2 ELBAS – WP2: Technological Aspects – Fire Scenarios and Technologies

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2.1 Introduction

2.1.1 Objective

The overall objective of this report is to screen current detection and suppression technologies and methods for maritime and onshore use, presenting design criteria for effective firefighting of electric vehicle (EV) fires onboard ferries. The specific objectives are:

- Technology and methodology review, including detection and firefighting equipment, interviews with manufacturers and qualitative assessment of technologies.
- Description of fire scenarios based on literature reviews, stakeholder interviews (shipowners, land-based emergency services, etc.), visit to ferries, study of current procedures, description of ro-ro spaces and operational modes.
- Modelling of electric vehicles fires onboard of ferries in chosen fire scenarios.
- Summary of lessons learned that can be used for further investigating mitigation strategies and measures on ferries.

2.1.2 Summary

Current detection and suppression technologies onboard ferries may need to be supplemented, due to the specific fire hazards of EV (re-ignition, potential for jet flames, increased production of toxic gases etc.). It is therefore important to ensure early detection and early control of fire spread. Early detection of these scenarios however is not trivial, thus further large-scale testing of systems and collaboration with car manufacturers is the key to overcoming some of these issues. Hydrogen detection is one of the possible options that need to be further tested. Another option would be to take advantage of existing closed-circuit television (CCTV) cameras by combining them with fast detection algorithms. Several suppression technologies may be effective in preventing fire spread to neighboring vehicles and should therefore be tested (e.g., fire blanket, portable sprinkler system and direct injection system). It is also important to provide firefighting training for the crew when using new methods to suppress or extinguish the fire.

Fire simulations of two ferry types are presented in this report: two-tier vehicle deck on an aluminum high-speed catamaran ferry and a traditional enclosed vehicle deck with hanging car deck of a Roro passenger ferry. The effect of different fire locations, different storage arrangements, effects on the aluminum structure, effect of sprinklers and different ventilation conditions were analyzed. Ignited vehicle location, distances among the cars, different heat release rates, HRR curves, sprinkler impact, jet fans operation and general ventilation were investigated. The simulations show that detection times may be longer when the first car ignited is placed in vicinity of the ventilation extraction point, thus, placement of EV cars within the deck may be an important consideration. Further, the simulations showed that detection times depend on the heat release rate curve prescribed, as well as the car location. For the fire curve on EV tests taken from literature using a slow growth rate, the detection times were twice as long compared to a fast-growing design fire curve.

Ventilation of a vehicle deck during a fire showed positive effects on the open vehicle decks of the high-speed ferry in certain locations. Whereas, for the modelled closed vehicle deck arrangement, it was shown that ventilation can become detrimental after a very short time and therefore it is not recommended.

Simulations showed that exposed and uninsulated aluminum structures can reach critical temperatures above the fire, 5 to 18 minutes after the fire starts, depending on the fire location and time for activation of

the sprinklers. This can result in a structural failure or that a car falls on another deck if no cooling action is taken and the fire is allowed to burn. Insulation of the exposed ferry structure is therefore recommended. Early sprinkler activation is the key to stopping the fire spread, the procedures should be developed and simplified with that in mind.

2.1.3 Introduction

The increase of EVs on Danish roads is as a major step towards achieving full climate neutrality by 2050. However, while EVs have obvious benefits for decreasing CO_2 emissions, they present unique and complicated challenges when it comes to fire safety. Ferries offer the attractive advantage of transport over long distances, saving EV drivers both kilometers driven and giving them a potential time to recharge. However, with this increase of EVs comes the increased risk of an EV fire on-board maritime transport. This adds additional demands for shipboard firefighting capabilities, both in terms of training and materials. Since EV fires are already considered complicated to tackle on land, the requirements for successful fire containment and extinguishing at sea presents a pressing need for updating and developing current standards and methods, this is evidenced by serval major projects besides ELBAS, notably: the European Union (EU) project LASH FIRE [1] and the German national funded project ALBERO [2].

The focus of this technical literature review is to address the specific hazards of electric vehicles aboard ferries. There are hazards from other alternative fuel vehicles (e.g., hydrogen fuel cell, natural gas vehicles, etc.), but because these vehicles are not as widely spread as EVs, the current analysis will be focused on the EV hazards. There are two key topics that the review will highlight: Early detection of a thermal runaway (TR) event and fire control methods.

General full-scale fire tests of EVs have been completed to compare the different fire phenomena between electric and traditional combustion engine vehicles [3 - 6]. In addition to these EV fire tests, the Research Institute of Sweden (RISE) has worked on two projects focusing on firefighting techniques in ro-ro spaces [7, 8]. Within the RISE projects were included EV fire tests. The National Fire Protection Association (NFPA) [9] has also worked on a project focusing on emergency response to incidents involving EVs. The NFPA project also included a few EV batteries fire tests. From review of all these tests, it was noted that the fire hazards for an electric vehicle have similar overall phenomena as an internal combustion engine vehicle (ICEV) but differ on several specific fire characteristics:

- Potential for jet flames to be projected from the sides of the vehicle as the superheated electrolyte gases eject from the battery modules.
- Increased rate of fire spread to neighboring vehicles (partially due to the jet flames)
- Slightly higher flame temperatures
- Increased production of toxic gases
- Reignition of vehicle after extinguishment of flaming combustion
- When the battery modules are involved in the fire, it is difficult to apply water directly to the modules.

These different properties of fires involving an EV make some of the traditional tactics for fire extinguishing ineffective. Thus, since there is no universally effective solution to these hazards, the existing methods and techniques need to be reviewed and updated. Additionally, the smoke toxicity aspect will be investigated.

2.2 Literature Review

2.2.1 Smoke from EV Fires and Toxicity

Smoke is a mixture of gases, aerosols and suspended solid particles, resulted from a burning material. Smoke from the burning of an ICEV is toxic and dangerous for health, as it contains CO, HF, HCl, SO_2 and small soot particles. Some gases produced (H_2, N_2, CO_2, methane, CO, HCN) are dangerous due to their asphyxiant action, i.e., these gases easily replace the oxygen in the air or prevent absorption of O_2 into the cells, causing unconsciousness. Others have acute irritant action, such as HF, HCl, SO_2, NO_2. Some studies indicate that the effect from irritants is more significant compared to the asphyxiant effect [10].

