Fire hazards onboard unmanned vessels

Fire protection of unmanned ships with conventional solutions

Joni Nylander

Master of Engineering in Autonomous Maritime Operations

Novia University of Applied Sciences

Helsinki Finland 16.12.2021

MASTER'S THESIS

Author: Joni Nylander

Degree Program: Master of Engineering

Specialization: Autonomous Maritime Operations

Supervisor(s): Johanna Salokannel

Title: Fire hazards onboard unmanned vessels - Fire protection of unmanned ships with conventional solutions

---

Date: December 16th, 2021 Number of pages: 55 Appendices: 1

Abstract

The maritime industry has witnessed several accidents caused by fires and history has proved that fires can even result in the loss of ships or human lives. Now shipping is becoming more autonomous and ship's crews are being reduced, creating new challenges for the fire management of future ships. The main aim of this thesis is to find out whether the fire safety of unmanned vessels can be ensured with the existing fire protection solutions.

The theoretical part of the thesis briefly introduces the physics behind fire and principles of fire extinguishing methods. Several different research papers were reviewed to obtain information on what these existing firefighting and fire prevention systems are and how they could be utilized to ensure the fire safety of unmanned vessels. The thesis presents most common fire extinguishing and fire detection systems, structural fire protection and potential high-risk sources.

Data on the suitability of existing systems for unmanned vessels was collected from a survey of 13 respondents as well as from the author's own work experience. The results show that unmanned ships can be equipped with a suitable combination of existing fire protection systems to ensure the fire safety of future ships. However, there is still much room for improvement, especially in the reliability of fire detection and fire management of new energy sources.

Language: English Key words: Autonomous maritime operations, fire hazards, unmanned vessels, fire protection

---

Table of contents

Appendices

Appendix 1. Questionnaire - Fire Hazards Onboard Unmanned Vessels

Definition of terms

CCTV	Closed-Circuit Television
CO2	Carbon Dioxide
DNV	Det Norske Veritas
DNV GL	Det Norske Veritas & Germanischer Lloyd
FSS Code	International Code for Fire Safety Systems
FTP Code	Fire Test Procedures Code
GHG	Greenhouse Gas
Halon	Halogenated Hydrocarbon
HFO	Heavy Fuel Oil
HRR	Heat Release Rate
IAS	Integrated Automation Systems
ICE	Internal Combustion Engine
IMO	International Maritime Organization
IR	Infrared
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MGO	Marine Gas Oil
SOLAS	Safety of Lives at Sea
STCW	The International Standards of Training Certification and Watchkeeping
THR	Total Heat Release
UV	Ultraviolet

1 Introduction

Fires are one of the most critical accidents that ships can encounter. Fires are a serious risk for cargo and persons onboard and even a total loss of the ship or lives is possible. Ships' crews play an important role in fire prevention, fire detection, firefighting and fire management. The International Standards of Training Certification and Watchkeeping (STCW) code sets minimum requirements for the safety training of seafarers. But what if there are no people on the ships in the future? Several questions may appear, such as whether the fire alarm is real and caused by a fire, whether it is possible to extinguish with portable fire extinguishers or whether a fixed fire extinguishing system needs to be activated. This situation can be complicated regarding unmanned vessels and answers to the questions need to be found in some other way.

As said, fire is one of the most critical accidents threatening ships. According to Zhang (2000, p. 3), the statistics shows that the reasons for fire incidents onboard, in a majority of cases, fall into one of these two categories:

- Failure of the provisions and arrangements in the ship as designed, or
- Failure of the human element to respond adequately to events.

The majority, approximately 80%, of maritime casualties are due to human error. This is a good thing for autonomous maritime operations, but it cannot be ignored that highly automated ships are still designed and constructed by humans. Unmanned ships must be designed and constructed even more reliably than manned vessels, because in case of a malfunction, there are no people to solve the problem that has appeared.

A major part of fire prevention takes place before a fire breaks out. Safety of Lives at Sea (SOLAS) provides basic principles for structural fire protection, fire detection, fire-extinguishing appliances, cargo handling and cargo storage. These principles follow ships all the way from the design table to the ship graveyard. If we look at history, maritime safety has often been improved after disasters, with the adoption of new conventions and regulations. The shipping industry is now at a point where we are steps away from autonomous and unmanned vessels and safety aspects need to be put in order before some disaster appears and forces authorities to react.

Obtaining reliable fire safety for unmanned ships will probably be more expensive and challenging than for conventional ships. Replacing human firefighters' mobility and situational awareness will be challenging and increase construction costs. It is obvious that unmanned vessels will be equipped with several different sensors and detectors as well as various fire detection and extinguishing systems, and this will make this research more interesting and provides new professional perspectives for the author and readers.

The author has more than ten years working experience as an engine officer onboard passenger ships and naval vessels. These vessels are designed and operated in different ways and information from a variety of sources is valuable in understanding the different opportunities and challenges involved in researching appropriate fire protection for unmanned vessels. The author also is a trained electrotechnical rating, and that ensures an understanding of this important area as well.

1.1 Problem formulation

The main question of the thesis is: Are the existing firefighting and fire prevention solutions suitable to ensure fire safety on unmanned vessels?

Conventional ships are protected with several different types of fire protection and detection systems. Ship fire protection consists of many systems such as structural fire prevention, several types of fire detectors, portable and fixed fire extinguishers, firefighters and people on fire management. But as we know, future ships are in many cases something else than conventional ones. For example, ships may not have firefighters onboard, ships may be designed totally differently, ships can be operated remotely, or ships can use a new type of energy as power source.

The real problem begins when a fire breaks out on a ship, and it is time to react to the threat that has arisen. Are the fire protection systems designed for conventional vessels also effective and reliable for unmanned vessels or should something completely new be developed?

1.2 Aim and delimitation

This master's thesis studies the suitability of existing fire protection and fire protection systems on unmanned vessels. The level of these systems sophistication, minimum requirements and the accepted effectiveness must be regulated and properly enforced by the maritime authorities, so no specific recommendations on this topic are given in this work. The main purpose of this thesis is to research advantages and disadvantages of different existing fire protection systems and see if they can ensure the fire safety of unmanned vessels. The thesis will not directly recommend any specific fire protection method that is suitable for all unmanned vessels.

1.3 Research problems

To achieve the desired results, it is necessary to understand fire as a physical process. It is also necessary to get familiar with what kind of fire protection systems markets offer and how widely they are installed on conventional ships. The working method of the systems and how they have succeeded in case of a fire is also important for this thesis. The differences between conventional and unmanned vessels need to be clarified and it must be investigated whether there are critical differences that must be remedied. This provides perspective to compare advantages and disadvantages of different systems and whether these systems can ensure the fire safety of unmanned vessels.

This thesis consists of seven main chapters. The first chapter is an introduction to the research project. Chapter two is theoretical, and it introduces the physics of fire and the main fire extinguishing methods. The physics behind the fires is a huge entity, so in this thesis it is described only as much as is necessary for understanding the fire extinguishing methods of the fixed fire extinguishing systems.

Third chapter is also theoretical, and it introduces fire prevention, fire detection and fire extinguishing systems used in fire protection of conventional vessels. It is important to have a knowledge of these systems before proceeding to study their suitability for unmanned vessels.

Chapter four is the methodological part of this research work. In this part the methodology of the thesis is described, and it is explained how data collection, selection and analysis are made. In chapter five the results of the established questionnaire are presented and analyzed.

The main subjects of the questionnaire are following:

- Fires onboard conventional vessels
- New energy sources

- Fires onboard remotely controlled and unmanned vessels

Chapter six is for discussion and recommendations. In this chapter I will go through my thoughts, compare fire prevention, fire detection and fire extinguishing systems and describe how they could be suitable for unmanned vessels. Chapter seven is for conclusions where the research project is summarized. In this chapter I will introduce some ideas that could be subject for further research projects.

2 Fire and fire extinguishing methods

The purpose of the following chapter is to give the reader a basic idea about fires and fire extinguishing methods. It is not an all-encompassing explanation, but it presents important facts in a nutshell to obtain the necessary information for this thesis.

A burning that causes or can cause damages can be identified as a fire incident. Burning is a chemical reaction between oxygen and fuel causing high temperature and light. Substances can burn in two different ways; either smoldering or with flames. In smoldering burning the chemical reactions occur on the surface of the burning substances. When chemical reactions take place in gaseous substance it results visible flames. Smoldering fires are possible when combining oxygen, fuel and enough heat. Burning fires are dependent of four things: oxygen, heat, fuel and a chemical chain reaction. This can be illustrated by the fire triangle, which is a simple model that helps to understand the necessary ingredients for most fires. (Hyttinen et al. 2019, p. 17-18.)

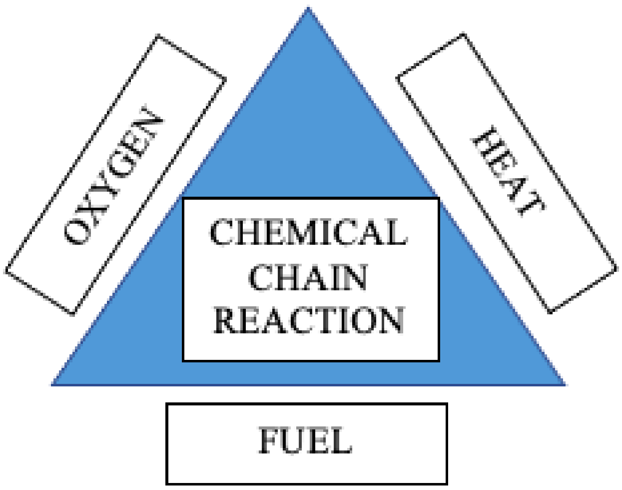

Figure 1. Fire triangle

Fire extinguishing can be determined as elimination of the prerequisite for burning. Removing any of these prerequisites will prevent the fire. If more prerequisite are removed, the extinguishing will be more effective. Fire extinguishing methods can be divided into four methods: Cooling, Smothering, Starvation and Interruption of the chemical chain reaction of the burning. (Hyttinen et al. 2019, p. 84.)

Cooling is a method in which heat is removed by lowering the temperature to the limits where the fire will extinguish. The most common method of cooling is to absorb the heat from the fire into an extinguishing medium, such as water or foam. Temperature equalizing is a method to cool down the burning liquids in tanks by mixing the hot surface with cooler liquid. When the temperature of the liquid cools enough, it is not capable to produce flammable gases and the fire will extinguish. Isolation of the heat and burning substance is a typical method to extinguish burning liquids, although it is also suitable for extinguishing solid substances. Flammable gases are not produced if the heat source is isolated from burning substance. Typical isolation mediums are foam and powder. Extraction of smoke removes huge amounts of heat and cools down the temperature of the fire. Smoke extraction can also be categorized as a starvation method because the removed smoke contains combustible particles. (Hyttinen et al. 2019, p. 84-88.)

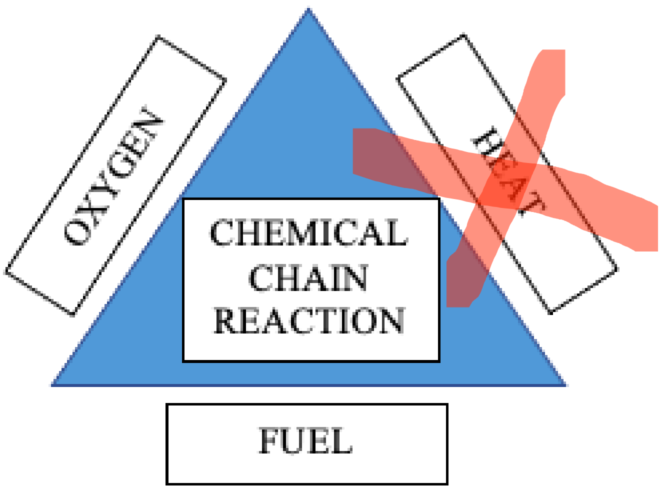

Figure 2. Fire triangle illustrating a cooling fire extinguishing method

In smothering, the oxygen level of the fire is reduced to the level at which the fire is no longer able to burn. Most of the blazing fires will extinguish if the ambient oxygen level is reduced to 12-15%, but smoldering fires can burn even at lower levels. Isolating the burning substance from ambient air or other oxygen supply, will make the fire itself consume oxygen level to that point where it is no longer able to burn.

Inerting is used for fire extinguishing and fire prevention. Inert is a non-combustible gas and is used to lower the oxygen content around the fire to extinguish the fire. In fire prevention, inerting systems are used to lower the oxygen content in the protected area, for example in tanks containing flammable liquids. (Hyttinen et al. 2019, p. 88-91.)

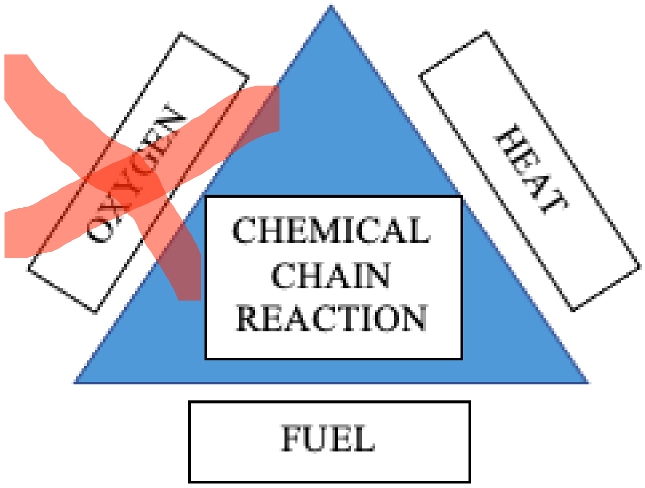

Figure 3. Fire triangle illustrating a smothering fire extinguishing method

Starvation means the isolation of burning or flammable substance. For example, the supply of flammable gas or liquid is shut off or moved away from the fire. If the fire is in a tank containing a flammable liquid, it is possible to transfer the liquid to another tank and the fire will extinguish in the absence of a combustible substance. (Hyttinen et al. 2019, p. 92-93.)

