling. Enables one directional approach and exit. Short crew heat/smoke exposure time	Tight parking may hinder hose preparation. If water shield protection or return is needed, this must be provided by additional hose/crew.
Manual water nozzle and hose	Versatile tool for manual firefighting Can offer extinguishing from a distance. Can offer heat protection. Smaller hoses e.g. 25 mm can be easier to maneuver and pull between vehicles avoiding stuck Enables one directional approach and exit	Tight parking may hinder hose preparation. Requires continuous presence of crew At least 4 members are needed for a dynamic fire strategy. Smaller hoses are lighter but offer large pressure drop.
Boundary Cooling nozzle	Enables one directional approach/exit, and if pushed in place by a rod, avoiding close contact with car on fire. Short time crew heat/smoke exposure. Allows for engagement at developed fire stage. Enables low level approach. Protective water shield provided by device itself on the way in. Can be used to cool gas tanks with open mounting. Equally usable with varying cargo configuration. Suppresses energy bursts in case of reignition.	Two devices needed to protect from fire in one car. Will not extinguish shielded fire inside vehicle. Requires 2 crewmembers for application plus, in a developed fire state, 1 protective hose operator, if water shield on return is needed. Tight parking may hinder hose preparation. Heavier in maneuver than hose or fognail. Decrease local visibility and work environment.
IR camera	Good to confirm the presence of fire or hot spots.	You need one hand busy to carry the device.

Equipment	Plus	Minus
	Necessary to monitor the evolution of the fire behavior taking periodic measures	Adding extra equipment will reduce the comfort of the firefighter in an stressful situation

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11 Indexes

11.1 Index of tables

Table 1: List of documents used for the review of regulations for manual firefighting……………………..20

Table 2: Minimum inspection and maintenance plan for manual fire-fighting equipment according to IMO MSC.1/Circ.1432………22

Table 3. Idea of a AVF drive line type characteristics overview………………………………………………………32

Table 4: Proposal for development of the STCW minimum standard of competence with regards APV manual firefighting..34

Table5: Pros and cons about the pieces of equipment tested……………………………………………………38

11.2 Index of figures

Figure 1: Comparison of amounts of released gas components from fully burned cars of EV and ICE type………30

Figure 2: Jovellanos Safety Training Centre. Gijon Maritime Rescue Coordinator Centre. Aerial picture..37

Figure 3: 70 mm hoses..38

Figure 4: 45 mm hoses..39

Figure 5: Different sizes hoses on fireground. Firefighters are holding a 25mm type.........................39

Figure 6: Figure 6. Water curtains. Finally, not used for testing...40

Figure 7: Bifurcations. Y pieces and hose connectors..40

Figure 8: Water nozzles...41

Figure 9: Boundary cooling devices. Version 2.0. Note the hooks for dragging or pulling into site......41

Figure 10: Dry Chemical powder extinguisher..42

Figure 11: Portable fire extinguisher...42

Figure 12: 2 & 5kg portable CO2 fire extinguishers…………………………………………………………………….43

Figure 13: Water mist lance..43

Figure 14: Portable radio apparatus……………………………………………………………………………………….44

Figure 15: Large fire blanket...44

Figure 16: Infra-red camera...45

Figure 17: Firefighters with full PPE..45

Figure 18: Flash-hood or balaclava..46

Figure 19: Fire boots...46

Figure 20: Overalls or undergarment...47

Figure 21: Fire helmet..47

Figure 22: Safety torch...47

Figure 23: Full BA set with air cylinder, backplate, face mask and demand valve..............................48

Figure 24: Free burn test set up...50

Figure 25: Location of temperature measurement...56

Figure 26: Temperature at the bottom and top in each zone in the free burn test.............................57

Figure 27: Temperature at burner, passenger, trunk, and engine compartment in the free burn test.......57

Figure 28: First response and manual firefighting test setup..58

Figure 29: Temperature at the bottom and top in each zone in the outdoor test. Dash lines in zone2 indicate the time of applying fire extinguishing equipment, with CO2 (a), powder (b), foam (c), blanket (d) and fog nail (e)..62

Figure 30: Temperature at burner, passenger, trunk, and engine compartment in the outdoor test. Dash lines indicate the time of applying fire extinguishing equipment..62

Figure 31: Scenario in the outdoor test with fog nail...63

Figure 32: Indoor test set up. BEV located at the corner..65

Figure 33: Temperature at the bottom and top in each zone in the indoor test. Dash lines indicate the time of applying hose at 10 min (a) and fog nail at 13 min (b)...68

Figure 34: Temperature at burner, passenger, trunk, and engine compartment in the indoor test. Dash lines indicate the time of applying fire extinguishing equipment..68