The use of batteries in an EV poses an additional source of potentially harmful substances generated during a fire. Smoke from EVs has been shown to contain more HF and some specific metals, such as Ni, Co, Li and Mn [6], compared to the smoke from ICEVs. This augments the health hazard for unprotected people present nearby, as hydrogen fluoride ion can be absorbed through the skin. In the blood it causes disruption in levels of calcium, potassium, and magnesium. The effects of inhalation and absorption through the skin may be delayed for 2-3 days [6]. Lecocq et al. tests showed that hydrogen fluoride yield can be 60% higher in EV compared to a conventional vehicle [5]. Others have reported dependence of HF measured on the type of battery and on State of Charge (SOC). Higher HF yield was noted in pouch cells compared to cylindrical batteries and batteries with lower SOC [6].

When Li-Ion battery ignites and releases toxic compounds, the knowledge of the rate of its release is crucial to fire safety and can indicate the time at which the amount of released toxin will pose health danger for humans. However, the amount of HF released depends on the condition of the battery, (i.e., electrolyte chemistry, SOC, charging state, battery configuration, etc.) thus HF concentrations can vary greatly. Several tests show this wide range of HF emission rates [10, 11]. Moreover, HF has a short half-life of 7 minutes and is easily absorbed by surfaces [6]. This means there is a lot of uncertainty involved in toxic gas release, which underlines the importance of early detection.

For early detection strategies it is important to note that before combustion, the battery releases a mixture of CO, CO_2, H2 and hydrocarbons. The SOC of the battery has been shown to influence the gas yield. These gases have a lower flammability limit (LFL) at 6% and wider flammability range, thus posing an explosion risk. Tests have shown that a period of flammable gases release can vary greatly (from 15 to 40 minutes) without ignition, this brings uncertainty for modeling [6].

Additionally, toxic, and flammable gases can be generated when using sea water as a firefighting medium. Electrolysis of salt water, caused by water impregnating a compromised lithium-ion battery (LIB) pack, can form hydrogen gas and chlorine gas. The rate of generation of these gases is found to be higher than when using fresh water. This must be considered since salt water is used as the primary firefighting medium onboard ferries. This bares consideration since within the closed compartments of a ro-ro ferry the generation of explosive and toxic gases can, if allowed to build up, pose a risk for explosion. Additionally, the generation of these gases can continue after extinguishment if the battery stays immersed in salt water. This is especially the case if the battery has been destroyed or has exposed electrodes as this allows water in direct contact with its metallic components (Li). However, it is not recommended to remove the compromised batteries from the water. Instead, consideration for continued gas generation is important for the responding fire crews. The cooling effect of the water is necessary to prevent the reignition of the battery pack.

2.2.2 Detection

When considering the fire risks of EVs, it is too late for fire prevention once a battery cell within the battery pack becomes compromised i.e., enters thermal runaway. Therefore, early detection is mission critical to reducing the overall fire risk. In the world of EVs, there are a variety of battery types, and more specifically electrolyte chemistries, which widens the scope of an idealized universal solution. An early sign of a potential thermal event within a battery is the off-gas event. When this event occurs, a small concentration of aerosolized electrolyte and vaporized electrolyte is released into the atmosphere. Off-gassing can occur when a battery is exposed to thermal, electrical, or physical abuse. However, the abuse type that has the highest likelihood of pushing a cell within a battery pack into an off-gas event is electrical abuse, specifically overcharging. It has been shown that monitoring for this off-gas event is still one of the better early detection options for predicting a potential thermal event. [12]

The key concern with this detection option is the different electrolytes used by the EV industry which produce a variety of species-specific gases. Baird et al. [13] presented an overview of vent gas composition for different battery chemistries and SOC, showing that hydrogen gas production may vary between approximately 3 to 45 percent of the volume fraction. This summary has shown that vent gases mostly consist of carbon monoxide and carbon dioxide, depending on the state of charge. However, using these gases for early detection may be problematic, as they are normally present within the atmosphere of a ro-ro ship loading and unloading cars. Instead, detection of hydrogen gas may be possible as an early detection method of a pre-thermal event. Temperature monitoring of the battery pack offers another method of pre-thermal detection. However, to do this externally (i.e., not from within the battery pack) gives some additional challenges due to the encapsulation of the battery packs. Detection options post-thermal event however are no different than traditional fire detection options: smoke/heat detectors, flame detectors, IR cameras, CCTV cameras, etc.

Aboard a modern ro-pax ferry, there are several mandatory fire detection devices. All fire safety requirements for ships are specified in their respective sections in SOLAS II-2 [14]. Since the focus of this review is on EV fires, the only area of the vessel that will be addressed is the vehicle deck. Primarily these areas are protected using a combination of smoke and heat detectors. The network of detectors is displayed on the navigation bridge on a monitor overlaying the plan view of the respective deck being monitored. In addition to the detectors, there are numerous CCTV cameras that give the navigation bridge live visuals of the accommodation and vehicle decks. If a detector alarm is triggered, the navigation bridge will be notified, and a response procedure will be followed. Additionally, as a precaution against ignition of flammable vapor build-up in closed ro-ro spaces an air change rate of 10 times per hour of the total air volume is normally required during the voyages. During the loading and unloading operations the flow rate is recommended to be increased to 20 times per hour. These ventilation conditions may impact the traditional and proposed detection and suppression methods.

According to SOLAS Chapter II-2, regulation 7, Detection and Alarm [15], smoke detectors are required in all stairways, corridors, and escape routes within accommodation spaces. The detectors shall be certified to operate in the smoke density between 2% and 12.5% obscuration per meter, when tested according to standards EN 54:2001 and IEC 60092-505:2001. In essence any type of smoke detector may be used as long as you operate within sensitivity limits and avoid unsuitable environments for sensors.

All detectors installed on board ships must be of an approved type, and on European registered ships they must be 'wheel marked' according to the MED directive 2014/90/EU.