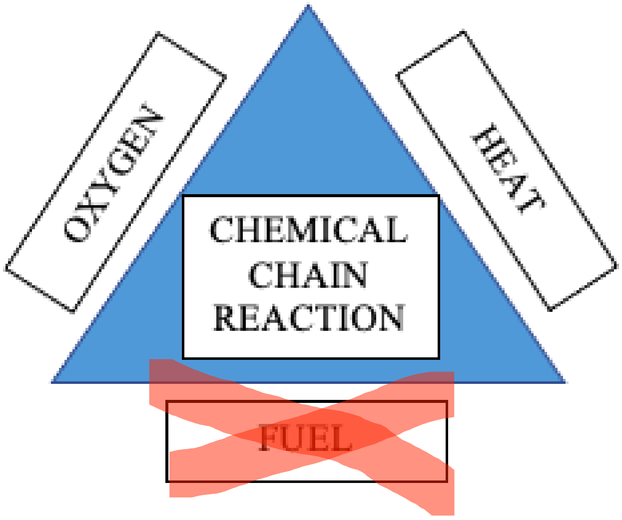

Figure 3. Fire triangle illustrating a starvation fire extinguishing method

Flame inhibiting is interruption of the chemical chain reaction of the burning. In smoldering burning the chemical reaction occurs on the surface of the burning substance, so this method is suitable only for flaming fires. Flame inhibition can affect the fire by chemically deactivating the intermediate free radicals or by physically placing molecules of the extinguishing agent in between the reactive species producing the non-continuation of the chemical chain reaction. (Hyttinen et al. 2019, p. 94-95.)

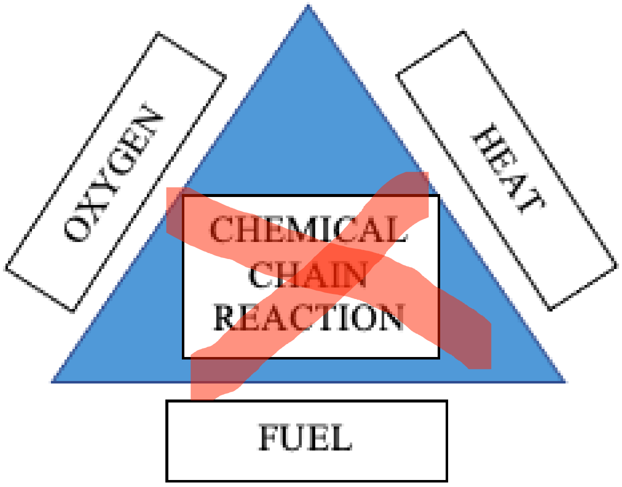

Figure 4. Fire triangle illustrating interruption of the chemical chain reaction of the burning

3 Fire safety on conventional ships

Although the number of fire incidents is relatively small in relation to other accidents at the sea, fire incidents can be identified as one of the main causes of the accidents, as the damage caused by the fires are often considerable (Häkkinen et al. 1996, p. 1). The key to successfully made extinction is to detect the fire early and remove one or more of the requirements of burning before the fire has reached a fully developed state.

SOLAS 74 Chapter II-2, regulation 2 provides functional requirements for fire protection of the ships:

- division of ship into main vertical zones by thermal and structural boundaries;
- separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries;
- restricted use of combustible materials;
- detection of any fire in the zone of origin;
- containment and extinction of any fire in the space of origin;
- protection of means of escape or access for firefighting;
- ready availability of fire-extinguishing appliances;
- minimization of possibility of ignition of flammable cargo vapour.

According to Zhang (2000, p. 2-3), the fire protection onboard can roughly be divided into three main parts: structural fire protection, fire detection and fire extinction. Structural fire protection can be classified as passive protection and is intended to prevent fire outbreaks and in a case of a fire to prevent the fire spreading. Fire detection and fire extinction can be identified as active fire protection due to their active characteristics and the main purposes are simply fire detection and fire extinction.

Statistics provided by the Norwegian classification society Det Norske Veritas (2000, p. 2) presents that engine rooms are the most common places where fires have started. Engine rooms are leading the statistics with 63 percent when cargo areas have 27 percent and accommodation areas only 10 percent. Approximately half of the fire incidents occur when a ship is at sea and no shore side external assistance is available.

3.1 Fire detection

The first and most important thing in the event of a fire is to detect the fire as soon as possible so that fire extinguishing can be started in the initial stage of the fire. Fire detection systems play a vital role in fire management and are stated as a main element in SOLAS chapter II-2. *"The fixed fire detection system shall be capable of rapidly detecting the onset of fire"* and *"After being installed, the system shall be tested under normal ventilation conditions and shall give an overall response time to the satisfaction of the Administration"*. When a detector recognizes the fire, the system shall initiate a visual and audible fire detection alarm signal at the control panel and indicating units. The alarm signal should include information of the active detector or at least the active section.

Fire detection systems may be individual or connected to ship's decision management system. Fire alarm system may be arranged with output signals to several other fire safety systems. All following systems listed by SOLAS chapter II-2 can be monitored and controlled remotely.

- paging systems, fire alarm or public address systems;
- fan stops;
- fire doors;
- fire dampers;
- sprinkler systems;
- smoke extraction systems;
- low-location lighting systems;
- fixed local application fire-extinguishing systems;
- closed circuit television systems;
- other fire safety systems.

3.1.1 Fire detectors

Detectors operated by heat, flame, smoke or other products of combustion, or combination of these factors are allowed in International Code for Fire Safety Systems (FSS Code). Detectors shall be located for optimum performance and the FSS Code lists several demands and restrictions on detector placement (IMO, 2015).

Heat detectors are suitable for rooms where other detector types may give false alarms due dirt or hot ambient air. Heat detectors can only be used in rooms where fire cannot spread into surrounding rooms and the heat caused by the fire reaches the detector. Usually, this type of point heat detectors may be disturbed by airflows from ventilations or fans and are slow to react before fire is burning with flames. (Kojo, 1996, p. 27.) According to Zhang (2000, p. 37), the most used sensing element type in heat detectors is bimetallic contact. Maximal heat sensitive detectors (M-detector) are activated when surrounded air temperature exceeds a predetermined value and mechanical bimetallic strip bends and close or open the loop. Differential thermal detectors (D-detector) will give an alarm if surrounded air temperature suddenly increases. Differential Maximal heat detector (DM-detector) is a combination of D-detector and M-detector.

FSS code has set 37 m^2 as the maximum surveillance floor area per heat detector. The maximum distance away from bulkheads is 4.5 meters and the distance between detectors shall not exceed 9 meters. (IMO, 2015.)

Flame detectors cannot detect smoldering fires, so FSS Code has stated that flame detectors shall only be used in addition to other fire detectors. Flame detectors are used in open spaces and spaces of large height or high ventilation where other detectors may have problems detecting smoke or heat from the fire. Flame detectors operate with infrared (IR) and ultraviolet (UV) spectral regions or combinations thereof. Infrared flame detectors are commonly used indoors because it is more sensitive and can operate even in dusty conditions. Ultraviolet flame detectors are used for outdoor surveillance because they are not sensitive to giving false alarms caused by solar radiation, as the wavelengths of the sources are different. (Kojo, 1996, p. 29.)

According to Zhang (2000, p. 38), the smoke detectors can recognize slowly growing fire and operate earlier than heat or flame detectors. Particle size of smoke varies a lot depending on what material is burning and what is the phase of the fire. Smoldering fires produces white high reflective smoke where particle size is 0,1 µm and flaming fires produces dark or almost opaque smoke with a particle size of only 0,01 µm. For this reason, it is important to consider which detector is appropriate for each protected room. (Tuomisaari, 1996, p. 19.)

Smoke detectors can be divided into optical and ionization detectors according to the operating principles. Ionization detectors have a measuring chamber and comparison chamber with electrodes. When smoke or other particles reach the measuring chamber, the current between electrodes differs compared to electrodes in comparison chamber and an alarm is given. Ionization detectors are most sensitive when particle size is small. (Tuomisaari, 1996, p. 19.)

Optical smoke detectors have two operating principles. Optical smoke detectors have light source, typically infrared, and photoelectric measuring cell in a chamber. When smoke or other particles enter the chamber between light source and measuring cell, the measuring cell recognize that sent light intensity has decreased and gives an alarm. The other operating principle is to point light source and photoelectric measuring cell so they cannot see each other. When smoke or other particles enters the chamber and scatters light, the photoelectric measuring cell recognizes the sent light and alarm is activated. Optical detectors are most sensitive when particle size is large. (Tuomisaari, 1996, p. 19.)

Smoke detectors are sensitive to be disturbed by airflow, steam, dust or other impurities, so FSS Code has set also demands and restrictions for placement of smoke detectors. Maximum surveillance floor area for smoke detector is 74 m^2 and the distance between detectors shall not exceed 11 meters and maximum installation distance from bulkhead is 5.5 meters (IMO, 2015).

Research paper by Zhang (2000) shows the response order of different type of detectors in fire tests. Seven different types of detectors were installed in the test room. The size of the room was 5 x 6 x 2,5 meters. In the first test the burning substance was gasoline. As the gasoline was burning without smoke, the only activated detectors were flame detectors. Both IR- and UV-detectors responded in a few seconds, while the other detectors did not respond within 10 minutes.

In the second test, oil was burned, which also emerged some smoke. The flame detectors responded again within few seconds and Gas detector was following in 30 seconds. Ionization smoke detector was activated after 3 minutes and it took 5 minutes for the optical smoke detector to activate. After 7 minutes of initiation of the fire, the heat detectors activated. (Zhang, 2000.)

In the third test the burning substances were wooden pieces. Fire produced a lot of smoke before flames occurred and the first active detector was the gas detector. The flame detectors reacted quickly when the flame came out, but the emerged smoke did not reach the smoke detectors immediately. The generated heat quantity was small and therefore the heat detectors did not respond. (Zhang, 2000.)

3.1.2 Video surveillance

According to Detection systems in open ro-ro and weather decks –report (Evegren et al, 2018), the main advantage of a Closed-Circuit Television (CCTV) system in fire protection is to use it to confirm the fire is real, when a fire alarm is active. Due to many false alarms, the fire must be confirmed to avoid negative consequences before fire extinguishing operations are initiated. A lot of critical time can be saved by CCTV confirmation compared to normal procedures, where a fire patrol is sent to the location of the alarm. Other advantage of CCTV system is a potential confirmation that fixed fire extinguisher has launched and thus it improves situational awareness. If the CCTV system has possibility to playback, the source of ignition can be found, even if the space is full of smoke and the camera shows smoke-filled image.

There were no investigated fire incidents in the Detection systems in open ro-ro and weather decks –report (Evegren et al, 2018), in which CCTV system was used as a means of detection. In some of incidents where CCTV system was available, the crew was attempting to use it for fire confirmation and assessment. CCTV systems may not view entire area but can still give an indication of the evolving situation.

According to Detection systems in open ro-ro and weather decks –report (Evegren et al, 2018), fairly new technology of CCTV detection systems has a high potential to be used as a means of detection. Three types of video detection system technologies can be identified. A smoke or combined smoke and flame video detection system can be connected to an existing CCTV system if the resolution of the cameras is sufficient. The system bases to software that analyze the CCTV camera feed, so it is only applicable in illuminated areas and reflections or moving shadows can cause false alarms.

Flame video detection system can use specially designed cameras or can also be integrated with existing CCTV system if the resolution of the cameras is sufficient. System has lower ratio of false alarms compared to smoke video detection systems. Experience in the oil and gas industry shows that the system is robust against dust, salt and moisture, so it is also suitable for marine conditions. (Evegren et al, 2018.)

Video detection systems using thermal cameras are more expensive than systems using traditional cameras, but they have the advantage of being able to detect thermal events that can cause a fire. Even a single prevented fire can be worth the money, as fires can cause huge financial losses and personal injury, or even loss of a ship or lives. This type of video detection is less sensitive to exterior lights and can be installed both indoors and on weather decks. (Evegren et al, 2018.)

3.1.3 Fire patrol

SOLAS II-2 7.8 requires an efficient fire patrol system for passenger vessels carrying more than 36 passengers. Each member of the fire patrol shall be provided with a two-way portable radiotelephone apparatus and shall be trained to be familiar with the arrangements of the ship as well as the location and operation of any equipment required. In some special category spaces, it is allowed to replace fixed fire detection system by a continuous watching fire patrol.

According to Detection systems in open ro-ro and weather decks –report (Evegren et al, 2018), the fire patrols continue to play an important role in detecting fires and in especially in fire confirmation. The report provides reliable information on fire detection in 10 fire incidents investigated and in three of them the fire patrol or crew detected the fire before fixed fire detection systems. The fire patrol is close to the source of the fire, so it is possible to successfully to perform first response and extinguish the fire in its initial stage.

3.2 Fire extinguishing

If the alarm has been confirmed to be a true, it is time to extinguish the fire. There are a wide variety of fire-extinguishing systems on the world market. FSS code (IMO, 2015) has categorized fixed fire extinguishers according to the principle of operation as follows:

- Fixed gas fire extinguishing systems
- Fixed foam fire extinguishing systems
- Fixed pressure water-spraying and water-mist fire-extinguishing systems
- Auto sprinkler, fire detection and fire alarm systems
- Fixed emergency fire pumps
- Fixed deck foam system
- Inert gas system

DNV (2005, p. 5) investigated fire incidents that have occurred in Ro-Ro spaces of RoPax vessels, vehicle carriers and general cargo Ro-Ro vessels. The results clearly show the connection between delayed activation of fixed extinguishing system and the major damages. For some reason, deluge systems were released mostly in minutes while the release times of CO2-systems were measured more often in hours. As the CO2 is harmful for humans, Johansson (2017, p. 22) concludes in his thesis that the reason for delayed launch of CO2-systems may be the afraid of loss of human lives.

The report Fires on Ro-Ro decks provided by Det Norske Veritas & Germanischer Lloyd (DNV GL, 2016) confirms that early launching of fixed extinguishing system reduce the damages caused by the fire. In report there were six cases out of nine where fixed extinguishing system was launched within 35 minutes or less and all these vessels suffered only minor damages. The rest three cases led to the total loss of the vessel.

3.2.1 Fixed gas fire extinguishing systems

According to Tuomisaari (1996, p. 23), fixed gas fire-extinguishing systems extinguish a fire with a gaseous substance, either by lowering the oxygen content or chemically disturbing the chain reaction. Gas fire extinguishing systems have no influence on conventional electrical equipment and are therefore typically used, for example, in main switchboard rooms or IT- and server rooms, where other extinguishing agents such as water, foam or powder could cause significant damage.