Figure 35: Car´s set up for the boundary cooling test...69

Figure 36: boundary cooling device tested at SAS ´facilities (version 1.0)..70

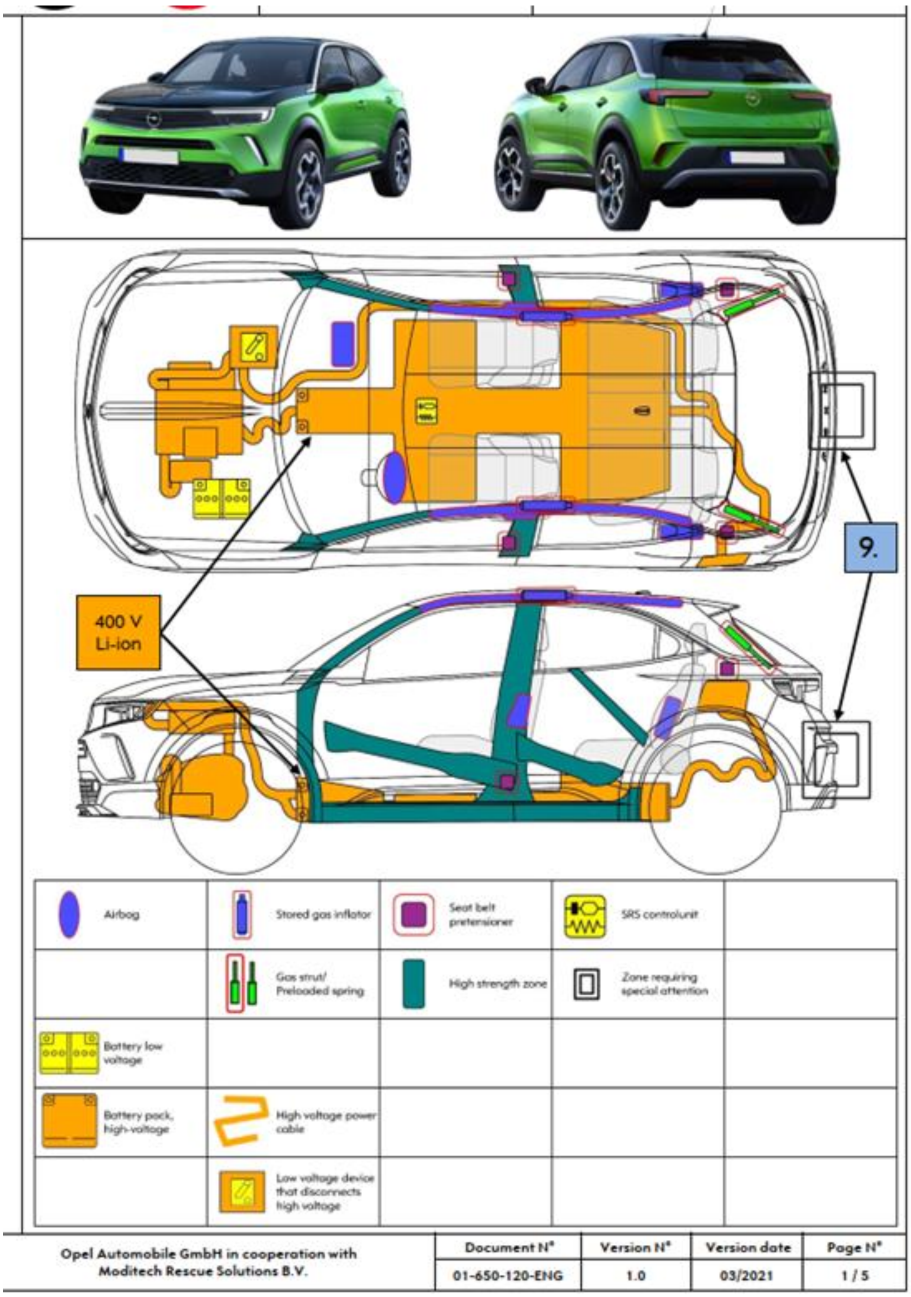
Figure 37: Updated boundary cooling device at SAS ´facilities. (version 4.0). October *2023* 70