2.2.2.1 Point and Line Detection

Smoke detection can be point or line (beam) detection. There are many types of detectors: ionization smoke detectors (not allowed in many countries due to presence of radioactive material), optical, laser, temperature and multicriteria. A common type of detector is the optical smoke detector that utilizes LED light source. When smoke enters the detection chamber it scatters the light resulting in an alarm. This type of detector is good at detection of both flaming and smoldering fires and white/grey smoke. The downside of this detector is its sensitivity changes with time and questionable suitability for environment with car exhaust gases. Laser detectors have high sensitivity that can be adjusted and are less sensitive to dust particles. Multicriteria detectors use several detectors with the purpose of avoiding false alarms (for example, smoke and temperature detectors), but have a higher price. Optical and multicriteria detectors (combination of smoke and heat detector) are commonly used onboard ro-ro vehicle decks and thus need to be tested for their effectiveness for fires starting with EV batteries.

2.2.2.2 Full Room Detection Options

There are several different volume detection systems currently on the market. Active air sampling is a volume detection system that operates by monitoring both the current ambient conditions unaffected by applied hazards and within the hazard (monitored) area. A user defined tolerance is set for allowable gas or particulate species gradient between the two monitoring environments and if it is found to be more than the defined threshold the fire alarm control panel can be set to go to alarm. By using a floating ambient condition this helps prevent a false alarm, for example using a propane powered forklift in a warehouse monitored with this system can account for the exhaust of the forklift and raise the alarm limit. These types of detection networks can be set to a highly sensitive tolerance which may be useful aboard a ro-ro ship's vehicle deck.

Aboard most modern ferries there is a network of CCTV cameras. These cameras provide a multilevel of security monitoring. Within the realm of fire detection, these cameras provide confirmation of fire after a smoke/heat detector activates. An alternative approach uses the fixed CCTV cameras, which can be trained with AI or visual algorithms to detect smoke and/or flames [16, 17]. The sensitivity for detection can be adjusted to accommodate for transient conditions such as steam plumes generated by vehicle exhaust during cold days. Thus, specific cameras overlooking the ro-ro vehicle deck can be trained to monitor excessive smoke production from a vehicle or flaming combustion. This technology has been implemented within engine rooms and proven effective in detecting both smoke and flame. The downside of these converted detectors are visual obstructions since they operate through line of sight and the lack of a dedicated uninterruptable power supply.

Another volume detection technology that is used aboard ferries is UV/IR cameras, which are primarily used in the ship's engine room to detect flaming fire. The combination of UV/IR sensors is good for flame detection and avoidance of false alarms, however these detectors carry a significant price tag, and as such are typically installed only for protect the mission critical regions of the ship. Alternatively, these detectors could be an option to monitor the ro-ro vehicle deck. The major concern with this detection option for battery fires is, however, the fact that once the flame in EV is detected it will be too late to prevent the thermal runaway.

2.2.2.3 *Vehicle Hotspot Detector*

As a part of the LASHFIRE project, a novel detection system has been tested in ro-ro spaces for hot spot detection prior to entering a ro-ro ship [18]. This method uses machine learning to analyze and provide real-time feedback on the heat signatures as a vehicle passes through. The conditions inside a ro-ro vehicle deck might be a challenge which has to be overcome for the system to be effectively used. Moisture, dust, and soot can reduce the performance of the detectors which requires a cleaner, brighter, and clearer atmosphere to perform best. This can be achieved by wipers and air flow barriers which are specifically designed for such detectors.

The sensors can be placed inside the ships or at the terminal. There are challenges for both locations such as weather conditions at the terminal and geometrical constraints if mounted on the ships. Regardless of the location, the sensors can be placed horizontally, vertically or as a combination of both. Once the sensors are mounted, for optimal functioning and operation of the sensors, the vehicle which is being checked should maintain a gap from the sensor without being too close or too far. However, more advanced but more expensive lenses with auto-zooming and focusing can be a solution for this issue.

2.2.2.4 *Discussion*

Ro-pax ferries, like all passenger ships on international or national trade, must meet statutory and class requirements with regards to fire protection, detection and extinction. However, with the new fire hazard of EVs, expansions in their detection capabilities are justified. An early sign of a potential battery failure is the release of hydrogen gas as the electrolyte within the abused battery vents decomposes. However, no significant testing was performed during this project investigating if an off-gassing event within an EV battery could be detected using a hydrogen gas detector external from the battery module. Specifically, a gas detector that is located well outside of the vehicle. The isolation of the battery cells within the battery module helps to protect the batteries from external abuse, but this configuration also prevents easily monitoring the battery with an early detection device.

If hydrogen gas detection is not a viable early detection option, then alternatives need to be addressed, in addition to the existing combination of smoke and heat detectors. A proposed compromise to existing detection methods is to take advantage of the large number of CCTV cameras aboard these vessels. As research into AI evolves and spreads into a variety of industries, this technology can be applied to provide intelligence to conventional devices. Applications of specific algorithms have proven effective for training CCTV cameras to detect flames and even smoke in some cases [16, 17]. If this technology can be proven equally effective as flame detectors, within the setting of a ro-ro vehicle deck, then instead of installing the expensive flame detectors the existing CCTV cameras can be a viable option.

Currently there are a limited number of charging stations found onboard ferries, and there is a serious pushback from shipowners due to the fire risk during charging [19]. In vessels that are already equipped with charging stations there is a potential to focus on early detection options along the charging distribution line. The traditional charging conditions aboard ferries involve carrying cables from the sides of the vessel, across and in between vehicles, to eventually arrive at the charging EV or reefer truck. EV manufacturers (Renault, Volvo. Tesla, BMW) prevent any transfer of data of the battery management system (BMS) through the charging connection. Although no immediate specific data can be collected from the BMS from the charging connection this connection may be a helpful mounting location for a detection device: hydrogen gas, smoke, and/or heat. A base level of these conditions should be determined to see if this detection location is viable. This was investigated further in the ALBERO project [2].

2.2.3 Fire Extinguishment Methods

Fires involving EVs are, in general, more difficult to extinguish than conventional vehicles due to the properties mentioned in section 2.1.3. These properties hinder the extinguishing of the involved EV, increasing the rate of flame spread to other vehicles which increases the fire growth. Therefore, the worst-case scenario will need to be addressed, which is a fully involved EV fire.