FSS Code (IMO, 2015) states principles for construction of fixed gas fire extinguishing systems. The storage of fire extinguishing medium shall be located outside the protected spaces and the fire extinguishing medium is discharged into protected spaces via discharge pipes and nozzles with melting temperature not less than 925°C. The system must be provided with audible and visible alarm in spaces where personnel have access. Automatic release of gaseous fire-extinguishing medium is prohibited.

The use of effective fire-extinguishing medium halogenated hydrocarbon (Halon) has been prohibited since 2000, because they cause depletion of the stratospheric ozone. Markets offers some gas mixtures as replacing medium, but the amount of the medium required is greater compared to Halon systems and may cause storage problems. After Halon systems were prohibited by IMO, the FSS Code (IMO, 2015) states only three gaseous fire-extinguishing mediums for fixed fire extinguishing systems.

- carbon dioxide,
- steam and

- equivalent fixed gas fire-extinguishing systems for machinery spaces and cargo pump-rooms

Carbon dioxide (CO_2) is an effective fire extinguishing medium without unwanted toxic decomposition products. The main extinguishing method of CO_2 is smothering and only tiny amount of its effectiveness is from its cooling capability. The cooling effect depends on the temperature of the medium and for example cooling effect of a portable CO_2 fire extinguisher is only 149 kJ/kg. CO_2 is not effective against smoldering fires or fires where the burning substance itself contains oxygen. Most of flaming fires will extinguish when oxygen content is reduced to 12–15%, but some substances can burn at even lower concentrations. To reach CO_2 concentration of 15 %, it is necessary to feed 0,6 kilograms of CO_2 per one cubic meter of air. CO_2 concentrations of 10% or more are harmful for humans and can even cause death. (Tuomisaari, 1996, p. 23; Hyttinen et al., 2019, p. 102-103.)

FSS code (IMO, 2015) demands the quantity of CO_2 shall be sufficient to give a minimum volume of 35% of the gross volume of the largest machinery space protected and 85% of the gas shall be discharged in 2 minutes. For vehicle and ro-ro spaces the minimum volume is 45% of the gross volume. For that reason, the amount of the CO_2 storage cylinders can be huge. For example, the main engine room of M/S Silja Serenade with a gross volume of 3680 m^3 is protected with 52 pcs of 45 kg cylinders (Kojo, 1996, p. 9).

Before the CO_2 system can be launched, several preparations must be made, which can mean that the launching times can be more than 15 minutes. As high content of CO_2 is harmful to people and can even cause a loss of life, the protected space must be evacuated. The system is ineffective if the room is not airtight, so the fire dampers, fire doors and other openings must be closed. SOLAS states that all opening, which may admit air to or allow gas to escape from a protected space, shall be capable of being closed remotely from outside of the protected space. All combustion engines need to be shut down to avoid gas losses and if engines are not shut off, they will anyway have emergency shut down when oxygen level decreases. To enhance redundancy, ships engines can be divided into different rooms with different fire zones. In a case of a fire, the ships electricity generation and navigation capability are ensured even if one of engine rooms has lower oxygen level. One solution, which is used also in navy vessels, is to construct combustion air ducts for engines directly from outside. (Kojo, 1996, p. 21.)

According to Zhang (2000, p. 47), the fixed steam fire-extinguishing systems were mainly installed on steamships with high-capacity boilers. The main extinguishing method of steam is smothering by displacing the oxygen from the air. Fixed steam fire-extinguishing systems require very large quantities of steam and have same disadvantages as water. The installation of fixed steam fire extinguishing systems is not highly recommended as SOLAS states following:

"In general, the Administration shall not permit the use of steam as a fire-extinguishing medium in fixed fire-extinguishing systems. Where the use of steam is permitted by the Administration, it shall be used only in restricted areas as an addition to the required fire-extinguishing system and shall comply with the requirements of the Fire Safety Systems Code." (IMO, 2014.)

The requirements for fixed steam fire-extinguishing systems are only very briefly set out in the FSS Code:

"The boiler or boilers available for supplying steam shall have an evaporation of at least 1 kg of steam per hour for each 0.75 m3 of the gross volume of the largest space so protected. In addition to complying with the foregoing requirements, the systems in all respects shall be as determined by, and to the satisfaction of, the Administration." (IMO, 2015.)

Equivalent fixed gas fire-extinguishing systems for machinery spaces and cargo pump-rooms are described in FSS Code briefly. Fixed gas fire-extinguishing systems equivalent to CO2 and steam systems shall be approved by the Administration based on the guidelines developed by the Organization. (IMO, 2015.)

Inergen and Argonite are marketing names for two alternative gas fire-extinguishing mediums. Both are gas mixtures of different inert gases and the extinguishing method is only smothering and no chemical reactions take place. Inergen contains Nitrogen, Argon and Carbon dioxide while Argonite is a mixture of Argon and Nitrogen. Unlike CO2 and Halon, these fire-extinguishing mediums are storage in gaseous state and, as a result, the storage capacity is about three times that of CO2. (Kojo, 1996, p. 21.)

Novec 1230 fire-extinguishing medium is a replacing medium for Halon. Medium is fluorinated ketone without chlorine and bromine and therefore has no effect on stratospheric ozone. According to Rinne & Vaari (2005, p. 103), the fire-extinguishing medium boils in the temperature of 49°C, so the main fire-extinguishing method is cooling and the oxygen is not displaced. As Novec 1230 is stored in liquefied state, the required storage capacity is 80% less compared to inert gases (3M, 2021).

3.2.2 Fixed foam fire extinguishing systems

High expansion foam systems are suitable for large and enclosed spaces, where amounts of foam are required quickly. The protected area is filled with foam that prevents air from reaching the fire. This is the primary fire extinguishing method, but foam will also isolate combustible material to reach the fire. As the foam is generated with water, the foam has also cooling effect when water comes in contact with the fire and vaporizes. (Arvidson et al., 2018.)

FSS Code (IMO, 2015) has special demands for fixed foam fire extinguishing protecting machinery spaces, cargo spaces and cargo pump rooms. The systems must be capable for manual launching and shall be designed to produce required foam rate within one minute of release and systems must have foam generating capacity that can completely fill the protected area within ten minutes. If the air for the system is supplied from outside the protected room, the arrangement shall be ventilated to avoid overpressure and to ensure the inflow while the space is being filled with the foam. Inside-air foam systems do not require ventilation system or overpressure opening because the system circulates air in the protected room. Inside-air foam systems are easier and more flexible to install and are used in enclosed areas, for example, engine rooms and therefore specific combustion gas and high temperature resistant foam concentrate is required.

The Table 1. below presents the pros and cons of the high expansion foam systems presented in the report Alternative fixed fire-extinguishing systems on ro-ro spaces, provided by European Maritime Safety Agency with project partners Bureau Veritas Marine & Offshore, Research Institutes of Sweden (RISE) and Stena Rederi (Arvidson et al., 2018, p. 36).

Pros	Cons
Foam fills the protected area and prevents unrestricted air to reach the fire.	*Foam generators are complicated; have a fan connected to a power supply, and need fresh air supply.*
Foam cools and limits heat radiation.	*Early detection, operation and short submergence times necessary for the performance.*
Evaporated foam decreases the oxygen concentration.	*The manual operation of the system may intentionally be delayed due to the concerns with clean-up of the foam.*
Covers and suppresses flammable liquid spill fires.	*High maintenance requirements and more failure modes than automatic sprinkler systems.*
Can control and suppress vapors from toxic or flammable liquid spills.	*Protected space must be well ventilated to avoid a positive pressure (valid for traditional out-side air systems).*
Typically uses less water than sprinkler systems (given that the space is relatively small).	*Environmental impact of foam.*
Additional benefits when foam is produced using inside air.	*Evacuation of the whole space required prior operation.*
	Manual fire-fighting difficult or impossible after the spaced is filled with foam.
	Limited or no publicly available fire test data for ro-ro space applications.

Table 1. The pros and cons of the high expansion foam systems (Arvidson et al., 2018, p. 36).

3.2.3 Fixed pressure water-spray & water-mist fire extinguishing systems

According to Tuomisaari (1996, p. 27-28), water is still the most common fire extinguishing agent because it is efficient, cheap, environmentally friendly and always available. Water has three main fire extinguishing methods. The most important method is cooling. When water evaporates, it can absorb the heat more than 2 MJ/kg. If water is sprayed in small droplets, the amount of sprayed water evaporates faster and fire extinguishing will be more effective. As the water evaporates, its volume increases approximately 1700 times displacing the same amount of air. This causes increased room pressure, which prevents new air from flowing in and the oxygen content in the room decreases. Small water droplets and fog can prevent heat radiation to transfer from flames to the substances that are not yet burning.

Fixed pressure water-spraying and water-mist fire-extinguishing systems can be roughly divided into two different categories, water spray systems and water mist systems. According to Tuomisaari (1996, p. 10), if 99% of the water sprayed exists in droplets with a diameter of 1 mm or less, it can be considered as water mist. In practice the droplets are smaller, so the water mists are divided into three groups based to their diameters.

Water spray systems, or so-called deluge systems, may look the same as sprinkler systems, but the operating principles are different. Water spray systems use sprayers that look pretty much same as sprinkler heads, but sprayers do not have quartzoid bulb. Section pipes are dry and unpressurized if the section valves remain closed. Section valves are manually operated and opening allows the supply water flow to the room through sprayers.

Water mist systems are becoming an increasingly more popular and are replacing traditional sprinkler systems, CO2-systems and already prohibited Halon-systems. Water mist systems are available with low, medium and high pressure and with several brand names such as hyper mist, micro-fog, high-pressure fog, ultra-fog etc. but the main principles are the same. All water mist systems result a very tiny droplets into the room or around the equipment protected.

High-pressure water is injected through specialized nozzles, which disperse the water droplets into a fine mist or even fog. Different systems are producing different size of water droplets from low-pressure systems with droplets size of 1000 microns to high-pressure systems with droplets size of 50 microns. Compared to the most of sprinkler systems with a droplets size of 5000 microns, water mist has certain properties that help it to extinguish fires. (Kaiser, 2018.)

- Cooling effect with quick cooling by evaporation latent heat
- Oxygen replacement effect by replacing the air with water vapor generated in a large quantity
- Shut-off effect when floating fog forming walls of water
- Smoke eliminating effect by absorbing and settling the floating smoke particles

According to Babicz (2015, p. 297), high-pressure water mist fire-extinguishing systems are suitable for total flooding and local application in machinery rooms. The system using only water without chemical additives is not harmful to humans nor the environment Water as extinguishing agent does not leave residues and therefore minimizes the following cleaning. As there is no need to evacuate personnel or ensure the air tightness of the protected room, the system can be activated immediately after a fire is detected and the fire is contained and extinguished in its initial stage. If the alarm turns out to be false alarm, resetting the system will return the system to standby mode and the vessel can continue service without interruption as there is no need to visit the port to recharge the system. In addition, the extinguishing agent is plain, fresh water in the form of mist, so system operating can be tested regularly without fear of equipment corrosion.

3.2.4 Automatic sprinkler systems

Automatic water sprinkler system is a combination of an automatic fire detection, fire alarm and fire extinguishing system. The system consists of several sprinkler heads installed in a protected room. System shall be divided into sections and FSS Code (IMO, 2015) has set a maximum of 200 sprinkler heads per section. Each sprinkler head must be able to supply 5 liters of water per square meter per minute. According to Kojo (1996, p. 26), this amount of water is not effective enough to extinguish liquid fires.

Water to sprinkler heads is supplied from a pressure tank via piping and each section pipes are equipped with a section stop valve. The system shall be wet type and therefore the system is always pressurized. The pressure tank should always be kept charged at the required pressure so that the system can always operate immediately, and no crew intervention is required to set it in operation. The system is pressurized with fresh water in normal operation conditions, but if the pressure drops under the required level, the system will be re-pressurized through the seawater connection from the fire main.

In a case of a fire, a quartzoid bulb in the sprinkler head detects a raising temperature and burst. A broken quartzoid bulb will allow water to flow out of the sprinkler head and extinguishing will begin. Section valve shall notice a dropping pressure in the section pipe and an audible and visual alarm shall be given on the bridge or on a continuously manned central control station (IMO, 2015).

3.2.5 Firefighters

According to my working experience and the opinion of my colleagues, the fire fighters have a great role in ships fire management. Fire fighters can act as effective mobile squads that can ensure effective fire extinguishing wherever it is needed. Fire fighters can sense the state of a fire and enhance the situational awareness of those people in charge of fire management duties. The amount of fire fighters varies depending on the size and type of the ship, but it can be said that the basics of the firefighting are trained for all seafarers and regular fire drills are held onboard. The requirements for the necessary safety training are specified in STCW.

3.2.6 Fan stops, fire doors, fire dampers and smoke extraction

Adequate ventilation of the vessels is implemented through several supply and exhaust air ducts. Airflow in the ducts is a result of several fans and nowadays these fans are equipped with frequency converters and are usually controlled by a computer-based program. Fire detection systems can be programmed to automatically stop the fans in the area where the given alarm is active.

Fire doors and fire dampers are installed to prevent the fire from expanding between the fire zones. According to SOLAS (IMO, 2014) the fire doors and fire dampers shall have local closing panels with indicators showing the status of the door or damper. Each fire zone shall have remote closing panel located in the fire control center. Both systems can be controlled electrically, so they can be connected and controlled by a computer-based program.

According to Andersson & Säterborn (2002, p. 16), fires can produce a huge amount of smoke and it must be extracted to reduce the negative effects, such as lowered visibility, toxicity, increased temperatures, and explosion risk. The main purposes of using smoke control systems are considered to:

- Keeping escape routes, and to some extent other areas, free from hot and toxic fire gases.
- Control and stop smoke mitigation to other fire zones
- Decimate the damaging impact of a fire on the constructions
- Make it easier for the fire-fighters to perform their tasks, such as find and rescue survivors, locate and extinguish the fire
- Clear affected areas from smoke after the fire has been extinguished

The absence of humans onboard makes some of these main purposes sound less important for unmanned vessels. However, this is not the case because if a fire breaks out during a dry docking or port time, there will be a lot of people on board.