Figure 38: Cooling device. Usability and accessibility...70

Figure 39: Cooling device version 4.0 Spray pattern..71

12 ANNEXES

12.1 ANNEX A. EV Safety instructions



12.2 ANNEX B. Results of the run-off water, analysed by lab (components written in Spanish)

Parámetro	Unidad	Resultado	V. R.	Procedimiento	Técnica	Incert. (k=2)
"In situ"						
Temperatura	°C	21.7	40	IA-ITCAL-11.0-13	Termometría	0.5°C
Conductividad a 20°C	µS/cm	2230	5000	IA-ITCAL-11.0-15	Electrometría	6%
pH a 25°C	Ud. pH	7.12	6 - 9	IA-ITCAL-11.0-12	Electrometría	0.08Ud. pH
Generales						
Aceites y grasas	mg/l	89.0	100	IA-ITCAL-11.0-59	E. Infrarrojo	28%
Amonio	mg N/l	1.5	60	IA-ITCAL-11.0-07	Electrometría	14%
Cianuros Totales	mg/l	0.098	2	IA-ITCAL-11.0-01	VIS-UV	26%
Color		Inapr. 1/20	Inapr. 1/40	IA-ITCAL-11.0-61	Diluciones	
Demanda Bioquímica de Oxígeno (DBO5)	mg/l	165	1000	IA-ITCAL-11.0-10	Electrometría	35%
Demanda Química de Oxígeno (DQO)	mg/l	494	1600	IA-ITCAL-11.0-02	VIS-UV	20%
Fenoles Totales	mg/l	3.0	2	IA-ITCAL-11.0-94	VIS-UV	18%
Fluoruros	mg/l	11.1	12	IA-ITCAL-11.0-79	C. Iónica	18%
Hidrocarburos totales	mg/l	80.2	15	IA-ITCAL-11.0-59	E. Infrarrojo	30%
Sólidos en suspensión	mg/l	161	1000	IA-ITCAL-11.0-03	Gravimetría	19%
Sólidos sedimentables	ml/l	3.0	10	IA-ITCAL-11.0-89	Volumetría	0.9ml/l
Sulfuros Totales	mg S2-/l	< 0.10	2	IA-ITCAL-11.0-124	UV-VIS	18%
Metales disueltos						
Cromo (VI)	µg/l	< 5.0	1000	IA-ITCAL-11.0-93	VIS-UV	32%
Metales totales						
Aluminio	µg/l	9700	15000	IA-ITCAL-11.0-64	ICP-MS	16%
Arsénico	µg/l	< 5.0	1000	IA-ITCAL-11.0-64	ICP-MS	19%
Bario	µg/l	258	10000	IA-ITCAL-11.0-64	ICP-MS	15%
Boro	µg/l	1035	3000	IA-ITCAL-11.0-64	ICP-MS	17%

ENAC ENSAYOS
Nº 286 / LE 486

entidad colaboradora de la administración hidráulica

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Fecha de emisión: 20 de abril de 2022

Director Técnico del Laboratorio de Ensayo: Manuel Gutiérrez Cambior

Los parámetros marcados con (*) se encuentran fuera del alcance de la acreditación.

EL LABORATORIO NO SE HACE RESPONSABLE DE LA INFORMACIÓN SUMINISTRADA POR EL CLIENTE.
LOS RESULTADOS DE ESTE INFORME SÓLO AFECTAN A LAS MUESTRAS SOMETIDAS A ANÁLISIS.
EL INFORME NO DEBE REPRODUCIRSE PARCIALMENTE SIN APROBACION ESCRITA DEL LABORATORIO DE ENSAYO EUROFINS ENVIRA INGENIEROS ASESORES, S. L.

EUROFINS ENVIRA INGENIEROS ASESORES S.L.: EMPRESA COLABORADORA DE LA ADMINISTRACIÓN HIDRÁULICA

Parámetro	Unidad	Resultado	Procedimiento	Técnica	Incert. (k=2)
Orgánicos - COV's HS-GC-MS					
Benceno	µg/l	408	IA-ITCAL-11.0-153	HS-GC-MS	28%
Tolueno	µg/l	71.4	IA-ITCAL-11.0-153	HS-GC-MS	30%
Etilbenceno	µg/l	7.7	IA-ITCAL-11.0-153	HS-GC-MS	32%
Xilenos (Suma m+p+o)	µg/l	13.0	IA-DI-028	HS-GC-MS	32%
BTEX (Suma)	µg/l	500	IA-DI-028	HS-GC-MS	
Orgánicos - PAHs GC-MS/MS					
*Naftaleno	µg/l	186	IA-ITCAL-11.0-157	GC-MS/MS	
Naftaleno	µg/l	> 1.0	IA-ITCAL-11.0-157	GC-MS/MS	
*Acenaftileno	µg/l	76.3	IA-ITCAL-11.0-157	GC-MS/MS	
Acenaftileno	µg/l	> 1.0	IA-ITCAL-11.0-157	GC-MS/MS	
*Acenafteno	µg/l	220	IA-ITCAL-11.0-157	GC-MS/MS	
Acenafteno	µg/l	> 1.0	IA-ITCAL-11.0-157	GC-MS/MS	
*Fluoreno	µg/l	25.9	IA-ITCAL-11.0-157	GC-MS/MS	
Fluoreno	µg/l	> 1.0	IA-ITCAL-11.0-157	GC-MS/MS	
*Fenantreno	µg/l	53.4	IA-ITCAL-11.0-157	GC-MS/MS	
Fenantreno	µg/l	> 1.0	IA-ITCAL-11.0-157	GC-MS/MS	
*Antraceno	µg/l	12.9	IA-ITCAL-11.0-157	GC-MS/MS	
Antraceno	µg/l	> 1.0	IA-ITCAL-11.0-157	GC-MS/MS	
*Fluoranteno	µg/l	24.2	IA-ITCAL-11.0-157	GC-MS/MS	
Fluoranteno	µg/l	> 1.0	IA-ITCAL-11.0-157	GC-MS/MS	
*Pireno	µg/l	32.0	IA-ITCAL-11.0-157	GC-MS/MS	
Pireno	µg/l	> 1.0	IA-ITCAL-11.0-157	GC-MS/MS	
*Benzo(a)antraceno	µg/l	6.8	IA-ITCAL-11.0-157	GC-MS/MS	
Benzo(a)antraceno	µg/l	> 1.0	IA-ITCAL-11.0-157	GC-MS/MS	

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