2.2.3.1 Current Fire Extinguishment Technologies

The only area of the ro-ro passenger ship being addressed in ELBAS, regarding fire control methods are on the vehicle decks. Onboard a vessel there are several methods for controlling a fire event. For simplicity the methods can be better understood as two primary methods: manual operations and remote operations. The manual operations would consist of the firefighting tactics performed by the fire crews aboard the vessel. Specifically, the personnel in the fire crews involved with manual operations are those with the title of smoke diver. These shipboard firefighters are the personnel who use turnout gear, or Self-Contained Breathing Apparatus (SCBA), and physically fight the fire with their existing equipment and training. The minimum quantity and quality of the manual equipment on a vessel is specified in the applicable SOLAS [14] and MARPOL [20] requirements.

The manual operations focused on the shipboard firefighters who place themselves near the fire hazard. The remote operations are the additional fire crew members who place themselves away from the fire hazard and cascading fire effects such as smoke build-up. Their purpose is to assist the shipboard firefighters with external perspective, prepare tools for use, or operate the fixed fire control systems. These systems consist of the overhead deluge sprinkler system and the ventilation control system.

2.2.3.2 Fire Control Technology and Methods

When the entire EV becomes engulfed in fire, a proportional firefighting response would be expected. The safest response with the existing technology would be remote operation, for example the fixed deluge sprinkler system, which would allow to control fire spread if initiated in the early phase of the fire. The response described above is a preferred one, but there is some uncertainty as to whether the current sprinkler system is sufficient, therefore testing is recommended. It should be noted that most of the tools and tactics recommended here are applicable in specific cases (i.e., in the case of search operations, long trip to the destination at the time of fire onset, reduction of the water usage for stability related issues, etc.).

In review of the existing technology and fire hazard of EVs onboard ferries several fire control methods are proposed. These options can function together or individually and be rapidly implemented aboard ferries without legislative changes. Additionally, the options may not be a universal solution for all ferries but must be adjusted for each case respectively.

2.2.3.2.1 Increased Training on Manual Fire Fighting Operations

Focus on increasing training for the crews helps to address delays in fire response. Specifically, identifying an EV, responding to an EV fire [21], and fire containment tactics [22]. The intentions of advanced training on firefighter tactics for EVs is to shorten the time for fire crew response and increase overall preparedness. This may also be considered relevant for all subsequent methods discussed.

2.2.3.2.2 Fire Blanket

A common fire control device for smothering small fires is the fire blanket. This technology has been improved to be an effective method to address EV fires. These EV fire containment blankets are typically made of proprietary materials to smother a fire. The blankets often come in dimensions roughly 6m x 9m and will fully cover most car type EVs. The blankets have built in handles so that firefighters can physically apply the containment blanket directly onto the burning vehicle. Recorded fire tests have shown effectiveness in quenching EV fires with limited exposure times for the fire fighters. These blankets have promising application onboard ferries due to their ease of mobility and effective prevention of fire spread to neighboring vehicles when correctly and timely applied.

There are concerns, however, about the ability of shipboard firefighters to effectively use this device onboard a ferry. The space available to work with on a vehicle deck is very different from the open parking lots used during fire testing. The reduced mobility onboard a ro-ro ship, along with potential snag points all around the work area may delay or prevent the use of this fire containment option. When communicating with manufacturers offering these products, the reduced mobility for this type of application is a valid concern and they recommend regular training [23]. Additionally, significant risks remain for overcoming roof mounted obstacles on EVs such as cross beams or cartop carriers. A possible solution for this is using multiple blankets and protecting the neighboring vehicles.

2.2.3.2.3 Li-Ion Fire Extinguishing Agents

There are two companies that offer agents specific for lithium battery fires, AVD [24] in the UK and Dafo [25] in Sweden. These systems function very differently regarding the interaction with the fire hazard, but both require direct application to the involved battery. The agent created by Dafo is called Forrex [25]. Currently, Dafo works directly with EV manufacturers and post-production vehicles to integrate early detection and fire extinguishing systems within the vehicles. Application of this agent requires an atomizing nozzle to adequately distribute the agent within the vehicle's battery compartment. Additionally, the system functions in combination with an early detection device [29] so that the thermal event has little time to develop.

The AVD agent, LithEX [24], stands for Aqueous Vermiculite Dispersion agent. This agent is made of a slurry of primarily water with a mix of vermiculate solution. When this agent is dispersed over the involved battery it cools the battery as the water evaporates. The vermiculite then forms an oxygen barrier over the batteries. High temperatures inside a battery will lead to oxidation of electrolyte and production of CO and CO2. Therefore, AVD does not fully stop the process but may greatly retard it. In fire testing with lithium batteries AVD agent is applied directly to the cells or modules [26]. This direct application would not be possible for EV fires onboard ferries as the battery modules will be fully contained within the battery casing inside a vehicle. The two agents are promising fire control agents but without fire testing for EVs external to the battery module there are uncertainties on their effectiveness.

2.2.3.2.4 Mobile Water Mist System

Excessive water weight is a major concern onboard ferries and can cause unbalance and potential capsize on often already top-heavy ferries. A more water efficient option for firefighting, is to use a manually placed water mist system. This system would be an option like the ones seen in the ALBERO project [2]. The concept could consist of two hose lines that feed separate mobile ground applicators (a stainless-steel pipe with specifically oriented water mist nozzles on it) that project a curtain of water around each side of the involved vehicle. This system has been effective in protecting the neighboring vehicles but not 100% effective in extinguishing the involved initial vehicle. This method of fire control method may work best in conjunction with an active smoke control system. The mobile water mist system can control the fire spread and growth while the excess smoke production can be extracted with the powerful ventilation system.

2.2.3.2.5 Direct Injection Systems

EV manufacturers do not recommend first responders to penetrate the battery module, but to apply water directly to exposed battery cells and open sections of the battery module [22]. Nevertheless, fire experimentation done by RISE has shown that direct injection of a cooling agent, be it water or an alternative fire extinguishing agent, is one of the most effective knockdown methods when dealing with EV battery fires [29]. Therefore, an electrically isolated direct injection device to flood the battery module with water may be an effective tactic in controlling the fire event within the battery module of an EV.