SOLAS 2- Regulation 8 – Control of smoke spread says: “*Suitable arrangements shall be made to permit the release of smoke, in the event of fire, from the space to be protected, subject to the provisions of regulation 9.5.2.1. The normal ventilation systems may be acceptable for this purpose.*”

According to Andersson & Säterborn (2002, p. 16), smoke management or smoke control is the general name for the methods of preventing smoke spread. Two different types of smoke management are defined as:

Active smoke control uses mechanically created pressure differentials to prevent smoke spreading between fire zones and as well to extract smoke from the ship. That mechanically created pressure is usually created with fans and dampers. Passive smoke control prevents smoke spreading from fire zone to other with bulkheads, fire dampers, fire doors etc.

Unmanned ships have no crew members passing through the aisles, so fire doors can be kept closed throughout the voyage. Fire dampers can be connected to the fire alarm system so that dampers close automatically in the area where the alarm is active. The ship protects itself autonomously, so the operator of the remote-control center does not need to take action to achieve controlled smoke management. Based on these factors, it can be concluded that the passive smoke control strategy is likely to be better for unmanned vessels.

3.3 Structural fire protection

According to Zhang (2000, p. 26), the structural fire protection can be categorized into passive fire protection and it has four basic principles:

- prevention of the possibility of fire outbreak on board the ship;
- division of ship into main vertical zones by thermal and structural boundaries;
- separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries;
- protection of means of escape and access for firefighting.

To minimize the possibility of fire outbreaks, SOLAS has requirements for ships construction materials and restrictions on use of combustible materials. Materials supplied to ships must meet the criteria of Fire Test Procedures Code (FTP Code). The purpose of

FTP Code is to ensure that materials shall have acceptable calorific value and shall not produce excessive quantities of smoke and toxic products during a fire.

FSS Code (IMO, 2015) has set demands for flammable liquids and for example use of fuel oil with a flashpoint of less than 60°C is prohibited. To avoid the ignition of leaking oils the SOLAS demands precautions to prevent any oil from coming into contact with heated surfaces and surfaces with temperatures above 220°C shall be properly insulated.

To contain a fire in the space of origin, SOLAS (IMO, 2014) has set requirements for division of a ship into fire zones. Ships shall meet following functional requirements:

- *the ship shall be subdivided by thermal and structural boundaries;*
- *thermal insulation of boundaries shall have due regard to the fire risk of the space and adjacent spaces;*
- *the fire integrity of the divisions shall be maintained at openings and penetrations.*

SOLAS II-2.2.1 states *"Ships of all types shall be subdivided into spaces by thermal and structural divisions having regard to the fire risks of the spaces."*. According to the above, the requirements can vary a lot depending on the type of ship. The main principle is to divide ships into main vertical fire zones and horizontal fire zones with appropriate class of a fire division. SOLAS II-2.3 divides the fire divisions into three classes. The strictest A-60 class is used in high fire risk spaces such as machinery spaces.

A class divisions are those divisions formed by bulkheads and decks which comply with the following criteria:

- *they are constructed of steel or other equivalent material;*
- *they are suitably stiffened;*
- *they are insulated with approved non-combustible materials such that the average temperature of the unexposed side will not rise more than 140°C above the original temperature, nor will the temperature, at any one point, including any joint, rise more than 180°C above the original temperature, within the time listed below:*
    - *class "A-60" 60 min*
    - *class "A-30" 30 min*

- *class "A-15" 15 min*
- *class "A-0" 0 min*

- *they are constructed as to be capable of preventing the passage of smoke and flame to the end of the one-hour standard fire test; and*
- *the Administration required a test of a prototype bulkhead or deck in accordance with the Fire Test Procedures Code to ensure that it meets the above requirements for integrity and temperature rise.*

B class divisions are those divisions formed by bulkheads, decks, ceilings or linings which comply with the following criteria:

- *they are constructed of approved non-combustible materials and all materials used in the construction and erection of "B" class divisions are non-combustible, with the exception that combustible veneers may be permitted provided they meet other appropriate requirements of this chapter;*
- *they have an insulation value such that the average temperature of the unexposed side will not rise more than 140°C above the original temperature, nor will the temperature at any one point, including any joint, rise more than 225°C above the original temperature, within the time listed below:*
    - *class "B-15" 15 min*
    - *class "B-0" 0 min*
- *they are constructed as to be capable of preventing the passage of flame to the end of the first half hour of the standard fire test; and*
- *the Administration required a test of a prototype division in accordance with the Fire Test Procedures Code to ensure that it meets the above requirements for integrity and temperature rise.*

C class divisions are divisions constructed of approved non-combustible materials. They need meet neither requirements relative to the passage of smoke and flame nor limitations relative to the temperature rise. Combustible veneers are permitted provided they meet the requirements of this chapter. (IMO, 2014.)

According to Rämö (1996, p. 7), bulkheads and decks constructed of steel withstand the initial stages of a fire, but lose their load bearing capacity when temperature rises to about 500°C. The fire resistance of aluminum structure is not at the same level as steel and aluminum can lose its load bearing capacity even in 200°C. Well-developed fires can reach temperatures of up to 1000°C.

SOLAS provides principles for escape routes so that crew and passengers can be evacuated safely. Firefighters can also use these escape routes to get to the location of the fire. The regulations vary depending on the type of vessel, but the main principle for all vessels is that at least two escape routes are available. Escape corridors and stairways must meet the A class requirements. (Zhang, 2000, p. 27.)

3.4 Safety centre and fire control station

SOLAS chapter II-2 regulation 23 gives principles for safety centre of passenger vessels constructed after July 1st 2010. The safety centre is a separate space adjacent to or a part of the navigational bridge, that provides equipment to assist with the management of emergency situations.

"Notwithstanding the requirements set out elsewhere in the Convention, the full functionality (operation, control, monitoring or any combination thereof, as required) of the safety systems listed below shall be available from the safety centre:"

- all powered ventilation systems;
- fire doors;
- general emergency alarm system;
- public address system;
- electrically powered evacuation guidance systems;
- watertight and semi-watertight doors;
- indicators for shell doors, loading doors and other closing appliances;
- water leakage of inner/outer bow doors, stern doors and any other shell door;
- television surveillance system;
- fire detection and alarm system;
- fixed fire-fighting local application system(s);

- sprinkler and equivalent systems;
- water-based systems for machinery spaces;
- alarm to summon the crew;
- atrium smoke extraction system;
- flooding detection systems; and
- fire pumps and emergency fire pumps.

In short, the safety centers are providing a space to assist with the management of emergency situations. It is not required for all type of the ships, but already used on ships where the risks are increased. Safety centre is a requirement for passenger ships where fire can cause harm for several people. For naval ships the safety centre is not mandatory, but the ships are usually equipped with one, as there is a huge fire risk if the ships are in the conditions they were designed.

3.5 Engine room

Engine rooms are vital for the operation of ships. The engine rooms are a source of propulsion and electrical power and most of the ship's technical equipment is located in the engine room. Typically, the ship’s systems are controlled remotely from engine control room via Integrated Automation Systems (IAS). IAS is a computer-based platform to operate and monitor ship’s technical systems. If IAS has an internet connect, it can be operated remotely, for example, from land based remote-control center.

Fires in the engine room are always very dangerous and must be extinguished quickly. Engine rooms are the most common places where the fire has started. DNV (2009) reported in 2000 that the engine room was the starting point for 63% of all fire incidents occurred, so it can be defined as a high-risk area. The most common cause of engine room fires is leaking fuel oil or lubricating oil mist that ignites when it hits a hot spot (Tuomisaari, 1996, p. 9).

Fires that occur on weather decks can burn with Heat release rates (HRR) more than hundreds of megawatts and fires that occurs in engine rooms or other interior areas where oxygen supply is limited, fires can reach up to 60-70 MW. The fire resistant engine room report (Häkkinen, et al., 1996, p. 9) simulates a small fire in an engine room. The simulation is based on the actual fire incident that occurred at M/S Mariella. The results show that the temperature rises to 1000°C and the fire reaches a heat release rate of 6 MW in about a minute. Since a six-kilograms powder fire extinguisher can extinguish a fire of about 1-2 MW, it is important to completely prevent ignition or at least begin effective extinguishing efforts immediately when the fire is in the early stages.

3.5.1 Fuel oil systems

According to DNV GL (2019, p. 3), the most of worlds fleet seagoing vessels are still using Heavy Fuel Oil (HFO) or Marine Gas Oil (MGO) as a source of propulsion and electrical power. Every substance has a calorific value which indicates the amount of total energy released as heat during complete combustion. Typical calorific value for HFO is 39 MJ/kg and 42 MJ/kg for MGO. According to Rinne & Vaari (2005, p. 123) the typical fuel oil flows in the main engine room of larger ships, such as tankers and container ships, might be in 300 bar high pressure system 0,2 kg/s and in 8 bar low pressure systems even 1,0 kg/s.

According to the previous, the theoretical amount of available fuel for the fire in cases of leaking fuel oil is a massive! The total amount of fuel that can ignite immediately depends on many factors, such as whether the leak is in a low-pressure system in which the fuel is in liquid form or in a high-pressure system where fuel is leaking in a more flammable form, but the main message is that the traditional fuel oils can be extremely dangerous in case of a malfunction or negligence.

3.5.2 New energy sources

New energy sources are becoming more widespread, and the maritime industry is following. Shipyards are designing and developing more environmentally friendly ships with new type of energy sources. DNV GL (2019, p 3) has published guidance paper Assessment of selected alternative fuels and technologies, which summarizes the current situation well: *"The shipping industry is under increasing pressure to act upon the Paris Agreement and reduce greenhouse gas (GHG) emissions. The substantial emission reductions which must be achieved over the next decades are expected to drive technology development and, in particular, the introduction of low-carbon fuels"*. In the same document, DNV GL says that the main challenges for shipping are to reduce emissions and introduce new propulsion technologies, so the future ships will have to rely on a broader range of fuels, propulsion solutions and energy efficiency measures.

When steamships were declined after World War II and most of the ships built were equipped with internal combustion engines (ICE) using marine diesel oil, it became clear that fuel oils as a source of energy are very dangerous. During these years and after several accidents we have learned how to decrease the probability of accidents and how to operate fuels safely. Nowadays, traditional fuel oils are still absolutely the most common energy source, but there already exists ships powered by for example Liquefied Natural Gas (LNG) and high-capacity batteries. Automotive industry has developed rapidly, and is already producing vehicles powered by batteries, LNG and hydrogen cells. All alternative fuel options are accompanied by advantages but also challenges, so we are currently in the early stages of the learning process.

Research Institutes of Sweden has investigated thermal propagation in Lithium-ion batteries. Heat release rate (HRR) can be influenced by multiple factors, such as state of charge, but the results show the combustion energy is approximately 5-20 times more than electrical energy. Total heat release (THR), which is integration of HRR, was 17-75 kJ/Wh meaning the 100 kW/h battery pack is equivalent to 70-300 liters of gasoline. During the tests it became clear that lithium-ion batteries have another disadvantage if thermal propagation occurs. Lithium-ion batteries can release huge amounts of extremely toxic hydrogen fluoride gases, which may be a challenge for firefighters. In the report the supposed fire extinguishing method is to use water mist due its great cooling capability and it may transform the toxic gases to a toxic liquid, which is easier to handle. (Larsson, 2018.)

Hydrogen, which is also potential future fuel alternative for shipping, has low CO2 emissions. Hydrogen calorific value is approximately 120 MJ/kg which is approximately three times the energy density of HFO. The high energy density also implies that the energy of a hydrogen explosion is about 2,5 times higher than common hydrocarbon fuels, meaning the explosions are more destructive and carry further. The duration of a fire is usually inversely proportional to the energy of combustion, so hydrogen fires will extinguish faster than hydrocarbon fires. (College of the Desert, 2001, p. 15.)

Hydrogen is in gaseous state in atmospheric conditions, which means it has a extremely low flashpoint of -253°C compared to the traditional minimum flashpoint of 60°C for MGO and HFO. Hydrogen is also flammable over a very wide range of concentrations in air and these two things combined make hydrogen leakages extremely dangerous. (College of the Desert, 2001, p. 17-19.)

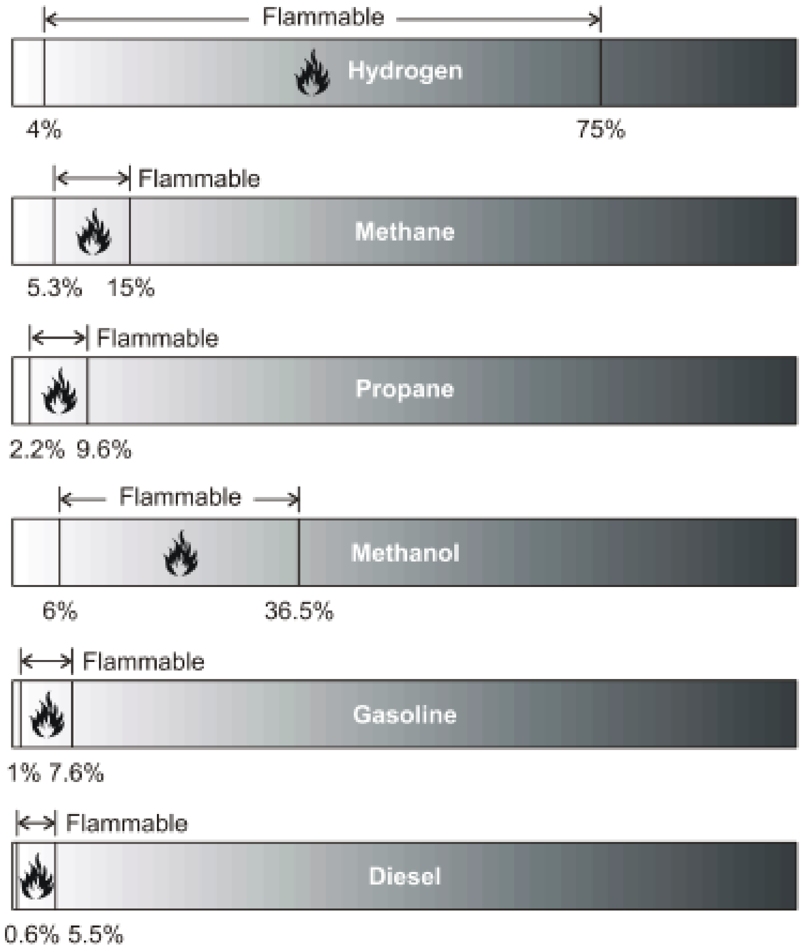

Figure 5. Flammability Ranges of Comparative Fuels at Atmospheric Temperature (College of the Desert, 2001, p. 20).

4 Research methodology

According to Dr. Thattamparambil (2020), choosing the right research methodology can have a big impact on the success and quality of a report. Research methodology is a specific technique or procedure used to select, collect, and analyze data on a topic (University of the Witwatersrand, 2021). Research methodology refers to the entire process in which a research problem is systematically solved using various research methods. To obtain the understanding of research methodology it is important to know the research methods and which of these methods are relevant for the research and what would they mean and indicate and why. (Kothari, 2004, p. 8.)

When we talk of research methodology we not only talk of the research methods but also consider the logic behind the methods we use in the context of our research study and explain *why we are using a particular method or technique and why we are not using others so that research results are capable of being evaluated either by the researcher himself or by others* (Kothari, 2004, p. 8).

The purpose of this section is to provide the reader with information to evaluate the validity of the thesis. This section explain which research methods were selected and why and provides answers to questions: How was the data collected and how was the data analyzed?

4.1 Method selection

The method selection procedure depends on the author's needs to obtain the desired result and the answer to the research question. When choosing a research method, it should be considered whether to use inductive or deductive approach, what is the research question, whether is it experimental, correlation or descriptive research and other considerations such as money, time, and data availability (Thattamparambil, 2020).

According to Streefkerk (2019), approaching for research can be inductive or deductive. Inductive reasoning is commonly used when there is only little literature on the subject and no theory to test. Inductive approach has three stages:

1. Observation;
2. Observe a pattern; and
3. Develop a theory.

According to Streefkerk (2019), in deductive reasoning some existing theory is tested and if there is no theory this approaching cannot be used. Deductive approach has four stages:

1. Start with an existing theory;
2. Formulate a hypothesis based on existing theory;
3. Collect data to test the hypothesis; and
4. Analyze the results: does the data reject or support the hypothesis?

As there was not exact theory about traditional fire protection systems installed on unmanned ships the deductive reasoning could not be used. As the inductive reasoning is more appropriate for this case it was chosen for approaching method of the thesis.

Qualitative and quantitative research are two typical data collecting and analyzing methods. Quantitative research is used to obtain facts in numerical and graphical forms to confirm assumptions and theories. The data collected in the quantitative research method is factual information on the subject and can be collected in several ways. According to Bryman (1988, p. 12), surveys, experiments, secondary data analysis, structured observation and content analysis are the main methods of quantitative research. Dr. Thattamparambil (2020) says that the use of quantitative analysis is suitable for confirming or testing a theory or hypothesis.

Qualitative research is used to obtain facts in words. This type of research method provides in-depth insights on topics that are not well understood. Typical data collection methods are interviews, focus groups, case studies, discourse analysis, and literature reviews. This research method is usually used to understand thoughts, concepts, or experiences of people. (Thattamparambil, 2020.)

Quantitative and qualitative research methods collect information in different ways and help to answer different type of research questions. The following table shows the main differences between the methods.

Quantitative research	**Qualitative research**
Focuses on testing theories and hypotheses	*Focuses on exploring ideas and formulating a theory or hypothesis*
Is analyzed through math and statistical analysis	*Is analyzed by summarizing, categorizing, and interpreting*
Mainly expressed in numbers, graphs, and tables	*Mainly expressed in words*
Requires many respondents	*Requires few respondents*
Closed (multiple choice) questions	*Open-ended questions*
Key terms: testing, measurement, objectivity, replicability	*Key terms: understanding, context, complexity, subjectivity*

Table 2. Comparison between Quantitative and Qualitative research (Thattamparambil, 2020).

The mixed method is a combination of in-depth study and numerical measurement, and according to George (2021), combining these methods can provide a more complete picture than independent quantitative or qualitative research because it takes advantage of both methods. Qualitative research method was selected for main research method for the thesis, because it is a less formal method of data collection and provides in-depth information on how respondents see the subject in reality. Quantitative research method, which is used to obtain facts in numerical form, was used to gather numerical facts about the fire incidents that have occurred and how they were extinguished.

4.1.1 Data collection

According to Kothari (2004, p. 95), there are two types of data. Primary data is something that is collected for the first time, and secondary data is something that has already been collected and processed by someone else. In this thesis both type of data was collected. Secondary data were collected from incident investigation reports and other study papers.

To collect primary data the initial plan was to conduct several semi-structured interviews, but my supervisor mentioned it could be a lot of work, so I decided to do one pilot interview and send one pilot questionnaire to my colleague. This type of pilot study is also recommended by Kothari (2004, p. 101) and is intended to highlight the weaknesses of the questionnaire and survey techniques. There was no big difference in the results, but the reporting of the interview took much longer, so it was obvious that the questionnaire was chosen as the main method of data collection.

The aim of the questionnaire was to get answers from as many different perspectives as possible, so I used my social network and carefully selected professionals who would probably respond. The questionnaire was sent to a carefully selected sixteen participants representing many different duties in the maritime industry in several countries. Thirteen of them replied, so it can be said that the number of responses was acceptable.

Answers were received from Finland, Sweden, and Ireland. The respondents are representing duties such as Chief Engineer, First Engineer, Technical Superintendent, Electro Technical Officer, Head of Kalmar Maritime Academy, Naval Architect, Nautical Surveyor, Research Manager, Marine Surveyor, Design Engineer and Ship Radio Surveyor, so the subject was researched from several different perspectives.

The respondents’ working experience at the sea or in maritime sector varies from 6 years up to 44 years. The working experience was quite comprehensive, as the calculated average working experience was 18 years. The questionnaire could be answered anonymously, but only two people informed that they wanted to remain anonymous. The person presentations of the respondents did not add value to the thesis, so I decided not to write person presentations. The names of the respondents are presented in this thesis but cannot be associated with individuals. Questionnaire is presented in more detail in chapter 5.

4.1.2 Data processing and analysis

The questionnaire was established in three different forms. The main answering method was Google Forms- survey administration software. This platform proved to be excellent for this purpose and it was easy to handle. The questionnaire was also sent to the respondents via email and two respondents wanted to fill paper versions. Email and paper answers were transferred to Google Forms by the author and finally all answers were saved to the authors computer for further use. Google Forms provided the tables presented in the chapter 5 and the averages were calculated with Microsoft Excel. All respondents replied in English, so no translations were required. Email and paper version of questionnaire is presented in Appendix 1.

The author has more than ten years working experience as an engine officer onboard passenger ships and naval ships. These types of vessels are designed and operated in different ways, providing a wide range of different work experience. This allows for several different perspectives on the research of the secondary data in the theoretical part and provided a readiness to engage in constructive discussions with colleagues and to analyze the gathered results from the questionnaire. During this thesis project, the author participated in the Maritime Fire Chief course in the Meriturva Maritime Safety Training Centre. The course was not directly for the thesis purposes, but it provided an opportunity to gather valuable information from professionals. The author also has an electrotechnical rating Certificate of Competency that ensures an understanding of the potential of this important area as well.

5 Questionnaire

This chapter presents the results of the questionnaire. The questions are explained and introduced along with the answers received. The main aim was to collect data about systems delivered to conventional vessels and how participants see them used in the future ships.

The questionnaire was divided into three main sections: Fires onboard conventional vessels, New energy sources and Fires onboard remotely controlled and unmanned ships. All main sections were individual but had obvious connection between each other.

5.1 Fires onboard conventional vessels

The first chapter contains seven questions about fires onboard conventional vessels. The purpose of this chapter was to obtain information on how respondents see fire hazards and to confirm their professionalism on the subject. The thinking of conventional ships also prepared the respondents for the following chapters. The respondents' work experience in the maritime sector was comprehensive and could be seen in the responses. All thirteen respondents showed impressive professionalism, so it can be concluded that the results of the questionnaire are relevant.

Q1. Have you been onboard ship while there was a fire?

The purpose of this question was to find out how many of the respondents have been onboard while fire broke out and what caused the incident. If the respondent answered yes or several times, he or she was directed to four additional questions. To obtain confirmation of the statistics presented in the theoretical part, it was asked where the fire took place, what cause the fire, how the fire was detected and how the fire was extinguished.

Only three respondents have not encountered a fire on board, so 77 percent have their own experience of a fire incidents. 23% of respondents have experience of more than one incident.

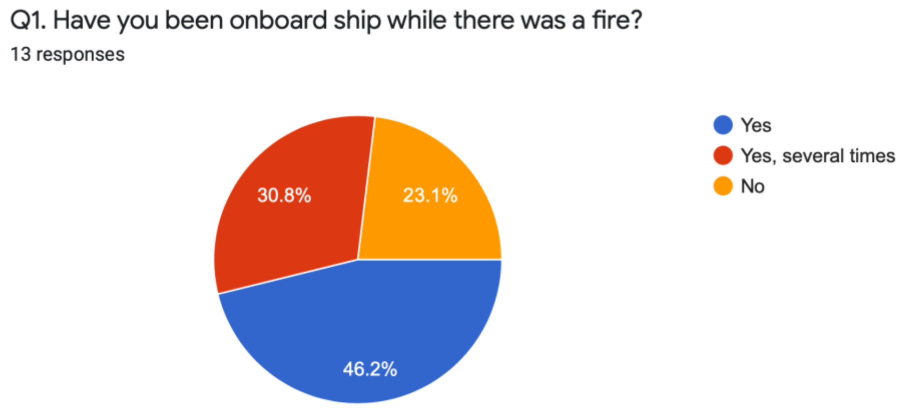

Figure 6. Participation of the respondents in fire incidents

According to the statistics presented in the theoretical part, 63 percent of reported fires took place in engine rooms, 27 percent in cargo areas and in accommodation areas only 10 percent. The results of the survey are in line with the theory, although slightly different. The results show that 48 percent of the fire incidents encountered by the respondents occurred in engine rooms, 30 percent in accommodations, and the remaining 22 percent in cargo spaces.

In the theoretical part it was mentioned that a burning capable leaking liquid is the most common burning substance in engine rooms and the survey confirms that. Leaking oil was the most common cause, but also alcohol, glycol, and Liquefied Petroleum Gas (LPG) was mentioned. Engine room fires that were not caused by a leaking liquid was an ash fire in a funnel and a generator meltdown.

One interesting cause of a fire was a Lithium-ion battery, that was charged in a cabin and suddenly overheated and started burning. Another mentioned battery fire originated on a car deck due to a short circuit in the car battery.

Malfunction in electrical equipment has caused several fires in engine rooms and in accommodation areas. The respondents mentioned six different fires that had started from electrical equipment such as lightning fixtures. The fires in which man was the obvious cause of ignition were a cabin fire started from a cigar, burning bread in a toaster and hot works.

If humans have a bad habit of being the source of ignition, however they have a great role in fire detection. About half of the reported incidents were detected by ship’s crew and half by the fire detectors. Smoke fire detectors detected 80 percent of the fires detected by the fire detectors and the rest 20 percent were detected by heat fire detectors. Other detection methods, such as flame fire detectors, CCTV, Sprinkler system or Fire patrol did not get any responses.

None of the reported 27 cases were extinguished with fixed fire extinguishing systems. Three of them extinguished by itself and the rest of the incidents needed the acts by humans. The most common way to extinguish the fire was first response with portable fire extinguishers or fire hoses.

Q2. How many of the given fire alarms are false alarms? From 0 to 100%

The purpose of this question was to get understanding how reliable existing fire detection systems are and is the given information accurate enough to be used to control fixed fire extinguishing systems without any confirmation. It became clear that the persons who has worked onboard passenger ships estimated much higher amounts of false alarm than persons who has worked onboard cargo or Navy vessels. The calculated result was that 83 percent of fire alarms given are false alarms. The highest estimation was 100 percent and the lowest was 10 percent, but it was mentioned that it only applies onboard cargo ships. One of the respondents highlighted that the activation of the detectors is mostly correct, but the cause is not a fire.

Q3. What is the role of CCTV in fire fighting management?

CCTV have taken huge steps in quality, but that also means that the amount of data to be transferred has increased and this may lead to situations where it is impossible to have monitoring in land based remote control centers. The purpose of this question is to clarify the roles of the CCTV and to get understanding how important the CCTV is in fire management.

It was surprising to me that everyone mentioned at least some role for CCTV and eight of thirteen pointed several roles. The most important role of CCTV with eleven votes was the use of CCTV to enhance situational awareness and the confirmation of the fire followed with nine votes. Only two persons mentioned the use of CCTV for fire detection and one respondent commented *"It is high threshold to launch fire extinguishing system if decision bases only for CCTV."*

Q4. How important are fire fighters in maintaining situational awareness in a case of a fire?

Acquiring situational awareness is one of the most important aspects for the persons in fire management in the case of a fire. As this investigation is about unmanned vessels, it also means that there are no firefighters onboard and for that reason it became necessary to investigate how important the role of the fire fighters in maintaining situational awareness is.

The scale was from 1 to 5, where 5 was *extremely important* and 1 *not at all important*. The average of the answers was 4.5 so it is obvious that firefighters have an important role in maintaining situational awareness during fires. This important role must be fulfilled onboard unmanned vessels in some other way.

Q5. Do you see smoke extraction to be used more during the fire or after extinction?

Smoke extraction is difficult and must be considered on case-by-case basis. In my opinion, smoke extraction during a fire requires feedback from fire fighters and as onboard unmanned vessels there is no possibility to receive that feedback, it became necessary to investigate whether smoke extraction is more important during a fire or after extinction.

92 percent of respondents see smoke extraction to be used more after the extinction and it is good news for unmanned vessels as it is easier to automate this method. Of course, this still requires feedback and confirmation that the fire has been extinguished and there is no risk that smoke extraction could cause a re-ignition.

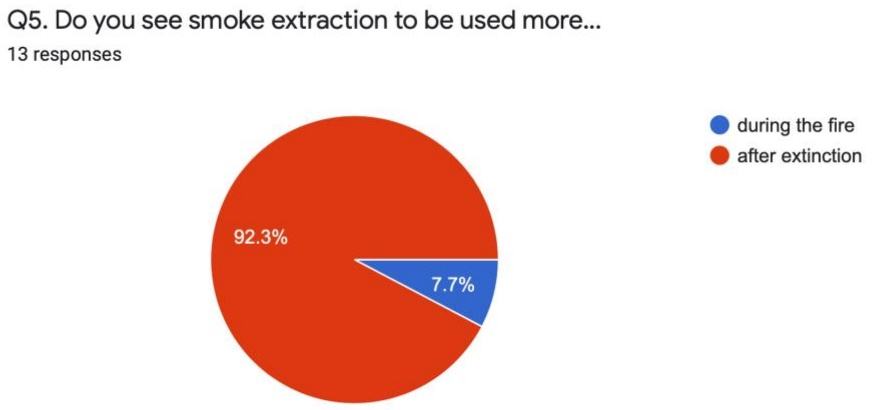

Figure 7. Voting ratio between smoke extraction during the fire or after extinction

Q6. What kind of fixed extinguishing systems have you worked with?