An example of a direct injection system is employed by the Rosenbauer Battery Extinguishing System Technology (BEST) [27]. This device penetrates the battery module in the correct area. The Rosenbauer BEST is a wheeled apparatus that is placed underneath the involved EV. The apparatus is connected to a hose line and a standard self-contained breathing apparatus (SCBA) and then it is ready to be used. The working principle of this apparatus is once in position underneath the EV the SCBA powers a pneumatic nail. Once the nail has penetrated the undercarriage into the battery pack, water begins flowing at 8 gal/min (30 l/min) at 100 PSI (6,9 BAR) to cool the battery. This is a novel concept that requires fire testing to prove effectiveness when implemented in a ro-ro ship. Identification of fire origin, and consistency in penetrating to the right depth to reach the burning battery cells may be potential issues to consider. The other concern with this method is that it can be costly, both in time and financial resources, it would require significant training for field applications, and risk increasing the fire hazard if an operator penetrates an uninvolved battery cell.

Another, more flexible direct injection system is an extinguishing e-lance with nozzles from Murer Feuerschutz GmbH [28]. It is designed to be used after the major EV fire is extinguished and there are signs of thermal activities in the battery pack. It is flexible because it is electrically isolated and equipped with different extension tubes allowing adjustments depending on circumstances. However, a sledgehammer is used to penetrate the battery with the e-lance tip. This requires both skill and strength to operate under very extreme conditions. Once the e-lance is placed securely into the battery pack the water can be allowed to run until the battery has cooled down sufficiently.

2.2.3.2.6 Water Submersion System

Submerging lithium batteries in water may not extinguish the fire if compromised cells have reached a thermal runaway event. However, this method will not escalate the hazard. This firefighting method is used onshore by fire brigades, where EV are lifted into a water filled container. Therefore, it is worth considering developing a rapid water submersion tank to surround the battery modules of EVs in water [29]. The concept of this fire control method is a quick field constructed water-tight barrier around the involved vehicle. It would consist of four barriers that can be placed around the vehicle, secured together, and filled with water to submerge the vehicle’s battery module in water. This method is not intended to extinguish the EV fire, but it is meant to control the fire event and prevent the fire spreading to the neighboring vehicles. The concern for this method is significant weight within a small area, but with the allowance of heavy machinery onboard the vessel it may not be a serious concern.

2.2.4 Recommendations and Conclusion

The recommendations and conclusions from the literature review are the following:

- ICEVs and EVs show similar total energy releases when experiencing similar fire scenarios.
- ICEVs and EVs fires vary with respect to smoke toxicity: EVs release higher concentrations of HF and some metals (i.e., Ni, Co, Li, Mn).
- ICEVs and EVs vary with respect to fire phenomenon: EVs can project jet flames and pose a significant risk of reignition, which significantly impact firefighting tactics.
- Further research and testing are needed for early detection methods of EV fires.
- Early detection and fast response by the fire crews is the key to controlling these fires safely.
- Taking advantage of existing CCTV cameras aboard combined with detection algorithms has some potential but needs to be tested onboard in a real setting.
- Advanced training of firefighter tactics for EVs is recommended to shorten the time for fire crew response and increase overall preparedness.
- Blankets and mobile sprinkler systems may be effective in preventing fire spread to neighboring vehicles when correctly and timely applied, but they should be further tested with regards to applicability in a ro-ro ship setting.
- Direct injection methods can be effective but need to be tested in a more realistic condition and if implemented requires in-depth crew training.

2.3 FDS modelling

Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) modelling tool that numerically solves a form of Navier-Stokes equations for low speed ($Ma < 0.3$) thermally driven flow with emphases on the heat and smoke transport from fires [30]. In this work FDS model is used as a tool to investigate chosen fire scenarios. FDS simulations allow the study of different scenarios which otherwise would not be feasible in a full-scale experiment. Once the model is set-up, any new fire safety solution can be tested.

A fire model is a simplified representation of an actual fire event, which means that there are several limitations and assumptions that must be kept in mind when looking at results. A list of limitations and assumptions is given in section 6.

2.3.1 Methodology

Methodology used in FDS modelling consists of several major steps, namely:

1. Categorization of Cars
2. Determination of Design Fires
3. Numerical Modelling of Cold Flow and Mesh Sensitivity Analysis
4. Numerical Modelling of Fire Spread
5. Conclusions

To represent different cars in a fire model simplification was needed. Cars were divided into 5 different categories based on an assumption that a car's calorific potential (i.e., energy) is proportional to its weight [4], see section 6.2 for the details.

2.3.1.1 Design fires

When a ferry vehicle deck of any arrangement is considered, it is possible for a fire to start on any type of car in any given location. However, it is time consuming and not feasible to try out all the possibilities during a numerical analysis. Therefore, it is important to select design fire scenarios which represent a possible high fire risk in the analysis.

The risk associated with EV fires can be higher in certain locations due to the geometry of the vehicle deck and ventilation system used. The geometry or the layout of the vehicle deck might make it difficult for a vehicle to be taken out or even reach the fire seat. Some of the zones within the deck might become recirculating zones or "dead" zones depending on the ventilation parameters leading to slower detection times and localized smoke accumulation. In addition, charging vehicles using an on-board charging station can also be considered as a high fire risk situation and the nearby area can be considered a high-risk area.

All the above details allow the analysis to be focused more on the identified areas rather than running simulations using random locations within the deck. Therefore, the layout of the vehicle decks, ventilation, charging stations and other such details which increase the risk of fire will be considered. The design fires for the analysis are selected based on the above reasoning and several scenarios are selected for two different vehicle decks.

2.3.1.2 Cold Flow Simulations and Mesh Sensitivity Study

As mentioned earlier, ventilation systems used inside the vehicle deck play a key role in the initial detection times and the smoke dynamics inside. Furthermore, it is also important that when the first car is set for ignition that the flow conditions inside the deck stabilize.

Before the introduction of combustion into the numerical model, it is important that the fire scenarios are established. To identify the possible dead zones or recirculation zones, the initial flow field is simulated using only the ventilation system activated ("cold" simulations). This preliminary analysis shows the time required to reach the steady conditions and the dead or recirculation zones, which can cause potential collection of hot gases.

Once this step has been completed, the mesh sensitivity analysis is performed using a simple scenario to test the accuracy of the calculations and find an optimum mesh resolution for the final analysis. The same scenario is modelled using different mesh resolutions, and the results are compared. The selection of the optimum resolution is done based on the accuracy of the results and computational cost for each resolution. Thereafter, chosen design fires are run using the desired optimum cell size selected in this step.

2.3.1.3 Numerical Modelling of Fire Spread

The modelling of fire spread between vehicles is dependent on many factors such as: ignition temperature of the first material to ignite, distance between the vehicles, type of the adjacent vehicle and geometrical features.

When a vehicle catches fire, it is often the tires or the polymer window seal or bumper which catches the fire first [31]. Both components are made of polymers, therefore the ignition temperature of rubber has been chosen as the threshold for catching fire and producing flames in FDS which was set to 250 °C. More studies are required to determine the ignition temperature of the material that is likely to ignite first. The value of fire spread was determined after investigating several values with the aim of reaching a heat release curve closer to the desired one. The value of 0.01 m/s was found to be a satisfactory assumption with regards to the fire spread in ro-ro vehicle deck.

2.3.2 Fire Scenarios

Simulations of two ferry types are presented in this report: a two-tier vehicle deck of aluminum high-speed catamaran ferry based on the arrangement of the EXPRESS 4, and a fully closed vehicle deck with a retractable hanging car deck as on the PEARL SEAWAYS.

2.3.2.1 EXPRESS 4

EXPRESS 4 is Molslinjen’s newest high-speed catamaran ferry, with an all-aluminum construction which has the capacity for 1006 passengers and crew, 425 parking spaces for cars on the vehicle decks and 610 m of truck lanes. The high-speed ferry sails at a speed around 37 knots (70 km/h) when loaded and is 109 m long and 30.5 m wide. Due to the high speed of the ferry, the journeys from Odden to Aarhus and Odden to Ebeltoft can be completed within 75 minutes and 55 minutes, respectively. The EXPRESS 4 is built of aluminum, which makes the ship potentially more vulnerable to the effects of a fire; However, EXPRESS 4 is constructed to and meets all of the statuary fire safety requirements for such vessels, and the ship never sails far from a port.

The ferry has 4 decks with the lowest two decks being the two vehicle decks. The third deck accommodates a seating area for passengers, a restaurant, and a coffee bar.

Figure 2.1: Locations of the vehicles ignited first in different fire scenarios on tier 1 and tier 2 of Molslinjen EXPRESS 4

The two open ended vehicle decks sit just above the twin hull structure of the ferry, see Figure 2.1. Truck lanes are only available on tier 1 which is the lower deck. This deck is also equipped with a charging station which can charge two vehicles at once, using only the 10 m cable provided onboard. Tier 2 is only allocated to smaller vehicles, excluding larger height vehicles such as container trucks. The ceiling heights of tier 1 and tier 2 are 4640 mm and 2140 mm respectively. The two tiers are connected via an internal fixed ramp which is also made of aluminum. Smoke detectors, heat detectors and flame detectors are present on both decks covering the whole area including the area under the ramp. Both decks are also equipped with a sprinkler system which can be activated manually in case of fire.

Before simulating a fire scenario with multiple vehicles on the decks, simulations without fire and simulations of single car fires were run to analyze the flow field within the decks and for the mesh sensitivity study (see section 6.) Several simulations were run representing different fire scenarios which are tabulated below in Table 2.1 with locations explained in Table 2.2 and shown on Figure 2.1. A detailed analysis of these simulations is presented in section 6.8.

Table 2.1: Initially ignited vehicles for different fire scenarios

Tier 1	Charging station – near wall	Location 1 (L1)
	Charging station – central	Location 2 (L2)
	Near air output	Location 3 (L3)
Ramp	On the ramp	Location 4 (L4)
Tier 2	Near air intake	Location 5 (L5)
	Near air output	Location 6 (L6)

Table 2.2: Summary of fire scenarios for Molslinjen

Tier	Location	Distance between cars	Jet fans (on/ off)
1	Charging station – near bulkhead	40 cm	Off after detection
1	Charging station – near bulkhead	60 cm	Off after detection
1	Charging station – near bulkhead	Single car	Off after detection
1	Charging station - central	40 cm	Off after detection
1	Charging station - central	60 cm	Off after detection
1	Near air out	40 cm	Off after detection
1	Near air out	60 cm	Off after detection
Ramp	On the ramp	40 cm	Off after detection
Ramp	On the ramp	40 cm	On
Ramp	On the ramp	60 cm	Off after detection
2	Near air in	40 cm	Off after detection
2	Near air in	40 cm	On

2	Near air in	60 cm	Off after detection
2	Near air out	40 cm	Off after detection
2	Near air out	60 cm	Off after detection

Several variables were varied in simulations described above: location of the initially ignited car and distance between the vehicles was varied between 40 cm and 60 cm. Additionally, jet fans were either switched off or switched on to see the impact on detection time and visibility.

2.3.2.2 PEARL SEAWAYS

MS PEARL SEAWAYS was built in 1989 initially for Viking Lines and later refurbished back into a car-passenger ferry for DFDS. It currently operates between Copenhagen and Oslo with a stop in Frederikshavn. In 2010 the ship experienced a fire in an EV left charging onboard located in the aft on the port side [19]. After the fire she was refitted and given its current name. The vehicle decks consist of two decks (deck 3 and 4), where deck 4 is a hanging car deck, which is accessed via a ramp that can be lowered down, when needed. The models of a closed vehicle deck used in ELBAS are based on DFDS's PEARL SEAWAYS layout and geometry. Dimensions precision when modelling is dependent on the size of the largest mesh chosen (i.e., in this case a mesh of 20x20x10 cm was used). See the mesh sensitivity analysis for further details in section 6.7.2.

When a fire is detected onboard PEARL SEAWAYS, the ventilation is switched off manually. The time to ventilation shut down will depend on the situation and decision times of people in charge. Generally, the crew has two minutes to react before an alarm sound goes out to the passengers. Therefore, this time of two minutes is used in the current simulations to close the ventilation. Closing of the air exhaust vent is done using a ramp function in FDS. Moreover, only the largest central air intake openings are closed at the same time, keeping few smaller openings left, assuming that the vehicle deck is not completely airtight. All these actions are undertaken to avoid the creation of pressure changes that may result in numerical instabilities in the simulation. Additionally, a system of jet fans is installed on the vehicle deck, but it was used once during construction works and since then has been obstructed by ceiling installations, deeming it useless for smoke control purposes.