This question is checking how widely different fixed fire extinguishing systems have installed onboard conventional vessels. Question contained six pre-determined systems and possibility to add so systems not included on the list.

a. Fixed CO2 fire extinguishing system

b. Fixed Halon fire extinguishing system

c. Fixed foam fire extinguishing system
d. Fixed water mist fire extinguishing system
e. Sprinkler system
f. Drencher / deluge system
g. Else, what?

All thirteen respondents have been working with fixed CO2 fire extinguishing system, but it was not surprising because of the IMO rules. Fixed water mist systems are also familiar for respondents and all of them have worked with them. Sprinkler systems are also spread widely and only one respondent have not worked with them.

Fixed FM-200 systems and FirePro Aerosol systems were mentioned once. FM-200 systems are gas-based fire suppression systems with the capability to absorb heat from the fire. FirePro fire suppression systems contains FPC compounds that transform into a rapidly expanding aerosol when discharged. The fire extinguishing method is interrupting the chemical chain reactions.

Q7. Launching of fixed fire extinguishing system can cause side effects. Estimate the threshold to launch each system with following fire-extinguishing medium.

Existing fire extinguishing systems may be installed on unmanned ships. Some of fixed fire extinguishing systems can cause unwanted side effects for the ship's systems or people. If the permission for system activation is given by a preprogrammed system instead of a human, it is important to know the launching threshold of each fire extinguishing system in advance to avoid unnecessary system breakdowns or human injuries.

The question contained six pre-determined systems using different fire extinguishing agents and a possibility to leave comments. The scale was from 0 to 10, where 0 was *the lowest threshold* and 10 was *the highest threshold*. Pre-determined fire extinguishing mediums are presented in the following table from agent with lowest launching threshold to the agent with the highest launching threshold.

Fire extinguishing medium	Threshold to launch
Water mist	3,6
Halon	5
CO2	5,1
Foam	5,6
Water	5,9
Powder	6,4

Table 3. Launching threshold for fixed fire extinguishing systems using different extinguishing agent

According to the results, the systems using water mist as fire extinguishing agent has clearly the lowest activation threshold. One respondent mentioned in the comment section that it is depending on the fire, material etc. One respondent highlighted that launching of CO2 and Halon has the highest threshold if there are people involved. This comment cannot be ignored, and it should be noticed when developing the fire extinguishing systems for unmanned vessels. As the future ships will still need sometimes humans onboard, such as maintenance works during dockings or harbour times, and so the ship can be manned even the fire extinguishing system is built for continuously unmanned conditions. Uncontrolled activation can even cause loss of lives!

5.2 New energy sources

As we know, new energy sources have become more common, and at some point most of the ships will not use traditional fossil fuel oils such as Heavy Fuel Oil (HFO) or Marine Gas Oil (MGO) as an energy source. New energy sources introduce new risks, and this section is investigating how the respondents see high-capacity batteries and hydrogen as a part of fire management.

Q8. Do you see high-capacity batteries as a risk in fire management?

The purpose of this question is simple. To examine how serious the risks of high-capacity batteries are in fire management. The scale was from 1 to 5, where 1 was *lowest* and 5 *highest*. It became clear that there exist worries about high-capacity batteries fire management. Ten respondents answered the highest option 5 and the remaining three answered the second highest option 4. The calculated average is 4,8, so we can state high-capacity batteries as a high risk in fire management and that cannot be ignored when developing future ships.

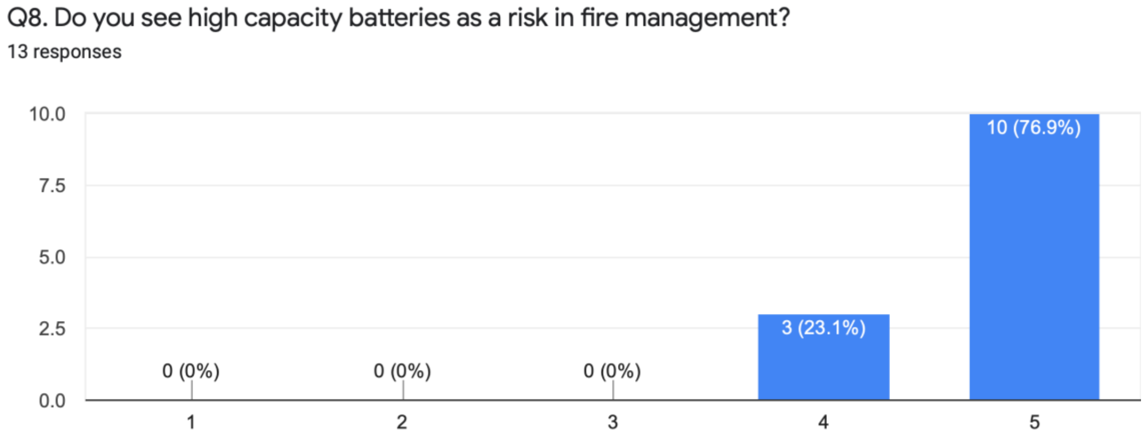

Figure 8. Result chart for high-capacity batteries risk factor

Q9. Do you see hydrogen systems as a risk in fire management?

This question has the same purpose than above mentioned question 8, but with the systems using hydrogen as an energy source. The scale was same the from 1 to 5, where 1 was *lowest* and 5 *highest*. The respondents see hydrogen as a risk for fire management, but with calculated average 4,3 it is seen less dangerous than high-capacity batteries.

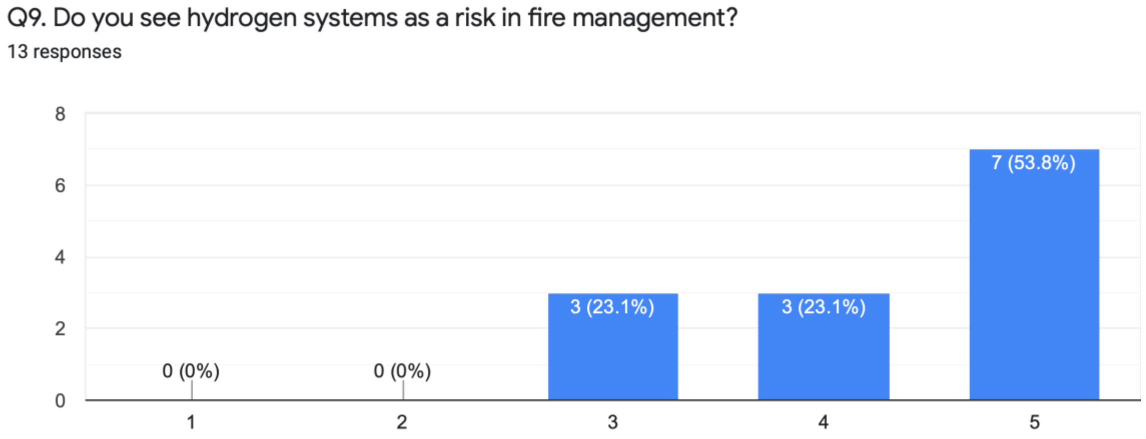

Figure 9. Result chart for hydrogen risk factor

Q10. Do you have any proposals how to extinguish high-capacity batteries?

The purpose of this question was to create brainstorming and see what kind of solutions pops out. The question is complicated and one respondent pointed out that even professional fire fighters are struggling with this. Nine respondents consider cooling to be the most effective fire extinguishing method and the most common solution for cooling with six votes was to immerse the entire battery package in water. One respondent was concerned about submerging the entire battery unit and it is obviously good consideration, especially if there is no other power supply onboard. One respondent proposed batteries to be divided into several small A60 compartments with separate launched fire extinguishing systems to improve redundancy, so perhaps batteries can be divided for smaller battery packages and located in individual spaces that can be flooded with water.

According to the answers, the respondents' knowledge and experience on the subject vary widely. One respondent did not have any experience about the topic and one respondent has some experience about successful fire extinguishing of an electrical vehicle with a fire blanket. One proposal was to use CO2 for flames and water for cooling, while other respondent proposed high volume of dry chemical extinguisher system, but unfortunately did not identify more specific. One answer was quite comprehensive and shows the professionalism of the respondents: "*Battery fire is self-igniting after extinguishing and the exothermic chemical process will generate heat for long time. Due to this, the battery pack needs to be cooled down. Water or foam are effective mediums for cooling and extinguishing. Continuing water mist is effective method of extinguishing large battery fire, as total submerging of the unit would be impractical. However, gaseous hydrogen can be formed at the event of battery fire when mixed with water. Powder, CO2 and Halon do not have cooling capabilities and therefore they shouldn't be used as only battery firefighting medium.*"

Q11. Do you have any proposals how to extinguish hydrogen systems?

This question has the same purpose as question 10, but regarding hydrogen as a burning substance. As the hydrogen systems are still uncommon and rarely installed on ships, only ten out of thirteen respondents answered this question. The most mentioned fire extinguishing method for hydrogen fires with six mentions was ceasing or shutting the hydrogen supply. This will probably be the best option, but many of the respondents has suggested also other fire extinguishing methods such as CO2, water, foam, powder and even effective, but prohibited Halon is mentioned. This makes me doubt whether all the respondents are still thinking about burning hydrogen or are they considering the entire situation, where surrounding combustible material are on fire.

One comprehensive answer was looking for the entire situation and has several fire extinguishing methods to solve the problem. *"The most important step in case of hydrogen fire is to cease the supply of more hydrogen. When flammable gases are used as fuel, the system needs to have fail-proof, automatic, and manual shut-down mechanism. After shutdown, the flame itself is difficult to extinguish, but cooling the surrounding area is vital to prevent the fire from spreading. Hot surfaces create serious possibility of re-ignition. Water (mist) is sufficient with gas fires, but foam and powder can also be used."*

5.3 Fires onboard remotely controlled and unmanned ships

In the questionnaire's parts 1 and 2, respondents met questions about some new risks and existing fire extinguishing systems and hopefully it provided perspective for the final chapter, which is closest to this master's thesis subject. One big piece of the puzzle is adapting traditional fire extinguishing and prevention systems into remotely controlled and unmanned ships. In this part the main purpose was to see how respondents see different kind of fire extinguishing and fire prevention systems in ensuring the fire safety of unmanned or remotely controlled ships.

Q12. Which of fire detection systems are most reliable for autonomous vessels?

As stated in the theoretical part, the most important thing after a fire has started is to detect the fire as soon as possible. Question 2 made it clear that most fire alarms are false alarms and if there are no people onboard to confirm whether the fire alarm is real or not, the fire detection system must be as reliable as possible. This question looks at how the respondents see reliability of different fire detection systems.

The question included six predefined most common fire detection systems and the option to choose something else. Predefined options were Smoke fire detector, Heat fire detector, Flame fire detector, CCTV, Sprinkler system and Machine vision with thermal cameras. The most chosen predetermined option with four vote was Machine vision with thermal cameras, but eight respondents suggested some combination of earlier mentioned systems. Systems with several different feedback methods can detect different type of fires, so such systems could be the most reliable solution. The traditional fire detectors were not considered reliable enough and only the smoke fire detector option was selected once.

Q13. Which of the fixed fire extinguishing systems are most reliable for autonomous vessels?

Structure of this question is a copy of question 12. Predefined options were: Fixed CO2 fire extinguishing system, Fixed Halon fire extinguishing system, Fixed Foam fire extinguishing system, Fixed water mist fire extinguishing system, Sprinkler system and Drencher / deluge system. This question divided opinions. Four respondents again proposed a combination of different systems and one of them also mentioned that it depends on the type of room protected. Five respondents chose fixed CO2 systems making it the most popular selection. That was surprising, because in questions 10 and 11, which asked about new energy sources, the CO2 solution only got a few votes. Fixed water mist systems, which were proposed also for fire-extinguishing of hydrogen and high-capacity batteries, got three votes making it the second most popular predefined option. Remotely controlled or unmanned vessels may not go hand in hand with new energy sources, so perhaps these two issues should be investigated separately.

Q14. How can a fire be managed if Fire Control Centre is located in land based remote operation center?

The purpose of this question was to identify if the respondents see huge problems with land-based fire control centers. The scale was set from 1 to 5, where 1 was *Not at all* and 5 was *No difference from traditional fire management*. None of the respondents did select the extremes and as the calculated average was 2,8, it can be stated that there is a difference between land-based fire control centers and traditional fire control centers, but it was thought that fires can be managed some way from land-based fire control centers. One respondent highlighted, that remote connections are never 100% reliable, but they must work to reach this level of fire management.

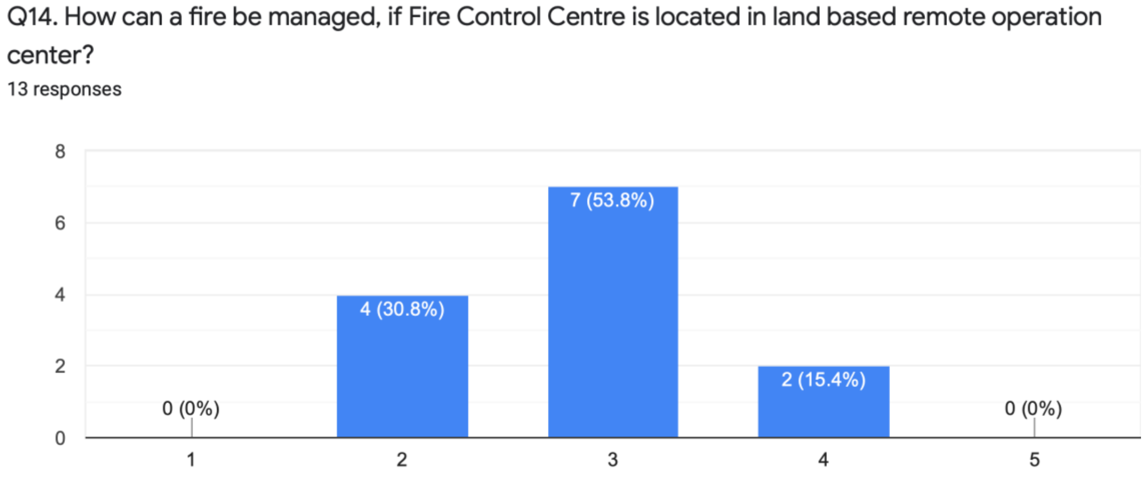

Figure 10. Result chart indicating how the answers divided in question 14.

Q15. Can fire detection system directly activate the fire-extinguishing systems when it recognizes the fire?

The decision to launch fire-extinguishing systems onboard conventional vessels are made by people depending on the fire situation. Fully autonomous ships mean there are no people to make decisions and this question investigated whether fire detection systems could control fire-extinguishing systems directly or is it necessary to have more confirmation before launching. The results were 50-50, until I received thirteenth answer turning the result slightly to the Yes-side.

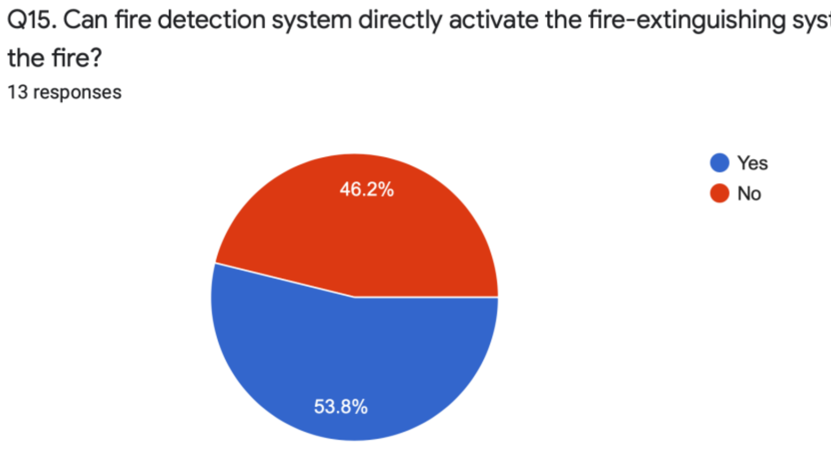

Figure 11. Voting ratio for question 15.

As there is no big difference in answers, the conclusions are difficult to set. In question 7 it was asked about the thresholds for launching different fire extinguishing systems and the results showed there were differences between the fire extinguishing systems. It is possible that one respondent was thinking about fire extinguishing systems using powder as fire extinguishing agent, while the other one studied this issue with water mist fire extinguishing systems in mind. Perhaps this should have been taken into account in order to get more precise answers to this matter.

Q16. Do you see cyber-attacks as a risk in fire management?

The subject of cyber-attacks is a huge entity and should be researched as an independent case. However, the topic is relevant and cannot be ignored in this thesis. The purpose of this question is to examine how serious the respondents see the risks of fire management if ships firefighting and fire prevention systems are under cyber-attack. The scale was from 1 to 5, where 1 was *Low risk* and 5 was *High risk*.

None of the respondents chose the Low-risk option but as many as four chose the highest option. The calculated average was 3,5 which means that the risks are seen as only slightly increased. The results were unexpected as there has been a lot of news coverage on the seriousness of the subject.

Figure 12. Result chart indicating how the answers divided in question 16 about cyber risks

Q17. What can happen if ships fire prevention systems are under cyber-attack and launched unnecessarily?

This question provided one possible scenario for how cybercriminals could disrupt a ship's operations. The purpose of this question was to collect possible scenarios that ships can meet if some fire-prevention system is activated unnecessarily. The answers for this question are as I expected for the questions about cybercrime. Two of respondents answered in abbreviated form "total disaster" and "catastrophe". The rest of the answers looked at the situation in more detail.

- *"The extinguishing media can cause electrical failures or problems to equipment. Also, free water surfaces can grow to dangerous levels if the draining of water is not carried out in some spaces (cargo decks below waterline for example)"*
- *"Shut down of critical systems i.e. internal combustion engine -> Loss of propulsion etc. MRCC and VTS alarmed and activation safety officials. Negative media attention and a lot of paperwork."*
- *"There are several risks. For example, there is a risk that in a case of fire, the fire extinguishing systems do not work properly or they can switch off etc."*
- *"Interruption of voyage, electrical malfunctions, inability to continue the voyage without service personnel's action, spoiling of the cargo."*
- *"May damage to on-board systems or machinery. May cause stability issues if drenching systems etc. are activated and not controlled."*
- *"In most case the ship's traffic stops. Depends which system is activated and what are the effects."*
- *"Depending on the fire extinguishing system. The ship may malfunction, stop or even sink."*
- *"Depends on extinguishing media, but machinery breakdowns are possible due to water or foam"*
- *"Ship will more than likely require persons to attend vessel to restart"*
- *"Depends on how good the backup systems are"*

Q18. Are conventional firefighting and prevention systems sufficiently reliable for unmanned vessels?

This last question summarizes the questionnaire and simply asks whether the conventional fire extinguishing and fire prevention systems are reliable enough for unmanned vessels. The scale was from 1 to 10, where 0 was *Not at all* and 10 was *Absolutely*. The calculated average was 5,6 and thus slightly more on the reliable side.

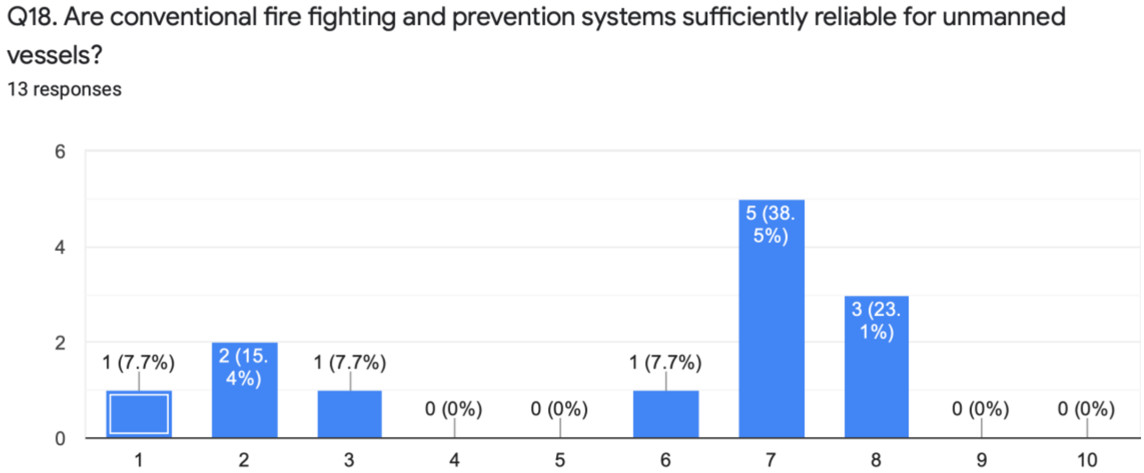

Figure 13. Result chart indicating how the answers divided in question 18.

The comment section included only one comment why the conventional systems are not sufficiently reliable. “Have to have more automation and perhaps, if not CCTV, so IR-cameras and so on.” There were also some comments on why conventional systems are capable to ensure the fire protection of unmanned ships and some aspects that should be taken into account in fire management of unmanned ships.

- *“Conventional water mist and CO2 systems should be reliable and are generally operated remote or electronically (in particular systems on High-Speed Craft).”*
- *“Existing systems can be combined with a functioning and reliable system for ships”*
- *“System probably are reliable enough, but how can it be sure that fire is extinguished, and system can start to revert back to normal. Post surveillance after fire?”*
- *“Conventional fire detecting system may be reliable for unmanned vessels, but my opinion is that the conventional fire extinguishing systems always need a human*

interaction at some point. Of course, I'm not familiar with the most modern systems at market."

According to the results and the comments on this chapter, the conventional fire protection and fire prevention systems can somehow ensure the fire safety of unmanned vessels but still has a great potential to improve. Many of the respondents repeated the word "combination" and I believe that a great combination of different fire extinguishing and fire prevention systems will soon be found as the autonomous shipping industry will continue developing.

6 Discussion and critical review

The absence of crew has both positive and negative aspects to the fire management onboard unmanned vessels. As mentioned, the most of incidents are human faults, but on the other side of the coin, humans can prevent fires with visual surveillance and preventive actions. The most effective way to extinguish a fire is to make quick fire extinguishing and usually it is made by humans with portable extinguishers. If there are no humans onboard, quick fire detection and fire extinguishing must be ensured in some other way.

It is possible to control almost all ship's systems and change data between ships and remote-control centers, but in my opinion, future ships should be able to solve most of the problems autonomously. Obtaining situational awareness in a case of incident can be difficult onboard, but in land based remote control centers it can be even more difficult or impossible.

Classification societies require that the safety level of autonomous or remote operated vessels is equivalent to- or better than conventional vessels. It seems that all the necessary systems already exist, but it is time to find the most suitable, reliable, and cost-effective combination to ensure the safety of future vessels. Ship owners, authorities and the maritime industry should have collaborative projects to find the solution we are looking for.

For the research project, it was important to understand how much energy can be involved in fires and how effective different fire extinguishing methods and systems are. In following paragraphs, I will reflect my personal opinions and introduce thoughts that has appeared during the research.

6.1 Fire detection

Fire detection appeared as a challenge in the questionnaire. It became clear that too many of given alarms are not caused by fire. The fire detectors themselves are sensitive but the fire confirmation appears as a problem if there is no human sense onboard.

In the questionnaire it was confirmed that CCTV is a good way to confirm whether the fire alarm is real and also to enhance situational awareness. CCTV has one enormous problem and so might be unusable for remote operations in the near future. The problem is that video surveillance requires a large amount of data transfer. It is not a problem to process that large amount of data onboard, and actually that is happening already in autonomous cars, but the problem appears when it becomes necessary to send the data via satellite to the shore based remote control center. In that case the communication system might be overloaded, and it has to choose vital data and reduce sending the secondary information. The 5G-network or similar might work in archipelago and coastal waters, but for ocean going ships the satellite system must be improved.

To minimize data transfer between ship and remote-control center, the data from CCTV can be processed onboard with a video detection system. The system can process that large amount of input data onboard and send simple output data such as pre-warning or an alarm with address to person in charge in a shore based remote control center or the system can solve the problem autonomously and activate preprogrammed fire management procedures. Machine vision with thermal cameras, which was the most proposed predetermined option in questionnaire, can also be connected to video detection system.

Traditional fire detectors can also be installed on unmanned or autonomous vessels, but as individual they cannot ensure reliable fire detection.

6.2 Fire extinguishing

The absence of fire fighters can cause problems in fire detection but also in fire extinguishing. The questionnaire confirmed that most of the fire incidents encountered by the respondents were extinguished by humans. Normally fire squads deal with the initial state of a fire and is later followed by assistance of fixed fire extinguishing systems. If there are no fire squads onboard, the fixed fire extinguishing systems must be activated in the initial state of a fire and there should not be any hesitation.

A combination of fixed fire extinguishing systems seems to be the correct way to ensure the fire protection of unmanned vessels. Fire extinguishing systems shall co-operate fully with a ship's other systems, such as fire detection systema, emergency shutdowns, fire dampers and smoke extraction. Fixed fire extinguishing systems must be selected considering the ship itself and the protected space.

Automatic sprinkler systema can deal fast and effectively with fires that occur and so they are common in accommodation areas, shopping areas and such as public spaces. In machinery spaces they are not allowed by the IMO. For unmanned vessels the system may not be suitable, because after the fire extinguishing or false launching, the section valve must be kept closed until the ruptured sprinkler head is replaced, thus the whole section is out of order for that time. The system also consumes huge amount of water and can thus affect the ship's stability.

CO2- or some other fixed gas fire-extinguishing system may be suitable for unmanned vessels. CO2 is an effective and fast way to extinguish the fire and system activation needs less consideration if there is not crew onboard and the fear of human incidents is not there. A negative aspect of the system is that the resolution of the Maritime Safety Committee prohibits the automatic release of CO2 agent, so it cannot be directly controlled by fire alarm system and release must be done for example from fire control station. False alarms can cause at least financial loss as systems with gaseous extinguishing medium requires service after release and at least some of the gas cylinders need to be replaced at the next port.

Systems using Halon as fire extinguishing agent had the second lowest launching threshold in the questionnaire. Halon is a very effective fire extinguishing agent and is safe to use as it is not life threatening. However, I do not see Halon as the fire extinguishing agent of the future, because it has harmful effects on the environment and its use is already prohibited.

Water mist fire extinguishing systems are probably the best solution for the interior and machinery spaces of unmanned vessels. Water mist systems have many benefits compared to other fixed fire-extinguishing systems. Water mist fire extinguishing systems consume only a small amount of water compared to traditional sprinkler or water spraying systems. This will prevent equipment in protected rooms from breaking and does not have significant impact on ships' stability. As the extinguishing agent is only water mist, these systems do not cause mess such as foam or powder systems and after launching no post-cleaning work is required.

One of the biggest advantages of water mist systems is that the system can be released immediately after a fire is detected or even if there is only a small suspicion of a fire. Unnecessary launch due to false alarm will not have consequences to human health or ships equipment. Water mist fire extinguishing systems can be reset without extensive service and therefore activation of the system does not cause an urgent need to visit a port for assistance. The low threshold for activating water mist systems was confirmed in the questionnaire as the respondents estimated water mist systems to have the lowest threshold of all systems. Water mist fire extinguishing systems have good cooling capability and can be a solution for extinguishing of high-capacity batteries.

6.3 Safety centre and fire control station

A fire control station is a place that provides an area where fire-fighting operations and other emergency procedures can be directly controlled. It can be an individual room or a part of a safety centre. Onboard manned ships several fire management systems are manually or remotely controlled from the safety centre or fire control station. Humans makes the decisions to use the systems when they think it is good for the situation of the fire.

In my opinion, Fire control stations of unmanned vessels can be located in land based remote control centers. The fire control station may be a computer-based program with capability to control all fire-fighting systems remotely. It may be an independent or a part of the entire remote operations program.