Distances between the cars onboard a ro-ro ship vary depending on the number and types of cars being loaded. According to the internal rules at PEARL SEAWAYS, when stowing and securing vehicles onboard, the recommended distances between the stowed cars are: 100 mm between the extremities of the car, 300 mm between the bumpers and 200 mm between a car and any fixed object. It was found however that these distances can often vary as smaller or larger spacing. In FDS simulations the distance choices are mesh dependent. (The mesh sensitivity analysis in section 6.7.2) and concluded in the distance between bumpers being set to 20 cm, due to distances of 25 cm measured onboard. Between neighboring cars two different distances were tested: 20 and 40 cm.

Simulations for the PEARL SEAWAYS cases were varied in respect to the choice of ignition Heat Release Rate (HRR) curve, distance between the cars in the lanes, position of the car for ignition, ventilation, and sprinkler activation. Additionally, assignment of HRR to the cars besides the ignition car was done using a randomization algorithm. Based on the categories described in section 6.2, the HRR curve for EV vehicle to be first ignited was designed based on the car weight categories and compared to HRR for a full-scale EV vehicle test. These comparisons are detailed in section 6. In simulation 40_5, the ventilation was kept at 20

m^3/s. After the fire started, it was activated to full capacity at 56.94 m^3/s to see the impact on smoke dynamics.

The modelling of sprinklers is challenging, and it is still not a well-validated capability in FDS. Hence, potential impact of sprinklers in the simulations 40_6 and 40_7, shown in Table 2.3. These simulations were modelled with so called freezing of HRR. In freezing of HRR it is assumed that the HRR will remain constant after the activation of deluge system, representing the sprinklers impact on preventing further fire growth. The two cases represent the estimated time interval for sprinklers activation, where the time to activation and minimum/maximum reaction time were accounted resulting in freezing of HRR after 337 and 537 seconds, respectively.

Table 2.3: Summary of fire scenarios for PEARL SEAWAYS

Simulation ID	Description	Ignition car, peak HRR [kW]	Distance between cars [cm]	Car position [zone]
20_1	Distance between cars 20 cm	10441	20	1
40_1	Distance between cars 40 cm	10441	40	1
40_2	Ignition in zone 2	10441	40	2
40_3	Ignition in zone 3	10441	40	3
40_4	Test fire curve	7069	40	1
40_5	Ventilation on	10441	40	3
40_6	Sprinkler – 5 min	10441	40	2
40_7	Sprinkler – 10 min	10441	40	2

Cars are placed in zones shown in Figure 2.2 below. In zone 1, the ignition car is in the corner under the deck, in zone 2 and zone 3 the ignition car is surrounded by other cars from all sides and located under the ramp.

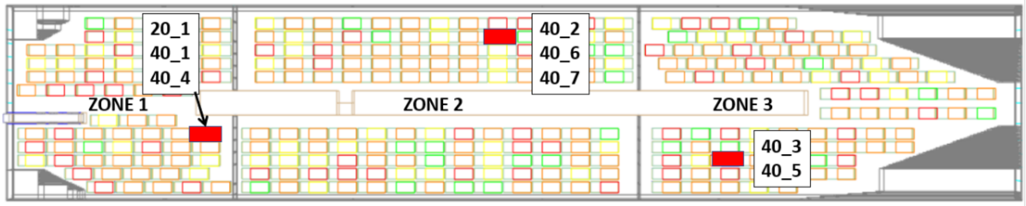

Figure 2.2: Positions of the cars for different fire scenarios in zones 1, 2 and 3 are marked red. Location of the car is marked with corresponding fire scenario numbers.

2.3.3 Simulation Results

Simulations can be very useful to identify issues and behavior of fire and smoke, but the results of such simulations are dependent on the geometry. The results presented below are based on the two case studies of ships and, therefore, any generalizations should be done with care. There is a need to perform this type of study more often to better quantify and inform owners and the crew of the specificities of their ship. Detailed description of simulation analysis can be found in section 6. Below, only the conclusions for respective ship type are presented.

2.3.3.1 EXPRESS 4

The effect of different fire locations, different parking arrangements, effects on the aluminum structure and different ventilation conditions were analyzed from the simulations run for different scenarios. Ignited vehicle location, distance between the cars and jet fans operation are the parameters that were investigated. The scenarios modeling flame spread did not have the sprinkler system (drenchers) on the vehicle deck activated. This was chosen in order to examine the '*worst case*' fires scenarios, modeling smoke and flame spread, and temperature rise.

Fires starting near the aft air outputs of the two decks showed longer detection times compared to other locations due to the layout of the detection system and the natural flow pushing the smoke away from the detectors nearby. In all cases the time taken between the detection and the time when flames spread to a second vehicle were much lower than the 10 minutes requirement for the crew to gather and prepare for the firefighting. The time for the fire spread to the next car varied from around 2 to 7 minutes.

Increasing the gap among cars from 40 cm to 60 cm resulted in longer fire spread times to an adjacent car, but with similar detection times for all the cases. This increased the time interval for the crew to gear up before the flames ignited the second car from around 3 to 8 minutes. This shows the importance of evenly distributing the cars on the two decks, especially during the low seasons, hence having a larger distance between the cars.

Keeping the ventilation system turned on during the fire, seems to have a positive effect for the fires occurring in the higher deck (tier 2). While for fires occurring on the ramp and on the lower tier 1 seem to benefit from just the natural air flow, without the need of jet fans. For the fires in tier 2, the jet fans were able to clear smoke and gases out and provide a path to the fire seat from tier 1 via the ramp to tier 2.

In some of the simulations preformed, the exposed, uninsulated deck plating of tier 2 reaches unsafe temperature at around 5 minutes into the fire with a fire occurring on the fixed ramp forward and could lead to a structural failure of the mezzanine deck (tier 2), when the sprinklers are not running. For fires in tier 1, the structure of the mezzanine deck takes around 18 minutes to reach these temperatures by which time, the crew should be able to reach the fire and cool down the surroundings. A failure in the mezzanine deck should not affect the whole superstructure. On the other hand, it could cause a car to fall from tier 2 to tier 1, which can lead to complications. This could potentially be avoided, by placing insulation covering the exposed area and ensuring that the sprinkler system is actively cooling. In all the cases, the deck flooring of the passenger deck never reached untenable temperatures and the insulation was effectively providing protection throughout the fires.

2.3.3.2 PEARL SEAWAYS

Chosen scenarios have shown that flame spread is dependent on location of the ignited vehicle. This can give an indication for a location of charging station or a zone for EV storage. Simulations showed that keeping the ventilation on during the fire can be dangerous if the deluge system is not activated within the first 10 minutes of the fire duration. The reason for this is that in the tested fire scenario ventilation was able to control a smaller fire for a short period of time, but once the fire spreads ventilation served as an oxygen supply and could not evacuate the smoke produced. Therefore, having ventilation on for the whole duration of the fire is not recommended.

The detection times for design fire curve (10,441 kW) are in order of 30 seconds, changing slightly depending on the ignition car placement. With test fire curve (7,069 kW) the detection time can be over 1 minute. It can even take a longer time because the test fire curve in this scenario was modified and the starting stage with extremely low heat release rate was cut out. This shows the need for alternative early detection methods. If sprinklers are activated within 5 minutes from the fire start in the right zone, then the fire can likely be contained for these types of fire scenarios, as it was observed in simulations and in live fire tests that in worst case scenario a fire can spread from one car to another in about 5 minutes.

The most favorable conditions can be created using early activation of the sprinklers in the fire location. It is important to be able to see the sequence of smoke detectors activation, especially for a decision on which of available zones to activate when a fire is detected in the middle of the ship (zone 2). It is possible to activate two sprinkler zones at a time. Nevertheless, to fully control a fire in zone 2, an activation of 3 sprinkler zones is required, detailed further in section 6.7.2. Whereas a fire in zones 1 or 3 can be fully controlled by two zones, assume that sprinkler activation is done at an early stage (5-10 minutes after the fire starts). This shows the importance of making sure that in case of a fire, the smoke detectors activation order is clear to the decision takers.

The placement of the cars with as large distance as possible also gives a time advantage. In the scenario when cars were stowed 20 cm from each other the second car ignited after 4.3 minutes and for distance 40 cm ignition occurred at 7.3 minutes. This gives approximately 3 minutes delay in fire spread to the second vehicle when cars are stowed at 40 cm compared to 20 cm, valuable time for the crew to react. The position of ignition vehicle in the aft based on the current scenarios is a favorable condition, both due to difference in a fire spread and better ability to control the fire. Nevertheless, a fire in 2010 may have happened in a most favorable location but was unfortunate to spread to a heavy vehicle placed nearby and to the other side of the nearest flood door (zone 2) due to the late sprinkler activation over the ignition source [19].

Tenability conditions are the conditions (such as smoke layer height, temperature, visibility) that are predefined to designate the available safe egress time (ASET). These conditions are specified for spaces where egress time for unprotected people is relevant. In the case of vehicle decks, no passengers are allowed for the whole duration of the trip. Tenability conditions in this case can be defined to see whether the crew can safely enter the space and/or reach the seat of fire. If the crew must enter to manually fight a fire on the vehicle deck, an entrance/exit in the aft is not recommended due to the steep staircase that in a stressful situation with heavy equipment may cause an injury. The optimal places are the entrances in the central part. Nevertheless, these entrances are not directly connected to each other and demand experience of being able to find a way up and down the stairs and past the cabins. It is then of high importance to identify the first detection locations to predict which direction the smoke will be spreading the most. For example, if the fire has started in zone 1 and no time is lost (fire is controlled within 5-10 minutes by drenchers), then the crew may consider using the closest exits. If the fire has been ongoing for more than 10 minutes, it would be safer to enter through the further exits, considering on which sides the fire has started.

2.3.4 Recommendations and Conclusions

The recommendations and conclusions presented below are based on the two case studies presented in this report, any generalizations should be made with care. There is a need to perform this type of study more often, to better quantify and inform owners and the crew of the specificities of their ship. Results presented in this section are based on the detailed analysis outlined in greater detail in section 6 (WP2 Appendix: Technological Aspects - Fire Scenarios and Technologies).

- Detection times may be longer when ignition car is placed in vicinity of ventilation outlets on Molslinjen. Thus, specific placement of EVs could be helpful.
- Detection time for a slow growing EV fire often observed in large-scale tests can be longer (double, compared to a fast-growing fire), thus development and testing of alternative early detection methods is recommended.
- A larger gap between two cars implies the flame spread might take longer allowing more time for the crew to muster and gear up before fighting the fire.
- Keeping the ventilation system (jet fans) running onboard the EXPRESS 4, may have a positive effect for smoke control during a fire on the upper vehicle deck (tier 2). On the enclosed vehicle deck (PEARL SEAWAYS) running ventilation during the fire may be dangerous and may lead to a fire spreading after 10 minutes.
- Exposed and uninsulated aluminum structures on EXPRESS 4 can reach critical temperatures from 5 to 18 minutes after the fire starts depending on the fire location and result in a structural failure. Insulation of ferry structures that can be exposed to fire is recommended.
- Time that crew has before the fire spreads to neighboring vehicles may vary between 2 and 6 minutes depending on the ship and location, according to tested scenarios.
- Early sprinkler activation is the key to stopping the fire spread, simple and clear procedures should be developed for this purpose. In cases where drencher zones (PEARL SEAWAYS) are not following the flood control door zones, the decision on the activation should be supported by information on sequence of detection activation, as well as visual inspection.
- In low season, cars should be distributed on all decks to minimize the risk of fire spreading to adjacent cars.
- It is recommended to perform simulations for each specific case, as the results will depend on geometry.

2.3.5 Modelling and Simulation Approach

One of the original purposes of this project was to investigate how fire simulation can give insights into how fire and smoke can spread within a ro-ro vehicle deck, and how current fire protection methods e.g., detection and suppression, perform given different simulated scenarios of an EV fire. The advantages of using simulation tools, is that it allows large, "*real*" scenarios to be investigated without having to test in an actual ship.

Within the world of Fire Safety Engineering (FSE), there are specifically design computational tools that allow FSEs to run fire scenarios and investigate the potential risks, consequences and life and property safety. The use of these tools is common practice in the design of buildings. However, this type of fire and life safety analysis seems to have found little traction in the maritime industry, even though these tools, typically implementing a form of computational fluid dynamics (CFD) for simulating smoke and fire development, would be applicable to e.g., ships just as much as they are used for buildings.

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