If the fire management is located in land based remote control centers, it may be difficult to get the complete picture of incidents. It is important that fire-fighting systems can be used without causing damage on a ship or its equipment if the launch has been based on a false alarm. If launching will cause damage, the operator must be sure that an alarm is a real and launching is good option at this stage of the fire.

6.4 Cybercrime

Cyber-attacks against fire control systems can have serious consequences. The most catastrophic situation would be that a cyber-attack would prevent a fire protection system or some part of it from operating when there is a fire onboard. This can lead to the loss of the ship and cargo. Connection loss or disturbance between the ship and the remote-control center may have the same consequences when the operator is not aware of the incident onboard.

If cybercriminals have access into systems, they may have control of all fire systems and launch fire extinguishing systems. Unwanted release of any system may have consequences for a ship. Water spraying systems can fill entire rooms and have negative effects on a ship's stability. Wet electrical appliances such as switchboards, generators or motors would not work as they are designed and that may have impacts for ships operation. Some fire-extinguishing systems, such as CO2, require extensive maintenance after launching. This can result in extra lay-up days at port and thus financial loss, as the ship is not operating. If the fire systems are not working properly, the ship's classification society, flag state or port state control authorities can prevent it from sailing.

If cybercriminals have access to the system of a ship with engine rooms equipped with CO2-fire-extinguishing systems, unnecessary launching of the CO2-system could have serious consequences. Onboard unmanned vessels, the launching of CO2 does not harm human health, but the launching may have an impact on internal combustion engines. Internal combustion engines, usually diesel engines onboard, require oxygen in the combustion process and it is provided from the surrounding air. When CO2-system is launched into the engine room, the liquefied carbon dioxide is released into the surrounding air and neutralizes the oxygen that is needed for the engines' combustion process. Lack of oxygen will reduce the power output and finally there will occur a shut down of the engine. CO2-system launching can be linked to fire dampers of air intake, so the system activation is also closing the dampers to prevent new fresh air flowing in. Even the closing of the air intake dampers may be sufficient to shut down the engines.

One possible solution to prevent unwanted engine shutdowns is to construct individual air intake ducts to the engines. This design is used on naval ships as they are designed to operate in contaminated areas and their HVAC system is capable to overpressure the entire ship through activated carbon filters. Engines require a huge amount of air, and that air mass cannot be filtered, so the engines have air intake ducts directly from outside. Another possible solution is to divide engines or other power sources to several different rooms, so if one room is on fire or CO2 is unnecessarily released it will not paralyze all propulsion or electricity supply.

6.5 Structural fire protection

Structural fire protection is one of the biggest factors in fire prevention. Legislation about structural fire protection must continue updating so it will be suitable for the most innovated vessels. The existing parts apply also in the future, but I found some thoughts that should be considered when developing ships with non-traditional solutions.

The most alarming issue is new types of energy sources. Hydrogen is flammable even at low concentrations in the air, has lower ignition point than traditional fuel oils and can even burn invisibly without smoke. Hydrogen systems and installations should be designed extremely carefully to avoid hydrogen leakage and the fire detection systems must be able to detect invisible fires.

High-capacity batteries have a risk of thermal runaway, which can cause toxic and flammable gases. These extremely dangerous gases should be able to be extracted in a controlled manner. If high-capacity batteries are burning, the burning process itself will release oxygen and the burning temperature can raise to a level where structures can collapse. In the questionnaire part, many respondents proposed a flooding option for extinguishing high-capacity battery fires. It is obviously an effective extinguishing method, but it may have consequences for a ship's stability and the flooded battery cells will be destroyed. Battery cells should be divided into several different rooms to ensure the stability of the ship and prevent healthy battery cells from destruction if there is a need to immerse burning batteries.

7 Conclusion

The main purpose of this thesis was to research different traditional fire prevention, detection and extinguishing systems and to determine their suitability for ensuring the fire safety of unmanned vessels. First I studied theory behind different systems and read several reports about fire incidents to get sufficient understanding about the basics behind the ship's fire safety. The fire safety is a huge entity and information is available in several books and internet sources.

After sufficient understanding was reached, I needed to get opinions from professionals working in the maritime industry. Interviews were excluded, because they cause an unreasonable amount of work and the desired results were also available from the questionnaires. The established questionnaire was successful, and the professionalism of the respondents was impressive. The results of the questionnaire supported the theory and my own opinions.

After all this research work, I believe the existing fire extinguishing, fire protection and fire prevention systems can be installed on unmanned vessels to ensure the fire safety of the ship, but the suitable combination of different systems must be found. The maritime authorities must set regulations for the level of these systems' sophistication, minimum requirements and the accepted effectiveness.

During the research, it became clear that most of the given fire alarms are false alarms and not caused by a fire. Fire confirmation must be more reliable, if the activation of fire extinguishing actions is controlled by a fire detection system. This issue could be solved with the combination of computer-based programs and several different inputs such as sensors and detectors. This issue could possibly be a good research area for another master's thesis or similar research project. The following few subjects may be interesting issues for further research:

- Reliable fire detection and confirmation systems for unmanned vessels
- How to ensure the fire safety of ships powered by hydrogen
- How to ensure the fire safety of ships powered by high-capacity batteries
- Ships' fire management from a land based remote control centre
- Fire management and return to normal operation autonomously

7.1 Acknowledgments

This has been a great journey with ups and downs. Working on ships is shift work and after the shift you go home, and the work stays on the ship. However, the writing process followed along, so it required attention at home, and it also required several late nights while I was on board. There were a lot of disruptions at work and sometimes it was hard to find motivation, but luckily my colleague kicked me forward when needed.

Overall, I have learned a lot and it has been a pleasure to see that there are extremely professional people working in the maritime industry. I would like to thank our AMO student group and everyone who has supported me at any stage of this thesis, but especially the following people: Thomas Finne, Johanna Salokannel, Aleksi Jerohin, Björn Pundars, Declan Black, Emmet Ryan, Joel Paananen, Markus Maksimainen, Olli Saarinen, Oskari Heikkonen, PA Ingman, Pasi Alajääski, Pekka Kiviahde, Timo Lamminen, Vesa-Matti Tala and Ville Valkonen.

For those starting their thesis, I recommend being honest about schedules and adding a few more days to be prepared to respond to changing situations. When something feels insurmountable, work temporarily with another part of the thesis before returning to the struggling part, and do not hesitate to ask for advice or opinions.

Reference list

3M. (2021). *How 3M™ Novec™ 1230 Fire Protection Fluid compares to other systems.* Retrieved from 3M web page: https://www.3m.com/3M/en_US/novec-us/applications/fire-suppression/vs-competition/#novec1230vsinertgas Date of Access 8.3.2021

Andersson, C., & Säteborn, D. (2002). *Smoke Control Systems Aboard - A risk analysis of smoke control systems in accommodation spaces on passenger ships*. Lund: Department of Fire Safety Engineering, Lund University.

Arvidson, M., Bisschop, R., Evegren, F., Faivre, J., Gustin, L. Karlsson, P., Leroux, J., Mindykowski, P., & Vicard, B. (2018). *Second study investigating cost-efficient measures for reducing the risk from fires on ro-ro passenger ships (FIRESAFE II)*. *Alternative fixed fire-extinguishing systems on ro-ro spaces*. European Maritime Safety Agency.

Babicz, J. (2015). *Wärtsilä encyclopedia of ship technology.* Helsinki: Wärtsilä Corporation.

Bryman, A. (1988). *Quantity and Quality in Social Research*. London and New York: Loughborough University.

College of the Desert. (2001). *Hydrogen Fuel Cell Engines and Related Technologies*. Palm Desert: College of the Desert.

Det Norske Veritas (DNV). (2000). *Engine room fires can be avoided*. Høvik: Det Norske Veritas.

Det Norske Veritas (DNV). (2005). *Fires on Ro-Ro Decks*. Det Norske Veritas.

Det Norske Veritas & Germanischer Lloyd (DNV GL). (2016). *Fires on Ro-Ro Decks*. Det Norske Veritas & Germanischer Lloyd.

Det Norske Veritas & Germanischer Lloyd (DNV GL). (2019). *Assessment of selected alternative fuel and technologies.* DNV GL.

Evegren, F., Frösing, M., Gustin, L., Leroux, J., Mindykowski, P., Vicard, B., & Willstrand, O. (2018). *Second study investigating cost-efficient measures for reducing the risk from fires on ro-ro passenger ships (FIRESAFE II)*. *Detection systems in open ro-ro and weather decks*. European Maritime Safety Agency.

George, T. (2021). *An introduction to mixed methods research*. Retrieved from Scribbr Social reading and publishing platform: https://www.scribbr.com/methodology/mixed-methods-research/ Date of Access 8.12.2021

Hyttinen, V., Tolonen, P., & Väisänen, T. (2018). *PALOFYSIIKKA*. (9th edition.). Helsinki: Suomen Pelastusalan Keskusjärjestö.

Häkkinen, P., Kojo, J., Nurmi, T., Rämö, J., Varoma, M., & Vesanen, J. (1996). *Paloturvallinen konehuone: projektin loppuraportti*. Otaniemi: Helsinki University of Technology.

International Maritime Organization (IMO). (2014). *SOLAS – International Convention for the Safety of Life at Sea*. (Consolidated edition). London: International Maritime Organization.

International Maritime Organization (IMO). (2015). *FSS CODE: International Code for Fire Safety Systems*. International Maritime Organization.

Johansson, L. (2017). *Laivapaloista laaditut raportit palokoulutuksessa*. Laurea University of Applied Sciences.

Kaiser, L. (2018). *WHAT ARE WATER MIST SYSTEMS?*. Retrieved from ORR Protection video transcript: https://www.orrprotection.com/mcfp/what-are-water-mist-systems Date of Access 8.3.2021

Kojo, J. (1996). *Paloturvallinen konehuone: projektin loppuraportti, Sammutus ja palonilmaisu*. Otaniemi: Helsinki University of Technology.

Kothari, C.R. (2004). *Research Methodology: Methods and Techniques*. New Delhi: New Age International Ltd.

Larsson, F. (2018). *Thermal propagation in lithium-ion batteries*. Research Institutes of Sweden.

Rinne, T., & Vaari, J. (2005). *The new fire extinguishing agents and technologies.* Espoo: VTT Technical Research Centre of Finland.

Rämö, J. (1996). *Paloturvallinen konehuone: projektin loppuraportti, Konehuoneen materiaalit*. Otaniemi: Helsinki University of Technology.

Streefkerk, R. (2019). *Inductive vs. deductive reasoning.* Retrieved from Scribbr Social reading and publishing platform: https://www.scribbr.com/methodology/inductive-deductive-reasoning/ Date of Access 8.12.2021

Thattamparambil, N. (2020). *How to choose the research methodology best suited for your study*. Retrieved from Editage Insights: https://www.editage.com/insights/how-to-choose-the-research-methodology-best-suited-for-your-study Date of Access 8.12.2021

Tuomisaari, M. (1996). *Konehuoneen sammutus- ja palonilmaisujärjestelmät*. Espoo: VTT Technical Research Centre of Finland.

University of the Witwatersrand, Johannesburg. (2021). *Research support guide for faculty and students.* Retrieved from University of the Witwatersrand LibGuides: https://libguides.wits.ac.za/c.php?g=693518&p=4914913 Date of Access 8.12.2021

Zhang, S. (2000). *Fire protection onboard: enhance fire safety by design*. Malmö: World Maritime University.

This questionnaire is a part of Master’s Thesis Fire hazards onboard unmanned vessels – Fire prevention and fire extinguishing of unmanned ships with conventional solutions.

Thank you for answering!

Name:

Title:

Working experience at the sea or in maritime sector:

Do you want to be anonymous? :

Fires onboard conventional vessels

Q1. Have you been onboard ship while there was a fire?

a. Where was it located?

b. What caused the fire?

c. How was it detected?

d. How was it extinguished?

Q2. How many of the given fire alarms are false alarms? From 0 to 100%

Q3. What is the role of CCTV in firefighting management?

a. Fire detection

b. Fire confirmation

c. Enhance situational awareness

d. None

e. Else, what?

Q4. How important are fire fighters in maintaining situational awareness in a case of a fire?

Not at all important 1 2 3 4 5 Extremely important

Q5. Do you see smoke extraction to be used more

a. during the fire or;

b. after extinction?

Q6. What kind of fixed extinguishing systems have you worked with?

a. Fixed CO_2 fire extinguishing system

b. Fixed Halon fire extinguishing system

c. Fixed foam fire extinguishing system

d. Fixed water mist fire extinguishing system

e. Sprinkler system

f. Drencher / deluge system

g. Else, what?

Q7. Launching of fixed fire extinguishing system can cause side effects. Estimate the threshold to launch each system with following fire-extinguishing medium. Scale is from 0 to 10, where 0 is the lowest.

a. Water

b. Water mist

c. Foam

d. Powder

e. CO2

f. Halon

Comments:

New energy sources

Q8. Do you see high-capacity batteries as a risk in fire management?

Low Risk 1 2 3 4 5 High Risk

Q9. Do you see hydrogen systems as a risk in fire management?

Low Risk 1 2 3 4 5 High Risk

Q10. Do you have any proposals how to extinguish high-capacity batteries?

Q11. Do you have any proposals how to extinguish hydrogen systems?

Comments:

Fires onboard remotely controlled and unmanned ships

Q12. Which of fire detection systems are most reliable for autonomous vessels?

a. Smoke fire detector

b. Heat fire detector

c. Flame fire detector

d. CCTV

e. Sprinkler system

f. Machine vision with thermal cameras

g. Else, what?

Q13. Which of the fixed fire extinguishing systems are most reliable for autonomous vessels?

a. Fixed CO_2 fire extinguishing system

b. Fixed Halon fire extinguishing system

c. Fixed Foam fire extinguishing system

d. Fixed water mist fire extinguishing system

e. Sprinkler system

f. Drencher /deluge system

g. Else, what?

Q14. How can a fire be managed if Fire Control Centre is located in land based remote operation center?

Not at all 1 2 3 4 5 No difference for traditional

Q15. Can fire detection system directly activate the fire-extinguishing systems when it recognizes the fire?

Q16. Do you see cyber-attacks as a risk in fire management?

Low Risk 1 2 3 4 5 High Risk

Q17. What can happen if ships fire prevention systems are under cyber-attack and launched unnecessarily?

Q18. Are conventional firefighting and prevention systems sufficiently reliable for unmanned vessels?

Comments: